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Irreducible Water Saturation Has Been Determined As the Key Factor Governing Hydrocarbon Production from Low Permeability Carbonate at the Wattenberg Field in the Denver Julesburg Basin

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Abstract

It is commonly known that geological structure and its resultant natural fractures are the predominant factors governing hydrocarbon production from carbonate reservoirs. Through a detailed petrophysical study on a low permeability carbonate play, the authors have obtained new understandings toward the reservoir properties of low permeability carbonate. First, in absent of major geological structures, reduced relative permeability to hydrocarbon is the primary trapping mechanism. Second, the irreducible water saturation range for low permeability carbonate increases significantly. Third, the enlarged irreducible water saturation range makes the curve of relative permeability to hydrocarbon much steep. Therefore, the relative permeability to hydrocarbon is very sensitive to water saturation, and formation water saturation becomes a critical factor affecting hydrocarbon production. The results of this petrophysical study have been successfully applied to identity the “fairways” among a huge low permeability carbonate deposition.

Introduction

The Niobrara Formation at the Wattenberg Field in the Denver-Julesburg basin is a low permeability carbonate reservoir (Figure 1). It continuously exists throughout the entire field. The Niobrara is a sequence of interbedded carbonate and marine shale. The gross thickness varies approximately from 250 to 350 feet. The permeability tested to the carbonate part is in the order of micro-Darcy. Largely because of it extremely low permeability and unconfirmed potential, this carbonate play used to be treated as a secondary objective for 10 years (between 1996 and 2006) by most operators at the Wattenberg field.

Started a few years ago, operators have renewed their interests toward the Niobrara Formation. Numerous pilot projects have been conducted by either separately completing or re-completing the Niobrara Formation. Before any wells are drilled, the first question operators have to answer is where are the best parts of the Niobrara Formation among such huge field as Wattenberg covering approximately 3600 square kilometers (more than 42 townships). In other words, how to define the boundaries dividing economic area and non-economic ones?

Many carbonate reservoir related paradigms have failed to find their usefulness at the Wattenberg field. For example, in typical carbonate formation natural fracture resulted from geological structure is a critical factor governing hydrocarbon production. At the Wattenberg field, many wells tested along two well-defined major faults are not better in performance than others. In order to find the petrophysical factor that controlling hydrocarbon production, the authors carried out a petrophysical study and found the method to delineate the “fairways” where the Niobrara Formation performs better than other part of the field.

The correlation between well-log calculated water saturation (Sw) and well performance

This petrophysical study is supported by a wealthy well log data resource, which includes digital well logs collected from more than one thousand wells where the Niobrara Formation has been penetrated when deeper formations were originally the primary targets. Using self-developed computer programs as well as commercial ones, we calculated the representative well log parameters of the Niobrara Formation, such as the porosity, SP, formation water saturation, and the cross-over area between the neutron and density curves. In order to search the distribution patterns of these parameters, we mapped these parameters. Their distribution patterns helped us identify the areas where the Niobrara reservoir quality is better than that of other part of the field.

As displayed by Figure 2 through Figure 5, the distribution patterns of these well log parameters suggest that the sweet spots of the Niobrara are largely situated at the northeast part of the field. This suggestion can be substantiated by the petrophysical significance carried by each well log parameters.

First, in some areas SP demonstrate significant negative deflection while no SP was observed in other part of the field. Even though we understand that SP can not be quantitatively related to permeability, the occurrence of SP suggests permeable formation. In the areas where SP exists the reservoir quality should be better. Second, through a similar petrophysical study performed on another formation the authors have correlated the solution gas/oil ratio with the cross-over area between the neutron and density curves. Large area suggests high solution gas oil ratio of the reservoir fluid. For depletion type reservoir, such as the low permeability carbonate reservoir, solution gas/oil ration can be proportionally correlated with reservoir energy. In order words, the large the cross-over area between neutron and density curves, the higher the reservoir energy and better well performances. Third, intuitively the higher the porosity and lower formation water saturation contribute to better reservoir volumetrics.

Comparing the area covered by low formation water saturation (blue contour line encompassed area in Figure 5) with the “sweet spots” suggested by well log parameters (SP, porosity, and crossover area between neutron and density), we noticed that the former is bigger than the latter by approximately 30% and the latter is encompassed by the former. Within the overlapped area, it is relatively easy to conclude that this area possesses better reservoir quality because of its better formation fluid transmissibility (SP), better reservoir volumetrics (porosity), and high reservoir energy (cross over area between neutron and density). Outside the overlap area, the formation water saturation is still low but other parameters are not promising. In order to determine whether the formation water saturation is a practically useful criterion to distinguish Niobrara reservoir quality, we compared well performances from wells with different formation Sw. We noticed that wells with low Sw constantly outperform wells with high Sw. We empirically picked a well-log calculated Sw to serve as Sw cutoff to delineate “fairways” of the Niobrara, and received encouraging well performance (Figure 6).

Based on the understandings and results discussed above, we suggest that formation Sw in the Niobrara can serve as a reliable criterion to delineate “sweet spots”. This method has “salvaged” a large area where other well log parameters do not indicate good reservoir qualities.

Why the formation Sw is a critical factor affecting well performance?

In order to understand the critical role formation water saturation plays in hydrocarbon production, we have to dig deep into two intrinsic factors associated with such low permeability carbonate as Niobrara Formation; reservoir trapping mechanism and its unique characteristics of relative permeability.

As displayed in Figure 7, the geological structure of the Niobrara Formation is syncline. There are no structural barriers to restrict hydrocarbon. Furthermore, the Niobrara deposition continuously covers the entire Denver-Julesburg Basin. It does not pinch out toward the boundaries of the basin. So it is not litholgy type of trapping mechanism. Therefore, its reservoir trapping mechanism can only be relative permeability type. As moving away from the center to the boundary of the field, water saturation increases. When water saturation reaches a certain high point where relative permeability to hydrocarbon approaches to zero, as a combined effect of low absolute permeability and high water saturation. The relative permeability trapping mechanism alone exhibits that formation water saturation is a critical factor influencing gas oil production from the Niobrara.

By “unique characteristics of relative permeability” we mean that the relative permeability to hydrocarbon curve of the Niobrara is more sensitive to changes of water saturation than conventional carbonate reservoirs. For instance, a small amount of increase in water saturation can cause a substantial decrease in relative permeability to hydrocarbon. To explain this suggestion, let’s revisit the relative permeability definition in conjunction with the micro-Darcy level absolute permeability of the Niobrara.

By the definition of relative permeability, relative permeability to oil curve has a range between 0 to1, and its domain is determined by two factors: the oil critical saturation and the irreducible water saturation (Figure 8). The critical oil saturation is the minimum oil saturation with that oil start to flow. The irreducible water saturation is the maximum water saturation with that water does not move. In other words, the range of relative permeability curve is constant while its domain depends on the combination of critical oil and irreducible water saturation. Statistically, the critical oil saturation fells in a range of 2%-5%, whereas irreducible water saturation varies from 10% to 20% (Calhoun, 1953; Amyx, 1960). The sensitivity of relative permeability to oil, or the curvature of the curve depends on two parameters; the water saturation domain and the pore structure. For the same type of formation the pore structures are similar, and its influence on relative permeability curve will not change dramatically. Therefore, the curvature of the relative permeability curve can be largely connected to water saturation domain.

Niobrara core sample tests reported a very high irreducible water saturation; varying between 45% and 55%. These test results can be substantiated by the fact that the Niobrara does not make any formation water at the Wattenberg Field. This abnormally high irreducible water saturation has substantially reduced the Sw domain of relative permeability curve. Compared to conventional carbonate reservoirs, the reduced Sw domain of the Niobrara makes the relative permeability curve very sensitive to water saturation. In other words, when Sw increases by a small amount, the relative permeability to oil will decrease by a big margin.

In summary, the formation Sw is so critical in hydrocarbon production from the Niobrara because of two factors intrinsic to the reservoir itself. First, relative permeability is the primary reservoir trapping mechanism. Second, the relative permeability to hydrocarbon is very sensitive to formation Sw change. A small increase in Sw can significantly reduce the relative permeability to oil. Therefore, formation Sw is a critical factor affecting hydrocarbon production from the Niobrara Formation.

Conclusions

Supported by the observations made from this petrophysical study as well as corresponding well performances, a few conclusions can be draw as below.

1. Well log computed formation water saturation can be quantitatively applied to evaluate reservoir quality of the Niobrara low permeability carbonate reservoirs.
2. High irreducible water saturation in the Niobrara has significantly reduced the water saturation domain of the relative permeability curves, and made the relative permeability to oil is very sensitive to formation water saturation.
3. A well-log calculated formation Sw can be empirically chosen to serve as a Sw cut off to delineate the “sweat spots” of the Niobrara Formation within the gigantic Wattenberg field.

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References

1. Calhoun, J. C.: “Fundamentals of Reservoir Engineering,” University of Oklahoma Press, Norman Okla., 1953
2. Amyx, J. W.: “Petroleum Reservoir Engineering Physical Properties,” The Agricultural and Mechanical College of Texas, McGraw-Hill Book Company, 1960

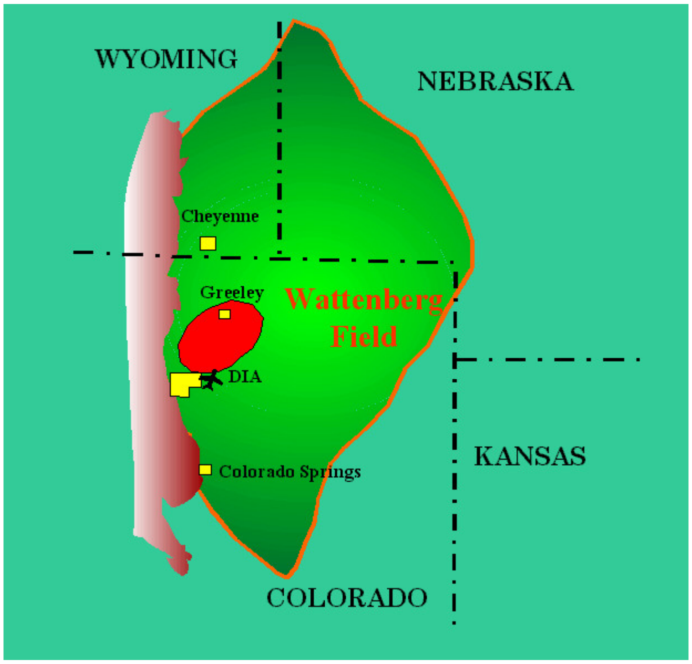

Figure1: Geographic location of Wattenberg field

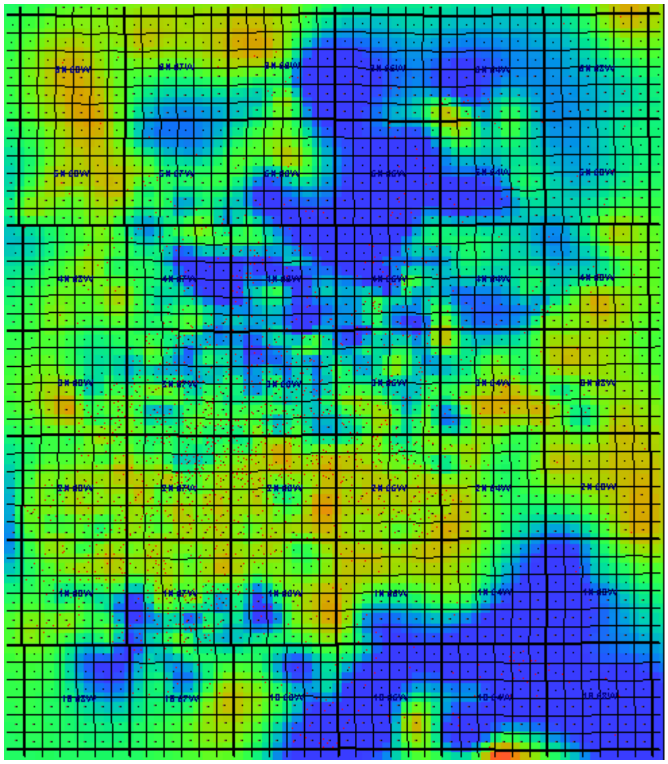

Figure 2: SP distribution; warm color represents high SP.

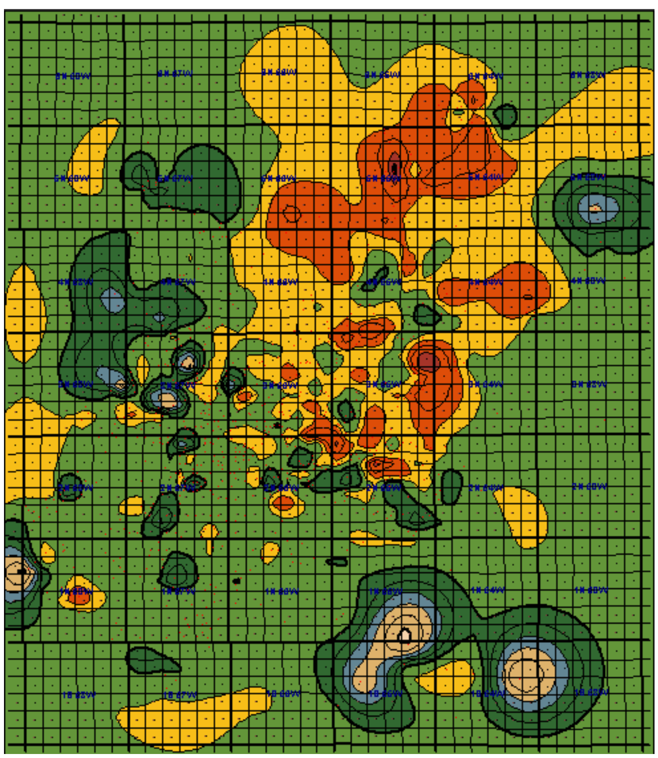

Figure 3: Area of cross-over between neutron/density curves, which has been proved to be a indicator of solution gas/oil ratio

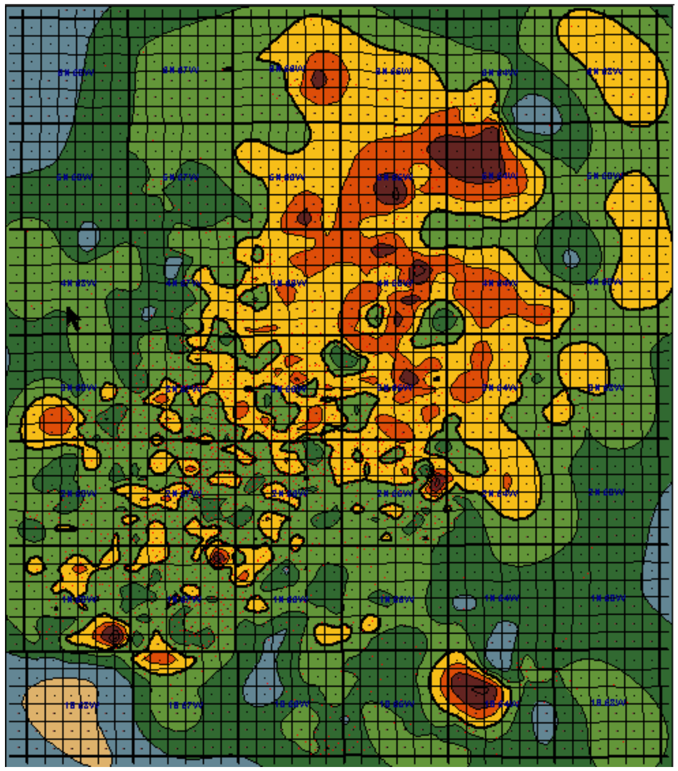

Figure 4: Porosity distribution

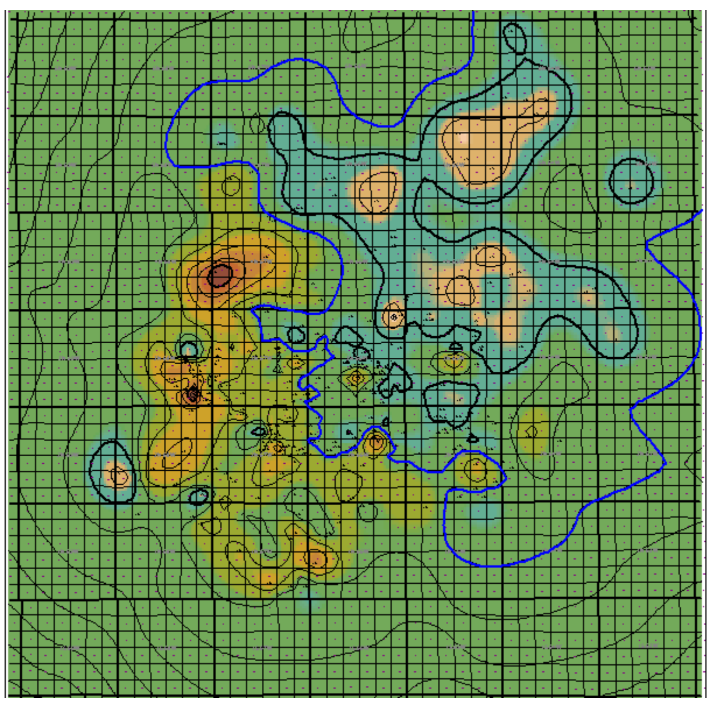

Figure 5: Well-log calculated formation water saturation, the solid blue contour line is an empirically determined Sw cutoff to define the “fairways”

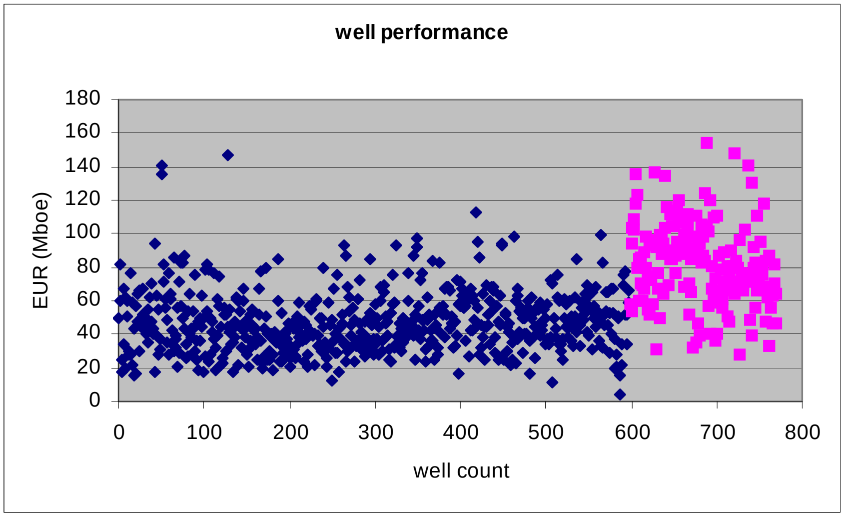

Figure 6: The pink dots represent combined reserves of Niobrara and another primary reservoir from wells picked by an empirically determined Sw cutoff while the blue ones are the reserves of the primary reservoir.

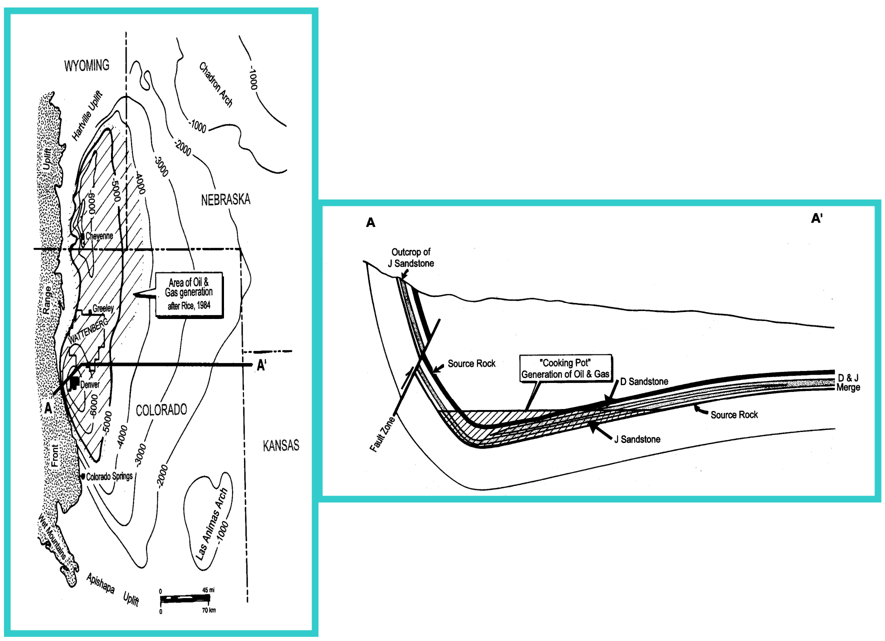

Figure7: Geological structure of the Niobrara Formation indicates that the Niobrara is neither structural nor lithological trapping mechanism.

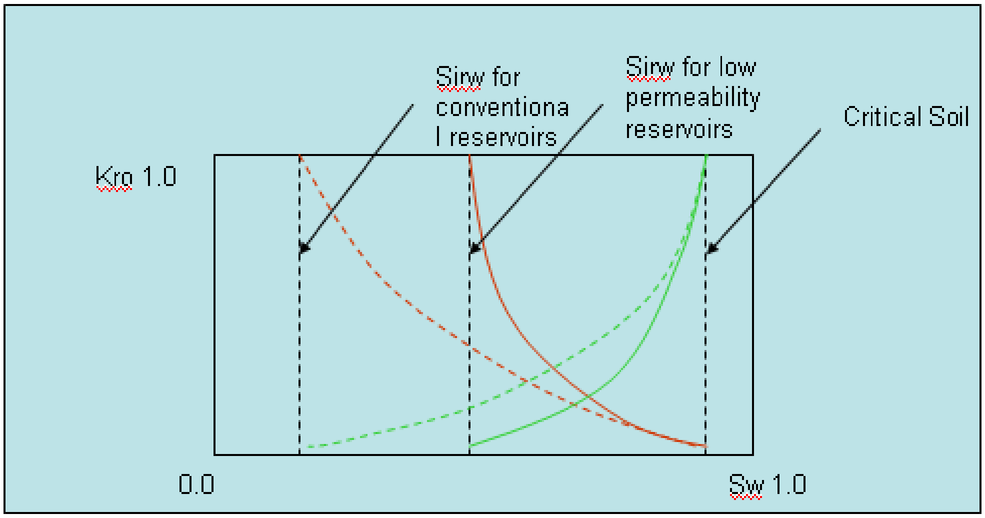

Figure 8: Elevated Sirw for low permeability carbonate has depressed the relative permeability curves, and made the relative permeability more steep and sensitive to Sw change.