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METHODOLOGY FOR CORRECTING BOTTOMHOLE TEMPERATURES ACQUIRED FROM WIRELINE LOGGING MEASUREMENTS IN THE ONSHORE U.S. GULF OF MEXICO BASIN TO CHARACTERIZE THE THERMAL REGIME OF TOTAL PETROLEUM SYSTEMS

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ABSTRACT

Characterization of the subsurface thermal regime is critical for understanding many facets of the petroleum system, from thermal maturation of organic-rich source rocks to thermal preservation and non-degradation of hydrocarbon accumulations. On a broad scale, paleo-heatflow has been mapped for the North American continent (Blackwell and Richards, 2004) as well as the contiguous United States (Blackwell et al., 2011). However, in situ reservoir temperature is a fundamental property (Cooper and Jones, 1959) that is difficult to accurately measure in the subsurface (Deming, 1989). Previous work has described the thermal regime of the offshore U.S. Gulf of Mexico Basin (Waples et al., 2004; Forrest et al., 2005; Nagihara and Jones, 2005; Husson et al., 2008); however, due to the lack of an applicable bottomhole temperature (BHT) correction method, virgin rock temperatures of the onshore portion of the basin remains largely uncharacterized in a regional or subregional context.

The abundance of BHT measurements offers a useful way to characterize the subsurface thermal environment, provided that they are corrected to reflect the reservoir temperature. This study develops BHT correction methods that are specifically calibrated for the onshore U.S. Gulf of Mexico Basin. These BHT corrections are empirically derived and are based on a newly compiled database of temperatures obtained from BHT wireline measurements and, to a lesser extent, from drill stem test (DST) data. The results of this investigation provide a unified BHT correction methodology for the onshore U.S. Gulf of Mexico Basin as well as provide 12 distinct BHT correction equations for each of the 12 physiographic provinces within the onshore Gulf Coast region. This study also characterizes the geothermal gradient regime across the onshore U.S. Gulf Coast, which ranges from 1.89ºF/100 ft in Sabine Uplift area to 1.39ºF/100 ft in the Southern Louisiana Salt Basin.

BACKGROUND

Due to the importance of obtaining accurate subsurface temperatures, a multitude of bottomhole temperature (BHT) correction methods have been developed. These BHT corrections fall into one of three general categories: (1) application of a published correction, (2) numerical modeling, or (3) an empirical derivation calibrated with measured data. Hermanrud et al. (1990) provided a comprehensive summary of the 22 published BHT correction methods widely in use worldwide. The two correction methods most commonly applied to the Gulf Coast region are the American Association of Petroleum Geologists (AAPG) correction developed by Kehle et al. (1970) and the Blackwell-Steele correction (Blackwell and Steele, 1989). These two corrections were intended for wells less than 10,000 ft in depth. Furthermore, both correction methods were empirically derived using shallow drill stem test (DST) data from the Anadarko Basin of Oklahoma, which is geologically dissimilar to the complex salt tectonic regime of the Gulf Coast region.

APPROACH

This U.S. Geological Survey (USGS) study develops BHT corrections for the onshore Gulf Coast region based on the robust empirical methodology derived by Waples and Ramly (2001) and Waples et al. (2004) for other geologic settings. These methods rely on statistical characterization of a population of BHTs to establish location-specific correction equations. The Waples and Ramly (2001) method is calibrated to shallow (less than 8000 ft

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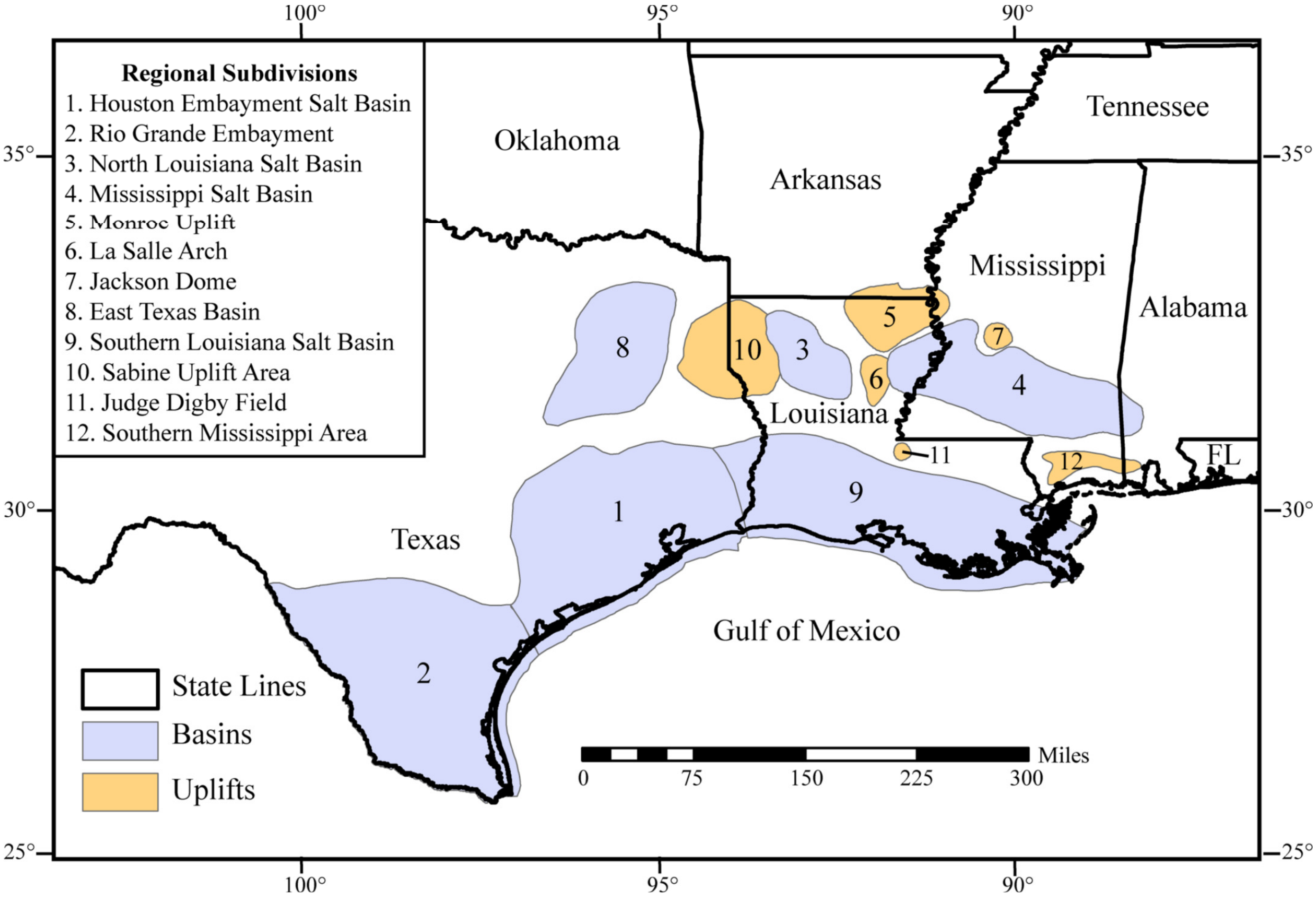


Figure 1. Location map of the study area. The 12 regional subdivisions within the onshore U.S. Gulf of Mexico Basin were based on the regional geologic framework of Ewing (1991).

in depth) data in the Malay Basin of offshore West Malaysia in the South China Sea. The Waples et al. (2004) method is calibrated to the Bay of Campeche offshore Mexico. As these corrections are calibrated for specific geographic areas, the direct application of a location-specific correction to a different geologic setting is not ideal. Each location has a different sedimentary package, burial history, tectonic setting, geothermal gradient, and petroleum system. Thus, empirical correction methods need to be derived for specific petroleum provinces individually.

Historically, BHT corrections have not been developed for the onshore U.S. Gulf of Mexico Basin, because of the absence of publicly available BHT databases. The USGS has recently compiled such a database from a variety of sources (IHS Markit, 2016; AIFE, 2015; Cambe Geological Services, 2010; Louisiana Department of Natural Resources, 2010; Burke, 2010a). This USGS study leverages the empirical methodology developed by D. W. Waples (Waples and Ramly, 2001; Waples et al., 2004), but formulates correction equations that are specifically calibrated with BHT measurements acquired over the onshore Gulf Coast region. The BHT correction equations derived in this study are directly applicable for correcting BHT measurements acquired over the domestic, onshore Gulf Coast region.

STUDY AREA

The onshore U.S. Gulf of Mexico Basin is one of the major hydrocarbon-producing regions of the United States and the world. Significant volumes of undiscovered hydrocarbon resources exist in the U.S. onshore coastal plain and State waters portion of the basin. Recent USGS resource assessments of Cretaceous and Tertiary strata estimated means of 3.09 billion barrels of technically recoverable undiscovered oil, 261.1 trillion cubic ft of undiscovered natural gas, and 6.66 billion barrels of undiscovered natural gas condensates (Dubiel et al., 2007, 2011).

Twelve physiographic subdivisions (Fig. 1) were delineated based on the regional geologic framework of Ewing (1991). Table 1 summarizes the data attributes for these 12 regional subdivisions of the onshore U.S. Gulf of Mexico Basin. This study represents one of the most geographically extensive, data-driven investigations of wireline temperature corrections and thermal gradients across the onshore Gulf Coast region to date.

PILOT STUDY USING DST AND BHT DATA

A pilot study was developed to establish if corrections derived from DST data are in agreement with corrections derived from BHT data. If so, BHT data can then be used in the absence of DST data to develop a robust correction. DSTs are recognized as a reliable source of temperature data, if relatively high flow volumes are obtained from the producing formation (Horner, 1951; Peters and Nelson, 2009). DSTs record the temperature of formation fluids at thermal equilibrium with the reservoir, which provides in situ reservoir temperatures as encountered in the subsurface. However, DST temperature measurements are not as widely available as BHT data. As previously discussed, BHT data are routinely recorded during wellbore operations, thus providing wide geographic and depth coverage over petroleum-producing provinces.

Table 1. Tabulation of data attributes and key results for the 12 regional subdivisions of the onshore Gulf Coast study area. Refer to text for discussion of findings. Asterisk (*) symbols indicate small sample size from which findings were calculated.

Region No.	Regional Subdivision	Data Pairs	Depth Range	Temperature	Population Trendline	BHT Correction	R^2 Value
		(no.)	(ft)	Range (ºF)	(ºF/100 ft)	(ºF/100 ft)	
1	Houston Embayment Salt Basin	1606	164 – 17,201	68 – 350	1.44	1.71	0.9921
2	Rio Grande Embayment	1899	512 – 15,509	85 – 374	1.65	1.93	0.994
3	North Louisiana Salt Basin	163	514 – 12,510	88 – 272	1.60	1.77	0.9891
4	Mississippi Salt Basin	280	405 – 19,034	51 – 320	1.24	1.41	0.9729
5	Monroe Uplift	20	1914 – 9770	100 – 224	1.59	1.59*	0.9364
6	La Salle Arch	6	2536 – 5008	106 – 138	1.32	1.32*	0.9234
7	Jackson Dome	9	2365 – 18,310	110 – 330	1.35	1.35*	0.9766
8	East Texas Basin	299	1429 – 15,200	87 – 325	1.60	1.77	0.9868
9	Southern Louisiana Salt Basin	577	1100 – 20,986	75 – 356	1.10	1.39	0.9777
10	Sabine Uplift Area	636	423 – 12,766	82 – 326	1.67	1.89	0.9949
11	Judge Digby Field	191	4010 – 23,472	98 – 402	1.35	1.50	0.9763
12	Southern Mississippi	81	3605 – 25,542	128 – 467	1.39	1.56	0.9854

Because of the relative abundance of both DST and BHT data, the Sabine Uplift area was selected for a pilot study. A database of DST–derived temperatures was compiled from two main sources (IHS Markit, 2016; AIFE, 2015) with specific criteria: (1) temperatures were obtained from DSTs with excellent mechanical integrity of the pressure test with no leaks present during the test; (2) DST temperatures were obtained from depths greater than 5000 ft and as deeply as possible; (3) multiple DST temperatures were present in a single wellbore; and (4) DST temperature measurements span a variety of depths throughout the wellbore. Additionally, to capture geographic variations across the Sabine Uplift area, well locations with DSTs were selected along a north-to-south transect and also along an east-to-west transect. These two transects intersected in the central portion of Panola County, Texas. A total of 44 robust DST temperatures (Fig. 2A) met these stringent criteria. This dataset spans a depth range of 5659–10,962 ft and a temperature range of 110–260ºF. Using the methods described by Waples and Ramly (2001) and Waples et al. (2004), the maximum temperature envelope of the Sabine Uplift DST dataset has a slope of 1.89ºF/100 ft.

To determine if these DST results are in agreement with BHT results, an additional 694 uncorrected BHTs from the IHS Markit (2016) database were analyzed (Fig. 2B). Using Waples methods, the maximum temperature envelope of the Sabine Uplift BHT dataset was also found to have a slope of 1.89ºF/100 ft. This agreement between the pilot dataset and the total population of wells indicates that BHT data can be used to establish a temperature envelope in the absence of DST data. The 11 other regions of the Gulf Coast study area were examined primarily using only BHT data.

INVESTIGATION

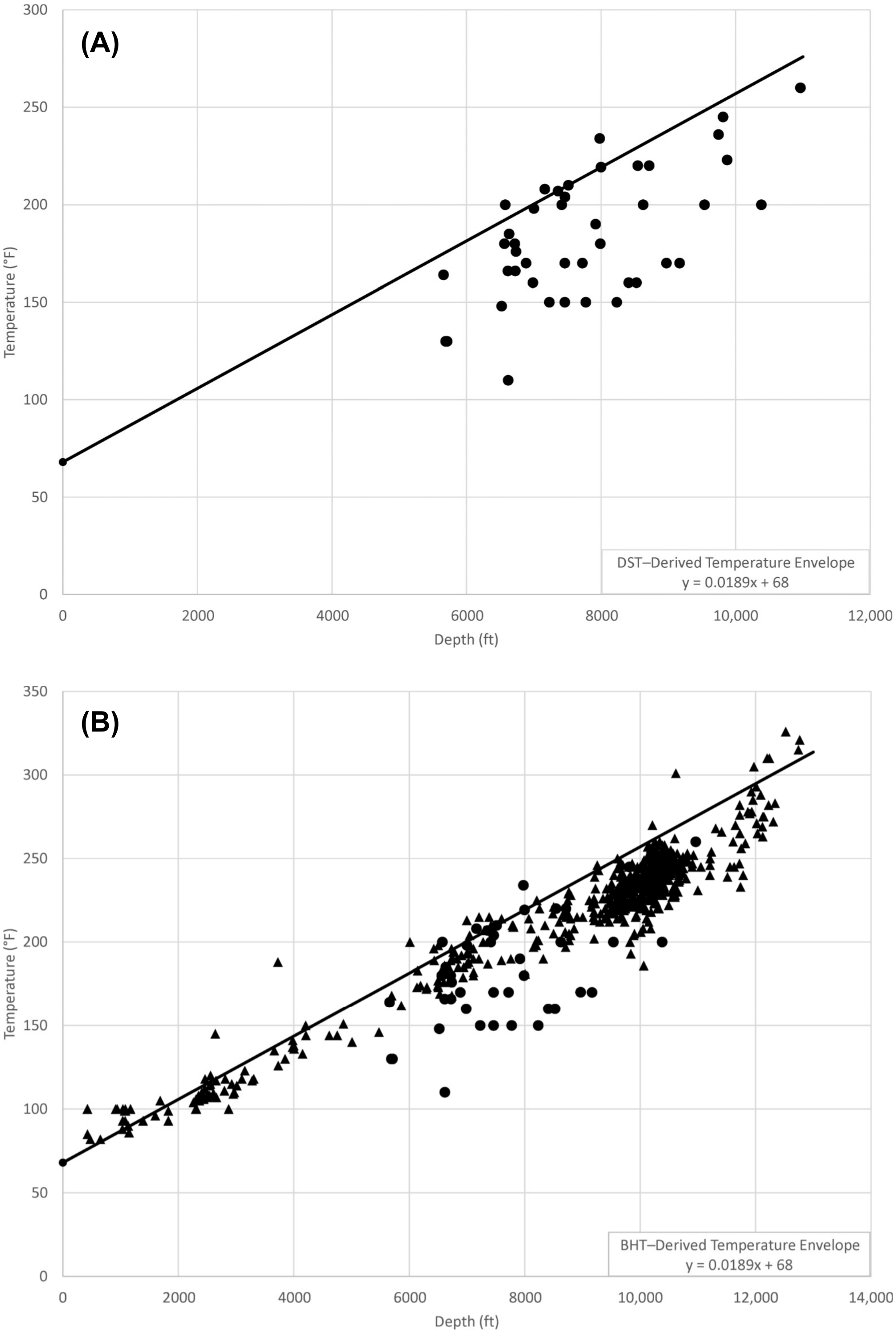
Databases were compiled from the deepest and hottest BHT measurements with the longest time since circulation (TSC) stopped for each of the 12 regional subdivisions (Fig. 1; Table 1). Note that stopping the circulation of drilling fluids can be precarious for wellbore pressure control but enables the wireline logging sensors to approach thermal equilibrium with the reservoir temperature. In practice, a robust wireline BHT measurement acquired in a wellbore is very rare; therefore, several methods have been developed for correcting this valuable wireline logging data.

In order to calibrate BHT correction equations for the Gulf Coast region, statistical properties of the empirical data were determined. Linear envelopes were constructed for thermal maximums, by depth, as follows. First, a trendline gradient for BHT was determined using least squares analysis. Second, each population of temperature data was binned by 2000 ft depth increments to create locally controlled standard deviations in temperature for each individual depth bin. Deeper well data can be more accurate because longer circulation time gives the mud time to equilibrate with the temperature of the reservoir rock (Shen and Beck, 1986). Binning the linear envelope ensures that the linear envelopes are not overly influenced by a large collection of shallow temperature data. Third, standard deviations of BHT were studied for all depth bins in all data populations. Based on the analysis of all 12 databases, we defined an upper bound of maximum BHT based on +1.5 standard deviations above the local mean for a given depth range. Fourth, linear gradients were constructed to represent this upper bound for each of the 12 geographic regions. These lines represent the maximum BHT envelopes of the population of data while honoring the statistical properties of the data in a repeatable method. Essentially, these envelopes provide the expected BHT to occur at each depth and for each geographic region; hence, they prescribe the corrected BHT by depth for specific locations within the Gulf Coast region. The envelopes also represent formation temperature by depth, which provides an estimate of the geothermal gradient for each of these regions.

RESULTS

Table 1 summarizes all the BHT corrections, population trendlines, and statistical properties by regional subdivision. For these equations, the dependent variable, y, represents temperature in Fahrenheit and the independent variable, x, represents depth in feet. Data attributes for the 5767 BHT data pairs covering the 12 regions are also provided in Table 1. A maximum depth of 25,543 ft and high temperatures ranging up to 467ºF were included in the study. Of particular interest, each of the 12 regional subdivisions exhibits a distinct BHT correction.

Figure 2. (A) Drill stem temperatures (DSTs), given in black circles, range from 110 to 260ºF in temperature and 5659 to 10,962 ft in depth. The DST maximum temperature envelope has a slope of 1.89ºF/100 ft. (B) A population of uncorrected bottom-hole temperatures (BHTs) is given in black triangles. The slope of the BHT–derived maximum temperature envelope is 1.89ºF/100 ft. Slopes from DST–derived and BHT–derived temperature envelopes are in agreement. Therefore, a population of BHT data can be used to establish a temperature envelope in the absence of DST data.



The Houston Embayment Salt Basin (Fig. 3A) contains 1606 data pairs with depths ranging from 164 to 17,201 ft and temperatures ranging from 68 to 350ºF. The population of data is described by the trendline equation y = 0.0144x + 68 with a coefficient of determination (R^2) value of 0.8536; while the linear envelope is described by y = 0.0171x + 68 with an R^2 value of 0.9921. The BHT correction is 1.71ºF/100 ft for the Houston Embayment Area.

The Rio Grande Embayment (Fig. 3B) contains 1899 data pairs with a depth range of 512 to 15,509 ft and a temperature range of 85 to 374ºF. The population of data is described by a trendline with a slope of 1.65ºF/100 ft with an R^2 value of 0.8839. The BHT linear envelope is described by the equation y = 0.0193x + 68 with an R^2 value of 0.9940. The BHT correction is 1.93ºF/100 ft for the Rio Grande Embayment.

The North Louisiana Salt Basin contains 163 data pairs that range in depth from 514 to 12,510 ft and range in temperature from 88 to 272ºF (Fig. 3C). Analysis yields a population trendline slope of 1.60ºF/100 ft with an R^2 value of 0.9849. The maximum BHT envelope is given by y = 0.0177x + 68 with an R^2

value of 0.9891 for this basin. The BHT correction is 1.77ºF/100 ft for the North Louisiana Salt Basin.

Results for the Mississippi Salt Basin are given in Figure 3D. The 280 data pairs span 405 to 19,034 ft in depth and 51 to 320ºF in temperature. The slope of the population trendline is 1.24ºF/100 ft with an R^2 value of 0.9077. The BHT linear envelope is described by y = 0.0141x + 68 with an R^2 value of 0.9729 for this regional basin. The BHT correction is 1.41ºF/100 ft for the Mississippi Salt Basin.

The Monroe Uplift area (Fig. 4A) contains 20 data pairs, which is an insufficient population size to conduct a robust statistical analysis using this depth-binning technique. Data range from 1914 to 9770 ft and 100 to 224ºF. In the absence of additional data, the 1.59ºF/100 ft slope of the population trendline, which can be described as y = 0.0159x + 68 with an R^2 value of 0.9364, was used to approximate the linear envelope. The BHT correction is 1.59ºF/100 ft for the Monroe Uplift area.

The La Salle Arch (Fig. 4B) contains six data pairs, thus the BHT correction was approximated by using the slope from the population trendline, which can be written as y = 0.0132x + 68 with an R^2 value of 0.9234. Data range from 2536 to 5008 ft and 106 to 138ºF. The BHT correction is 1.32ºF/100 ft for the La Salle Arch region.

Jackson Dome (Fig. 4C) included nine data pairs, and in the absence of additional data, the population trendline equation was used to approximate the linear envelope. This equation is described by y = 0.0135x + 68 with an R^2 value of 0.9766. Data range from 2365 to 18,310 ft and 110 to 330ºF. The BHT correction is 1.35ºF/100 ft for the Jackson Dome region.

The analysis of East Texas Basin (Fig. 4D) brings us back to a robust investigation with 299 data pairs covering a depth range of 1429 to 15,200 ft and a temperature range of 87 to 325ºF. The population trendline exhibits a slope of 1.60ºF/100 ft and an R^2 value of 0.9396. The BHT maximum envelope is given by y = 0.0177x + 68 with an R^2 value of 0.9868. The BHT correction is 1.77ºF/100 ft for the East Texas Basin.

The Southern Louisiana Salt Basin contains 577 data pairs (Fig. 5A). Depths range from 1100 to 20,986 ft and temperatures range from 75 to 356ºF. The slope of the population trendline equation is 1.10ºF/100 ft with an R^2 value of 0.8149. The maximum BHT envelope is given by y = 0.0139x + 68 with an R^2 value of 0.9837 for this basin. The BHT correction is 1.39ºF/100 ft for the Southern Louisiana Salt Basin.

The Sabine Uplift area has 636 data pairs, with a dense clustering of data in the deeper, hotter region for additional calibration (Fig. 5B). The depth ranges from 423 to 12,766 ft with a temperature range from 82 to 326ºF. The trendline gradient is 1.67ºF/100 ft with an R^2 value of 0.9381. The maximum BHT envelope is described by y = 0.0189x + 68 with an R^2 value of 0.9949. This elevated temperature is expected over the thermally anomalous Sabine Uplift area due to extensive uplift and subsequent erosion of the sedimentary blanket (Nunn, 1990; Ewing, 2009). The BHT correction is 1.89ºF/100 ft for the Sabine Uplift area.

The results from Judge Digby Field (Fig. 5C) are derived from 191 data pairs that represent the deeper, hotter measurements from this prolific natural gas field in the Tuscaloosa Trend of Louisiana. This database (Burke, 2010a) is publicly available. The depth reaches a maximum of 23,472 ft and the temperatures are as high as 402ºF. The population trendline has a slope of 1.35ºF/100 ft and an R^2 value of 0.8342. The maximum BHT envelope is given by y = 0.015x + 68 with an R^2 value of 0.9763 for this location. This is in accordance with previous observations in the literature (Burke, 2010b) of the anomalous geothermal gradient and subsequent hydrocarbon preservation at depth in this location. The BHT correction is 1.50ºF/100 ft for Judge Digby Field, Pointe Coupee Parish, Louisiana.

Data for the southern Mississippi (Fig. 5D) geographical region were obtained from an unpublished database that was manually derived from log headers. The carefully selected 81 data pairs reach a maximum depth of 25,542 ft and an ultra-high temperature of 467ºF. The population trendline slope is 1.39ºF/100 ft and with an R^2 value of 0.9075. From analysis of this database, the BHT envelope is given by y = 0.0156x + 68 with an R^2 value of 0.9854. The BHT correction is 1.56ºF/100 ft for this southern Mississippi geographical region.

The slope of BHT corrections for each of the 12 subdivisions were compared (Fig. 6), and these slopes range from 1.93ºF/100 ft to 1.32ºF/100 ft. The Sabine Uplift area and Rio Grande Embayment exhibit geothermal maxima for the region, and Judge Digby Field and Louisiana Salt Basin exhibit geothermal minima for the region.

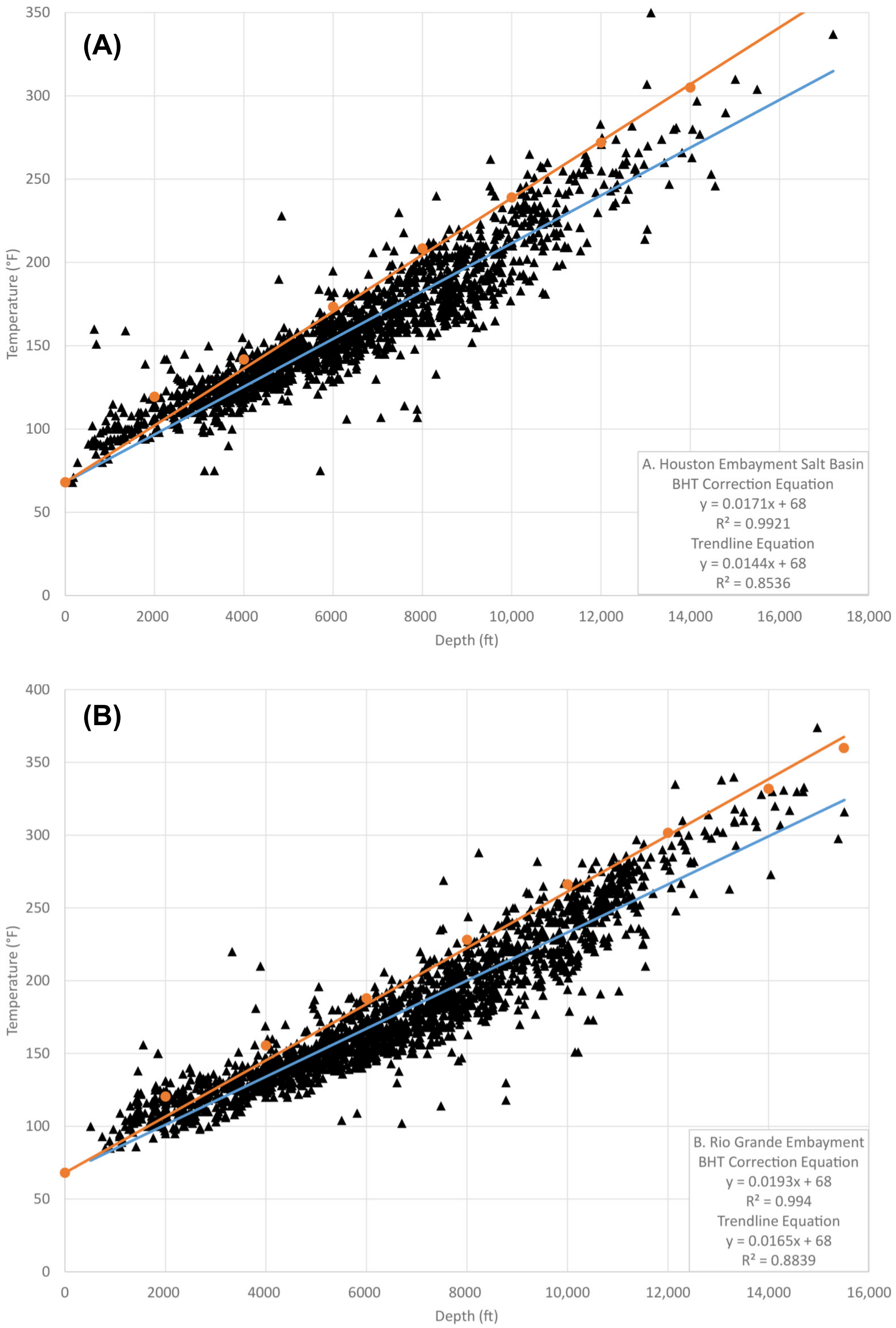
COMPARISON TO OTHER BHT CORRECTIONS

The USGS corrections established in this study were compared to several empirical corrections available in the literature, namely (1) the ZetaWare (2006) correction, (2) Waples et al. (2004) shallow-water Mexico correction, (3) the AAPG correction (Kehle et al., 1970), and (4) the Blackwell-Steele correction (Blackwell and Steele, 1989), which incorporates findings from Harrison (1983). The parameters of depth and TSC were studied independently by constructing two separate databases. One dataset contains data throughout the entire depth range of interest to study the behavior of the USGS corrections at shallow, intermediate, and deeper depths. The second dataset contains the temperature data from wells with the longest duration TSC measurements to study the effects of TSC on the USGS correction. The data-rich Sabine Uplift area was used for these investigations.

Figure 7 shows the variation of temperature with depth over a depth range from 1622 to 16,206 ft, TSC values from 2.0 to 18.5 hr, and a temperature range of 100 to 353ºF. Uncorrected BHTs for the Sabine Uplift area are plotted as grey triangles, showing the range of data for this regional subdivision. Black diamonds represent the USGS corrected BHT data; the black trendline defines the maximum temperature envelope as a continuous function with depth. Yellow circles were calculated using the Waples et al. (2004) correction, which was empirically derived from shallow-water and shallow-borehole data from the nearshore environment of eastern Mexico. This correction overestimates formation temperatures and results in corrected temperatures that are much higher than any recorded BHT measurements in the Sabine Uplift area. This is true even for ultra-deep boreholes with long duration circulation times in which higher temperatures would be expected. The ZetaWare (2006) correction, in red, overestimates formation temperatures in the shallow borehole, but provides a reasonable estimation of the maximum temperatures below depths of 10,000 ft. The AAPG correction (Kehle et al., 1970), in blue, is a third-order polynomial expression in depth. This correction slightly overestimates the maximum temperature envelope. The Blackwell-Steele correction, which was calibrated to the Anadarko Basin, Oklahoma, shown in green, requires subtracting as much as 60ºF from ultra-deep measurements. This substantially underestimates the temperatures for the Sabine Uplift area. This comparison study indicates that the USGS method is most applicable to the onshore Gulf Coast region because it is calibrated using data from each regional subdivision.

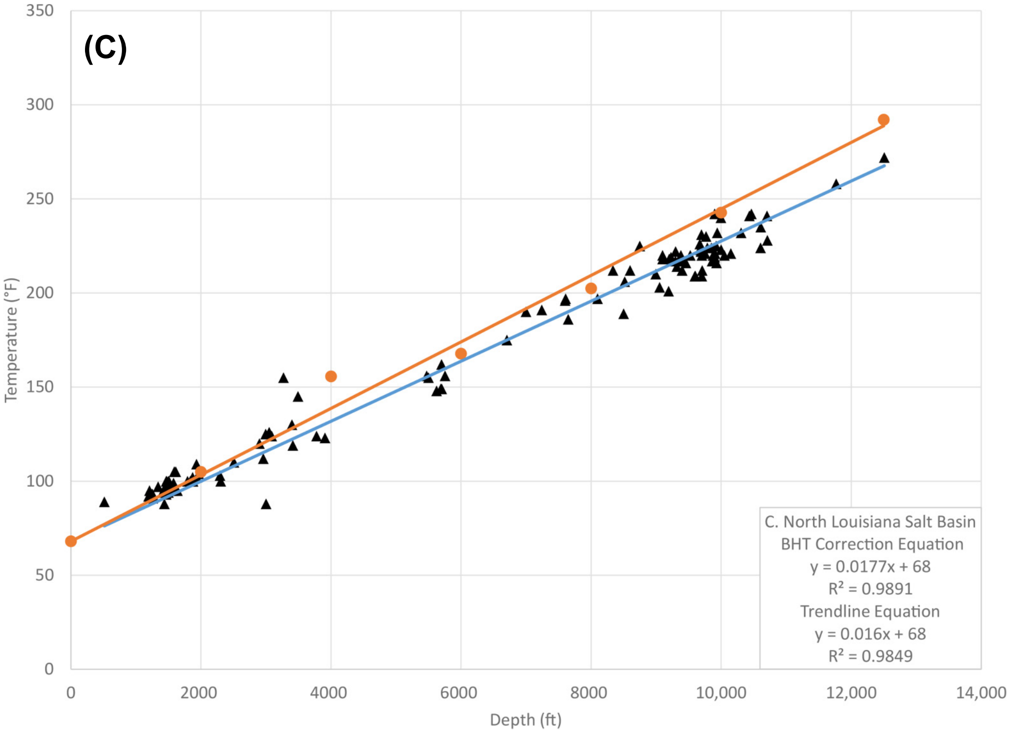
Figure 8 examines the influence of TSC duration on various temperature correction methods over a depth range from 3761 to 15,776 ft, in which TSC values range from 18.0 to 36.0 hr and temperatures range from 149 to 342ºF. Grey triangles are uncorrected BHT data for the Sabine Uplift area. Black diamonds show the USGS corrected BHTs. The Waples et al. (2004) correction, yellow circles, overestimates temperature for the entire depth range of investigation. The AAPG correction by Kehle et al. (1970) overcorrects for the majority of the measurements,

Figure 3. Distribution of uncorrected bottomhole temperatures (black triangles) acquired from wireline logging measurements for (A) Houston Embayment Salt Basin, (B) Rio Grande Embayment Area, (C, FACING PAGE) North Louisiana Salt Basin, and (D, FACING PAGE) Mississippi Salt Basin. The population trendline is given in blue, the orange circles are +1.5 standard deviations above the local mean for a given depth range, and the BHT correction line is given in orange and represents the linear regression of the +1.5 standard deviations.



especially in the shallower sections. However, the two deepest points below 15,000 ft honor the maximum temperatures encountered. The ZetaWare (2006) correction, red circles, relies heavily on TSC and should provide the most accurate representation of maximum subsurface temperatures. However, this correction overestimates temperature in the shallow section, appears random in the 8000 to 10,000 ft depth range, and underestimates temperature in the ultra-deep section. In the Blackwell-Steele (Blackwell and Steele, 1989) corrected BHTs, green circles, shallow measurements are corrected accurately; however, BHTs are greatly underestimated for intermediate and deeper depths. This underestimation is caused by the polynomial expression in depth, which was calibrated using shallow measurements from the Anadarko Basin, Oklahoma.

These findings indicate that the USGS correction, which was specifically calibrated using data from this region, is the most applicable empirical method to apply to this area. Other empirical corrections, calibrated for other basins, even those relying



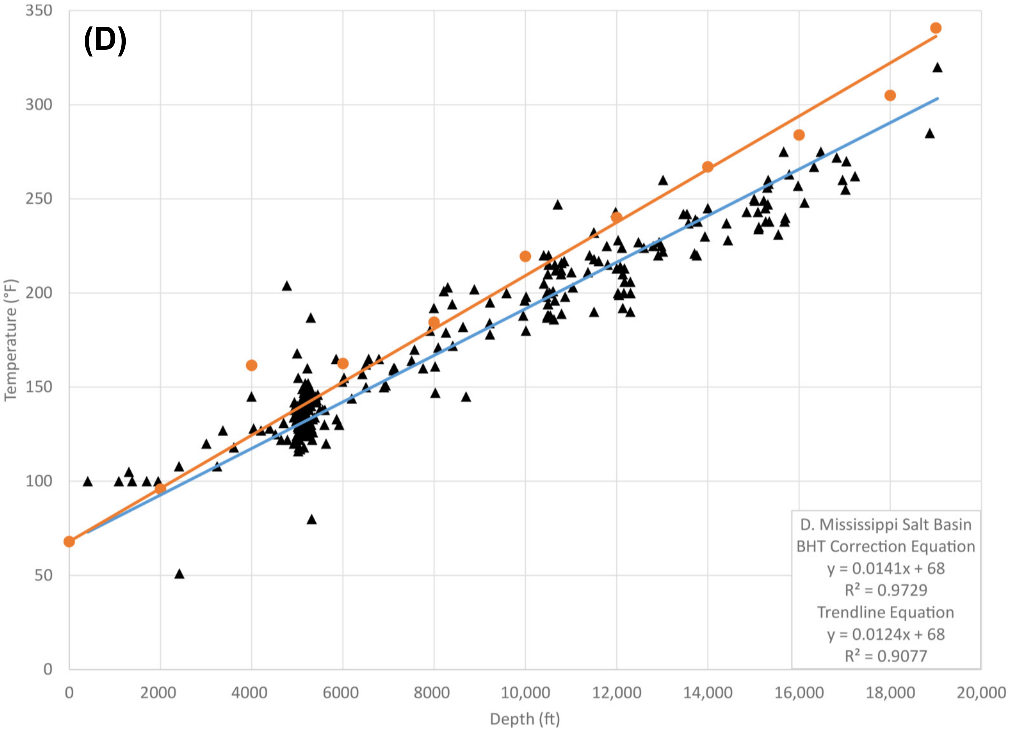


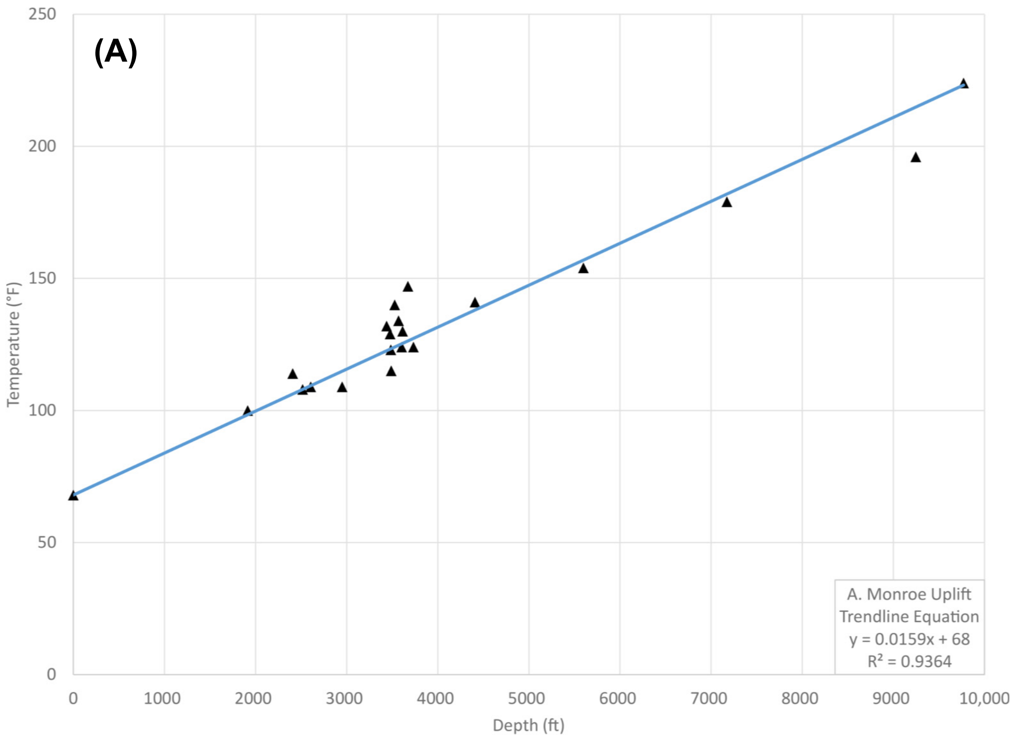
Figure 3, continued. Distribution of uncorrected bottomhole temperatures (black triangles) acquired from wireline logging measurements for (A, FACING PAGE) Houston Embayment Salt Basin, (B, FACING PAGE) Rio Grande Embayment Area, (C) North Louisiana Salt Basin, and (D) Mississippi Salt Basin. The population trendline is given in blue, the orange circles are +1.5 standard deviations above the local mean for a given depth range, and the BHT correction line is given in orange and represents the linear regression of the +1.5 standard deviations.

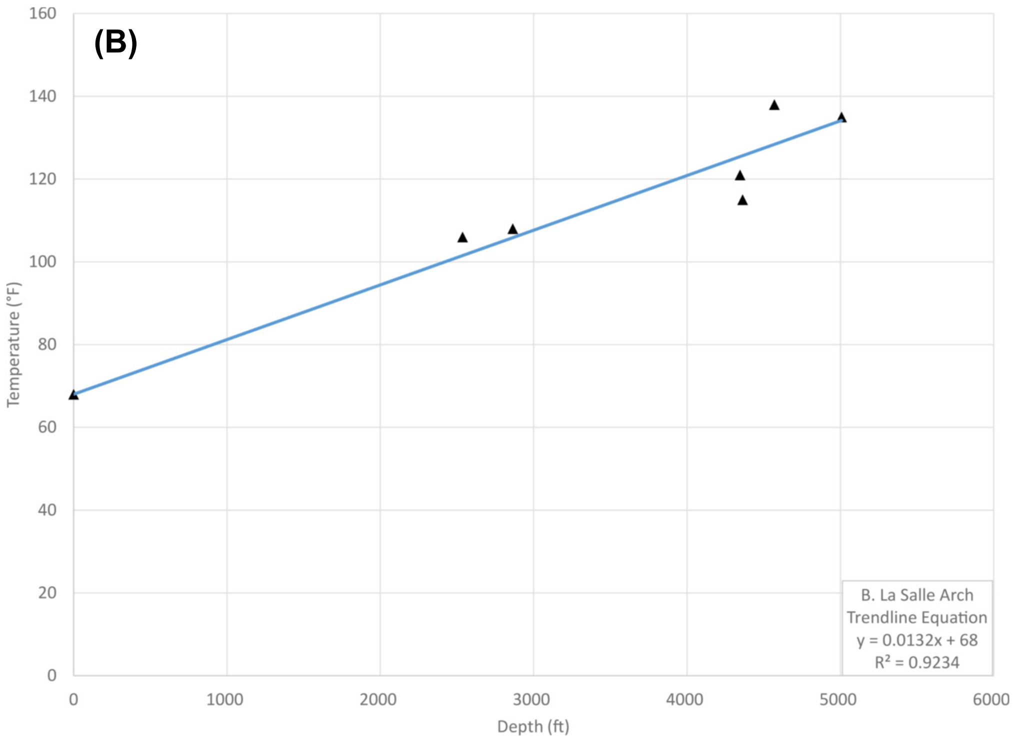
heavily on TSC duration, are less suited for application in this location.

GEOLOGIC MODELS FOR DISTINCT TEMPERATURE REGIMES

The onshore U.S. Gulf of Mexico Basin is geologically complex; accordingly, variations in subsurface temperature are expected to exist. Several plausible geologic models could explain the different thermal regimes in the 12 distinct geologic regions. Thinner sedimentary packages, such as those found in the Sabine Uplift, Monroe Uplift, La Salle Arch, and Jackson Dome may contribute to the elevated temperature regimes encountered in those regions. In areas of thinner sedimentary packages, heat from depth is closer to the surface compared to regions with thicker sedimentary packages (McKenzie, 1978; Bjørlykke et al., 1988). Salt in the sedimentary sequence plays a complex role in thermal energy transfer, because the geometry of the salt body and the history of salt evacuation strongly influence the mechanics of heat flow (Talbot, 1978; Jackson, 1995). Observations

Figure 4. Distribution of uncorrected bottomhole temperatures (black triangles) acquired from wireline logging measurements for (A) Monroe Uplift, (B) La Salle Arch, (C, FACING PAGE) Jackson Dome, and (D, FACING PAGE) East Texas Basin. The population trendline is given in blue, the orange circles are +1.5 standard deviations above the local mean for a given depth range, and the BHT correction line is given in orange and represents the linear regression of the +1.5 standard deviations. Note the absence of an orange BHT correction line for (A) Monroe Uplift, (B) La Salle Arch, and (C) Jackson Dome due to insufficient population sizes for a robust statistical analysis using this precise depth-binning technique. For these three areas, the BHT correction was approximated by using the slope from the population trendline.





from this investigation show decreased subsurface temperature regimes for the Mississippi Salt Basin and the Southern Louisiana Salt Basin. The North Louisiana Salt Basin and Houston Embayment Salt Basin exhibit subsurface temperature regimes that are median to cool as compared to the overall Gulf Coast region. The East Texas Basin is dominated by the peripheral faulting of the Mexia-Talco Fault System (Hager and Burnett, 1960). In this area, the subsurface temperature regime is observed to be elevated due to possible fluid migration through fault conduits. As fluids migrate from depth into shallower regions, thermal energy is transferred upward. Where the thick sedimentary section along the Cretaceous shelf margin has not had sufficient time to reach thermal equilibrium with the surrounding strata, lower than expected temperatures are observed. These regions include Judge Digby Field and the Southern Louisiana Salt Basin. The deep Tuscaloosa Trend of Mississippi and Louisiana (Burke, 2010b) also display lower than expected temperatures for these reasons.

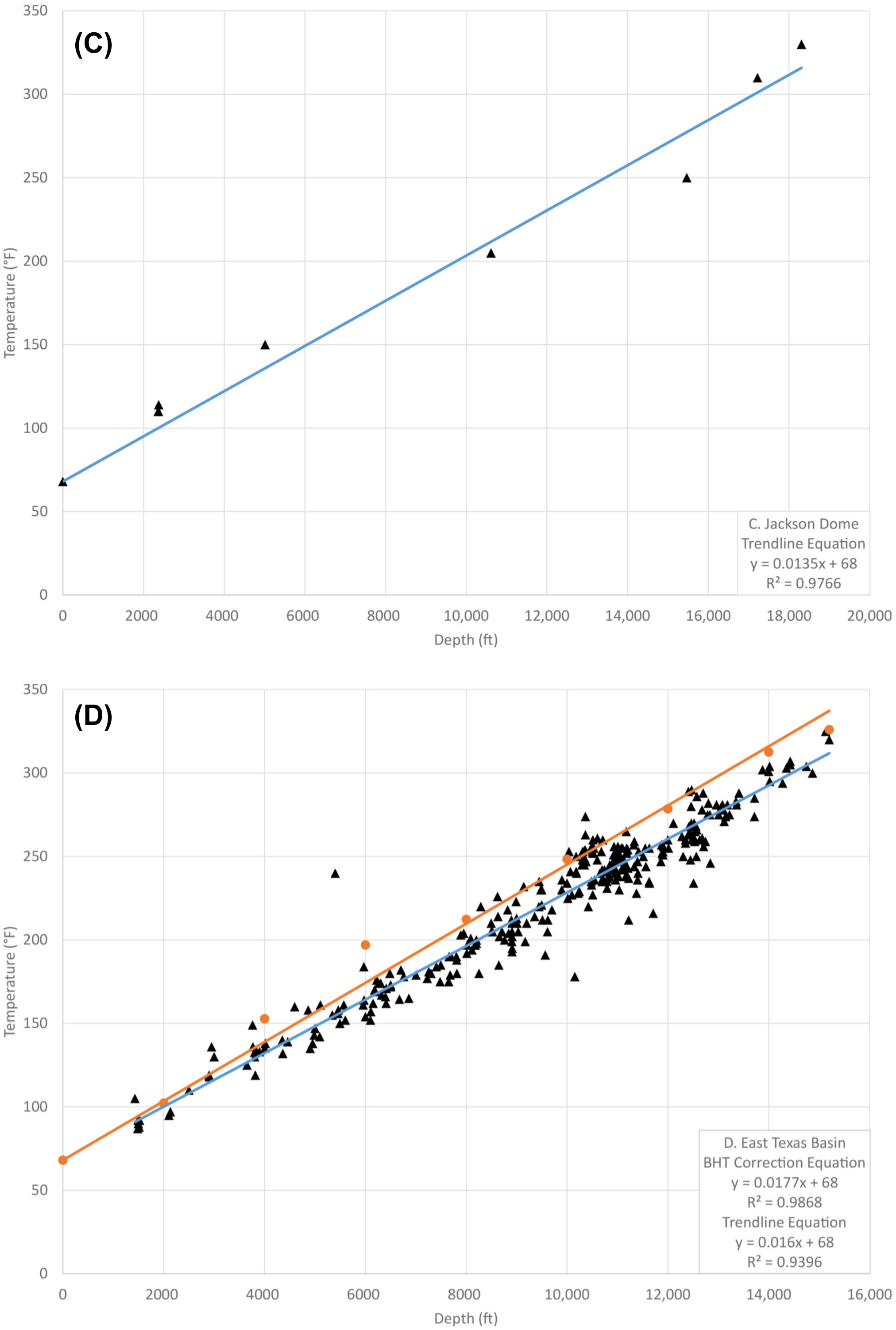


Figure 4. Distribution of uncorrected bottomhole temperatures (black triangles) acquired from wireline logging measurements for (A, FACING PAGE) Monroe Uplift, (B, FACING PAGE) La Salle Arch, (C) Jackson Dome, and (D) East Texas Basin. The population trendline is given in blue, the orange circles are +1.5 standard deviations above the local mean for a given depth range, and the BHT correction line is given in orange and represents the linear regression of the +1.5 standard deviations. Note the absence of an orange BHT correction line for (A) Monroe Uplift, (B) La Salle Arch, and (C) Jackson Dome due to insufficient population sizes for a robust statistical analysis using this precise depth-binning technique. For these three areas, the BHT correction was approximated by using the slope from the population trendline.

DISCUSSION

This USGS method is appropriate for correcting BHT data acquired in the onshore U.S. Gulf of Mexico Basin because the method (1) is specifically calibrated based on empirical data from regional subdivisions across the onshore Gulf Coast, (2) captures the geologic complexity of this region by investigating 12 geologic subdivisions within the onshore Gulf Coast, (3) extends the BHT correction methods to more than twice the depth of any previous empirical techniques, (4) is one of the most data-driven, publicly available studies of BHT corrections for the Gulf Coast region, and (5) is founded upon high-quality temperature data from BHT and DST datasets. Because the onshore Gulf Coast is an important petroleum producing province in the United States and the world, it is important to apply an appropriate BHT correction methodology specifically tailored for the conditions and depths encountered in this geologically complex region. Compared to several prominent empirical corrections available in the

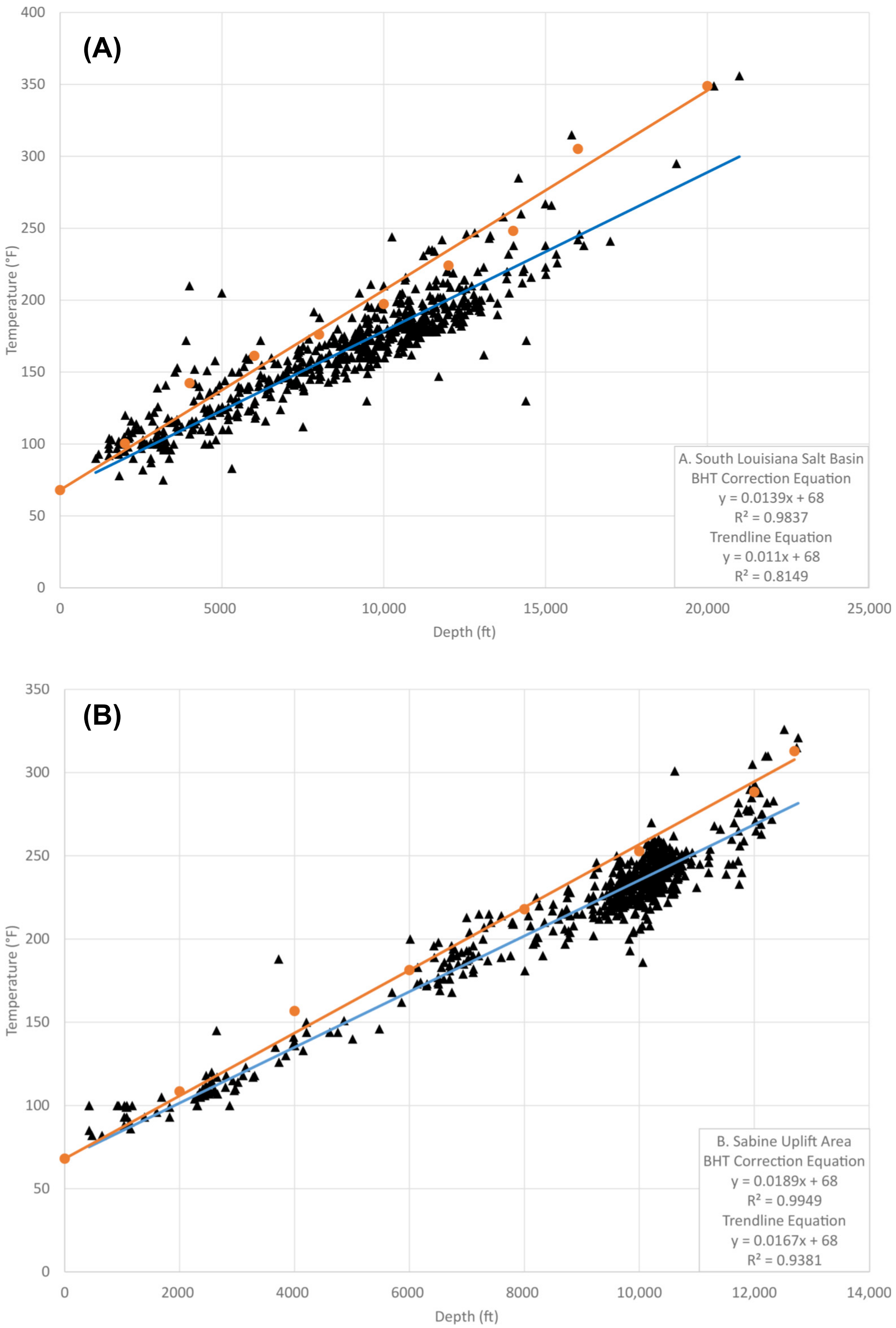


Figure 5. Distribution of uncorrected bottomhole temperatures (black triangles) acquired from wireline logging measurements for (A) South Louisiana Salt Basin, (B) Sabine Uplift area, (C, FACING PAGE) Judge Digby Field, Pointe Coupee Parish, Louisiana, and (D, FACING PAGE) southern Mississippi area. The population trendline is given in blue, the orange circles are +1.5 standard deviations above the local mean for a given depth range, and the BHT correction line is given in orange and represents the linear regression of the +1.5 standard deviations.

literature, it was found that the USGS method most accurately handles BHT data for the Gulf Coast region. No other publicly available empirical correction is calibrated using data for the onshore Gulf Coast region.

The method described in this study is calibrated specifically for the onshore U.S. Gulf of Mexico Basin by statistically defining maximum bottomhole temperature envelopes for 12 Gulf Coast geologic regions within the onshore U.S. Gulf Coast region. Each region exhibits a distinct temperature profile. Consequently, the correction equation for one Gulf Coast region is not characteristic of a neighboring region. Therefore, a multitude of BHT correction equations were developed in a geographical context to capture the complexities of the study area.

The USGS corrections for BHT measurements describe the maximum temperature as a function of depth; thus, they are also indicative of geothermal gradients in each of these 12 regional provinces. Geothermal gradients range from 1.39ºF/100 ft in the South Louisiana Salt Basin to a geothermal gradient of 1.89ºF/100 ft in the Sabine Uplift area. Several geologic models are introduced that could explain why the 12 distinct physiographic provinces exhibit different thermal characteristics. These regional geologic models include thinner sedimentary packages,

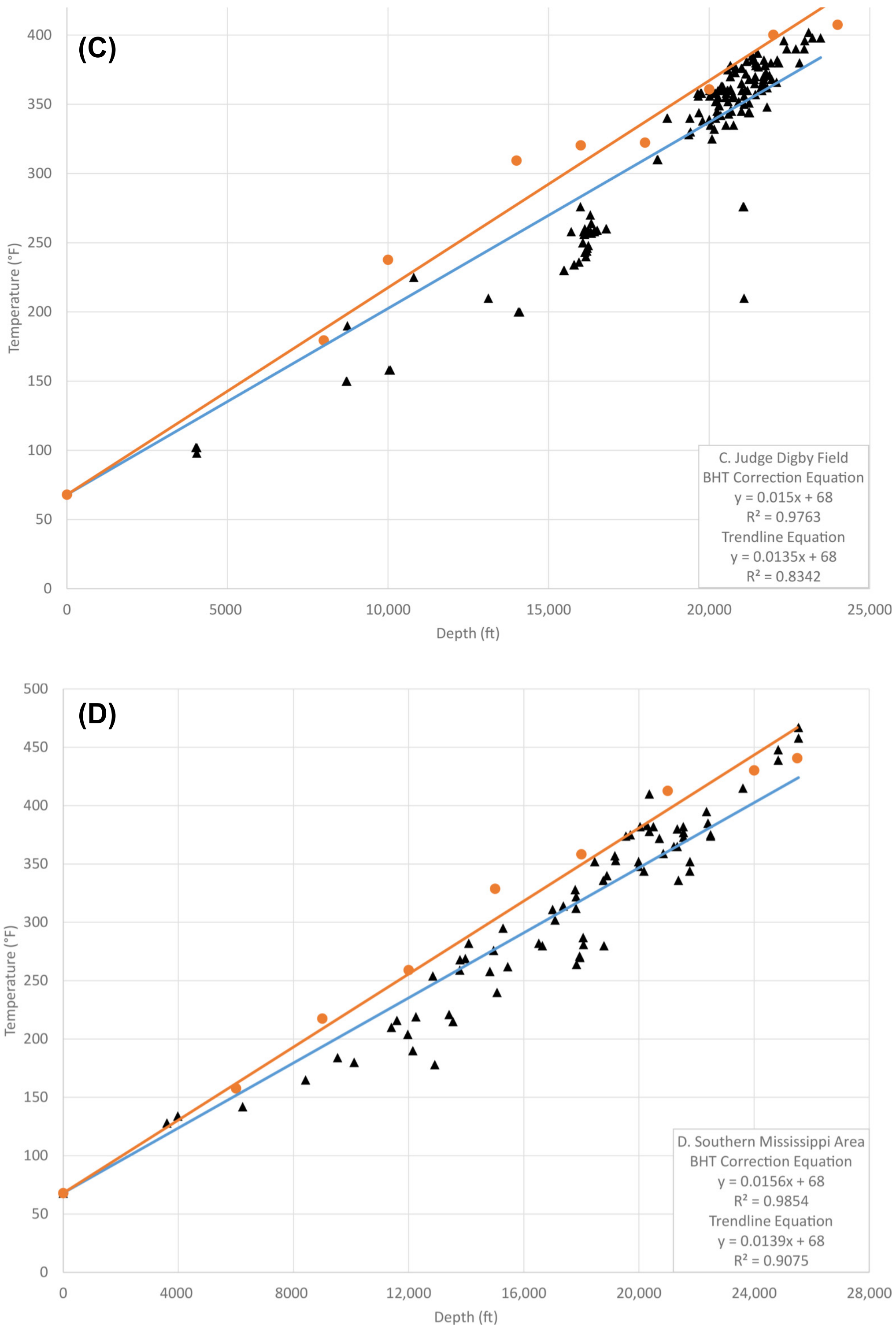


Figure 5. **Distribution of uncorrected bottomhole temperatures (black triangles) acquired from wireline logging measurements for (A, FACING PAGE) South Louisiana Salt Basin, (B, FACING PAGE) Sabine Uplift area, (C) Judge Digby Field, Pointe Coupee Parish, Louisiana, and (D) southern Mississippi area. The population trendline is given in blue, the orange circles are +1.5 standard deviations above the local mean for a given depth range, and the BHT correction line is given in orange and represents the linear regression of the +1.5 standard deviations.**

the presence of salt, peripheral faulting systems, and thick sedimentary section along the coastal margin to explain the regional variation in subsurface temperatures observed in this investigation.

NON-ENDORSEMENT CLAUSE

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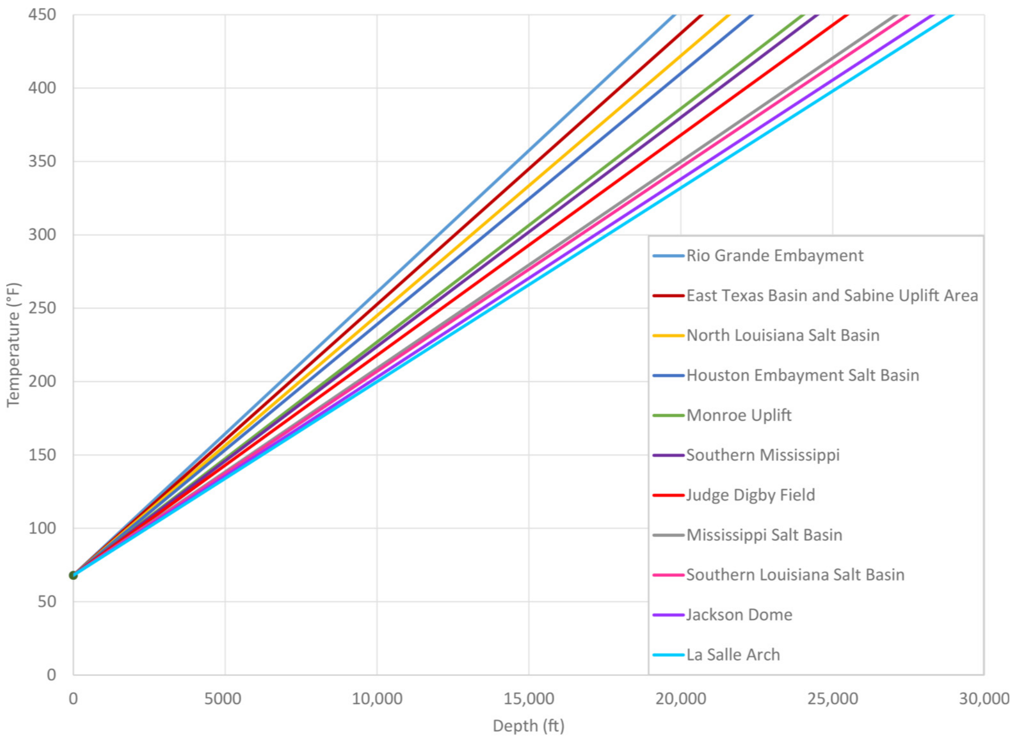

Figure 6. Summary of the slope of all BHT corrections derived from this study of 12 regional subdivisions over the onshore U.S. Gulf of Mexico Basin study area. Each of the 12 regional subdivisions exhibit a distinct BHT correction specifically calibrated to that region. Note that the Sabine Uplift and East Texas Basin trendlines overlap.

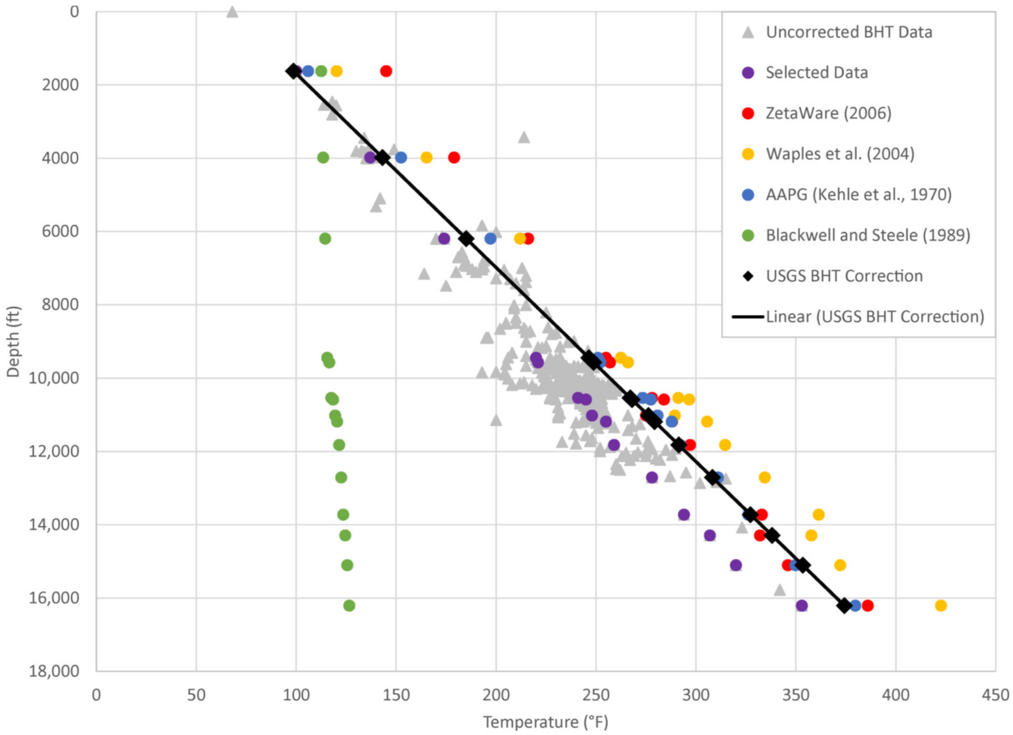

Figure 7. The USGS correction method was compared to other prominent empirical methods available in the literature. The effect of depth variation was studied for each method. Results indicate the USGS method is most applicable to the onshore Gulf Coast because it is calibrated using data from this region.

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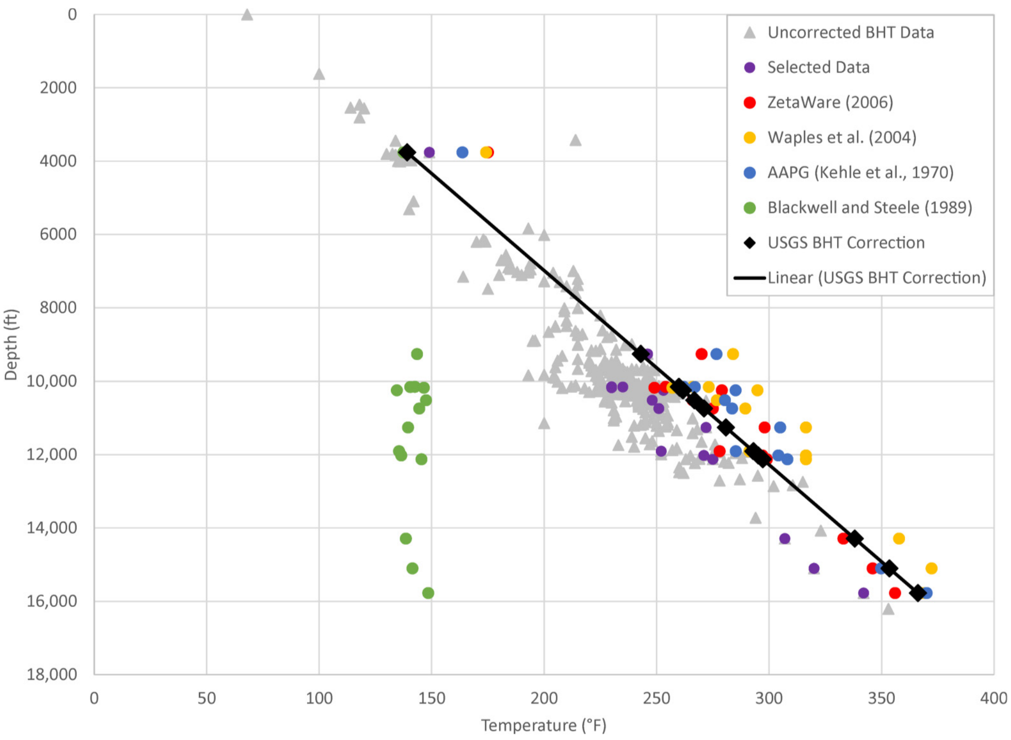

Figure 8. The influence of TSC duration was studied for the USGS correction method and various correction methods in the literature. Findings indicate the USGS method is most applicable for correcting bottomhole temperatures in the onshore Gulf Coast because it is calibrated using data from this region.

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