CHAPTER 8

The Origin of Jonah Field, Northern Green River Basin, Wyoming

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ABSTRACT

Prolific production at Jonah field and many other fields in the Green River basin is dependent on the presence of overpressure. In the Gulf Coast and other areas, plots of shale resistivity and shale sonic transit time versus depth have been used to identify overpressured zones. The same technique has been proposed to map overpressure compartments and their boundaries in the Rocky Mountain region using well logs or, alternatively, interval velocities determined from seismic data. At Jonah field, the top of the overpressure (determined by continuous gas flaring during drilling) correlates within a few hundred feet to a drop in shale resistivity and increase in shale transit time. However, studies of nearby wildcat wells and detailed cross sections through both overpressured and normally pressured wells show that the log anomalies extend significantly beyond the overpressured area. Velocity and resistivity changes in the area around Jonah tend to follow a stratigraphic boundary near the base of the Tertiary Fort Union Formation instead of tracking the top of the overpressured volume.

Early studies of Jonah field considered the hydrocarbons in the field to be derived from vertical migration of gas from regional overpressure conditions 2000–3000 ft (610–915 m) deeper. The upward migration was presumed to be controlled by the presence of extensive microfractures that form a leakage chimney between large sealing faults. This study suggests that the log anomaly both within and surrounding Jonah provides an alternative interpretation. Until the middle Tertiary, overpressure conditions extended up to the base of the Fort Union and resulted in undercompaction of Cretaceous shales, as reflected by resistivity and velocity anomalies. Late Tertiary relative uplift initiated slow leakage of the overpressure conditions wherever the system was not tightly sealed. As a result, the top of the overpressure has been dropping with time over most of the northern Green River basin. The sonic and resistivity anomalies are irreversible, and the logs reveal the signature of the former overpressured and undercompacted conditions.

Based on this new model, Jonah field represents a high remnant of the former regional top of overpressure instead of a leakage chimney from a deeper overpressured generation cell. If this model is correct, exploration methods should focus on the seal conditions that prevent leakage instead of fracture models that promote leakage.

INTRODUCTION

Basin-centered Gas Accumulations and the Sweet-spot Concept

Basin-centered gas accumulations have been a major focus of exploration efforts in the Rocky Mountain region since the mid-1980s. The concept of a basin-centered accumulation dates back to the work in the Elmworth area of Alberta, where Masters (1979, 1984) described what was termed a “deep basin gas field” in the western Canada sedimentary basin. Subsequent work in other Rocky Mountain basins by the U.S. Geological Survey and


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The discovery and early development history of Jonah field was summarized by Robinson (2000). Jonah field was discovered in 1986–1987 with the drilling of two wells by Home Petroleum Corporation, the Jonah Federal 1-4 and 32-34, both of which encountered continuous gas shows and flared gas from about 8500 ft (2600 m) to total depth. The initial completion results of these wells were disappointing, and the field was considered non-commercial. McMurry Oil Company “rediscovered” Jonah field with the completion of the Jonah Federal 1-5 in 1993, which encountered continuous gas shows from 8429 ft (2570 m) to total depth of the well. Subsequent development drilling in 1994–1995 outlined a large, poorly defined area of gas-saturated Lance Formation (Upper Cretaceous), where the top of continuous gas shows began at or a short distance below the top of the Lance. Sandstones in the overlying Fort Union Formation (Paleocene) had low resistivity, appeared wet on logs, yielded only minor or no gas shows while drilling, and were drilled with normal mud weights. An intervening section of shale and shaly sandstones, tentatively correlated
with the “Unnamed unit” of Tertiary age on the Pinedale anticline (Law and Johnson, 1989), yielded erratic shows and appeared to be either normally pressured or perhaps transitional into the overpressured section below (Figure 1). The initial interpretation of Jonah field, based on the degree of overpressuring in these three wells, continuous gas shows over thousands of feet, lack of significant water production, and inability to detect any obvious structural or stratigraphic trapping components, was that Jonah must be a basin-centered gas accumulation (Battin and Clark, 1994).

The best evidence for the top of the overpressured section was the onset of continuous mud-log hydrocarbon shows in both sandstones and shales, which generated a constant gas flare through a gas buster and the need to increase mud weight to control the well. McMurry, Snyder Oil, and other operators in the area called this point the “top of flare,” and it was widely assumed to be coincident with the “top of flare,” and it was widely assumed to be coincident with the top of significant overpressure. Drilling mud weights above the top of flare vary between operators but are generally less than 9.5 lb/gal (1140 kg/m²), which is equivalent to a pore-pressure gradient of 0.494 psi/ft (11.2 MPa/km). Below the top of flare, the operators commonly mud up to 9.7–10 lb/gal (1160–1200 kg/m²) and, in many wells, reach weights greater than 11 lb/gal (1320 kg/m²) at total depth, equivalent to pore-pressure gradients of 0.572 psi/ft (12.9 MPa/km) (Figure 1). Within the field area, there are relatively few publicly available pressure buildup tests. Warner (1998) cited formation pressures in several tests of the early wells equivalent to pore-pressure gradients of 0.54–0.58 psi/ft (12.2–13.1 MPa/km), whereas the shut-in drillstem test pressures for several dry holes in the area surrounding Jonah indicate that the Lance is normally pressured outside the field (Table 1). Montgomery and Robinson (1997) reported that pore-pressure gradients in the field could reach as high as 0.70 psi/ft (15.8 MPa/km) based on the prefracture-stimulation breakdown tests.

In 1994, the McMurry Jonah Federal 4-8 and the Snyder Oil Jonah Federal 3-15 were drilled immediately south of the Home Petroleum wells and the Jonah Federal 1-5 well (Figure 2). The Jonah Federal 4-8 did not have any significant shows down to its total depth of 11,000 ft (3350 m) and had significantly lower porosity and resistivity than the nearby productive wells. The Jonah Federal 3-15 also did not encounter strong gas shows until 11,240 ft (3430 m), more than 2700 ft (820 m) deeper than the top of gas shows in the wells just 1.5 mi (2.4 km) north.

Subsequent reprocessing of a regional northeast–southeast 2-D seismic line revealed a subtle fault separating the productive wells from the two dry holes to the south. This fault zone became known within Snyder Oil as the “Line of Death” and is now known to form the south boundary of the field (Robinson, 2000). In 1996, Amoco acquired a 51-mi² (13,200-ha) 3-D seismic survey over Jonah field. Although many interesting details of the structural configuration of the field emerged from these data (Warner, 1998; Vega and Hanson, 2001), the most significant features imaged were the south boundary fault and a previously unrecognized western bounding fault (Figure 2). Amoco was drilling a well, the Corona 7-24, just west of this fault when the preliminary processing results were delivered. The Corona 7-24 proved to be a dry hole with no significant gas shows down to a total depth of 10,214 ft (3113 m), a mirror image of the conditions on the south side of the southern boundary fault. A test in the Corona 7-24 recorded a downhole pressure gradient of only 0.447 psi/ft (10.0 MPa/km) (Table 1).

Since the recognition of these two major bounding faults, all development drilling operations have been confined to the areas north and east of the faults or, more properly, fault systems, where the top of the pressure surface is approximately 2500 ft (760 m) higher than the surrounding region (Bowker and Robinson, 1997; Montgomery and Robinson, 1997; Warner, 1997a, b, 1998). The operators at Jonah quickly developed a simple model for the distribution of overpressure shown in Figure 3, with a more or less flat-topped overpressure surface near the base of the Fort Union Formation. Warner (1998) concluded that the top of the pressure surface is structurally controlled and rises abruptly between the bounding fault blocks (Figure 3). Our detailed mapping of the top of continuous mud-log shows confirms his interpretation (Figure 4).

To date, attempts to extend production south or west of the intersection of these major fault systems have been unsuccessful. The wildcat tests near Jonah field have not encountered overpressure conditions until they penetrated the basal Lance Formation or upper Mesaverde at depths of 11,000 ft (3350 m) or greater (Table 1). Development drilling has proven that Jonah is a fault-bounded pressure compartment, and it is probably the best example in the Rocky Mountain region of a field where overpressure conditions pop up above what has been interpreted as a regional basin-centered gas accumulation. This observation led to the revised interpretation that Jonah may not be a basin-centered gas field but is instead a gas plume or leakage chimney rooted in a deeper, regional basin-centered gas accumulation. Warner (1997a, p. 129), for example, stated that “minor high-angle faults may be responsible for upward migration of overpressured gas into the thermally

Jonah Field: Case Study of a Giant Tight-Gas Fluvial Reservoir
immature upper Lance section where it is trapped beneath a shale top seal.” Law (2002) also concluded that Jonah is a gas chimney rooted in the regionally pervasive but deeper gas accumulation previously described by Law (1984).

OVERPRESSURE DETECTION FROM SONIC AND RESISTIVITY LOGS

Wire-line logs have been used to detect overpressure, particularly in the Gulf Coast and other Tertiary basins, since at least the mid-1960s (Hottman and Johnson, 1965; MacGregor, 1965; Foster and Whalen, 1966; Ham, 1966). These techniques are based on the response of resistivity, sonic, density, and neutron logs to the porosity of the rocks and their ability to quantify changes in porosity with increasing burial depth and compaction. The loss of porosity in a sedimentary section with increasing burial depth is commonly approximated by an exponential function of the form proposed by Athy (1930):

$$\phi = \phi_0 e^{-bz}$$  \hspace{1cm} (1)

where $\phi$ is the porosity at depth $Z$, $\phi_0$ is the initial porosity of unconsolidated sediment at the time of deposition (the “mud-line porosity”), and $b$ is a compaction coefficient related to lithology. By taking the logarithm of each side of equation 1,

$$\ln \phi = \ln \phi_0 - bZ$$  \hspace{1cm} (2)

a semilog plot of porosity versus depth (depth is linear) is expected to yield an approximately straight line. In the simple case of a continuously subsiding section with no erosional removal of sediments, the slope of the trend is the compaction coefficient, $b$, and the intercept at depth $= 0$ is the log of the mud-line porosity (Figure 5A, B). If there has been uplift and erosion, the porosity at the present-day surface will be some value less than the porosity of unconsolidated sediment (Figure 5C). The thickness between the present surface and an extrapolated point where the trend reaches the mud-line porosity, $\phi_0$, provides an estimate of the amount of removed section (Magara, 1976).

Several studies have demonstrated a change in the porosity-versus-depth relationship between the first several hundred meters of burial, where mechanical compaction of the sediments is the dominant process, and the deep-burial regime, where chemical compaction is dominant (Burrus, 1998). Although an exponential function can approximate the overall porosity loss with depth, no single set of coefficients fits the entire regime from surface to deep burial. Consequently, in some basins, it may be necessary to fit one equation to the section above 3000 ft (910 m) with a large value for $b$ and a different equation with a low value for $b$ in the deeper rocks. Hunt et al. (1998), on the basis of shale-cuttings data, even suggested that the loss of porosity with depth might be modeled best with a set of piecewise linear instead of exponential equations. Regardless of the subtleties of fitting one or more equations to the overall porosity-versus-depth trend, in the case of the northern Green River basin, several thousand feet of shallow overburden have been erosionally removed by late Tertiary exhumation, and any deviations in the shallow regime have been truncated. This study determined that a single exponential equation can be fit to the entire lower Tertiary section from the base of the surface casing to the top of the Lance Formation. Any error in the model equation at shallow-burial depths will result in increased error in the estimate of removed overburden, but this estimate was not a primary goal of the study.

Using equation 2 to predict porosity is only valid for a single and constant lithology. Different lithologies compact at different rates and have different characteristic values for the constant $b$. Because of this, basin compaction studies commonly focus on fine-grained rocks and assume all shales in the section compact at similar rates. If there are interbedded shales of distinctly different lithologies, for example, organic-rich shales or hard siliceous shales, they may deviate from the “normal” shale compaction trend. Shale points of similar lithology can be selected using various criteria for shaliness and lithology, such as a gamma-ray (GR) log, spontaneous-potential (SP) log, and neutron-density porosity separation. Several types of geophysical logs are linearly related to porosity and can be substituted into equation 2 as proxies for porosity, including sonic transit time, bulk density, and neutron-porosity logs. Resistivity (or its inverse, conductivity) also varies as a function of porosity, although the relationship is nonlinear, and other effects, such as surface conductivity of the clays, salinity changes of the interstitial waters, and hydrocarbon saturation, all contribute to shale

Figure 1. Type log from the Home Petroleum Jonah Federal 1-4, the first well drilled at Jonah field, showing the major stratigraphic units, key markers, mud-log gas shows ($T_{gas}$), and mud weight while drilling (MUDW). $T_{fu0}$ = base of Tertiary Fort Union Marker; GR = gamma-ray log; ILD = deep induction log; DT = sonic transit time.
<table>
<thead>
<tr>
<th>Well Name</th>
<th>Location (Township, Range, Section)</th>
<th>Test Interval (ft)</th>
<th>Formation</th>
<th>Bottomhole Pressure (psi)</th>
<th>Pressure Gradient (psi/ft)</th>
<th>Estimated Permeability (µd)</th>
<th>Source</th>
</tr>
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<tbody>
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<td><strong>Wells inside Jonah</strong></td>
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<td>Jonah Federal 2-5</td>
<td>T28N, R108W, 5</td>
<td>core 9581–9591</td>
<td>Lance</td>
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<td></td>
<td></td>
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<tr>
<td>Stud Horse</td>
<td>T29N, R108W, 27</td>
<td>core 10,411–10,429</td>
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<td>Butte 11-27</td>
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<tr>
<td><strong>Tests of wells outside Jonah</strong></td>
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<td>Sublette Flat 1</td>
<td>T27N, R107W, 7</td>
<td>6925–7112</td>
<td>Fort Union</td>
<td>2207</td>
<td>0.319</td>
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<td>Fort Union</td>
<td>2207</td>
<td>0.319</td>
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<td>Sublette Flat 1</td>
<td>T27N, R107W, 7</td>
<td>10,236–10,267</td>
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<td>T27N, R108W, 27</td>
<td>8344–8406</td>
<td>Mesaverde</td>
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<td>Lombard Canyon Unit A-1</td>
<td>T27N, R108W, 33</td>
<td>7944–7981</td>
<td>Ericson</td>
<td>1783</td>
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<td>Prairie Hen Unit 1-A</td>
<td>T27N, R110W, 30</td>
<td>6202–6264</td>
<td>Mesaverde</td>
<td>2339</td>
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<td>Wardell Federal 1</td>
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<td>11,011–11,100</td>
<td>?</td>
<td>5642</td>
<td>0.512</td>
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<td>Golden Gate Unit 1</td>
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<td>Ferry Island Unit 1</td>
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<td>Pinedale Unit 7</td>
<td>T30N, R108W, 15</td>
<td>8040–8062</td>
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<td>New Fork Unit 2</td>
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<td>Fort Union</td>
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<td>Wagon Wheel 1</td>
<td>T30N, R108W, 5</td>
<td>7340–7400</td>
<td>Fort Union</td>
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<td>0.313</td>
<td>IHS Energy</td>
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<tr>
<td>Wagon Wheel 1</td>
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<td>10,978–11,070</td>
<td>Lance</td>
<td>6748</td>
<td>0.615</td>
<td>IHS Energy</td>
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</table>
conductivity. Both sonic logs and resistivity logs have proven useful for compaction studies and overpressure estimation. Density and neutron logs are considered less reliable because of their sensitivity to borehole conditions and washouts.

For compaction to proceed normally, fluids must be able to freely escape as the section compacts, which implies normal or hydrostatic pore pressures. If a compacting section is unable to continuously expel fluids, usually because of low permeability, rapid deposition, and a lack of continuous carrier beds to conduct the fluids away, part of the overburden will be borne by the interstitial fluids, and overpressure will start to develop. As a result, the rate of compaction is reduced and does not follow an exponential loss of porosity with depth. This deviation from a normal compaction trend caused by vertical loading is known as “disequilibrium compaction.” Both qualitative overpressure detection and quantitative estimates of the magnitude of overpressure are based on deviations of the observed compaction-versus-depth trend from an ideal compaction curve fit through the shallow, normally pressured section.

Disequilibrium compaction is thought to be the most common cause of overpressuring in young, rapidly subsiding sedimentary basins, such as the Gulf Coast basin (Osborne and Swarbrick, 1997; Swarbrick and Osborne,
Other mechanisms proposed as common causes of overpressuring are summarized in Table 2. Numerical models have shown that most of these mechanisms other than disequilibrium compaction are unable to account for the very high overpressures observed in many basins (Swarbrick et al., 2002), including the Greater Green River basin. One notable exception may be fluid expansion resulting from hydrocarbon generation (Spencer, 1987) or thermal cracking of oil to gas in a closed system (Barker, 1990). Gas generation from type I or type II kerogen is associated with a volume expansion of as much as 200% and is capable of generating significant overpressure at least locally within rich source rocks (Burrus, 1998; Meissner, 2000). Law and Dickinson (1985) proposed that basin-centered gas accumulations in the western United States formed by hydrocarbon generation induced overpressure, wherein gas was forced into low-permeability sandstone reservoirs, displacing all movable water and creating regionally extensive overpressure cells. As a note of caution, although the volume expansion associated with kerogen conversion to gas may be large, the gas generated expands into a very much larger volume of reservoir and non-source rocks and will suffer a substantial pressure drop as it expands.

**Sonic-log and Resistivity-log Anomalies in the Jonah Field Area**

Figure 6A and B are examples of typical wells in the Jonah area illustrating the sonic-log and resistivity-log anomalies. These logs have been filtered using the GR log to display only points with high shale volume, but no other lithologic criteria were used to discriminate between types of shale. A linear trend of resistivity and sonic transit time is observed from the top of the logged interval to a point near the top of the Lance Formation. At this point, both curves drift off the trend to lower resistivities and higher transit times (lower velocities), and a new, subparallel trend is established within several hundred feet. The top of the overpressure, as determined by continuous mud-log shows and shown by the total gas curve in the far right track, occurs within a few hundred feet.
of the transition to the lower resistivity and velocity trend. Through the transitional zone, the sandstones may yield strong gas shows, but the gas drops back to background levels in the interbedded shales. We interpret the sandstones between the normally pressured Fort Union and the top of the sonic anomaly as slightly over-pressured or normally pressured gas sandstones. All of the Jonah field logs we have examined have similar profiles, where the resistivity and the sonic logs break back from the shallow-burial trend at nearly identical depths. This is important because most wells were not logged with a sonic tool, and therefore, resistivity becomes the key measurement for mapping the top of the anomaly.

The sonic trend above the top of the Lance can be projected upward to a theoretical mud-line interval transit time of 189 $\mu$s/ft (620 $\mu$s/m) (Figure 5C). The difference between the projected sediment thickness to the mud line and the actual thickness to the present-day surface of the Earth provides an estimate of the amount of overburden removed since maximum burial. For the examples shown in Figure 6, more than 5000 ft (1500 m) of section has apparently been removed. One problem with this calculation is the extremely low slope of the trend line. Even small changes in the projected trend to honor values in a particular shale zone can change the removed overburden estimate by hundreds of feet. Furthermore, as discussed previously, any deviation of

Figure 4. The top of the overpressure determined from continuous mud-log shows at Jonah field.
the actual trend from the assumed exponential trend at shallow-burial depths results in additional error in the removed overburden estimates. Dickinson (1989) estimated 1100–1500 m (3600–4900 ft) of erosion at the Wagon Wheel well on the Pinedale anticline. Coskey (2004; Figure 4), using vitrinite reflectance data to estimate the amount of removed overburden in the Jonah–Pinedale area, concluded that from 1400 to more than 6000 ft (430 to >1830 m) of section has been eroded, with a best fit estimate of 3600 ft (1100 m). The timing and precise rates of erosion are unknown, but all the overburden was likely stripped during the post-Miocene regional exhumation of the Rocky Mountain region (Dickinson, 1989).

Because of the coincidence of the log anomaly with the top of the overpressure at Jonah field, it seems reasonable to expect the top of the overpressure to track the log anomalies throughout the northern Green River basin. Figures 7 and 8 are cross sections through Jonah field and adjacent wildcat wells, showing the resistivity-log, sonic-log, and mud-log gas curves. The sonic-log and resistivity-log anomalies do not track the top of the overpressure beyond the limits of the field; instead, they remain at approximately the same stratigraphic position despite the fact that the top of the overpressure deepens by 2000–3000 ft (610–910 m) to the west and south. Mud weights, gas shows, and a few well tests outside the Jonah compartment, but within the anomalous sonic and

Figure 5. Sonic transit time (DT) vs. depth trends for a compacting section of a uniform shale lithology. (A) DT plotted on a linear scale versus depth displays an exponential curvature; (B) DT on a semilog scale versus depth is a linear trend; (C) trend for the same well if several thousand feet of section was eroded. Projecting the observed DT at the surface (141 μs/ft; 463 μs/m) upward to the original mud-line DT (189 μs/ft; 620 μs/m) yields an estimate of the removed overburden to be 5000 ft (1500 m).
resistivity interval, indicate that this section is normally pressured to slightly underpressured (Table 1). The under-compaction signature recorded by the logs and the top of present-day overpressure are obviously decoupled in the area surrounding Jonah field.

**DISCUSSION**

**Sonic and Resistivity Anomalies as Paleopressure Indicators in the Rocky Mountain Region**

In many Tertiary basins, including the Gulf Coast region of the United States, burial depths have steadily increased with continuous subsidence. The rate of subsidence and rate of sediment input to these basins have varied over time, but the creation of accommodation space has kept pace. In these basins, which form the overwhelming majority of the case histories for overpressure detection from logs, a close correspondence between the top of the overpressure conditions and the initial deviation from the local compaction trend on resistivity and sonic logs has long been recognized.

In foreland basins, including Laramide basins of the Rocky Mountain region, the geological history is more complex. These basins have typically seen a principal subsidence phase, during which most of the basin-filling sediment was deposited, followed by one or more

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**Table 2**

Common Mechanisms for Abnormal Pressure Development in Sedimentary Basins (after Osborne and Swarbrick, 1997).

<table>
<thead>
<tr>
<th>Overpressure Mechanisms</th>
<th>Cause</th>
<th>Expected Magnitude (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stress-related compaction</strong></td>
<td>vertical loading (rapid burial)</td>
<td>thousands, limited by rock failure</td>
</tr>
<tr>
<td>Disequilibrium compaction</td>
<td>lateral loading</td>
<td>thousands, limited by rock failure</td>
</tr>
<tr>
<td>Tectonic compression</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fluid-volume increase</strong></td>
<td>heating and expansion of water with increasing burial depth and temperature</td>
<td>~100</td>
</tr>
<tr>
<td>Aquathermal expansion</td>
<td>gypsum → anhydrite dehydration</td>
<td>7–100</td>
</tr>
<tr>
<td>Mineral transformations</td>
<td>smectite → illite transformation</td>
<td>unclear</td>
</tr>
<tr>
<td></td>
<td>smectite dehydration</td>
<td>~100</td>
</tr>
<tr>
<td>Hydrocarbon generation</td>
<td>kerogen → gas transformation</td>
<td>70–6000 in source rock itself</td>
</tr>
<tr>
<td></td>
<td>kerogen → oil transformation</td>
<td>70–6000 in source rock itself</td>
</tr>
<tr>
<td></td>
<td>oil → gas (in-situ cracking)</td>
<td>hundreds in reservoir rock</td>
</tr>
<tr>
<td><strong>Fluid movement</strong></td>
<td>salinity contrasts across semipermeable shale membranes</td>
<td>hundreds, but theoretically as much as 3000</td>
</tr>
<tr>
<td>Osmotic pressure</td>
<td>elevated recharge areas</td>
<td>tens to hundreds, depending on elevation difference</td>
</tr>
<tr>
<td>Hydraulic or potentiometric head</td>
<td>hydrocarbon-water density contrasts</td>
<td>1–1000, depending on column height and density difference of phases</td>
</tr>
<tr>
<td><strong>Underpressure Mechanisms</strong></td>
<td>uplift and removal of overburden</td>
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<tr>
<td>Differential discharge</td>
<td>cooling and contraction of pore fluids with relative uplift</td>
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<td>Differential gas flow</td>
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<td>Osmosis</td>
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<td>Rock dilatancy</td>
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<td>Pore-fluid cooling</td>
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periods of relative uplift, during which substantial amounts of sediment were eroded. If an interval of strata in one of these basins becomes overpressured at any time in its burial history because of disequilibrium compaction and then is subsequently uplifted, the present-day pressure may not accurately reflect the net state of compaction.

Figure 6. Typical sonic transit time-resistivity anomalies in the Jonah area. (A) Jonah field well, McMurry Oil Stud Horse Butte 15-28 (SW SE Sec. 28, T29N, R108W), with less than 300 ft (90 m) between the log anomaly and the top of overpressure; (B) a well outside the overpressured area, HS Resources Holmes Federal 5-1 (SW NW Sec. 1, T27N, R109W), with more than 3800 ft (1160 m) between log anomaly and the top of overpressure. GR = gamma-ray log; $R_{sh}$ = filtered deep resistivity in shales; DT$_{sh}$ = filtered sonic transit time in shales; $T_{gas}$ = mud-log total gas curve.
Figure 7. Southwest–northeast cross section across Jonah field showing position of resistivity anomaly relative to the top of overpressure. A large-scale version of this cross section is included on the CD-ROM with this publication as Appendix E. JF = Jonah Federal. SHB = Stud Horse Butte.
Figure 8. Northwest-southeast cross section across Jonah field showing position of resistivity anomaly relative to top of overpressure. A large-scale version of this cross section is included on the CD-ROM with this publication as Appendix E. JF = Jonah Federal. SHB = Stud Horse Butte.
Total pore pressure decreases with uplift and erosion because the trapped fluids cool and the pore system dilates as the net overburden stress is reduced. Leakage of the overpressured fluids can occur if faults and fractures are activated and form permeable paths for fluids to migrate away from the overpressured interval. In a leaky section, the top of the overpressure will drop stratigraphically as the interval is uplifted.

Sonic and resistivity logs in the Rocky Mountain region probably respond to undercompaction of the sediments in an overpressured section just as they do in younger basins. Where overpressure results from disequilibrium compaction, the sonic-log and resistivity-log anomalies will mark the top of the overpressure during the compaction phase. The undercompacted rock fabric is an irreversible change that does not diminish as the section is uplifted. The only way to compact the rocks to the degree expected from a normal compaction gradient and thereby erase the undercompaction signature would be to rebury them to their former maximum depth in an open state, where pore fluids can freely escape. Therefore, in a section that has undergone relative uplift and fluid leakage during the uplift phase, the top of the present-day overpressure will lie somewhere below the log anomalies that mark the top of the overpressure during the burial and compaction phase. This decoupling of present overpressure with the position of the log anomaly is exactly what we observed in the area surrounding Jonah field.

Rathbun (1968) described conductivity anomalies in the northern Green River basin that he attributed to changes in pore pressure, and these were used as mappable parameters. Evers and Ezeyinim (1983) developed a set of calibration charts to predict pore pressure from conductivity and sonic transit time anomalies and presented a comparison of the predicted and actual pressures for the Wagon Wheel 1 well on the Pinedale anticline. They concluded that the method was accurate in this area to within ±0.03 psi/ft (0.679 MPa/km) of depth, or 300 psi (2.069 MPa) at 10,000 ft (3000 m). Subsequently, Prensky (1986), in a study of well-log responses in the northern Green River basin, found a poor correlation between the top of the conductivity anomaly in the Pinedale area and the top of the overpressure estimated from mudweight data. Noting the close proximity of the conductivity anomaly in wells on the Pinedale anticline with the Cretaceous–Tertiary boundary and with a major change in GR intensity at approximately the same depth, Prensky (1986) concluded that the conductivity anomaly was a stratigraphic phenomenon related to a change in bulk mineralogy near the base of the Fort Union. He further concluded that shale conductivity and shale transit time plots would not be useful for pore-pressure prediction in the Green River basin because of complex changes in lithology through time, the lower salinity of pore waters compared to the Gulf Coast basin where the techniques were developed, and differences in the mechanism presumed to be responsible for overpressuring (hydrocarbon generation versus disequilibrium compaction). Prensky (1986) did not offer any explanation for the observation made by Rathbun (1968), which this study confirms, that the conductivity anomaly seems to cross stratigraphy from east to west, until it is present near the base of the Hiilard Shale on the west flank of the basin and in the La Barge platform area.

Although we concur with Prensky’s (1986) observation that the resistivity and sonic anomalies in the Pinedale area roughly coincide with the Cretaceous–Tertiary boundary, it is not clear that this is a result of a change in shale mineralogy. Equally likely is that the sandstones and shales of the Tertiary are poor seals and had higher fluid transmissibility during compaction, consequently follow a normal compaction-versus-depth curve. The sandstones and shales in the Lance and at least part of the underlying Mesaverde, however, apparently had poor transmissibility and are undercompacted relative to the shallower, normally compacted, and normally pressured Tertiary units. Thus, the log anomalies follow the stratigraphic boundary, at least in this immediate area, because of a fluid-transmissibility contrast in the major units, which may or may not be related to mineralogical differences.

Surdam et al. (1997, their figure 12) proposed another explanation for the sonic-log anomaly, wherein relatively small levels of gas saturation in the shales can generate in a significant increase in sonic transit times. They cited laboratory data showing that as little as 5% gas saturation in the matrix porosity can result in a strong decrease in the compressional wave velocity (Timur, 1987). In this model, the top of the overpressure coincides with the onset of gas generation and results in partial gas saturation throughout the shales. The principal problem with this hypothesis is that an increase in gas saturation in the shales should result in an increase in average shale resistivity and not a decrease. Studies of mature source rock shales invariably document a major increase in resistivity that coincides with the top of hydrocarbon generation because pore waters are displaced by nonconductive hydrocarbons (e.g., Meyer and Nederlof, 1984; Schmoker and Hester, 1990), which is the opposite of what we observed in the Lance section in and around Jonah. Additionally, available vitrinite reflectance data at Jonah indicate that shales in the Lance are immature and have not reached the onset of gas generation (Bowker and Robinson, 1997; Coskey, 2004).
Jonah Field: Is It Really Just a Paleopressure Remnant?

The presence of a sonic-log and resistivity-log anomaly throughout the area surrounding Jonah field suggests that the Lance section is undercompacted and, at its maximum burial depth, was overpressured over a broad area of the northern Green River basin. Gas shows and marginal gas production from nearby wildcats further suggest that the Lance section contains some gas, but it is normally pressured or underpressured outside the field boundaries. These two observations, in combination, lead us to propose the following model for the origin of Jonah field.

The top of the overpressure was widely established as a regional surface during the early to middle Tertiary. The position of this surface coincides with the anomaly we see today on sonic and resistivity logs. The exact timing and burial history of the northern Green River basin is poorly constrained, in large part because portions of the section are now missing and therefore cannot be directly dated. Maximum overburden was probably attained significantly after deposition of Paleocene strata but before the middle Miocene. Coskey (2004), for example, suggests that most of the removed section is Wasatch, and erosion begins at about 5 Ma. The stratigraphic position of the top of the regional overpressure was controlled by the low permeability of the Lance section, which is composed of a heterolithic assemblage of low-permeability sandstones and shales that impeded fluid flow out of the section during burial. The sandstones of the lower Fort Union in the Jonah area have good lateral continuity, are regionally porous and permeable, and allowed fluids expelled during compaction to escape the system. Consequently, the Fort Union is currently normally pressured, exhibits high water saturations, and has probably always been normally pressured.

At its time of maximum burial, at depths 3000–5000 ft (910–1500 m) greater than today, the entire Lance section was receiving gas charge from deeper, more mature source rocks (Coskey, 2004). The Lance itself is thermally immature in the Jonah area (Warner, 1998; Coskey, 2004). Gas migrated vertically through a regional system of joints and fractures that must have been sufficiently extensive to contact a high percentage of the reservoir sand bodies. The formation was somewhat overpressured because the Lance had lower transmissibility than the overlying strata and, consequently, was in a state of disequilibrium compaction, resulting in the sonic-log and resistivity-log anomalies found today both within and around the field.

The lithostatic overburden decreased in direct proportion to the rate and amount of erosion during late Tertiary uplift. The porosity of the sandstones increased slightly as the pore system dilated with reduced confining stress and the section cooled with uplift, resulting in contraction of the trapped gases. Total reservoir pore pressure decreased, although the pore-pressure gradient may have actually increased with relative uplift because of the high compressibility of gas (Figure 9) (Katahara and Corrigan, 2002). Another factor to consider is that during uplift, erosion, and cooling, the top of the active hydrocarbon generation window falls away from the Lance in rough proportion to the amount and rate of erosion. It is unlikely that active hydrocarbon generation was able to contribute to overpressured conditions in the Lance once uplift commenced.

The sharp difference in pressure gradients across the field boundaries, with similar reservoir rock properties and identical burial histories within and outside the field, can be explained by a difference in the rate of fluid leakage out of the Lance section during uplift. The Jonah compartment appears to be very tightly sealed and has retained its gas charge during uplift. Leakage of fluids out of Jonah was limited by extremely low-permeability seals on three sides of the field. The major fault zones on the south and west flanks of Jonah form lateral sealing surfaces that are capable of maintaining a pressure differential greater than 1000 psi (6.9 MPa) over short distances. The top of the gas accumulation at Jonah coincides with the shaly, low net-to-gross Unnamed unit. This apparently sealing interval separates overpressured, gas-charged Lance sandstones from water-saturated and normally pressured Fort Union sandstones.

These three major sealing surfaces, two fault systems, and a top-sealing shale, form a structural trap similar in geometry to the bow and decking of a ship. Because the bow is fortuitously pointed directly updip, fluids were unable to leak out of the trap as the system was uplifted. The top-sealing shale, however, is truncated by post-Lance erosion a short distance to the south and west of Jonah (Coskey, 2004). If the truncation edge of the Unnamed Tertiary was within the present field area, anywhere north and east of the intersection of the two major bounding faults, a large part of the accumulation would have likely leaked upward into the Fort Union, and the field would be much smaller or might not even exist.

In the area surrounding Jonah, gas freely escaped upward into the overlying Fort Union section as the interval was uplifted. The exact mechanism and pathways for leakage are speculative, but it is likely that gas leaked through a system of regional joints and fractures. This regional fracture system may very well be identical to that inside the field, but a key difference is that outside the field, there are no lateral or top seals to prevent gas from migrating.
out of the Lance into the Fort Union. The Lance sandstones outside Jonah still retain some gas saturation because minimal free water was available to be imbibed as the section was uplifted, but they have lost a large portion of their charge and yield much weaker gas shows during drilling. Jonah field is a tightly sealed and overpressured compartment that stands high above the surrounding top of the pressure surface, much like a mesa above an eroded landscape. The top of the overpressure surface surrounding the field, established in the early Tertiary at maximum burial depth, has been dropping since uplift and erosion began in the late Miocene or Pliocene. Because Jonah field owes its origin to the preservation of overpressure conditions during uplift, and maintaining this state of overpressure is a direct result of the unique sealing conditions at Jonah, exploration for additional overpressured accumulations of this kind should focus on sealing and trapping conditions that will prevent leakage. This is in stark contrast to the prevailing exploration philosophy for basin-centered gas sweet spots, which emphasizes finding fractures and areas of enhanced reservoir quality favorable for gas leaking upward into shallower horizons.

CONCLUSIONS

The Lance Formation consists of highly discontinuous sandstones in a shale matrix. Fluids contained in the Lance were unable to freely escape the section during rapid burial, and as a consequence, the fine-grained sediments are undercompacted relative to their former maximum burial depths. Sonic and resistivity logs through the Lance and Mesaverde retain a strong signature of reduced velocity and reduced resistivity directly related to undercompaction during burial. The top of the anomalous sonic velocity-versus-depth and resistivity-versus-depth trends generally coincides with the top of the shaly Lance section and is everywhere beneath the more continuous and permeable Fort Union sandstones.

Coincidentally, the top of the anomalous velocity and resistivity profiles corresponds, within a few hundred feet, to the top of the overpressured gas in Jonah field, leading to the idea that the geophysical signatures might be directly related to the presence of overpressure. Regional examination of logs, however, demonstrates that the anomalies extend far beyond the field limits and persist at roughly the same stratigraphic position, clearly demonstrating that the anomaly is decoupled from present-day pressure conditions.

The best explanation for the similarity of velocity-resistivity profiles inside and outside Jonah is that they record the former top-of-pressure conditions attained at maximum burial, and the signature was frozen into the rocks during subsequent exhumation. Jonah field is thus an anomalous remnant of former regional overpressure conditions that were established during maximum burial conditions in the early or middle Tertiary.

The origin of Jonah field is therefore related to relative rates of fluid leakage out of the Lance section during relative uplift. Jonah field is tightly sealed on two
sides by impermeable sealing faults and is sealed on the top by a thick, low-permeability shaly interval. Outside Jonah field, fluids were able to leak updip through fractures and escaped the system. Where the fluids were unable to escape, a deep, overpressured system was able to survive uplift to much shallower depths. Thus, a multi-tcf gas accumulation in the Greater Green River basin owes its origin to the preservation of gas charge and overpressure over millions of years of regional uplift and erosion.

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Jonah Field: Case Study of a Giant Tight-Gas Fluvial Reservoir