Reservoir Characterization of the Pennsylvanian Cleveland Sandstone C Unit, Cleveland Field Unit, Northeastern Oklahoma*

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Abstract

The Cleveland Field in northeastern Oklahoma has produced an estimated 50 MMBO since its discovery in 1904. A re-evaluation of this mature oil field was undertaken to identify bypassed "pay" and to estimate the ultimate hydrocarbon recovery using high-resolution reservoir data. The study was focused on the Middle Pennsylvanian (Desmoinesian) Cleveland Sandstone in what is now the "Cleveland Field Unit." The Cleveland Sandstone, which is approximately 120-200 ft thick, is composed of four distinct depositional units, or units (A, B, C, and D, in descending order). Considerable oil has been produced from the B unit of the Cleveland as evidenced from recent core and log data. Yet other oil-bearing units in the Cleveland, only subtly finer grained and more interbedded than the B unit, have been discounted because older tests and calculations from vintage logs resulted in past assessments that these sandstone bodies are effectively non-productive. However, modern tools for evaluation, along with innovative drilling and completion techniques, have rendered these same sandstones to be profitable, productive units. Unit C, which best exemplifies this re-evaluation, is highlighted here. The techniques used in this study are thought to have application in other mature fields, especially in the Mid-Continent.

Introduction

The initial discovery of oil in the Cleveland Sandstone was in 1904, near the town of Cleveland, Pawnee County, Oklahoma (Campbell, 1997), on a structural feature (at approximate depth of 1600-1800 ft MD) on the Cherokee Platform in northeastern Oklahoma (Figures 1, 2, and 3). Production in the field has been from several Pennsylvanian and older Paleozoic reservoirs, with the largest allocation coming from the Bartlesville sandstone and the Cleveland "B" units, the second of four Cleveland units recognized during this study. Recently Mid-Con Energy, LLC initiated a data-acquisition and integrated reservoir-characterization program, followed by a infill-drilling program, targeting the Cleveland Sandstone for the purpose of enhancing oil recovery by waterflood. Each unit of the Cleveland Sandstone has been analyzed and assessment of its potential for waterflooding has been made.

This article focuses on the C unit, which is third from the top of the Cleveland. It has good potential for significant primary and secondary production even though it had been previously bypassed due to its low-resistivity, low-contrast features.

The Cleveland Field Unit consists of approximately 200 wells within 1760 acres, with approximately 175 wells having conventional wireline logs available for study. This control, especially the modern logs (acquired post-1970) of 40 wells, allowed recognition of four Cleveland units throughout the study area. These logs were correlated to three wells (Figure 3) with borehole image logs and whole cores through the entire Cleveland interval. In addition to the routine core analysis, cores were analyzed using X-ray diffraction, thin-section petrography, capillary pressure, and laser particle-size analysis. These data were integrated with geometric data (thicknesses and structure, primarily) to characterize the original and current saturations, shale volume, porosity and permeability (So, Sw, Ø, Vsh) of the reservoirs.

Geologic Setting

The Cherokee Platform, which is the dominant feature of northeastern Oklahoma west of the Ozark Uplift, is characterized as a relatively tectonic element (Figure 1). However, it is characterized by numerous faults (Figure 2), dominated by strike-slip movement, undoubtedly related to the Paleozoic active elements of southern Oklahoma (Ouachita, Arbuckle, and Wichita-Criner uplifts).

At the level of the Checkerboard Limestone above the Cleveland Sandstone, the Cleveland structure is a heart-shaped dome, with three culminations (Figure 4), that developed along a major north-northeast-trending fault zone (Figure 2), with significant strike-slip component of movement that occurred episodically during the Paleozoic and later. Structural dip at the Cleveland level in the study area ranges from 20 to 100 ft. per mile. The Cleveland Sandstone lies between the widespread Checkerboard Limestone (above) and the “Big Lime”/Oswego / Lenapah Limestone (below) in the Marmaton stage (upper Desmoinesian).

Regionally the Cleveland has been divided into upper and lower units. Based on wireline signatures, Campbell (1997) described the depositional environment of the lower Cleveland Sandstone, as shallow marine, and fluvial-deltaic, for the upper Cleveland (Figure 5). The source area of the Cleveland Sandstone has been widely accepted as having been the Ouachita uplift (Rascoe and Adler, 1983). Krumme (1981) mapped the general thickness of the Cleveland Sandstone regionally as a series of channels, ranging in thickness from 10 to 160 ft. The Cleveland field, as mapped by Krumme, was formed as part of a channel system that flowed generally from southeast to northwest. Paleocurrents on outcrop are consistent with Krumme’s findings. Krystinik and Lupo (2011) and Krystinik (2013) consider the Cleveland in northeastern Oklahoma to be composed of incised valley deposits overlain by deltaic sediments. Evidence (core, log, outcrop) from this study suggests that the Cleveland Sandstone represents an overall progradational sequence, with the “C” unit composed primarily of stacked distributary channels.

Stratigraphy and Petrology

In the study area, the Cleveland Sandstone has been divided into four units (A, B, C, and D), in descending order (Figure 6). These divisions of the Cleveland are based on examination of cores from three wells, with calibration of wireline-log signatures to the cores. These cores were examined for grain size, sedimentary structures, and composition.

Characterization of Cleveland C Unit

The C unit is predominantly very fine- to fine-grained sandstone, light to dark brown, and moderately to well sorted. Grains are loosely cemented, primarily with silica and secondarily with dolomite. Common sedimentary structures are massive, planar, and cross bedding, with some interbedding of shale and siltstone (Figure 7). This sandstone contains shale rip-up clasts, along with soft-sediment-deformation structures, especially in the lowermost part. Quartz and feldspar, with some muscovite, are the major constituents of the C unit, with quartz and carbonate cement. Both primary porosity and secondary porosity are present (Figure 8).

Based primarily on the internal features of the Cleveland Sandstone, especially the boundaries between the individual units (Figure 9), the Cleveland is considered to represent a deltaic system, with prominent channel deposits, distributaries to incised fluvial, and various other elements of a major delta complex, generally grouped as delta fringe. The internal features of the units, especially texture and lower and upper contacts, may be inferred from log signatures with reasonable confidence.

Because boundaries between the units are associated with interbedded to interlaminated, very fine-grained sandstone and shale, the deltaic complex probably did not migrate completely out of the study area during deposition of any part of the Cleveland; these interbedded, interlaminated sandstone and shale probably are the record of interdistributary-tidal flat-delta front (fringe) environments. Both the C and B units, which show somewhat serrated blocky wireline signatures, seem to be interpreted best as channel-fill material. The C unit probably is a multistoried (two genetic units) distributary-channel deposit (Figure 9). The B unit, coarser than the other units, likely was deposited upstream from the depositional tract for the C unit. The A unit records the transition from a delta to a shallow-marine setting.

Bootle et al. (2009) note that the average vertical resolution for conventional wireline logging tools is 5 ft. This limited vertical resolution restricts detailed lithologic definition; therefore, sandy shale, interbedded to interlaminated sand and shale, clay-rich sand, etc. are commonly manifested as suppressed resistivity, “lazy” density-neutron curves, and a “spikey” gamma-ray curve (et al., 2006). This may lead to bypassed pays and/or miscalculation of volumes of oil in-place.

Petrophysical Analysis

For this study, wireline logs were available from 240wells, but only 40 wells have modern well logs (acquired post-1970), which were used for petrophysical analysis. The older vintage logs were excluded in order to ensure uniformity of data.. Only two wireline-logging companies were used for all of the modern logs. Water samples from wells that are open only in the Cleveland Sandstone were taken in order to measure resistivity of the formation water.

Methods and Calculations

Petrophysical analysis was divided into two major activities:

- Core analysis (both routine [porosity, permeability, water saturation, oil saturation, and grain density] and special [X-ray diffraction, capillary pressure, LPSA, etc.] by Core Labs Inc.). Figure 10, a porosity-permeability semi-log plot for C unit from core analysis, shows an expected exponential change in permeability with arithmetic change in porosity.

- Analysis of Wireline Data (resistivity, neutron porosity, density porosity, gamma ray, spontaneous potential, microlog, and caliper) calibrated to core data in order to generate petrophysical parameters, using Hydrocarbon Data Systems (HDS) Petrophysical evaluation software. This evaluation includes calculations of porosity, permeability, shale volume, hydrocarbon volume, and current/original water saturation. Improvement in estimated porosity and permeability resulted from use of a shale-corrected effective- porosity equation and from the Timur equation for estimation of permeability (Roller, C., 2014, personal communication).

Porosity-Permeability

As described previously, the Cleveland Sandstone, composed primarily of quartz with feldspar, is a subarkose. Clays mainly are chlorite, illite, and kaolinite. Grain size is very fine-grained to fine-grained. Sorting is good to moderate. Average grain density is 2.68 g/cm^3.

With consideration of effective stress at reservoir depth, porosity-permeability data (from 202 core plugs) for the C unit are:

Porosity Range (%)	8.1-18.6
Klinkenberg Permeability Range (mD)	0.005-65.3
Average Porosity (%)	15.19
Average Permeability (mD)	12.29

Having a suite of porosity, resistivity, SP, and gamma-ray logs allows for development of reliable estimates of the most essential reservoir components: shale volume, total porosity, effective porosity, and water saturation. These statistics can be integrated with information about reservoir geometry to assess reservoir quality and estimate current oil in-place

Shale Volume and Effective Porosity

Estimating volume of shale in sandstones is based on values derived from the gamma-ray log, with the preferred (“first order”) estimate (Asquith and Grykowski, 2004) being:

$$V_{Sh} = \frac{(GR_{shale} - GR_{log})}{(GR_{Shale} - GR_{Sandstone})})$$

Total and effective porosity of the Cleveland Sandstone were calculated; total porosity was computed by using only bulk-density logs. As noted above, matrix density (or grain density) was considered to be 2.68 g/cm^3, and fluid density (i.e., density of drilling-mud filtrate) was assumed to be 1 g/cm^3.Bulk density correlated closely with helium porosity measured from core plugs.

Calculating effective porosity is made to account for shale within pores and then to calculate water saturation and ultimately to estimate oil in-place. For this study, effective porosity was calculated by using core-calibrated total porosity and applying:

$$PhiE = PhiT * (1 - Vsh)$$

Where, PhiE = effective porosity, PhiT = total porosity (density porosity), Vsh = shale volume.

Water Saturation

Estimating water saturation from wireline logs involves the integration of porosity, resistivity, and formation water resistivity. Water samples were collected from wells that produce only from the Cleveland Sandstone; analyses show that a reliable estimate of water resistivity is 0.059 ohm-meters (at formation temperature).

Because the Simandoux Water Saturation equation, given below, accounts for clay in sandstone, it was used to estimate water saturation in the C unit of the Cleveland.

$$Sw = \left[\frac{.4R_w}{\emptyset_e^2}\right]\left[\sqrt{\frac{5*\emptyset_e^2}{R_w*R_t}+\left(\frac{V_{sh}}{R_{sh}}\right)}-\left(\frac{V_{sh}}{R_{sh}}\right)\right]$$, where

h= Shale Volume, *h*= True Formation Resistivity from shale, ∅ = Effective Porosity, = Formation Water Resistivity, Rt= True Formation Resistivity.

Calculated average water saturation at the time of the study (2014) was 45.1%. For comparison, the Archie equation, with tortuosity factor of 1, cementation exponent of 1.73, and saturation exponent of 2, yields water saturation of 69.4%. The total porosity in the C unit is 18.1%, whereas the effective porosity is 13.7%.

Reservoir Geometry: Thickness and Distribution

By use of the HDS software, thicknesses of gross sandstone, porous sandstone, and net-pay sandstone were compiled, based on cut-off values for Vshale <50%, (total) porous sandstone >15%, and net pay <60%. Figure 11 is the net pay thickness map for the C unit.

It is estimated that oil in-place in the C unit is 29 million barrels (of the 50 million barrels in the entire Cleveland).

Conclusions

- Cleveland Sandstone is divisible into four units (A, B, C, and D in descending order) in the Cleveland Field Unit.
- The most productive unit has been "B" due to higher permeability, but "C" offers the best opportunity for additional production by current secondary methods.
- The Cleveland is interpreted as having been deposited in a fluvial-dominated deltaic system, formed as a multistoried complex in which deposition ranged from an active channel to a prodelta setting at or near its top.
- Principal framework constituents of the Cleveland Sandstone, a subarkose, consist primarily of quartz and feldspar, with some muscovite.
- For calculation of Sw, effective porosity and the Simandoux equation were used. Sw is 45.1% and effective porosity is 13.7%. Earlier calculations, probably using the Archie equation, may have contributed in Cleveland C unit having been previously by-passed.
- Oil presence in commercial quantities in the Cleveland is evidence of vertical migration of hydrocarbons along fault(s) instrumental in development of a well known local structure. Improved methods for calculation of water saturation, etc., coupled with fault-related trap and vertical migration, resulted in "discovery" of significant oil reserves. It is proposed that these features exist in a number of other localities not only in northeastern Oklahoma but also in other tectonically similar areas.

References Cited

Asquith, G. B., and D. Krygowski, 2004, Gamma Ray (Chapter 3):Basic Well Log Analysis (2nd edition): AAPG Methods 16, p. 31-36.

Bootle, R.J.R., M. Waugh, M.S. Bittar, F. Hveding, W.E. Hendricks, and S. Pancham, 2009, Laminated sand shale formation evaluation using azimuthal LWD resistivity: SPE Paper 12890 (presented at SPE Annual Technical Conference and Exhibition, New Orleans, LA January 1, 2009.

Campbell, J.A., 1997, The Cleveland Play: Regional Geology: Oklahoma Geological Survey Special Publication 97-5, p. 13-29.

Krumme, G.J., 1981, Stratigraphic Significance of Limestones of the Marmaton Group (Pennsylvanian, Desmoinesian) in eastern Oklahoma: Oklahoma Geological Survey Bulletin 131, 67p. Website accessed October 12, 2017, http://www.ogs.ou.edu/pubsscanned/BULLETINS/bulletin131.pdf.

Krystinik, L., 2013,Exploring for tight oil in the Pennsylvanian Cleveland Sandstone on the Nemaha Ridge using high resolution 3D seismic and stratigraphic analysis: A new play in an old area: Applied Petroleum Geology Lecture. Oklahoma State University. Stillwater. 2013.

Krystinik, L., and T. Lupo. 2011, High-resolution 3-D sequence stratigraphy delineate new tight oil play: The American Oil and Gas Reporter, July 2011. Website accessed October 12, 2017, http://www.aogr.com/magazine/editors-choice/high-resolution-3-d-sequence-stratigraphy-delineate-new-tight-oil-play.

Marsh, S., and A. Holland, 2016, Comprehensive fault database and interpretive fault map of Oklahoma: Oklahoma Geological Society Open-File report (OF2-2016, 15p. Website accessed October 11, 2017, http://ogs.ou.edu/docs/openfile/OF2-2016.pdf.

Passey, Q.R., K.E. Dahlberg, K.B. Sullivan, H. Yin, R.A. Brackett, Y.H. Xiao, and A.G. Guzmán-Garcia, 2006, Petrophysical properties of thinly bedded formations (Chapter 6): Petrophysical Evaluation of Hydrocarbon Pore-thickness in Thinly Bedded Clastic Reservoirs: AAPG Archie Series, no. 1, Chapter 6, p. 61-71.

Rascoe, B., Jr., and F.J. Adler, 1983, Permo-Carboniferous hydrocarbon accumulations, Mid-Continent, U.S.A.: AAPG Bulletin, v. 67/6, p. 979-1001.

Roddy, C.M., 2014, Reservoir Characterization of the Middle Pennsylvanian Cleveland Sandstone, Cleveland Field Unit, Pawnee County, Oklahoma: M.S. thesis, Oklahoma State University, 111p.

Simandoux Equation References

Simandoux, P., 1963, Dielectric measurements on porous media application to the measurement of water saturations: study of the behaviour of argillaceous formations: Revue de l'Institut Francais du Petrole 18, Supplementary Issue, p. 193-215.

TAMU (Texas A&M University), 2010, Formation Evaluation, PETE 663, Shaly Sand Evaluation – B, Summer 2010, 61p. Website accessed August 15, 2018, http://www.pe.tamu.edu/blasingame/data/z_zCourse_Archive/P663_10B/P663_Schechter_Notes/PETE_663_SHLY%20SD_B.pdf.

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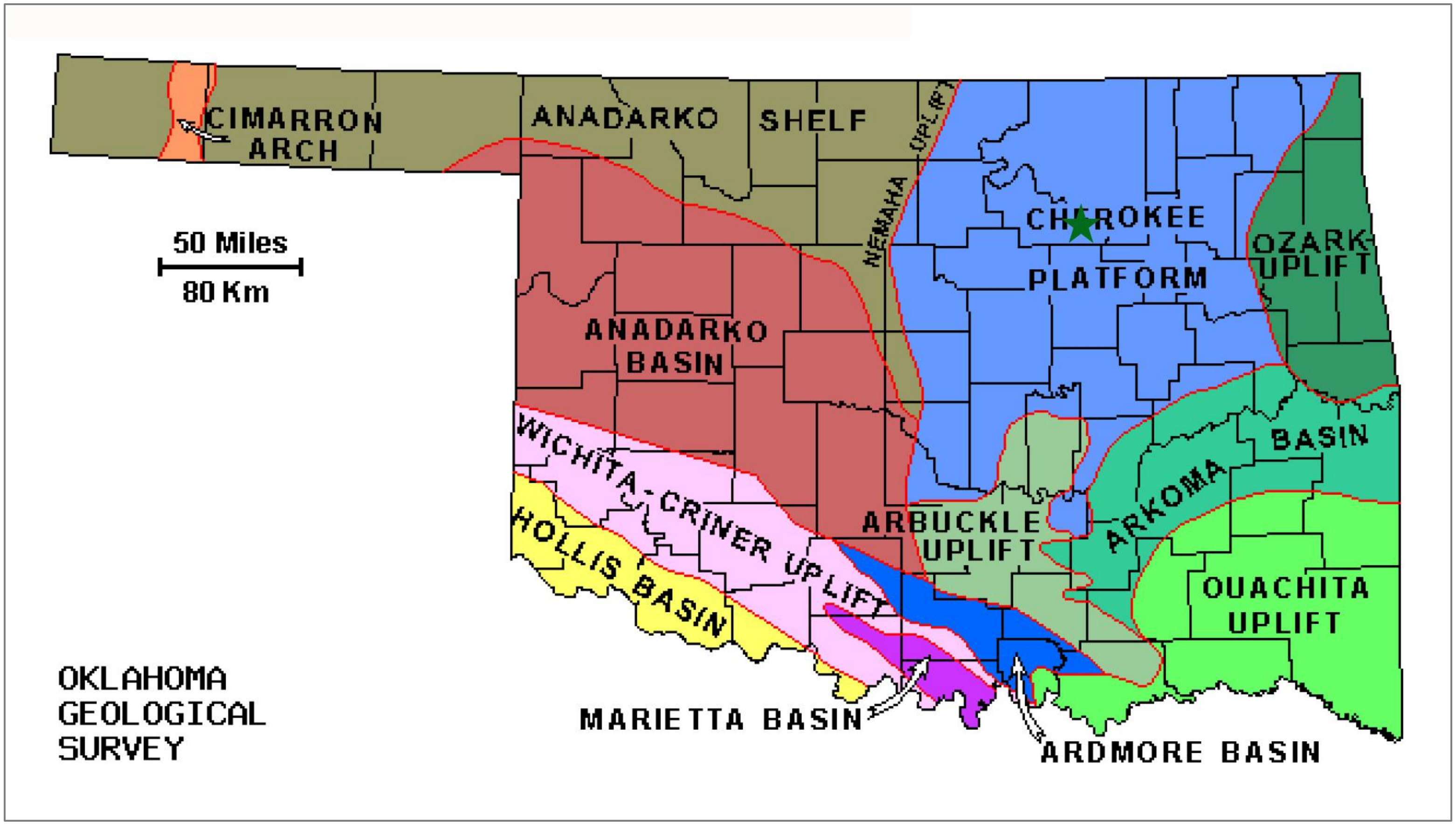

Figure 1. Geologic provinces of Oklahoma (after Campbell, 1997), showing the relation of the Cherokee Platform to the other geological provinces in Oklahoma. Star represents the approximate location of the study area.

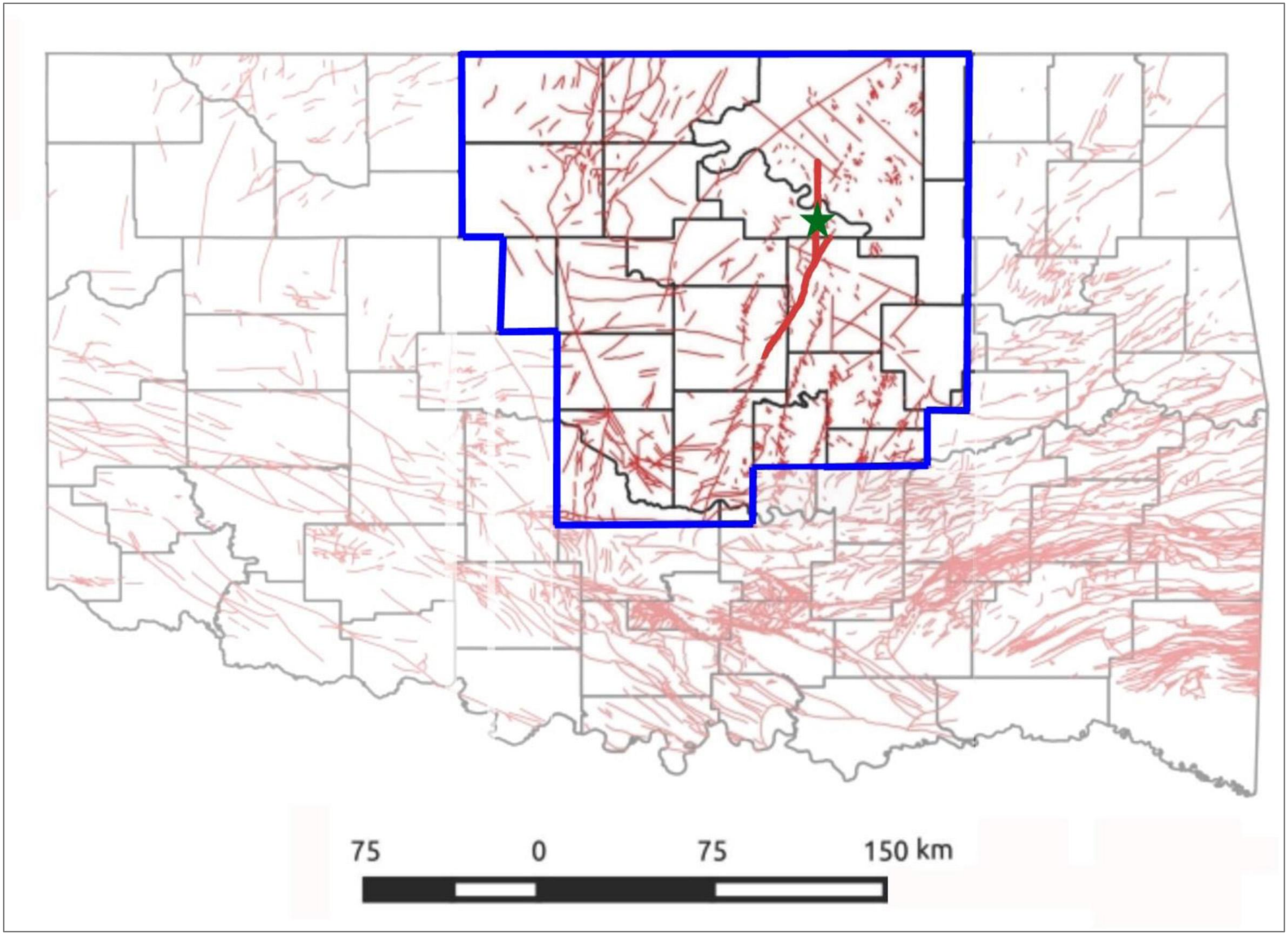

Figure 2. Interpretive fault map of Oklahoma, exclusive of the Panhandle. Outlined is the relatively stable tectonic area west of Ozark uplift. Location of Cleveland Field is shown (by star), also shown (in wider band is position of regional fault associated with structure of Cleveland Field. Modified from Marsh and Holland (2016).

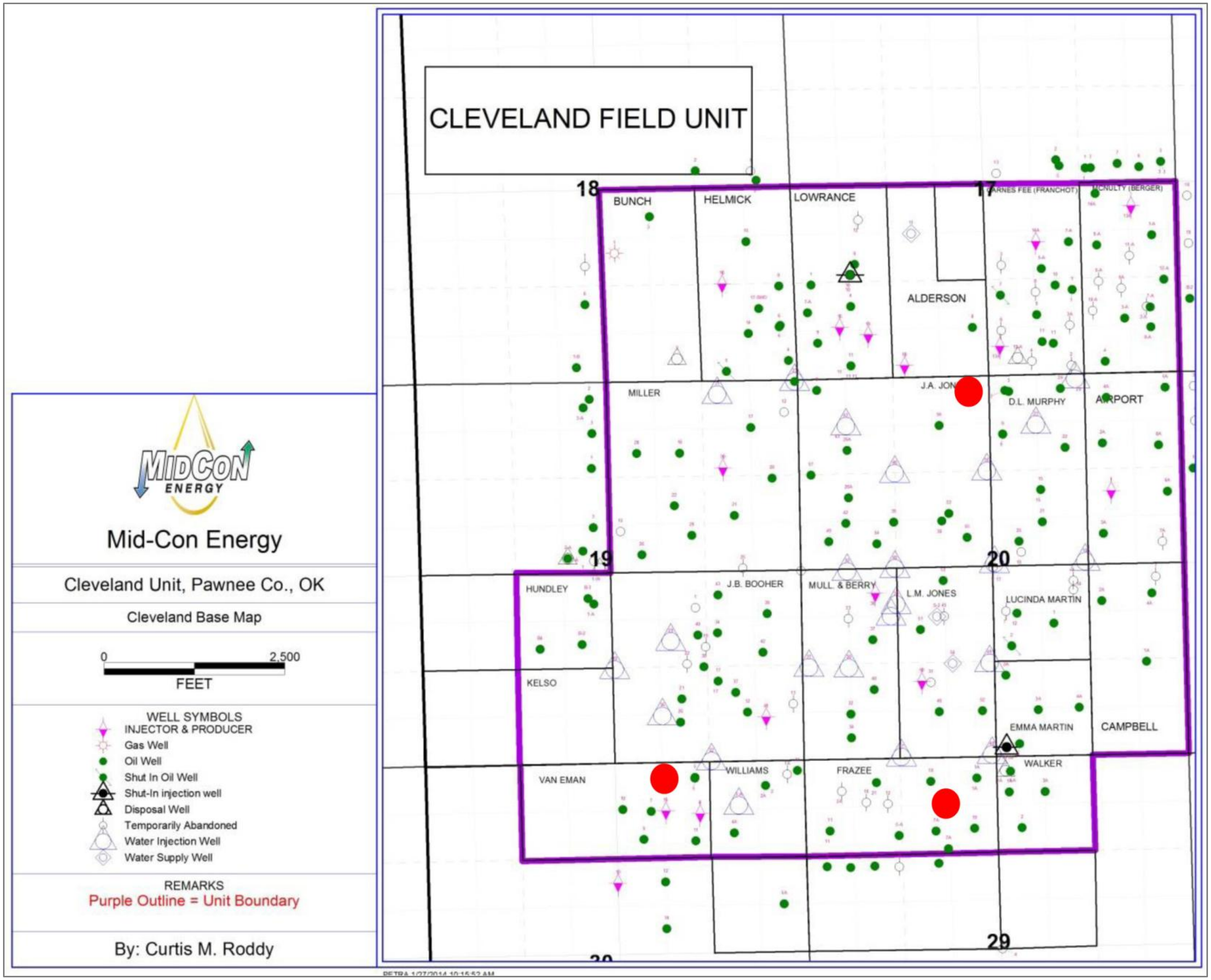

Figure 3. Map of the Cleveland Field Unit, which is located in T.21N, R.8E, Pawnee County, Oklahoma.

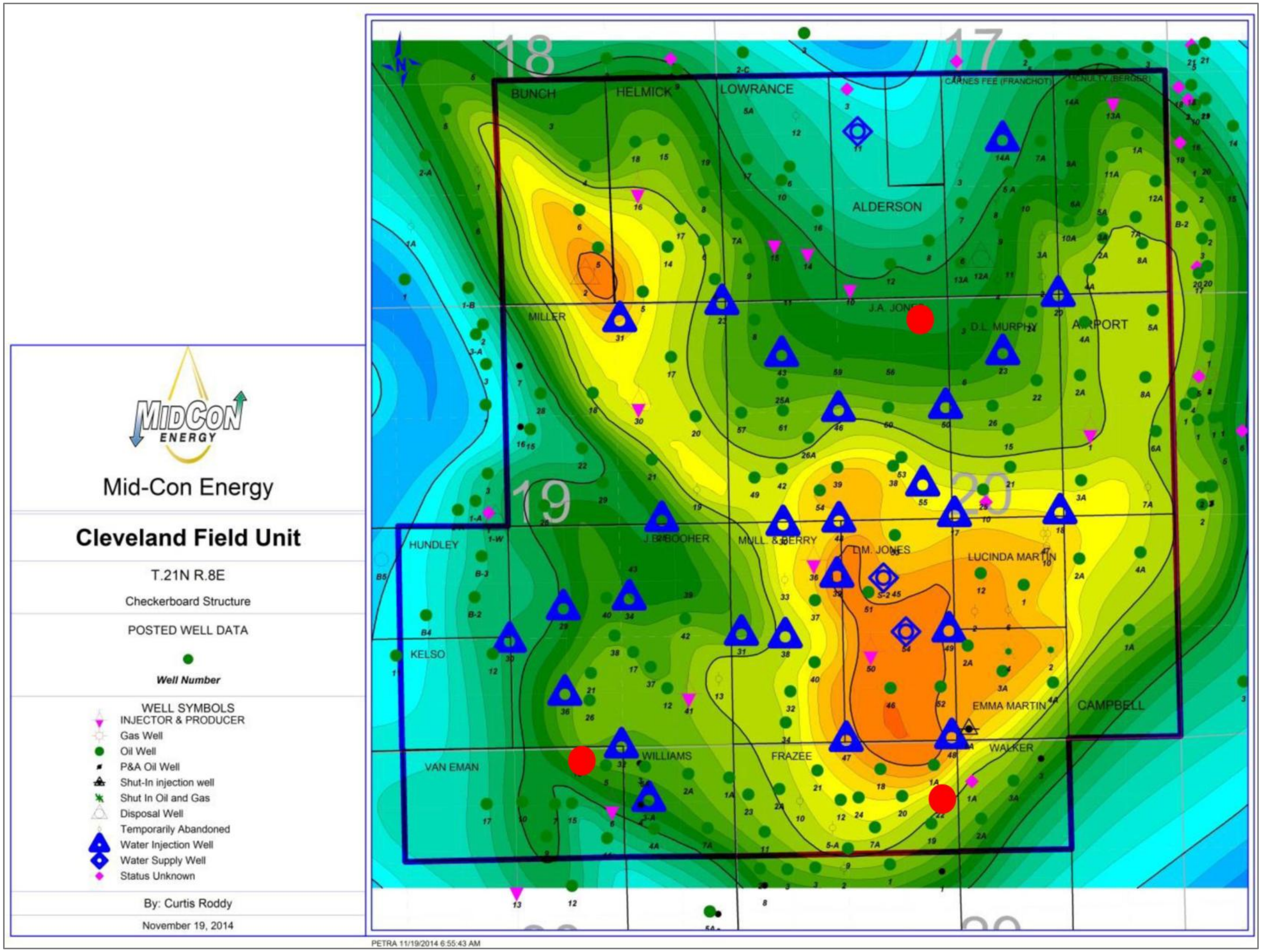

Figure 4. Structural contour map of the top of the Checkerboard Limestone, Cleveland Field Unit, T.21N, R.8E, defining ñCleveland dome.ò Subsea elevations. C.I. 20 ft.

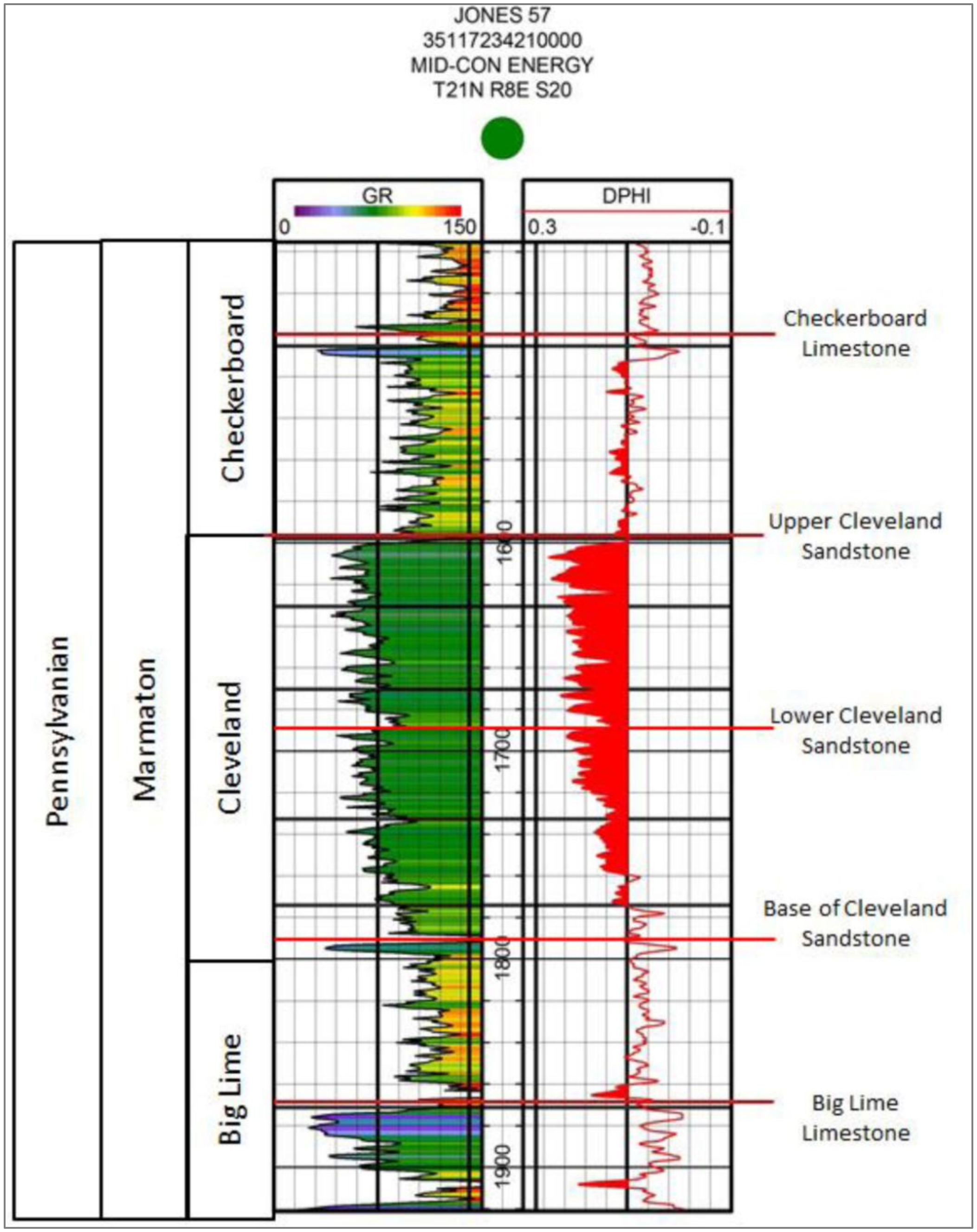

Figure 5. Representative wireline log of the Cleveland Sandstone, with delineation of upper and lower units generally recognized regionally. Boundaries of the two units are based largely on changes in porosity and gamma-ray values.

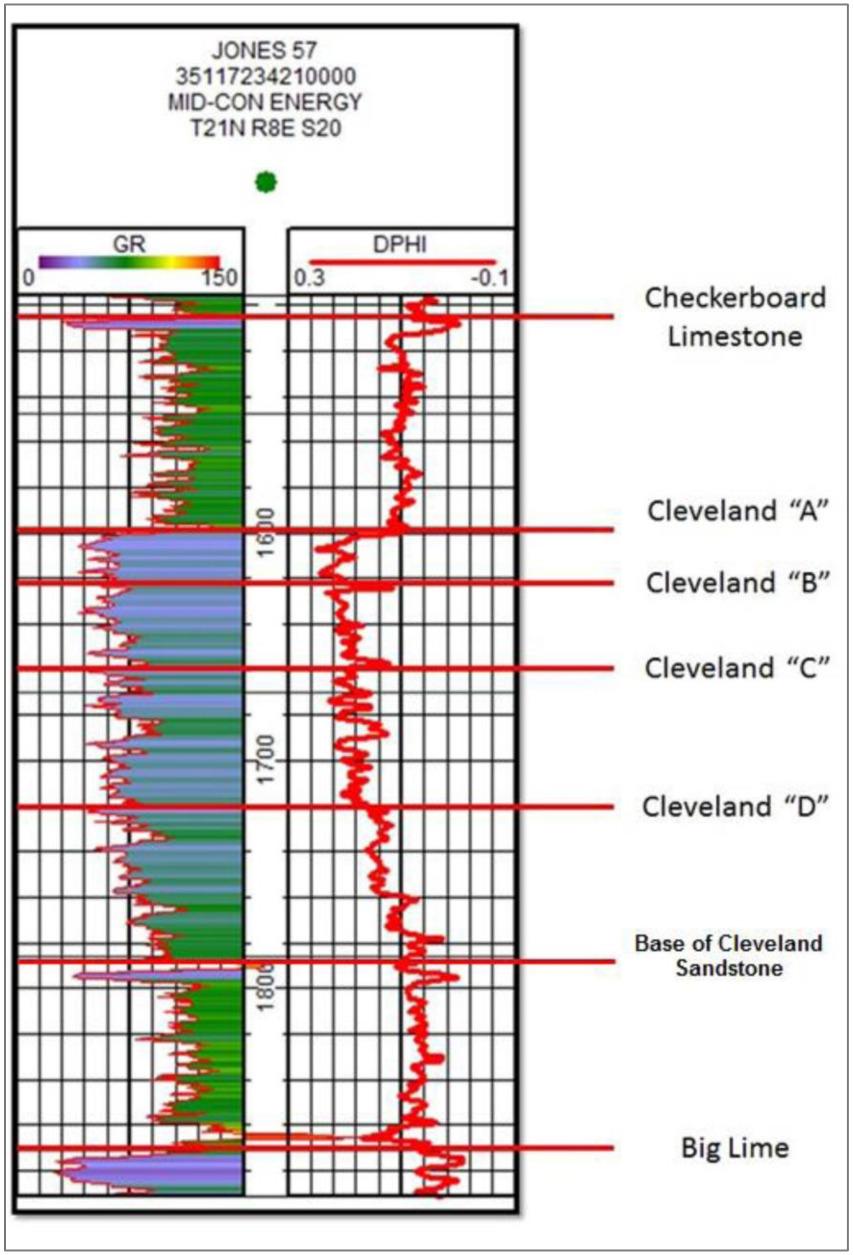

Figure 6. Representative log of oil well (in Section 20, T.21N., R.8E.), with production from the upper part of the Cleveland Sandstone. Gamma-ray is measured in API units and DPHI (Density porosity) is measured in porosity units.

Figure 7. Core photographs from the Cleveland C unit. Core is 3.5 inches in width. A. 1650 to 1654 ft, well location: Section 20, T.21N., R.8E. Dark brown to light brown, very fine-grained sandstone. Shale rip-up clasts and shale laminae. Inclined bedding with shale interbeds (in upper one-third): cross bedding and/or contemporaneously deformed bedding. B. 1747 to 1751 ft., well in Section 29, T.21N., R.8E: Brown to light brown, very fine-grained sandstone. Horizontal bedding/laminae, cross bedding above shale lamina (in lower part).

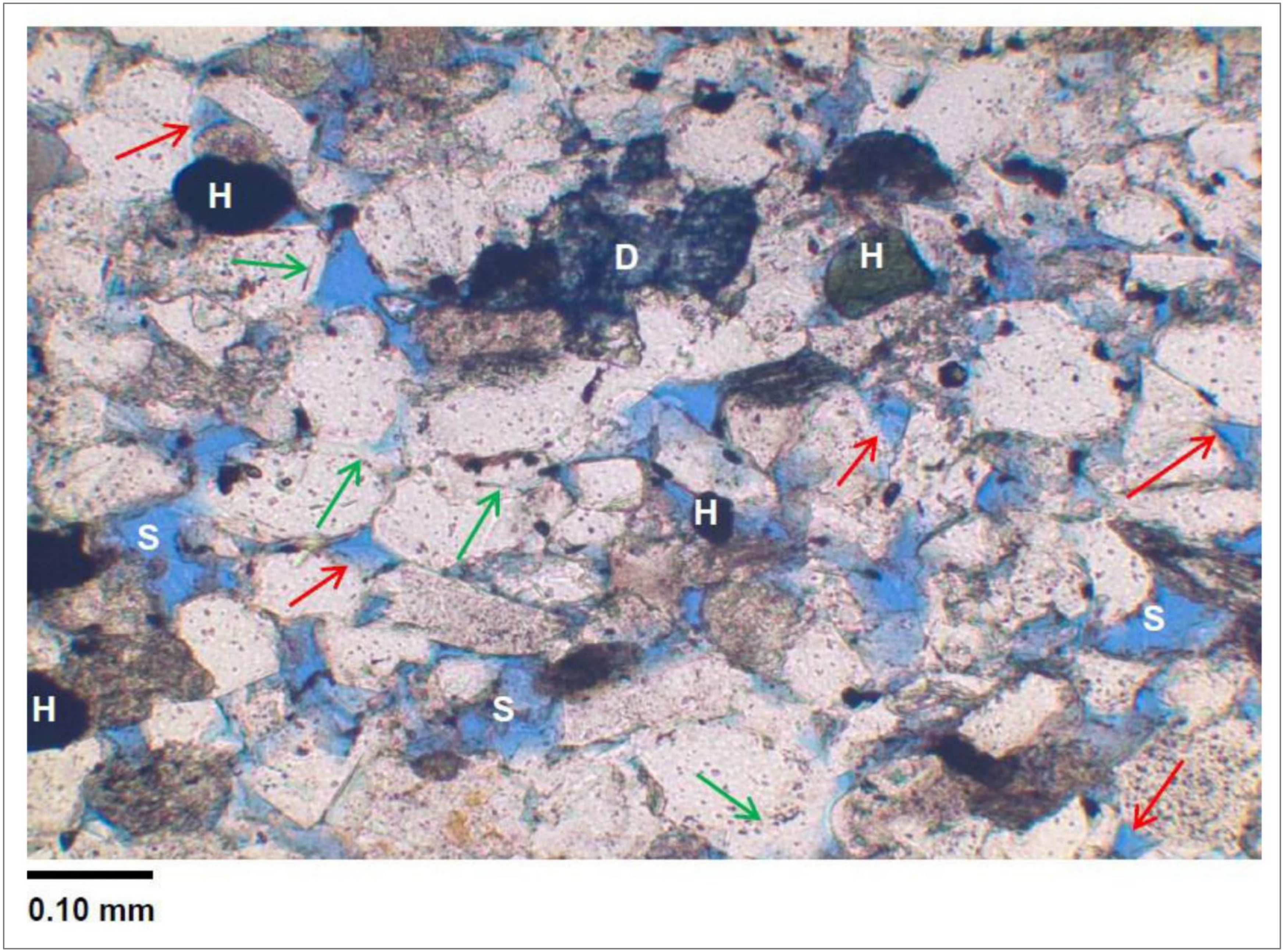

Figure 8. Photomicrograph of C unit. Grains are very fine to fine in size, moderately sorted, and tightly packed, with irregular to long contacts where secondary porosity (S) is not present. Green arrows indicate quartz overgrowths; dolomite cement (D) is present. The majority of the porosity is secondary porosity (S). Heavy minerals (H) are also present.

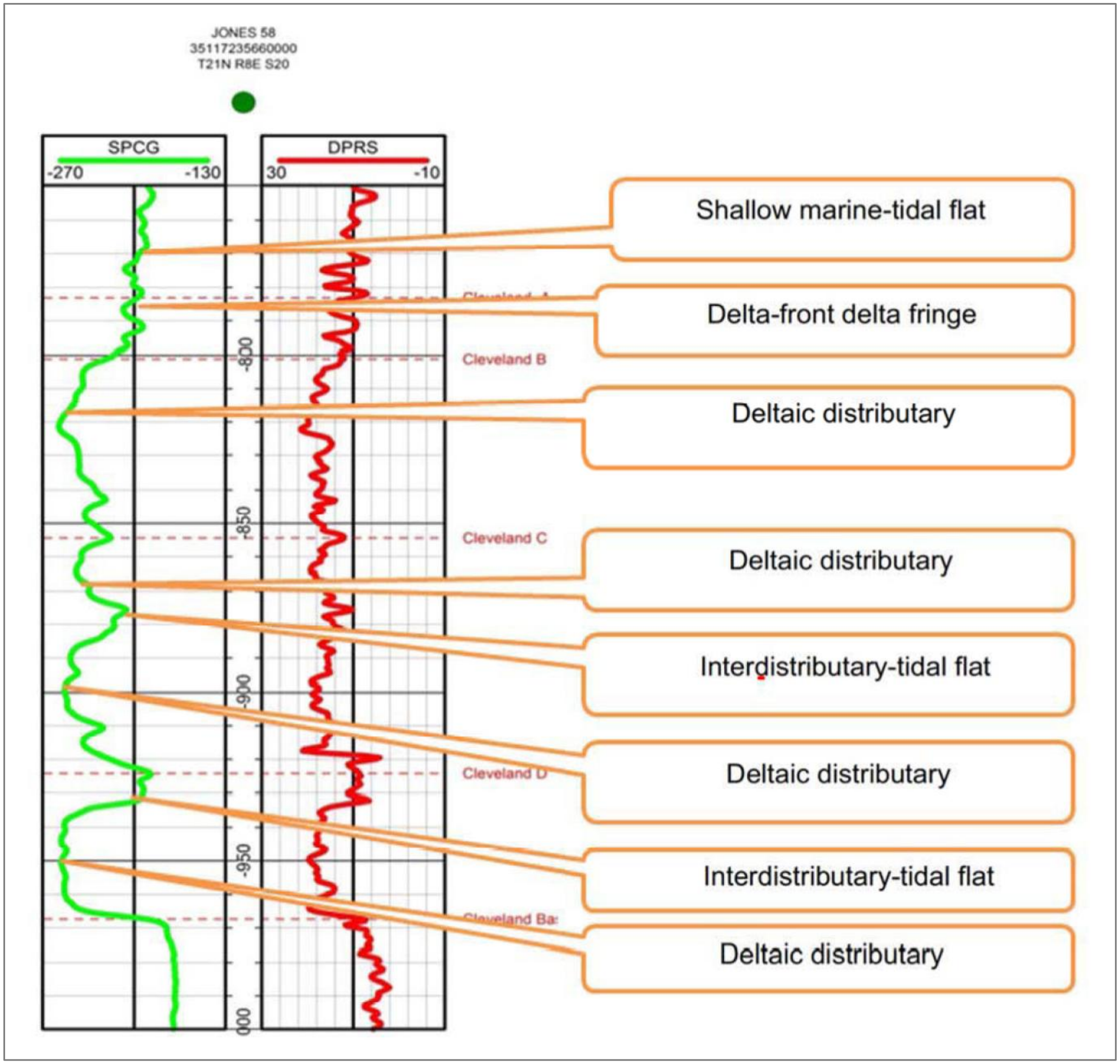

Figure 9. Wireline log of Cleveland Sandstone from well in Section 20, T.21N, R.8E, with spontaneous potential (green) and density porosity (red) curves. The interpreted depositional environments are shown for each unit. C is stacked deltaic distributaries, with interdistributary – tidal flat below, between, and above the channel deposits.

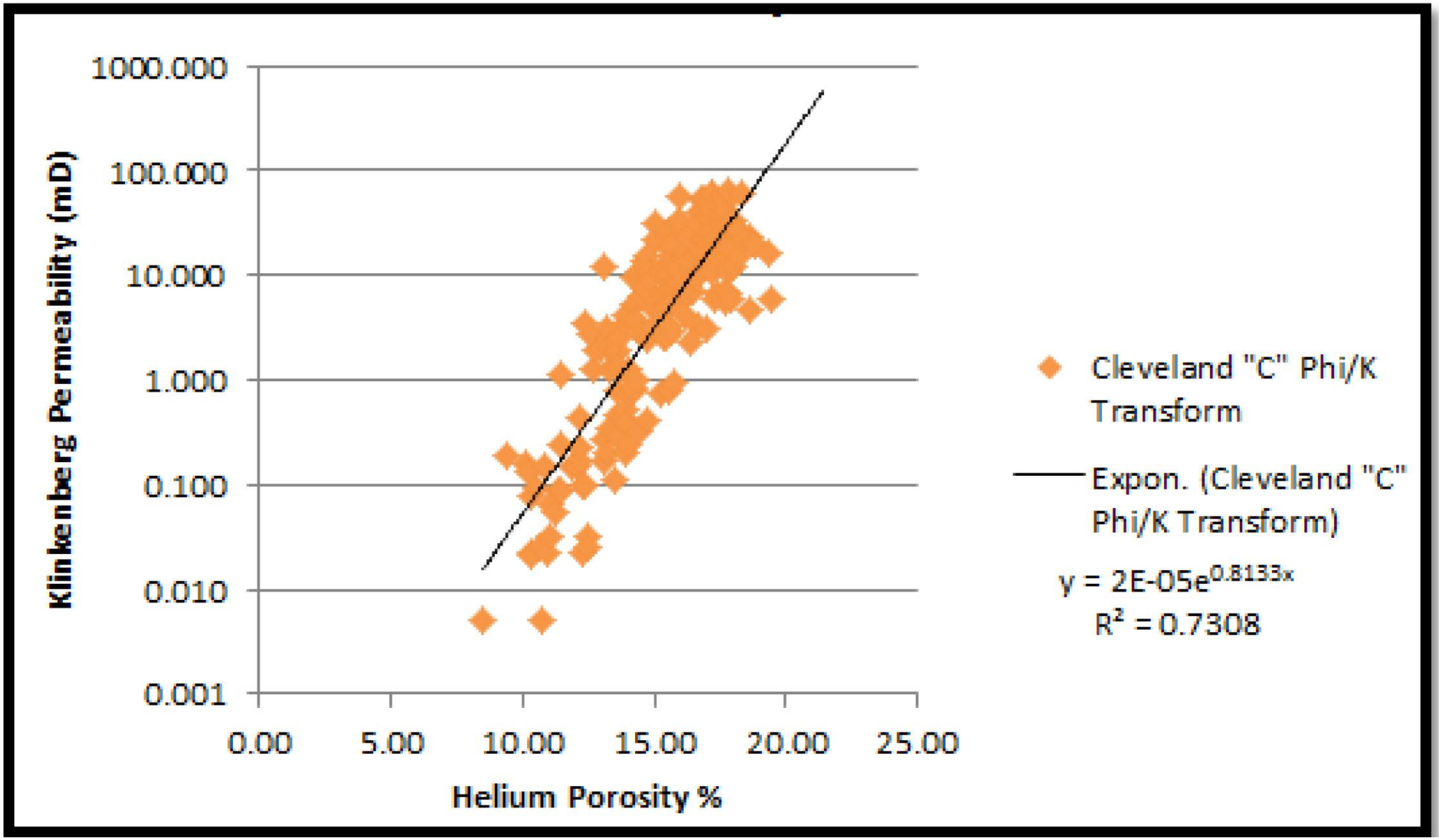

Figure 10. Porosity-permeability plot for the Cleveland C unit in the study area. Porosity and permeability database is results of analysis of 202 core plugs.

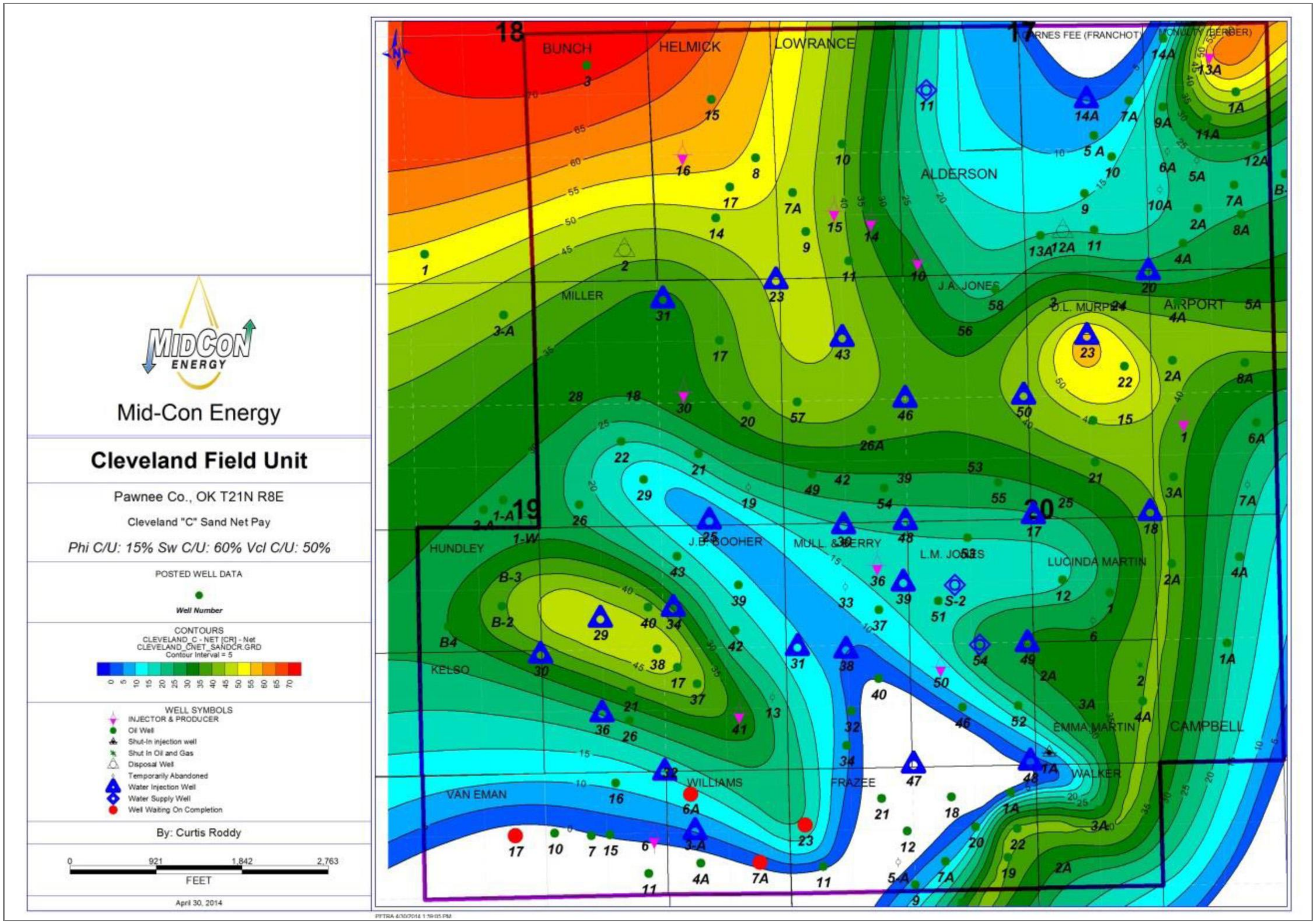

Figure 11. Cleveland “C” net pay sandstone map (total Phi >15%, Vsh<50%, Sw<60%). Sand is widespread, but absent in parts of the south and northeast. Relatively thick trends are rather narrow, except in the northwest where the sand is thickest and more “blanket’like.” Contour interval 5 ft.