RESERVOIR IMAGING

Surface measurement aids imaging

Surface pressures are used to accurately and independently image a complex reservoir.

AUTHORS

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A wave mechanic's approach to pressure transient analysis, based on a radial element capillary wave model, has been employed to produce simple 2-D images of reservoir boundaries and thus reservoir shape. This methodology could provide a method for independently corroborating seismically derived images of a reservoir at relatively low cost. In the gas well case history presented here, a "blind" test, using pressure data collected at the surface, has resulted in a reservoir image that closely matches the seismic interpretation.

Pressure transient energy imaging

The fundamental difference in this approach is a more complex model of the reservoir than that which the diffusivity model of conventional pressure transient analysis is based. Imagining the reservoir as a complex network of capillary stream tubes allows us to process discontinuities in pressure data more directly for the information contained in them, rather than smoothing them out to fit a simpler model.

Starting in the 1930s, when pressure transient technology was introduced by William Hurst, singular behavior or abrupt changes in pressure declines on semi-log plots were noted in data and directly related to reservoir boundaries (Hurst, 1968; Jones, 1957; Jones, 1961; Matthews, et al., 1967). The radius of investigation, based upon an effective drainage volume was recognized as an effective measure of distance to the permeability limit. Interference testing performed in the mid- to late-'80s with precision pressure gauges detected the pressure step associated with the boundary between the growing cone of influence and the remainder of the reservoir. Subsequent to the development of the physics of capillary-entry-pressure diffusion shockwave fronts, radial capillary models were developed that explained the singular behavior associated with the shockwave striking a boundary.

Traditional theory assumes capillary pressure is small and can be ignored, allowing us to use the diffusion equation with fixed boundaries. The capillary wave model recognizes the effects of capillary pressure and derives the velocity of a wave front. This velocity of the shockwave front, when integrated over time, produces the radius of investigation equation. The wave front acts as a boundary to the depletion volume of the cone of influence. When the pressure history is derived by basic integration of the energy equation, the result is the familiar relationship of the mid-time slope. The capillary model is fully developed in the references (Goldsberry, 1998, Goldsberry, 2000).

Under the capillary wave model, when flow is initiated or when a major rate change is imposed, capillary shockwave fronts propagate from the well bore. These fronts are composed of many radial capillary pathways that grow coincident with the traditional radius of investigation. The small initiating capillary breakdown pressure that exists at each pore throat produces this physical phenomenon. These pressure steps have been measured in core analysis labs, but never incorporated into transient models. Each capillary is analogous to a ray of light: a ray goes out and strikes a boundary and is reflected, and amplitude and frequency are factors of the boundary and its angle. When these capillary ray clusters strike a reservoir boundary, they act in unison to provide specific information about that boundary.

Recognition of a physical wave allows the use of the transient test as a means for "sideways logging" of the formation boundaries. The shockwave represents an expanding container that encompasses a growing volume of pressure depletion around the well bore as the well begins to flow. Initially, as the shockwave expands, the response is as though the well is in an infinitely large reservoir. When the cone of influence reaches a sealing boundary, the section of capillaries that strikes the limit stops growing, resulting in a reduction of flow to the well bore at the original pressure decay rate. A short fall in flow is made up by an abrupt increase in the rate of drawdown at the well bore. This compensates for the loss of growth of the cone of influence at the boundary.

All flow demands on the formation are constrained by the static capillary pressure differential required to initiate flow. Once a capillary pathway is established, it remains established until acted upon by a sufficiently large pressure difference to open the non-flowing pore throats that make up the wall of the capillary. These capillaries will eventually break down due to the asymmetry caused as boundaries are encountered. The capillaries as formed can withstand a sufficient pressure imbalance to sustain radial flow away from the well. Capillary memory sustains the flow paths to the well and serves to produce the

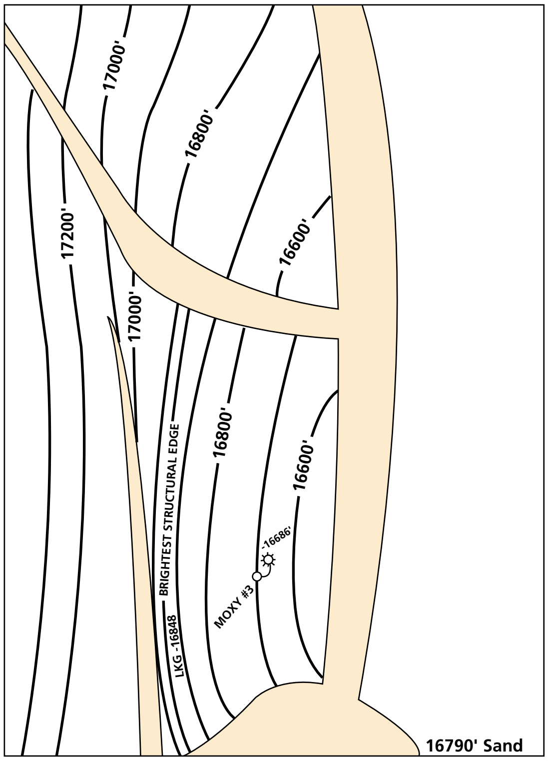


Figure 1. In this case history, the operator mapped the reservoir as a complex fault closure associated with a large bright spot.

abrupt increase in the semi-log derivative when a boundary change is encountered by the shockwave front.

The rate of increase in slope provides information to the radial capillary model that generates a "shape at point of contact" for the limit. In other words, each limit is defined both by distance from well and by angle of deviation from a straight line. In a reservoir with four sides, this means the analyst would detect four slope changes at four times, each related by distance from the well and shape.

However, direction is and will remain an unknown. But it is possible to develop a relative disposition of limits by using an energy model of the cone of influence with its secondary cones to account for the total energy of pressure decay. The relative disposition of the limits to each other is a function of their shape and some parameters from the radial capillary element model called "angles of splay." The limits can be arranged by holding the first limit at a fixed position, say, conventional map north, and then placing the other limits around the well so as to optimize fit to the computed energy growth pattern. In a 4-limit model, relative arrangements can be 1-2-3-4, 1-3-2-4, 1-2-4-3, and 2-1-4-3, etc. Other permutations are the mirror images of these.

Case history

In the case history presented here, the operator mapped the reservoir as a complex fault closure associated with a large bright spot (Figure 1). An independent test of the seismic-based map of the reservoir was carried out using our energy mapping methodology. Flowing tubing pressure and flow rate were measured with a high precision dual quartz gauge surface recorder while producing the well using minimal choke changes to sustain rate. During the test the well was producing at a constant rate of 11 MMcfd of 0.62 gravity gas and 363 b/d of 42°API condensate, with a bottomhole pressure in excess of 14,800 psia. The flow rate and flowing tubing pressure data were recorded and converted to downhole conditions by an independent contractor. The data were then analyzed along with a baseline petrophysical analysis derived from openhole electric logs. The reservoir transient pressure analysis was performed "blind" to the existing geologic interpretation, for a wholly independent comparison.

An image was developed from five indicated boundary contacts (or changes), calculating in-place volume integrals as a guide to reservoir shape. Computed angle-of-intersection calculations showed that although four boundaries were contacted, the angle factors indicated a rectangular arrangement with the system growing beyond one projected corner. Later, a fifth boundary change appeared that was consistent with a gas/water contact. Finally, the need for a major rate change ended the test.

The heavy green line in Figure 2 shows the best energy fit arrangement for the boundaries and their projections. The leak was associated with the fourth boundary. This map was developed solely from surface pressure and flow data measurements combined with information on fluid composition and the operator's analysis of pay properties.

An overlay of the geologic map derived from seismic with an inverted overlay of the energy map reveals that although the exact location of the gap on side four is not seen, the four limit shapes, a gap in one boundary and a gas/water contact beyond the gap were all recognized (Figure 3).

The gas in-place reserve calculations from the test indicated 26 BCF at the time of the fourth boundary and 34 BCF at the time of the gas/water contact. Beyond the gas water contact, the test is measuring the energy contribution of both gas and water. These values were consistent with the operator's integrated map volumes and a third-party reservoir engineer's in-place reserves for this region of the reservoir. The mapped reservoir extended beyond the radius of investigation of the test.

Pressure measurement

It should be noted that variations in the accuracy of porosity, fluid mobility, pay count, water saturation, compressibility and the downhole pressure conversion will all contribute to the energy map's deviation from the true reservoir shape. The

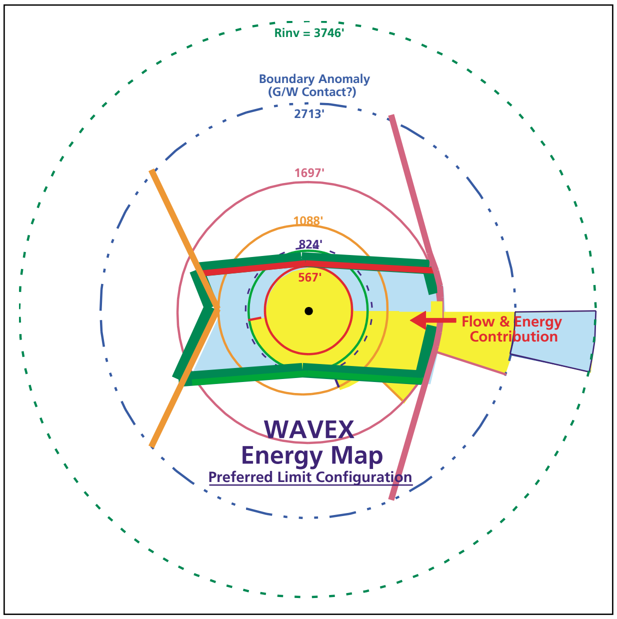
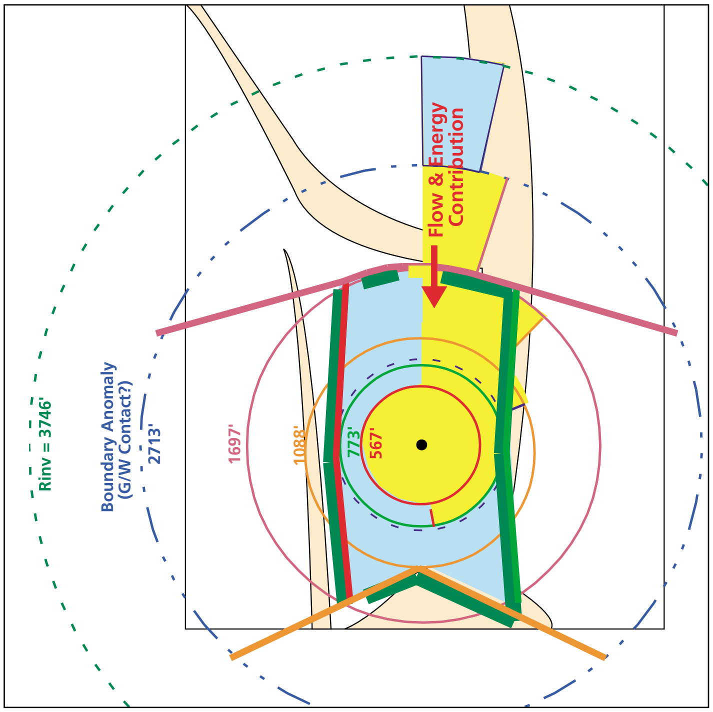


Figure 2. The heavy green line shows the best energy fit arrangement for the boundaries and their projections.



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accuracy of the map is directly related to the accuracy of the bottomhole pressure data. The gauge has to be stable enough to conduct a drawdown test of 1,200 hours duration. This degree of gauge stability was necessary to compute the rate of energy growth that pointed out the opening to and characteristics of a gas/water contact. Only then was it possible to map the reservoir and assess its volume. The key to transient analysis of this type is the ability to see the relative pressure changes with a gauge that is accurate and stable over time.

The map is also dependent upon an accurate pay count and petrophysical analysis. The reservoir engineers must provide "on the mark" petrophysical information from electric logs for this process to succeed.

Potential for applications

The potential applications of this methodology are significant. Essentially, it provides a means for obtaining an independent assessment of reservoir shape and size from simple surface measurements, without the need for wireline pressure measurements. Wireline-free testing has many advantages: tools and equipment are not subject to loss or damage; data collection is simple; pressure and flow rate are measured feet apart rather than miles apart; and the cost of wireline operations is eliminated. Since transient analysis is based largely upon relative pressure rather than absolute pressure, the inaccuracies introduced by measuring from the surface and computing the bottom hole values generally relate to compressibility computations and small differences in well skin calculations. The conversion technology has evolved from essentially dry gas wells to gas wells producing up to 300 barrels per million cubic feet of combined condensate and water. Some single-phase oil wells can be modeled under specific circumstances.

In locations such as offshore jackets and caissons, the opportunity to avoid costs associated with wireline equipment and jackup boat charges strongly favors a surface gauge approach. The key to surface measurements is transducer quality and the technology level of the algorithm used to convert surface data to bottomhole.

Good well testing also involves a fixed choke or a close approximation of constant rate flow. Downhole measurements often are made from locations well above the completion. If there is a fluctuating fluid level or change in flow regime below the downhole gauge, there is little or no advantage for the downhole measurement. If the well is hot, the reservoir engineer often is asked to analyze data that is an artifact of a slow thermal gauge failure rather than an accurate reflection of the well. Often, the only practical way to test a well that is hotter than 410°F is from the surface.

We should recognize also that long-range testing is practical only in the drawdown mode. Boundary information cannot be gleaned beyond the radius of investigation, and a large radius of investigation takes time. Surface measurements during the initial production drawdown allow the operator to do more testing for less money. The total cost of producing an energy map is less than the cost of a good production log.

In this case history, and in others presented earlier (Goldsberry, 2000, 2001), the operators developed confidence in the property by tackling the confirmation problem from two independent geophysical processes and arriving at the same answer. The reservoir information obtained in this manner is either generally correct or there are massive and compensating errors in both independent imaging techniques. E&P

Acknowledgement

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