Petrophysical and Geophysical Characterization of Karst in a Permian San Andres Reservoir, Waddell Field, West Texas

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ABSTRACT

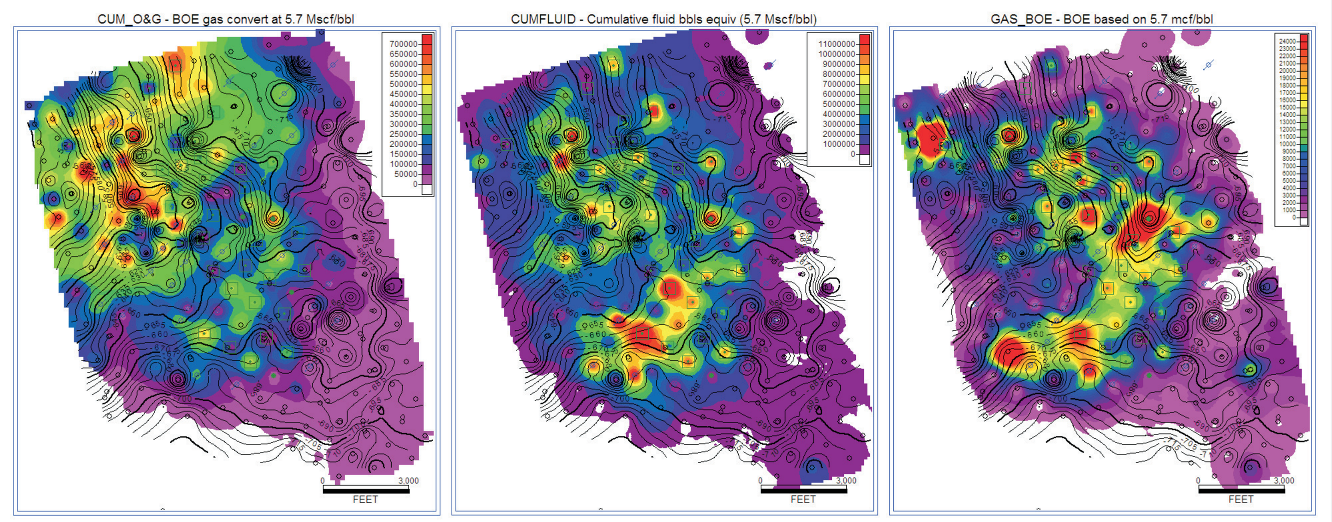
A significant number of carbonate reservoirs worldwide have been modified by karst. Karst can impact reservoir performance either by enhancing or destroying porosity/permeability.

We integrated core, log, 3D seismic, and production data to identify the nature, distribution, and impact of karst in a Permian San Andres carbonate reservoir in Waddell Field, west Texas. The reservoir in our study area is highly compartmentalized and fluid production is extremely variable. Reservoir heterogeneity appears to be related to stratigraphy and diagenesis, as well as karst features associated with a subaerial exposure surface at the top of the San Andres Formation. Core data indicate that the uppermost San Andres consists of sporadically porous "macro" karst, characterized by intense chaotic brecciation and anhydrite replacement, followed by isolated, late stage anhydrite dissolution. The karst overprints high frequency sequences composed of gypsiferous oolitic, fusulinid, and skeletal packstone-grainstone reservoir rock with moldic, vug, and fracture porosity. We used wireline log petrophysical solutions to quantitatively discriminate the anhydritic karst from the underlying packstone-grainstone strata in uncored wells. The base of the karst zone corresponds to a sharp decrease in seismic impedance, and 3D seismic data are used to map the base of karst between wells. The karst zone exhibits high variability in thickness; however, the zone is generally thicker on higher portions of a SE-trending anticline that runs through the study area, suggesting a structural control on karst development. Seismic data show that the karst zone truncates the base of the porous reservoir in some areas and seismic attributes reveal potential reservoir compartment boundaries. Better understanding of local karst control on fluid flow in this reservoir can improve reservoir management decisions.

BACKGROUND AND PURPOSE OF STUDY

An approximately 2 square mile (5 square km) area of Waddell Field, in the Permian Basin of west Texas, is characterized by variable fluid production, with overall fluid production an order of magnitude greater than in surrounding areas of the field. Recoveries of oil and gas for wells in and adjoining this "high volume area" range between 100 M BOE and 1 MM BOE per well. Overall, nearly 50% of the wells produce 250 M BOE or less. In the high volume area, production is typically 300 M BOE and more per well.

Operator-interpreted tracer and pressure data indicate a highly compartmentalized reservoir with an active water drive. Reservoir heterogeneity appears to be related to stratigraphy and diagenesis, as well as anhydrite-cemented karst features associated with the subaerial exposure surface developed on the top of the Permian San Andres Formation.



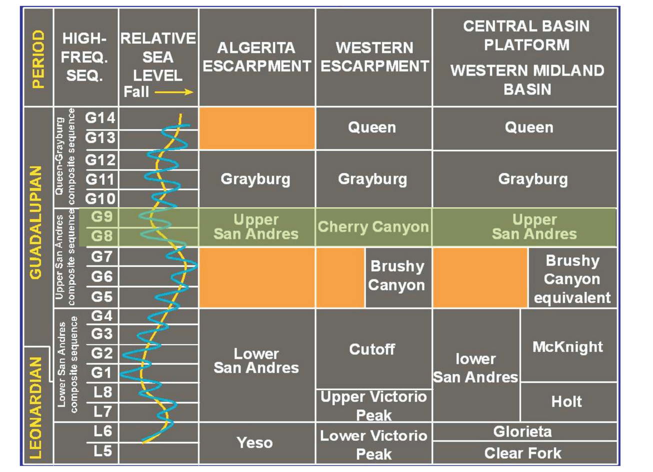
Cumulative oil and gas (left), cumulative total fluid (oil+gas+water) (center), and cumulative gas (right) maps in barrels of oil equivalent (BOE) showing the "high volume area" of Waddell Field. A conversion factor of 5.7 MCF gas to one equivalent bbl of oil was used in the conversion to BOE. Depth contours for the top of the San Andres Formation are superimposed.

The present study aims to characterize the variability within the San Andres reservoir by making use of a variety of geological, petrophysical, and geophysical analyses. In particular,

- Multi-mineral models are essential for estimating effective porosities that provide good matches with core.
- Statistical zonation of well logs provides a consistent method for identifying the base of karst.
- Seismic horizon mapping provides details on the configuration of the reservoir interval.
- Seismic impedance allows us to determine interwell porosity variation.
- BVW profile analysis is useful for assessing spatial continuity of the reservoir.
- Multi-trace seismic attributes, such as volumetric curvature, provide added detail in our interpretation of reservoir compartmentalization.

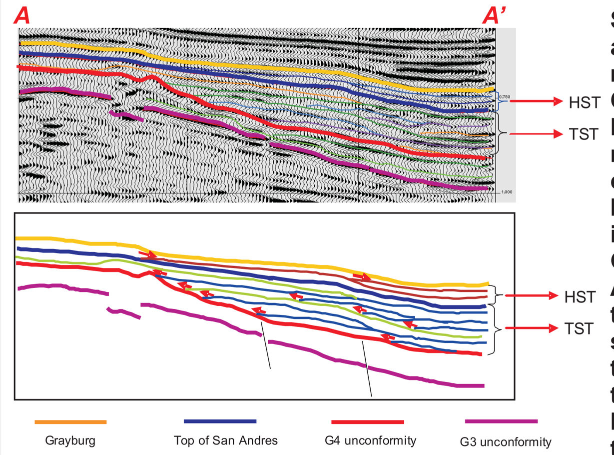
GEOLOGICAL SETTING

The sequence framework for the Upper Permian (Guadalupian) San Andres Formation is based on the study of surface exposures in the Guadalupe Mountains of West Texas. The dolomitic reservoir in Waddell Field is comprised of cyclic oolitic grainstones, specifically G8 and G9 high frequency sequences (HFS) believed to be 4th-order (0.1-1 Ma) periodicity (French and Kerans, 2004). In the "high volume area", the regional stratal boundary that separates G8 from G9 has not been precisely located and tied into the regional stratigraphic framework.



Stratigraphic column for upper Leonardian and lower Guadalupian section in the Permian Basin. After Ruppel and Bebout (2001).

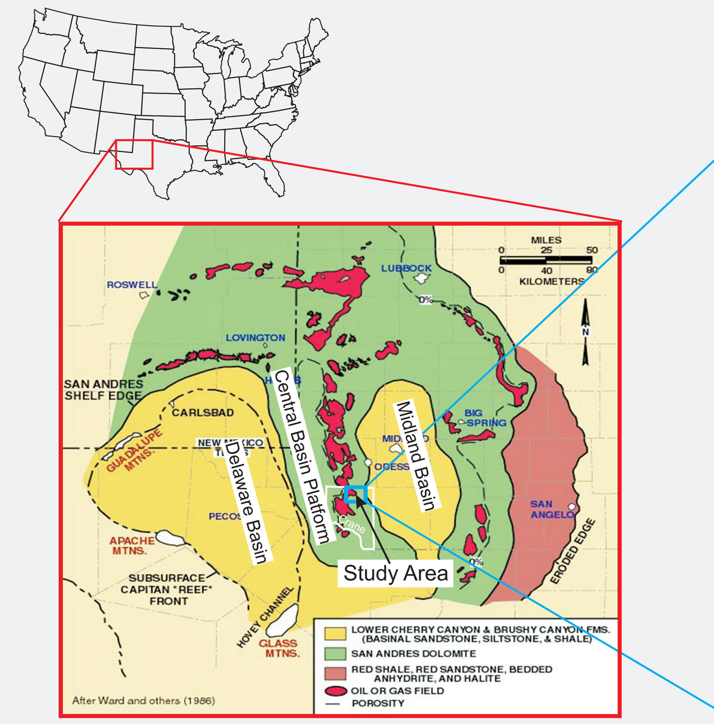
The G8 and G9 HFS reservoir interval overlies a regional bypass surface corresponding to the top of the Brushy Canyon in the outcrop (also equivalent to the top of G4 HFS). Interpretations of surface exposures of these strata indicate that the inner and middle ramp lithofacies during the G8 HFS underwent backstepping, while the G9 HFS was involved in forward stepping, reflecting relative fall in sea level (French and Kerans, 2004). These observations, coupled with seismic interpretations on the eastern edge of the Central Basin Platform (Qifeng Dou, pers. comm.), suggest that the succession of oolitic shoals in Waddell Field are comprised of a retrogradational to aggradational to progradational stratal architecture resulting in southeastward lateral accretion of a shallow shelf through Waddell Field toward the eastern margin of the Central Basin Platform.



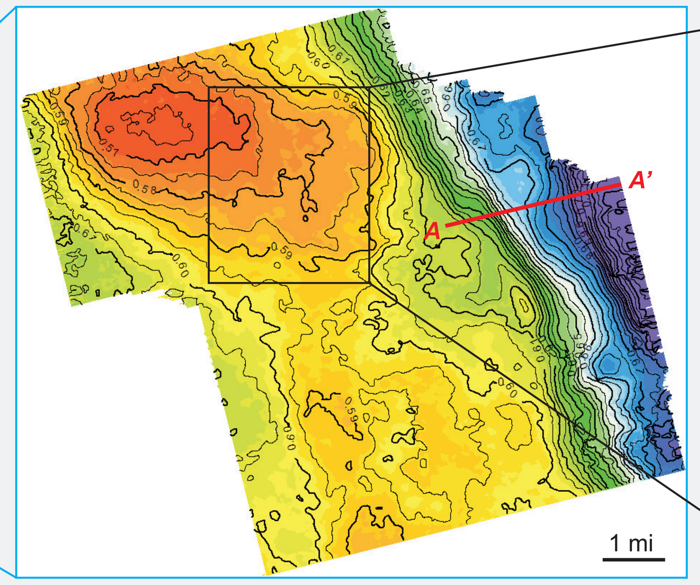
Seismic profile *A-A'* across the shelf margin of the Central Basin Platform showing reflector configurations that lead to the interpretation of the G4 to top San Andres as a transgressive systems tract and the top San Andres to Grayburg as a highstand systems tract.

Structurally, the "high volume area" of Waddell Field is located on the east central flank of the Central Basin Platform.

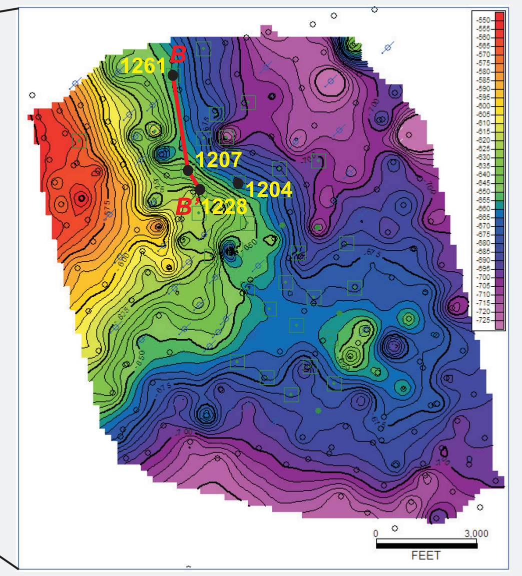
The northwest portion of the "high volume area" is structurally higher than areas to the south and east, although the highest structure does not correspond to the highest production. A southeast-trending plunging anticline approximately two miles long crosscuts the study area, showing a relief of approximately 75 ft (23 m) and a width of approximately one mile (1.6 km). A shallow saddle in the central mapped area exhibits elevated gas and total fluid production.



Simplified geological map of the San Andres Formation in the Permian Basin showing locations of major oil fields (Scholle, http://geoinfo.nmt.edu/staff/scholle/guadalupe.html; after Ward et al.,1986). Our study area is in Waddell Field, northern Crane County, TX, located on the east central flank of the Central Basin Platform.



A time structure map of the top of the Grayburg from a 3D seismic survey over Waddell Field shows the regional structural configuration. The black box highlights the "high volume area" study area.

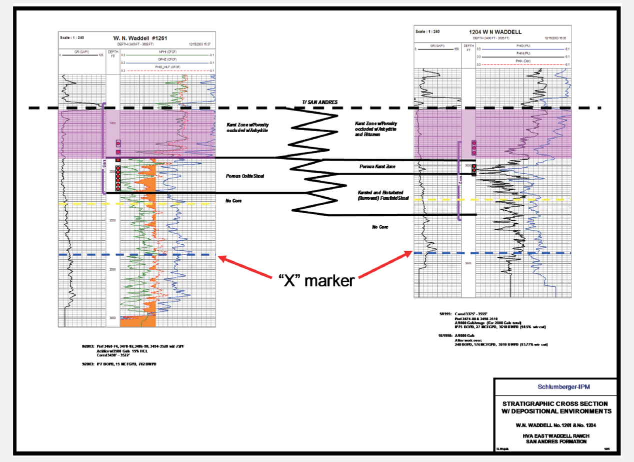


Subsea depth map of the top of the San Andres Formation for the "high volume area" of Waddell Field.

STRATIGRAPHIC ANALYSIS AND PETROPHYSICAL CHARACTERIZATION

LITHOFACIES

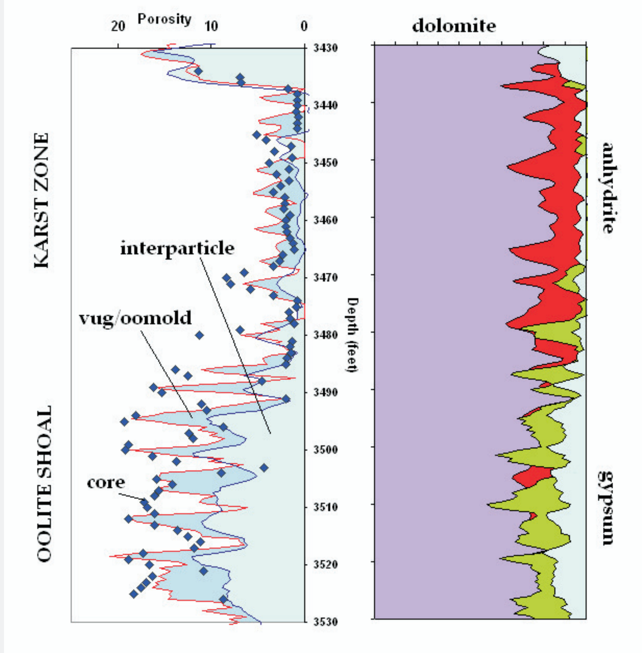
Cores of the upper San Andres Formation were taken from two wells within the "high volume area", W. N. Waddel #1204 and W. N. Waddell #1261. Core descriptions provided by the operator indicate an upper karst interval in these wells involving macroscopic collapse and chaotic brecciation and extensive anhydrite replacement of gypsum in the upper San Andres Formation. In contrast, the "porous karst zone" and "karsted and bioturbated fusulinid shoal" below the main karst zone in well #1204 is less intensely karsted, without macro-scale chaotic brecciation and anhydrite replacement. This cm-scale dissolution and brecciation is recognized here as "micro" karst where the matrix is essentially intact. The matrix properties in the microkarst intervals are also probably dominant in terms of fluid flow. Thus, the lower karsted zones in well #1204 are placed in the in situ bedded carbonate reservoir of the San Andres Formation.



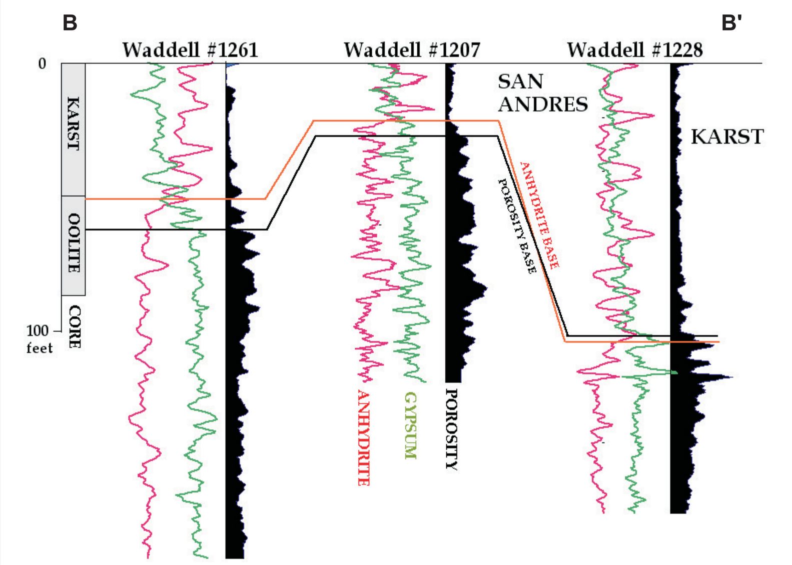
The gross producing interval in the "high volume area" has been identified as the porous zone between the base of the tight, anhydritic karst and an informal stratigraphic marker we have labeled the "x" marker, which lies approximately 150 ft (46 m) below the top of the San Andres Formation. This reservoir interval is composed of shoal-water, oolitic, fusulinid, skeletal grainstones and packstones, characterized by biomoldic and oomoldic porosity with scattered vugs and fractures. The pore space is partly occluded by gypsum, making distinction of true pore space difficult due to the low bulk density of gypsum and its waters of hydration. Log compositional analysis was used to discriminate actual pore space.

POROSITY FROM LOG DATA

Compositional analysis of the cored interval of the San Andres Formation in well #1261 was made using the density, neutron porosity, and bulk photoelectric factor logs to solve for proportions of dolomite, anhydrite, gypsum, and porosity. The sonic log is a good measure of interparticle porosity, but is largely insensitive to larger pores that occur as vugs or oomolds. The compositional solution for the San Andres Formation in well #1261 was used to compute a variable matrix transit time, using weights that matched the proportions of dolomite, anhydrite, and gypsum. This estimate of sonic-derived porosity is shown below left, together with the porosity from the compositional analysis and core measurements of porosity. The porosity estimated from compositional analysis represents a volumetric measure of porosities of all kinds and shows a good concordance with core data. The sonic porosity is a close match with compositional porosity in zones where all the pore space is probably interparticle, but shows distinctive deviations in higher porosity zones where part of the pore space is vuggy or oomoldic. In the karst zone, the sonic porosity suggests that the low pore volumes are dominated by vugs. In the oolite shoal, the higher porosity developments appear to be about equally divided by interparticle and oomoldic pore space.



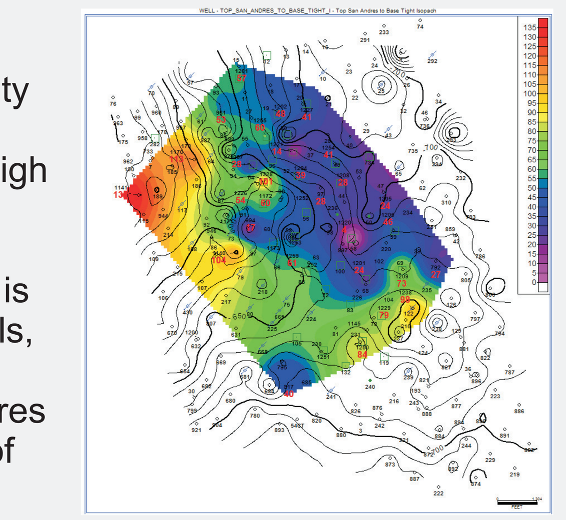
The high content of anhydrite and low porosity of the karst zone was strongly differentiated from the more porous section below the karst which also appeared to be more gypsiferous. Two log variables were used independently to estimate the base of the anhydrite zone: the sonic log and the anhydrite content estimated from the density, neutron porosity, and photoelectric factor curves. The lower boundary of the karst zone was calculated by a zonation program which locates zone boundaries such that variability is maximized between the zones while minimizing variability within the zones (Bohling et al., 1998).



An example of the results of the karstic zone methodology is shown for the cored well #1261 well and two neighboring wells. In well #1261, the core description subdivision of the upper San Andres Formation between the karst zone and porous, oolitic shoal facies is closely matched by the zonation picks based on the sonic and estimated-anhydrite logs. Note the significant variation in thickness of the interpreted karst zone in the three wells.

Estimates of the depth of the base of the low-porosity zone and anhydrite phase at the top of the San Andres Formation were compiled for all wells with density, neutron, photoelectric factor, and sonic logs. In wells where only a sonic log was available, the estimate was restricted to the base of the low-porosity section.

Generally, the thickness of the low porosity Karst zone is greatest on the southeast-trending anticline that cuts through the "high volume area". However, this zone shows high spatial variability, punctuated by anomalies where the "karstic" interval is either markedly thick or thin. In a few wells, there was no evidence of a low-porosity, anhydritic zone at the top of the San Andres and this was interpreted as an absence of karst development.



Isopach map of upper tight zone of San Andres Formation interpreted as karst, with top of San Andres Formation subsea depth contours superimposed.