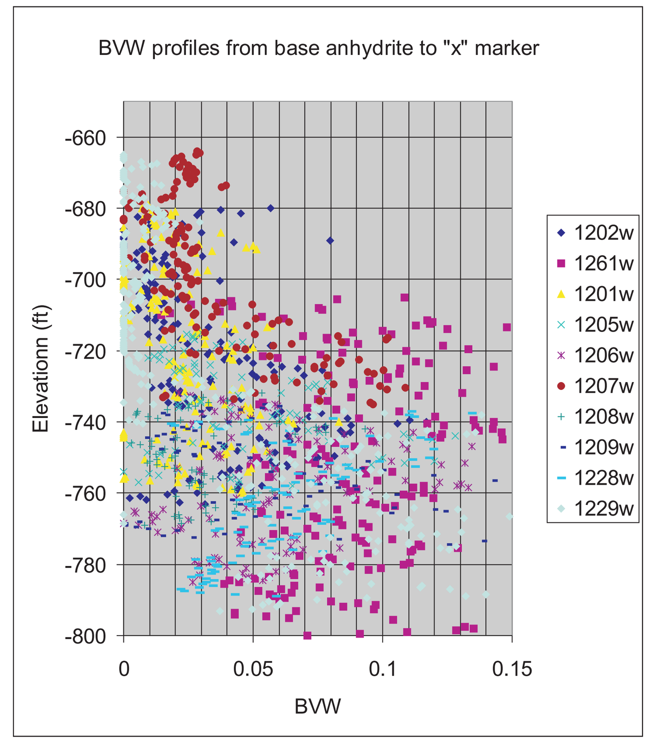
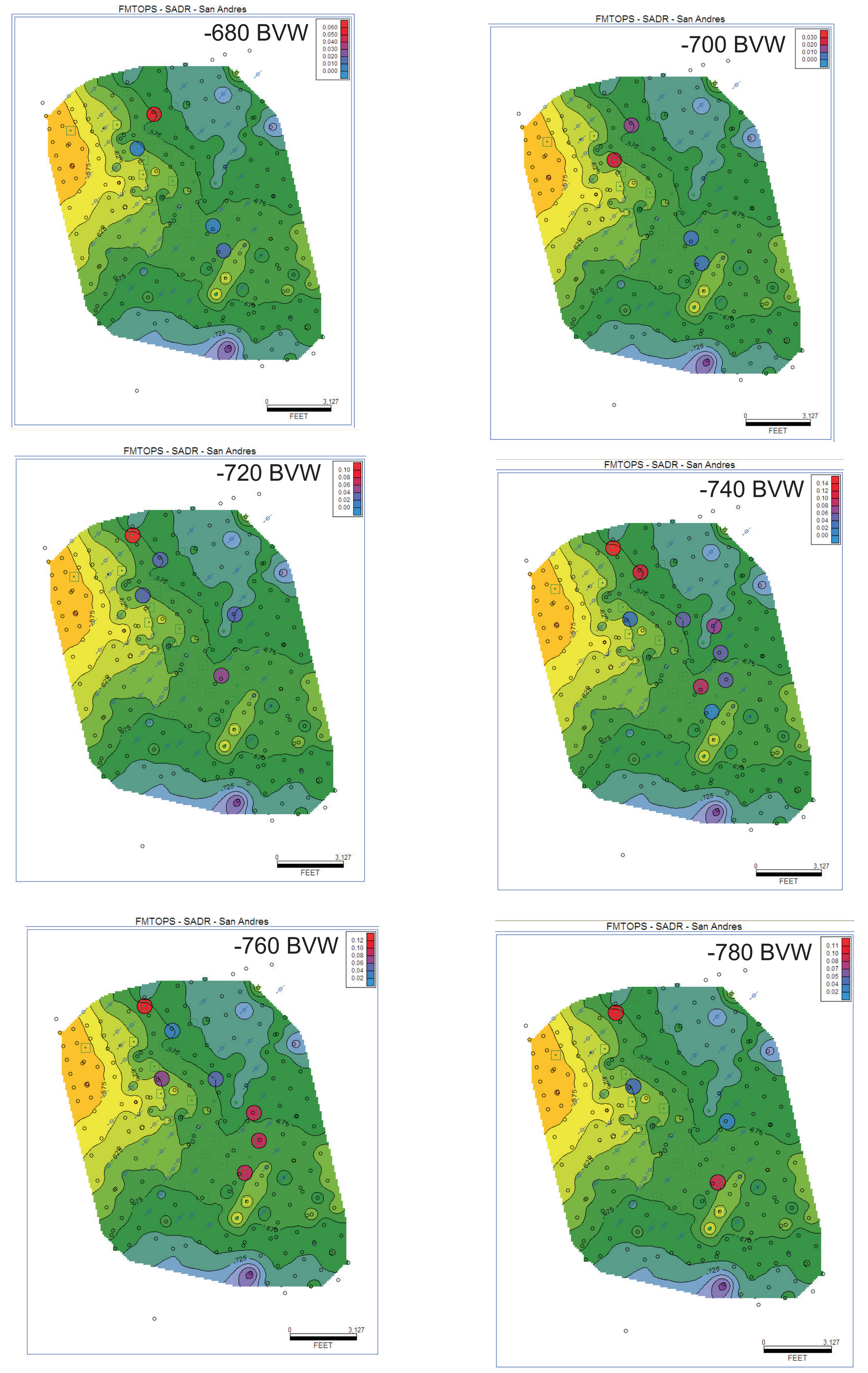
RESERVOIR CONNECTIVITY AND COMPARTMENT BOUNDARIES

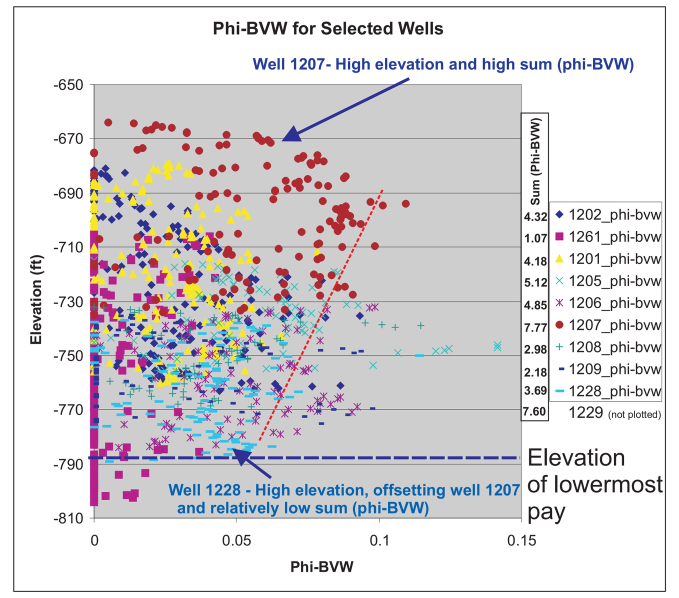
BVW ANALYSIS

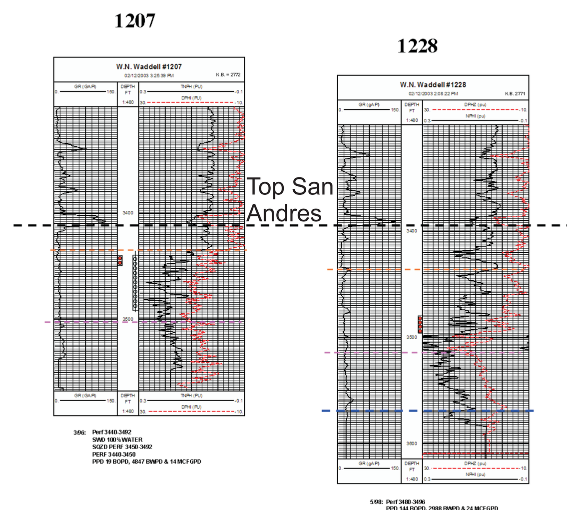




Bubble maps of BVW at a given elevation (subsea in feet) are superimposed on the top of San Andres subsea depth map. These maps show a range in BVW values that are not closely tied to elevation on top of the San Andres Formation. Moreover, values vary markedly by depth in an individual well, reflecting the variation of porosity in the cyclic packstone-grainstone interval. The depth slices also do not show any pattern of BVW variation with depth, paralleling the BVW vs. depth plot above. This lack of depth pattern indicates that there is not a strong field-wide transition zone, but rather local well-scale variations in reservoir properties.

PHI-BVW ANALYSIS

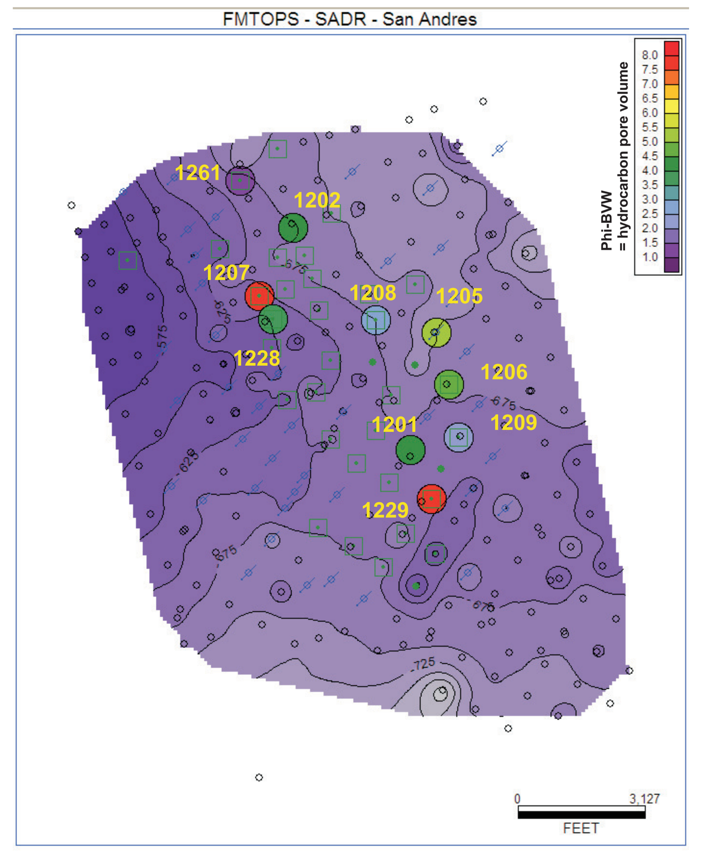




Phi-BVW depth profiles (left) of wells #1228 and adjacent #1207 are on opposing ends of the depth cluster. Well #1228 is more tightly clustered at lower values at greater depth due the presence of thick karst, while the phi-BVW points associated with well #1207 are noticeably higher at higher elevations. While both wells are essentially the same elevation at the top of San Andres, as can be seen in the map below, the deeper karst at the location of well #1228 leaves pay in the packstone-grainstone facies at greater depths. The contrast in location of the porous interval in these two wells can be observed in the cross section on the right.

Observations of the Phi-BVW depth profile plot:

- Well #1261 is nearly the lowest in elevation and has the smallest cumulative Phi-BVW of 1.07.
- Well #1202 is adjacent to well #1261 and at the same elevation at the top of the San Andres, as seen in the map at right. However, the pay interval in #1202 occurs at a higher elevation due to thinner overlying karst. The additional pay interval and higher elevation apparently led to a relatively high cumulative phi-BVW of 4.32 vs. 1.07.
- Well #1205, near well #1208, has the lowest top of San Andres, but pay is relatively high and cumulative phi-BVW is moderately elevated, 5.12, compared to 2.98. Phi-BVW profiles are similar in pattern, but elevation of pay in #1205 is higher due to less deeply penetrating karst. Thus additional section is available for hydrocarbon accumulation.
- Well #1228 is located adjacent to well #1207 in a structurally high position on the top of the San Andres, but the pay interval is around 35 feet lower. The phi-BVW profiles are in sharp contrast to one another, 7.77 (one of the highest values) vs. 3.69. Additionally, the maximum pay values (phi-BVW) for individual points decline from 0.1 to 0.5 in well #1228, as indicated by the orange dashed line in the phi-BVW depth plot. Other wells follow this trend of phi-BVW decline with depth suggesting a decline in hydrocarbon saturation, perhaps an indication of transition.
- Most of the indications of pay (phi-BVW), other than in well #1261, reside at elevations above -788 feet. This may be an indication of the proximity of an oil/water contact.



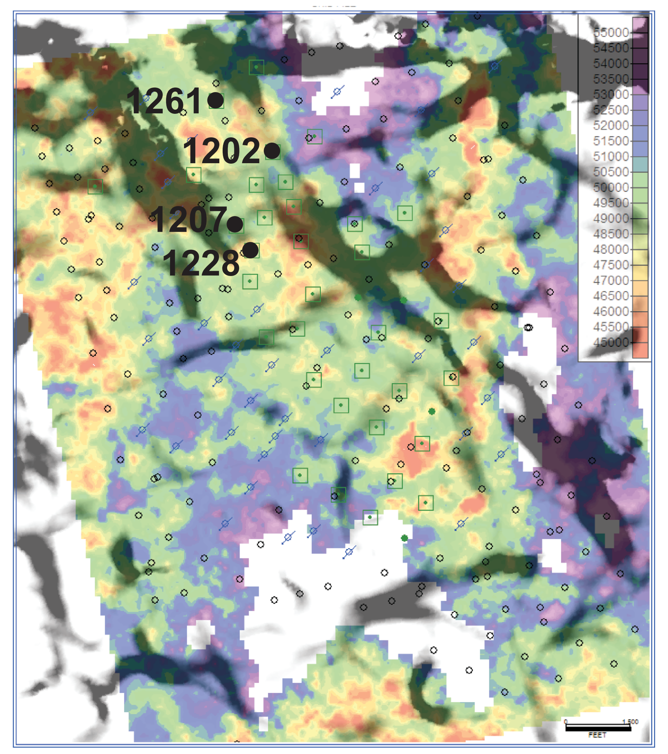
Structure map top of San Andres Formation. Bubbles depict cumulative Phi-BVW in the pay intervals of each well. Phi-BVW is an indication of hydrocarbon pore volume. No clear pattern is noted, including offset wells with large contrast in pay and structurally low wells with higher pay calculations. Maps of cumulative oil and gas production in the "high volume area" show similar variation on a well-to-well level.

SEISMIC ATTRIBUTE ANALYSIS

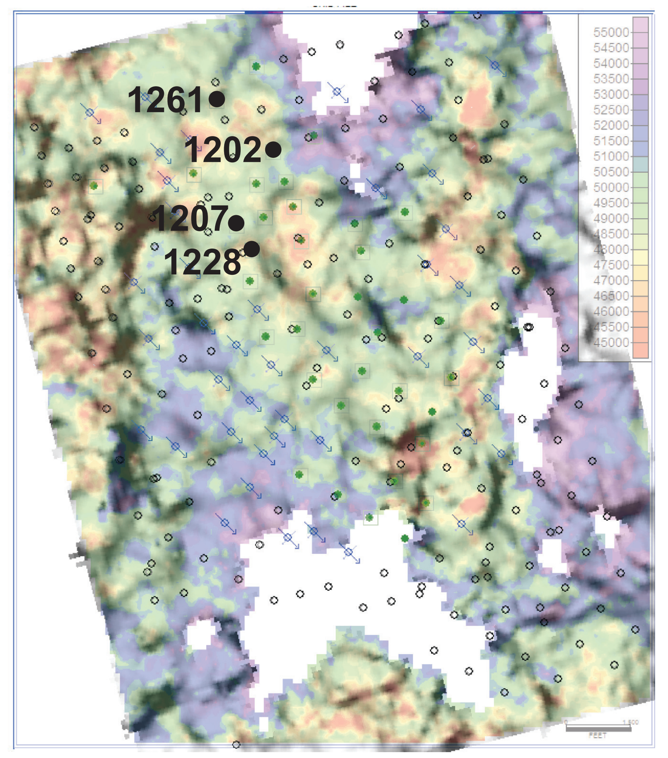
Low mean impedance in the reservoir interval has been shown to correspond generally to high mean porosity. However, lower mean impedance also appears to correlate with lower cumulative hydrocarbon pore volume from Phi-BVW, as is shown by wells #1261 and #1228 (which have a thicker karst zone), compared to wells #1202 and #1228 (which have a thinner karst zone). This correspondence between high porosity and low hydrocarbon pore volume is most likely explained by the fact that the high porosity is developed deeper in the reservoir interval (as was indicated by the center of gravity map) and in areas with thicker karst, the lower porosity upper reservoir will be cut out, so that only the deeper high porosity interval will contribute to the mean porosity.

A most positive curvature map (showing antiform bending) extracted from the seismic data volume along a Devonian horizon approximately 0.6 seconds below the San Andres shows that there is a significant deep-seated structural control to the northwest-trending features in the "high volume area". As can be seen by the interleaved most positive curvature and mean reservoir interval impedance maps, there is also an indication that crosscutting north to northeast-trending features on the Devonian surface also impacted porosity development in the San Andres.

A most positive curvature map extracted along the "x" marker shows some of the same structural trends as the Devonian horizon but also shows a finer network of lineaments that enclose areas with diameters on the order of 1500 ft (450 m). These features may indicate reservoir compartmentalization at a single-well scale.



Most positive volumetric curvature extracted along a Devonian horizon (approximately 0.6 seconds below the San Andres) superimposed on the mean impedance map for the base karst to "x" marker interval. Black corresponds to tight positive (antiformal) curvature.



Most positive volumetric curvature extracted along the "x" marker horizon superimposed on the mean impedance map for the base karst to "x" marker interval. Black corresponds to tight positive (antiformal) curvature.

GENERAL OBSERVATIONS OF PHI-BVW PLOTS AND MAPPING

After petrophysical cut-offs are applied and the pay intervals of reservoir are identified, effective porosity can be subtracted from the BVW, the bulk volume water, to estimate hydrocarbon pore volume. Displaying a depth profile of phi-BVW can provide an indication of a hydrocarbon transition zone, where values decrease with depth, eventually dropping to zero at the hydrocarbon/water contact. Similarly, widespread scattering of points with no pattern reveals complex heterogeneity with no transition zone or oil or gas water contact.

The phi-BVW depth plot shows some vague patterns related to local reservoir heterogeneity that appears to be developed at the well scale, related to the strong karst overprinting that has generally reduced the more continuous pay developed in the overlying grainstone-packstones. Thus, karst diagenesis pays a significant role in the heteogeneity in the "high volume area".

Well-scale heterogeneity is similarly reflected in the cumulative production and seismic attribute data. Seismic attribute analysis suggests an element of structural control on this heterogeneity.

CONCLUSIONS

- A wide range of fluid recoveries is noted in wells in the "high volume area" of Waddell Field. Higher production generally comes from 1) the main structural high, 2) along the northeast flank of the southeast-trending anticline that runs through the area, and 3) along a narrow northeast-trending area roughly corresponding to a structural saddle on the anticline.
- In the "high volume area", tight, anhydritic "macro" karst at the top of the San Andres Formation cuts down into the underlying porous reservoir.
- The karst zone exhibits high variability in thickness but is generally thicker on the higher portions of the southeast-trending anticline.
- The porous carbonate reservoir interval below the karst is locally thin on the saddle area of the anticline.
- A seismic horizon corresponding to the"x" marker (base of porous reservoir) can be interpreted across the impedance volume. This horizon is truncated by the base of karst in some areas, suggesting an associated change in reservoir type/quality in these areas.
- A comparison of mean and center of gravity measures of porosity indicates that higher porosity is developed lower in the pay interval.
- The mean seismic impedance of the reservoir interval corresponds well with mean porosity from well logs and allows porosity approximation in areas of poor well control.
- The impedance maps suggest that the porous San Andres shoals that comprise the pay appear to have N-NE trends, oblique to the main San Andres structure.The pattern of shoal development may be controlled by deep-seated structure.
- Local karst development appears to be at a well scale, greatly reducing the reservoir quality, which causes variability in oil and gas production, even within this high volume area
- A combination of factors appears to be responsible for the pay distribution in the high volume area of Waddell Field.

References

Bohling, G.C., J. H. Doveton, W. Guy, W.L. Watney, and S. Bhattacharya, 1998, PfEFFER 2.0 manual, Kansas Geological Survey, Lawrence, Kansas, 161 pp.

French, V. L., and C. Kerans, 2004, Accommodation-controlled systems-tract-specific facies partioning and resulting geometric development of reservoir grainstone ramp-crest shoal bodies, in Integration of outcrop and modern analogs in reservoir modeling: AAPG Memoir 80, p. 171-190.

Kerans, C., F. J. Lucia, and R. K. Senger, 1994, Integrated characterization of carbonate ramp reservoirs using Permian San Andres Formation outcrop analogs, AAPG Bulletin, v. 78, p. 181-216.

Ruppel, S. C., and D. G. Bebout, 2001, Competing effects of depositional architecture and diagenesis on carbonate reservoir development: Grayburg Formation, South Cowden field, west Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 263, 62 p.

Ward, R. F., C. G. St. C. Kendall, and P. M. Harris,1986, Upper Permian (Guadalupian) facies and their association with hydrocarbons--Permian Basin, west Texas and New Mexico: AAPG Bulletin, v. 70, p. 239-262.

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