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Reservoir Conformance: Tracking Gas/Water Contacts via Capillary Shockwave Fronts

Fred L. Goldsberry, WAVEX, Inc., Jeffrey T. Holland, Murphy Exploration & Production Co., William E. Gross, Chieftain International (U.S.) Inc., Rudy C. Wildenstein, Bellwether Exploration Co., and David L. Salzman, El Paso Energy Co.

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Abstract

Much of the technology developed in the oil industry today is the result of cooperative engineering research efforts between operating companies with a problem and a technology developer with a potential solution. Often all parties discover the unexpected in the course of making physical measurements. In this case, the data captured showed the advancement in time of the limit singularity associated with a gas/water contact. The purpose of this paper is to share knowledge that may be useful to other operators, particularly those with permanent pressure gauge completions in oil and gas wells, or those operators who may use precision pressure gauges to monitor the flowing tubing pressure of a gas well.

The authors' companies have engaged in joint reservoir evaluation efforts to resolve rapidly declining production behavior in gas wells. The efforts were based upon pressure transient well evaluations utilizing the capillary shock front theory to map the gas cap at the time of the test. Two examples are presented that illustrate water contact boundary progression just prior to the onset of water production in each of the wells. The joint efforts have resulted in a better understanding of how to use operational shut-ins to monitor gas/water contacts from the inception of flow to the point of water encroachment. The goals of this effort are to see the end coming and perhaps delay the end in order to maximize well production. The secondary goal is to predict the end so as to avoid unnecessary post mortem efforts to repair a well that has watered-out.

The first case is a test of a deep well in Louisiana that was being evaluated for rapidly declining pressure and flow rate. The second well was offshore in the Gulf of Mexico that was being evaluated for geology and remaining reserves. The movement of the limit contacts over time is illustrated with a sequential limit mapping presentation. A second test is presented to show an overlay of two tests performed two weeks apart, just before the well watered out.

Introduction

Since the introduction of the first mechanical pressure gauge, pressure transient data has shown segmentation when plotted on a semi-log plot of pressure vs. $\log_{10} t$. This led to early observations of specific abrupt changes in slope that were best described as mirror image wells or offset wells that appear to "turn on" when the boundary is contacted by the cone of influence. Often these singularity slope changes were noted as abrupt or "turning on a single data point." This was originally ascribed to friction in mechanical gauges. The advent of accurate electronic pressure gauges eliminated the argument for gauge friction and led to an investigation for other causes.

There were other problems noted by Professor Park Jones in the mid-1960's relating to the correlation of distance to the first boundary as observed and theoretically calculated. Where the interference or fault boundary was known with reasonable certainty through fault cuts in the well or interference patterns, the correct calculated distance was computed using the radius of investigation equation. Jones(6) published several papers that noted that the theoretical superposition derived distance solution for the doubling of semi-log slope at the first limit differed substantially from the observed distance. The first monograph by Russell and Matthews(7) contains both relationships but cites the radius of investigation more often in the text. About that time, Jones was pursuing volumetric calculations for a possible solution to the problem. These efforts ceased upon his death in 1967. Don Clark and Bill Hurst(3,4, and 5) made the principal author of this paper aware of this area of uncertainty and Jones' work in the early 1980's. About the same time as Jones, Rowan(8) was pursuing an investigation of surface wave mechanics as a possible explanation for routine observations in test data that were not explained by potential flow theory. Capillary shockwave theory is an extension of those earlier lines of reasoning.

Interference test data acquired in the late 1980's revealed that the segmented pattern is propagated from a producing well during the transient phase of a well test. This result is at variance with the traditional diffusion model, which mathematically cannot produce discontinuities in the solution. This led to work on the basic mechanics of capillary flow initiation, which produced the shockwave front model[1,2] used for this analysis. The shockwave is formed as flow is initiated. It is the mechanism that breaks down the initiating capillary pressure at succeeding pore throats allowing the depletion region around the well bore to expand to the reservoir limits.

A model for transient flow was developed that included this shockwave front and the capillary memory induced by the initiating capillary pressure. This is another way of describing the overcoming of the initiating shear stress. Fluid inertia was also included in the model. The result was a radial capillary model based upon fluid memory to the direction of flow. An energy solution was developed for the individual segments that allow limits to be detected and evaluated individually. From that came a limit by limit energy mapping technique that has been routinely applied to reservoirs for the past six years.

A consistent observation made over the years is that the pattern of slope shifts for each individual well is repeatable. In gas reservoirs we often see the gas/water contact as a discrete limit. In some cases, it has been possible to determine which limit is the water contact through detailed analysis of the irregularities in the semi-log slope shift. The principal use of the technology is to produce an image of the reservoir, which can be overlaid on the 3D seismic image to independently confirm the geologic geometry of a reservoir. Often when a well is behaving differently than the seismic image would suggest, it is possible to investigate the reservoir geometry independently in order to diagnose the possible problem. The pressure transient views the reservoir from the inside out, from the well to each of the boundaries. Many times, depositional problems such as braided channels can be described by pressure responses that are too small to be defined seismically.

In the year 2000, two tests were conducted and evaluated to assess strange behavior in producing wells. In each case, pressure transients two to three weeks apart saw a change in the slope shift pattern. Following these events one well began to produce water and the other watered out completely. The purpose of this paper is to share a practical method for monitoring the movement of gas/water contacts using spaced pressure transient measurements.

Case 1 – Deep Louisiana Test

The subject was a newly completed well that was showing signs of possible accreting skin damage or restricted reservoir size. The test was designed to take advantage of an operational shut-in. This would allow the well to be stabilized, then to be flowed for two-weeks to assess the reservoir for permeability, skin, and limits. Following the drawdown, a four-day buildup was planned to confirm limit contact times.

The results initially appeared to be inconsistent. It is not unusual for a buildup to suffer derivative suppression when compared with the drawdown. This is the result of a cone of influence continuing to grow behind the original shock front while the pressure in the region immediately around the well is building. Horner analysis overcomes this problem for very short duration DST's. The energy map developed from the drawdown is more likely to be the correctly scaled image. The ΔP plots for the drawdown and buildup will overlay about one third of the time.

It was clear that a limit had occurred at 0.45 hours and that two more had occurred during a data collection gap between 9 and 21 hours. The before and after slopes projected to a point at 16 hours. This would have been a single limit of 110° of curvature or almost a right angle. The system became linear after this point. The data is shown in Figure 1 with the limits marked by triangles. The resulting energy map is shown in Figure 2. The presence of a limit often looks like a small choke change followed by a doubling of the semi log derivative when no choke change has actually occurred. The buildup was analyzed independently, then compared to the drawdown test.

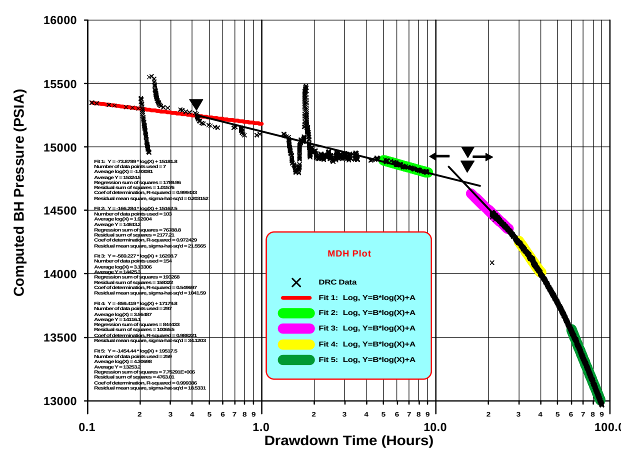

Figure 1. Drawdown Data with Limits Marked

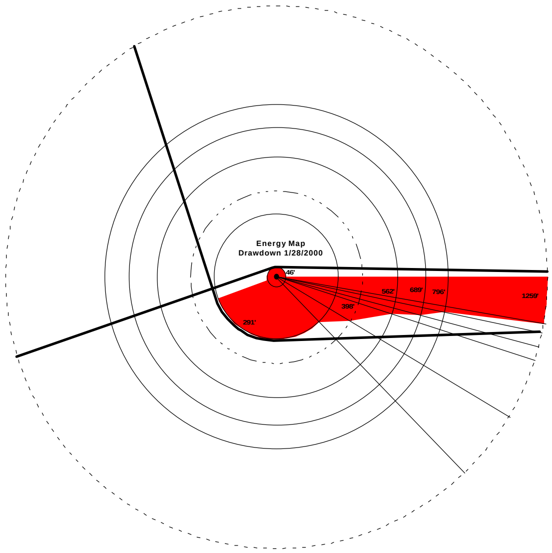

Figure 2. Energy Map Derived from Drawdown

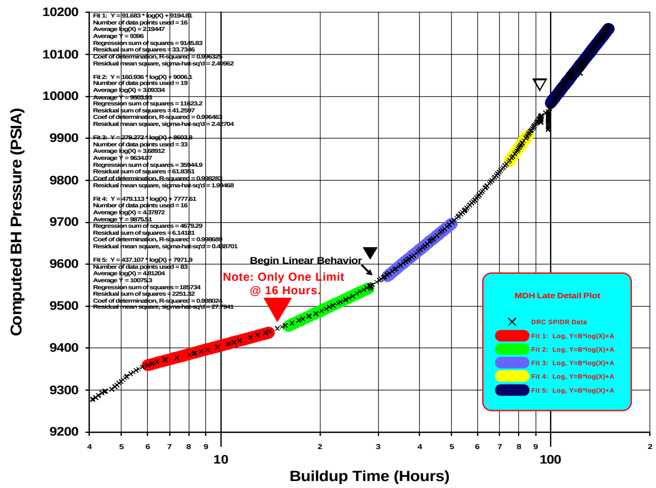

Figure 4. Buildup MDH Plot Detail after 10 Hours

The buildup of Figure 3 indicated a larger permeability that further suggested the reservoir was growing at the end of the test. The buildup repeated the limit at 0.42 hours and also showed a second clear limit contact at 0.9 hours. There was a pressure anomaly shown in the buildup that would be consistent with a small non-sealing fault. The derivative slope recovers its original value before 10 hours indicating the non-sealing nature of the resistance to flow anomaly.

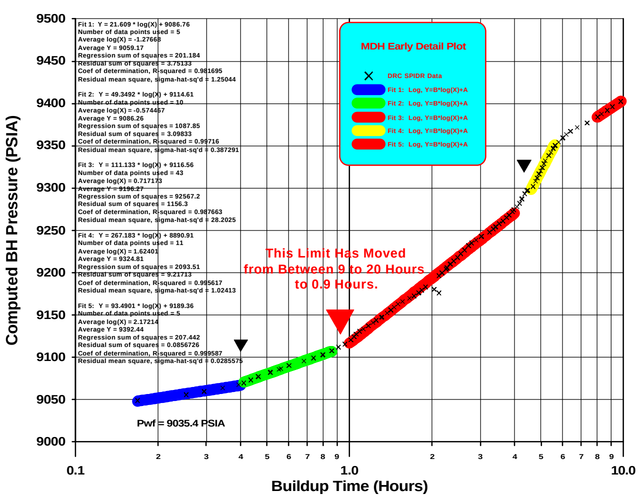

Figure 3. Early Buildup MDH Plot Detail

The data continue on Figure 4, which indicated a clear limit contact at 16 hours. But this is a straight limit not a corner. This data was mapped without correcting for the derivative slope suppression as a quick look at what was occurring. This is presented below in Figure 5. Both tests map as parallel limit systems but the maps show different near well limit configurations. These findings were communicated to the operators and partners.

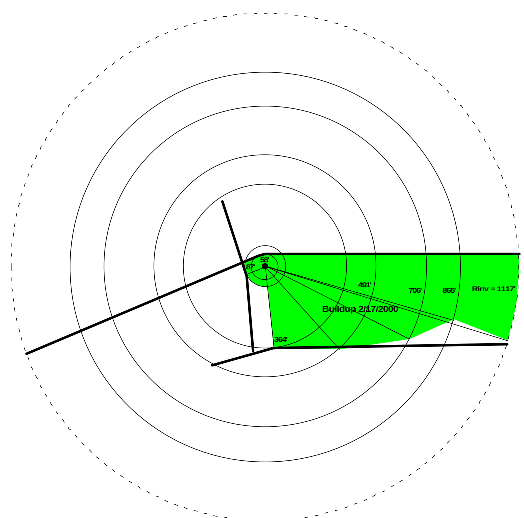

Figure 5. Energy Image Based upon Buildup

The response was a production plot from the operator, which showed that the well had just begun to increase water production immediately prior to the buildup. The water rate then increased after the well was placed back on production. Figure 6 shows the overlay of the two maps. From this it is clear that one of the limits had moved relative to all of the others. If the buildup map is shrunk to the same dimensions of the drawdown map, the change would be more pronounced.

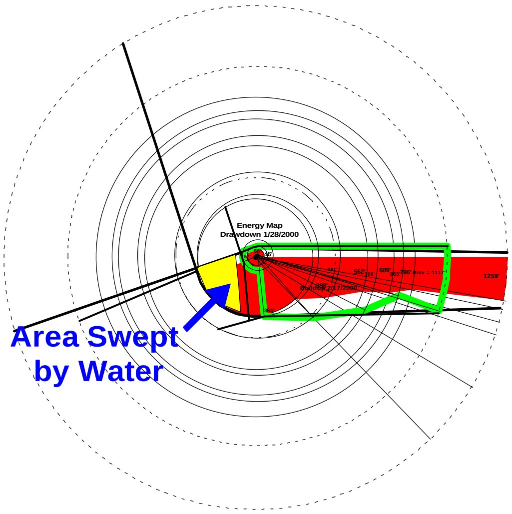

Figure 6. Overlay of Energy Maps

In spite of the discontinuous nature of the drawdown data, it is clear that a limit moved from somewhere in the 9 to 21 hour range to the 0.9-hour range. Had we acquired initial drawdown data it is reasonable to assume that this contact may have moved a considerable distance over the prior 4 months. Our timing involved a significant stroke of luck to be in the right place at the right time to see this dramatic change. In larger and broader reservoirs, we would expect to observe movement over longer periods of time. In a water drive reservoir with an expected life of say 5 years, one would expect annual or semi annual buildups to show relative movement of a gas/water contact. The subject well continues to produce water. It apparently is a very long parallel limits system as it rebuilds toward original pressure repeatedly only to follow the same repetitive transient when on production. Figure 7 represents an overview of the entire test sequence. It is a picture that summarizes the events better than words.

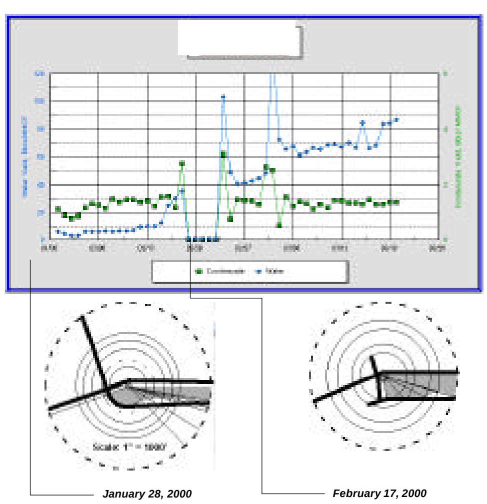

Figure 7. Production Summary in Pictures

Case 2 - Comparison of Two Succeeding Buildups

The second example required no mapping exercise. We knew the result before the report was written. The second test was offshore in the Gulf of Mexico. This test had a different objective in that the mapping exercise was to confirm the reservoir geology of a mature field to assess whether any gas was being left behind. Five wells were tested producing a high degree of conformance to the map. The last well of the series presented a surprise. A buildup test was conducted for reservoir limits, then the well-placed on production for three weeks. Just before the pressure gauge was to be removed from the tree, a final shut-in of the well occurred for four days. The gauge was returned with a note that it had watered out during shut-in and was now dead. Figure 8. Shows the ΔP Vs Log_{10} t plot for the first buildup with the second ΔP Vs Log_{10} t curve just prior to watering out.

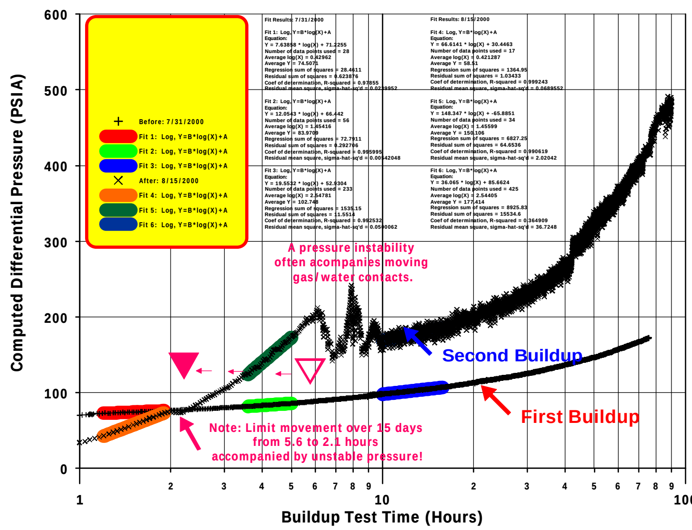

Figure 8. Direct Overlay of Sequential Buildup Tests

The purpose served by this plot is to demonstrate that a process as simple as overlaying successive data sets from a series of buildups or drawdowns can produce an early warning that something is moving toward the well.

Conclusion

The options here are quite broad. In dealing with water production, we often have different situations that require different operational responses. Water coning involves restricting flow to optimize water disposal costs or perhaps to minimize water production. Many companies operate with a view to increase flowrate in gas reservoirs in order to outrun water. In some cases distortion of an approaching gas/water contact may mean reducing flowrate to prevent fingering as an agent of premature completion failure.

As artificial intelligence progresses in downhole applications, it will be possible to expect a smart well completion to measure its reservoir limits during each operational shut-in and respond appropriately by restricting flow or by opening the choke automatically. It may be programmed to provide an alarm and diagnostic to the production engineer.

A final image is presented in Figure 8. This is an image of a shock front passing through a static observation well. Pressure depletion begins in a reservoir only when fluid begins to flow from a pore. For this to happen, the initial stress at the pore throat must be overcome to initiate flow from the pore. The breakdown of this small initial fluid shear stress in successive pore throats is a slow process. It represents a moving barrier to depletion or better said, ***"a moving reservoir boundary."***

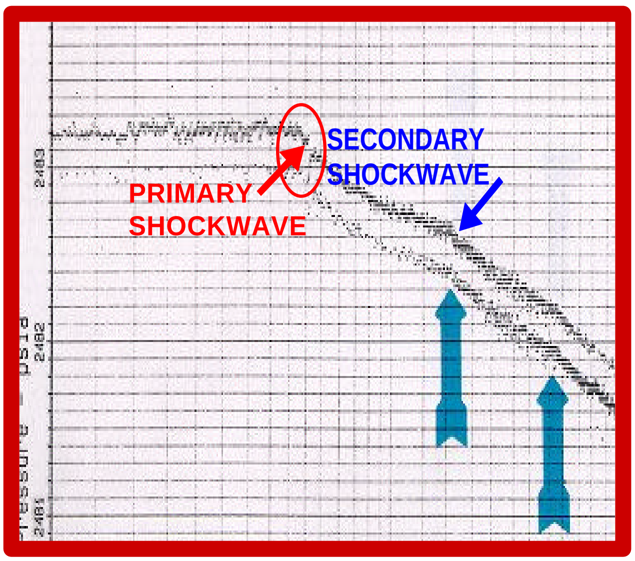

Figure 9. Primary Capillary Pressure Shockwave *Located at $R_{inv} = 2(ht)^{1/2}$ (Reference 1)*

These pressures produce an induced radial anisotropy that leads to the necessary formation of secondary capillary shockwave fronts as the moving boundary encounters the actual sealing boundaries or water boundaries of the reservoir. It is the formation of these secondary depletion regions around the well bore that provides the basis for discrete limit detection and dimensioning. ***This small capillary pressure step is the physical event that exists at the radius of investigation.*** By using this diffusion wave, it is possible to track gas/water contacts using successive shut-in and flow periods.

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