The following is excerpted and adapted from *Pinedale Anticline*, authored by Scott Montgomery, the latest in IHS Energy's *Petroleum Frontiers* series, a quarterly investigation into the most promising hydrocarbon horizons and provinces. The 56-page publication includes more than 70 figures and an extensive bibliography. The material presented here is from Chapter 4.

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Lance Reservoirs: Variation and Compartmentalization

Reservoir Heterogeneity

Productive gas reservoirs in the Lance Formation of the Pinedale Anticline consist predominantly of amalgamated channel fill sandstones deposited in braided stream environments. These sandstones occur within the upper portion of an overpressure cell related to gas saturation build-up in low-permeability strata. Approximately 150-300 ft of net productive sandstone exist within the Lance at any one location. High gas saturations have been observed in nearly all sandstone intervals that occur within the overpressure cell.

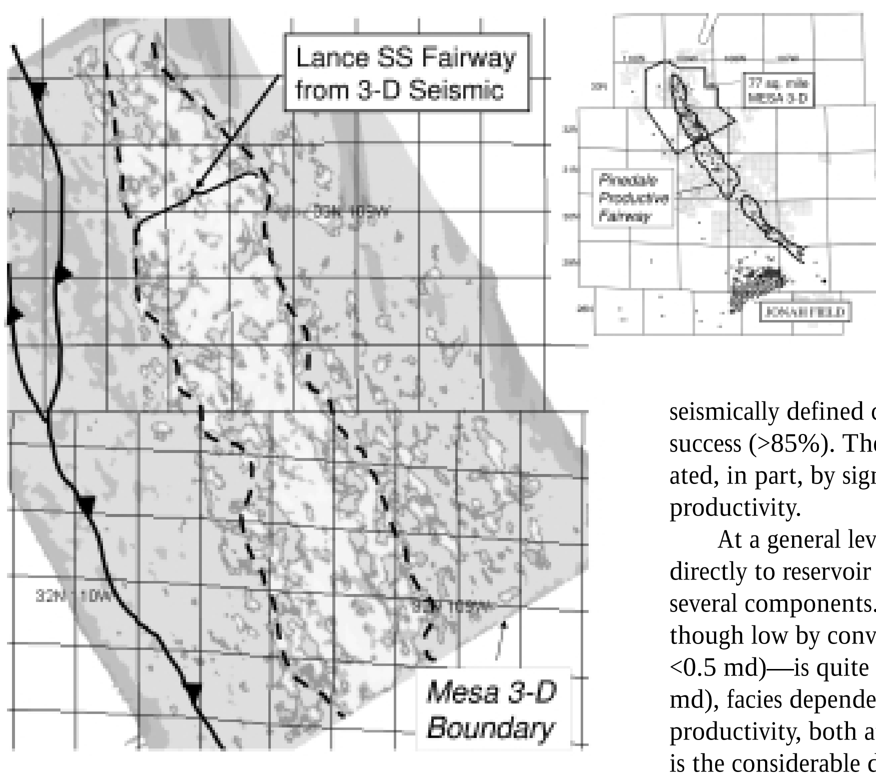

Figure 4.1. Outline of Lance Sand fairway, northern Pinedale Anticline (Mesa area), based on attribute analysis from 3-D seismic data. Adapted from Ultra Petroleum.

Seismic characterization of the Lance has been greatly advanced by new 3-D data. Such data have been used to outline a distinct and fairly well-bounded reservoir fairway (Fig. 4.1), based on attribute analysis. As implied by Fig. 4.1, the central fairway varies from about 1.5 to 2.5 miles in width and is continuous for tens of miles along strike of the anticline. Local prospective areas also exist along the eastern flank of the structure, being more sparse on the western flank. Wells drilled within this seismically defined central fairway have a high chance of success (>85%). These high success rates, however, are moderated, in part, by significant variations in actual reservoir productivity.

At a general level, limitations on productivity are tied directly to reservoir heterogeneity. Such heterogeneity has several components. One of these is reservoir quality, which—though low by conventional standards (average permeability <0.5 md)—is quite variable (permeability range 0.005-1.0 md), facies dependent, and a known factor affecting well productivity, both at Pinedale and Jonah. A second component is the considerable degree of lateral change in thickness, geometry, lithology and also hydrocarbon saturation of sand zones, even between closely spaced wells. Examples of such heterogeneity are frequently seen in closely spaced wells, even those spaced no more than 50 ft apart, as shown in Figs. 4.2

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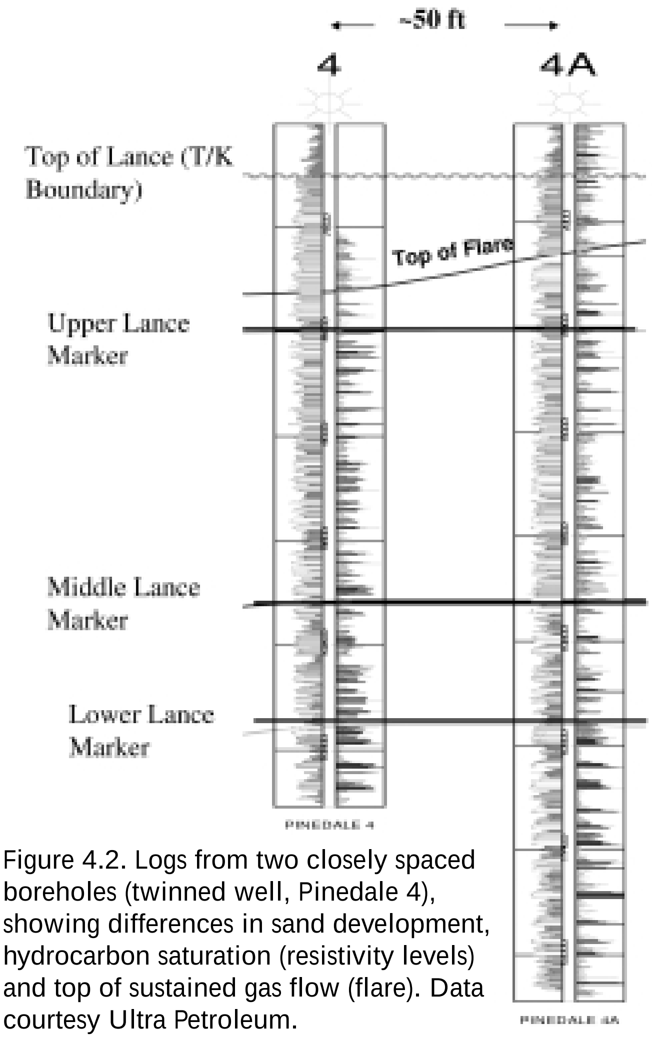

Figure 4.2. Logs from two closely spaced boreholes (twinned well, Pinedale 4), showing differences in sand development, hydrocarbon saturation (resistivity levels) and top of sustained gas flow (flare). Data courtesy Ultra Petroleum.

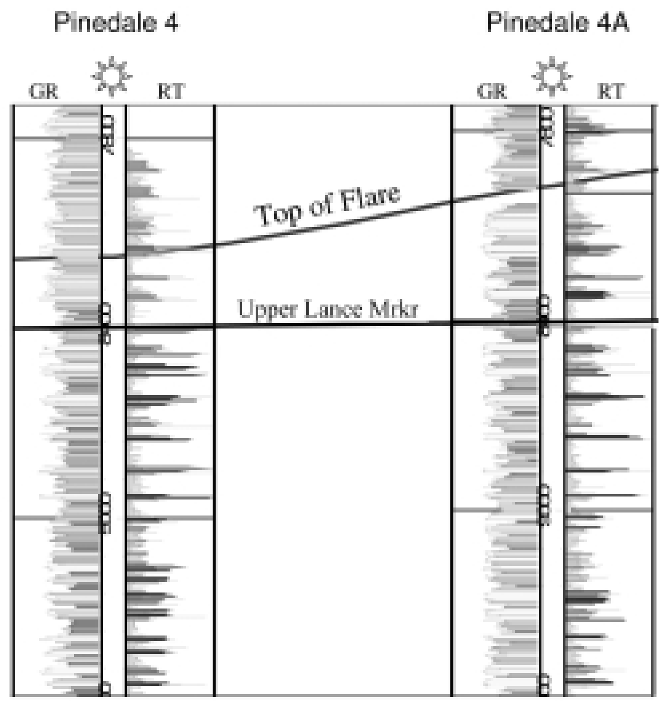

Figure 4.3. Enlargement of Figure 4.2 (part), including productive portion of upper Lance, below top of flare. Lateral heterogeneity shown by these closely spaced wells (~50 ft horizontal separation) suggests difficulty of mapping individual reservoir zones, either through log or seismic data. Such heterogeneity also implies the need for close spacing to adequately drain the Lance. Data courtesy Ultra Petroleum.

and 4.3. Fig. 4.2 shows gamma ray and resistivity log data, and interpreted lithology, for two wells in the central portion of the anticline, the Pinedale 4 and its twin, the 4A. Fig. 4.3 provides a closer look at a productive portion of the upper Lance in these same wells. Sand development and hydrocarbon saturation levels (from resistivity spikes) vary considerably between these two boreholes, especially in the section below 9,000 ft depth.

A third component of reservoir heterogeneity, not well understood as yet, is the degree of natural fracturing within the Lance (see Chapter 2).

All three of these factors contribute toward compartmentalization. Such compartmentalization, both vertical and lateral in nature, is evident from other lines of evidence as well, according to information supplied by geoscientists at Schlumberger and Ultra Petroleum. Such evidence refers, for example, to changes in water salinity and variations in pressure. Other factors may relate to differences in gas/water saturation, to

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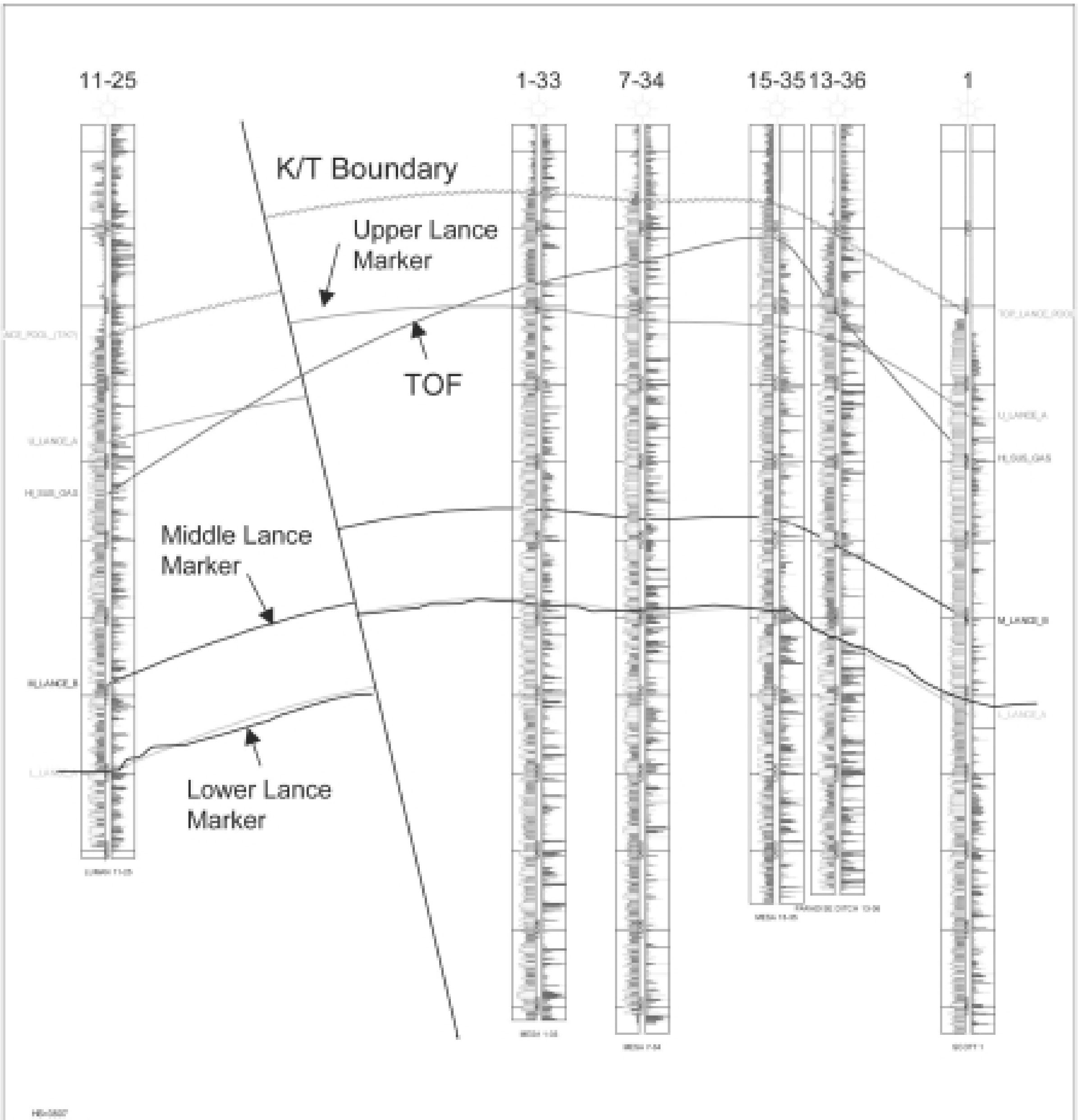

Figure 4.4. West-east structural (dip) cross section, northern Pinedale Anticline (Mesa area), showing selected stratigraphic markers and top of sustained gas (top of flare = TOF). Section is hung from 7800-ft depth line. Source: Ultra Petroleum.

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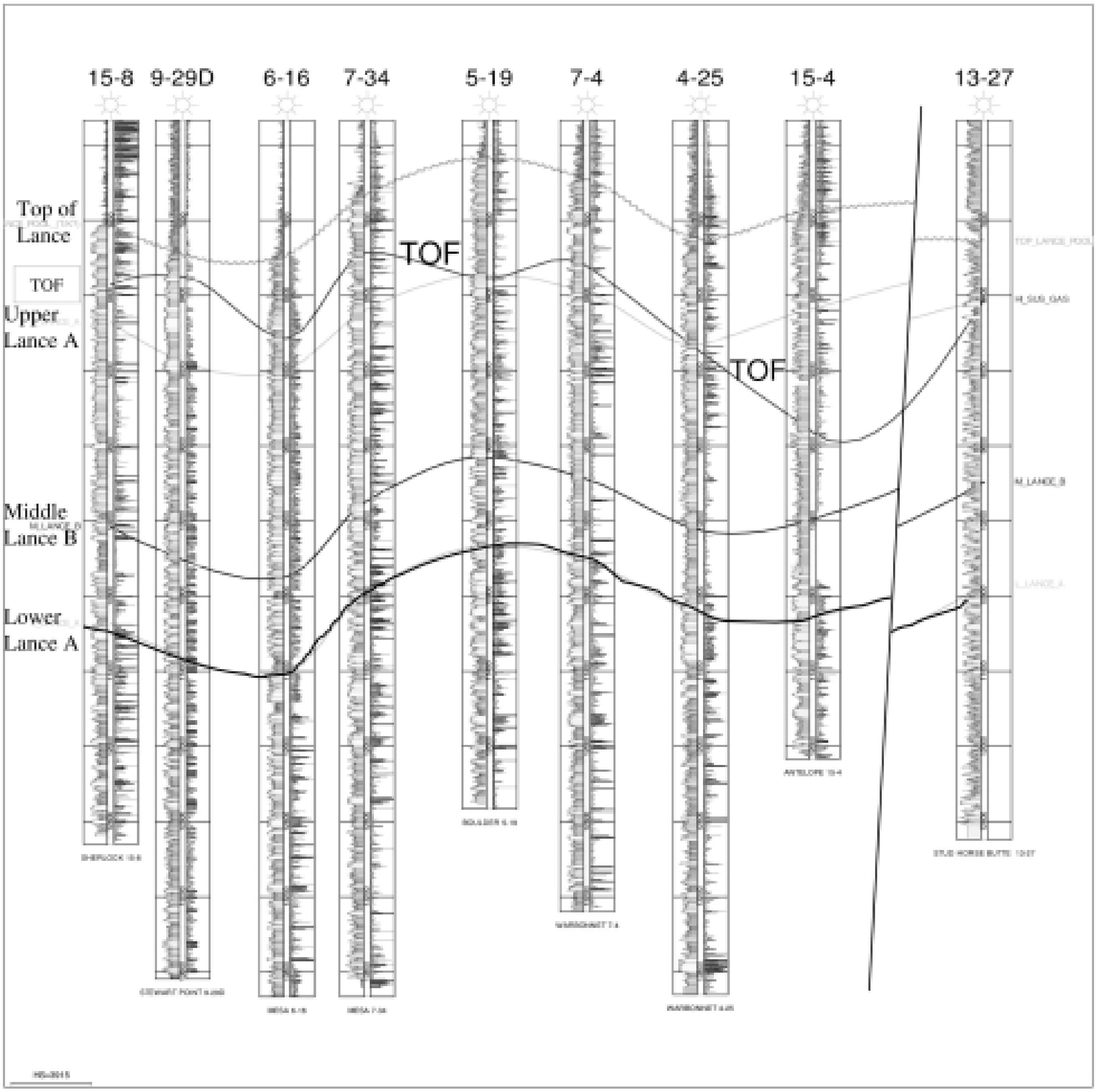

Figure 4.5. North-south structural (strike) cross section, Pinedale Anticline to Jonah Field. Section showsthat top-of-flare does not accord with stratigraphy along strike of anticline. Source: Ultra Petroleum.

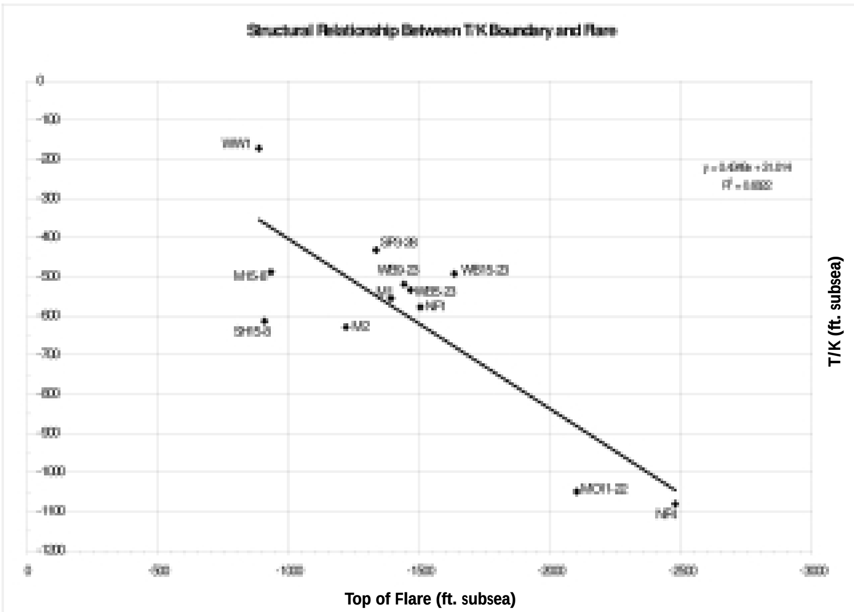

Figure 4.6. Subsea top of flare (Lance Formation) plotted against Subsea depth of Tertiary-Cretaceous boundary. Source: Ultra Petroleum.

thickness and composition of seals, and to proximity to faults. As yet, there are insufficient data to map out and predict relevant trends.

Top of Flare: Primary Geologic Controls

Appearance of first sustained gas flow in the Lance Formation is generally referred to as "top of flare" by Pinedale operators. Top of flare (TOF) usually serves as the practical upper limit to potential economic production. As indicated by Fig. 4.3 and the log cross sections of Figs. 4.4 and 4.5, TOF does not occur at a consistent stratigraphic position across or along strike of the Pinedale structure. Relative to the Cretaceous-Tertiary boundary (top of Lance) on Fig. 4.4, for example, it varies from 800 ft below the top of the Lance in the Mesa 11-25 well to only 150 ft deeper in the 15-35 well. Similarly, Fig. 4.5 indicates TOF is about 100 ft below the top of the Lance in the 9-29D well, but over 1,000 ft deeper in the 15-4 well, near the southern end of the anticline. Generally speaking, the strike section of Fig. 4.5 shows an overall deepening of the

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TOF southward. The TOF surface, therefore, has considerable relief over the Pinedale structure. Mud weight does not appear to affect it.

Analysis of several factors suggests that there are two geologic controls on depth to TOF. The first, and stronger, of these controls is structural position. Fig. 4.4 suggests such a relationship. A plot of TOF versus structural position (subsea depth of Tertiary-Cretaceous boundary) for wells from the north, central and south portions of the Pinedale Anticline is given in Fig. 4.6 and indicates the relationship in more detail. Dip-oriented log cross sections across the anticline consistently show a rise in the TOF from flank to crest. Interestingly, the crestal portion of the TOF surface does not correspond with that of the anticline itself, but rather is displaced a mile or so to the east, suggesting, perhaps, late-stage eastward tilting of the structure.

A second controlling factor appears to be the sandstone/shale ratio of the Lance. Fig. 4.7 is a plot of this ratio (in

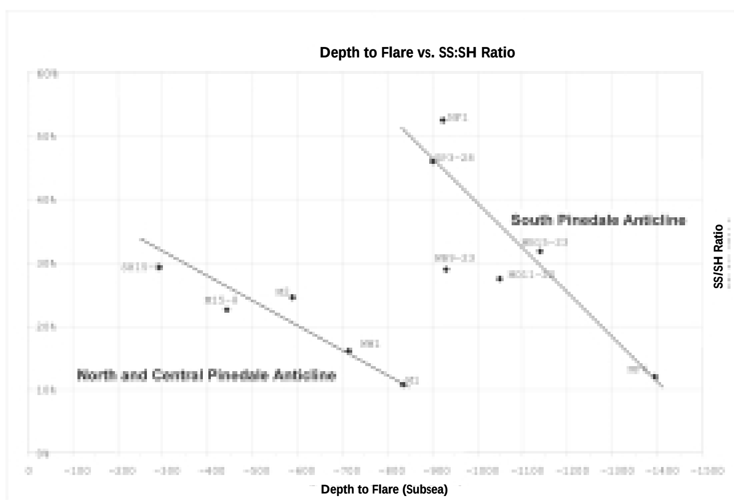

Figure 4.7. Subsea top of flare plotted against sandstone/shale ratio (in %). Source: Ultra Petroleum.

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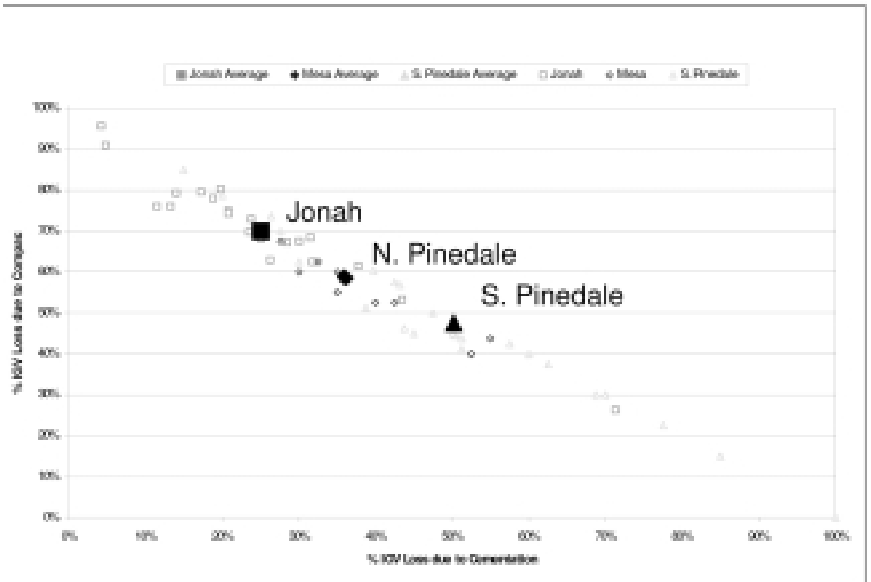

Figure 4.8. Loss of intergranular pore volume by compaction versus by cementation for Pinedale and Jonah fields. Source: Ultra Petroleum.

percent) against depth to flare (subsea elevation). The graph suggests two trends, one for the central and northern portion of the anticline, the other for the southern part. Both inferred trends suggest that increasing amounts of sandstone in the upper Lance correlate with shallower TOF. In part, this also reflects the fact that depositional trends for sand-rich facies of the Lance correspond to the axial trend of the anticline (see Chapter 3). It should be noted, however, with regard to Fig. 4.7, that the trends shown are qualitative, as the logs used to derive the SS:SH percentages were not normalized.

Several possible conclusions can be interpreted from this information. If TOF can be assumed to mark (or parallel) the ceiling to the overpressure cell in the Pinedale area, it would appear that overpressure is affected by structure. At Jonah, the structural relationship seems related to faulting, in particular to fault-seal compartments that have allowed gas to migrate into the upper Lance and overlying lowermost Tertiary section. At Pinedale, faulting is less prevalent. One possibility appears to be that the Lance sands were charged at a fairly early stage—during the initial stages of folding—and that continued deformation, in conjunction with sandstone abundance, influenced the distribution of overpressure across the structure.

Patterns of Change along Strike

The foregoing discussion implies that significant changes take place in productivity-related factors along strike of the Pinedale structure. Figs. 4.8-4.11 amplify this conclusion with other types of evidence.

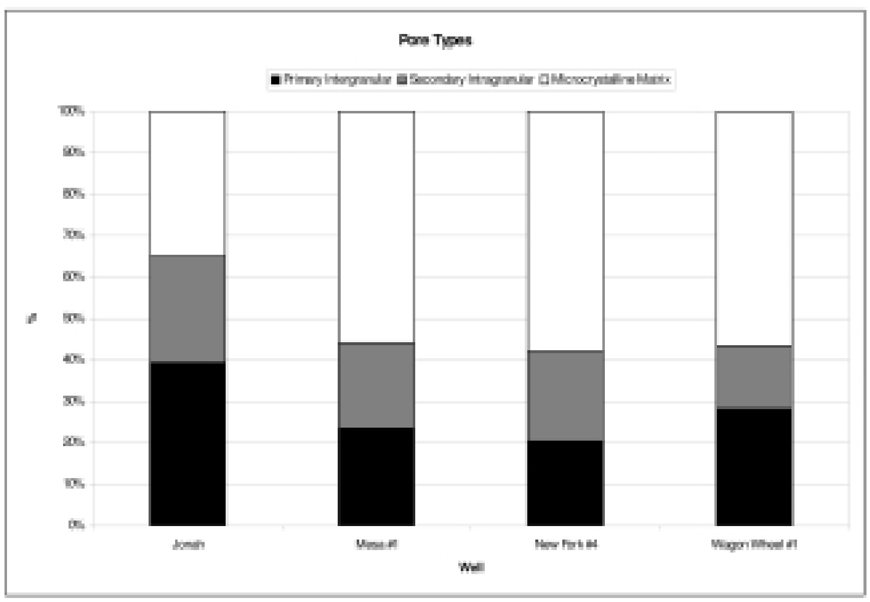

Figure 4.9. Pore type differentiation for different areas, Jonah-Pinedale fields. Source: Ultra Petroleum.

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Fig. 4.8 plots the estimated loss of intergranular pore volume by compaction against that by cementation (so-called "Houseknecht Diagram") for Pinedale and Jonah fields. As shown, there is a distinct division between north and south Pinedale and Jonah. In general, the Lance in the Pinedale Field has lost more pore volume through cementation, relative to compaction, than at Jonah. The largest difference, moreover, is exhibited between Jonah and south Pinedale; this suggests that the Pinedale Thrust forms a significant barrier in terms of post-burial history and related events. There is a suggestion from Fig. 4.8 that pore fluids were mobilized in different fashion along the Pinedale structure.

This conclusion is also supported by Fig. 4.9, which distinguishes different pore types observed for Lance sandstones in portions of the Pinedale Field and in Jonah. A much higher percentage of primary intergranular porosity and a significantly smaller amount of micro-porosity typify samples from Jonah Field. This corresponds, in part, to the more important role of compaction (versus cementation) in reducing primary pore space. Equally distinct is the similarity of pore types in all three areas of the Pinedale Field (Wagon Wheel well from the central part of the field), i.e. primary intergranular (~23%), secondary intragranular (~21%) and microcrystalline (~67%). Again, the strong differences between Jonah and south Pinedale (New Fork) implies an important boundary that divided two burial history domains.

Another area of evidence for change along structural strike comes from mud weight data. Graphs of mud weight versus depth for wells in north (Stewart Point), north-central (Mesa), south-central (New Fork) and south (Warbonnet) Pinedale are shown in

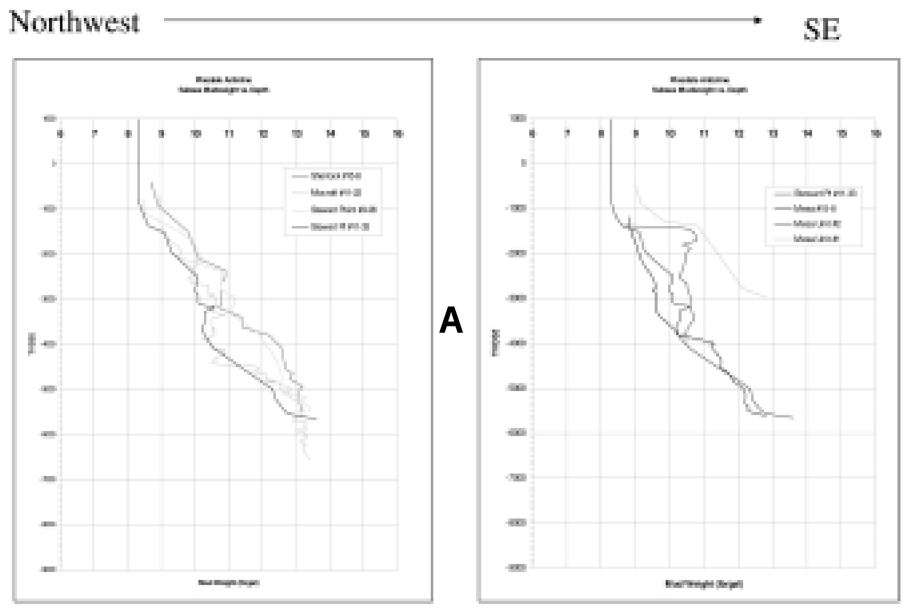

Figure 4.10. Mud weight profiles for wells in Pinedale Field. A) Stewart Point – Mesa areas; B) New Fork – Warbonnet areas. Source: Ultra Petroleum.

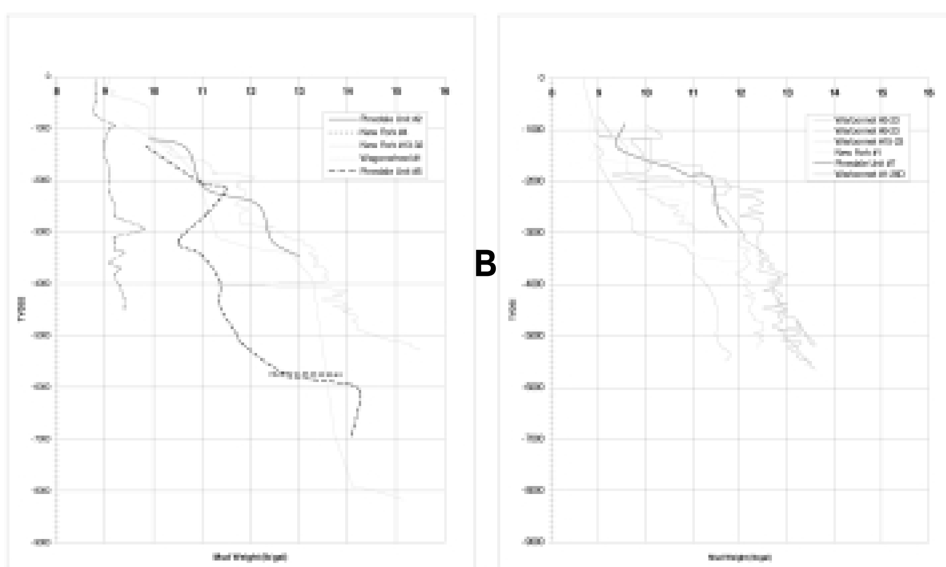

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Fig. 4.10. These plots indicate significant variation in mud weight for various depths among the different areas, implying an important degree of pressure compartmentalization. In addition, wells within each defined area also exhibit important differences. Equally important, the curves of Fig. 4.10 display a stair-step type profile, strongly suggestive of vertical compartmentalization. For certain wells, e.g. in the Stewart Point area, mud weight profiles imply as many as four or five major pressure compartments over a 4,000-ft vertical interval. Comparison between mud profiles and log-determined lithology indicate that seals between compartments are floodplain shales.

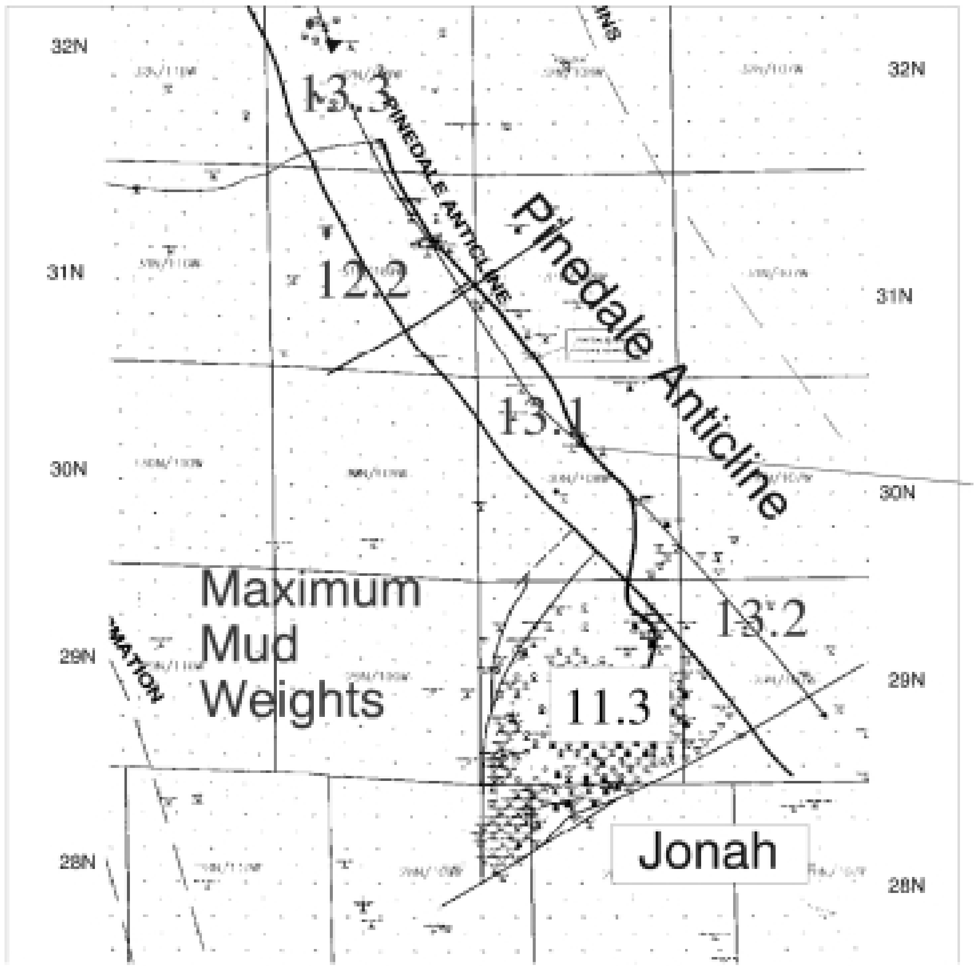

Figure 4.11. Maximum mud weights within Lance Formation, for different portions of Pinedale Anticline and Jonah Field. Source: Ultra Petroleum.

Changes in maximum mud weight along strike of the Pinedale fold are also shown by the map of Fig. 4.11, which gives average maximum weights for the Lance in Pinedale and Jonah fields. Several cross faults have been included on this map, to suggest the interpretation that observed changes represent structurally controlled compartmentalization. As noted, pressure compartments in Jonah Field are documented to be structurally defined, with faults acting as lateral pressure seals.

Fig. 4.11 also indicates that mud weights are higher on the Pinedale Anticline than at Jonah and that the Pinedale Thrust is a distinct pressure barrier between the two fields. There is a significant increase in maximum mud weight (level of overpressure?) across this fault, from 11.3 lbs/gal to 13.2 lbs/gal. Deformational history thus appears an important determinant of differences in overpressure and its detailed distribution.

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Conclusions

The data and discussion included in this chapter provide strong evidence for a high degree of lateral and vertical compartmentalization within the Lance Formation and, by extension, the upper Mesaverde Group. Such compartmentalization is caused, apparently, both by structural and depositional factors. Structural factors appear to have particular relevance at larger levels of scale, with the possible important exception of fracturing. Depositional factors, on the other hand, are crucial at the well bore scale.

Examination of lithology, reservoir quality, well log patterns, mud weight data and other information indicates that compartmentalization within the Lance is below current well spacing (20-40 acres). Examples of closely spaced wells (< 100 ft) show significant changes in sandstone occurrence and thickness. This implies that drainage radius can vary considerably for different productive sandstone zones within a vertical section of Lance. Sand bodies tend to be narrow and elongated; thus closely spaced wells oriented in the strike direction for a particular sand body may drain the same reservoir, but not others. Any thick vertical section of Lance includes sand bodies of different geometry and orientation, a fact confirmed by dipmeter logs.

An important, as-yet insufficiently studied aspect to compartmentalization is the degree and distribution of natural fracturing. Using data from the recently shot 3-D seismic surveys over the Pinedale structure, detailed fault mapping and fracture identification can perhaps now be done (see Chapter 2). Pressure prediction from 3-D seismic data is also a possibility for future scientific study.

In general, the overall reservoir system at Pinedale appears more complex and dynamic than at nearby Jonah Field, and will likely require more extensive analysis to accurately characterize. One important aspect that the two productive areas share, however, is that close borehole spacing (e.g. 10 acres) is justified to adequately drain the large vertical thicknesses of reservoir involved. Using multiple boreholes from single pads would appear an advisable approach.

Editor's Note:
All figures courtesy of Ultra Petroleum