Benefits of 3D poststack depth migration: Case study from the Potash Belt of Saskachewan

Dr. Balazs Nemeth, Terry Danyluk, Arnfinn Prugger - Potash Corporation of Saskatchewan
Steve Halabura - North Rim Exploration Ltd.

Summary

Saskatchewan potash mining companies rely extensively on 3D seismic programs to identify potential geological problems in advance of underground mining. Traditionally, seismic data have been used to map large anomalies (greater than 200 m across), those considered to be a significant hazard to mining operations. However, recent advances in seismic data acquisition and processing have made detection of much smaller scale anomalies possible (i.e.- features considered minor nuisances by the mine operator). With these improvements in resolving power, and with recent advances in computer modeling capability, there has been a push to integrate and combine all available earth science data into a single, "Common Earth Model" (eg.- Garrett et al., 1997; McGaughey and Morrison, 2000). We feel that this approach will help us identify, predict, and illuminate any potash ore zone anomalies (large and small) more accurately. But while most earth science data are referenced in spatial coordinates – the mine map is the most important of these for us – seismic data still tend to be presented in two-way travel time rather than depth. Depth migration is the only way to move the seismic data from time to depth with the required precision. After testing a number of algorithms, the post-stack PSPI approach (Gazdag and Squazerro, 1984) was adopted. The resulting depth migrated seismic images significantly improved our understanding of major structural disturbances seen in the data; we feel that these disturbed zones have been delineated much more accurately than before. Depth migration also improved the overall resolution of the seismic data; this allowed us to predict small-scale ore zone anomalies that could not be seen in the time-migrated data. Our predictions are currently being "ground-truthed" by mining into the regions covered by the 3D seismic data volume.

Introduction

Salts of the Middle Devonian Prairie Evaporite Formation extend over much of the Williston Basin region of west-central North America. Saskatchewan potash companies mine potash ore (used as fertilizer) at 20 – 30 m from the top of the 200 m thick salt unit, at about 1000 m depth. The most prominent structural disturbances of the Devonian strata in the Williston Basin are salt collapse structures. Dissolution of evaporite beds can result in formation of near vertical breccia-fracture chimneys in overlying layers as they "drop" into the voids created by washing out of underlying salts (Gendzwill, 1978; Gendzwill and Lundberg, 1989). This localized fracturing of normally impermeable carbonate rocks can create reservoirs that are dangerous for potash mining operations. Mining into one of these collapse zones would result in cost increases for the mining operation at best (i.e.- no ore), and in some instances even the loss of the mine (Gendzwill and Martin, 1996; Prugger and Prugger, 1991). Therefore, Saskatchewan potash mining companies routinely utilize seismic surveys to map these collapse structures in advance of mining.

On a time migrated 3D seismic section collapse structures appear as vertical zones where seismic reflectivity is completely or partially lost throughout the Devonian strata, and ever higher (Figure 1A). The loss of reflectivity is inferred to be the result of scattering of seismic energy from the brecciated zone in the central core of the collapse. Collapse cores are thought to be a few hundreds of meters wide, and they can extend from depths of 1000 m right to surface. The non-reflective region is often surrounded by an apparent draw-down, or broad "dishing", of reflectors near the central breccia-cavern. This effect has been attributed to a fracture halo surrounding the central zone of the collapse that results in lower than normal seismic velocities (Figure 1 B). The "dishing" of layers below the Prairie Evaporite unit near collapse cores is usually explained by the time-delay effect of this fracture-induced, slow-speed zone in higher strata. We first questioned this model when we found that sonic logs from wells drilled near the central area of a collapse do not show any reduction in velocities. We also found that velocities measured from the potash mining level near a collapse region show no slowing in carbonates just above the Prairie Evaporite (Danyluk et al., 1999). In other words, there is no data to corroborate the inference that salt-dissolution collapse zones are surrounded by low-speed "fracture halos"; in fact, any non-seismic data we do have indicates the absence of any such zone.

Depth migration algorithm

It was felt that migration of seismic data from time to depth might help shed light on the shape and character of these apparent slow-speed zones near salt-collapses. After trying a number of methods for migration of a 3D seismic data volume, the PSPI algorithm of Gazdag and Squazerro (1984) was chosen because of its unconditional numeric stability. The migration algorithm was implemented with an adaptive choice of reference velocities, similar to the approach of Bagaini et al. (1995). An iterative depth migration approach, described by Yilmaz (2001), was adopted to perform the depth imaging. Input to this algorithm is the processed, unmigrated 3D seismic time-stack, and an initial 3D velocity-structure model based on a nearby sonic log. The velocity-structure model is refined after each application of the algorithm (i.e.- re-pick layer interfaces in the most recent seismic data volume). The result of this approach is an improved 3D seismic data volume (in depth), and a corresponding 3D velocity-structure model. This iterative procedure is repeated until there is no change to the resulting seismic data volume.

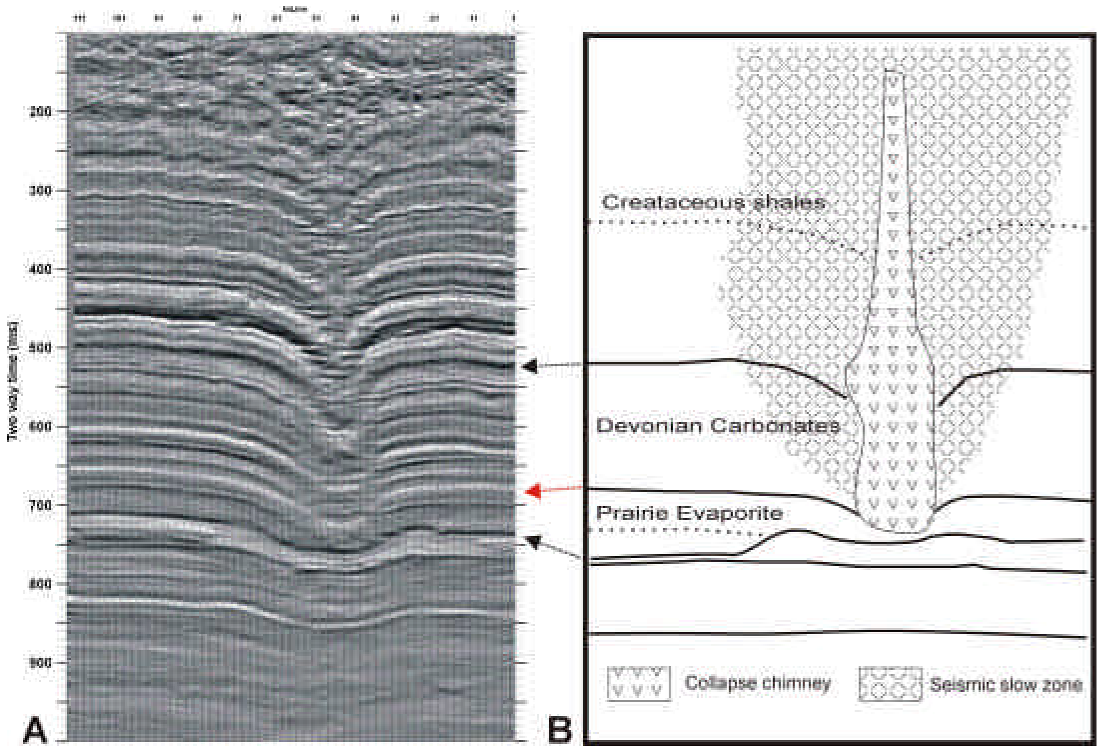

Figure 1. Cross line from a time migrated 3D volume across a collapse feature (A) with the 'old' geological model for collapses (B). The upper arrow marks the top of Devonian strata, middle red arrow shows the top of the Devonian salt unit (Prairie Evaporite), and the bottom arrow indicates the base of it.

Depth migrated image of the collapse

The seismic image of the collapse after depth migration is plotted with the corresponding time-migrated section in Figure 2. The core of the collapse chimney appears on both seismic cross sections as a significant loss of horizontal reflectivity. But in the depth-migrated data (Fig. 2 B), the transition from the disturbed zone to the normal stratigraphy (edge of the collapse) is very abrupt. This implies that there is no disturbance of Devonian strata outside the central collapse region, that there is in fact no slow-speed "halo" surrounding the collapse core. Horizons below the Devonian salt layer are not affected by the collapse structure above. The "dishing" that is apparent on the time image of the collapse has been completely removed by the depth migration.

Curiously, we found that the low velocity zone responsible for the distorted time image is located somewhere in the Upper Cretaceous shales, between the surface and about 200 m depth. The nature of this feature is largely unknown at present, and its relation to the collapse structure is not understood. This anomalous slow-speed region is located in a seismically blind zone (above the first reflective horizon), and it does not show up on the first breaks, behaving as a hidden refraction layer. Its velocity properties, therefore, were resolved by estimating the effect of the anomaly, and by implementing geological constraints during the velocity model building process.

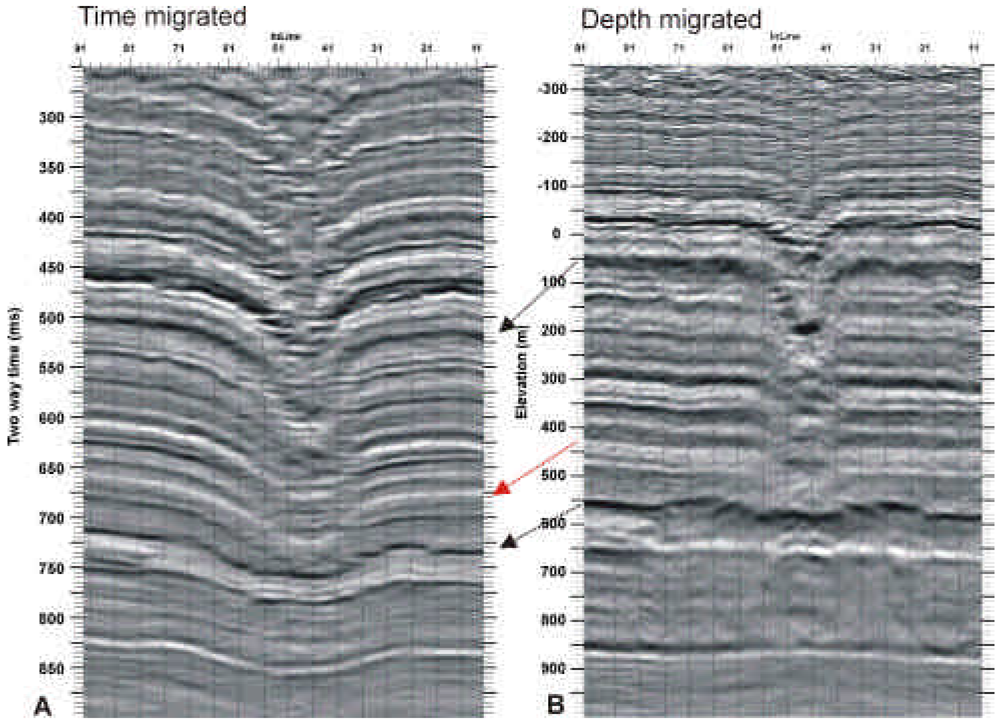

Figure 2. Comparison of the same cross-line from the depth and time migrated 3D volume. The arrows show the location of the same reflectors as on Figure 1. The depth migration removed the apparent “dishing” of the stratigraphy around the collapse chimney. Note, that the depth migrated section has much higher spatial resolution.

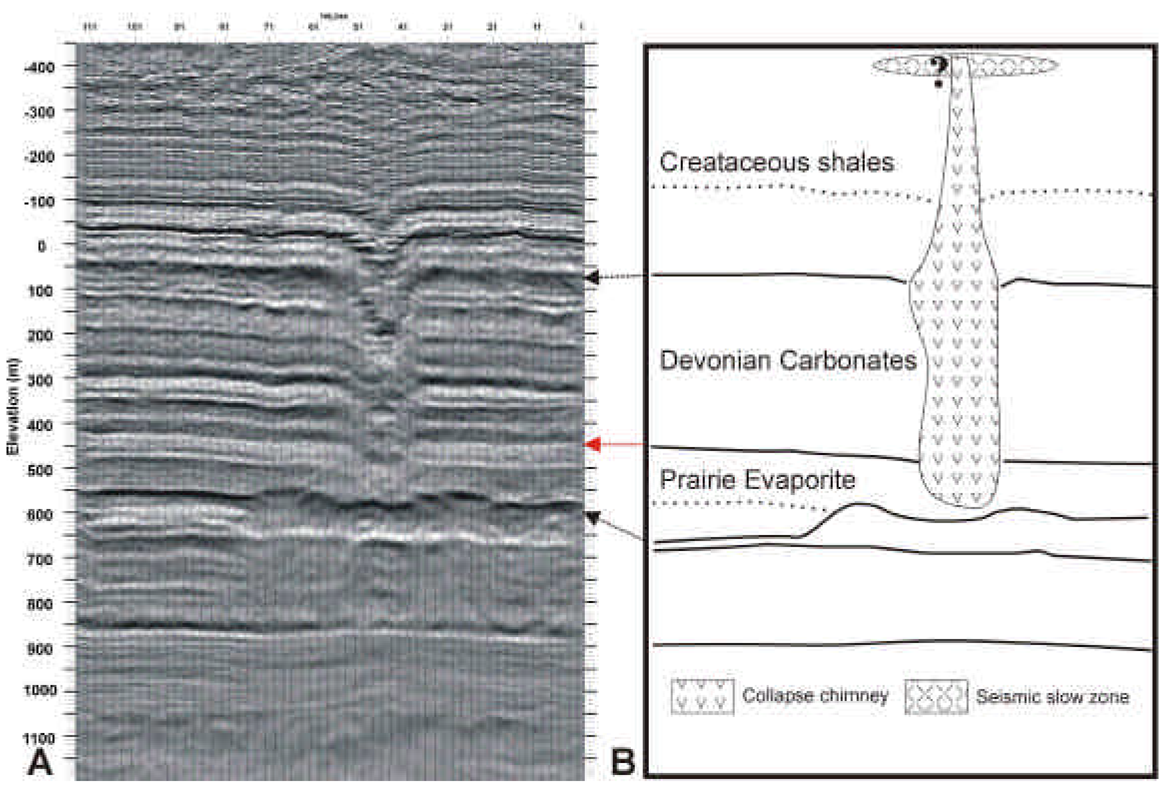

Figure 3. Cross line from a depth migrated 3D volume across a collapse (A) with the new geological model for collapses (B). The arrows mark the same horizons as on Figure 1.

Other benefits of the depth migration

Besides removing the distortion caused by velocity anomalies and presenting the section in depth rather than time, the depth migration also improved the spatial resolution of the section significantly. This was an unexpected (but very welcome) result for us. This can be explained by the differences between the time and depth migration approach. Time migrations assume that the energy from a buried single diffractor has a perfect hyperboloid shape in a 3D seismic volume (Bancroft, 1997). This is only true when there is no lateral variation in seismic RMS velocities; in other words, when the layers in the earth are perfectly horizontal with no lateral velocity variations.

Any deviation from this ideal earth would cause the time migration not to perform perfectly, resulting in a blurred migrated seismic image. Depth migrations, however, can properly handle distorted hyperboloids, and focus the energy back to the proper location of the diffractor. This is especially the case when there is significant velocity variation present in the survey area. The better focusing of the depth migration allowed us to predict potash ore zone anomalies that are a few meters thick and few tens of meters wide. These predictions are currently being "ground-truthed" by mining into the regions covered by the 3D seismic data volume.

Conclusion

Poststack depth migration was found to be a very useful tool, providing us with a better quality image of the subsurface. It helped us to delineate structural anomalies (collapses) more accurately, and to predict ore zone anomalies more precisely. By moving the seismic data from time to depth, we can more easily integrate the seismic observations with other earth-science data into a "Common-Earth-Model". Building of the velocity models that are required for the depth migration, and analysis of improved seismic images that resulted from this, forced us to refine and re-think our geological models.

Acknowledgement

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