Thermal Gradient Trends in the Tuscaloosa Marine Shale Play Area: Preliminary Results from Studies to Support Oil and Natural Gas Resource Assessments

Celeste D. Lohr, Paul C. Hackley, Brett J. Valentine, and Catherine B. Enomoto

U.S. Geological Survey, 12201 Sunrise Valley Dr., National Center MS 956, Reston, Virgina 20192

GCAGS Explore & Discover Article #00142*
http://www.gcags.org/exploreanddiscover/2016/00142_lohr_et_al.pdf
Posted September 13, 2016.

*Abstract extracted from a full paper appended to this *GCAGS Explore & Discover* article as a digital addendum to the 2016 volume of the *GCAGS Transactions*, and delivered as a poster presentation at the 66th Annual GCAGS Convention and 63rd Annual GCSSEPM Meeting in Corpus Christi, Texas, September 18–20, 2016.

ABSTRACT

The U.S. Geological Survey (USGS) is preparing to conduct an oil and natural gas resource assessment of undiscovered, technically recoverable unconventional resources in the Tuscaloosa marine shale (TMS) play area of Mississippi and Louisiana. In support of the assessment, this study aims to provide insight and reduce uncertainty in the timing of hydrocarbon generation and delineation of thermal maturity boundaries by examining corrected bottom hole temperatures (BHT). In this study, BHT data were obtained from the IHS Energy Group[1] database for 982 wells spread over 23,707 mi^2 in 22 Louisiana parishes and 17 Mississippi counties. Wells with BHT, log total depth, and time since circulation data were used to calculate a corrected BHT using previously published methods for correcting log-derived temperatures. Thermal gradients, calculated from the corrected BHT values, were interpolated using geographic information system software to create a thermal gradient map for the TMS play area using BHT data for all available depths.

The thermal gradient map reveals a south-southeast to north-northwest trending present-day area of high gradient values from southwestern Mississippi to northeastern Louisiana. Lower gradients are present in Mississippi in the southwestern corner of Wilkinson County and southern Amite County. The south-southeast to north-northwest trending thermal maximum crosses the Adams County High. Previous USGS research attributed anomalous higher Lower Cretaceous thermal maturity on the Adams County High to paleoheat flux, which is consistent with higher present-day thermal gradients. Higher thermal gradients in our study area may be associated with: (1) heat-producing elements within igneous intrusives in the Monroe Uplift, LaSalle Arch, and Jackson Dome, or (2) high conductivity of buried salt deposits.

[1]Use of company names such as IHS Energy Group, Zetaware, Utilities, and Microsoft Excel does not imply an endorsement by the U.S. Government.

Originally published as: Lohr, C. D., P. C. Hackley, B. J. Valentine, and C. B. Enomoto, 2016, Thermal gradient trends in the Tuscaloosa marine shale play area: Preliminary results from studies to support oil and natural gas resource assessments: Gulf Coast Association of Geological Societies Transactions, v. 66, p. 1099–1108.

Thermal Gradient Trends in the Tuscaloosa Marine Shale Play Area: Preliminary Results from Studies to Support Oil and Natural Gas Resource Assessments

Celeste D. Lohr, Paul C. Hackley, Brett J. Valentine, and Catherine B. Enomoto

U.S. Geological Survey, 12201 Sunrise Valley Dr., MS 956, Reston, Virginia 20192

ABSTRACT

The U.S. Geological Survey (USGS) is preparing to conduct an oil and natural gas resource assessment of undiscovered, technically recoverable unconventional resources in the Tuscaloosa marine shale (TMS) play area of Mississippi and Louisiana. In support of the assessment, this study aims to provide insight and reduce uncertainty in the timing of hydrocarbon generation and delineation of thermal maturity boundaries by examining corrected bottom hole temperatures (BHT). In this study, BHT data were obtained from the IHS Energy Group[1] database for 982 wells spread over 23,707 mi^2 in 22 Louisiana parishes and 17 Mississippi counties. Wells with BHT, log total depth, and time since circulation data were used to calculate a corrected BHT using previously published methods for correcting log-derived temperatures. Thermal gradients, calculated from the corrected BHT values, were interpolated using geographic information system software to create a thermal gradient map for the TMS play area using BHT data for all available depths.

The thermal gradient map reveals a south-southeast to north-northwest trending present-day area of high gradient values from southwestern Mississippi to northeastern Louisiana. Lower gradients are present in Mississippi in the southwestern corner of Wilkinson County and southern Amite County. The south-southeast to north-northwest trending thermal maximum crosses the Adams County High. Previous USGS research attributed anomalous higher Lower Cretaceous thermal maturity on the Adams County High to paleoheat flux, which is consistent with higher present-day thermal gradients. Higher thermal gradients in our study area may be associated with: (1) heat-producing elements within igneous intrusives in the Monroe Uplift, LaSalle Arch, and Jackson Dome, or (2) high conductivity of buried salt deposits.

INTRODUCTION

The U.S. Geological Survey (USGS) is conducting an oil and natural gas resource assessment of undiscovered, technically recoverable unconventional hydrocarbon resources in the Tuscaloosa marine shale (TMS), a tight oil play located in southwestern Mississippi and southern Louisiana. Unconventional hydrocarbon resources are generally regionally extensive and recovered from geologic strata with low permeability that require artificial stimulation for commercial production (Johnson and Doré, 2010); they also lack well-defined hydrocarbon-water contacts and distinct accumulation boundaries (Schmoker, 2005). While most shales do not have sufficient permeability to produce hydrocarbons without stimulation, they do have the necessary porosity to contain economically viable amounts of gases and liquids (Berch and Nunn, 2014).

[1]Use of company names such as IHS Energy Group, Zetaware, Microsoft Excel, and ESRI ArcGIS does not imply an endorsement by the U.S. Government.

Lohr, C. D., P. C. Hackley, B. J. Valentine, and C. B. Enomoto, 2016, Thermal gradient trends in the Tuscaloosa marine shale play area: Preliminary results from studies to support oil and natural gas resource assessments: Gulf Coast Association of Geological Societies Transactions, v. 66, p. 1099–1108.

In support of the assessment, previous work (Lohr et al., 2015) produced a localized thermal gradient map that, while valuable, lacked the spatial context provided by a larger regional study. This report covers that exanded scope of data and focuses on systematic thermal gradient trends in the TMS play area to provide constraints on burial history and hydrocarbon generation and complement previous work by the authors (Hackley et al., 2015; Valentine et al., 2015).

GEOLOGIC SETTING

The TMS is part of the Tuscaloosa Group, which is within the Upper Cretaceous Series (Fig. 1), and represents a complete depositional cycle (Spooner, 1964). The Tuscaloosa Group's lower, middle, and upper units represent the transgressive, inundative, and regressive components of the depositional cycle, respectively (Spooner, 1964). The lower Tuscaloosa consists of arenaceous and argillaceous sediments; the middle Tuscaloosa, or marine Tuscaloosa herein known as the TMS, is a dark grey marine shale that contains argillaceous components and minor calcareous zones; and the upper Tuscaloosa consists of mudstones, shales, siltstones, and sandstones (Spooner, 1964). According to IHS Energy Group (2016), the Tuscaloosa Group has cumulatively produced approximately 1.1 billion barrels of oil (BBO) and 6.8 trillion cubic ft of gas (TCFG) in Mississippi and Louisiana. The Judge Digby Field in Pointe Coupee Parish, Louisiana, is one of the most prolific natural gas

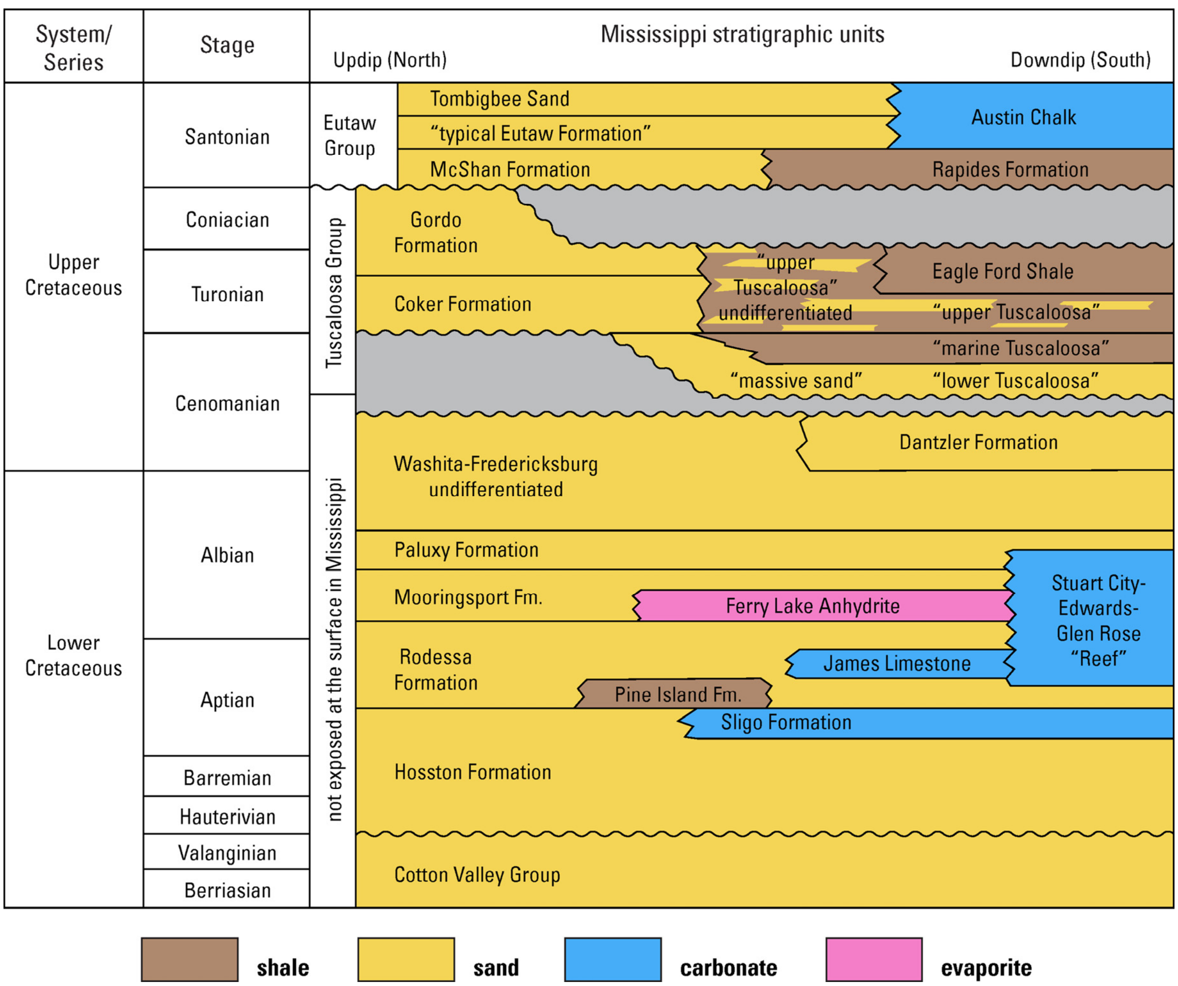

Figure 1. Generalized Cretaceous stratigraphic column for Mississippi (modified after Dockery, 1996).

producers from the lower Tuscaloosa (Burke, 2010). In a USGS assessment of undiscovered conventional gas resources, Pitman et al. (2007) found that the Tuscaloosa Downdip Gas Assessment Unit contains approximately 16.2 TCFG.

The sands and shales of the Tuscaloosa Group are thickest in southeastern Louisiana, where over 3000 ft (915 m) of section have been penetrated, and thinnest over structural highs such as the Monroe Uplift (Sohl et al., 1991). Based on unpublished well log observations, the Tuscaloosa Group ranges from approximately 500 to 2500 ft (152 to 762 m) thick in our study area (Fig. 2). The shale interval between the sands of the upper and lower Tuscaloosa varies in thickness from 500 ft (152 m) in Pike County in southwestern Mississippi to approximately 800 ft (244 m) in Washington and Tangipahoa parishes in southeastern Louisiana (John et al., 1997, 2005).

The primary zone of interest is in the base of the TMS (Fig. 2) and is characterized by a high log resistivity zone of 5 ohm-m or more, which varies in thickness from 0 to 325 ft (0 to 99 m) (John et al., 1997). Where the TMS high resistivity zone is present in southern Mississippi and eastern Louisiana, the overall Tuscaloosa Group averages about 1000 ft (305 m) thick based on well log observations. The high resistivity target zone lies between the Wiggins Uplift in southeastern Mississippi and the LaSalle Arch in eastern Louisiana (Fig. 2). Allen et al. (2014) suggested that the area between these two structural highs is a broad structural low where increased depth of burial of the TMS trend may have provided the necessary temperature and pressure for the maturation of organic-rich strata. However, we observe that present-day burial depths of the TMS continue unchanged on strike well outside of the mapped high resistivity zone shown in Figure 2.

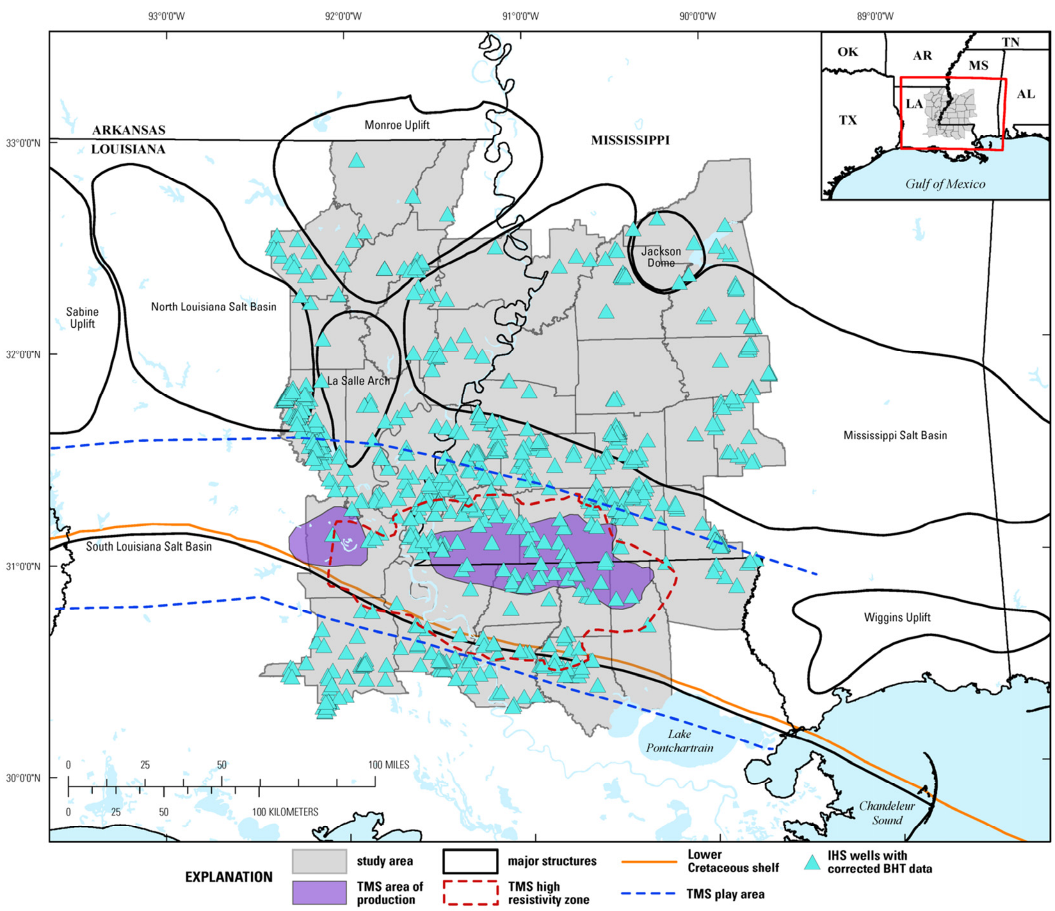

Figure 2. Map showing the study area, major geologic structures, distribution of corrected BHT data, and the TMS play area and high resistivity zone (modified after Allen et al., 2014). The TMS area of production is derived from IHS Energy Group (2016) proprietary production allocated data.

The TMS is considered to be a potentially significant unconventional play area due to its thermal maturity, large lateral extent and thickness, proximity, and potential similarity to the successful Eagle Ford Shale play (Berch and Nunn, 2014). Based on well log analysis and production history, there is little uncertainty that the TMS retains oil in place (Dubiel et al., 2012). Previous work by John et al. (1997, 2005) estimated the TMS to have 7 BBO recovery potential. Currently there are more than 70 horizontally drilled wells producing from the TMS (IHS Energy Group, 2016), most of which are within the high resistivity zone (Fig. 2). The TMS has cumulatively produced approximately 7.7 million barrels of oil (MMBO) and 4.3 billion cubic ft of gas (BCFG) in Mississippi and Louisiana (IHS Energy Group, 2016). Of this cumulative production from the TMS, Mississippi has produced approximately 6.4 MMBO and 3.6 BCFG, whereas Louisiana has produced about 1.3 MMBO and 0.7 BCFG (IHS Energy Group, 2016).

METHODS

A total of 1378 uncorrected bottom hole temperature (BHT) values from 982 unique digital well log headers, with depths ranging from 374 to 22,546 ft (114 to 6872 m), were obtained from IHS Energy Group's proprietary well database (Fig. 3A). These data were distributed over a 23,707 mi^2 (61,401 km^2) study area of 22 Louisiana parishes and 17 Mississippi counties that encompass the TMS play area and high resistivity zone of interest. Wells used in this study do not specifically target the TMS formation depth and include BHT data whose log total depths (LTD) both penetrate and do not penetrate the TMS.

Digital well log headers with BHT information, but incomplete BHT, LTD, and time since circulation (TSC) data, were completed, where possible, by downloading proprietary raster logs from IHS Energy Group's (2016) Lognet subscription service and inserting the missing data. Using this technique, 121 BHT, 147 LTD, and 183 TSC measurements were inserted into the digital well log headers. The BHT and LTD data were converted to degrees Celsius (°C) and meters, respectively. Average land surface temperature data for each county were obtained from World Media Group (2016) in degrees Fahrenheit (°F) by searching for the county, selecting the "Weather" menu link, and using the "Annual Average Temperature" of the selected county; the temperature was then converted to °C.

Well log headers with log runs that contained BHT, LTD, and TSC data were adjusted using Waples and Ramly's (2001) and Waples et al.'s (2004) methods for correcting log-derived temperatures. Waples and Ramly's (2001) method focused on well data shallower than 11,483 ft (3500 m), whereas Waples et al.'s (2004) method focused on deep well data from 11,483 to 21,325 ft (3500–6500 m). Because Waples and Ramly (2001) did not include data deeper than 11,483 ft (3500 m), application of their method in deep wells is speculative; therefore, we used this method only for wells shallower than 11,483 ft (3500 m). The Waples et al. (2004) method was specifically designed for deep wells to increase confidence in the correction, therefore we used this technique for correcting BHT at depths of 11,483 ft (3500 m) and deeper.

The ZetaWare[1] (2006) online BHT correction calculator tool for the Waples et al. (2004) method was considered, but for unknown reasons the corrected BHT from the calculator did not match corrected BHT calculated in Microsoft Excel[1] from Waples et al.'s (2004) study. Because we could not ascertain why the ZetaWare (2006) corrected BHT values were different, we chose to use correction equations obtained directly from the two studies referenced above.

Wells shallower than 11,483 ft (3500 m) were corrected using Waples and Ramly's (2001) correction equation:

$$T_{corr} = T_{surf} + f \cdot \left(T_{meas} - T_{surf}\right) \qquad (1),$$

where

$$f = \frac{-0.1462 \cdot \ln(TSC) + 1.699}{0.572 \cdot Z^{0.075}} \qquad (2).$$

In Equation 1, T_{corr} is the corrected temperature, T_{surf} is the surface temperature in °C, and T_{meas} is the measured temperature in °C. In Equation 2, f is the correction factor, TSC is in hours, and Z is the depth in meters at which the BHT value was measured.

Wells with depths from 11,483 ft (3500 m) and deeper were corrected using Waples et al.'s (2004) correction equation (Eqs. 3 and 4):

$$T_{corr} = T_{surf} + f \cdot \left(T_{meas} - T_{surf}\right) - 0.001392 \cdot \left(Z - 4498\right) \qquad (3),$$

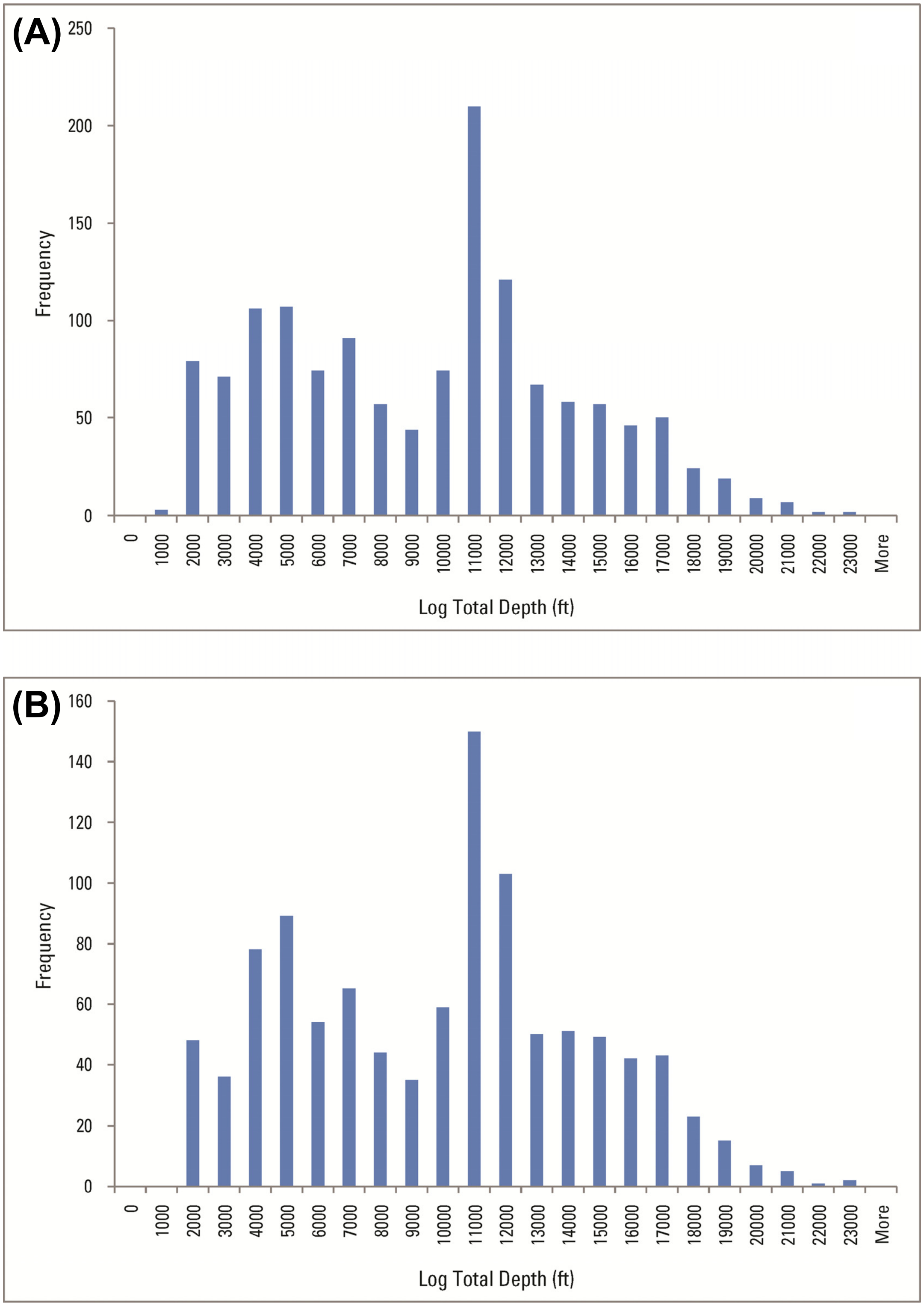

Figure 3. (A) Distribution of log total depth of 1378 uncorrected BHT. (B) Distribution of log total depth of 1049 corrected BHTs used in this study to create a thermal gradient map. 1000 ft = 304.8 m.

where

$$f = 1.32866^{-0.005289TSC} \quad (4).$$

Both approaches were used to correct 1049 BHT (Fig. 2) from 781 unique well log headers with depths ranging from 1400 to 22,546 ft (427 to 6872 m) (Fig. 3B); insufficient information was available to correct the remaining 329 uncorrected BHT. Corrected BHT were converted back to °F and thermal gradients were calculated for uncorrected and corrected BHT using the following basic equation (Eq. 5) modified from Forrest et al. (2007):

$$Geothermal\ Gradient = \left[\frac{T_{meas} - T_{surf}}{LTD}\right] \cdot 100 \quad (5),$$

where T_{meas} and T_{surf} are in °F, *LTD* is in ft, and *Geothermal Gradient* is in °F/100 ft.

The thermal gradient calculations were then interpolated using different interpolation methods—such as inverse distance weighting, global polynomial interpolation, kriging, and empirical Bayesian kriging—in the Geostatistical Wizard tool within ESRI's ArcGIS[1] software. The empirical Bayesian kriging method (Table 1) had some of the smallest prediction errors, or the difference between the prediction and measured value (Johnston et al., 2001), for this dataset and was used to create a thermal gradient map for the study area. Smaller prediction errors include a mean error close to zero, a root-mean-square and average standard error that are as small as possible, and a root-mean-square standardized error close to one (Johnston et al., 2001).

Data with high variability in areas of concentrated data points on the thermal gradient map were reexamined by verifying the digital log header information to corresponding raster logs. Incorrect data, such as BHT or LTD digital typographical errors, were corrected and the thermal gradients were recalculated. Six corrected BHT data, three of which could not be verified with a raster log, were discarded because values were too low or high with respect to the corresponding depth data and nearby corrected BHT data. After completing quality control, a revised thermal gradient map was created.

RESULTS

Thermal gradients were derived from Waples and Ramly's (2001) and Waples et al.'s (2004) equations for 1049 BHT values, which range from ≤1.26 to ≥3.24°F/100 ft (≤2.29 to ≥5.90°C/100 m) (Fig. 4). The thermal

Table 1. Empirical Bayesian kriging properties used that had the smallest prediction errors for the data. This kriging-based interpolation method accounts for the error introduced by estimating the semivariogram model, which is done by simulating many semivariograms from the input data (Krivoruchko, 2012).

Subset Size	89
Overlap Factor	1
Number of Simulations	100
Output Surface Type	Prediction
Transformation	None
Semivariogram Type	Power
Neighborhood Type	Standard Circular
Maximum Neighbors	25
Minimum Neighbors	19
Sector Type	1 Sector
Angle	0
Radius	0.0210354
Predicted Value: X	-91.02864
Predicted Value: Y	31.61596

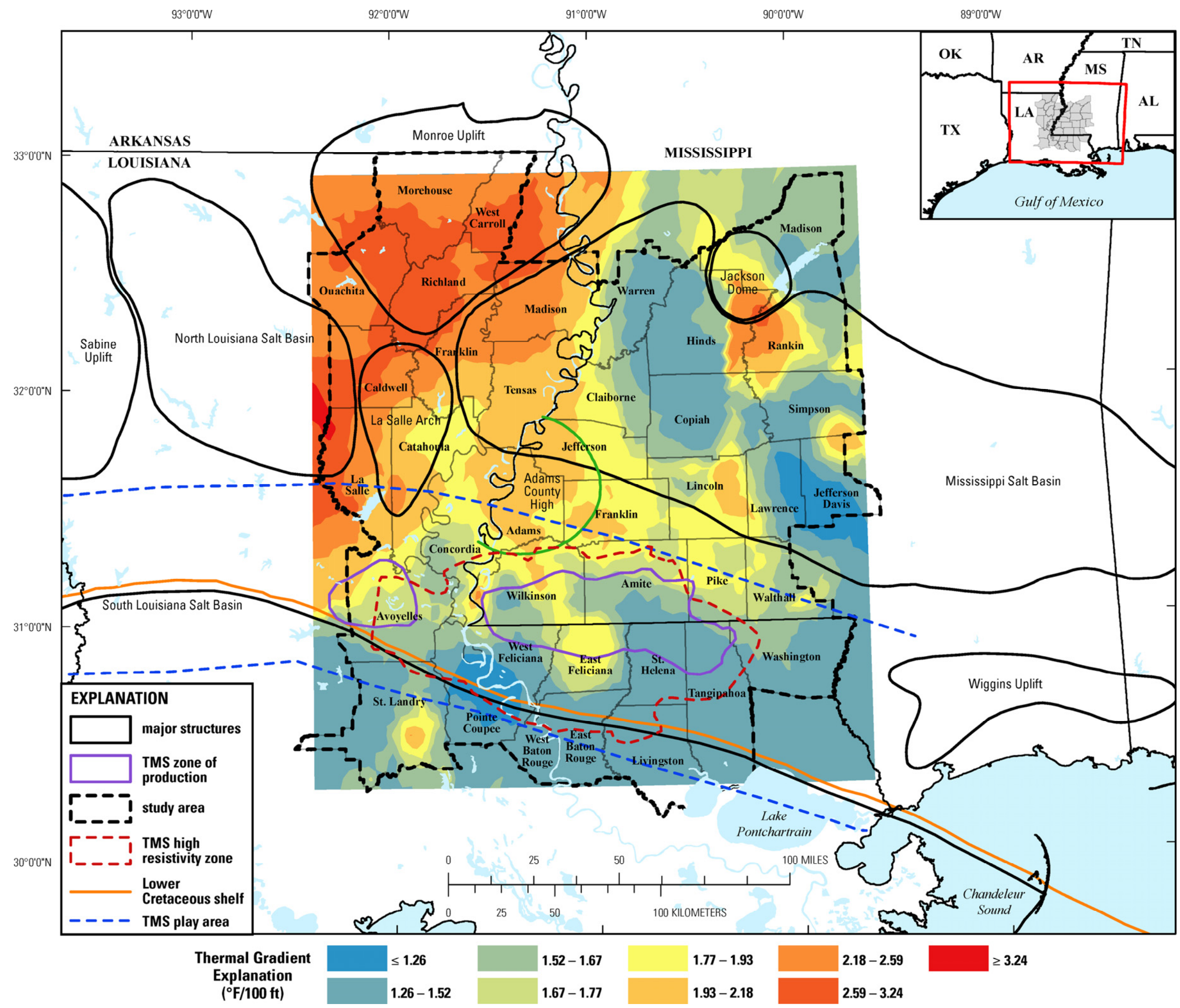

Figure 4. Thermal gradient map in °F/100 ft derived from Excel calculations using Waples and Ramly's (2001) and Waples et al.'s (2004) methods for correcting log-derived BHT data. The TMS play area and high resistivity zone are modified after Allen et al. (2014), whereas the Adams County High location, illustrated in green, is adapted from Gazzier and Bograd (1988) and Valentine et al. (2014). The TMS area of production is derived from IHS Energy Group (2016) proprietary production allocated data. 1°F/100 ft = 1.82°C/100 m (Klett, 2005).

gradient map reveals a south-southeast to north-northwest trending thermal high from Amite, Wilkinson, Franklin, and Adams counties in southwestern Mississippi to East Feliciana, Concordia, Tensas, Franklin, and Madison parishes in northeastern Louisiana. A lower gradient is present in the southwest corner of Wilkinson County and southern Amite County. The south-southeast to north-northwest trending thermal maximum crosses the Adams County High.

The thermal gradient map also reveals higher thermal gradients in the counties and parishes within the northern and north-central extent of the TMS play area and high resistivity zone. In Mississippi, Adams, Franklin, northern Wilkinson, Amite, and Pike, and western Walthall counties have higher thermal gradient values that range from 1.77 to 2.18°F/100 ft (3.22 to 3.97°C/100 m); respectively cooler thermal gradients range from 1.26 to 1.77°F/100 ft (2.29 to 3.22°C/100 m) in the southern areas of Wilkinson, Amite, Pike, and Walthall counties. Similarly in Louisiana, La Salle, Catahoula, northern Concordia and Avoyelles, and central East Feliciana parishes have higher thermal gradients that range from 1.77 to 3.24°F/100 ft (3.22 to 5.90°C/100 m) within the TMS play area and high resistivity zone. Relatively cooler thermal gradients range from ≤1.26 to 1.77°F/100 ft (≤2.29

to 3.22°C/100 m) in Pointe Coupee, West Feliciana, St. Helena, Tangipahoa, Washington, and southern Concordia and Avoyelles parishes.

DISCUSSION

Previous research by our team attributed anomalously higher thermal maturity on the Adams County High north of the TMS play area—determined by solid bitumen reflectance (BR_o) in the Lower Cretaceous section—to paleoheat flux, which is consistent with higher present-day thermal gradients (Hackley et al., 2014a, 2014b; Valentine et al., 2014). Hackley et al.'s (2014a, 2014b) and Valentine et al.'s (2014) studies examined BR_o data from rock samples collected from the Lower Cretaceous Aptian-age section in the southern Mississippi Salt Basin. They found that maturity of these samples increased with depth from the southeast to the west in the basin and continued to increase as the section shallowed westward on the Adams County High. The increased thermal maturity discussed in these investigations, specifically on the Adams County High, complements this thermal gradient study in that higher thermal gradients were found on the Adams County High north of the TMS play area, consistent with anomalous thermal maturity. However, though this thermal gradient study illustrates higher thermal gradients on the Adams County High, similar anomalous thermal maturity has not been documented in the Upper Cretaceous.

The thermal gradient trends (Fig. 4) in this study are generally consistent with Southern Methodist University's heat flow map of the conterminous United States (Blackwell et al., 2011). Although the TMS zone of production shows that most of the current production occurs within the high resistivity zone (Figs. 2 and 4), there does not seem to be an obvious relationship between production and thermal gradients (Fig. 4). Production occurs within areas that have higher thermal gradients which range from 1.77 to 2.18°F/100 ft (3.22 to 3.97°C/100 m) in Wilkinson County and East Feliciana and Avoyelles parishes. Likewise, production also occurs within areas that have relatively lower thermal gradients which range from 1.26 to 1.77°F/100 ft (2.29 to 3.22°C/100 m) in Mississippi's Wilkinson and Amite counties and Louisiana's Avoyelles, West Feliciana, St. Helena, and Tangipahoa parishes. However, since the wells used in this study include BHTs from all depths in the study area and do not specifically target the TMS, it is possible that targeting a specific formation, such as the TMS, by omitting wells that do not penetrate it may result in different thermal gradient patterns.

Areas of high heat flow in north Louisiana may be attributed to buried igneous rocks within the LaSalle Arch (Berch and Nunn, 2014; Nunn et al., 1984) and Monroe Uplift (Berch and Nunn, 2014; Byerly, 1991; Nunn et al., 1984). Similarly in central Mississippi, Upper Cretaceous hypabyssal rocks located near Jackson Dome (Byerly, 1991; Moody, 1949; Monroe, 1954) and Triassic basalts from the northern margin of the Mississippi Salt Basin (Byerly, 1991) may also explain higher thermal gradients in these areas. Additionally, a small portion of our study area fell within the eastern section of the North Louisiana Salt Basin where there is also higher heat flow, which Nunn et al. (1984) suggested may be due to high conductivity of salt deposits.

CONCLUSION

In an expansion of previous work, corrected BHT data in this study resulted in identification of a thermal high trending from south-southeast to north-northwest across southwestern Mississippi to northeastern Louisiana. In northeastern Louisiana this is potentially attributed to buried igneous rocks or to high conductivity of salt deposits. Near the TMS play area, a present-day thermal high across the Adams County High is consistent with anomalous higher thermal maturity in the Lower Cretaceous which previously was attributed to paleoheat flux; at this time, though, a similar anomalous thermal maturity in the Upper Cretaceous has not been documented. Thermal gradient spatial trends remain less defined in the portions of our study area with limited corrected BHT data. Suggested future work may include: (A) using only BHT data from wells that penetrate the TMS, which may result in slightly different thermal gradient trends; and (B) a comparison of calculated thermal gradients to vitrinite reflectance (R_o) or BR_o values from the TMS to better understand the geology and burial history of the Adams County High and thermal maturity in the TMS play area.

REFERENCES CITED

Allen, J. E. Jr., M. A. Meylan, and F. T. Heitmuller, 2014, Determining hydrocarbon distribution using resistivity, Tuscaloosa marine shale, southwestern Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 64, p. 41–57.

Berch, H., and J. Nunn, 2014, Predicting potential unconventional production in the Tuscaloosa marine shale play using thermal modeling and log overlay analysis: Gulf Coast Association of Geological Societies Journal, v. 3, p. 69–78.

Blackwell, D., M. Richards, Z. Frone, J. Batir, A. Ruzo, R. Dingwall, and M. Williams, 2011, Temperature at depth maps for the conterminous US and geothermal resource estimates: Geothermal Resources Council Transactions, v. 35, p. 1545–1550. GRC Record 1029452.

Burke, L., 2010, Temperature and preservation rates in the deep Tuscaloosa Formation, Judge Digby Field, Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 60, p. 77–86.

Byerly, G. R., 1991, Igneous activity, *in* A. Salvador, ed., The geology of North America, v. J: The Gulf of Mexico Basin: Geological Society of America, Boulder, Colorado, p. 91–108.

Dockery, D. T., 1996, Toward a revision of the generalized stratigraphic column of Mississippi: Mississippi Geology, v. 17, p. 1–9.

Dubiel, R. F., O. N. Pearson, J. Pitman, K. Pearson, and S. Kinney, 2012, Geology and sequence stratigraphy of undiscovered oil and gas resources in conventional and continuous petroleum systems in the Upper Cretaceous Eagle Ford Group and related strata, U.S. Gulf Coast region: Gulf Coast Association of Geological Societies Transactions, v. 62, p. 57–72.

Forrest, J., E. Marcucci, and P. Scott, 2007, Geothermal gradients and subsurface temperatures in the northern Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 55, p. 233–248.

Gazzier, C. A., and M. B. E. Bograd, 1988, Structural features of Mississippi: Mississippi Department of Natural Resources Bureau of Geology, Jackson, scale 1:500,000.

Hackley, P. C., B. J. Valentine, C. B. Enomoto, C. D. Lohr, K. R. Scott, F. T. Dulong, and A. M. Bove, 2014a, Aptian 'shale gas' prospectivity in the downdip Mississippi Interior Salt Basin, Gulf Coast, USA: Unconventional Resources Technology Conference (URTeC) Paper 1922696, Denver, Colorado, 9 p.

Hackley, P. C., B. J. Valentine, C. B. Enomoto, and J. L. Coleman, Jr., 2014b, U.S. Geological Survey unconventional petroleum systems research in south Mississippi: Observations on burial history and thermal maturity in the Cretaceous: Mississippi Geological Society Bulletin, v. 63, no. 3, Jackson, p. 9–14.

Hackley, P. C., B. J. Valentine, C. D. Lohr, and C. B. Enomoto, 2015, Burial history and heat flow in the Tuscaloosa marine shale play area: Preliminary insights from petrographic approaches: Geological Society of America Abstracts with Programs, v. 47, no. 7, p. 83.

IHS Energy Group, 2016 [includes data current as of May 6, 2016], ENERDEQ U.S. production allocated data: Englewood, Colorado.

John, C. J., B. L. Jones, J. E. Moncrief, R. Bourgeois, and B. J. Harder, 1997, An unproven unconventional seven billion barrel oil resource—The Tuscaloosa marine shale: Louisiana State University Basin Research Institute Bulletin 7, Baton Rouge, p. 1–21.

John, C. J., B. L. Jones, B. J. Harder, and R. J. Bourgeois, 2005, Exploratory progress towards proving the billion barrel potential of the Tuscaloosa marine shale: Gulf Coast Association of Geological Societies Transactions, v. 55, p. 367–372.

Johnson, H., and A. G. Doré, 2010, Unconventional oil and gas resources and the geological storage of carbon dioxide: overview: Petroleum Geology Conference Proceedings, v. 7, London, U.K., p. 1061–1063.

Johnston, K., J. M. Ver Hoef, K. Krivoruchko, and N. Lucas, 2003, Using ArcGIS geostatistical analyst: ESRI, Redlands, California, 300 p. <http://dusk2.geo.orst.edu/gis/geostat_analyst.pdf> Accessed October 27, 2015.

Klett, T. R., 2005, Conversion factors (approximate), chapter 27, *in* U.S. Geological Survey Southwestern Wyoming Province Assessment Team, compilers, Petroleum systems and geologic assessment of oil and gas in the southwestern Wyoming province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS–69–D, 7 p., <https://pubs.usgs.gov/dds/dds-069/dds-069-d/REPORTS/69_D_CH_27.pdf> Accessed April 21, 2016.

Krivoruchko, K., 2012, Empirical Bayesian kriging implemented in ArcGIS Geostatistical Analyst: ESRI ArcUser, Fall 2012 issue, Redmond, California, p. 6–10, <http://www.esri.com/news/arcuser/1012/files/ebk.pdf> Accessed April 21, 2016.

Lohr, C. D., P. C. Hackley, B. J. Valentine, and C. B. Enomoto, 2015, Preliminary thermal gradient evaluation in the Tuscaloosa marine shale play area: Geological Society of America Abstracts with Programs, v. 47, no. 7, p. 83.

Monroe, W. H., 1954, Geology of the Jackson area, Mississippi: U.S. Geological Survey Bulletin 986, 113 p.

Moody, C. L., 1949, Mesozoic igneous rocks of northern Gulf Coastal Plain: American Association of Petroleum Geologists Bulletin, v. 33, p. 1410–1428.

Nunn, J. A., A. D. Scardina, and R. H. Pilger, Jr., 1984, Thermal evolution of the north-central Gulf Coast: Tectonics, v. 3, p. 723–740.

Pitman, J. K., R. F. Dubiel, P. H. Nelson, J. Kibler, R. R. Charpentier, T. A. Cook, T. R. Klett, R. Pollastro, and C. J. Schenk, 2007, Assessment of undiscovered gas resources in the Upper Cretaceous Tuscaloosa and Woodbine formations, western Gulf province of the Gulf Coast region, Louisiana and Texas, 2007: U.S. Geological Survey Fact Sheet FS–06–3146, 2 p., <http://pubs.usgs.gov/fs/2006/3146/> Accessed April 22, 2016.

Schmoker, J. W., 2005, U.S. Geological Survey assessment concepts for continuous petroleum accumulations, chapter 13, *in* U.S. Geological Survey Southwestern Wyoming Province Assessment Team, compilers, Petroleum systems and geologic assessment of oil and gas in the southwestern Wyoming province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS–69–D, 7 p., <https://pubs.usgs.gov/dds/dds-069/dds-069-d/REPORTS/69_D_CH_13.pdf> Accessed April 21, 2016.

Sohl, N. F., E. Martinez R., P. Salmeron-Urena, and F. Soto-Jaramillo, 1991, Upper Cretaceous, *in* A. Salvador, ed., The geology of North America, v. J: The Gulf of Mexico Basin: Geological Society of America, Boulder, Colorado, p. 205–244.

Spooner, H. V., Jr., 1964, Basal Tuscaloosa sediments, east-central Louisiana: American Association of Petroleum Geologists Bulletin, v. 48, p. 1–21.

Valentine, B. J., P. C. Hackley, C. B. Enomoto, A. M. Bove, F. T. Dulong, C. D. Lohr, and K. R. Scott, 2014, Organic petrology of the Aptian-age section in the downdip Mississippi Interior Salt Basin, Mississippi, USA: Observations and preliminary implications for thermal maturation history: International Journal of Coal Geology, v. 131, p. 378–391.

Valentine, B. J., P. C. Hackley, C. B. Enomoto, O.D. Scholl, and C. D. Lohr, 2015, Preliminary thermal maturity and organic petrology of the Upper Cretaceous Tuscaloosa marine shale, Mississippi, USA: Geological Society of America Abstracts with Programs, v. 47, no. 7, p. 455.

Waples, D. W., and M. Ramly, 2001, A statistical method for correcting log-derived temperatures: Petroleum Geoscience, v. 7, p. 231–240.

Waples, D. W., J. Pacheco, and A. Vera, 2004, A method for correcting log-derived temperatures in deep wells, calibrated in the Gulf of Mexico: Petroleum Geoscience, v. 10, p. 239–245.

World Media Group, 2016, USA.com: World Media Group, LLC, Basking Ridge, New Jersey, <http://www.usa.com/> Last accessed October 19, 2016.

Zetaware, 2006, ZetaWare, utilities—BHT correction, GoM Waples et al. 2004 : ZetaWare Inc., Sugar Land, Texas, <http://www.zetaware.com/utilities/bht/waples_gom.html> Last accessed October 19, 2016.

.