Acoustic and shear impedance images, obtained from deterministic simultaneous inversion of a high-resolution crosswell seismic survey, were used to obtain the internal structure of Niagaran reef in Michigan. The crosswell seismic survey was conducted using two monitor wells external to the reef. These wells had depths that extended beyond the depth of the reef, and imaging used reflections from above and beneath the reef, resulting in the best seismic images of any Niagaran pinnacle reef obtained to date. The top of the reservoir can be clearly distinguished, as well as its lateral extent or dipping edges. Reflection events internal to the reef are evident; some are fairly continuous across the reef and others are discontinuous.

The wide angles used in crosswell imaging result in AVO character not usually observed in surface data. The data include reflections from angles that range beyond critical for many interfaces, and some reflections are visible only for a small range of angles, presumably near their critical angle. Inversion of the seismic data increased the resolution of the internal structure of the reef and showed a distribution of internal layers that is reasonable for this reef. The shear impedance results were more sensitive in this carbonate environment and seem to correspond to variations in porosity within the reef structure, as well as anhydrite plugging. Signal attenuation appears strong when seismic raypaths pass through the upper part of the reservoir; this may be due to intrinsic attenuation and/or scattering of events due to the locally strongly varying gas saturation and extremely low fluid pressures. The seismic images obtained, and their interpretations, as assisted by inversion, provide insight into the internal geometry of this reef and match the geologic interpretation of the reef model quite well. The results provide data that should be useful for reservoir management.

Introduction

Surface seismic observations have developed a large set of auxiliary observations that provide a robust evaluation of reservoir properties but this technology is still limited in resolution by many factors. Crosswell seismic data can significantly improve resolution of the vertical and lateral heterogeneity of the carbonate reservoirs, as pointed out by several investigators (Lazaratos, et al., 1991; Lazaratos, 1993; Rector et al., 1995) due to the closer location of sources and receivers to the reflectors, and to the higher frequencies that this allows.

The wide angles in crosswell imaging provide additional information not present in typical surface seismic acquisition; this often includes the critical angle. In some instances, the critical angle may provide the only range in which a reflection can be observed above background noise, and inclusion of these angles in a final stacked image can be beneficial (Trisch, 2006; Pennington et al., 2008). Beyond the critical angle, severe phase rotation of the wavelet occurs, and the stack can be degraded. Therefore, for most detailed amplitude variation with angle (AVA) studies, a restriction to narrow angles may be prudent.

Inversion involves converting the seismic data into formation properties by integrating the reflection coefficients that are in turn derived from the reflection amplitudes (Debye and van Riel, 1990; Pendrel and Van Riel, 1997). Through inversion, one can generate an image of acoustic impedance for normal-incidence reflections. In addition, this technique can be extended, through the use of a concept called elastic impedance, to data that are not normal incidence. One can create partial stacks from different angle ranges and invert them, solving simultaneously for an Earth model in which the three elastic properties (compressional and shear impedances plus density) are consistent across all angle ranges. Because the crosswell data have angles that are far from normal incidence, the results will present a case not previously encountered in the literature on inversion and interpretation.

The target reef, with its one-well Springdale Field, is part of the Niagaran (Silurian) reef trend in the northern part of the Michigan Basin. These reefs have been important hydrocarbon producers with a cumulative production of 475 MMBO (76 × 10^6 m^3) of oil and 2.8 TCF (79 × 10^9 m^3) of gas (Wylie and Wood, 2005). The crosswell data set was recorded from dedicated monitor wells outside the reef at 2000-ft (600-m) interwell distance. The survey was designed to have shots and receivers at depths ranging from much shallower to much deeper than the reef which was at a depth of 4700 ft (1425 m). A sweep of 100–3000 Hz was used, and final stacked images contained 1000-Hz data. The fluid pressure inside the reef is 25–50 psi. Details of the acquisition and initial processing were described by Trisch and Pennington et al.

Oil or gas reservoirs in reefs can be extremely heterogeneous. Geologists model reefs with many internal layers and zones (lithofacies) where many of these identified facies are not likely to be productive in a hydrocarbon reservoir or can provide internal barriers to flow and isolate compartments. The identification of these facies will improve the recovery of oil significantly. Surface seismic typically cannot image these internal facies, but the application of crosswell seismic and inversion techniques will improve the image by 1–2 orders of magnitude, as seen in the following sections.

High-resolution crosswell imaging

Figure 1 shows the raw data from a common-receiver gather and spectrum for a receiver at 5830 ft, with source locations ranging (every 10 ft) from 4140 to 6000 ft. The arrivals are
Figure 1. A common-receiver gather and its spectrum.

Figure 2. Processed crosswell seismic data. Color background represents velocity model (in kft/s) determined by crosswell transmission tomography (errors can be large near the edges of the image). Wiggle traces are the migrated stacked seismic data from crosswell reflection imaging (from above). Various logs are displayed along the edges, at the locations of the Burch (left) and Stech (right) boreholes. Vertical axis is in depth, ranging from 4000 to 6500 ft (1210–1970 m). Warmer colors (red, yellow) indicate high velocity values. Top of the reef is at 4665 ft.

Figure 3. Angle gathers at CMP 1000, midway between the wells, from above (left) and from beneath (right). The angles are 25–90° (from left to right on the horizontal axis). Vertical axis is in time.

Figure 4. (a) Stacked image of Springdale crosswell data, from above (left) and from beneath (right). (b) The spectra for the same data sets, for a time gate within the reef only. The reef is readily visible as the low-amplitude region at depths of about 4700–5000 ft near the center of the image. Green lines are seismic horizons. Low-amplitude reflections can be seen within the reef. The image “from below” is more detailed than the one “from above” and is richer in high frequencies.

clear and distinct, and reflections and converted phases are apparent even in this gather, prior to stacking.

The initial processed image is shown in Figure 2. The acquisition survey allowed reflection imaging in the usual configuration in which sources and receivers are at depths shallower than the reflector, providing an image “from above.” The data, however, also allow imaging “from beneath” (sources and receivers at depths below the reflector). Angles range from about 30° to near 90° (Figure 3).
the wavelet results in largely incoherent stacking, and these postcritical angles may not contribute to (nor damage) the stacked image significantly. Interfaces for which a critical angle exists in one direction (e.g., from above) are those for which there is no critical angle in the other direction (from below), and vice versa.

The amplitudes of reflectors from within the reef itself are low, especially for the image obtained from above the reflectors. We attribute this to attenuation and scattering of signal as it passes through the complex upper part of the reef, where gas saturation likely varies locally, reservoir pressure is extremely low, and structural complexity of the reef is evident. The image from beneath does not pass through this complexity and only experiences the gas saturation and low pressures at the upper edge of the image, allowing most of the reef image to be higher quality. Thus, in complex environments within hydrocarbon reservoirs, the ability to image from beneath may often be a great advantage. Of course, this involves having deep wells, deeper than the reservoir, in which to locate the sources and receivers.

**“From above” versus “from beneath” CSSI inversion**

The deterministic inversion of partially stacked seismic amplitude data used in this paper is based on the constrained sparse spike inversion (CSSI) algorithm used in software provided by Fugro-Jason (Debye and van Riel, 1990; Pendrel and van Riel, 1997). This inversion algorithm can be used in two ways; full-stack (which is often assumed for surface data to be zero-offset “acoustic”), or based on angle stacks representing limited ranges of angles in each stack (nonzero offset, or “elastic”). Particularly in our crosswell data, the full-stack inversion is, of course, not “acoustic” because of...
the wide angles involved, so the resulting image (Figure 5) is referred to here as showing “apparent” impedance, without reference to acoustic or elastic response. As long as the angles included in the full stack do not include many critical-angle reflections, the resulting apparent impedance can be used as an indicator of some formation property (or combination of properties); in our case, the formation property indicated is almost entirely porosity, because the seismic properties of the carbonate rocks in the reef depend strongly on porosity, but only weakly on fluid content. On the other hand, the elastic inversion from a series of partial stacks can be conducted over the full range of acquisition, or they could be restricted to limited ranges in an effort to avoid complexity from phase rotations beyond critical angles; in either case, we may be able to determine additional properties of the reservoir, or in this instance, make use of that approach which provides the image with best detail.

However, when we discuss the “from above” and “from below” processing and images, we should notice a major issue in which the packaged inversion procedures assume that the reflection series is encountered from the top down, and therefore avoid a pitfall in assuming that straightforward use of packaged inversion suites can be used on the traces in either case without modification. It is important to recall that although, for zero-offset data, the reflection observed from above is the same amplitude of the reflection observed from below, but with opposite sign. Yet, for all nonzero angles, the amplitude will vary strongly, depending on which layer is encountered before the interface, and which after (Figure 6). So a simple sign change, at any angles other than normal incidence, is not sufficient. Our approach to solve this issue was by “flipping” the “from beneath” seismic traces (top down, or last sample to first sample), then perform the inversions using standard software, and then “flip” the resulting image back so that the shallow depths are again on top. Figures 7 and 8 show the elastic inversion results for P- and S-impedances from above and from beneath.

The elastic inversion results are products of a simultaneous inversion using the full Zoeppritz equations, and should, therefore, be valid, assuming that our input data contained sufficient breadth of angles to constrain the results; however, we are suspicious of postcritical handling of phase rotations, both in the inversion process and in the initial processing of angle traces. In any case, the results show a distribution of internal layers that is reasonable for this reef. Again, the inversion results “from beneath” provide an image of the internal structure of the carbonate reef that appears to be higher resolution than “from above” (compare Figures 7 and 8). This is consistent with our observations based on the from above and from beneath seismic images. Also, it seems that the shear impedance results are more sensitive in such a carbonate environment and indicate which events represent zones of higher porosity (low impedance) and which are lower porosity (higher impedance). This may be a result of a greater sensitivity of shear impedance than acoustic impedance to porosity, or it may indicate that greater complexity that results from (albeit weak) fluid sensitivity of the acoustic impedance, or both.

Imaging from beneath results in apparently higher resolution, showing layers that are more continuous than imaging from above. This is probably related to the fact that the ray-paths connecting sources and receivers beneath the reef with their reflection points do not experience the attenuation and/ or scattering that those above the reef do, either because of the simpler geologic structure at the base of the reef, or because of the fluid and pressure distribution within the upper, produced, portions of the reef. The areas of lower apparent impedance (yellows to reds) suggest higher porosity, while those of higher apparent impedance (greens to blues) suggest lower porosity, with some layers probably having all porosity occluded by anhydrite plugging.

We note that the original oil-water contact in the reef coincides roughly with the lithologic boundary where the lower-porosity reef material (containing the hydrocarbon reservoir) overlies higher-porosity reef material, typical of Michigan reefs. After 30 years of production, the fluid contact is no longer expected at this location, and we do not presume to image it.

Reef interpretation
The upper part of the reef appears to be an attenuating zone in both imaging geometries (from above and from beneath); this supports the notion that it is a property of the reef at this location that causes the signal attenuation, probably varying gas saturation and/or fluid pressures that are causing intrinsic attenuation or that are resulting in the high density of scatterers rendering the signal less coherent. In any case, the image “from above” is not as high-resolution as the one “from beneath.”

Amplitudes are easily contaminated by many factors such as scattering, geometric spreading, source and receiver coupling, radiation patterns, and transmission/reflection effects. For scattering and intrinsic attenuation, however, the high-
Borehole geophysics

The frequency components of the seismic signal are attenuated more rapidly than the low-frequency components. Carrillo et al. (2007) calculated the attenuation coefficient for the same data set (from above) by using the analysis of traveltimes and average frequencies for transmitted rays. Figure 9a shows the “apparent” elastic inversion for the crosswell data from beneath. The low impedances shown at the base of the reef match the high-attenuation zone estimated by Carrillo et al. More internal details are shown in the inversion where this attenuation zone has a variation in porosity.

Figure 10 shows the shear impedance produced by the elastic inversion of partial stacks imaged from beneath compared with one of the geological models by Gill (1973). His model was based on many core samples from Michigan reefs. We can use the inversion results to divide the reef into three zones as suggested by Gill. It is apparent that the low-impedance area on the inversion results shown inside the organic reef stage correspond to the reef detritus zone in Gill’s model. A similar conclusion can be verified for details within the biohermal stage. Because the shear impedance is more dependent on the variation in porosity than the fluid distribution, it seems that shear impedance is highlighting the internal lithologic features of the reef quite well.

**Conclusion**

Crosswell seismic imaging has demonstrated its ability to provide extremely high-quality images of reservoirs such that internal features within the reef can be imaged and characterized. Resolution is about 40 times that of surface seismic in the same area (50 Hz versus 2000 Hz).

The amplitudes of reflectors from within the Springdale reef are low, however, and especially so for the image obtained from above. We attribute this to attenuation and scattering of signal as it passes through the complex upper part of the reef, where gas saturation likely varies locally, reservoir pressure is extremely low, and structural complexity of the reef is evident. The image from beneath does not pass through this complexity and only experiences the gas saturation and low pressures at the upper edge of the image, allowing most of the image to be higher quality.

Until techniques are developed that properly account for crosswell seismic inversion from beneath, we treat the two (above and beneath) data sets independently, rather than providing additional constraints on the simultaneous inversion. Recall that the reflection observed from above is not just the inverse of the reflection observed from below (with a simple sign change), at any angles other than normal incidence.

The most valuable aspect of the reservoir characterization in this study has been the inversion of data. But, because inversion techniques have not yet been developed that properly account for phase rotations beyond critical angle, it is probably most appropriate to restrict inversion to stacks that do not exceed that angle. Within this limited range, elastic inversion may be conducted with reasonable results, as demonstrated at the Springdale site. Although “acoustic” inversion also provides meaningful results, the interpreter must recognize that
the resulting image is not truly “acoustic” impedance, but some sort of narrow-angle “elastic” impedance, referred to in this report as “apparent” impedance. Nonetheless, at these angle ranges and in this lithologic environment, a decrease in apparent impedance can be interpreted as an increase in porosity within the reef, while an increase in apparent impedance can be interpreted as a decrease in porosity, perhaps anhydrite-plugged at the extreme, within the reef.

Some shear impedances seem to highlight the internal features of the reef best and the resultant inverted images of the pinnacle Niagaran reef are the best images available to date. **TLE**

References


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