PS Production-Induced Capillary Breakdown of Reservoir Barriers*

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Abstract

Slope changes on p/z vs. cumulative production plots and other production responses have been interpreted as breakdown of reservoir barriers. Petroleum flow through the barrier can be caused by either percolation through a water-wet barrier pore system (capillary breakdown) or fracturing the barrier. This paper investigates the capillary barrier breakdown mechanism by numerical modeling of flow across barriers isolating reservoir compartments.

Capillary barrier breakdown results from increasing capillary pressure in the barrier by decreasing water pressure. Water in the barrier communicates with water in the producing compartment, so pressure drop by production reduces water pressure in the barrier. Capillary pressure increases at the barrier contact with the undrained (high petroleum pressure) compartment. When the capillary pressure reaches the barrier threshold capillary pressure, petroleum from the undrained compartment invades the barrier and quickly extends across the barrier. This is barrier breakthrough. Although the barrier is "broken", flow across the barrier is miniscule at breakthrough. Barrier breakthrough is not barrier breakdown.

With further production, capillary pressure continues to drop. Petroleum relative permeability in the barrier increases and cross-barrier petroleum flow increases. Even where the barrier petroleum relative permeability is high, petroleum flow may be negligible if the total flow resistance of the barrier is high.

Capillary barrier breakthrough is expected in any barrier separating reservoirs with production pressure differences greater than the barrier threshold pressure. In contrast, significant cross-barrier petroleum flow (barrier breakdown) requires low petroleum flow resistance combined with moderate capillary threshold pressure. This combination is rare unless the barrier is exceptionally narrow. Barrier breakdown may be rare in real compartmentalized gas reservoirs and absent in reservoirs where petroleum can flow around the barrier.

Apparent changes in p/z slope, especially those early in the production, might alternately be explained by improper average reservoir pressure estimation and gas contribution from tight facies.

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One Minute Sumary

Capillary barrier breakdown during production occurs as an incremental process controlled by the cross-barrier pressure difference and barrier properties. Breakthrough occurs by a displacement front invading the barrier in response to cross-barrier pressure differences. Breakthrough is not the same as breakdown (significant flow across the barrier). Because barrier absolute permeability and relative petroleum permeability are low, significant cross-barrier flow occurs only after a significant cross-barrier pressure difference develops and only for barriers with relatively low cross-barrier flow resistance (such as narrow barriers).

Barrier behavior can be predicted from expected cross-barrier pressure differences and barrier properties. p/z plots show subtle differences that could in theory distinguish barrier breakdown from other causes of p/z slope change. However, p/z differences are subtle and likely to occur early in production where pressure data are not representative of the whole-field pressure decline.

Some Basic Terms

<u>Capillary pressure</u>: petroleum pressure minus water pressure at a specified location.

<u>Flow Resistance</u> (R): flow length (ΔL) divided by permeability (k). Equals flow area (A) divided by transmissibility (T).

<u>Production index</u> (PI): Total flow rate divided by pressure drop. As used here, it is total fluid production rate from the well in stock-tank bbls fluid per day divided by the difference between initial reservoir pressure and well bottomhole pressure in psi.

<u>Transmissibility</u> (T): normalized flow/pressure difference. Can be described in terms of static properties (flow area times permeability divided by flow length) or dynamic properties (production rate times viscosity divided by pressure difference).

Introduction and Background

Many reservoirs have stratigraphic or fault barriers. Barrier behavior influences oil and gas field production patterns, yet barriers are especially difficult to model in standard reservoir simulations. Abrupt permeability contrasts create numerical problems on standard gridding. Fault barriers are typically represented by column offsets with transmissibility modifications, a simplification that prohibits assigning two-phase flow properties. Barrier behavior is commonly approximated by pseudoizing surrounding cells or assuming generalized transmissive properties (e.g., Manzocchi et al. 2002).

The process of barrier breakdown is especially problematic. Barrier breakdown is the change from sealing behavior to significantly transmissive behavior during production. It is called upon both to explain unpredicted changes in watercut during oil production and p/z (pressure divided by gas compressibility factor) slope changes against cumulative gas production. As discussed by Zijstrata et al. (2007) and Manzocchi et al. (2010), other processes could explain some of the features that could be interpreted as barrier breakdown. Manzocchi et al. (2010) modeled capillary breakdown of fault barriers and concluded that capillary breakdown could occur in reservoirs, but was probably rare. Unfortunately, the simulator used by Manzocchi (Eclipse) had problems that required modification of cells adjacent to the faults. These modifications may have obscured the causes and evolution of capillary barrier breakdown discussed by Manzocchi et al. (2010).

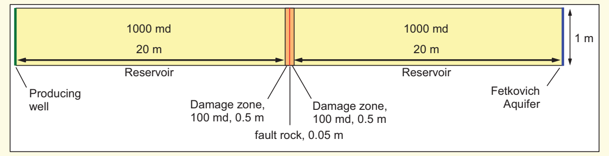
The goal of these study is to understand the process of capillary barrier breakdown and cross-barrier flow behavior after breakdown to help understand and predict fault barrier behavior in reservoir simulations. Relatively small-scale, detailed barrier flow models were simulated so that the underlying physics can be understood and in some cases modeled analytically. The concepts and insights developed from these models guide understanding of fault-barrier behavior in more complex reservoir simulations so that fault flow properties in these more complex models can be suitably simplified. This approach is significantly different from some previous studies (Al-Busafi et al 2005; Manzocchi et al. 2002) where larger-scale models with upscaled barrier properties are used to evaluate behavior of wells distant from the fault barrier.

This study reports results of proprietary work for the Rock Deformation Research, Ltd. Fault Foundation Industrial Research program from 2007 to 2010. The simulator used in these studies (FlowSim) does not appear to have the problems reported for the Eclipse simulator by Manzocchi et al. (2010). The pseudoization approach of Manzocchi et al. (2002, 2010) was not necessary and was not utilized in these fine-scaled models.

Results of homogeneous fault-rock breakdown under different wettability assumptions are reported first. Modeling is then focused on water-wet homogeneous barriers. Pressure and saturation behavior before, during, and after breakthrough were investigated in more detail and related to properties of the homogeneous barrier. It was found that two variables controlled flow behavior as homogeneous barriers breakdown: the threshold pressure and the flow resistance. Heterogeneous layered barriers are controlled by the same basic controls as homogeneous barriers. However, lateral heterogeneity allows flow around the tightest barrier, thus mitigating the effects of low permeability fault rock on total cross-barrier flow.

Finally, alternate proposed explanations for changes in p/z vs. cumulative production slopes were modeled to determine if there are subtle differences in the p/z behavior that could be used to distinguish barrier breakdown in gas fields from other causes of p/z slope changes.

Generalized Model Characteristics



Although models are for generalized barriers, concepts of fault-rock barriers were used as a guide for model design. Models are essentially two dimensional and consist of three lithologies: a reservoir (1000 md), damage zone (100 md), and fault core (variable permeability). The model is 20 cm (1 cell) wide and 1 m (5 20 cm cells) high. The reservoir is 20 m long (20 cells, each 1 m long) on either side of the barrier. The damage zone is 0.5 m (5 10 cm cells) long in the flow direction, and the fault core is 5 cells each 1 cm wide. In most of the early models, the fault rock was assigned 0.01 mD. In later models, the thickness and permeability of the fault rock was altered to determine controls on cross-barrier flow. The number of cells in the fault core was also increased in some models to better characterize the cross-barrier flow and pressure distributions within the barrier.

Upper and lower surfaces are no-flow boundaries. Flow is always from right to left. Production from a well on the left side of the model controls flow rate. Aquifer support at the right edge of the model is simulated by a Fetkovich aquifer kept at initial reservoir pressure. The aquifer support is turned on for oil simulation and off for gas depletion simulation. The well produces at a constant rate until some bottomhole pressure limit is reached, at which production rate is controlled by the bottomhole pressure. Simulation was generally stopped when the production rate changes.

Wettability is modeled by shape of capillary pressure and relative permeability curves, especially the endpoint saturations and crossover points. Capillary pressure curves are scaled using J-function relationships. For simplicity, relative permeability and capillary pressure relationships to saturation are assumed to be the same in drainage and imbibition. Relative permeability assignments affect the shape of the displacement front and the flow resistance at the displacement front, but do not affect the overall processes observed in the models. In black-oil simulations, oil/water viscosity ratio was kept close to 1 except where noted. Gas simulations use either a pure methane gas or an ideal gas with z factor of 1.

Intermediate and Oil Wettability

Intermediate-wetted barrier in an intermediately wetted reservoir were modeled using zero threshold pressure and symmetric relative permeability curves with equal endpoint permeabilities. This is a black oil simulation with equal oil and water viscosity.

Models show minimal effects of the barrier (Figure 1). There is no barrier breakdown because the barrier is partially saturated at start of production. A displacement front forms at the aquifer (right) edge and quickly marches across model, just as it would in the absence of the barrier. There is an abrupt step in reservoir pressure at the barrier that develops quickly after production starts. Pressure does not change significantly until the displacement front crosses the barrier. Pressure gradient across the barrier rises slightly when the displacement front crosses the barrier.

Oil-wetting causes higher oil saturation in the low permeability barrier than in the reservoir. Oil permeability is therefore higher in the oil-wet barriers than in intermediate-wetted barriers of equal absolute permeability. The barrier is therefore less of a pressure barrier than intermediate- or water-wet barriers.

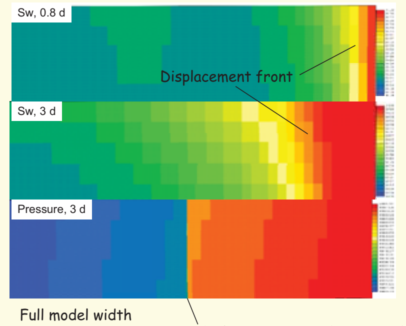


Figure 1. Saturation and pressure distribution in a flow model with an intermediately wetted barrier. The barrier significantly affects pressure (lower figure), but does not significantly affect movement of the displacement front.

Water-Wet Barrier Behavior

A number of gas-water and oil-water barrier flow models were run with saturation and relative permeability characteristic of water-wet barriers. In all cases, barriers were initially water saturated. There are three general results. Models with thick, low permeability barriers were always sealing; that is, there was no significant cross-barrier flow. Where barriers have a combination of low total flow resistance but high barrier threshold pressure, water can flow across the barrier but petroleum does not. Where barriers have relatively low barrier threshold pressure and low to moderate flow resistance, both petroleum and water flow across the barrier.

No Cross-Barrier Flow

Models show no significant cross-barrier petroleum or water flow where either (1) capillary pressure developed by production is less than barrier threshold pressure or (2) barrier has a high cross-barrier flow resistance due to a long flow length or low phase permeability. This is the initial state of barriers in all water-wet models. It is the final state of barriers with exceptionally high threshold pressure and low absolute permeability.

Cross-Barrier Water Flow

Water selectively flows across barriers where capillary pressure does not exceed barrier threshold pressure, and the barrier is thin enough so that the total flow resistance to water is relatively low. Water flowing through the barrier supports pressure in the producing (left) compartment and prevents development of capillary pressure sufficient for petroleum to displace water from the barrier. In this example, the cross-barrier pressure difference is only about 100 psi when the displacement front forms (Figure 2A, upper).

As oil is produced from the left compartment, oil and water pressure in the left compartment drop. Water drains from the barrier into the left compartment. If water saturation in the right compartment is not irreducible, water can move from the aquifer through the right compartment to the barrier. This water displaces oil to form a displacement front in the left compartment down-flow from the barrier (Figure 2A). The displacement front then moves towards the producing well while the right compartment remains oil-saturated (Figure 2B).

The barrier water saturation remains high, thus preventing oil flow through the barrier (Figure 2C). Oil saturation increases at the right edge of the barrier in response to capillary pressure enhanced by water pressure drop (forced drainage). If water saturation were irreducible in the right compartment, water could not flow across the compartment and aquifer pressure could not support displacement.

This behavior requires that the barrier have high threshold pressure and a short flow length. It is expected to be rare during production, but it may be more common in exploration settings where capillary pressures are relatively low.

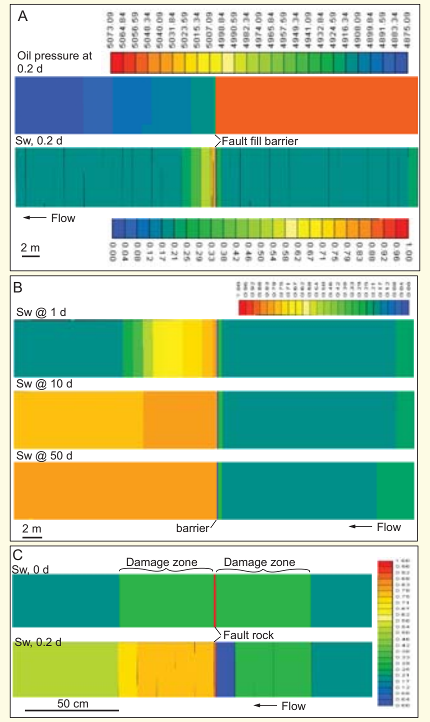


Figure 2. Saturation and pressure distribution in models with a thin, water-wet barrier with high threshold pressure. (A) Water flows from the aquifer across the barrier to form a displacement front left (down flow) from the barrier. Cross-fault water flow starts almost immediately with production, and continues until the left compartment is drained. (B). Even after the displacement front has moved completely across the left compartment, oil in the right compartment has not been mobilized across the barrier. In detail (C), water saturation increases down flow (left) of the barrier and decreases up-flow from the barrier.

Cross-Barrier Petroleum Flow

Petroleum flows into a water-wet barriers where capillary pressure exceeds the threshold pressure of the barrier. Cross-barrier petroleum flow is significant if barrier flow resistance to petroleum ($L/(k_a k_r^o)$) is low. These two criteria are met where the barrier is thin and relatively permeable. The barrier must first develop partial petroleum saturation before petroleum can cross the barrier. This is the barrier breakdown process.

As production reduces the oil pressure in the left compartment, barrier water pressure drops, thus increasing the capillary pressure on the right side of the barrier. Oil invades the barrier once the capillary pressure exceeds the threshold pressure (Figure 3, top). Water is displaced into the left compartment, slightly increasing water saturation adjacent to the barrier (Figure 3, middle).

Once the barrier has broken down, oil flows across the barrier, oil pressure in the right compartment drops, and a displacement front forms at the interface with the aquifer (Figure 3, middle). The displacement front then moves across the model with relatively small effects from the barrier except for higher flow resistance across the model (Figure 3, bottom).

Effects of the barrier can be tracked by changes to the production index (PI). PI drops when the barrier breaks down because the barrier adds to flow resistance across the model (Figure 4). When the displacement front reaches the barrier, PI decreases even more. Sum of phase permeabilities is lowest at the displacement front, so the displacement front adds to the total flow resistance of the model. When the displacement front crosses the low permeability barrier, the total flow resistance of the model increases and the PI drops. After the displacement front crosses the barrier, PI increases due to higher water cut (Figure 4). Shape of the PI vs. cumulative production curve will change with relative permeability assignment.

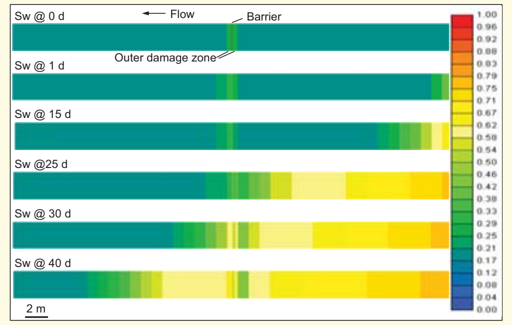


Figure 3. Water saturation in a water-wet flow model with a barrier with low threshold pressure. Barrier rapidly breaks down, after which the displacement front initiates against the aquifer interface and moves across model. The only effect of the barrier on saturation is banking of a small amount of oil after the displacement front crosses the barrier. .

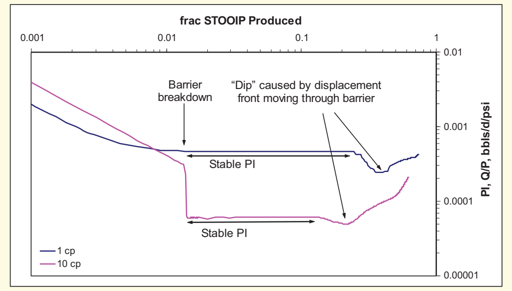


Figure 4. Variation of production index (PI) with cumulative production. PI initially drops until the barrier breaks down, after which it stabilizes. PI drops when the displacement front crosses the barrier. PI then rises due to increasing water saturation (water has lower viscosity, so PI increases with water).

Production Rate, Cross-Barrier Pressure Difference, and Barrier Behavior

The ultimate controls on water-wet barrier behavior are its threshold pressure, its permeability, and its thickness. Capillary pressure develops due to pressure differences across the barrier. If capillary pressure exceeds barrier threshold pressure, cross-fault petroleum flow is possible. In these simulations, pressure support can only develop by cross-barrier flow. Thus, the cross-barrier pressure is ultimately controlled by the flow rate (established by well production rates).

Figure 5 shows the model saturations and pressures during uniform PI flow for identical models with different production rates. Higher production rates cause larger cross-barrier pressure differences (Figure 5, left bottom). Petroleum can flow across the barrier, so the displacement front develops at the aquifer interface (Figure 5 right bottom). Low rates (low pressure gradient across barrier) causes barrier to be transmissive only to water because capillary pressure is insufficient for petroleum flow across the barrier (Figure 5, upper left). The displacement front forms down-flow from barrier in the left compartment (Figure 5 upper right). Where the pressure drop across the barrier is slightly higher than the threshold pressure, it is possible for two displacement fronts to develop simultaneously, one at the aquifer interface and the other downflow from the barrier (Figure 5 right, middle).

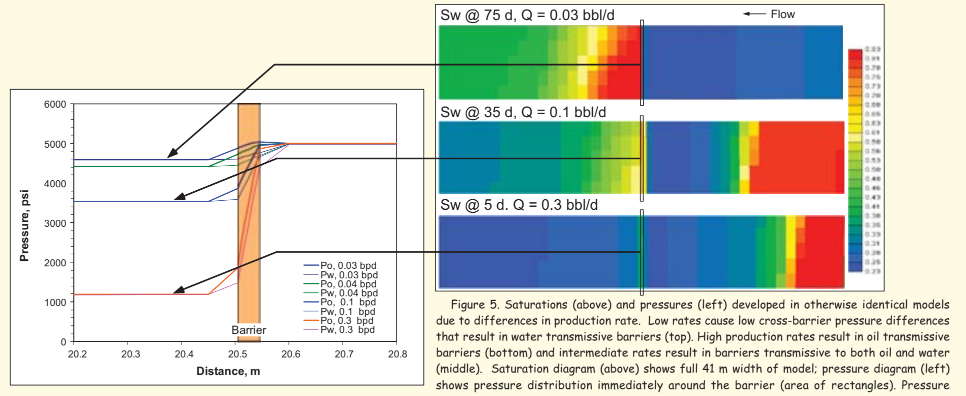


Figure 5. Saturations (above) and pressures (left) developed in otherwise identical models due to differences in production rate. Low rates cause low cross-barrier pressure differences that result in water transmissive barriers (top). High production rates result in oil transmissive barriers (bottom) and intermediate rates result in barriers transmissive to both oil and water (middle). Saturation diagram (above) shows full 41 m width of model; pressure diagram (left) shows pressure distribution immediately around the barrier (area of rectangles). Pressure distributions within barrier are not shown.

Depletion Reservoirs (Gas)

Interaction of a displacement front with the barrier causes complexities in pressure and saturation that make the simplicity of barrier breakdown harder to visualize. These problems can be avoided by modeling depletion (gas) reservoirs. Reservoirs and barriers in gas reservoirs are water wet, so the process of barrier breakdown in gas reservoirs should be similar to that of water-wet oil reservoirs, only uniform flow developed after barrier breakthrough is pseudo-steady flow that will continue nearly to abandonment pressure. Models were constructed to assess the details of gas breaking through the barrier. In all cases, the same general phenomena were observed.

First, the barrier is 100% water saturated and is a barrier to gas flow (Figure 6A). Cross-barrier gas pressure difference therefore increases as gas pressure drops in the producing (left) compartment. Water pressure in the producing compartment also drops, so water flows from the barrier into the left compartment and water pressure in the barrier drops. This increases capillary pressure at the right edge of the barrier until it reaches the barrier threshold pressure. A displacement front forms in the barrier which moves across the barrier. Once gas reaches the left side of the barrier, it has broken through the barrier and gas can flow across the barrier (Figure 6B). Cross-barrier pressure difference is greater than the barrier threshold pressure (Figure 7)

Gas break through does not mean barrier break down. Immediately after breakthrough, gas relative permeability is too low for cross-barrier gas flow sufficient to match pressure drop in the left compartment. Gas pressure difference between compartments and the capillary pressure in the barrier continue to rise (Figures 6C, 7). This causes gas saturation in the barrier to increase. Gas-phase permeability rises in response to higher gas saturation. The higher phase permeability combined with higher pressure gradient increases cross-barrier gas flow. If gas pressure drops sufficiently in the producing compartment, cross-barrier gas flow will reach pseudo-steady flow and the barrier has broken down (Figure 7). During pseudo-steady flow cross-barrier gas pressure difference and water saturation within the barrier remain approximately constant as pressures deplete in both compartments.

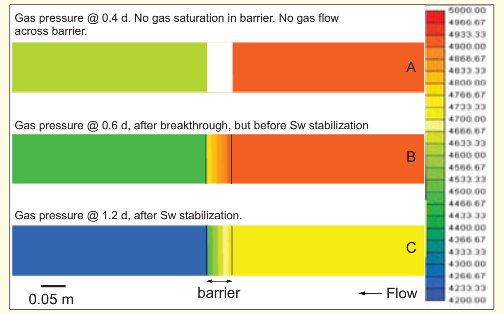


Figure 6. Gas pressure changes during fault rock breakthrough associated with production. (A, Top) Production from the left compartment lowers gas pressure while right compartment gas pressure remains at discovery pressure. Gas pressure not shown in the barrier, because gas does not occupy the barrier. (B, Middle) A steep gas pressure gradient develops in the barrier after gas invades the barrier and gas flows across the barrier. (C, Bottom) The pressure gradients across the barrier become relatively constant during pseudo-steady flow, but pressures drop in tandem as gas is produced from the left compartment. From Chapter 4.5, 2007 RDR Foundation annual report.

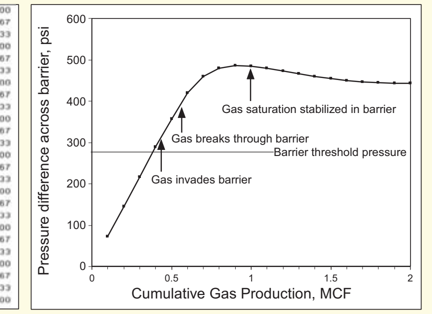


Figure 7. Cross-barrier pressure difference during modeled gas barrier breakdown shown at right. Prior to production, cross-barrier pressure difference is assumed zero. Production creates a gas pressure difference across the barrier. When pressure difference approaches the barrier threshold pressure (270 psi in this example), gas invades the barrier. Cross-barrier pressure difference increases until pseudo-steady flow develops and cross-barrier pressure difference becomes near constant. From Chapter 4.5, 2007 RDR Foundation annual report.

In Figure 7, pseudo-steady flow across the barrier is established within the first two days of production and less than 10% of the GIP is produced. Pressures in the isolated compartment track pressures in the drained compartment after pseudo-steady flow initiates and the two pressures decline in tandem (Figure 8).

The p/z slope in the producing compartment changes as the barrier breaks down (Figure 8). Gas for this model was modeled with z = 1, so Figure 8 is a p/z plot, and Figure 9 is the gas originally in place (GIP) interpreted from the slope of p/z vs. cumulative production. Prior to breakdown, the slope indicates a reservoir GIP volume of the producing compartment which is half that of the total model. After barrier breakdown, slope of the p/z plot approximates the GIP of the total model. Barrier breakdown leads to the p/z curve slope change expected from theory.

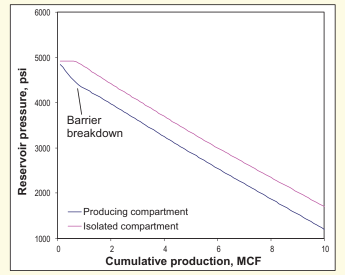


Figure 8. The p/z vs. cumulative production plot for barrier breakdown simulation. The gas z factor is modeled as 1.

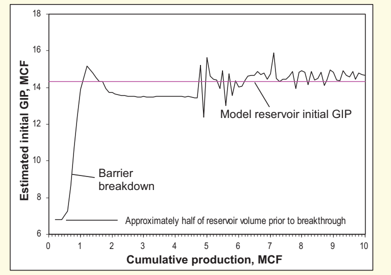


Figure 9. Gas in place (GIP) estimated from instantaneous p/z vs. cumulative production curve. Prior to barrier breakdown, GIP estimate from p/z slope is approximately equal to that of drained compartment. After breakdown, GIP estimated from slope approximately equals the GIP for the entire modeled reservoir. The gas z factor is modeled as 1.

Production-Induced Capillary Breakdown of Reservoir Barriers

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Barrier Breakdown Controls

A series of models were run with different barrier widths and permeabilities to test controls on barrier breakdown relative to barrier breakthrough. The modeled reservoir is a depletion gas reservoir with same reservoir properties in all cells except those of the barrier. Production rate, fluid and relative permeability properties were the same in all models. A J-function relationship between threshold pressure, relative permeability, and square root of permeability/porosity was used to assign saturation to the barrier.

The cross-barrier gas pressure when gas first invades the barrier is almost identical to the barrier threshold pressure plus pre-production reservoir capillary pressure (Figure 10). In these models, pre-production capillary pressure was assumed to be consistent with 100 m gas column. Taller gas column capillary pressures contribute more to the capillary pressure needed to invade the barrier. Rocks with low threshold pressure can be invaded by pre-production static capillary pressure alone and are baffles, not barriers, during production.

Cross-barrier pressures needed for pseudo-steady flow (barrier breakdown) depend on barrier threshold pressure, absolute permeability of the barrier, barrier thickness, and production rate. Gas invades barriers with higher permeability soon after production starts. At slow production rates, cross-barrier pressure at gas breakthrough and pseudo-steady flow are quite close to barrier threshold pressure. At high production rate, cross-barrier pressure different at pseudo-steady flow can be significantly higher than the barrier threshold pressure, assuming pseudo-steady flow is achieved.

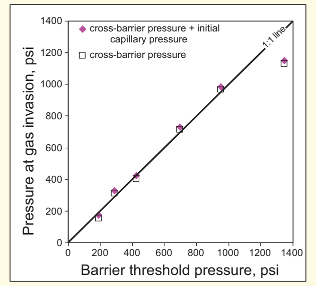

Figure 10. Barrier threshold pressure vs. pressures at which gas first invades the barrier. Cross-barrier gas pressure difference (black squares) and sum of cross-barrier gas pressure difference and initial capillary pressure (pink diamonds) are approximately the same as the barrier threshold pressure.

Barrier behavior can be monitored by well production index (PI) in these simple models. The PI is approximately the inverse of the slope of the p/z vs. cumulative production curve. The change from approximately flat PI to increasing PI marks barrier invasion and breakthrough (Figure 11). PI after pseudo-steady flow is re-established becomes relatively constant with production, but at approximately twice the pre-breakthrough value due to drainage of a larger reservoir volume.

Pseudo-steady flow is reestablished soon after invasion in models with high permeability barriers (Figure 11). Models with lower permeability barriers (higher threshold pressure) establish pseudo-steady flow late in production history. For the tightest barriers (750 m/mD flow resistance), pseudo-steady flow is not reestablished; the reservoir depletes first.

The transition from gas invasion to barrier breakdown is controlled by the barrier single-phase flow resistance and not just the threshold pressure. Single-phase flow resistance is the flow path length (barrier width) divided by barrier's absolute permeability. The higher the flow resistance, the longer it takes to reestablish pseudo-steady flow for a given production rate.

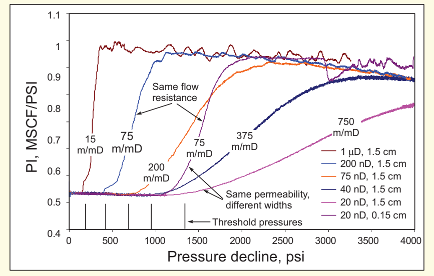

Figure 11. Production index vs. pressure decline. PI decreases during pseudo-steady flow due to variation in z with decreasing pressure. All models run at the same production rate, so barrier properties alone control the transition from gas invasion to pseudo-steady flow.

Implications for Modeling Barrier Breakdown

Focus on threshold pressure is probably appropriate if the issue is petroleum invasion of the barrier. For reservoir simulations, the interest is barrier breakdown, not barrier invasion. Models indicate that flow behavior of homogeneous, continuous barriers can be approximated by two barrier properties: barrier threshold pressure and flow resistance. Barrier threshold pressure is related to absolute permeability using J function scaling, and flow resistance is the barrier width divided by absolute permeability. This simplification allows barrier flow resistance to petroleum to be analytically modeled using Corey relationships, J-function scaling, and these two parameters.

This concept can be expanded to composite barriers (continuous barriers with multiple layers) because composite barriers can also be described by total flow resistance and a threshold pressure. Cumulative single-phase resistance is additive across the barrier. The barrier threshold pressure is that of the tightest continuous component of that barrier. In the example at right (Figure 12), the barrier has two layers, one layer 1.5 cm thick of 0.1 microDarcy and another 0.75 cm thick of 100 microDarcies. Essentially all flow resistance is in the 0.1 microDarcy bed. Gas-phase flow resistance is higher due to low relative permeability, but it tracks the single-phase flow resistance.

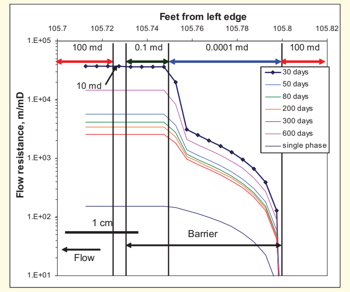

Figure 12. Flow resistance in a two-layer barrier. The low permeability (0.0001 mD) layer comprises most single phase and gas-phase flow resistance. Gas-phase flow resistance is much higher than single-phase flow resistance, but tracks the single phase resistance. High flow resistance at the down-flow edge of the barrier is caused by capillary end effects.

Model for Barrier Breakdown

Results of models of water-wet breakdown confirm and expand general concepts of barrier breakdown discussed elsewhere (Brown 2003; Manzocchi et al. 2010). Variations in pressure and water saturation are illustrated on Figure 13 (right).

Initial conditions are 100% Sw in the barrier and low Sw in the reservoir, water pressure equal everywhere, and gas pressure equal in the two compartments. Capillary pressure is in equilibrium with saturation (Figure 13A).

Production lowers petroleum pressure in the left compartment. Because water and petroleum pressures are linked by the capillary pressure-saturation relationship and saturation has not changed, the water pressure also decreases. Water flows from the barrier into the left compartment in response to the water pressure gradient. This increases capillary pressure at the right side of the barrier, because pressures in the right compartment have not changed. When capillary pressure exceeds the barrier threshold pressure, petroleum invades the right side of the barrier (Figure 13B). Water is displaced out the left side of the barrier. Gas invades the barrier as a displacement front that rapidly moves across the barrier. Once the displacement front reaches the left side of the barrier, petroleum can flow from the right to left compartment (Figure 13C).

Although petroleum flows across the barrier, petroleum (and water) pressure in the producing compartment initially drops faster than in the isolated compartment. Cross-barrier gas pressure difference increases and capillary pressure in the barrier increases. If pressure continues to drop, sufficient cross-barrier pressure difference develops for pseudo-steady flow (depletion reservoir) or constant PI (displacement). This is barrier breakdown (Figure 13D). The pressure difference between compartments (ΔP, Figure 13) remains approximately constant and greater than the threshold pressure of the barrier during pseudo-steady flow. Where the barrier has high flow resistance, no pressure difference is sufficient to support pseudo-steady flow, and the barrier does not completely break down.

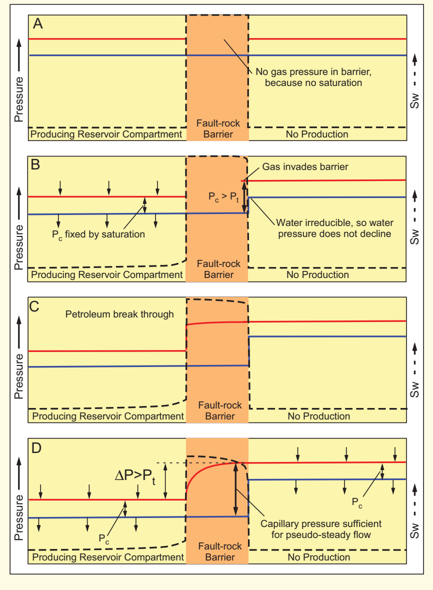

Figure 13. Barrier breakdown. (A). Initial conditions. (B) barrier invasion. (C) Barrier Break through. (D) Barrier breakdown.

Cross-Barrier Pressure and Capillary Pressure

Capillary pressure at the up-flow edge of the barrier will always be the sum of the pre-production capillary pressure and the cross-barrier petroleum difference minus the water pressure difference across the barrier.

Where the reservoir is close to irreducible water saturation (S_{wi}; Figure 14A), water in the isolated compartment will have low or no effective permeability. Prior to intrusion of petroleum into the barrier, petroleum and water pressure remain at discovery levels. Cross-barrier petroleum pressure difference is the pre-production pressure minus pressure in the producing compartment.

Where water saturation is significantly above S_{wi} (Figure 14B), both K_r^w and $k_r^p > 0$. Water can flow into the barrier when barrier water pressure is drawn down, and petroleum pressure decreases. As water flows from the isolated compartment into the barrier, petroleum will flow towards the barrier in response to decreasing water pressure. Prior to intrusion of petroleum into the barrier, the petroleum flow decreases S_w up-flow from the barrier in response to increased capillary pressure. Capillary pressure at the up-flow edge of the barrier remains the sum of the cross-barrier pressure difference and pre-production capillary pressure, but the petroleum-pressure difference is now less than the pre-production minus producing pressure.

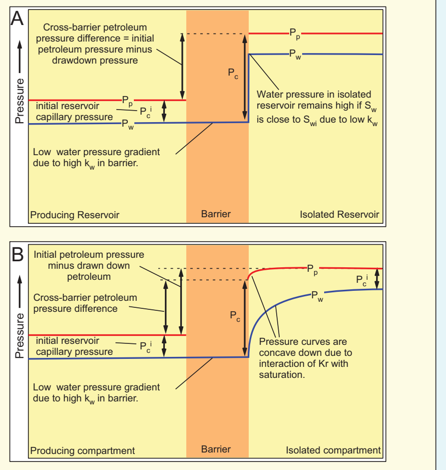

Figure 14. Capillary pressure and cross-barrier pressure prior to petroleum invasion of barrier. (A) Where the reservoir is near S_{wi}, pressure in the isolated reservoir remains at discovery pressure until the barrier breaks down and cross-barrier petroleum difference is the pre-production pressure minus drawn down pressure. (B) If the reservoir $S_w > S_{wi}$, water flows from the isolated compartment, reducing P_w in the isolated reservoir near the barrier. Capillary pressure at the sealing interface increases and petroleum pressure decreases. The cross-barrier petroleum pressure difference is less than initial pressure minus the pressure in the producing compartment.

Which Barriers Are Likely to Fail When?

Relationships between cross-barrier pressure difference, permeability, and threshold pressure can be used to predict the earliest possible time of barrier failure during depletion production. Threshold pressure is proportional to the permeability in rocks with matrix porosity (Figure 15). The lower the permeability, the higher the threshold pressure. As discussed previously, time when a barrier is invaded by petroleum can be predicted from the pre-production capillary pressure in the reservoir and the cross-barrier pressure difference that develops from production. Invasion is a necessary first step to barrier breakdown. If a barrier is not invaded by petroleum, it cannot fail by capillary breakdown. Thus, cross-barrier pressure difference can be used to predict the earliest possible failure time for barriers with known permeability.

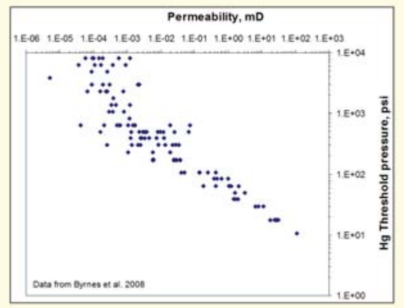

Figure 15. Hg capillary pressure as a function of permeability for tight gas sandstones. Essentially all other valid, Klinkenberg-corrected permeability data for matrix pore systems follow this trend. Data from Byrnes et al. (2008).

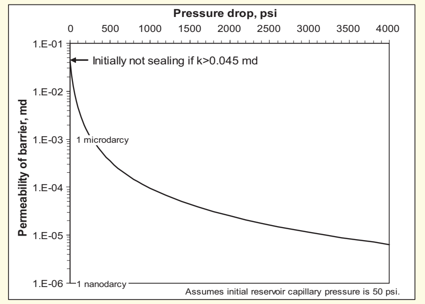

Figure 16. Permeability of barriers that fail in response to gas pressure decline in a depletion reservoir based on correlation between permeability and threshold pressure. Porosity is assumed to be 0.1. Initial capillary pressure was assumed to be 50 psi, so rocks with permeability greater than 0.045 mD were transmissive at start of production.

If the reservoir has water saturation close to irreducible and the barrier isolates a compartment, that compartment will maintain pre-discovery gas pressures until the barrier is invaded. The cross-barrier pressure difference is therefore the pressure drop due to production. Figure 16 is a plot of predicted permeability of a barrier as a function of pressure decline in a gas depletion reservoir with an initial reservoir capillary pressure of 50 psi. The curve is concave upwards. Because the curve flattens with pressure decline, barriers that are likely to fail will most likely fail early in production.

Permeabilities of barriers that fail late in production are so low that their flow resistances are likely to be high unless they are unusually thin. If their flow resistance is high, then they are not likely to reach pseudo-steady flow, especially where failure is late in the pressure decline. Figure 17 shows flow resistance as a function of barrier permeability and width. Assuming that 1 cm is the minimum barrier width likely for a fault of sufficient length to isolate a compartment, minimum flow resistance of a 10 nD barrier is 1000 m/mD. If the more likely width of 10 cm is assumed, flow resistance is 10,000 m/mD. It is unlikely that barriers with flow resistance this high will reach pseudo-steady flow unless pressure decline rates are exceptionally slow.

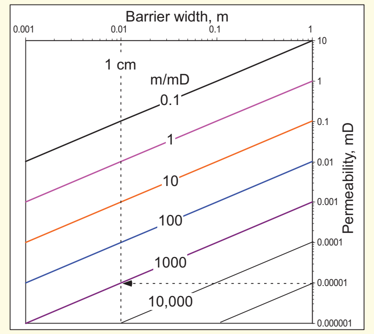

Figure 17. Single-phase flow resistance in m/mD as a function of barrier absolute permeability and width.

Discontinuous Fault Barriers

Low permeability water-wet barriers require substantial cross-barrier pressure difference before petroleum invades the barrier, much less establishes constant PI flow (Figure 16). Discontinuous fault barriers relatively far from injection or production wells are unlikely to develop high cross-fault pressures unless they are linked by stratal or other fault barriers. Discontinuous fault barriers are therefore less likely to have flow across the fault-rock itself during production. Flow will go around the tight fault rocks.

Subsurface flow is dominated by the path of least resistance. Where a circuitous pathway is present around a barrier, the flow develops a parallel flow pattern, and most flow goes around rather than through the low permeability barrier (Figure 18). This keeps cross-fault pressure low and fault rock is not invaded. Only if the barrier is continuous or near continuous is flow forced through the low permeability fault rock comprising the barrier (Figure 18B).

The question naturally arises as to how large of a discontinuity is needed to allow flow around rather than through the fault rock. This issue is addressed by a single-fluid phase model of flow through a discontinuous barrier (Figure 19). Under modeled conditions, a barrier with 5% or more of its area open to around-barrier flow will have essentially no flow through the low permeability fault rock and all flow around the fault rock. Two-phase flow lowers phase permeability through fault rocks even more than single-phase flow, so the fraction of open area around the barrier must be even lower to force flow through the barrier.

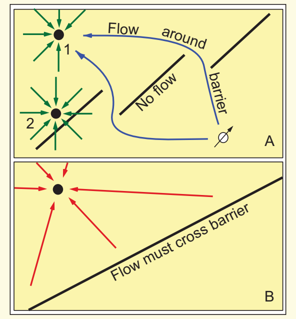

Figure 18. Conceptual flow model near fault barriers. (A) Discontinuous fault barriers (black line). Fluids from injector (lower right) or water drive can flow around faults towards producers (upper left). Drawdown around wells close to a fault barrier (well 2) may cause flow across the fault. (B) Where faults (black) are continuous and isolate a compartment, there is a potential for large pressure differences across the fault. This could force flow across the fault rock.

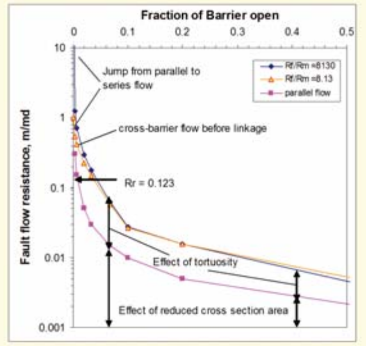

Figure 19. Single-phase flow of water through a barrier zone with holes in the barrier. As the fractional area of the holes through the barrier zone decreases, flow resistance increases due to increased tortuosity and reduced cross-sectional flow area. However, the fraction of open barrier must be reduced to less than 5% of the barrier area before significant flow is forced through the barrier. Because this is a single-phase model, there is no capillary pressure to overcome; it is just the difference in flow resistance along different pathways that prevents significant cross-barrier flow. If capillary effects are considered, petroleum would completely bypass tighter parts of the barrier at even lower fraction of the barrier that is open.

Other Causes of p/z Inflections

It has become recognized that p/z vs. cumulative production slope changes can be caused by lack of pressure equilibration in tight reservoirs (e.g., Zijlstra et al., 2007). An apparent change in p/z slope is not uniquely indicative of barrier breakdown, much less barrier breakdown by capillary failure.

A series of models were run to determine if there are subtle changes in the p/z plots that might indicate whether capillary barrier breakdown is responsible for the slope change. Five models were considered: a homogeneous reservoir, a homogeneous reservoir with a barrier, a reservoir with tight facies away from the well, and two baffle models with different degree of baffling (fraction of baffle open to flow). Two series of models were run, those with highly permeable main reservoir (1000 mD) and those with a tight main reservoir (0.01 mD). Barriers and tight facies had significantly lower permeability for each of the model series.

In general, the permeable models show differences only early in production (Figure 20). Facies changes that cause transient effect result in concave downwards, increasing PI curve early in the production history whereas the barrier model shows a sigmoid behavior during barrier breakdown before PI stabilizes after pseudo-steady flow is established. Baffle models were identical to homogeneous models due to high permeability through holes in the baffle. After barrier breakdown and facies equilibration, GIP predicted from p/z matches model GIP in all models.

Results are more complex in the tight reservoir because transient effects are present in all models (Figure 21). Permeability was sufficiently low in all models that the well does not communicate with the edge of the reservoir in any of the models. Barrier breakdown models have a sigmoidal PI curve during barrier breakdown, whereas other models show concave downward behavior throughout production. Homogeneous model shows the least concavity, the facies model the most, and the barrier models lie between. None of the models have p/z slopes that closely approximate actual GIP.

Based on these models, the main criterion by which capillary barrier failure might be identified in reservoir p/z plots is the presence of two inflections. The first inflection (concave upwards) causes the increasing GIP expected from barrier breakdown. The second inflection (concave downwards) marks initiation of significant flow across the barrier. Unfortunately, these features are close together in time and have sufficiently small magnitude that they would probably not be identified from actual field data, especially in the presence of other reservor heterogeneities (Figure 22).

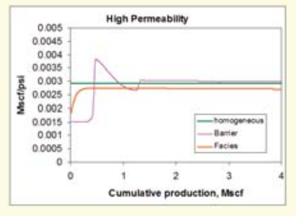

Figure 20. P/z slope (as Mscf/psi) against cumulative production for the high permeability models. The baffle model was identical to the homogeneous model, so results are not plotted. Results are shown only for the early part of production so that slope changes near barrier breakthrough (at 0.43 Mscf) are more apparent.

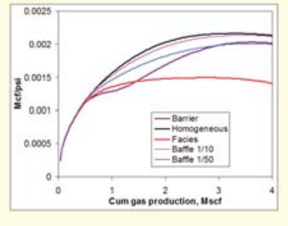

Figure 21. P/z slope (as Mscf/psi) against cumulative production for the low permeability models. Only early results are shown. All trends except the barrier model are concave downwards, The barrier model has two inflections, one concave up and one concave down. .

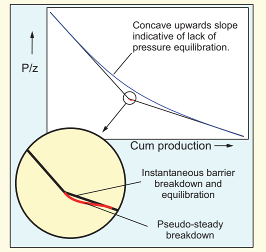

Figure 22. Schematic p/z vs. cumulative production showing expected features of models showing lack of pressure equilibration, instantaneous barrier breakdown (expected for mechanical failure) and pseudo-steady breakdown (expected for capillary failure). Inflections on capillary breakdown model are quite subtle.

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Conclusions

Modeling studies validate the following barrier behaviors:

- Oil-wet and intermediate-wetted barriers reduce flow only by their phase flow resistance (width divided by phase permeability). Barriers do not breakdown or significantly affect displacement fronts moving across the barrier. Such barriers can be modeled with standard reservoir simulators without explicit gridding.
- Water-wet barriers increase total flow resistance of the reservoir, and the flow resistance varies during production due to changing petroleum saturation in the barrier. Such behavior is difficult to model without fine-scale explicit representation of the barrier.

The remaining conclusions concern flow through water-wet barriers.

- Water-wet barrier breakdown involves three steps: invasion (petroleum first enters the barrier), breakthrough (petroleum first crosses the barrier and potentially contributes to production), and true barrier breakdown (cross-barrier petroleum pressure difference remains nearly constant with production).
- Water-wet barriers can be selectively permeable to either petroleum or water. Barriers are water transmissive where flow resistance is low, threshold pressure is high, and production rates are slow. This behavior is probably rare. The barrier is petroleum transmissive where flow resistance is low and barrier threshold pressure is low. Gas flow across the barrier supports production in depletion reservoirs. In displacement reservoirs, fronts form in the isolated compartment and sweep across the barrier into the producing compartment. When barrier flow resistance is high, flow across the barrier is likely to be negligible even where petroleum breaks through the barrier.
- Both theory and modeling indicate that barrier invasion occurs where the sum of pre-production capillary pressure plus cross-barrier petroleum pressure difference equals the barrier threshold pressure. Barrier breakdown requires higher capillary pressure than barrier invasion, but the invasion criterion can be used to establish minimum conditions at which barriers might possibly break down. Barriers are most likely to break down early in pressure decline. Barriers that fail after significant pressure drawdown are likely to have a high flow resistance that delays or prevents pseudo-steady flow.
- Barriers that do not isolate reservoir compartments are less likely to fail because flow around the barriers reduces cross-barrier pressure difference. A surprisingly small hole through a barrier will allow sufficient flow to prevent significant flow through the barrier even if two-phase properties are ignored.

Thus, the major factors that should be considered for evaluating flow behavior of reservoir barriers are (1) connectivity or extent of the barrier, (2) flow resistance of the barrier, (3) threshold pressure of the barrier and (4) expected pressure behavior of the reservoir.

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