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Elemental (XRF), Mineralogical (XRD), and Organic Geochemical (programmed pyrolysis) Analyses Used to Determine the Contribution of Reservoir Quality to Differential Wellbore Production of Single-Pad, Multi-Lateral Wells in the Eagle Ford, South Texas, USA.

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Summary

Differential initial production was recorded between four on-structure, single-pad horizontal wells targeting the Eagle Ford shale in South Texas, USA. Drill cuttings from two up-dip and two down-dip laterals were captured on the next adjacent pad and analyzed using Energy Dispersive X-ray fluorescence (ED-XRF), powdered X-ray diffraction (PXRD), and programmed pyrolysis analyses prior to completion. Results were used to evaluate reservoir quality before investigating completions strategy as the two major factors responsible for overall production.

Although mineralogy and elemental signatures related to organic richness and paleodepositional environment were similar between up- and down-dip laterals, a few key organic geochemical parameters differed along dip. Although a subtle difference in thermal maturity assessed through pyrolytic Tmax values was noticed between up- and down-dip laterals, Hydrogen Index (HI) values and calculated Transformation Ratios remain very consistent among the wells. Additionally, estimated oil cracking does not yield significant differences among the wells. However, estimated secondary gas cracking does indicate that up to 65% more gas was produced in down-dip laterals and may have produced significantly more gas-drive to increase oil recovery in these laterals.

The studied wells have now been completed using a similar completion strategy to the first where differential production was observed. Initial flow-back tests are scheduled soon and based on this

analysis, a higher gas/oil ratio is expected from down-dip laterals. This difference maybe the result of increased gas-drive exhibited by down-dip laterals and should be more pronounced after initial production.

Introduction

Four single-pad 1,060m laterals were drilled targeting the roughly 2˚ southeasterly dipping Eagle Ford in South Texas, USA. Two wellbores, U1 and U2, are oriented up-dip and two wellbores, D1 and D2, are oriented down-dip perpendicular to strike. Oil and gas production from the down-dip wells are known to be 86% greater than the up-dip wells after 10 months online. The GOR is 93% greater in the down-dip wells over the up-dip wells. Wellbore surveys and traditional mud-logging suggested that all four wellbores maintained their position in the selected target reservoir. This difference in initial production was significant enough to warrant altering future drilling programs provided the greater production in the down-dip laterals could be anticipated and the nature of the greater production quantitatively ascertained. Both reservoir quality and completions design could be primarily responsible for the differential production. Wireline petrophysical logs could be cost prohibitive in the laterals while routine core analysis would require a modification to the drilling program and may not determine the nature of reservoir variability over the length of the laterals.

Quantitative mineralogical, elemental, and organic geochemical analysis of cuttings brought to surface by drilling was chosen as a cost-effective measure to rapidly evaluate reservoir quality along the length of four laterals drilled on an adjacent pad with the same drilling and similar completions design. In this way, reservoir quality and wellbore positioning could be assessed prior to investigating and modifying the completions strategy or the drilling program.

Method

Drill bit cuttings were caught onsite at the flow line using sieves, recorded using lag depth, wet bagged, stored at ambient temperatures, and transported to laboratory facilities. Material sampled represented drilling cuttings, oil-based (diesel) drilling fluid, loss circulation material (LCM), and drilling fluid additives. Material was screened, hand-picked for non-rock components such as LCM, and washed in light soapy water. Contaminated drilling cuttings were then placed under vacuum and extracted using an ultrasonic bath and organic dichloromethane (DCM) solvent to remove oil introduced in the drilling fluid. Remaining cuttings materials are dried using a low vacuum. Thirty grams (30g) of dried cuttings material are split for analysis, with the remainder kept for archive. The analysis split is powdered and homogenized using a ball mill with tungsten-carbide vials and agitator balls. Powdered, homogenized material must pass 100 mesh sieve, with any coarse particles re-milled until all material passes.

The resulting powdered, homogenized cuttings material is then directly analyzed by the Source Rock Analyzer (SRA), a proprietary Weatherford Laboratories programmed pyrolysis instrument. The SRA yields organic geochemical values of the cutting samples including free hydrocarbon content (S1), remaining hydrocarbon generation potential (S2), thermal maturity via Tmax, Total Organic Carbon (TOC), and a variety of meaningful parameters such as hydrogen index (HI), oxygen index (OI), and normalized oil content. For oil-based drilling fluid contaminated samples, the DCM extraction removes S1 below 1 mg/g and is thus not used for interpretive purposes. Blanks and standards are used to track instrument performance and calibrate the instrument due to changes in atmospheric or operating conditions.

The same powdered, homogenized cuttings material is also directly measured by the Olympus Terra™ portable powdered X-ray diffraction (PXRD) instrument. The PXRD instrument uses a stationary 10W 30kV Cobalt tube and stationary 2D Peltier cooled CCD capable of a measuring between 5-55 2Θ. Ten (10) common mineral species and a total or 'bulk' clay value were at a high enough weight percent to be quantified from the cuttings using a reference intensity ratio (RIR) method. Pure mineral compounds are used to routinely check instrument performance and calibration.

Four grams of powdered, homogenized material is weighed out into aluminum cups and pressed over 10800 kg to form pellets. Sample pellets are then analyzed in the XEPOS™ HE Energy Dispersive X-ray fluorescence (EDXRF) unit using a 50W end-window X-ray tube and a Peltier cooled Silicon Drift Detector to quantitatively measure 12 major elements including chlorine (Cl) and 20 trace elements. Internationally recognized Geochemical Reference Materials (GRMs) are used throughout the analysis process and represent matrix-matched material with published values. GRM values are used to track instrument performance and correct for element drift.

After pyrolysis values are quality controlled, diffractograms are quantified for mineralogy, and elements are corrected for drift, all data is uploaded into Isologica™ for analysis and interpretation.

Conclusions

Analysis of the mineralogical character of the four lateral wellbores revealed the Eagle Ford target to be carbonate dominated, averaging 67 wt% calcite across all four wellbores and containing only 15 wt% average framework silicate grains (quartz + feldspars), 14 wt% total clay, and 4 wt% other minerals such as pyrite. Total Organic Content (TOC) is negatively correlated to calcite content (R^2=-0.43), where clay was only weakly positively correlated to TOC (R^2=0.24). Major element data stoichiometrically confirm the calcite-carbonate dominated lithology of the target but also reveal key relationships between TOC, paleoredox, and organic matter flux element proxies. TOC was found to have a statistically significant correlation to SO_3 (R^2=0.92), V (R^2=0.88), Cr (R^2=0.81), Ni (R^2=0.94), Cu (R^2=0.94), As (R^2=0.94), and Mo (R^2=0.95) in all four wells. These elements tend to become enriched in marine settings where organic matter accumulation is fostered by reducing conditions within the pore space of bottom sediments due to restricted basinal conditions (Tribovillard et al. 2006). The presence of free hydrogen sulfide under reducing conditions (euxina) can further enrich these elements during depostion (Algeo and Rowe 2012; Algeo and Tribovillard 2009; Tribovillard et al. 2006).These paleoredox and organic richness proxies confirm that organic matter was reaching de-oxygenated bottom water conditions that favored their depostion and burial in these sediments.

Wellbore position was also evaulated using survey and corresponding elemental data. Two wellbores revealed elemental indications of deviating from the target interval. Using silica-normalized Rb values, a 275 m stretch of lateral D1 and 50 m of U1 appears to deviate lower than the target. From the Author's previous elemental study of the Eagle Ford in the region, the Rb/Al_2O_3 ratio tends to increase in the lower Eagle Ford and rise significantly in the Buda.

All four wellbores contain significant concentrations of TOC in excess of the generally accepted 2 wt% needed for adequate unconventional reservoir production (Hunt, 1979). While S1 values are erroneous due to solvent extraction, Hydrogen and Oxygen Index (HI and OI, respectively) values were useful in determining kerogen quality. Tmax values converted to Ro values reveal that the reservoir section samples entered the late oil to early wet gas/condensate window for Type II kerogen (Barker, 1974; Espitalié, 1986). All four wellbores presented HI and OI values indicating original Type II kerogen (Espitalié, 1985) while build-section samples representing the overlying Austin Chalk produced significantly higher OI values. The relatively high OI values seen in some target Eagle Ford samples may have been the result of mixing with more oxidized organic matter (perhaps inertinite). Additionally, a greater contribution of evolved CO_2 to S3 during low temperature pyrolysis (<390 ˚C) may have been due to mineral matrix interaction associated with the relatively high wt% calcite in these samples (Espitalié et al., 1977). Despite using sieves to screen cavings from cuttings, some finer up-hole material can be incorporated with the cuttings sample. The degree of up-hole cavings incorporation in the cuttings was evaluated using elemental data. Based on alumina and silica normalized values of K_2O, Sr, and Rb compared to the summation of carbonate and siliciclastic elements, samples from three of the wellbores contain material that included some degree of contamination and were removed from the organic geochemical interpretation.

While TOC values and kerogen Type are similar between all four wells, the down-dip laterals contain Tmax values that are 3.6 - 5.4˚C higher on average than up-dip laterals after removing samples with significant suspected cavings contamination. If Tmax values were a reflection of a local geothermal gradient, this gradient should be reflected in HI values as well, however, HI remains relatively consistent across all four wellbores. Transformation Ratios based on present-day HI values are essentially the same for all four wells averaging 82.5%. This suggests that the difference in Tmax values observed between the up- and down-dip laterals did not result in differences in kerogen transformation.

Tmax converted Ro values (*sensu* Teichmüller and Durand, 1983) were also used to estimate the percent of oil and gas cracking yield along each wellbore path. Estimated oil yields vary across the wells and reveal no consistent trend amongst up- (Ave U1=359 bbl/acre-ft, Ave U2=388 bbl/acre-ft) and down-dip (Ave D1 = 383 bbl/acre-ft, Ave D2 = 373 bbl/acre-ft) laterals. Thus, estimated oil cracking does not yield greater oil generation in down-dip laterals. However, up-dip laterals seem to contain nearly 65% less secondary cracked gas than the down-up wells (126 Mcf/acre-ft average up-dip vs. 194 Mcf/acre-ft down-dip average). This significant difference in the estimated amount of cracked gas could be an important factor in the conveyance of oil and ultimately, oil recovery. Gas-drive is known as an important factor in Eagle Ford production and this differential in secondary cracked gas may be principally responsible for the greater oil production post completion.

In this case, a 65% increase in secondary gas generation may have resulted in creating greater gas-drive potential and produced greater oil recovery. This hypothesis will be tested by measuring the gas/oil ratios in the up- and down-dip laterals during initial flow-back testing. Moreover, this difference in secondary gas generation may become more demonstrable over the long run after sustained production is measured.

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