AAPG HEDBERG CONFERENCE
"***Variations in Fluvial-Deltaic and Coastal Reservoirs Deposited in Tropical Environments***"
APRIL 29-MAY 2, 2009 – JAKARTA, INDONESIA

Exploring Complex Fluid Distributions in Tropical Fluvial-Deltaic to Shoreface Reservoirs in the Malay Basin

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Oil and gas fields in the Malay Basin, Malaysia are found in a series of stacked, prograding fluvial-deltaic and shoreface reservoirs folded into faulted anticlines during basin inversion. Although none of the geologic components (e.g., reservoir, trap, and seal) are particularly unusual in the Malay Basin, the interaction of these relatively straight-forward components leads to the development of highly variable fluid contacts. Some of the critical elements that lead to complex fluid segregation include:

- Reservoir development generally below seismic resolution. This has led to reservoir models based on well-log correlations, and these have proven to be challenging when lateral facies variations are undersampled by wells.
- Reservoir facies that change laterally within the structural closure.
- Stratigraphic seals (e.g., shale-filled channels) that interrupt otherwise continuous reservoir intervals.
- The contribution of non-net reservoir intervals that nevertheless contribute to fluid leak.
- Faults that offset reservoir intervals at the crest of the structure but tip out on the flanks, often within the structural closure.

We have found that the resulting complex interactions between reservoirs, seals, and structures and the gas, oil, and water fluids contained within them become understandable via a step-wise workflow we term Reservoir Connectivity Analysis (RCA). We have used RCA in a number of field studies in the Malay Basin to rationalize existing, complex fluid contacts, to identify potential by-passed oil opportunities for in-fill drilling, to support continued field development and well placement decisions, and ultimately to improve field recovery. RCA studies result in rigorous predictions of fluid type, fluid pressure, and/or fluid contacts for any given well location, so the value of the models, the geologic input to those models, and the resulting predictions have been tested by subsequent drilling.

In this presentation, we discuss RCA results from Tx and Ty field studies. In the Tx field study, the primary technical question was whether production from the gentle north-flank of the field would have drained the oil from the undeveloped steep south-flank of the field from beneath the gas-oil contact (GOC). RCA was used to construct a series of risked predictions based on uncertainties in the details of geologic connections. Three development wells drilled into a fault block on the south-flank discovered a full oil column as predicted by a majority of the pre-drill scenarios.

The Ty field study, on the other hand, led to predictions of gas and oil distribution, contacts, and pressures in the undeveloped Central Fault Block based on relationships derived from the developed Eastern Fault Block and appraisal drilling in the remainder of the field. The Ty I-reservoirs involved in this study were deposited in a lower delta plain and thus add an element of stratigraphic complexity arising from the rapid lateral facies variations present in this depositional setting. The Ty I-reservoirs create a series of stacked gas and oil pays so wells drilled into the Central Fault Block provided the opportunity to test the RCA predictions for a complex three-dimensional network of reservoirs.

In both studies, we recognize a number of geologic elements that inhibit the communication of buoyant gas and oil fluids overlying water, including:

- Lateral seals, both stratigraphic (e.g., channel margin) and structural (fault juxtaposition of reservoir against a sealing facies)
- Folding of a laterally confined reservoir across an anticline where the thickness of a reservoir unit (meters) is much less than the amplitude of the fold (100's of meters)
- Shale-filled channels, which can serve to separate and isolate otherwise continuous, older reservoir intervals

We also recognize geologic features that promote the vertical communication of fluids, including:

- Channel incisions through thin delta plain shales
- Fault juxtaposition connections that allow connection of adjacent reservoir intervals across fault windows

Both of these connection types (fault juxtaposition windows and stratigraphic connection windows) offer the opportunity to separate gas, oil, or water fluids when put in the context of the current depth-structure. For example, the up-dip structural limit of a channel incision presents an opportunity to limit a gas column in the deeper reservoir interval via a spill relation, and the same is true for the shallowest point in a fault juxtaposition window. The down-dip limit of both the stratigraphic incision and the fault juxtaposition window also offer the opportunity to separate fluids, but in this case the denser fluid (e.g., oil beneath gas or water beneath oil). We term this spill relationship 'breakover' to distinguish it from the more conventionally recognized spill of the less dense fluid.

Taking all of these geologic factors into account, we arrive at an understanding of multiple, separated aquifers, all to varying degrees modestly above a hydrostatic aquifer pressure. The number of independent aquifers would have been initially smaller before gas and oil fill of the reservoir. Oil and gas have blocked many of the reservoir connections that would have allowed aquifer communication. There are also a number of independent gas and oil columns, separated by stratigraphic and structural spill and breakover points. The result is a large and complex array of gas-oil and oil-water contacts that otherwise defy comprehension.

Many predictions generated by the RCA study have been tested by limited in-fill drilling in the central fault block. Although the number of actual wells is small, each well tested multiple reservoir intervals so the number of tests is significant. Each of the wells discovered fluid types and fluid contacts within the range of predicted outcomes. In this instance, too, care was taken to describe alternative fluid scenarios to account for uncertain geologic input. In those instances where the results fell outside the predicted range of outcomes, the well results were readily rationalized by modifying structural and/or stratigraphic interpretations in accord with the well results and always within the context of the connectivity framework already established.

This final point bears further discussion because sometimes the RCA exercise elucidates details of the stratigraphic framework that are otherwise elusive, given stratigraphic elements below seismic resolution and that undergo facies changes between individual well penetrations. For example, shale-filled channels are proven by limited well and core observations, but their orientation and distribution are difficult to map from those observations alone. However, because they serve to separate fluids, the fluids observed within wellbores away from the channels can inform on the continuity and extent of those channels. In another example, thin sands were encountered in two wellbores near the crest of the central fault block. These sands were wet, even though wells off both flanks contain gas and oil at deeper structural levels. Because these sand intervals exist outside the previously interpreted channel axis, we are led to the interpretation of sand bodies that pinch out off on the south flank of the structure, creating stratigraphically trapped water in an otherwise continuous hydrocarbon column. With this general geometric picture in mind, we put these observations into the context of the existing stratigraphic interpretation and come up with an interpretation of limited crevasse splay deposits outside a fluvial channel or small delta lobes developed in a prograding distributary system. **Both of these interpretations lend an element of refinement to the overall complex stratigraphic interpretation, an element derived from considering how these stratigraphic elements expressed in a structural context lead to the separation and isolation of different fluid types.**

In summary, the complex facies distributions in fluvial-deltaic environments, expressed in even the simplest of trap geometries (a faulted anticline) leads to the development of complex fluid separation and connections. However, the application of a rigorous methodology (RCA) that integrates structural and stratigraphic interpretations with observations of gas, oil, and water distribution, pressure, and contacts, leads to the development of a detailed understanding of the interactions between fluids and geology. The resulting connectivity model is able to rationalize existing fluid observations within the framework of the geologic understanding and has true predictive capability that has been successfully tested. It is this predictive capability that offers great benefit at profitably maximizing gas and oil recovery in this complex reservoir environment.