Source-Rock Evaluation. Best Tactics for Finding the Sweet Spots within Unconventional and Conventional Reservoirs in the Permian Basin*

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Abstract

Accurate determination of organic matter characteristics in hydrocarbon source-rocks is of key importance in evaluating petroleum systems. Organic geochemical analysis is a powerful tool that can provide a wide range of crucial information to exploration geologists. Such information include kerogen type, thermal maturity, transformation ratio, and generative petroleum potential. The scientific literature is full of case studies that provide evidence for the accuracy of organic geochemistry data and how they were successfully utilized to find economic discoveries. Nonetheless, like other exploration tools, organic geochemical data need to be strategically employed to avoid erroneous interpretations and obtain maximum benefit. Three examples of useful techniques for the identification of high-graded drilling targets within organic-rich unconventional and conventional reservoirs in the Permian Basin are presented from the Woodford Formation and the lower Permian Wolfcamp shales. For the unconventional examples, these techniques include mapping total organic carbon (TOC), vitrinite reflectance equivalents (VRe), transformation ratio (TR), and T_{max} data to locate areas of high organic content, optimal thermal maturity, and favorable gas/oil ratios (GOR). Additionally, the use of pressure- depth plots to establish fluid contacts and migration pathways away from the "petroleum kitchen" is demonstrated for a conventional play.

Introduction

The four basic physical components of conventional hydrocarbon systems are the source-rock, reservoir- rock, hydrocarbon trap, and a cap-rock (seal). In the case of unconventional systems, these traditional components are often combined in a single rock unit. Although all petroleum-system components are nominally of equal importance, one can argue that the presence of organic-rich source-rock horizons is the essential foundation of any petroleum system. Therefore, it is of prime importance for petroleum geologists to carefully study and evaluate all plausible source-rock units in order to accurately locate sweet spots and make sound, lowest-risk drilling decisions. This evaluation has two components that often complement each other, analytical data and results of maturity modeling. Among the powerful analytical methods to characterize source-rock richness and generation potential is programed pyrolysis, which generates a suite of key organic geochemical

parameters such as total organic carbon (TOC), S1 (hydrocarbon shows), S2 (hydrocarbon yield from kerogen cracking), genetic potential, production index (PI), hydrogen index (HI), oxygen index (OI), and T_{max} (thermal maturity). For explanation of the different pyrolysis parameters, the reader may refer to Tissot and Welte (1984), Peters and Cassa (1994), and Dembicki (2017).

Interpreting pyrolysis data requires experience to avoid making costly mistakes. It also requires sufficient knowledge about the geological, burial, and thermal history of the formation under investigation. Unfortunately, all too often geology, engineering, production, and geochemistry are not adequately integrated in the development of drilling locations for hydrocarbon plays. Therefore, the purpose of this paper is to show three examples of strategies using commonly obtainable datasets to find the best drilling targets within the Upper Devonian Woodford Formation and the lower Permian Wolfcamp shales in the Permian Basin.

The Permian Basin is one of the most-prolific hydrocarbon-producing basins in the USA, and perhaps the largest unconventional petroleum play worldwide. According to the U.S. Energy Information Administration (EIA), as of September 2018, the Permian Basin has produced more than 33.4 billion barrels of oil and about 118 trillion cubic feet of natural gas over a period of about 100 years (EIA, 2018a). During 2017, the Permian Basin accounted for 20% of the total crude oil and about 9% of the total dry natural gas production in the USA, with estimated remaining proven reserves, as of 2016, to exceed 5 billion barrels of oil and 19.1 trillion cubic feet of natural gas (EIA, 2018a, b).

The Upper Devonian Woodford is an organic-rich formation composed predominantly of black shales with large amounts of preserved marine organic matter (Comer, 1991). It extends over much of the Permian Basin and acts as both source- and unconventional reservoir-rock, the latter especially when it is highly fractured (Comer, 1991). The Woodford Formation has the highest TOC content (5–8 wt%) in portions of Crane, Ector, Pecos, Reeves, Ward, and Winkler counties (Figure 1). It has also been the subject of several studies due to its favorable lithology, TOC, reservoir properties, thermal maturity, and saturation (Bammidi et al., 2011; Hemmesch et al., 2014; Drake et al., 2018). Organic-geochemical data from additional examples of potential economic discoveries within the Woodford Formation in the Delaware Basin are discussed herein.

The Pennsylvanian–lower Permian Wolfcamp shales contain organic-rich horizons that exist throughout the greater Permian Basin area, including the Delaware Basin, Central Basin Platform, and the Midland Basin. Petroleum companies in the Permian Basin commonly subdivide the Wolfcamp shales into four operational units known from top to bottom as the Wolfcamp A, B, C, and D (Baumgardner et al., 2016). The Wolfcamp A and B units are the most drilled targets in the Permian Basin (EIA, 2018a). In 2016, the U.S. Geological Survey calculated technically recoverable mean resources of 20 billion barrels of oil and 16 trillion cubic feet of gas in the Wolfcamp shales in the Midland Basin (Gaswirth et al., 2016). The Wolfcamp shales have recently been under extensive scrutiny owing to their optimal geological, geochemical, and maturity characteristics for petroleum production (e.g., Baumgardner et al., 2016; Gaswirth et al., 2016; Kvale and Rahman, 2016; MacRitchie and Zobaa, 2019; Hackley et al., 2020). Additional discussion of potential commercial target areas within the lower Permian Wolfcamp shales in the Delaware Basin is introduced herein based on production and organic geochemical data.

Methodology

Programed pyrolysis data are obtained through the thermal decomposition of organic matter in an inert atmosphere. As described by Dembicki

(2017), the process involves placing about 50 to 100 milligrams of ground rock samples in the pyrolysis oven and heating them to 550°C in the presence of helium.

Evolved volatile organic materials as well as CO_2 are measured and recorded as S1, S2, and S3 peaks on a pyrogram. The S1 peak represents the amount of free hydrocarbons that can be volatilized out of the rock without cracking the kerogen while the S2 peak represents the existing potential of a rock to generate hydrocarbons (Peters and Cassa, 1994). The S3 peak indicates the amount of oxygen associated with the kerogen in the sediment (Dembicki, 2017). Other reported parameters include TOC as well as T_{max} which is the recorded temperature at maximum S2 generation. Using the aforementioned values, additional critical parameters such VRe can be calculated using Jarvie's (2018) equation:

$$VRe = 0.0165 \times T_{max} - 6.51$$

T_{max} cutoff values used in this paper are after Peters and Cassa (1994). Mapping of TOC, T_{max}, VRe, and TR was done manually using an open-source graphic designing software. Regional TOC and VRe data for the Woodford Formation are from Comer (1991) and Entzminger and Miller (2004). VRe and TR data for the Woodford's seven control wells in Loving, Ward, and Winkler counties were obtained with permission from Doug Waples, Sirius Exploration Geochemistry Inc.

For many small petroleum companies, datasets and resources are limited, thus finding ways to make the most use of the data available is critical. The three examples presented in this paper show that meaningful interpretations of organic geochemical data can lead to high-grade exploitation targets where minimal datasets are obtainable. But like any dataset, organic geochemical data are best used in integration with all the other available data for a given prospect or play.

Discussion

Mapping VR, VRe, and TR

Vitrinite reflectance (VR) can be measured with reasonable accuracy on many rock samples, but measured VR values are not always reliable, for a variety of reasons. Such reasons include misidentification of vitrinite-like solid bitumen, sample selection (core, cuttings, outcrop), contamination with particulate drilling additives, organic matter weathering and oxidation, among others (Cardott, 2012; Hackley et al., 2013). To replace or supplement measured VR values, we can calculate VR using standard modeling software, and we can estimate reflectance-equivalent values (VRe) for samples that were analyzed using a number of alternative techniques. Measured VR values in the Permian Basin are of questionable accuracy because of the nature of the Paleozoic organic matter. Thus, it is better in the Permian Basin to augment VR datasets with calculated VRe values from modeling. However, even the best VR and VRe datasets cannot resolve another issue; the increase in VR values with increasing thermal stress (the effects of temperature over geologic time) which is not directly related to hydrocarbon generation. The validity of VR and VRe as proxies for hydrocarbon generation across the broad range of maturities that constitute the hydrocarbon-generation window requires local calibration, as shown by Waples and Marzi (1998). Mapping vitrinite reflectance equivalents helps high-grade an exploration area of interest (AOI) by suggesting the most-likely areas for the necessary level of hydrocarbon generation to have been achieved. The main problem is that VR is not as accurate a technique as many people believe for mapping maturity and/or product types for

similar unconventional plays across basins. Both mean activation energy and transformation ratio (TR) can be used to increase maturity accuracy. Mean activation energy is a measure of hydrocarbon generation which can be calculated from programed pyrolysis (Waples et al., 2010; Waples, 2016). This parameter will not be discussed further in this paper, although it has been used successfully in the Permian Basin. Instead, we will discuss the use of TR as a direct measurement of hydrocarbon generation in the next section.

VR and VRe values do not directly quantify levels of hydrocarbon generation; they are indicators of thermal stress, and any application to estimating hydrocarbon generation from reflectance values involves calibration with some yardstick of generation, such as TR. Transformation ratio can be obtained from "as-received" samples, but Waples and Tobey (2015) have demonstrated the advantages of working only with extracted samples, especially within the main hydrocarbon generation window. With the original S2 and HI, one can determine the TR. With TOC, VRe, and TR, one can more accurately predict sweet spot areas where the source rock is most likely to be exploitable as an unconventional reservoir.

Mapping only VRe for a source rock play can provide misleading results. In the mid-2000's there was great interest in the Woodford unconventional oil play on the Central Basin Platform (CBP). In the same formation, an unconventional gas play in the Delaware Basin was developing until gas prices collapsed. As oil became more commercially favorable, attention was turned to determining what areas would be most favorable in the same formation for oil. Figure 1 represents the thickness and TOC for the Woodford Formation, one of the richest source rocks in the Permian Basin. The Woodford was deposited in the Tobosa Basin, a precursor to the Permian Basin. Over most of the Tobosa Basin, preserved TOC is greater than 1% (Comer, 1991). The Woodford is thickest and has the highest TOC in Pecos, Reeves, Ward, and Winkler counties of Texas, within the Delaware Basin and CBP. Figure 2 shows the structural complexity and thermal maturity of the Woodford Formation. Throughout much of the southern Delaware Basin, the Woodford is in the gas window. Additionally, the Woodford is either absent, or appears to be immature over a significant portion of the CBP, but there does seem to be an area along the western edge of the CBP that is in the oil window. This area is structurally complex, so knowing where to explore is a challenge (Figure 2).

There have been numerous horizontal Woodford wells drilled in Andrews, Winkler and Ward counties attempting to establish a commercial play, but without much success to date. This presents a puzzling question: why has a world-class source rock like the Woodford Formation not been more productive on the CBP where it is very thick? It is already established that the Woodford generated much of the oil in many fields on the CBP (Zumberger, 2013). This question can be answered by adding the TR into the equation. Rocks with > 0.7 VRe are considered to be in the main oil window (Peters and Cassa, 1994). This general rule is applicable thus far for conventional plays and was used successfully in the Bakken play where Parshall and Sanish fields were discovered in the Williston Basin. To the contrary, the Woodford Formation in the Delaware Basin has proved to be different. Figure 3 (left), shows seven wells with VRe data that illustrate the areas of high maturity (gas: > 1.4 VRe) as well as within the oil generation window (< 1.4 VRe). The three wells with 0.68, 0.69, and 0.93 VRe did produce some oil but were noncommercial tests. Many more Woodford horizontal wells have since been drilled on the western edge of the CBP with similar noncommercial results. As mentioned previously, the VR and VRe proxies must be calibrated to correspond to hydrocarbon generation. Understanding how much source rock transforms from kerogen to petroleum is of critical importance when trying to establish a play from source rocks (Waples and Tobey, 2015; Tobey and Campbell, 2016). We find that the calculated TR of the kerogen is a critical element in appraising the level of hydrocarbon generation.

Figure 3 (right) shows the TR of the Woodford Formation in the area. Note the two wells of 0.68 and 0.69 VRe have a TR of only 0.01. This means about 1% of the potential generation has occurred, which means oil has indeed been generated in the area but apparently not enough to be commercial. Combining both VRe and TR data (Figure 3), the green zone outlines the area that is the most prospective for unconventional oil in this play. This green zone lies between the Woodford gas productive basin area and the Woodford Central Basin unproductive oil area round the 0.5 line mapped using TR data which appears to approximate peak oil for the Woodford in the Permian Basin. Recent discoveries now show this area is within the sweet spot for Woodford unconventional oil. Marathon Oil announced in November 2019, two very productive Woodford horizontal wells in this green zone (Marathon Oil, 2019). The initial 30-day production of the two wells were 365 boepd/1000 ft of lateral (70% oil) and 240 boepd/1000 ft of lateral (48% oil).

Understanding migration pathways for conventional reservoirs

The use of pressure-depth plots helps establish fluid contacts and migration pathways for conventional plays. Pressure-depth plots can be produced with drill-stem test data, which are vital in forecasting well productivity. It is important to select tests where the final shut-in or flowing pressure has built to near reservoir pressure as can be seen in Figure 4. Without test charts, scout ticket data can be utilized to select useable data where significant amounts of fluid were recovered. Tests should be from the same horizon or within pressure communication, as on a truncation boundary, with said horizon. Figure 5 is a pressure versus depth plot of tests within the Woodford Formation in the northwest portion of the Permian Basin – Lea and Roosevelt counties, New Mexico (Entzminger and Miller, 2004). Three fluid compartments (circles, squares, and triangles) are plotted from the data in the region. Pressure versus depth plots show fluid contacts as the water is plotted on a 0.453 psi/ft gradient and oil or gas gradients are plotted based on the gravity of the fluid. Where these gradients intersect is the fluid contact, see inset on Figure 5.

Oil analysis by the ARCO research lab from the northern portion of the Delaware Basin revealed that many of the Silurian–Devonian fields like Denton, Gladiola, Bluitt, and South Peterson are sourced from the Woodford Formation (Entzminger and Miller, 2004). The Woodford Shale truncates or has less than one percent TOC in northern Lea and Roosevelt counties of New Mexico (Figure 1). For Woodford oil to be found in these northernmost reservoirs, it has likely migrated. Understanding the migration pathway(s) provides insights for other potential fields along migration routes. Following up the pressure versus depth plot for fields AA, BB, A, B, C, and D, one sees they are on the same pressure gradient and along a similar potential migration trend. Coupled with the structure map of the Woodford Formation, it is easy to follow the migration pathway the Woodford sourced oil likely took to the fields in the northwestern portion of the Permian Basin (Figure 5). For an explorationist prospecting in areas away from a quality source rock, or a source rock that has not matured sufficiently to charge nearby reservoirs, it is critical to understand the petroleum system and how hydrocarbons could have migrated into a region.

Mapping T_{max} and production data

Mapping T_{max} from programed pyrolysis data can be a very powerful tool guiding an unconventional play, if placed in context with other regional data. Figure 6 (left) provides five T_{max} datapoints from cuttings and sidewall cores within the Wolfcamp A and B units in Reeves County, Texas. Using some general T_{max} categories for product types, one can divide the area into high GOR (>5000 cfg/bo) and low GOR

(<5000 cfg/bo) zones, but how that could be divided has several possibilities, depending on many factors such as kerogen organofacies, and structural trends. Published regional faults (Shumaker, 1992; Ewing, 2013) suggest a northwest-southeast trend which would provide a reasonable divide between the high and low GOR zones. However, like most geological interpretations, it is best to integrate multiple proxies and data sources. In the present case, mapping T_{max} alone would have led to drilling high GOR uneconomic wells. Integrating production data, provided another guide to optimal areas for the economic, low GOR wells. Figure 6 (right) of the production data suggests a northeast-southwest trend between the high and low GOR zones, which what was ultimately used for the MDC Texas Energy's drilling program. Other data like 3D seismic, which may not be available or affordable, could have shown that the published fault trends did not include a deep fault trending northeast-southwest. This fault is located along the division line between the high and low GOR zones shown in Figure 6 (right).

In early 2017, only a handful of wells were economic along this transition area between high GOR and low GOR zones. Today, over 100 economic unconventional wells exist, proving that combining pyrolysis and production data can be very powerful, when product type is essential in establishing an area for a commercial drilling program.

Conclusions

Whether evaluating conventional or unconventional reservoirs in any petroleum system, organic geochemical data are essential. Their value can be greatly maximized through the integration with other crucial information such as drill-stem test and production GOR data. Three useful examples were shown using data from the organic-rich Woodford Formation and Wolfcamp shales in the Permian Basin. The first example involves supporting VR and VRe data with TR to guide drilling economic unconventional horizontal wells. The second example uses pressure-depth plots coupled with subsurface elevation data to determine hydrocarbon migration pathways along a given pressure gradient to predict further economic drilling targets near areas of economic discoveries. The third example involves mapping T_{max} values assisted by previously available production-based GOR data to precisely delineate areas of high and low GOR for profitable, low GOR unconventional horizontal wells. As with most projects, utilizing several methods and datasets leads to better interpretations.

Acknowledgements

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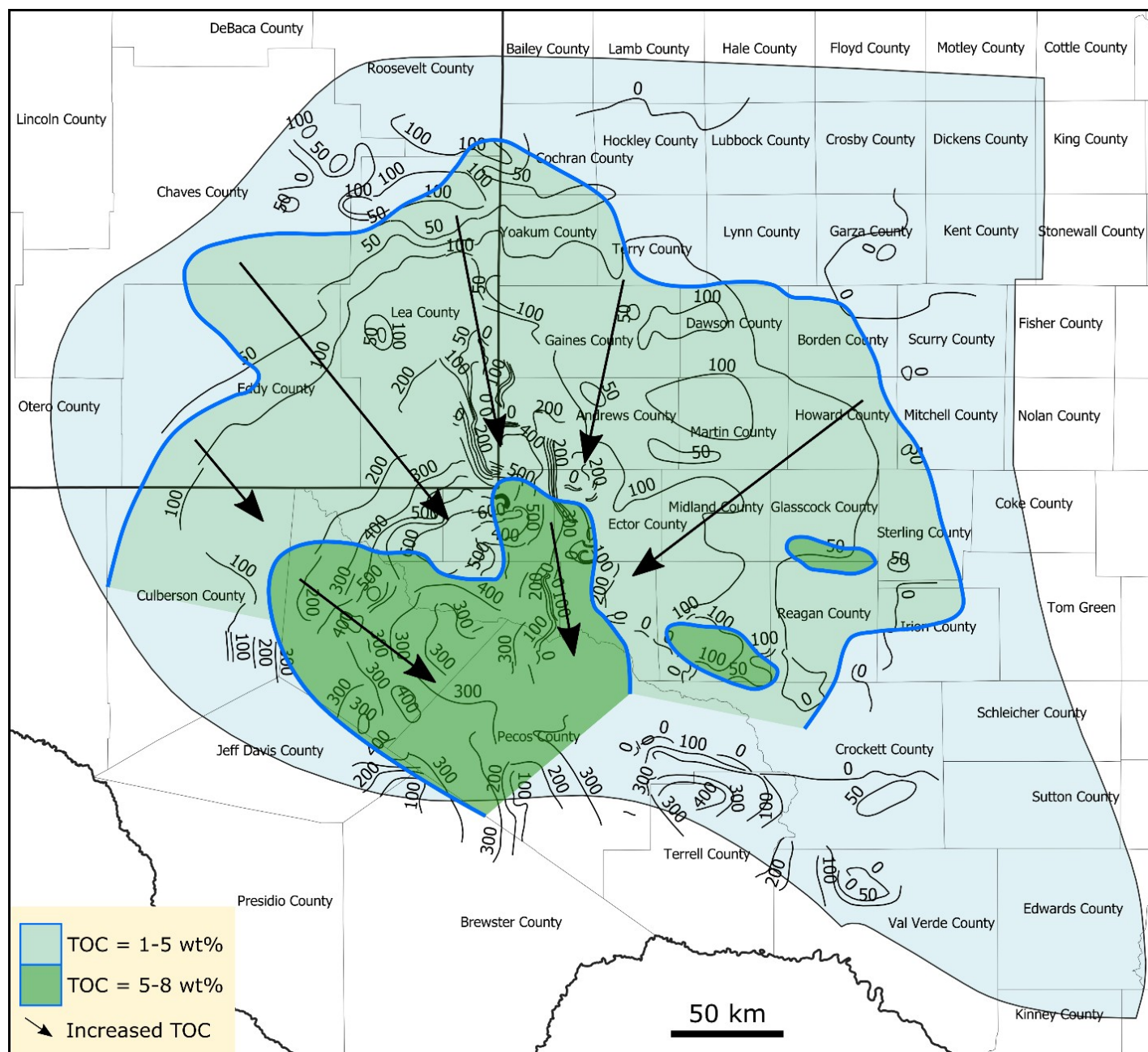
Figure 1. Thickness variation map for the Woodford Formation within the greater Permian Basin area shows the distribution of TOC content along with the observed trends of increased TOC and formation thickness. Modified from Comer (1991) and Entzminger and Miller (2004).
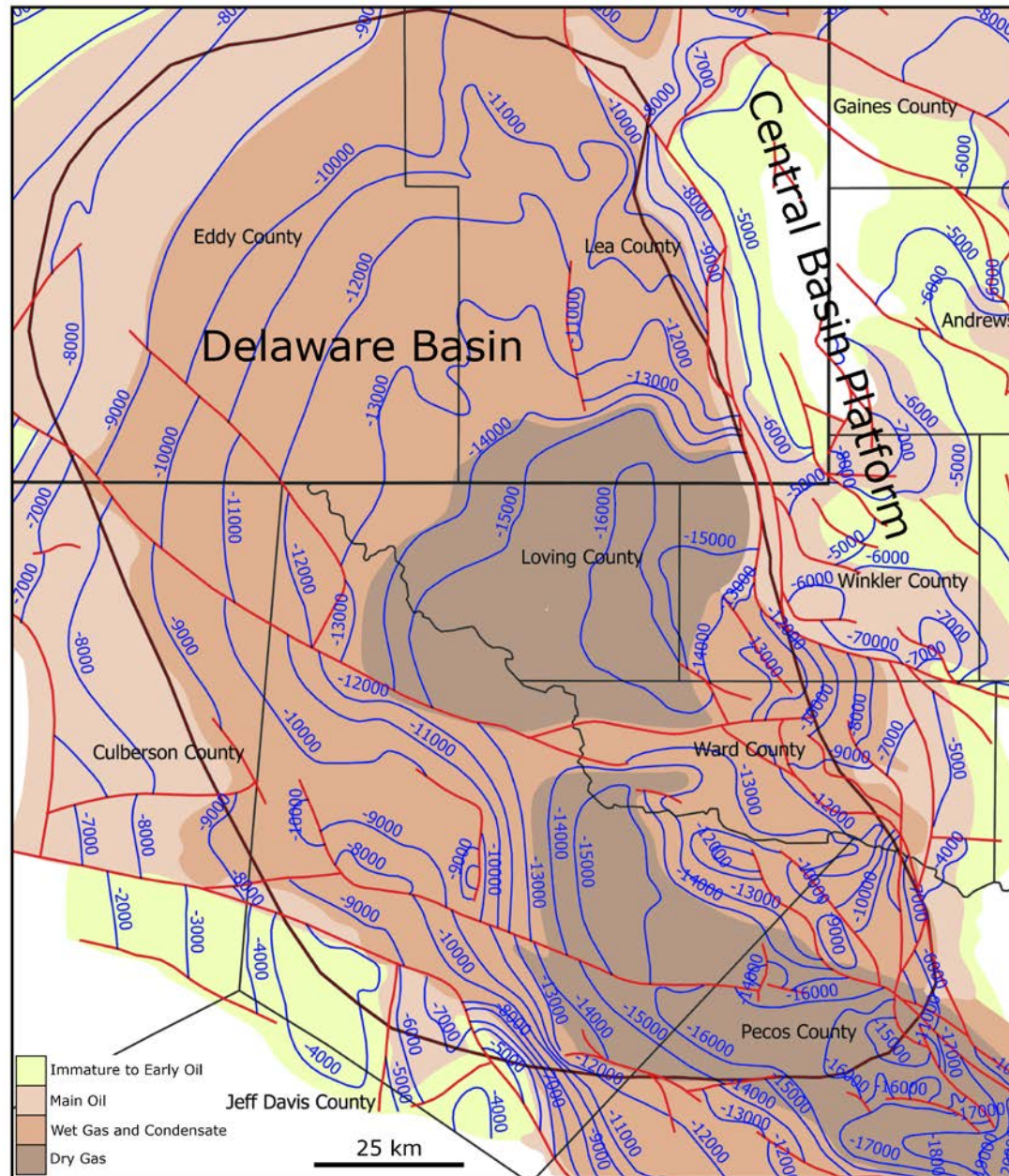
Figure 2. Structure contour map of the Woodford Formation in the Delaware Basin and the Central Basin Platform shows major faults (red lines) as well as the different zones of organic thermal maturity based on VRe data. Modified from Comer (1991) and Entzminger and Miller (2004).
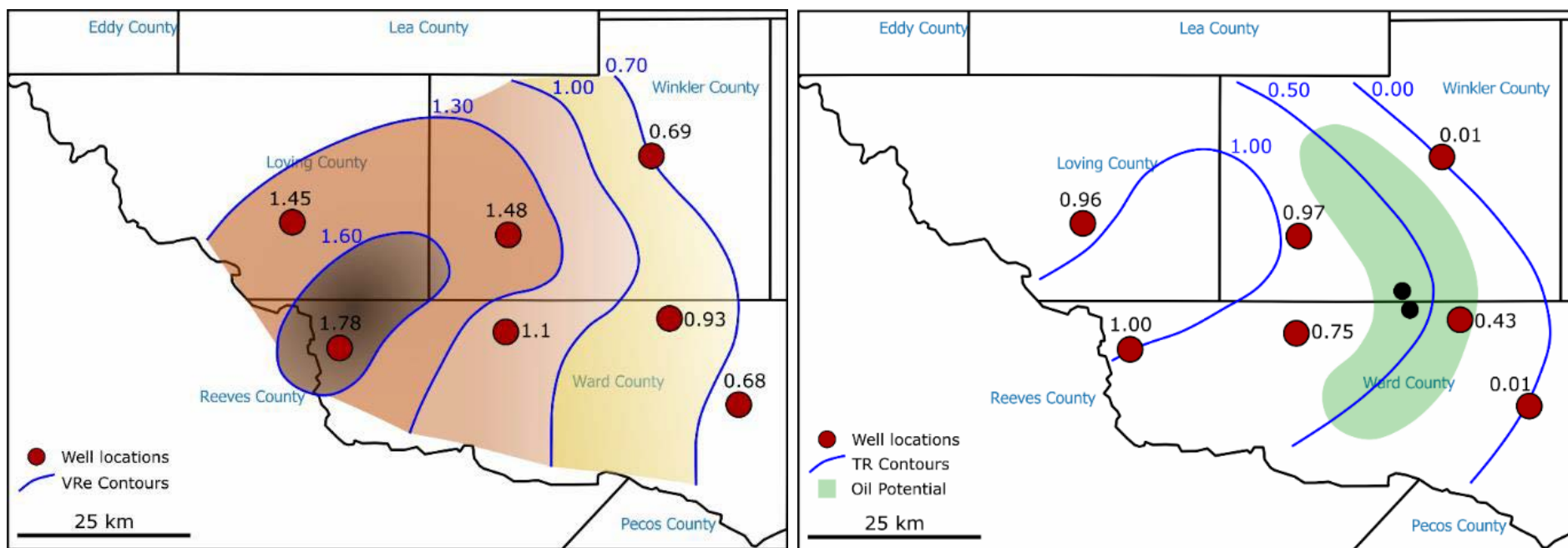
Figure 3. Woodford VRe and TR data for seven control wells within Loving, Ward, and Winkler counties, Texas shows the prospective region (green zone) of optimal maturity and petroleum generation. Map data was obtained with permission from Doug Waples, Sirius Exploration Geochemistry Inc., however interpretations are the authors'. Approximate locations of Marathon's recent Woodford horizontal wells are represented by the black dots.
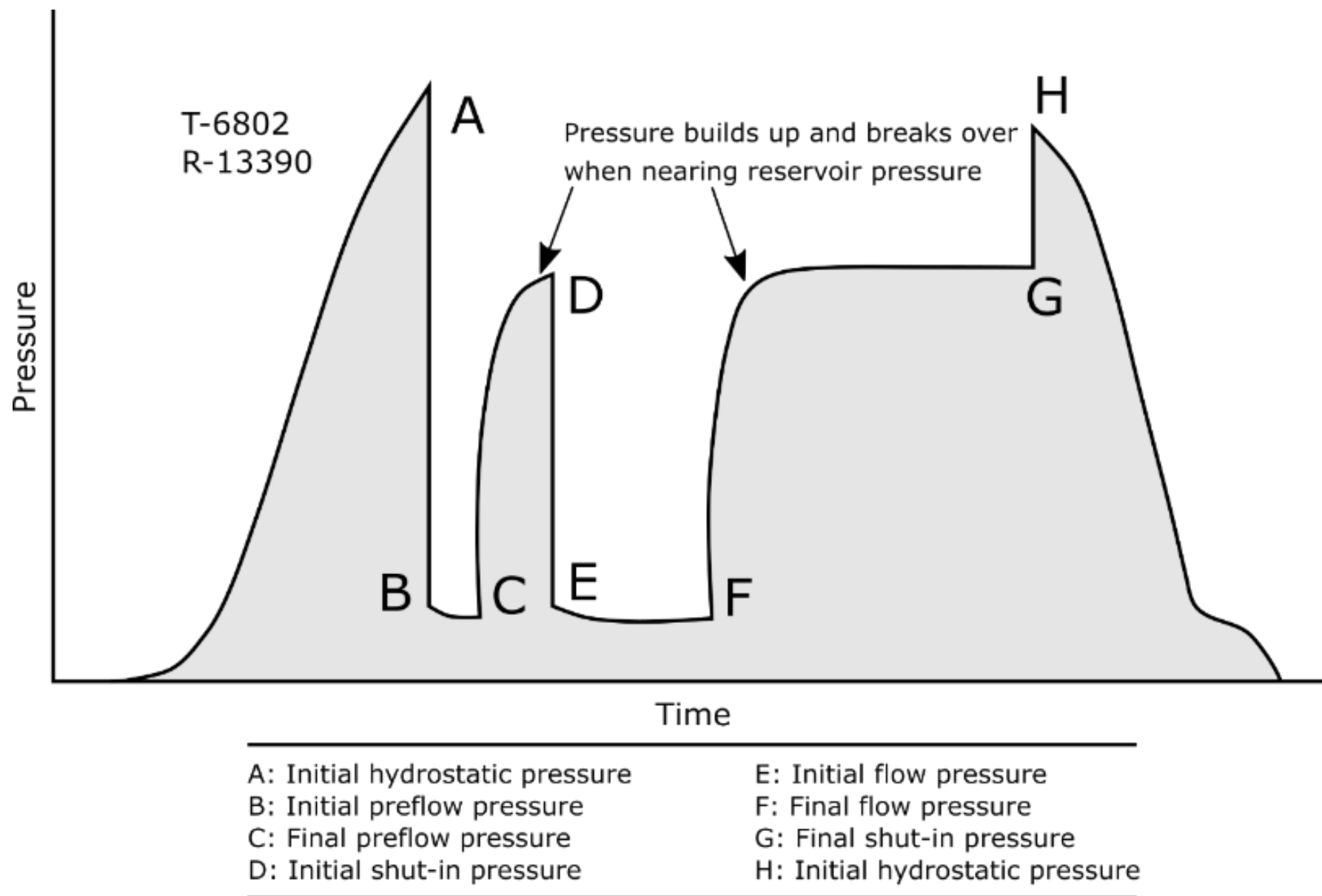
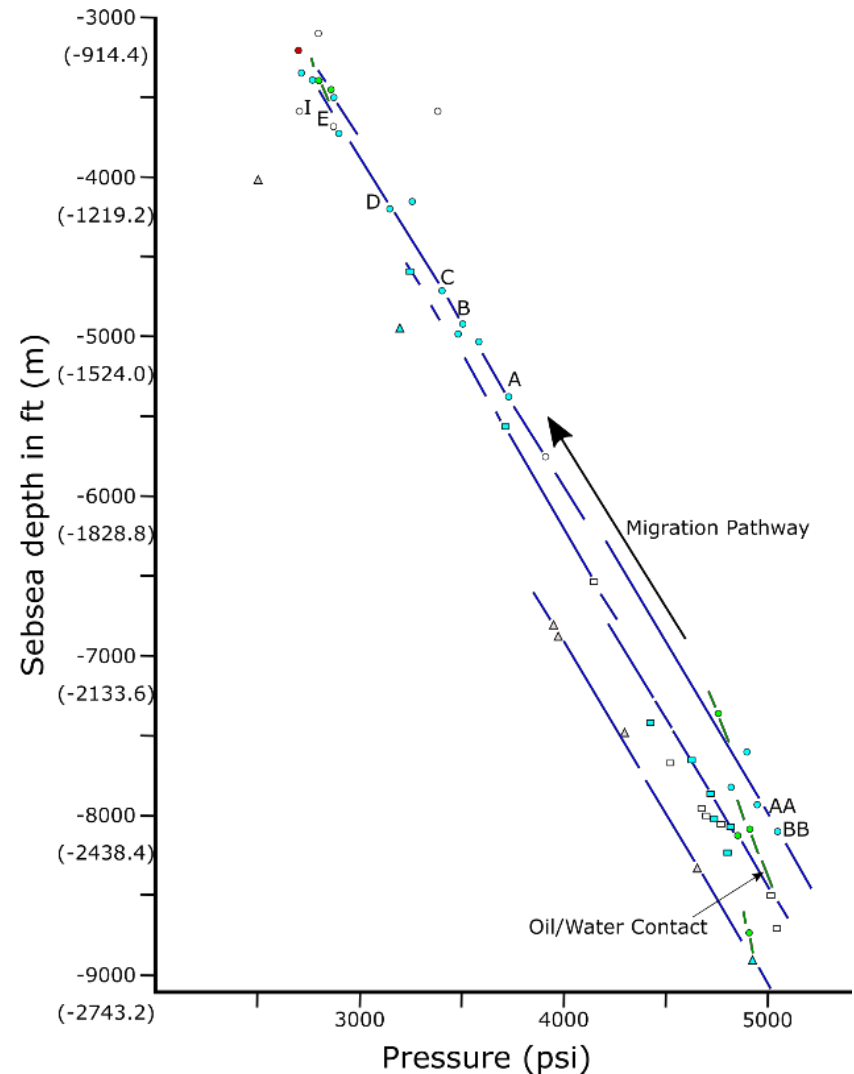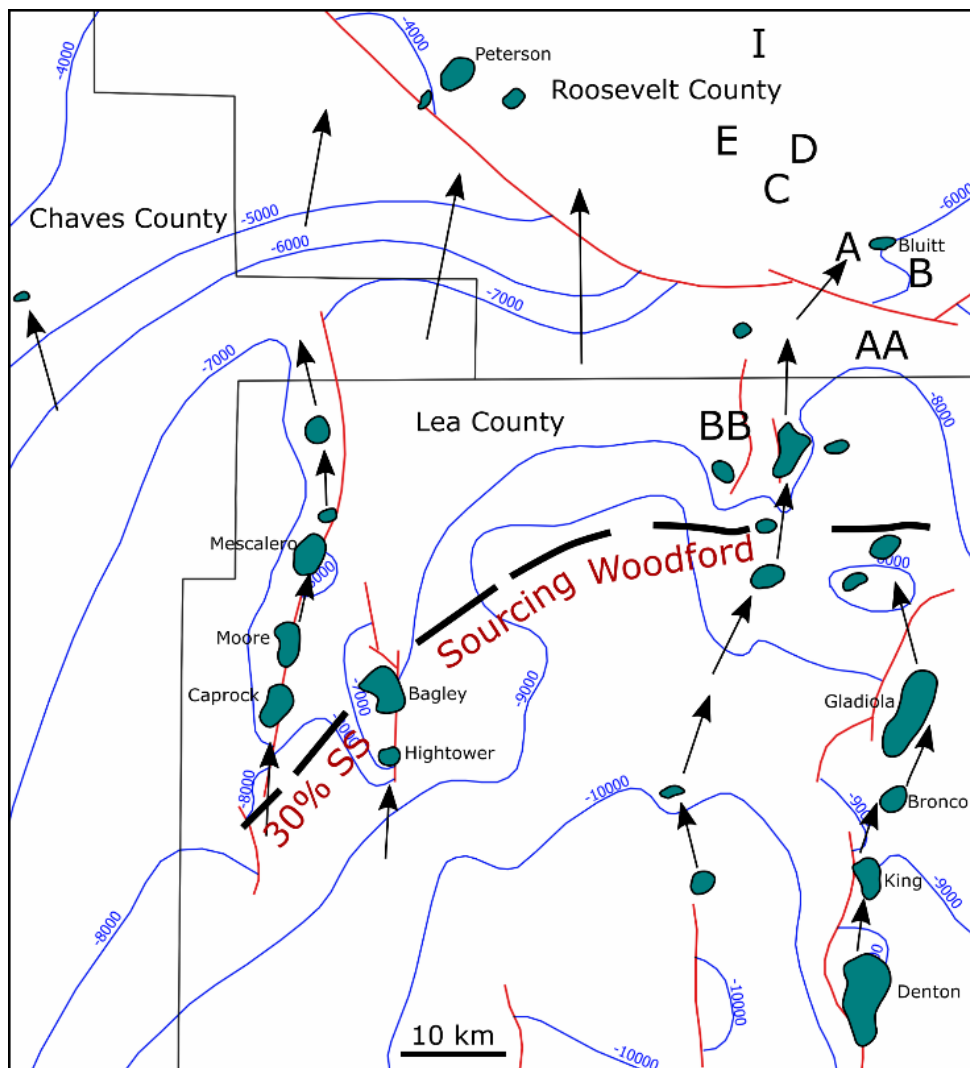Figure 4. Example drill-stem test chart of a well drilled in Andrews County, Texas.

Figure 5. Left: Structure contour map of the Woodford Formation in the northwest portion of the Permian Basin – Lea and Roosevelt counties, New Mexico shows the location of major oil fields (green) and inferred hydrocarbon migration pathways (arrows). Structural data are after Comer (1991). Right: Pressure versus depth plot of tests within the Woodford Formation for fields and wells AA, BB, A, B, C, and D shows they are on the same pressure gradient and along a potential similar migration trend. Circles, squares and triangles differentiate the datapoints representing the three fluid systems. After Entzminger and Miller (2004).
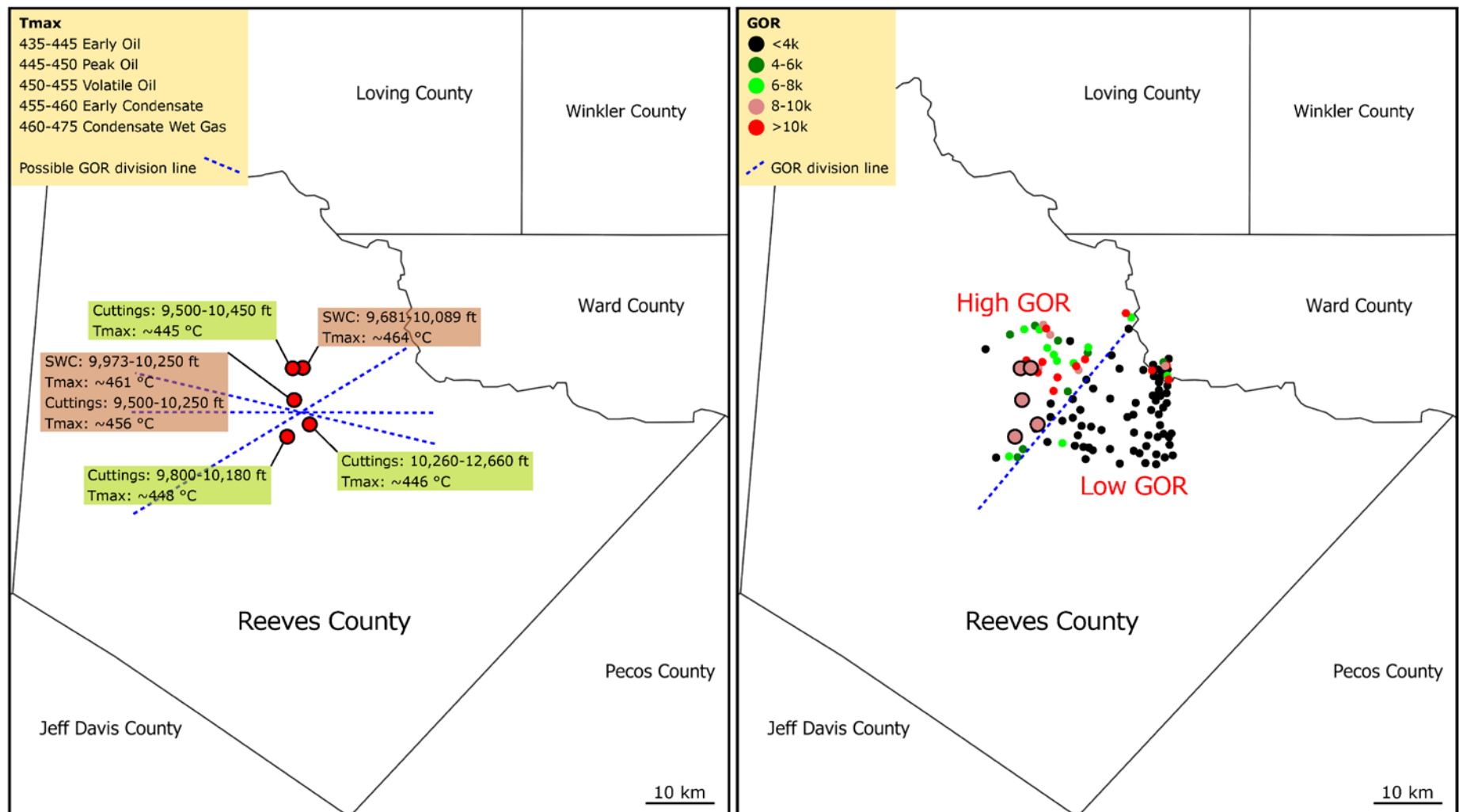
Figure 6. Left: T~max~ datapoints from cuttings and sidewall cores within the Wolfcamp A and B units in Reeves County, Texas. Several possible GOR division lines can be inferred based on T~max~ alone, providing less target constraints and more drilling risk. Right: GOR values based on production data for the Wolfcamp A and B units in Reeves County, Texas. These data when combined with T~max~ values provide much better constraints on zones of high (>5000 cfg/bo) and low (<5000 cfg/bo) GOR.