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3-D DEPTH IMAGE EXPERIENCES IN THE DEEPWATER GULF OF MEXICO

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Abstract

Depth imaging is an important part of the deepwater play in the Gulf of Mexico, and especially for the subsalt. Experiences with numerical models, physical models and live data show that it is possible to obtain stratigraphic quality images under salt given the right conditions. Given the right velocity model, depth imaging can have a substantial impact on the quality of seismic interpretations, as the signal can be positioned correctly and noise reduced when compared to time imaging. Obtaining stratigraphic quality seismic depth images also requires the appropriate handling of the coherent noise. Pre-stack and post-stack depth images have been generated in areas of drilling interest in the Gulf of Mexico. Drilling results have been able to bear out the interpretation benefits from this imaging.

INTRODUCTION

The purpose of this paper is to illustrate the use of 3-D depth imaging in seismic exploration and development concentrating on the deepwater Gulf of Mexico subsalt where depth imaging is an integral part of that play. And although the tradition of depth imaging grows from interests in structural definition of hydrocarbon traps, the quality of depth imaging in 3-D is now high enough to also have significant impact in reservoir definition and stratigraphic imaging.

Time imaging generally employs significant elements of a "flat earth" processing model, and cannot correct for significant spatial variations in earth velocity. Therefore time imaging is forgiving of small earth-model errors but fails when velocity varies rapidly.

In a sense, depth imaging is a correcting lens attempting to place the reflected energy in its correct xyz depth position. But along with the increase in image accuracy, comes the danger of not having the right earth velocity to make the corrections. Because depth imaging does such exact calculations of the ray paths, it is very sensitive to errors in our interval velocity model of the earth. Depth imaging, then, must be considered in a context much wider than a migration algorithm, and must at least also include velocity analysis, accuracy, and representation.

SUBSALT DEPTH IMAGING

As a representation of depth imaging, Figure 1 shows a model of seismic ray propagation. In Figure 1, the individual CMP rays in black illustrate how the seismic energy travel path through sediments suffers small "kinks" at the interfaces where the velocity changes. In contrast, at the salt boundaries the change in angle is quite large, and so this body acts as a distorting lens for imaging the reflectors below. The cross-section shows how rays constituting a single CMP gather hit the subsurface irregularly over a 5000-foot horizontal area. The inset in Figure 1 helps illustrate this difference in time and depth imaging. The plot of offset versus time shows the ray arrivals as recorded at the surface. Ideal time imaging requires the arrivals to fall along a hyperbola, whereas clearly they do not.

Accurate depth imaging, however, is designed to correct for these distortions and place the events in their appropriate horizontal and vertical position. The effect of depth imaging is to use the source-receiver pairs whose common reflection points are the same, based on good knowledge of the velocity through which the rays travel. The small kinks are honoured directly, and all ray bending is taken into account. Where no salt exists in Figure 1, the rays generally make it to the surface without much distortion. Through the salt, however, the salt/sediment velocity contrast of 2 to 1 has a large effect where the rays intersect the salt interface at a non-normal angle. Rays can emerge from the salt displaced thousands of feet horizontally. Depth imaging corrects for these variations whereas time imaging does not.

Effective 3-D depth imaging of surface seismic data can be accomplished using the required elements of; 1) appropriate acquisition coverage, 2) a robust and accurate velocity representation of the subsurface, 3) 3-D ray tracing, 4) a depth migration algorithm, and 5) an imaging expert.

An example of a depth-migrated subsalt is shown in Figure 2. Several good points can be made from this seismic image. Notice the complexity of the salt-sediment interface at the top. Faults and small-scale folds with 3-D geometry make the interface have local dips up to 45 degrees immediately adjacent to planar salt sections. Below the salt, prospective reflections (marked) can be seen that terminate both to the left and right under non-illuminated shadow zones. Imaging may not be possible in the no-data locations as calculated from ray tracing. These shadow zones, apparently due to post-critical ray blockage, are common when the dips of the reflector and the base salt become too discordant. Even so, the imaging below salt shows very encouraging events that resemble the type of deepwater turbidite sands expected in a stratigraphic trapping position. The consistent higher amplitude events lose reflectivity up the paleo-dip as would be expected if they are deposited in a paleo-low. Utilizing the depth image, then, the prospective horizons under the salt were drilled. Sands were encountered in the zone of interest at the dip rates shown in the cross section.

POST STACK TIME AND DEPTH IMAGING COMPARISON

Depth imaging is not only converting the time recordings to depth, but is also positioning the data at the appropriate horizontal and vertical depth location. When comparing the two approaches in a simple velocity area, they should give comparable results. However, comparisons in complex velocity areas will be different. As an example of post-stack time versus depth 3-D imaging, refer to Figures 3 and 4. The difference between these sections is the migration velocity and the migration algorithms. In both cases, the input data are stacked in the time domain. The geology of the area is quite interesting. As observed in the time section of Figure 3, the shallow central anticline is underlain by a salt diapir. Deeper, the east dip extends from the center to the edge of the data and a no-data zone extends under the salt from the center to the west.

Comparing the 3-D depth-migrated data (Figure 4), one sees significantly new information. First, a base of the salt can be seen in the depth-migrated data (A). Although the reflectivity of the base is not as stable as the top salt reflector, the base can be mapped in 3-D.The reason one can now see this reflector is that depth migration is honoring salt velocity and structure. It has correctly assembled the appropriate data, from both within and out of the plane of the section, into its coherent xyz location.

Deeper events in the depth image (B) imply a quite different structural history. The possibility of deep block faulting is suggested. This also sets the structural framework of the middle section (C) where dips have changed from monoclinal east to that of a half anticline. This is a significant change to the understanding of the structure. In addition, the characteristics of the reflectors on the east flank are also different in the depth image. Unfortunately, in the west flank of the subsalt, the noise characteristics have not improved sufficiently to complete the subsalt picture. The attractive west dip segment (D) is a multiple. The subsalt section here probably cannot be improved using the stacked data as input to migration.

The high impact of depth migration is due to its application where the velocity model is complex. The salt velocity is about twice that of the sediments, and waves traveling through salt rapidly deviate from trajectories appropriate to the time processing model of a layered earth. Additional differences are due to horizontally changing velocity in the sedimentary section. Although lateral sedimentary velocity variation is often modest, in some areas it can vary by up to a few thousand feet per second over several thousand feet, as it does below salt in Figure 4. Thus the impact of depth imaging is fairly small above salt but quite large in the deeper central section where imaging is greatly affected by the rapid velocity contrasts of the geology.

NOISE CONSIDERATIONS IN DEPTH IMAGING

Depth migration is often applied in complex velocity environments where signal is desired in otherwise noisy areas. Because this is so, an understanding of the noise characteristics of these areas and how the imaging algorithm handles them becomes important. What we need to classify as coherent noise includes surface waves, refractions, mode conversions, multipaths and multiples. These are most common in areas of complex structure and high velocity contrasts, to the degree that the noise may be ten times stronger than the signal itself. The noise is not inherent in depth imaging, but depth imaging is more commonly used in areas with these noise characteristics, thus we can expect depth images to commonly contain noise.

Seismic reflection energy converted to refractions is a coherent noise in our imaging. Although this energy is not dominant, it can easily be misinterpreted as signal especially at critical locations like the salt-sediment interface Conversion of compressional energy to shear also represents a significant noise characteristic of our data. This mode conversion is especially strong at the carbonate and salt. Another type of unwanted reflection energy is multiples. Examples of strong multiple generators are the air-water interface, ocean bottom, carbonate layers and salt. Complicating this situation are the shorter path, interbed multiples spawned among the brighter reflectors. Although they are no stronger individually than free-surface multiples, the interbed population increases geometrically with the number of bright multiple generating interfaces, instead of proportionately as do the simple multiples. This is the coherent noise challenge in subsalt imaging.

Figures 5 and 6 show 3-D depth-migrated traces of data before stacking. In Figure 5, the sedimentary signal is very strong, the velocity is well behaved, and the gathers are quite flat prior to stacking. With close inspection, some noise (multiples) can be seen that appears to be parabolic and turning down at the far offsets (to the right). In Figure 6, a continuation of the same sedimentary section is represented subsalt, where extensive mode conversions and multiples exist. The same flat reflectors are in these data, but they are about ten times weaker than the coherent noise. The subsalt seismic signal is also weaker due to the conversion of much of the energy to noise.

All of the coherent noises described above exist in the time-imaged seismic sections, because they are a result of the seismic acquisition and the wavefield paths over which they travel. The depth imaging does not create the noise, but does distribute it differently than does time imaging. In the poor image portions of Figures 2, 3 and 4, the section is dominated by coherent noise.

3-D PRESTACK DEPTH IMAGING

With a good earth velocity model in areas of complex geometry and velocity, imaging accuracy and precision are improved by pre-stack depth migration, which puts the signal in the right location for each separate seismic trace and corrects for the lens effects of large velocity contrasts. Because the depth imaging areas are challenging, however, the signal-to-noise ratio can vary greatly. It becomes important to recognize noise and improperly positioned signal on the gather data, and relate these back to the 3-D stacked volume to complete an effective interpretation.

The following example shows a direct comparison of pre-stack and post-stack imaging of data from a 3-D physical model resembling bodies of the Gulf of Mexico. 3-D seismic data was acquired in the tank of the Allied Geophysical Laboratory (AGL) at the University of Houston and imaged to measure the differences of pre-stack and post-stack imaging. The

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model was built of a flat Plexiglas sheet of constant initial thickness milled to specifications of predefined statistical roughness as noted in faulted and folded real salt bodies exhibiting topological self-similarity placed over a reflector model of a fault and two small anticlines, with 4 rods inserted below to act as line. 3-D linear marine seismic acquisition was then performed over the model (AGL Model 93).

Comparing an enlarged portion of the post-stack and pre-stack 3-D depth-migrated data on a cross section of the model (Figures 7 and 8, respectively) shows why pre-stack imaging is preferred for stratigraphic quality imaging. The target horizon, anticline and fault are much clearer on the pre-stack data, and the lateral resolution of the four rods is clearly superior. Despite the fact that the model is of constant reflectivity, the post-stack depth image of the target horizon is too poor to pick, and an amplitude map would be meaningless. Compare this with the same dark event on the pre-stack imaged data. The pre-stack image is structurally superior and also more appropriate for stratigraphic interpretation.

In an example similar to the model salt ledge, live data shows how pre-stack depth imaging can be an advantage over post-stack depth imaging beneath and around a salt tongue. The subsalt image of this post-stack depth-migrated section shows significant coherent noise (predominantly multiples) and little recognizable signal. The same pre-stack data were depth migrated prior to stack, and the subsalt image was improved. The prospective reservoir was revealed in the area of the tip of the salt ledge. The pre-stack data from this project were used in the selection of a drilling target, and the reflector noted was found to contain hydrocarbons. The dip of the reflector (approximately flat) was found correct from dip meter logs. Downhole acoustic and petrophysical log data also show that the reflection characteristic of the reservoir is correct, as the hydrocarbons cause a "bright spot" relative to the surrounding section.

CONCLUSIONS

Depth imaging is rapidly increasing in use in exploratory and development areas. For complex velocity and structural regimes, large differences can sometimes be seen from depth versus time imaging, as depth imaging can change the position, dip and amplitude of reflectors. Prestack depth imaging can also be advantageous over poststack depth imaging under the right conditions. In either case, the noise characteristics of the depth-imaged data are different from those of the time-imaged data, and must be taken into account during interpretation.

Success in depth imaging can be achieved by using:

- A versatile 3-D earth model and robust model editor
- Accurate velocity analysis and representation
- Robust 3-D forward modeling of rays and waves
- Visualization of ray tracing
- Gather and stack interpretation tools
- An accurate and efficient migration algorithm
- High quality geological/geophysical interpretation capabilities
- Imaging specialists with sufficient amounts of courage

Depth imaging is currently common in several plays around the world including over-thrusts, subsalt, the West African offshore, and the North Sea. As depth imaging matures, it will become increasingly useful in older exploration areas and applications where stratigraphic quality is important. The trends that have made 3-D depth imaging possible, (advances in hardware, software, and imaging expertise) will continue and cause this technology to spread. As it does, we will be challenged to produce the best possible quality images and required to adequately describe their uncertainties.

ACKNOWLEDGMENTS

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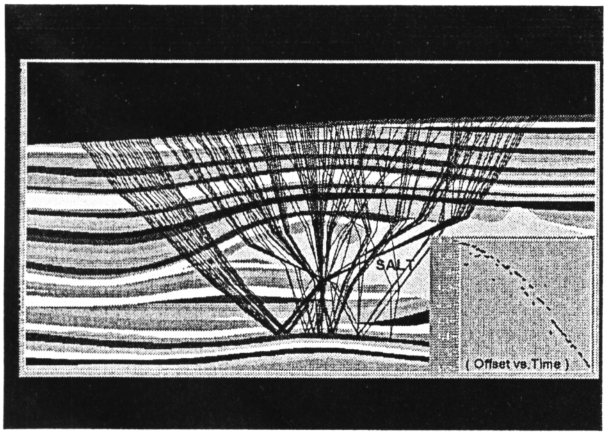

Figure 1 – Ray-traced cross-section of a salt model showing the distortion of the ray paths for reflectors below the salt.

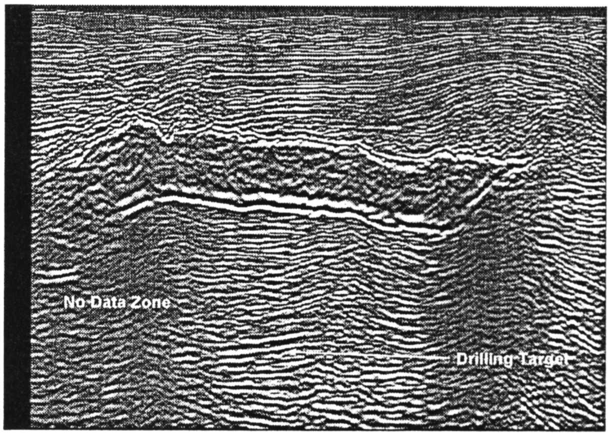

Figure 2 – Depth migrated seismic section showing the rugosity of the salt at the upper interface and the shadow zones of imaging at the tip and the root.

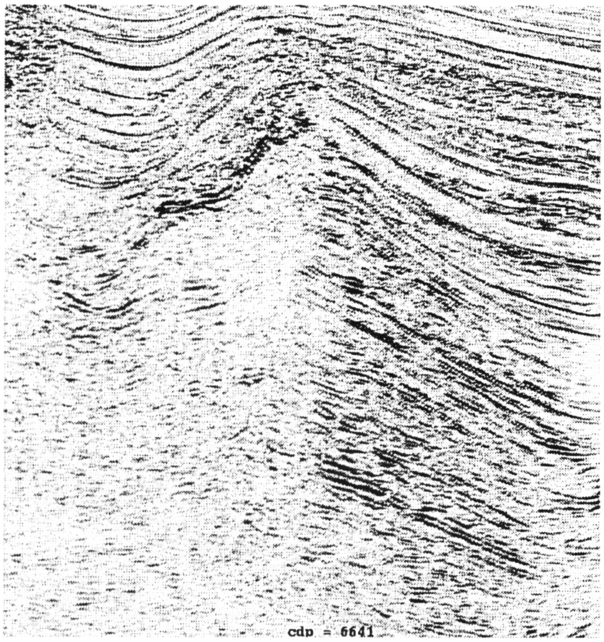

Figure 3 – 3-D time migrated seismic section.

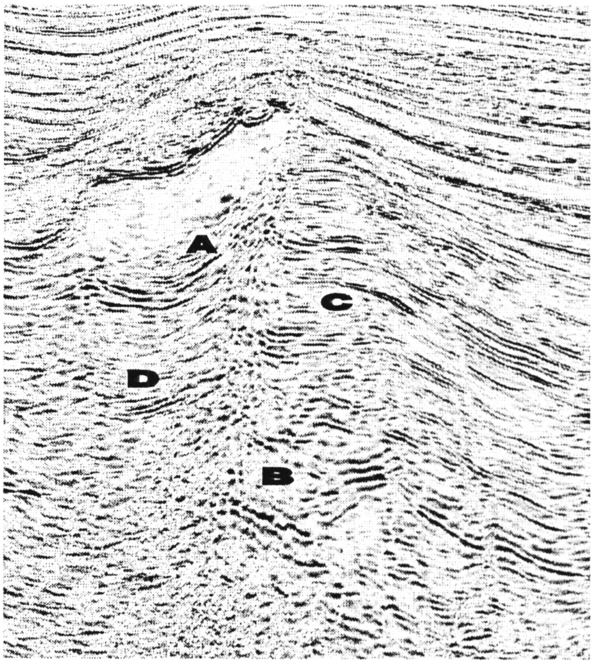

Figure 4 – 3-D depth migrated seismic section.

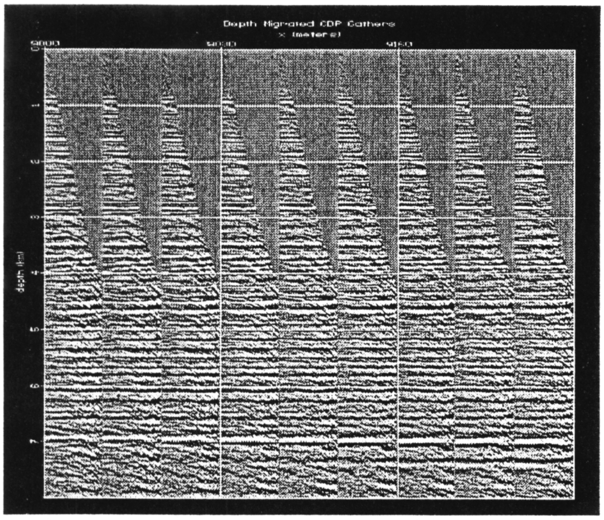

Figure 5 – 3-D prestack depth migrated gathers. Note flatness of the events representing signal.

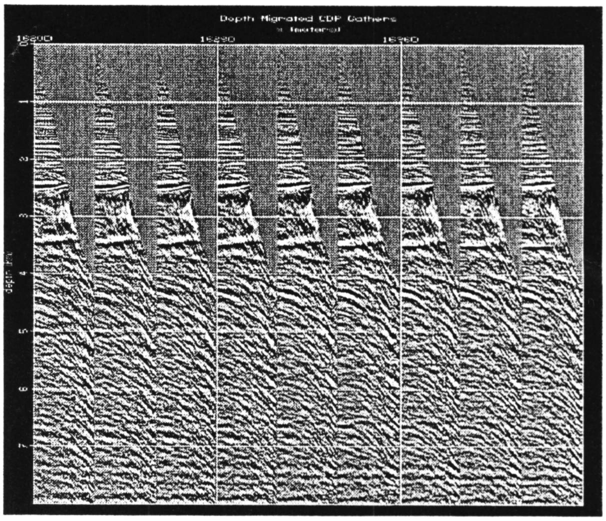

Figure 6 – 3-D prestack depth migrated gathers imaging through the salt lense. Note the multiples and mode conversions now dominate the section.

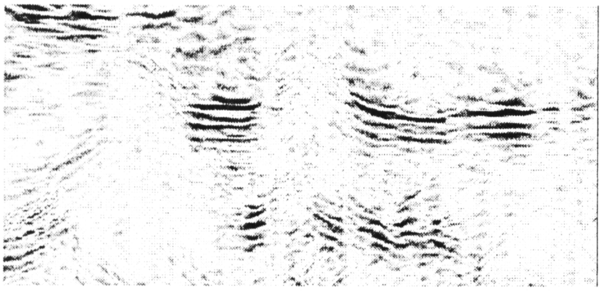

Figure 7 – 3D post-stack depth migrated physical model line.

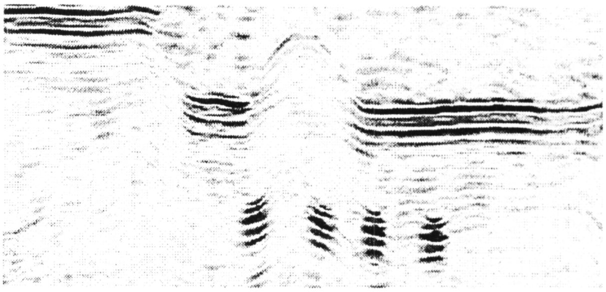

Figure 8 – 3-D pre-stack depth migrated line. Structure, amplitudes and diffractors are correctly handled.