New insights from a 3D earth model, deepwater Gulf of Mexico

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A 3D earth model, a geophysical / geologic three-dimensional (3D) model of the earth, is best described in terms of its exploration objective. This means that when its geologic target is established, the model is designed to represent the geologic environment surrounding the prospective target. The areal extent covered can range from regional (i.e., hundreds of OCS blocks) to a detailed nine blocks.

At minimum, the earth model is an accumulation of the results of multiple sciences approximating the earth's lithology. At best, through the skilled interpretation of integrating the results of these sciences, it can bring new insight through the refinement of the salt configuration.

The 3D earth model described in this article encompasses 144 square miles—16 OCS blocks in the deepwater region of the Gulf of Mexico. The primary objective—i.e., to establish a quantitative interpretation of the structural configuration of the base of an allochthonous salt mass as shown on Figure 1—was achieved through the following steps:

- Assess the velocity field in the project area and interpret a calibrated clastic sediment velocity model suitable for the generation of the pseudo-density conversion for density / depth surfaces used in the 3D earth-modeling scheme.
- Build a 3D earth model based on detailed full tensor gradient and regional marine gravity data constrained by bathymetry, density / depth surfaces derived from the calibrated clastic sediment velocity model, a seismically interpreted top of salt horizon, the magnetic basement structure surface, and the Mohorovicic discontinuity surface.

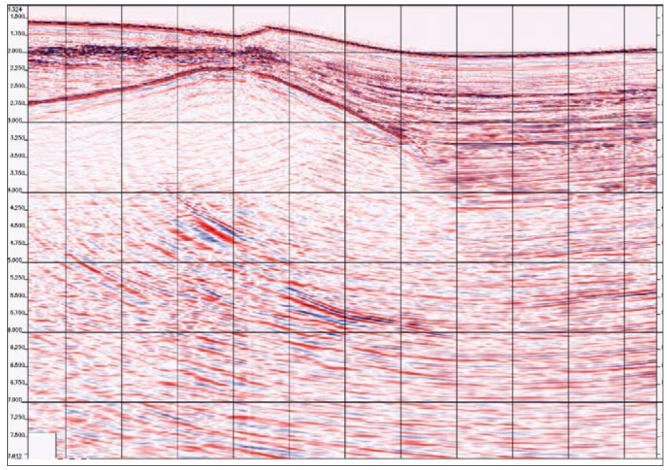

Figure 1. Seismic section illustrates the problem of determining the base of an allochthonous salt mass. The deeper reflectors show the possibility of the sedimentary section under the salt, but how far laterally and at what depth does it truncate against the salt are questionable (Seismic section courtesy of Veritas).

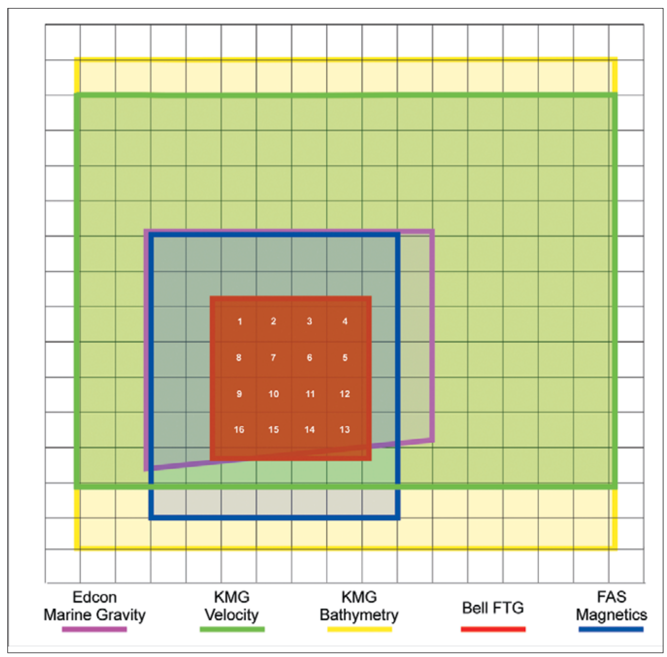

Figure 2. Database index map exhibits the areal extent of the data coverage required to successfully achieve the 3D Earth Model objectives. The numbered OCS blocks noted on all the maps shown are arbitrary. All the data were subsets from extensive nonexclusive geophysical surveys.

The geophysical problem that we faced in this project is fairly simple to describe. Analyses of why the base of salt seismic reflections were so weak were equivocal and confounding, given the disparity between the smooth, well imaged top of salt and the poorly defined base. Figure 1 illustrates the problem of determining the base of the allochthonous salt mass. The deeper reflectors clearly show that sedimentary section goes some distance under the salt, but how far and at what depth they truncate against the salt was questionable. Several hypotheses were advanced. Among these were the possibilities that the base of salt was rugose and thus dispersing the rays (not a preferred view) or that the salt was much thicker than had been anticipated. Because of the concern for trap integrity, a 3D earth model was undertaken to provide quantitative indications of the trapping surface.

Database. This 3D earth model is based on the integration of several geophysical and geologic databases made available for the project. The Database Index Map (Figure 2) exhibits the areal extent of the data coverage required to successfully achieve the objectives. The numbered OCS blocks noted on all maps shown are arbitrary. All data grids were variable. All data were subsets of extensive nonexclusive surveys—i.e., a 3D seismic survey acquired by Veritas DGC; a regional gravity data set acquired by Edcon; an IGC detail basement structure interpretation based on high-resolution aeromagnetic data acquired by Fugro Airborne Surveys (FAS); and a detailed full tensor gravity gradiometry data set acquired by Bell Geospace.

The bathymetry (Figure 3) was supplied by Kerr-McGee as a water-bottom depth file in digital form. The grid, which has 200 × 250 m line spacing, covered 167 OCS blocks. The depth has been referenced to sea level. The seafloor topographic relief varies across the area, ranging between 1040 and 1640 m.

Bell delivered the 3D FTG data as tensor gradients (Txx, Tyy, Tzz, Txy, Txz, and Tyz). Figure 4 shows a subset of the tensor field in the zz direction. The data collected between July and September 1999 were in a 2000-m east / west and 1000-m north / south grid. This detailed survey covered a 4

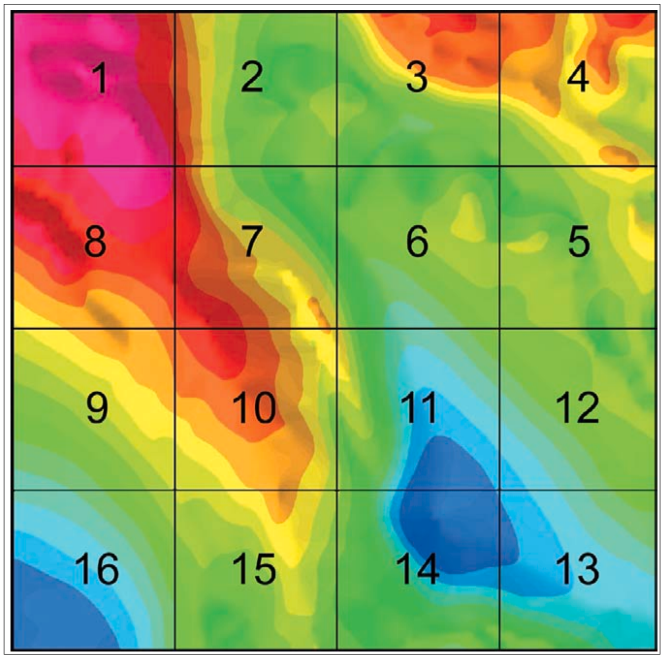

Figure 3. Bathymetry was supplied by Kerr-McGee as a water bottom depth file in digital form. The depth has been referenced to sea level. The seafloor topographic relief varies across the area between 1040-1640 m.

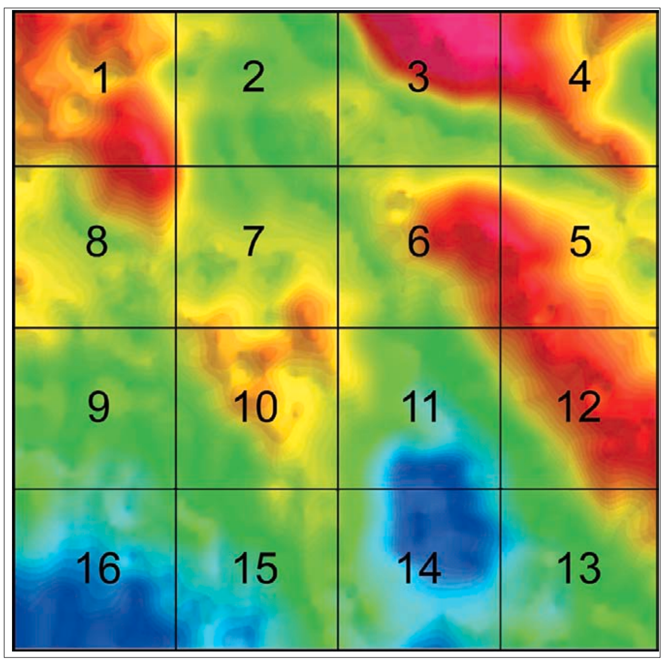

Figure 4. The Bell tensor gradient field Tzz is shown above. It is one of six tensor gradients (Txx, Tyy, Tzz, Txy, Txz, and Tyz), which covered a 4×4 OCS block area surrounding the prospect. It is considered as one of the key tensors used in this interpretation.

× 4 OCS block area surrounding the prospect. The key tensors used in this interpretation were Tzz and Txz.

The marine gravity survey was acquired by Edcon in the mid-1980s. The Bouguer gravity database utilized was a 48 OCS block subset from Edcon's nonexclusive regional database. The data were delivered in a 3000-ft grid file.

We used an imaging velocity model from Kerr-McGee, covering 150 OCS blocks in the Gulf of Mexico area. Initially, the quality of the data was considered moderate, with some interval articulation errors that required correction in the vicinity of a salt dome. The depth extent was to an average of 10.0 s. This velocity model was edited and calibrated before generating a pseudo-density volume that would be used in the 3D-earth modeling scheme. The index map shows the area covered by the imaging velocity model.

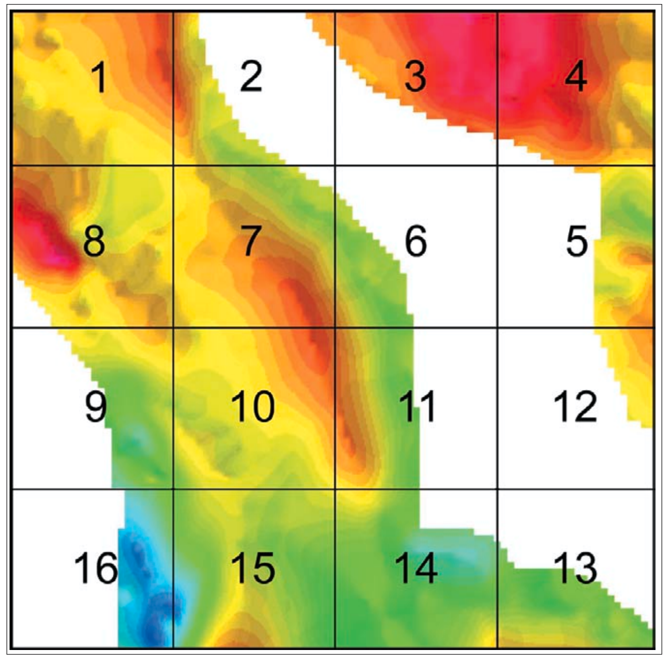

Figure 5. Kerr-McGee top of salt horizon interpretation was seismically derived. The surface covered the 16 blocks of interest with considerable overlap blocks to avoid limiting the areal extent of the 3D earth model. Null zones indicated were interpreted as areas deprived of the shallow allochthonous salt.

Kerr-McGee supplied the seismic-derived interpretation of the top of salt horizon (Figure 5). The grid consists of 200 × 250 m spacing and covered the 16 blocks of interest with considerable overlap blocks to avoid limiting the areal extent of the 3D earth model. Null zones indicated the areas deprived of shallow allochthonous salt.

Detailed basement structure interpretation for the deepwater protraction areas has been done by IGC using the FAS 1992 and 1998 high-resolution aeromagnetic (HRAM) surveys. The 16-block prospect area was covered by the HRAM 0.6 × 0.6 km survey grid. The interpretation consists of a profile by profile analysis of the data, which results in a hand-contoured magnetic basement structure map that delineates basement depths and faults. The interpretation has applications to each of the following: pre- or postsalt depocenters, delineations and extrapolations of basement transforms, and lineations, reservoir constraints, and favorable oil migration pathways. The area covered by the basement interpretation is outlined on the Data Index map.

We used an IGC-developed first-phase interpretation of the Mohorovicic Discontinuity (Moho) configuration and depth over the entire Gulf of Mexico. The Moho surface used for this model was a subset from this interpretation, which was based on a constrained inversion of the satellite derived gravity data using a 3D-earth model. Area-wide geophysical and geologic constraints were also utilized from nonproprietary refraction seismic and well top data, and very limited magnetic data. The Moho depths range from 26 000 to 28 000 m, too deep to have any seismic interest, but providing this surface completes the geophysical earth model.

Density/depth surfaces. The abundance of velocity information generated from 3D seismic data enables the incorporation of a velocity volume into the interpretation of a traditional 3D gravity model. The correct utilization of this plethora of the information becomes paramount. Strict adherence to stringent criteria is critical in order to maintain valid derivation of

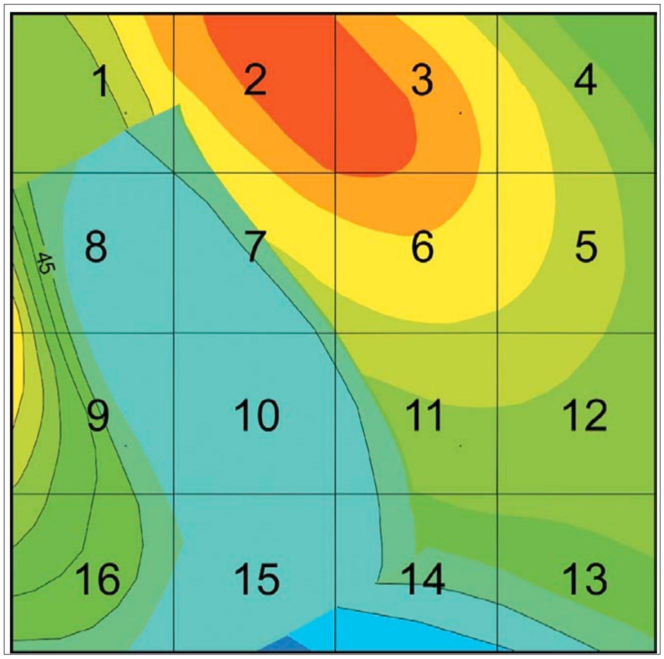

Figure 6. IGC basement surface interpreted from FAS aeromagnetic data as the depth to the top of crystalline or igneous crust. From a regional perspective, the 16 block area of interest lies on the north half of a broad, subcircular basement platform. Subsea depth ranges from 40 000 (red) to 46 000 (light blue) feet.

the corresponding pseudo-density volume that is to correctly represent the sedimentary section.

After running quality control procedures on the Kerr-McGee imaging velocity data, it was noted that below 5.0 s in two-way time the velocity data had been extrapolated with an almost flat interval velocity. This is not acceptable for converting to a pseudo-density volume.

Further, it was observed that the velocities were fast over basement lows and slow over basement highs, contrary to the norm. And, the Kerr-McGee top of salt horizon indicated that salt was located in the basement lows, which led to the conclusion that the provided imaging velocity model had salt velocity influence and was not representative of clastic sediment velocities below 3000 m. The imaging velocities below 5.0 s were therefore clipped.

The interval velocity to density conversion had to be accomplished in segments. A modified Gardner equation was successfully applied to the interval velocity to a depth of 3000 m. This generated pseudo-density surfaces to 3000 m. Below this depth, an IGC proprietary extrapolation function was added.

Magnetic basement structure. From a regional perspective, the 16 block area of interest (AOI) lies on the north half of a broad, subcircular basement platform (Figure 6) with an average subsea depth of 45 000 ft (13 720 m). Within the AOI area, the platform is dissected by a series of primary northwest-southeast and secondary northeast-southwest faults with suggestion of right-lateral motion in addition to vertical offset. The faults set up northwest-southeast trends of relatively narrow basement horsts and grabens. Tops of the basement horst blocks average about 40 000 ft subsea.

As previously noted, the small AOI area limited definition and interpretation of long wavelength magnetic anomalies representative of deeper basement. Depth analysis of this local area was possible due to the extensive coverage of the HRAM surrounding the 16 OSC blocks.

We define the basement interpreted from magnetics as the top of crystalline or igneous crust. It may or may not locally correspond with what is sometimes termed acoustic, geologic or economic basement. In the Gulf Coast literature, there are references to a "Buffler basement" which is—as defined by DeBalko and Buffler (1992)—actually a mid-Jurassic sequence boundary (MJS) interpreted from seismic reflection and / or refraction data. It is important to recognize that this "Buffler basement" or MJS may in places lie close to or be identical with crystalline basement, but in other places may be thousands of feet shallower than igneous basement.

3D earth model results. We built and interpreted a 3D salt (low-density) configuration model based on the Bell Geospace full tensor gradient and the Edcon marine gravity data. The results derived utilized the IGC 3D earth-model scheme. The seismically derived top of the salt horizon interpreted by the Kerr-McGee staff geophysicists remained constant throughout the interpretation process. The pseudo-density volume, magnetic basement structure, and the Moho surface were also held constant.

The full tensor gradient (FTG) was limited in areal extent covering only 16 OCS blocks. High frequency anomalies are observed in the tensor data. The configuration of the base of the shallow salt / sediment interface is derived primarily from the short frequencies anomalies attributed to FTG data. The long wavelength components of the data, which are attributed to deep sediment / salt interfaces, were interpreted to be minimal. Any separation of the allochthonous from autochthonous salt volumes was not discernible using the FTG data. Therefore, the salt configuration interpreted from the 3D gradient model alone was considered limited, due in part to the limited data coverage.

The observed marine gravity data exhibit a long wavelength component not seen in the FTG data, partly a result of the 48-block data coverage. The deeper salt configuration interpreted is associated to longer wavelength anomalies observed in the marine gravity data. The minimal high frequency content may be attributed to the 3000-ft data grid derived from a 3 × 6 mile line network.

The final results presented were derived from the integrated interpretation of both sciences, the gradient and marine gravity data sets.

Salt configuration. Two types of salt bodies were modeled, a shallow allochthonous salt and a deeper autochthonous salt. The delineation and configuration of the salt masses can best be understood by a review of the shallow salt isopach and the sediment isopach maps shown on Figures 7 and 8, respectively. The base of the shallow salt was interpreted as having an average depth of 5000 m. There are indications of salt domes extending to great depth in the center of block 8 and trending into the southwest quadrant of block 7. The shallow allochthonous salt thickness modeled averages less than 1500 m (4920 ft) except in blocks 1, 7, and 8, where it thickens to more than 5000 m (16 400 ft). In areas where the shallow salt deepens and meets the interpreted deep-seated autochthonous salt, the boundary between the salt masses is considered arbitrary. What can be determined are zones where sediments are at a minimum to nonexistent. The sediment isopach map, Figure 8, which is an interpretation of the thickness of sedimentary section existing between the allochthonous and autochthonous salt bodies, delineates these varying thicknesses.

The interpretation of the configuration and depth estimate to the top of the autochthonous salt mass is at best an estimate. From sea level, the depth to the top of deep salt ranges from 4800 to 10 800 m (15 740-35 420 ft). The initial depth to

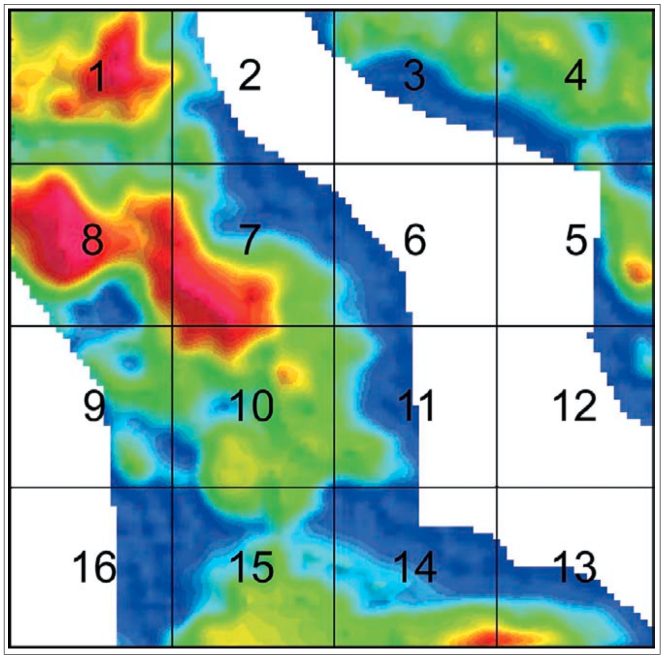

Figure 7. Shallow salt isopach—a salt thickness map based on the seismically interpreted top of salt horizon and the 3D earth model interpretation for the base of the shallow allochthonous salt. The results met premodel expectations, showing a salt body varying in thickness from 1500 to 5000 m. Two surprises were found: a deep salt root north and west of the prospect proper, and the rugosity of the salt base.

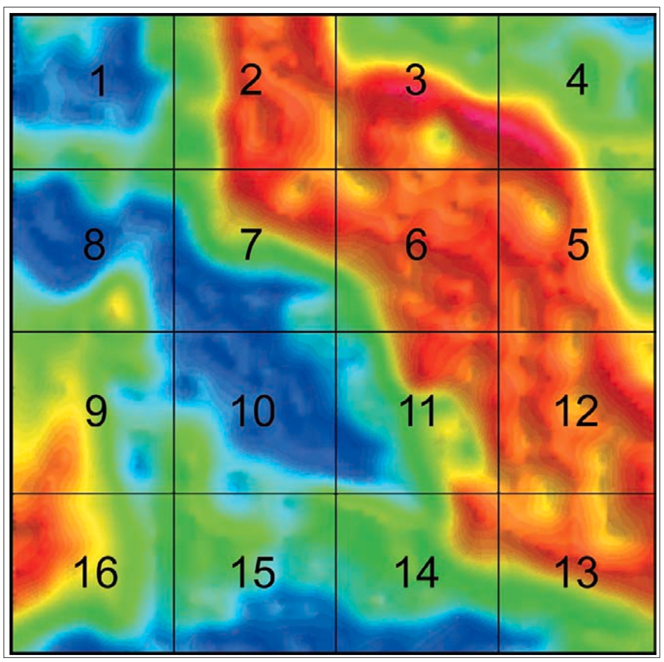

Figure 8. Sediment isopach—an interpretation map from the 3D earth model results delineates the varying thickness of sediment section existing between the allochthonous and autochthonous salt bodies.

the base of the deep-seated salt was given at 12 000 m. The model result indicates that at 12 000 m or deeper, the autochthonous salt is more than likely nonexistent in the modeled area.

Geologic significance. The modeling indicated that an inversion of structure has occurred in this area of the Gulf, apparently caused by early salt tectonics. This deepwater area lies in a small minibasin between two salt bodies, close to the ocean floor. The two salt bodies and the minibasin all have a north northwest-south southeast orientation. The local bathymetry reflects the presence of the shallow salt bodies, and the sedimentary section lies beneath a present-day topographic low with the same orientation.

The potential fields interpretation was prompted by the presence of a prospect lying along the edge of the minibasin. This prospect consisted of an amplitude trapped up against the base of an allochthonous salt bed poorly imaged by seismic in the critical trapping area. The seismic data were shot in an east-west direction, allowing only near-trace energy to be collected without the interference from one of the two salt bodies. This acquisition problem is one of the reasons that the salt base imaging was inadequate. The key to the trap was the base of salt. If the base of the allochthonous salt was too shallow, there would be a risk to the trap. Initial seismic interpretations of the salt base indicated a suitable trap existed and that salt thickness was in the neighborhood of 2 km. The 3D earth model later confirmed this. However, the reflected energy from the base of salt had been too weak to inspire confidence in the seismic interpretation alone.

The modeling of the shallow allochthonous salt met premodel expectations, showing a salt body varying in thickness from 1500 to 5000 m. Two surprises were found: a deep root extending more than 5 km deep north and west of the prospect proper, and the rugosity of the salt base. The shallowest part of the salt is about a mile to the east of the rootstock. This latter discovery provided a suitable rationale for the inability of the seismic data to image the base.

New insight: rugosity and inversion. These final results demonstrated the power of the 3D earth model in resolving the shallow salt / sediment interface problem. Equally important was the discovery that this synergistic approach could produce new and valuable insight into salt rugosity and an interesting inversion of structure apparently caused by early salt tectonics. Without the high frequency gravity tensor data, it is unlikely that we would have detected the rugosity.

As expected, the rugosity does raise some issues with salt mechanics which demand other explanations for this rugosity. Within a mile we observe 1500 m relief on the base of the salt in a fashion that is not easily explained by salt tectonics. Approximately 20% of this relief could be due to unaccounted density variations, which in itself does not resolve the tectonic problem, requiring additional data and further investigation.

The fact that the shallowest part of the salt does not lie directly above the rootstock is interesting in light of the fact that seismically it was interpreted that the western salt, which traps the prospect, had not traveled very far from its original position. This conclusion comes from the salt structure deduced from the 3D earth model. Before the earth modeling was completed, it was anticipated that the minibasin would have been over a basement topographic low. It was believed that the sediment thickening along the basin axis was due to the salt withdrawal. However, when the depth to magnetic basement was interpreted, it was discovered that today's minibasin lies on top of a basement horst. The seismic-derived top of shallow salt horizon map (Figure 5), when overlaid on the basement structure map, (Figure 6), indicates that the shallow allochthonous salt is nonexistent over basement structure high, which trends northwest-southeast centered over blocks 2 and 6. These data show that the picture of salt deposition in the early western Gulf of Mexico is more complex than suggested by Peel et al. (1995) but in agreement with Peel et al. (2001).

Indeed, the data indicate that the salt root lies above a large basement graben, just west of the prospect, which has as much as 2500 m relief. The northeastern salt body on the other side of the minibasin also lies directly above a basement low, albeit one with much less relief, merely 1200 m. The correlation is made by overlaying the shallow salt isopach (Figure 7) to the basement structure (Figure 6) maps.

The sediments impinged on the edges of the salt-filled graben, causing the salt to mobilize upward. The steep walls of the graben would have prevented the salt from spreading laterally. This then created a topographic high where there had been a topographic salt-filled low. This initial salt swell then funneled the sediments across the old horst which by then had become a topographic low, creating the sediment-filled minibasin on top of the former basement high. The basin-centered sediment thickening is not due to salt withdrawal but to salt mobility along the basin edges. One of the implications of this work is that the initial Jurassic salt was not entirely pervasive across the Gulf during its deposition. At least in this area, the salt was deposited in deep lows, which then acted as the source for the local salt bodies. And, at least in this area, the early salt tectonics resulted in an inversion of topographic structure, which has persisted until this day.

Final comments. The discerning with confidence the geometry or configuration of the low-density section is a common salt / sediment interface problem that continues to repeat in the exploration efforts in the deepwater regions of the world. This interpretation project was initiated due to the presence of a prospect lying along the edge of a prospective minibasin with an associated trapped amplitude poorly imaged by seismic data.

The final results validated the 3D earth model approach in resolving the salt / sediment interface problem. Equally significant, a byproduct of this synergistic approach has provided new and valuable insight into rugosity and salt tectonics.

The 3D earth model at best is the accumulation of results from multiple sciences approximating the earth's lithology and the salt's configuration. The success in predicting the depth to a salt / sediment interface is dependent upon the type and quality of the data, and how the model is built. The data utilized in this project are considered state-of-art. The interpretation results presented were achieved by utilizing the optimum benefits from each science and the incorporation of them into a constrained model. The final results are considered excellent and accepted with a high degree of confidence due to the methodology of the integrated modeling scheme, the state-of-art data utilized, and the fit to other exploration efforts.

Due to the frontier nature of this area, well information was limited. Therefore, additional well and / or velocity control would improve the final calibrated clastic sediment velocity model, and ultimately, the pseudo-density volume. All would further refine the depth results to the salt / sediment interfaces derived from this interpretation.

Suggested reading. "Seismic stratigraphy and geologic history of Middle Jurassic through Lower Cretaceous rocks, deep eastern Gulf of Mexico" by DeBalko and Buffler (Gulf Coast Association of Geologic Societies, 42nd Annual Conference, *Transactions*, 1992). "Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: A preliminary analysis in Salt Tectonics: a global prospective" by Peel et al. (*AAPG Memoir 65*, 1995). "Paleogeographic evolution of the deepwater frontier of the Gulf of Mexico during the Late Jurassic to Cretaceous," by Peel et al. (AAPG 2001 Annual Meeting). "Earth model integrates data to improve interpretation" by Prieto (*The American Oil & Gas Reporter*, 1998). "3D earth models 101," by Prieto (*TLE*, 1999). TLE

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