Productive Wrench Grabens Imaged on 3D Seismic, Tiger Ridge Field, Blaine and Hill Counties, Montana

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Summary

The Tiger Ridge field was discovered in 1966 and has produced over 288 BCF from fault traps created by gravitational sliding off of the Bearpaw Uplift during the Eocene (48-58 mybp). The primary reservoir is the marine shoreface facies of the Upper Cretaceous (Campanian) Eagle Sandstone, which has porosities ranging from 18-30% and permeabilities ranging between 50 and 250 md in the field area. Production occurs in fault blocks ranging in size from <100 acres to over 2000 acres, with individual wells producing between 50 mmcfg and 13 bcfg. Before 2006, exploration for these fault blocks was done using subsurface mapping and an extensive 2D seismic grid. This mapping had identified several large tear faults that separate the field into areas where the local faulting has a similar style and grain. These tear faults often bifurcate and create large grabens that have been considered non-prospective because the 2D data does not allow features within them to be imaged and mapped with confidence. In early 2006 the first 3D survey in the field was acquired by Devon Energy. The Cricket 3D survey was designed to image the faults that control the gas accumulations and allow for continued development in the field. Using the 3D data, an area previously identified as a graben was found to contain several tilted fault blocks that provide a favorable trapping configuration for Eagle gas accumulations. Although in many areas the grabens are only a few hundred feet across, in this particular area the graben-bounding faults are more widely spaced, with the graben being several thousand feet across. Individual fault blocks within the graben that contain Eagle Sandstone cover about 35 acres and are rotated and tilted in a consistent direction. The graben-bounding faults exhibit both normal and reverse throw along their trace, indicative of lateral offset. Despite having minimal throw in some areas, these faults effectively separate fault blocks within the graben from productive fault blocks outside the graben. This allows Eagle gas wells separated by only a few hundred feet and at a similar structural elevation to produce from separate accumulations with no interference across the graben-bounding faults. Since acquiring and interpreting the Cricket 3D survey, Devon has acquired two additional 3D surveys in the Tiger Ridge field and is continuing to identify and exploit accumulations that would not have been found using only 2D seismic data.

Introduction

With only 2D seismic, the wrench aspect of the larger graben-bounding faults was not well understood in Tiger Ridge. Fault correlation from 2D line to 2D line does not always make sense because variations in throw and miss-ties are common. On 2D seismic, these large grabens were identified primarily on the basis of consistent fault trends and poor intra-graben data quality (due in part to shallow velocity variations within the graben areas). Intra-graben prospects have not been common and wells drilled in the interpreted grabens were prone to failure due to low structural position (relative to the gas column), and due to complex intra-graben faulting. Migration of the 2D data rarely allowed adequate resolution of steeply dipping intra-graben reflectors.

One of the key ideas that came about because of the Cricket 3D survey was that the blocks internal to the large Cricket Graben moved independently from the blocks outside of the graben, thus allowing variability in the throw across the graben-bounding faults. Farther to the south, in Section 5, 30N-18E, the narrow portion of the graben has clear normal offset of as much as 250 feet. As the graben widened to the north (Figure 2), larger interior blocks between the graben bounding faults were rotated, resulting in fault blocks that dip counter-regionally to blocks outside the graben, and are steeply dipping. This rotation resulted in variable offset relative to blocks outside the graben.

Evaluation of the 3D seismic shows that Bearpaw Uplift graben systems are more complex than previously thought based on 2D seismic analysis and well control. During the uplift of the Bearpaw Mountains, large blocks of Judith River, Claggett, Eagle and Telegraph Creek slid North and South off of the structure along Niobrara glide planes. In Tiger Ridge, the more competent Eagle broke into smaller blocks and separated along these larger N-S trending zones of weakness to form grabens. The blocks moved at different rates, causing apparent wrench motion along the grabens. As previously discussed, the lateral movement caused rotation of the intra-graben fault blocks. The less competent Claggett and Judith River formations slumped into any available accommodation space, particularly into voids left in larger grabens. Later, the grabens also acted as conduits for distribution of extrusive volcanics. Steeply dipping Judith River, Claggett and volcanic rocks add to the complexity of the reflectors within the grabens. Imaging issues associated with steeply dipping beds and rapid velocity variations require 3D migration to observe complex intra-graben geometries.

Structural Interpretation

The “Cricket” wrench graben, shown in the Eagle Shoulder structure map (Figure 1), and interpreted on the 3D survey, shows bounding faults which have variable vertical offset from 250 feet normal to 25 feet reverse offset. The interior structure of the graben is dominated by northwest to southeast trending faults, which are down-to-the-south normal faults. Each block is high on the northeast corner and low on the southeast corner (Figure 2). The structuring on these blocks appears to post-date the formation of the graben and appear to be related to differential movement on the bounding graben faults as previously discussed. The widening of the graben, coincident with these “inter-graben” fault blocks may be related to duplexing and thickening of the Upper Niobrara.

Prior to acquisition of the 3D survey, several wells had been drilled within the boundaries of the graben, all in a downdip and/or faulted-out position. Several pre-3D wells drilled inside the graben were not optimally placed to test the interior blocks. These wells, highlighted in yellow on Figure 1, were drilled on the basis of limited 2D data and penetrated faults or entered the Eagle in downdip positions. The Dehlbom 32-11-31-18, 32-11A-31-18, the Ramberg 29-13-31-18 and the Paulson 32-4-31-18 found non-commercial gas in a downdip position due to thin pay. The Paulson 32-4-31-18 drilled in 1972 has 31 ft of net pay in a downdip position, but never produced.

The Paulson 32-02-31-18 which was more optimally placed on the updip portion of the northernmost graben block, tested 42 of net pay and is expected to produce an economic volume of gas. The Paulson well, which had a unique gas/water contact relative to wells outside the graben, was considered to be an excellent indicator that there could be additional potential in the graben. This well showed that economic quantities of gas could be found in "graben" blocks. This well also showed that the Eagle Formation within the interior fault blocks could be prospective due to the fact that adjacent wells, outside the graben, are not in pressure communication across the large bounding grabens. The intra-graben normal faults also seem to further compartmentalize the Eagle reservoir. While the larger and older bounding-graben faults appear to cut deeper, into the lower Niobrara near the top Carlisle, the intra-graben faults are mostly normal faults that appear to sole out in the Upper Niobrara shales. These faults have a significant amount of offset (20-50 feet estimated.)

With the acquisition of the Cricket 3D survey, previously unidentified structural styles and prospecting pitfalls were brought into the prospect identification work flow. Wrench faulting, while always a factor in Rocky Mountain geological interpretation, was not considered to be significant in previous 2D fault block interpretation. With the addition of the 3D seismic, it became clear that wrench faulting was not only common in this area, but perhaps important as a way to compartmentalize "pressure cells/" The 3D interpretation and depth conversion resulted in the Eagle Shoulder structure map shown in Figure 1 and resulted in the staking of four intra-graben prospect wells.

Graben Drilling Program

The first well drilled in the Cricket Graben (post Cricket 3D) was the Kane 32-10A-31-18, which TD'd July 2007. Figure 2 shows a map with all post-3D graben wells drilled in 2007 and 2008 and the line of section for the arbitrary seismic line in Figure 3. The seismic line in Figure 3 shows that the Kane 32-10A-31-18 well and subsequent wells were drilled in the most updip portion of each intra-graben fault block. The Kane 32-10A-31-18 well was drilled mere hundreds of feet from the Dehlbom 32-10-31-18, across the graben-bounding fault. The Kane well found 62 ft of net pay, and is expected to be a good producer for this field. The Dehlbom well had a pressure of 60 psi in 2004 after producing for six years. The Kane 32-10A-31-18 graben well had an initial pressure greater than 300 psi, which is excellent for these shallow Eagle reservoirs, and shows clear pressure separation between the two wells. All of the post-3D Cricket Graben wells have Upper and Middle Eagle pay. The Kane well confirmed the structure and more importantly confirmed the presence of separate pressure compartments within the graben.

The three additional intra-graben prospects drilled in 2008 are the Dehlbom 32-14A-31-18, Dehlbom 32-7-31-18, and Dehlbom 32-14-31-18, which were drilled in additional fault blocks, as shown in Figures 2 and 3. These wells have 84, 73, and 65 ft of Eagle net pay, respectively, and are expected to be good Eagle producers (Table 1). The Kane 32-10A-31-18, which has had good initial production, is expected to perform well, based on production data from the past year and a half.

Conclusions

As additional 3D surveys are acquired in the Tiger Ridge field, it is expected that additional graben locations will become viable for infill drilling. The four wells drilled in the Cricket Graben total a significant amount of added reserves for the Tiger Ridge Eagle asset. These wells would not have made an attractive target based on existing 2D data alone. The 3D seismic offered insight into additional structural styles that can be considered on the 2D data or 3D data in this structurally complex area. Additional "graben" block prospects may be found in mature portions of the field if intra-graben blocks and wrench structural styles are considered.

Acknowledgements

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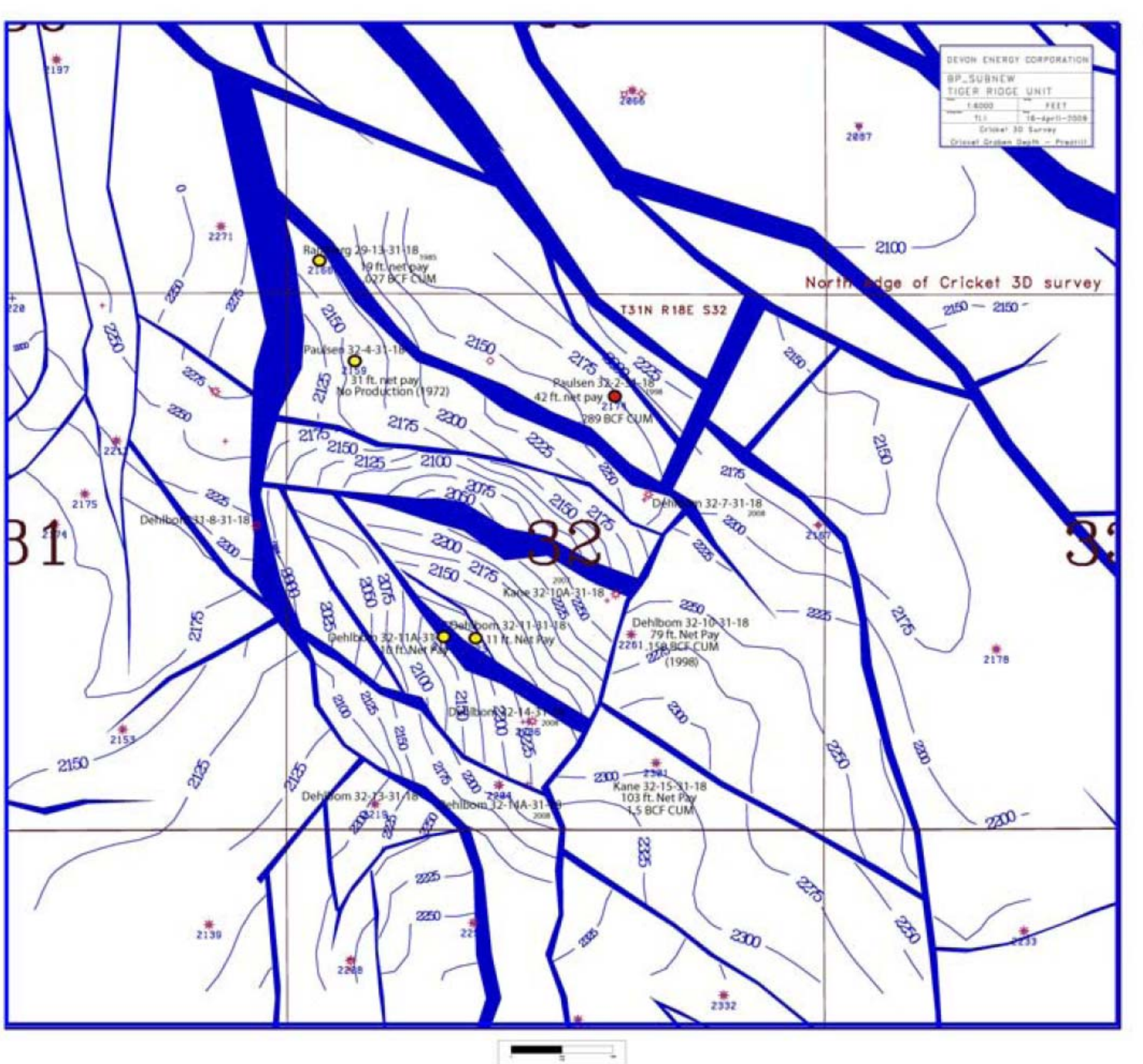

Figure 1. Eagle Shoulder structure map. Pre-3D wells have been highlighted. The Paulson 32-2-31-18 well, which had 42 feet of net pay, is shown in red.

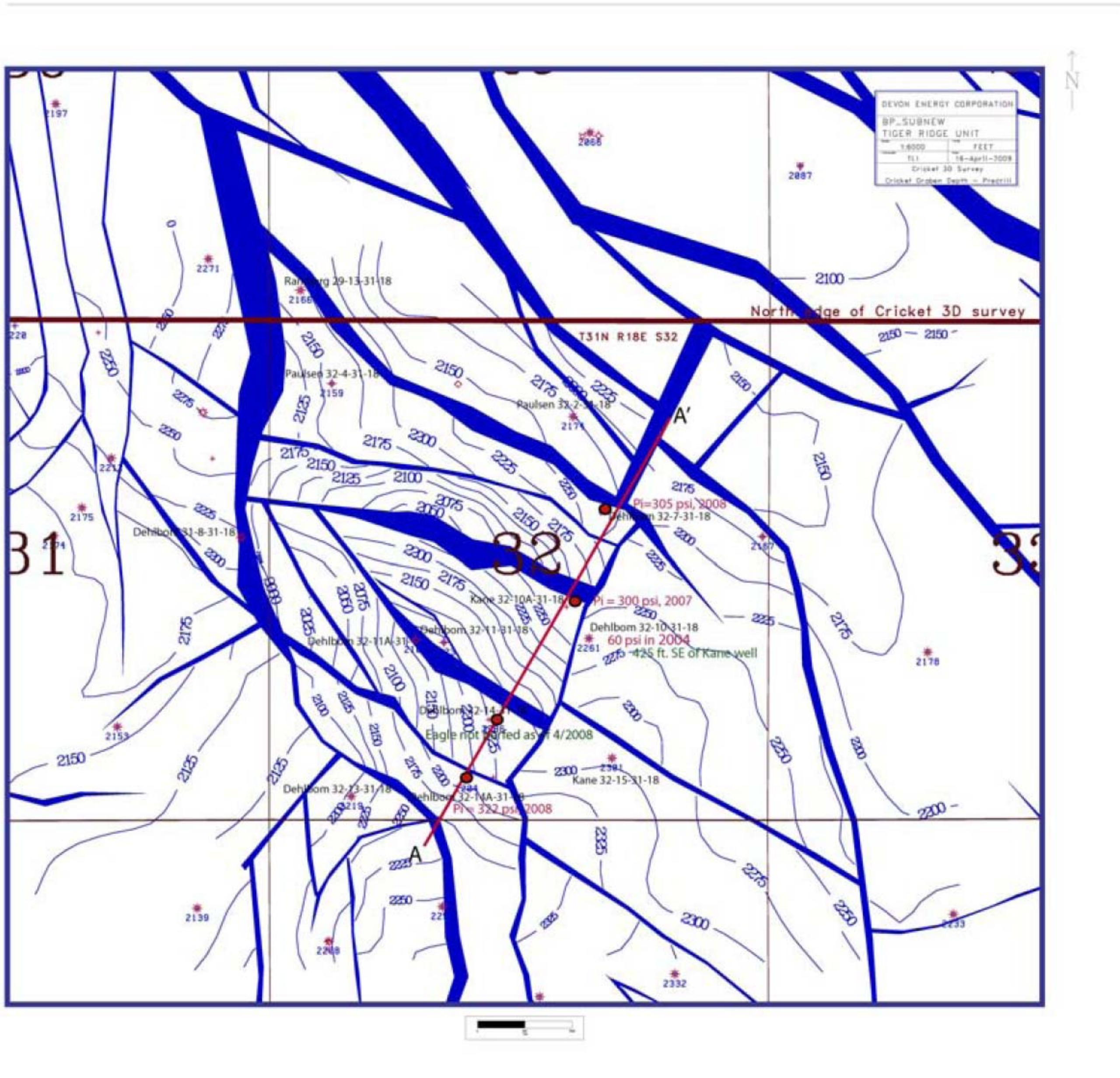

Figure 2. Eagle Shoulder structure map, with post-3D wells dip seismic line trajectory. Initial pressures are shown.

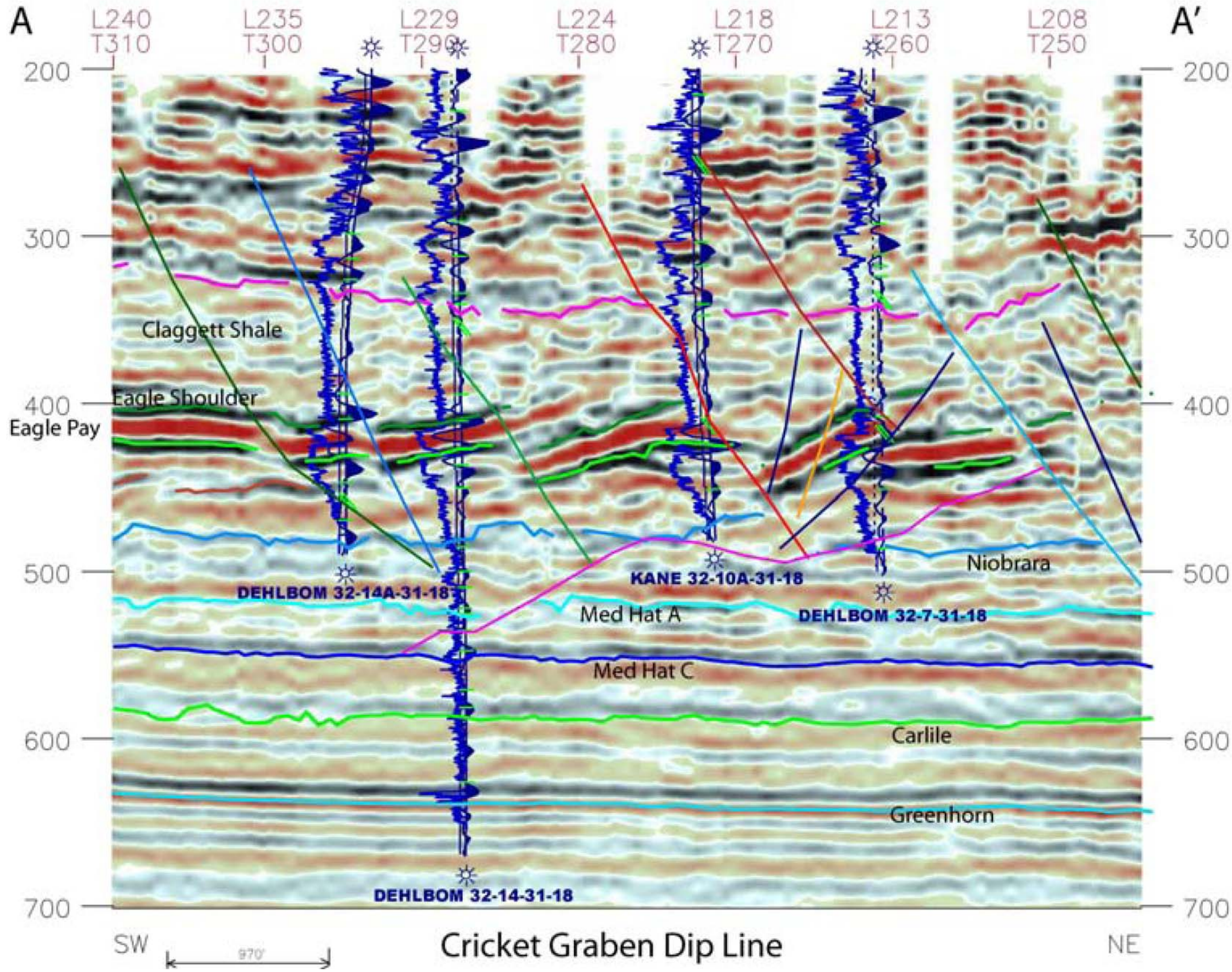

Figure 3. Dip seismic line across intra-graben fault blocks. Post-3D wells are shown.

UWI (API)	Spud Date	Well Name	Well Number	Block size	Actual Eagle Net Pay	Initial Pressure
250052368500	11/8/2007	KANE	32-10A-31-18	46	66	Pi = 300 psi
250052372800	7/16/2008	DEHLBOM	32-14A-31-18	32	92	Pi = 322 psi
250052371200	7/23/2008	DEHLBOM	32-7-31-18	35	81	Pi = 305 psi
250052371300	8/4/2008	DEHLBOM	32-14-31-18	33-45	77	Not tested to-date

Table 1. Summary of graben-well Eagle reservoirs in post-3D wells.