An integrated geoscience workflow to improve unconventional play assessment – an example from the SCOOP/STACK, Oklahoma

Adriana Perez[1*], Graham Spence[1], Paola Fonseca[1], Inna Tusybulkina[1] and Vincent Durussel[1] highlight some important outcomes, which help to reduce geological uncertainties and provide greater insight into the study area's exploration opportunities.

Introduction

In the last few years, the liquid-rich plays of the SCOOP (South Central Oklahoma Oil Province) and STACK (Sooner Trend Anadarko Basin Canadian and Kingfisher Counties) have attracted increased exploration and development interest from E&P companies, particularly on the Devonian-Mississippian targets. This interest has led to these unconventional plays being some of the most active in the Lower 48, especially in the Anadarko Basin. However, work is still required to gain a complete understanding of hydrocarbon generation, migration and distribution within the main reservoir facies and the correlation with produced hydrocarbons (Al Atwath et al., 2015; Symcox et al., 2019; Abrams and Thomas, 2020).

The complexity of the area's structural evolution, facies distribution and source rock alteration has led to varying hydrocarbon maturity and production trends within the basin. Ultimately, this has resulted in the production of mixed hydrocarbons from multiple charges. This complexity can lead to miscalculations of Original Oil In Place (OOIP) and poor estimation of the composition of hydrocarbon-in-place and its production potential – all resulting in uncertainty in the valuation of mineral rights in a given area.

To achieve a better understanding of the area's complex geology, CGG applied an integrated geoscience workflow to three multi-client 3D seismic surveys it recently acquired within the SCOOP and STACK area. This multi-disciplinary approach focused on geophysical, petrophysical and geochemical assessments, resulting in enhanced definition of the Mississippian and Woodford plays. These assessments revealed important aspects associated with the area's key geological features that should be considered to improve the economic success of SCOOP and STACK plays. This article highlights some important outcomes from this workflow, which will be described and discussed through its different sections. Additionally, newly generated data is presented and discussed across the study area.

The main aspects discussed here focus on 1) basin evolution, which has played an important role in source maturity and hydrocarbon generation 2) Source rock characterization, including source rock properties and quantification of the hydrocarbon content using a newly developed pyrolysis method and 3) reservoir characterization based on the integration of regional information and data generated from seismic reservoir characterization. These aspects are discussed to assess their implications on hydrocarbon distribution within these unconventional resources.

In the last section of this article, we propose a play assessment workflow that could be applied to address uncertainties associated with these plays. This workflow comprises 1) a regional or basin-scale evaluation based on 3D petroleum systems modelling (3D PSM) and 2) a more detailed evaluation based on the integration of seismic reservoir characterization into petroleum systems modelling on a local scale. This type of integration has already been successfully applied on different plays (both conventional and unconventional) and could be adopted here to gain an improved understanding of hydrocarbon migration and distribution within target intervals in more specific areas of interest. The combination of these two different approaches is a significant feature of this workflow and provides key subsurface properties, such as lithology, porosity, fractures and faults (potential migration pathways), in order to identify oil-saturated reservoir rocks bearing in-situ and/or migrated hydrocarbons. The play assessment workflow will provide results, which could be of benefit for de-risking potential drilling targets by highlighting areas and intervals within the basin hosting key indicators for hydrocarbon production success.

Basin evolution

The Anadarko Basin is one of the most important intracratonic basins in the USA where significant reserves of oil and gas have been established (Adler, 1971). This asymmetric basin hosts a sedimentary column, which is nearly 12 km thick at the deepest section of the basin (Mahlon et al., 1991). The basin is bounded on the east by the Nemaha Uplift, with the Arbuckle Mountains and Ardmore Basin to the southeast, and the Wichita Mountains and the Amarillo Uplift to the south. A generalized stratigraphic column for the Anadarko Basin is shown in Figure 1. Significant discoveries in the Mississippian and Devonian sediments resulted

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in the development of the SCOOP and STACK plays (Figure 2). Hydrocarbon distribution in these unconventional plays is complex due to the basin's tectonic and sedimentary history, with the resulting facies variation playing a critical role in petroleum migration and accumulation.

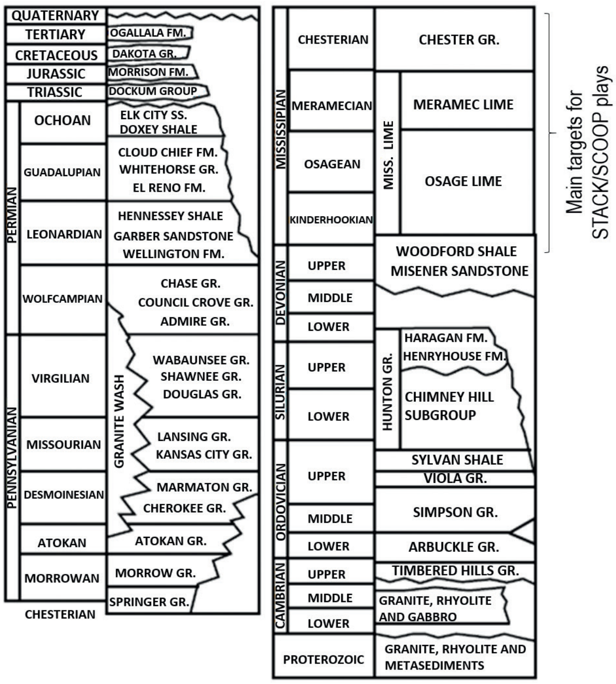


Figure 1 Generalized stratigraphic column for the Anadarko Basin. Modified after Carter et al., AAPG Bulletin, v. 82, no. 2, p. 291-316. (after Johnson and Cardott, 1992). AAPG© 1998, reprinted by permission of the AAPG whose permission is required for further use.

The present-day configuration of the Anadarko Basin is the result of the area's tectonic evolution, which started in the Precambrian Period. It began with the opening of the Ancestral Atlantic, which initiated in the Late Precambrian to early Cambrian, generating a rift that extended from the northwest to the craton, from a re-entrant of the plate margin, known as the Oklahoma Aulacogen. Cooling and subsidence resulted in the formation of a broader superimposed basin, known as the southern Oklahoma trough (Mahlon et al., 1991). The Pennsylvanian was a time of major change in the history of the Anadarko Basin (Johnson, 1989). During this time, the Wichita Orogeny occurred and developed a foreland basin by compression and tectonism with the relatively rapid accumulation of approximately 10 km of sediments in 10-20 million years (Gilbert, 1992, in Lee and Deming, 1999). During the Permian, as much as 2 km of sediments were deposited in the Anadarko Basin. The post-Paleozoic burial history of the Anadarko Basin is more controversial and less constrained, as most Mesozoic and Cenozoic strata have been eroded. There is geological evidence for sedimentary deposition in the Anadarko Basin during the Mesozoic Period, but it is difficult to precisely constrain the magnitude and timing of sedimentary events (Lee and Deming, 1999). Extension of the Cretaceous Seaway across the Anadarko Basin during the last great inundation of the western interior of the United States implies that sedimentary strata were deposited in a marine environment during the Cretaceous Period. Sedimentation into the basin ceased with the formation of the Rocky Mountains during

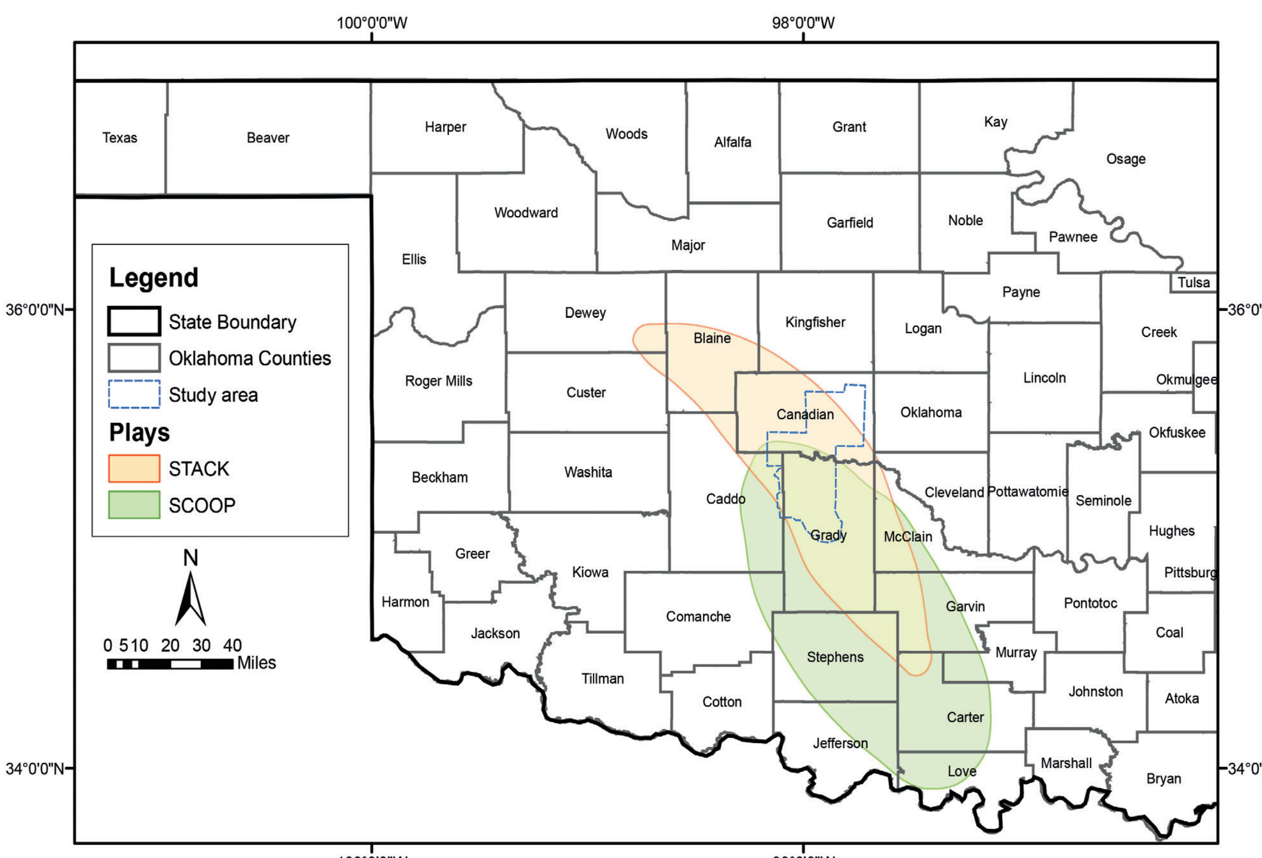


Figure 2 Extension of the STACK and SCOOP plays in the Anadarko Basin, Oklahoma. Modified from https://www.shaleexperts.com.

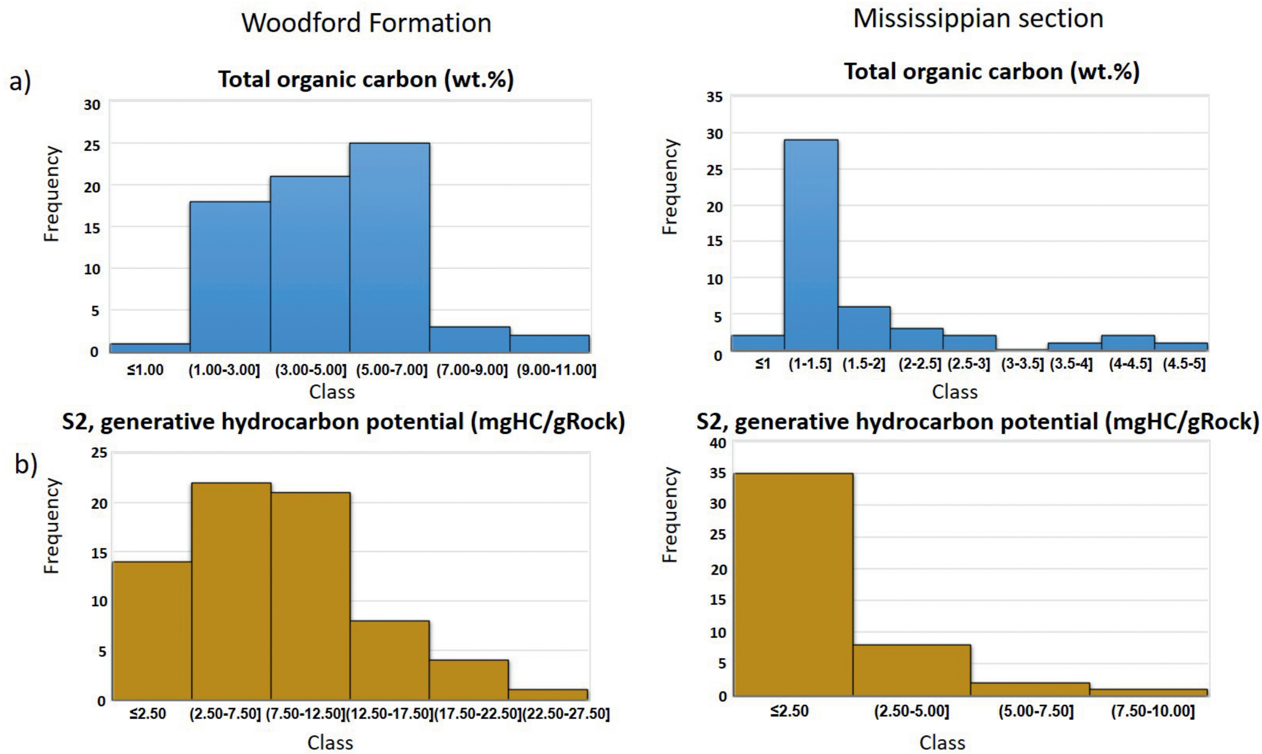


Figure 3 Geochemical properties of the Woodford Formation and Mississippian section within the study area based on a) total organic carbon (TOC) and b) S2 generative hydrocarbon potential.

the Laramide Orogeny in the Late Cretaceous and early Tertiary, which raised and induced an eastward and southward tilt to the entire region and eventually caused withdrawal of the Cretaceous Sea (Lee and Deming., 1999). Remnants of Triassic, Jurassic, Cretaceous, and Tertiary sedimentary strata (200-500m-thick) are found today in the western parts of the Anadarko Basin and the Oklahoma Panhandle (Johnson et al., 1972; Johnson, 1989). Interpretation based on maturity data given by the vitrinite reflectance provided by Lee and Deming (1999) suggests that an estimated eroded thickness of 1-3 km is associated with the post-Paleozoic Era. Based on this, it is likely that maximum sediment thicknesses in the Anadarko Basin were reached in the Late Cretaceous or Tertiary and followed by a few kilometres of subsequent erosion (Lee and Deming, 1999).

Due to the basin's evolution, different tectonic provinces were generated which had important variations in their thermal history (paleo-heat flow). It has been suggested that heating of the deep basin occurred at two different times, during which the shelf area was relatively stable, with the basin cooling from the Permian onwards. The shelf area was never deeply buried, and because the high heat events were confined to greater depths, thermal histories of the shelf and the deep basin are completely different (Pawlewicz, 1989). As a result, maturation of source rocks is highly variable across the basin, especially in the Woodford Formation. This aspect played an important role in the hydrocarbons generated from the Anadarko shelf to the deep basin. The deep basin started the hydrocarbon generation and expulsion processes before the shelf area. A regional maturity map of the Woodford Formation suggests that this source rock is marginal-mature to post-mature with respect to liquid generation (Cardott, 1989, 2012). The estimated eroded thickness associated with the post-Paleozoic Era has important implications for the burial history when the basin history is reconstructed. The additional burial of sediments after the Pennsylvanian would have increased source rock maturation and contributed to overpressure generation in the Anadarko Basin. This aspect of the basin in general remains unclear due to the lack of information relating to the post-Paleozoic section and maturity data, which would help to calibrate the thermal maturity trend of this section across the basin.

Source rock characterization

Geochemical analysis of rock samples was included as part of our integrated workflow. Rock samples from the Woodford Formation and Mississippian section were considered for this source rock evaluation. The Woodford Formation (Upper Devonian – Lower Mississippian) represents one of the most important source rock units in the SCOOP and STACK plays within the Anadarko Basin. This is a carbonaceous, siliceous, pyritic dark grey to black shale that was deposited in a marine environment under anoxic conditions during a global sea level transgression (Romero and Philp, 2012; Wang, 2016; Abrahams and Thomas, 2020). The Woodford Shale has excellent source rock potential, dominated by organofacies B based on Pepper and Corvi (1995) classification (Abrahams and Thomas, 2020).

Basic source rock screening with total organic carbon (TOC) determination and pyrolysis analysis was performed on cuttings samples from 13 wells in Canadian and Grady counties (Figure 2). Results show that present-day geochemical properties of the Woodford Formation host TOC values of 0.72 to 11%wt (average 4.65%wt). Generative hydrocarbon potential (S2) values

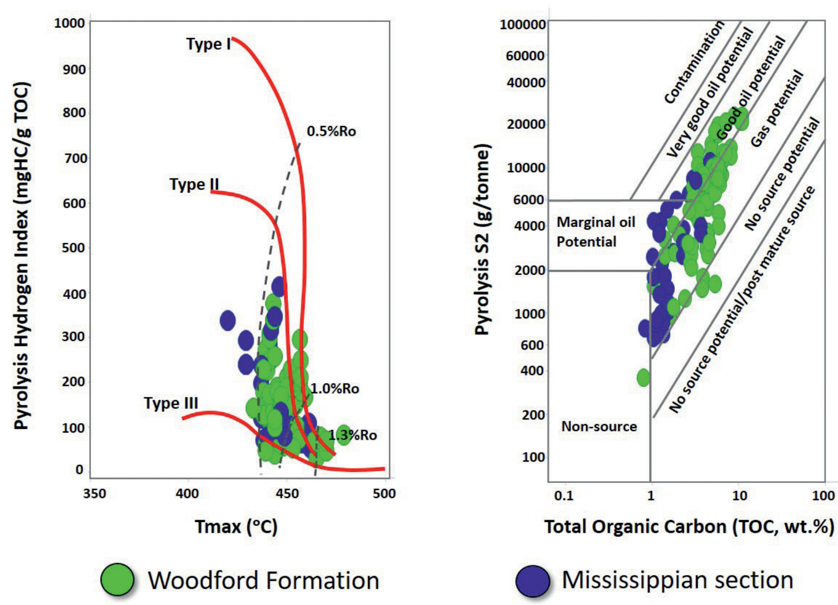


Figure 4 Geochemical analysis results a) cross-plot of Hydrogen Index against Tmax and b) cross-plot of pyrolysis S2 against TOC for the Woodford Formation and Mississippian section within the study area.

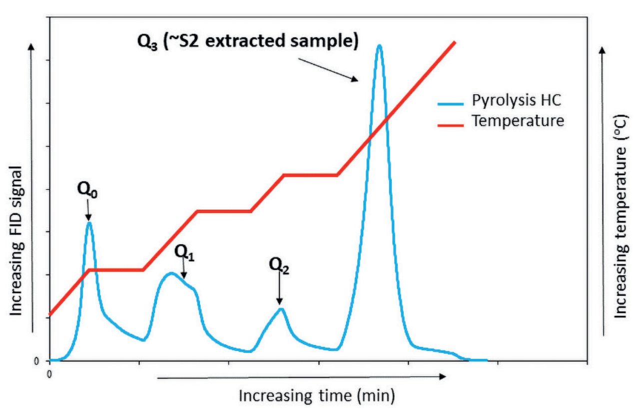


Figure 5 Proprietary pyrolysis method applied to rock samples for hydrocarbon (HC) content determination and source rock evaluation. **Q_0:** Corresponds to evaporated hydrocarbons released from stage 1. This peak represents the lightest HC, still present on the sample, (mostly free HC). **Q_1**: Hydrocarbons released from the rock from stage 2. This peak is dominated by the medium molecular weight components. **Q_2**: Most resistant hydrocarbons released from the rock from stage 3. Mainly adsorbed HC on the kerogen. **Q_3(~S2):** Pyrolyzable hydrocarbons generated from organic matter from stage 4. This is equivalent to S2 values (after removing HC carried over S2 peak by solvent extraction).

are recorded from poor to excellent (up to 20mgHC/gRock), with an average of 3.91 mgHC/gRock, (Figures 3 and 4).

Source rock maturity was evaluated by pyrolysis and organic petrography analysis. Unreliable Tmax values were removed from the data set, and then converted into equivalent vitrinite reflectance according to Jarvie's equation (Jarvie et al., 2001). Measured vitrinite reflectance (indigenous) was limited by the low abundance of vitrinite particles (low number of measurements). Therefore, equivalent %Ro values were obtained on bitumen measurements. The thermal evolution of the Woodford Formation within the study area suggests a transition from the oil window to the start of the post mature stage (0.8 -1.3%Ro) with increasing depth of the Woodford Formation. Measured geochemical properties at the present day (TOC, S2, HI) have been reduced due to the maturation process (Figure 4). Consequently, original properties should be higher than measured values, suggesting *very good to excellent* source rock properties.

In addition to the Woodford Formation, other secondary source rocks have been identified within the Mississippian strata. Organic-rich zones within the Mississippian carbonates show good source rock quality and generative potential in both northern Oklahoma and southern Kansas (Al Atwah et al., 2015). In order to evaluate this aspect, cuttings samples from the Mississippian strata were analysed. Present-day geochemical properties measured in 54 samples show TOC values ranging from 0.66 to 4.69 wt. %, with an average of 1.77 wt.%. The generative hydrocarbon potential given by the S2 peak from pyrolysis analysis showed values from 0.67 to 8.42 mgHC/gRock with an average of 1.96 mgHC/gRock (Figure 3). The level of maturity ranges from 0.7 to 0.9 %Ro based on equivalent vitrinite reflectance values calculated from Tmax and reflectance measurements.

Based on the geochemical analysis results, the Mississippian section shows *fair to good* source rock properties according to Peters and Cassa's classification (Peters and Cassa, 1997). By applying a cutoff on the Gamma Ray (GR) signal >120 API as a proxy to quickly identify the potential source rock intervals, it was observed that only thin beds (average 10 ft) host these high GR responses. These results are consistent with the log response observed within the majority of the evaluated wells. The higher TOC values obtained on these sections are likely associated with thin laminated intervals that are rich in organic matter. Although the maturation process has affected the original geochemical properties, it suggests a limited source potential for this unit within the study area due to the low thickness (volume) of these intervals.

Evaluation of hydrocarbon content in rock samples

In addition to source evaluation, the hydrocarbon content (preserved) of rock samples was estimated or quantified. This analysis was performed by applying a new pyrolysis method, which better estimates total hydrocarbon content and evaluates the different proportions of the molecular weight components. Variations as well as significant heterogeneities have been observed in the composition of oil produced from Mississippian strata in the STACK/SCOOP, which cannot be explained by in-situ hydrocarbon charge models from the Woodford Formation (Symcox and Philp, 2019). Oil produced by the Woodford Formation has shown important variations, especially in its maturity level, which does not always compare to the in-situ maturity of the source rock (Al Atwath et al., 2015; Symcox and Philp, 2019; Abrams et al., 2020). For instance, within the SCOOP play, oil and condensate samples produced from horizontal wells have shown similar geochemical fingerprints, while showing maturity differences. The API gravities are highly variable with no strong correlation to depth or reservoir (Abrams et al., 2020). From oil analysis, some geochemical features have been reported by analysing the low and high molecular weight components. In produced oil, the estimated maturity from the light hydrocarbons is not always in agreement with in-situ rock maturity (Abrams et al., 2020). Therefore, it is suggested that the low molecular weight hydrocarbons are dominated by the migrated fractions with high maturity. On the contrary, the estimated oil maturity from the high molecular weight biomarker compounds is in agreement with in-situ rock maturity. This suggests that the low concentration biomarker (high molecular weight compounds) signature reflects the in-situ derived petroleum (Abrams et al., 2020). This evidence infers that in these plays a simple hydrocarbon local charge model from the Woodford Shale to the main reservoir facies within the Mississippian section is unlikely to be the main scenario.

To further investigate the hydrocarbon charge of the study area, new geochemical analysis was performed on Woodford Formation rock samples from the previously mentioned 13 wells across Canadian and Grady counties using a new proprietary pyrolysis method. With this new method, a small amount of rock powder is heated in four temperature stages, starting from 90ºC to up to 650ºC. Five parameters are measured: Q0, Q1, Q2 and Q3 (equivalent to S2 peak) and Tmax, (Figure 5). This new method allows for a better quantification of the oil composition analysed by the Q0, Q1 and Q2 parameters. Additionally, a more accurate evaluation of the source rock properties was achieved due to removal of the hydrocarbons carrying over to the S2 peak (i.e. recognized as a shoulder on the left side of S2 peak) in bitumen-rich source rocks. The resultant Q3 parameter is equivalent to the S2 peak in extracted samples analysed by the standard Rock-Eval® Basic/Bulk-Rock method.

The total hydrocarbon content was measured by the sum of parameters Q0, Q1 and Q2. This value represents the remaining hydrocarbons content preserved in the rock sample. Total hydrocarbon content can be affected by evaporative loss of the lightest hydrocarbons during core and cuttings collection, storage and sample preparation and subsequent sample analysis. Results showed that, with the exception of one sample, the values ranged from 1.0 to 7.06 mgHC/gRock, suggesting *good-to-excellent* hydrocarbon content. This range was observed in samples from the Woodford Formation hosting a maturity level from peak to late mature 0.74 to 1.30 %Ro. Although the samples analysed are cuttings, good amounts of hydrocarbon were preserved in the rock, most likely associated with the strong sorption of oil in the shale owing to its high organic content (Jarvie, 2014).

As expected with increasing maturity, generated hydrocarbons change in composition from medium to high API gravity. This pattern was observed in some wells which showed good correlation between increasing Q0 and Q1 (light and medium molecular weight components) and a high degree of maturity. However, exceptions were observed in some wells located in the central and northeastern part of the study area where the Woodford Formation hosts a less mature level (~0.7-0.8 % Ro-eq). In these wells, a high proportion of light-medium molecular weight components (Q0 and Q1) were obtained, which was comparable with the proportion observed in other locations where this formation hosted a higher degree of maturity (1.2-1.3 % Ro-eq) (Figure 6). Obviously, this trend could be affected by the different factors already mentioned above. However, it could also be the case that the remaining composition evaluated in these areas reflects the possible mixing of in-situ generated hydrocarbons with migrated hydrocarbons from more mature areas, affecting (increasing) the light to medium hydrocarbon composition. In this case, the results could also suggest preferential migration of hydrocarbons from south to northeast.

These outcomes could support the geochemical evidence reported by other studies, suggesting that the Woodford itself and the Woodford-Mississippian plays could be a complex hydrocarbon system with mixed indigenous (locally generated where Woodford Shale is mature) and migrated hydrocarbons generated from more mature areas deep within the basin.

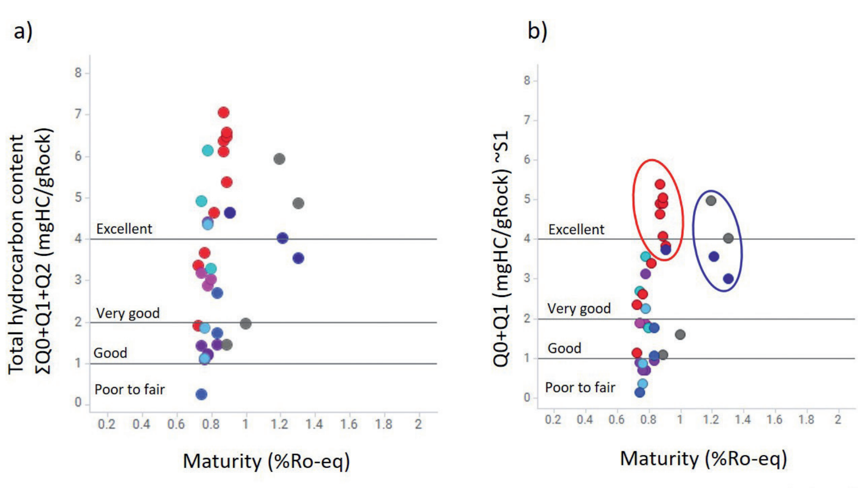
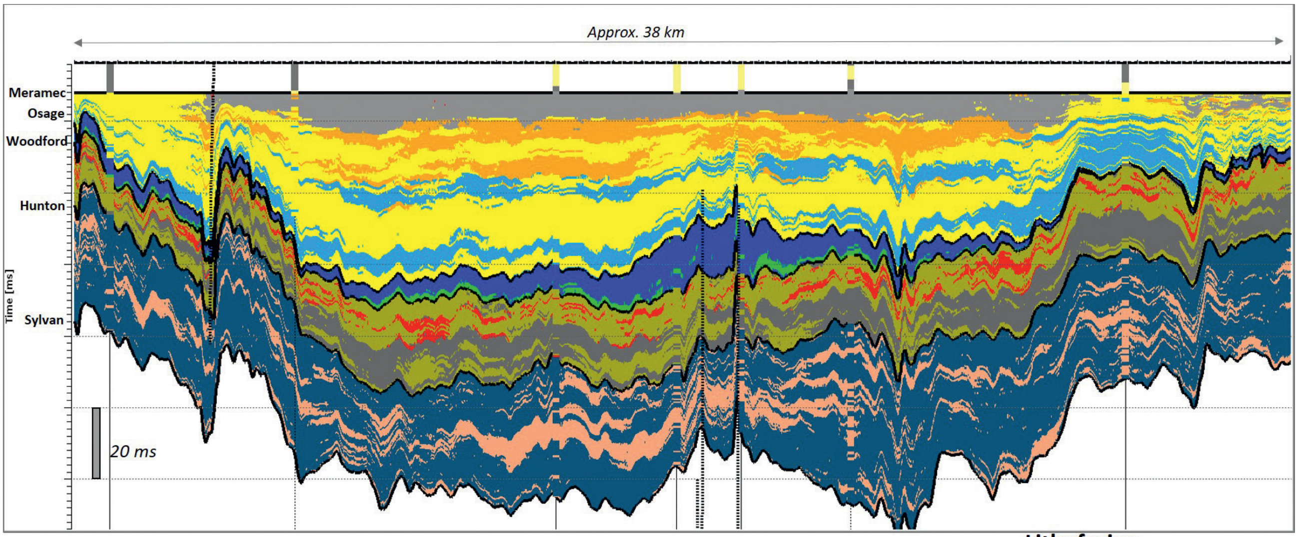


Figure 6 a) Total hydrocarbon content in rock samples, b) Estimated amount of light and medium molecular weight components given by the sum of the Q0 and Q1 parameters. In less mature areas, some wells showed a high proportion of Q0 and Q1 components compared to other wells at the same maturity level (red ellipse). More mature areas are dominated by a higher proportion of Q0 and Q1 components (blue ellipse).



Lithofacies

MERAMEC	5		Argillaceous siltstones
	6		Prospective limestones
	7		Argillaceous siltstones - **Clay rich**
	8		Argillaceous siltstones, rare argillaceous carbonate fragments
OSAGE	13		Argillaceous siltstones intercalated with argillaceous limestones
	14		Argillaceous limestones intercalated with argillaceous siltstones
WOODFORD	10		Siliceous mudstones **Clay Rich**
	11		Siliceous mudstones
	12		Siliceous mudstones Highest Kerogen - Lowest Sw
HUNTON	15		Clean limestones intercalated with argillaceous siltstones
	16		Argillaceous limestones intercalated with argillaceous siltstones

Figure 7 Most probable facies from seismic reservoir characterization (geostatistical inversion) displayed along arbitrary lines across the STACK play from Meramec to Hunton Formations. The highly-detailed results show the lateral and vertical variations in facies and help to fine-tune the stratigraphic interpretation and populate the geological model for reserve assessment. The section has been flattened along the Meramec horizon. Image courtesy of CGG Multi-Client.

Reservoir characterization

This step focused on a petrophysical evaluation and the integration of resulting properties with seismic data in order to identify lateral and vertical variations in the rock properties within the main target intervals away from the wells. The main target reservoirs in the SCOOP and STACK plays are in the Woodford Formation, the Mississippian Group (Osage, Meramec, Chester and Sycamore formations) and the Springer Group (Figure 1), (Symcox and Philp, 2019). Important variations in reservoir properties within the target intervals have been described for the STACK and their correlative facies in the SCOOP play (Cullen, 2017; Thomas, 2018). The Mississippian-Meramecian Series in the STACK and laterally equivalent units within the Caney Shale and Sycamore Limestone in the SCOOP consist of a succession of interbedded silty limestone, quartz-rich calcareous siltstone, argillaceous siltstone, and organic-rich mudstones (Miller et al., 2019).

The regional model of the Mississippian consists of three stratigraphic zones: the Sycamore and Osage, Meramec and Caney. The Osage is a succession of carbonates and mudstones overlying the Woodford Shale. The thickness of Mississippian strata commonly ranges between 300 and 900 m across the basin (Johnson, 1989). They thin from north to south and pinch out in the northern Caddo and Grady counties. The Sycamore Formation unconformably overlies the Woodford Shale to the south of the Osage pinch-out. The Sycamore and Osage are considered as a single zone because the precise location of the interpreted Osage pinch-out is uncertain. A second reason is that both the Sycamore Formation and Osage are lithologically similar but more carbonate-rich than the overlying Meramec (Miller et al., 2019).

These units represent a time of climatic transition, with global temperature cooling and sea level falling (Read, 1995 in Miller et al., 2019). Depositional environments and lithofacies relationships between the Osagean and Meramecian sediments are not thoroughly resolved and are still under discussion by different authors, due to the sparse regional correlation of depositional environments in the Meramec in the subsurface of Central Oklahoma linked to southern Oklahoma (Miller et al., 2019). Recent studies have shown both a lithostratigraphic and an approximate chronostratigraphic correlation between the Sycamore of southern Oklahoma and the Meramec of central Oklahoma. Based on this, it has been suggested that the upper Sycamore Formation thins to the north and lithostratigraphically correlates with the lower Meramec while the upper Meramec correlates with the lower Caney Formation. Miller et al., (2019) suggested that shale content increases in the southeastern down-dip direction for Sycamore, Meramec and Caney. These lateral reservoir changes in the Mississippian units play an important role in hydrocarbon distribution across the STACK and SCOOP plays.

Seismic reservoir characterization is one method used for capturing subsurface variations away from well control, which can be applied to both conventional and unconventional plays when modern high-quality seismic data is available. This type of evaluation is based on seismic inversion processes, which convert the reflectivity of 3D seismic data into elastic rock properties: compressional wave (Ip) and shear wave (Is) impedance. These properties are the product of velocity (compressional, Vp and shear, Vs, respectively) and bulk density (RHOB). Through these parameters, rock properties, such as lithology and porosity, can be estimated within the subsurface. This technique was used to understand the facies variations across the study area.

Geostatistical inversions performed by CGG in the STACK plays showed lateral and vertical facies variations from the Woodford to Meramec Formations (Figure 7). This geostatistical inversion process included the characterization of rock-constrained petrophysical lithofacies within target formations. Within the study area, it has been observed that the Meramec Formation hosts prospective limestone with higher calcite content (>30%, lithotype 6) which was observed in the upper and lower part of this Formation with a thickness of 10 to 40m. These facies thin to the south and they are almost absent towards the SCOOP play. In the Osage Formation, intervals with more than 20% of calcite were identified (lithotype 14). This facies is present across nearly the whole of the study area but displays some variations in its thickness and petrophysical properties, especially porosity. The Woodford Formation has vertical variations in its facies, being dominated by argillaceous mudstone at the base and more siliciclastic facies towards the top. It was also observed that facies dominated by high siliciclastic content decreases toward the south and southwestern part of the study area. Important development targets are likely to be dominated by lithologies with high quartz contents, >50% (Lithotype 11) and some thin intervals within facies exhibiting low water saturation, <30% (Lithotype 12).

Play assessment workflow for identifying exploration and development targets

In this last section of the article, we propose an alternative solution for play assessment to take into account all the complexities of these unconventional resources using an integrated approach. This approach is based on a combination of seismic reservoir characterization and petroleum system modelling and offers the advantages of reducing uncertainties and effectively identifying new exploration opportunities. This comprehensive workflow will help to characterize hydrocarbons (origin and type) and identify facies variations observed within the Woodford-Mississippian intervals and their hydrocarbon potential. These aspects play an important role in defining exploration and development targets and estimating reserves. To achieve this play assessment, it is essential to have a better understanding of how the petroleum system works all the way from regional basin scale down to local scale for a specific area of interest.

As mentioned in the previous section, seismic reservoir characterization is one of the techniques applied to characterize geological variations within a sedimentary column. Generally, in conventional plays, this type of evaluation, or static modelling, is meant to assess reservoir properties within relatively small areas (field scale). Conversely, in unconventional plays, this evaluation can include the source rock owing to the fact that the most of the reservoir and source rock units are represented by the same geological formation or are juxtaposed to reservoir units (hybrid system). In this case, new advances in seismic reservoir characterization include the evaluation of important aspects relating to the source rock, such as Total Organic Carbon distribution (TOC), as well as more recent developments relating to kerogen quality (Hydrogen index, HI) and maturity (%Ro), (Winter et al., 2018).

To assess hydrocarbon distribution within the subsurface, dynamic forward simulation techniques such as petroleum systems modelling (1D, 2D and 3D) can be applied to improve play assessment. This allows for an improved understanding of hydrocarbon generation, expulsion, migration, accumulation and preservation over geological time. As part of this comprehensive assessment, seismic reservoir characterization results (facies variations and porosity) are integrated into the 3D petroleum systems modelling (local-scale, high-resolution model). If available, the incorporation of fractures and faults, identified in the seismic data, can be critical inputs to petroleum systems modelling as they can indicate preferential migration pathways for hydrocarbons. An understanding of tectonic evolution is also an important step in this evaluation, as it provides information on the nature and timing of the main geological events that may have affected hydrocarbon generation, expulsion, migration and accumulation, as well as the timing at which the faults and discontinuities were likely to have acted as migration pathways. In the Anadarko Basin, this combination of techniques will help to improve our understanding of both how the petroleum systems operate and the preferential direction of petroleum migration and help us to assess how migrating hydrocarbons have mixed with the in-situ generated hydrocarbons in the STACK and SCOOP plays.

In order to take into account the migrated hydrocarbons (generated from the deeper area of the basin), we propose to perform this assessment in two stages.

1) A regional or basin-scale evaluation based on 3D petroleum systems modelling (3D PSM), using a low-resolution model. This regional-scale 3D PSM would take into account the deep

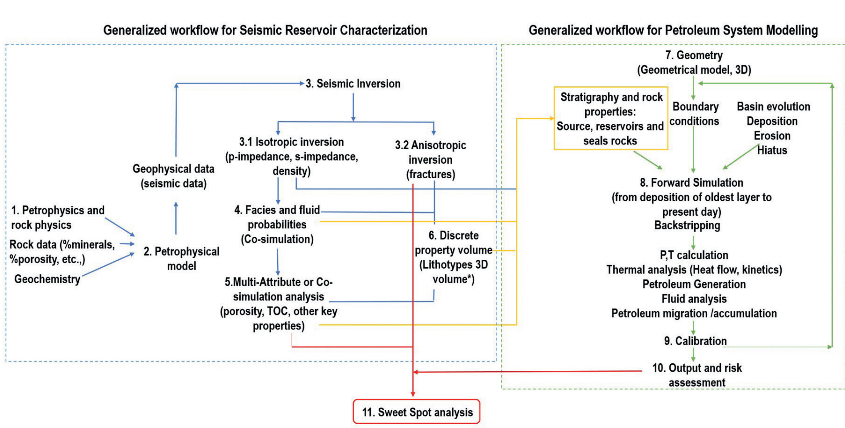


Figure 8 Integrated workflow for STACK/SCOOP plays assessment. Blue lines: Seismic reservoir characterization workflow. Green lines: Petroleum systems modelling workflow. Yellow lines: information that can be integrated into 3D basin modelling. Red lines: Sweet spot analysis based on the integration of results from seismic reservoir characterization and petroleum systems modelling.

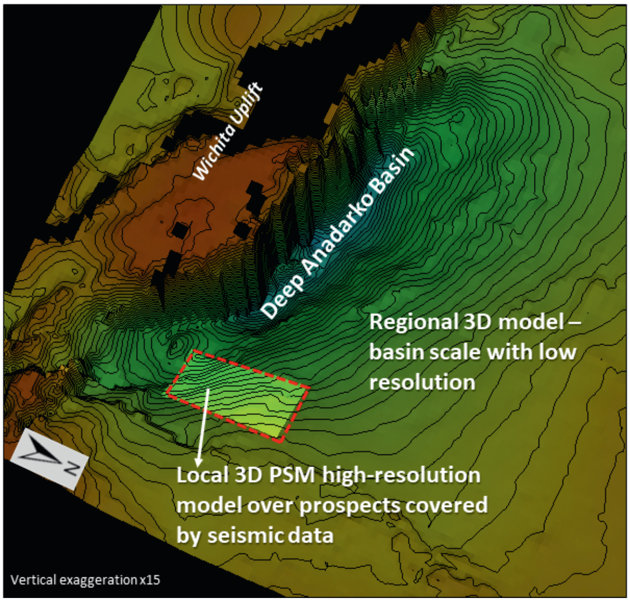


Figure 9 Example of detailed local study with a high-resolution model (grid cell size x: 222m, y: 223m z: variable m) which would form a fully-integrated part of the overall lower resolution regional model in the Anadarko Basin.

Anadarko Basin area where the main source rock has reached a high level of thermal stress. This regional evaluation would assess the amount of hydrocarbons generated in the deep basin that could potentially migrate into the STACK and SCOOP play areas.

2) A comprehensive local-scale study (over prospects covered by seismic data). This second stage would combine the detailed static model created from the seismic reservoir characterization results and the dynamic simulation provided by 3D PSM (Figure 8). The result of this local study would be a high-resolution model suitable for more detailed evaluation, which would be fully integrated into the overall (regional) model (Figure 9). Modelling software can work with both high- and low-resolution grids in a combined model to perform hydrocarbon migration analysis using different migration methods at different scales. Therefore, in this second step, the generated hydrocarbons from the original low-resolution regional model would be incorporated into the local high-resolution model. This enables both migrated and in-situ hydrocarbons to be evaluated within the study area.

For the detailed evaluation, the key facies and reservoir property volumes derived from the seismic inversion results that could be used as input data for the locally refined model are:

* Most probable facies volume: This shows the distribution of lithologies given by the highest probability value among all the lithology types. This information can be used to improve understanding of the vertical and lateral variations of the facies within the main target intervals.

* Porosity volume: this is usually derived from seismic data using rock physics correlations from petrophysical analysis of available logs. This volume can be calculated based on the relationship between P-Impedance and porosity on well logs. It helps to identify facies that can act as the best-quality reservoir and others that can act as seals (poor-quality reservoir) as key elements of the petroleum system.

* Fracture density or crack density volume: these volumes are indicators of fracture distribution. This is a very important aspect to be considered in the Mississippian Limestone. Indeed, Ward, 1965 (referenced in Adler, 1971; Ball et al., 1971) suggested the importance of the fracture system in the pre-Chesteran Mississippian in the Anadarko Basin. According to Ward (1965), whole core measurements indicate an average fracture porosity of 2%. In areas where the fracture density is high, permeability can be significantly high (Ward, 1965). Fracturing stresses were generated by the orogenies affecting the Nemaha Ridge and the Anadarko Basin. Open fractures improve permeability and have a high impact on hydrocarbon migration.

Conclusions

The unique geological evolution of the Anadarko Basin played an important role in the complex present-day distribution of hydrocarbons. Variations in the burial history across the Anadarko Basin have had a significant impact on the thermal evolution of the main source rock intervals, which controlled petroleum generation, expulsion/migration and accumulation. Geochemical evidence indicates that petroleum produced from the Mississippian strata and Woodford Formation of the STACK/SCOOP is likely related to a complex charge model system rather than a simple in-situ hydrocarbon charge model. Geochemical analysis performed on rock samples also shows additional evidence of a mixing of migrated and in-situ hydrocarbons already suggested by other studies, indicating a preferential direction of hydrocarbon migration generated from deeper areas within the basin. Facies within the Woodford and Mississippian strata revealed by the seismic reservoir characterization showed that prospective lithotypes demonstrate lateral and vertical heterogeneity. Therefore, hydrocarbon distribution across the STACK to SCOOP plays is also controlled by facies variations, indicating the requirement for more detailed evaluation and correlations. All the aspects described in this study have highlighted the complexity of these unconventional resources, which require more thorough evaluation in order to optimize and de-risk potential drilling targets.

Resource assessment for local targets needs to include a good understanding of the basin and its petroleum system at a regional scale. An integrated approach can provide a comprehensive overview of the regional petroleum systems by providing greater insight into hydrocarbon generation, expulsion, migration and accumulation within the deep basin as well as its implications for the STACK/SCOOP plays and other local areas.

Multiple advantages can be derived from this type of assessment, including:

*Detailed evaluation of hydrocarbon distribution based on an assessment of the migrated and in-situ generated hydrocarbons and facies variability. This can also be compared with and validated by geochemical analysis.

*More effective sweet spot identification and evaluation.

As an additional advantage, this evaluation workflow helps to identify new exploration opportunities within the study area and reduce geological uncertainties through the generation of an improved geological model.

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