GCAGS JOURNAL A Publication of the Gulf Coast Association of Geological Societies www.gcags.org

Identifying Spikes in Sonic Slowness and in Resistivity in the Tuscaloosa Marine Shale Using Continuous Wavelet Transform

Carol Wicks and Samiha Naseem

Department of Geology and Geophysics, Louisiana State University, E235 Howe Russell Geoscience Complex, Baton Rouge, Louisiana 70803, U.S.A.

ABSTRACT

The Tuscaloosa Marine Shale (TMS) is an unconventional play in central Louisiana and southwestern Mississippi. Based on studies of a limited number of cores from the TMS, other researchers have noted that the facies and the character of the porosity (pores as opposed to fractures) exhibit changes over small depth intervals (<1 ft); however, the changes in facies and porosity at that scale are often not discernible in the wireline logs. In this study, the continuous wavelet transform (CWT) technique was a means to identify small depth intervals over which abrupt changes in the response of geophysical well logs occurred as a means to highlight small depth intervals with changes in the character of the porosity.

Based on geophysical wireline logs of resistivity and sonic slowness, our work determined the depth intervals over which wavelet spectral power was high. These depth intervals correspond to depth intervals over which there are spikes (either positive or negative) in sonic slowness. Our interpretation is that the character of the porosity changes at these depth intervals; however, it is not clear if that change in character is from pores (background) to fractures (spikes) or if the change in character is due to the presence of thin sands (spikes) within the surrounding fractured shale (background). Nonetheless, our project highlights the usefulness of wavelet transforms as a means to discern changes in geophysical well logs over short depth intervals. In addition, these results highlight the heterogeneous nature of the porosity within the TMS and might be useful in reservoir characterization and well development efforts.

INTRODUCTION

The Tuscaloosa Marine Shale (TMS) is a proven oil reservoir in Louisiana and Southern Mississippi. The potential of the TMS as an oil-bearing unit was first identified by Alfred C. Moore in 1969 (as cited in John et al. [1997]) who analyzed over 50 wells in the region. John et al. (1997) identified a primary zone of interest that was marked by high resistivity at the base of the TMS. Barrell (2013) subdivided that high resistivity zone into a basal sandy shale, a calcareous shale in the middle, and a non-calcareous shale at the top.

Studies of the TMS have revealed interbedded layers (Singh et al., 2009) over which the lithology, mineralogy, and porosity vary. Core data becomes important as those data provides direct visual evidence of varying characteristics that can be difficult to discern in wireline logs. There are very few published studies that use core to highlight heterogeneity in the TMS. Based on data from one core for the TMS, Lu et al. (2011) found heterogeneities in porosity and lithology at centimeter to decimeter scales. Lithologic heterogeneities were linked to spatially variable concentrations of minerals. Illite, quartz, and kaolinite were present in high concentrations. Calcite was associated with either localized coarse grained or fossil bearing sediments. Variation in the relatively low porosity was observed and that variation was associated with pyrite framboids, organic matter, and intragranular pores in quartz or calcite. However, acquiring core is not always feasible and therefore there is a need for an alternative method that can be used to discern changes in porosity (and other characteristics) over short depth intervals.

The potential of the TMS to serve as an economically viable reservoir of oil is linked to our understanding its porosity, specifically identifying changes in character of the porosity over short depth intervals. However, identifying such changes from detailed descriptions of cores is expensive and from wireline logs is difficult. Thus, this work discusses a mathematical method, the continuous wavelet transform, to identify changes in porosity over short depth intervals from logs of sonic slowness (reciprocal of sonic velocity and has units of microseconds per foot) and resistivity in the TMS.

Manuscript received February 14, 2017; revised manuscript received June 9, 2017; manuscript accepted June 21, 2017.

GCAGS Journal, v. 6 (2017), p. 92–98.

Wavelet Transform

Wavelet analysis is a Fourier Transform windowing technique that uses variable sized windows. Mathematically, the wavelet analysis is a convolution of a wavelet function, such as the Morlet or Haas, with a spatial and/or temporal signal (Addison, 2002). The wavelet function can be stretched (scaling) and moved (translation) along the entire length and/or extent of the original signal. The result is contours values of the wavelet coefficients (Fugal, 2009) as a function of scale and translation. If the values of the coefficient are high, then the wavelet matched the signal. If the values of the coefficient are low, then the match between the two is poor.

Wavelet transform has been used in previous geologic and geophysical studies (Prokoph and Barthelmes, 1996; Chandrasekhar and Rao, 2012; Jansen and Kelkar, 1997; Prokoph and Agterberg, 2000; Soliman et al., 2001; Rivera et al., 2002). These studies demonstrated that the wavelet transform was an effective mathematical tool that can be used to discern changes in well log data. Using a wavelet analysis, Chandrasekhar and Rao (2012) identified the tops of oil and/or gas formation pay zones in the Bombay High oil fields. Rivera et al. (2002) used wavelet analysis to support stratigraphic analysis and interpretation. Pan et al. (2008) identified formation interfaces from well log data. Based on data from extensive cores, Li and Loehle (1995) analyzed the spatial variability of permeability at a radioactive waste disposal site. An analysis of well log data was used to identify faults and unconformities and to evaluate spatio-temporal distribution and determine sediment accumulation rates of oil source rocks (Prokoph and Agterberg, 2000). Jansen and Kelkar (1997) analyzed well production data in order to estimate fluid flow paths and existence of flow barriers within the reservoir rocks. In addition, Sahimi and Hashemi (2001) used wavelet analysis to identify fractures within a synthetic well log. The usefulness of a wavelet analysis on wireline log data is clear—wavelet analysis can be used to detect variations changes in the wireline log data that are invisible to the human eye (Rivera et al., 2002; Chandrasekhar and Rao, 2012).

Study Objective

The objective of this study is to determine if continuous wavelet transformations can be used to detect small-spatial-scale changes in the porosity of the Middle Tuscaloosa Formation of the Tuscaloosa Group (this is more commonly known as the TMS; Puckett and Mancini, 2001).

METHODS

Study Area

The TMS is found in the subsurface as a linear belt across central Louisiana and southwestern Mississippi (Fig. 1). The TMS is the middle stratigraphic unit of the Tuscaloosa Group and belongs to the Cretaceous Gulf Series (Figs. 2 and 3). The Tuscaloosa Group is underlain by the Washita Group and overlain by the Eutaw Group. The Tuscaloosa Group is divided into Upper Tuscaloosa, TMS, and the Lower Tuscaloosa. The sands and shales of the Tuscaloosa Group are over 1000 ft thick and represent a complete depositional sequence consisting of a lowstand system tract, transgressive system tract and a highstand system tract (Barrel, 2013; John et al., 1997).

Data

Logs of resistivity and of sonic slowness from 12 wells in Mississippi were used in this study (Table 1). Our study focused primarily on sonic slowness. Formation tops for the TMS and for the basal unit of the high resistivity portion (John et al., 1997) interval were available from some of the wells (Berch, 2013; Allen, 2013). The methods described by Berch (2013) and by Allen (2013) were used to pick the formation tops in the remaining wells.

Sonic slowness is a measure of a formation's capacity to transmit sound waves. The sonic response for any given formation is a function of its lithology and rock texture, particularly porosity and fluid composition. High values indicate that the sound waves take longer to travel through the medium and return back to the detector, indicating a higher porosity; whereas, lower values indicate that a lower porosity.

Resistivity measures the resistance to electrical current in a formation due to both the nature of the porous media and associated fluids. In this study, logs of deep resistivity were used and indicate the resistivity of the subsurface away from the well bore (the uninvaded zone; Rider, 2002); although standard deep resistivity logs are technically influenced by the invaded zone, they are widely used as a proxy for true formation resistivity. High resistivity can be attributed to either the presence of hydrocarbons (hydrocarbons have a higher resistance to electrical current than water does) or to low porosity; whereas, lower values of resistivity indicate depths at which the porosity is high and pores are filled with water of varying salinity.

Wavelet Analysis

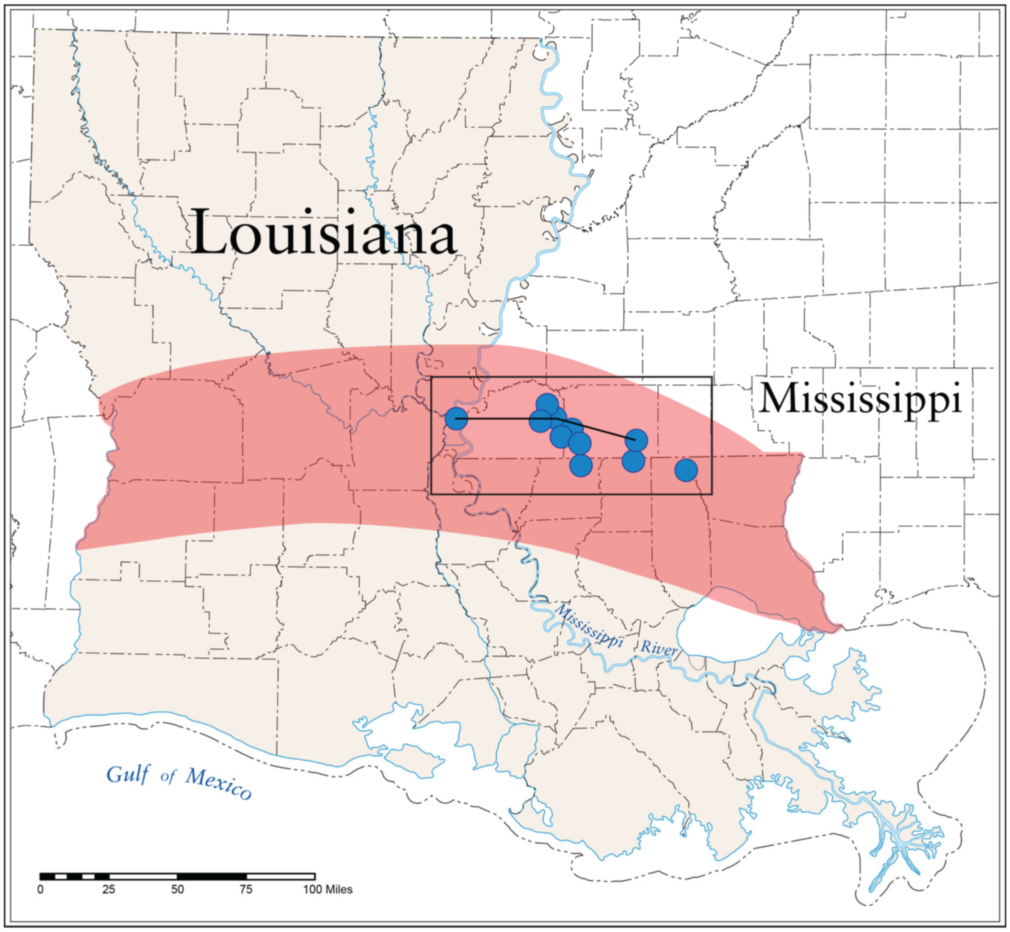
In wavelet transformation, the signal to be analyzed is convolved with the mother wavelet (the unstretched wavelet) and the transformation is computed by stretching and translating the wavelet along the data (Graps, 1995). Following the method of Sahimi and Hashemi (2001), we calculated the wavelet-power spectrum using a procedure outlined in the online interactive tool (http://atoc.colorado.edu/research/wavelets/) provided by Torrence and Compo (1998) with documentation provided by Research Systems, Inc. (2005). [We note that we have assumed that noise in the logging data has been removed by the logging engineer at the wellsite and therefore all logging data were treated as being noise-free.]

RESULTS AND DISCUSSION

Our results show high level of wavelet power which correspond to depth intervals at which sonic slowness spiked (either increase or decreases). For instance, for the log from well Neyland Heirs 1–37 (API 230520501), there are three zones of high spectral power that are clearly outside of the cone of influence (due to edge effects, cross-hatched pattern) (Fig. 4). These three zones correspond to an increase in sonic slowness, a decrease in sonic slowness, and an increase in sonic slowness as you progress down the log. These spikes in sonic slowness are likely visible without having performed a wavelet transformation.

For the log from well Longleaf Enterprises (Oryx) (API 2315721574), spikes in sonic slowness are not as readily apparent (Fig. 5); however, the power spectrum of the wavelet transform clearly highlights three spikes, an increase, a decrease, and an increase as you progress down the log. Note that the depth resolution of wavelet analysis is on the same vertical resolution as that of the logging tool, which is about 2 ft for sonic slowness and between 3–10 ft for resistivity (Rider, 2002). This means that the depths identified using the wavelet analysis technique are still much coarser than those identified by Lu et al. (2011) using the core. Nonetheless, these small-scale changes in the features which are easily overlooked in visual inspection of log data are easily identified in wavelet power spectrum leading to a more realistic interpretation of the heterogeneity of the character of the porosity within the TMS.

There are corresponding changes in resistivity and sonic slowness across the study area (Naseem, 2016) (Fig. 6). These are interpreted as depths at which the character of the porosity is different from that at adjacent depths. Although, correlation of



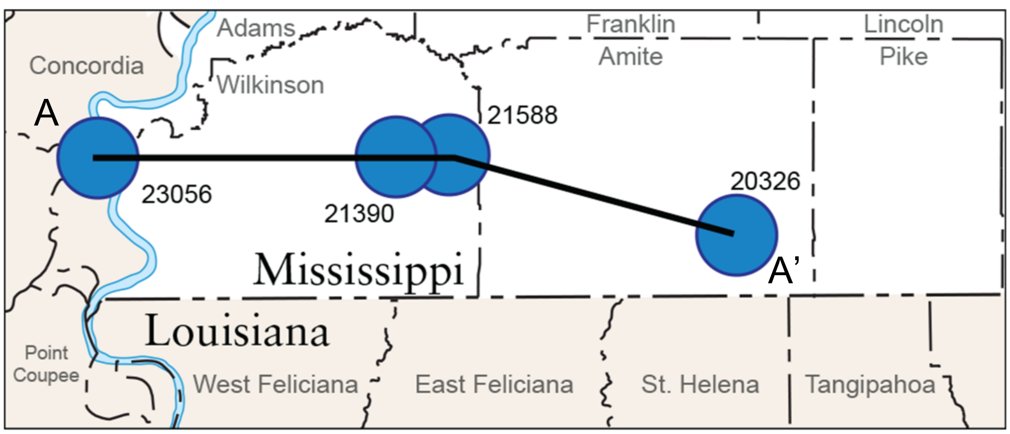


Figure 1. (A) Map of Louisiana and Mississippi showing the extent of the Tuscaloosa Marine Shale (TMS). (B) Inset map showing the location of wells and the along strike cross-section A−A'.

these possible layers across the study area is difficult. Future studies should incorporate more well data with complete logging suites at finer depth resolution, if possible.

SUMMARY AND CONCLUSIONS

In agreement with Sahimi and Hashemi (2001), wavelet transformation can be used to identify spikes in sonic slowness and resistivity that are not discernable during visual inspection of logs. Wavelet transformation, either discrete wavelet as carried out by Sahima and Hashemi (2001) or continuous as used in this study, distinguish types of data that have different distributions. As the distribution of pores and of fractures are not the same, wavelet transforms are able to see the differences and highlight short depths intervals over which the distributions differ. This allows us to see changes in sonic slowness, and by inference porosity, in the geophysical well logs. In the TMS, depth intervals at which spikes in sonic slowness and resistivity occur show a rough correspondence across the study area and might highlight depth intervals of enhanced porosity that could be targeted for exploration.

REFERENCES CITED

Addison, P. S., 2002, The illustrated wavelet transform handbook, 2nd ed.: Institute of Physics Publishing, Edinburgh, Scotland, 464 p.

Allen, J. E., 2013, Determining hydrocarbon distribution using resistivity, Tuscaloosa Marine Shale, southwestern Mississippi: M.S. Thesis, University of Southern Mississippi, 62 p.

Barrell, K. A., 2013, The Tuscaloosa Marine Shale: An emerging shale play, 2013: Houston Geological Society Bulletin, v. 55, no. 6, p. 43 and 45, <https://www.hgs.org/sites/default/files/

CRETACEOUS	GULFIAN	SELMA	SELMA CHALK (UNDIFFERENTIATED)	CHALK
		EUTAW	EUTAW (EAGLE FORD)	GRAY SHALE & BASAL SAND
		TUSCALOOSA	UPPER TUSCALOOSA	SANDS & SHALES
			MARINE SHALE	DARK GRAY MARINE SHALE
			LOWER TUSCALOOSA	LENTICULAR SANDS & SHALES WHITE, COARSE-GRAINED
	COMANCHIAN	WASHITA-FREDERICKSBURG	DANTZLER	SANDS & SHALES
			UNDIFFERENTIATED	PREDOMINANTLY LIMESTONE
		TRINITY	PALUXY	VARIABLE COLORED SANDS & SHALES

Figure 2. Generalized stratigraphic column of the study area (modified after Howe, 1962, as cited in John et al., 2005). The TMS belongs to the Cretaceous Tuscaloosa Group. The entire Group represents one complete cycle of sea level rise and fall resulting in the deposition of the Lower Tuscaloosa, the TMS, and the Upper Tuscaloosa. Studies and well results have proven the source and reservoir potential of the TMS.

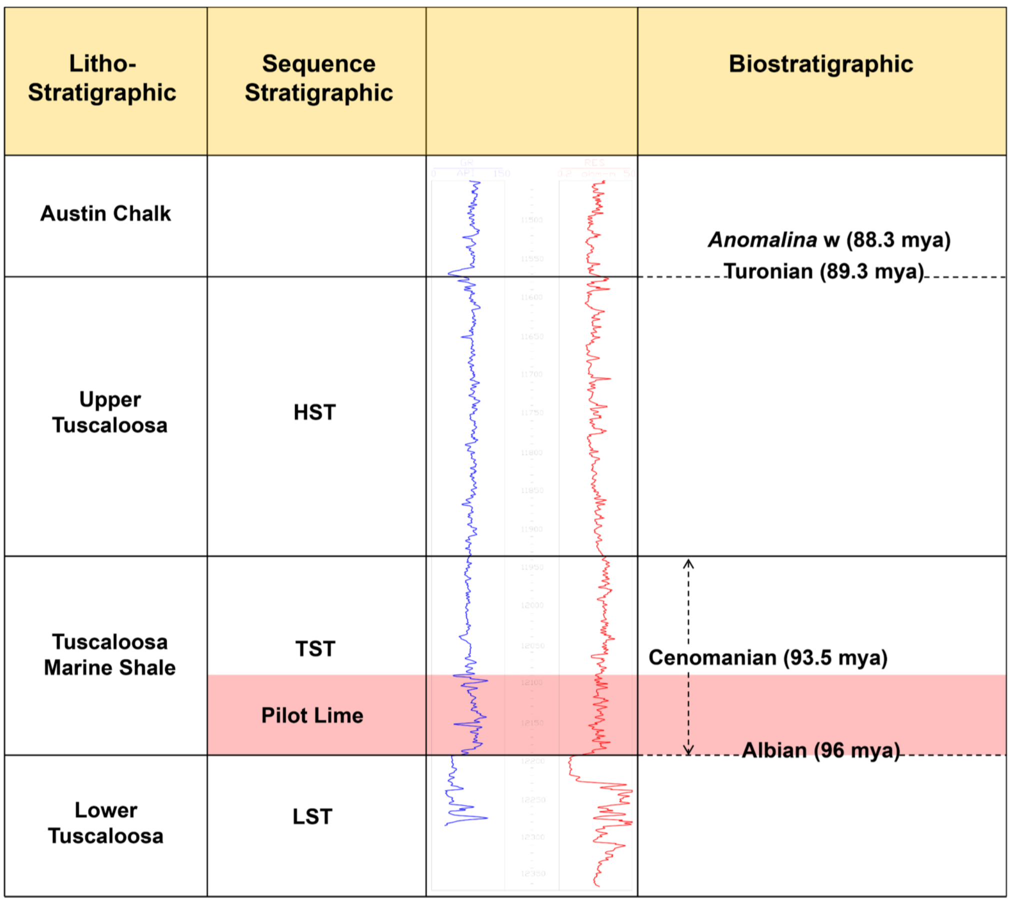


Figure 3. Reference log of the Tuscaloosa Group (modified after Barrell, 2013). The two curves are spontaneous potential (SP) on the left and the deep induction resistivity (ILD) on the right. The base of the Tuscaloosa Group is represented by the prograding wedges of the Lower Tuscaloosa (yellow-filled sands on SP) that have high resistivity and are therefore hydrocarbon bearing (red-filled ILD). The Lower Tuscaloosa gradually fines upwards into the TMS as can be seen on the SP log. On the ILD, the high resistivity zone continues upwards for about 100 ft into the shale which is the target interval of this shale play.

bulletins/Bulletin-February-2013.pdf> Last accessed September 13, 2017.

Berch, H., 2013, Predicting potential unconventional production in the Tuscaloosa Marine Shale play using thermal modeling and log overlay analysis: M.S. Thesis, Louisiana State University, Baton Rouge, 85 p., <http://digitalcommons.lsu.edu/gradschool_theses/3676/> Last accessed September 2017.

Chandrasekhar, E., and V. E. Rao, 2012, Wavelet analysis of geophysical well-log data of Bombay offshore basin, India: Mathematical Geosciences, v. 44, p. 901–928, doi:10.1007/s11004-012-9423-4.

Fugal, D. L., 2009, Conceptual wavelets in digital signal processing: an in-depth, practical approach for the non-mathematician: Space and Signals Technical Publishing, San Diego, California, 374 p.

Table 1. Basic data from the wells.

Well API	Well Name	Top of high resistivity zone (ft)	Base TMS (ft)
1702923056	M C Knapp 17	12024	12162
2300520326	Chamberlain	11470	11584
2300520467	Anderson “C” 1	11933	12076
2300520501	Neyland Heirs 1–37	11883	12027
2300520507	Piker A	12527	12678
2300520556	Chase Donald L.	12015	12184
2315721390	Foster Creek Corp 3	11822	11968
2315721566	Longleaf Enterprises (Seagull)	11867	11995
2315721574	Longleaf Enterprises (Oryx)	11916	12069
2315721588	Ark-Smith PJ Hrs	11734	11850
2315721602	Longmire	11737	11888
2315721659	CMR "A" 3	11540	11645

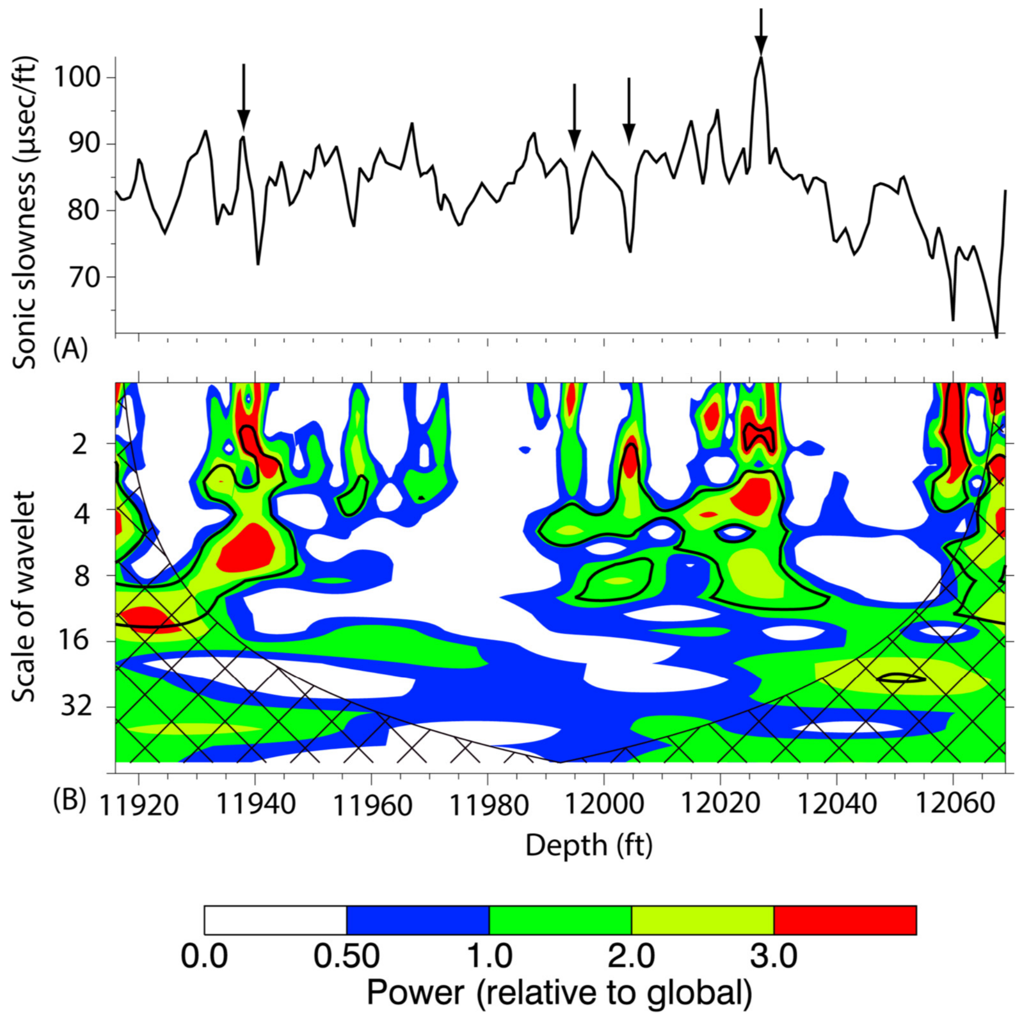


Figure 4. Upper figure is plot of sonic slowness against depth for well Neyland Heirs 1–37. Vertical arrows highlight depths of spikes (either positive or negative) in sonic slowness and the corresponding high power. Lower plot is wavelet power spectrum that has been adjusted for red noise and is relative to a global wavelet power spectrum. As Morlet wavelet was used, the unit of the scale of the wavelet can be considered in feet (Torrence and Compo, 1998). Cross-hatched pattern delineates the wavelet power spectrum into two regions: data likely to have been influenced by edge effects (cross-hatched) and are therefore not useful versus data that are not likely to have been impacted by edge effects.

Graps, A., 1995, An introduction to wavelets: Institute of Electrical and Electronics Engineers Computational Science and Engineering, v. 2, no. 2, p. 50–61, doi:10.1109/99.388960.

Jansen, F. E., and M. Kelkar, 1997, Application of wavelets to production data in describing inter-well relationships: Society of Petroleum Engineers Paper SPE–38876–MS, Richardson, Texas, 8 p., doi:10.2118/38876-MS.

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, 21 p.

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.

Li, B. L., and C. Loehle, 1995, wavelet analysis of multiscale permeabilities in the subsurface: Geophysical Research Letters, v. 22, no. 23, p. 3123–3126, doi:10.1029/95GL03552.

Lu, J., K. Milliken, R. M. Reed, and S. Hovorka, 2011, Diagenesis and sealing capacity of the middle Tuscaloosa mudstone at the

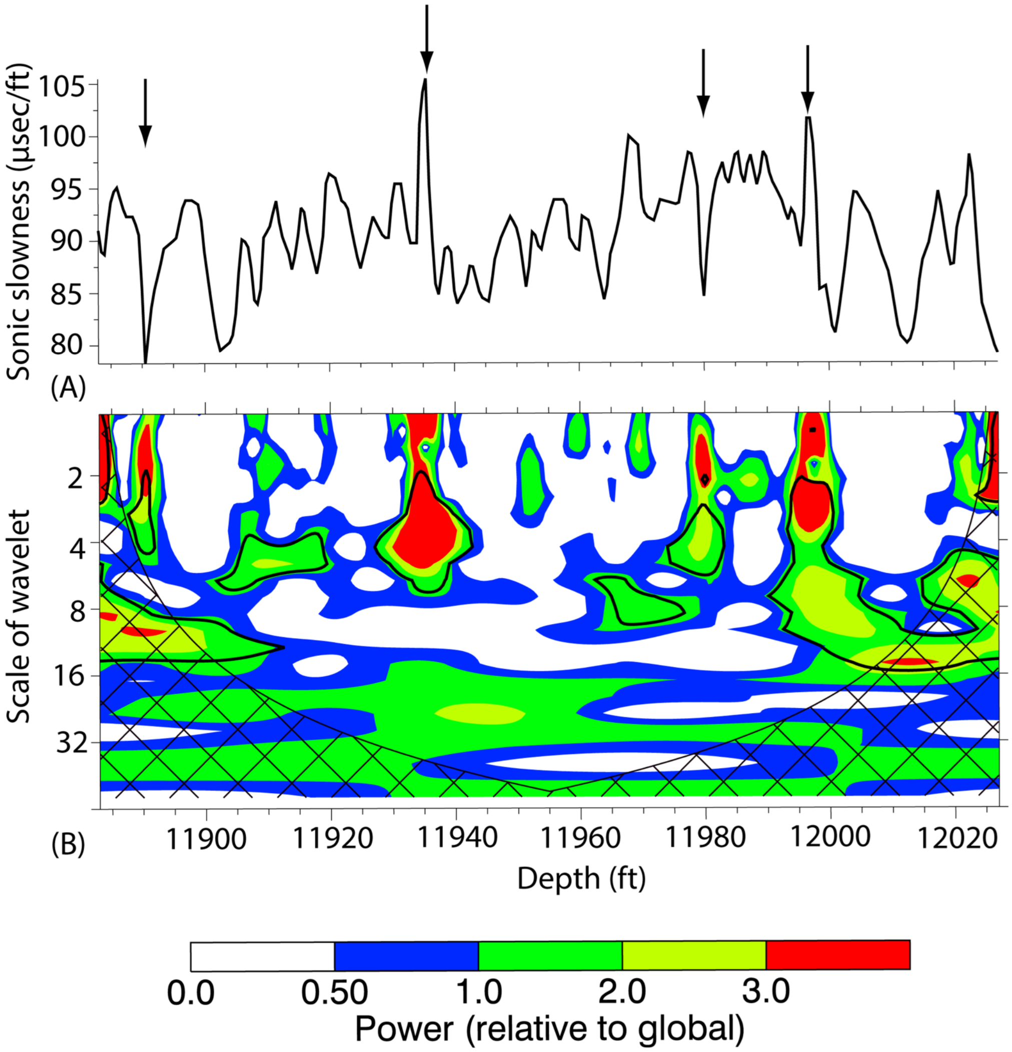


Figure 5. Similar to Figure 4, the upper figure is a plot of sonic slowness against depth for Longleaf Enterprises (Oryx) well and the lower figure is the wavelet power spectrum (corrected for red noise and relative to the global wavelet). Vertical arrows point to depths of spikes in sonic slowness and corresponding high values of power.

Cranfield carbon dioxide injection site, Mississippi, U.S.A.: Environmental Geosciences, v. 18, p. 35–53, doi:10.1306/eg.09091010015.

Naseem, S., 2016, Using wavelet transforms to detect small-scale features within the Tuscaloosa Marine Shale, Louisiana and Mississippi: MS thesis, Department of Geology and Geophysics, Louisiana State University, Baton Rouge, 72 p., <http://digitalcommons.lsu.edu/gradschool_theses/2514/> Last accessed September 13, 2017.

Pan, S.–Y., B.–Z. Hsieh, M.–T. Lu, and Z.–S. Lin, 2008, Identification of stratigraphic formation interfaces using wavelet and Fourier transforms: Computers and Geosciences, v. 34, p. 77–92, doi:10.1016/j.cageo.2007.01.002.

Prokoph, A., and F. Barthelmes, 1996, Detection of nonstationarities in geological time series: Wavelet transform of chaotic and cyclic sequences: Computers and Geosciences, v. 22, p. 1097–1108, doi:10.1016/S0098-3004(96)00054-4.

Prokoph, A., and F. P. Agterberg, 2000, Wavelet analysis of well logging data from oil source rock, Egret Member, offshore eastern Canada: American Association of Petroleum Geologists Bulletin, v. 84, p. 1617–1632, doi:10.1306/8626bf15-173b-11d7-8645000102c1865d.

Puckett, T. M., and E. A. Mancini, 2001, Upper Cretaceous sequence stratigraphy, U.S. Eastern Gulf Coastal Plain: American Association of Petroleum Geologists Search and Discovery Article 90050, Tulsa, Oklahoma, 3 p. <http://www.searchanddiscovery.com/pdfz/abstracts/pdf/2005/2001hedberg/ndx_puckett.pdf.html> Last accessed September 13, 2017.

Research Systems, Inc., 2005, Wavelet toolkit user's guide, wavelet version 6.2: Boulder, Colorado, 114 p., <http://vis.lbl.gov/NERSC/Software/idl/help6.2/wavelet.pdf>. Also available at <http://northstar-www.dartmouth.edu/doc/idl/html_6.2/Wavelet_Power_Spectrum.html> Accessed July 2016.

Rider, M., 2002, The geological interpretation of well logs, 2nd. ed., rev.: Rider-French Consulting, Sutherland, Scotland, 280 p.

Rivera, N., S. Ray, A. Chan, and J. Jensen, 2002, Well-log feature extraction using wavelets and genetic algorithms: American Association of Petroleum Geologists Search and Discovery Article 45587, Tulsa, Oklahoma, 8 p. <http://www.searchanddiscovery.com/abstracts/pdf/2002/annual/extended/ndx_45587.pdf> Last accessed September 13, 2017.

Sahimi, M., and M. Hashemi, 2001, Wavelet identification of the spatial distribution of fractures: Geophysical Research Letters, v. 28, p. 611–614, doi:10.1029/2000GL011961.

Soliman, M. Y., J. Ansah, S. Stephenson, and B. Manda, 2001, Application of wavelet transform to analysis of pressure transient data: Society of Petroleum Engineers Paper SPE–71571–MS, Richardson, Texas, 13 p. doi:10.2118/71571-MS.

Singh, P., R. Slatt, G. Borges, R. Perez, R. Portas, K. Marfurt, M. Ammerman, and W. Coffey, 2009, Reservoir characterization of unconventional gas shale reservoirs: Example from the Barnett Shale, Texas, U.S.A.: Oklahoma City Geological Society Sub-collection: The Shale Shaker, v. 60, no. 1, p. 15–31.

Torrence, C., and G. P. Compo, 1998, A practical guide to wavelet analysis: Bulletin of the American Meteorological Society, v. 79, p. 61–78, doi:10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2.

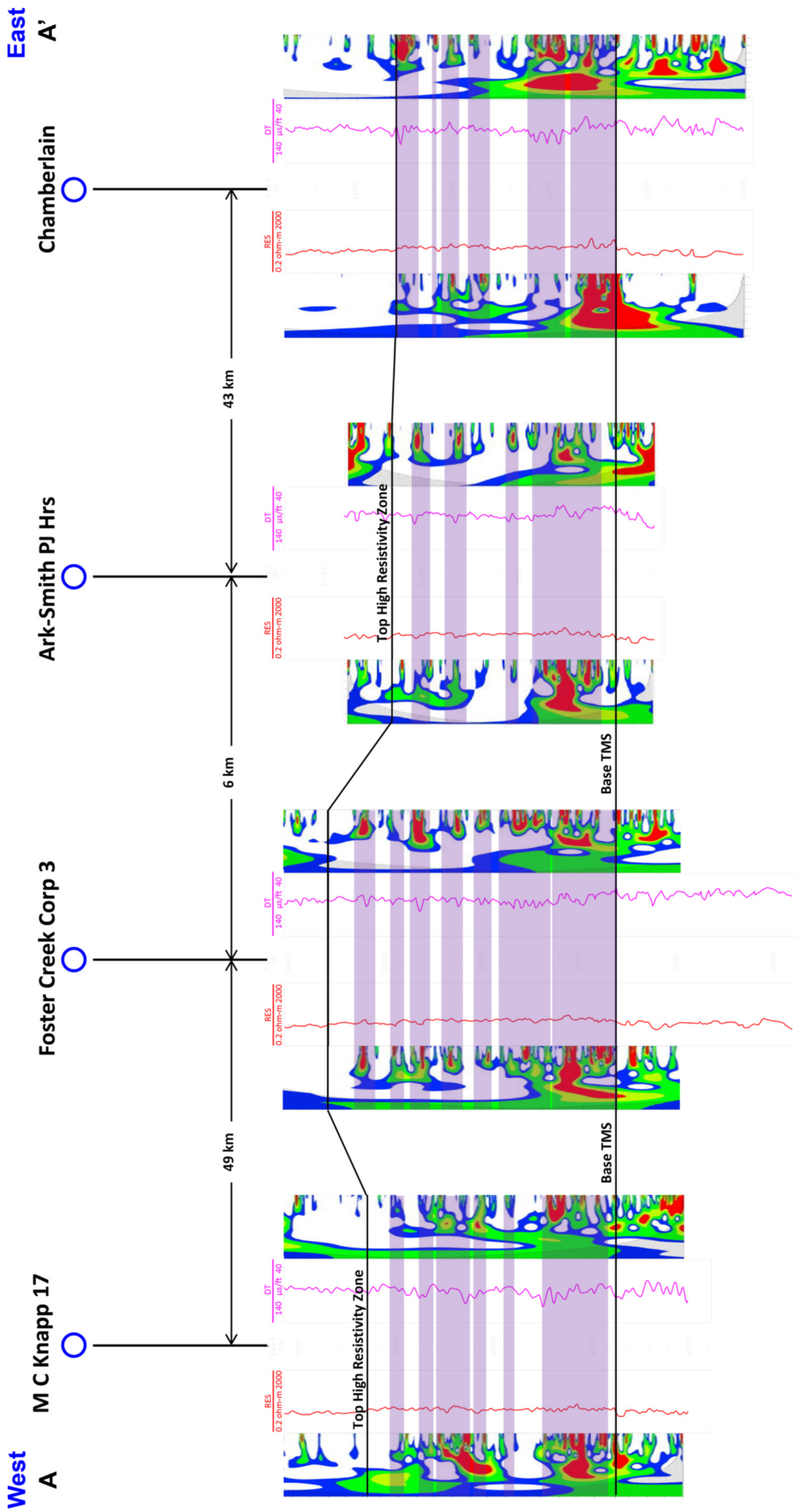


Figure 6. Strike cross-secion A–A' including the M C Knapp 17, Foster Creek Corp 3, Ark-Smith P J Hrs, and Chamberlain wells showing correspondence of high spectral power across between sonic slowness and resistivity at individual wells and rough correspondence across regional scale.