

Detailed 3D Seismic Imaging of Paleozoic Karst / Collapse Disturbances in Saskatchewan: Case Study from the Potash Belt

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Saskatchewan potash mining companies use 3D seismic surveys extensively to identify and map zones of geological disturbance in advance of mining. Just over 100 square miles of 3D seismic data have been acquired at four POTASHCORP minesites since the first survey was conducted at Lanigan in 1988. In 1999 we initiated a research effort to find improved methods of migrating these data to depth. After trying a number of pre-stack and post-stack methods for migration of our data volumes, the PSPI (Phase-Shift-Plus-Interpolation) algorithm of Gazdag and Squazerro (1984) was chosen. The algorithm was implemented with an adaptive choice of reference velocities (after Bagiani et al., 1995), using an iterative depth migration approach (Yilmaz, 2001) as described in Nemeth et al. (2002). PSPI depth migration requires feedback-coupling of earth modeling, seismic interpretation, seismic processing, and migration computations. Data are seamlessly transferred back and forth amongst all of these software components. The end result of this iterative migration approach is a 3D seismic data volume in depth, and a corresponding 3D velocity-structure model. The method benefits from geological constraints imposed during the modeling phase. In fact, this process has forced positive communication amongst geophysicists, geologists, and mining engineers. The most important result of application of PSPI migration to 3D seismic data is an improved seismic data volume that is in depth. This was expected, since any removal of distortion caused by lateral and/or vertical velocity variations should result in improved seismic data. A second benefit is that the method significantly improves lateral and vertical spatial resolution in the seismic data volume, which was surprising but very welcome. Data from the Allan potash mine near Saskatoon is shown in Figure 1.

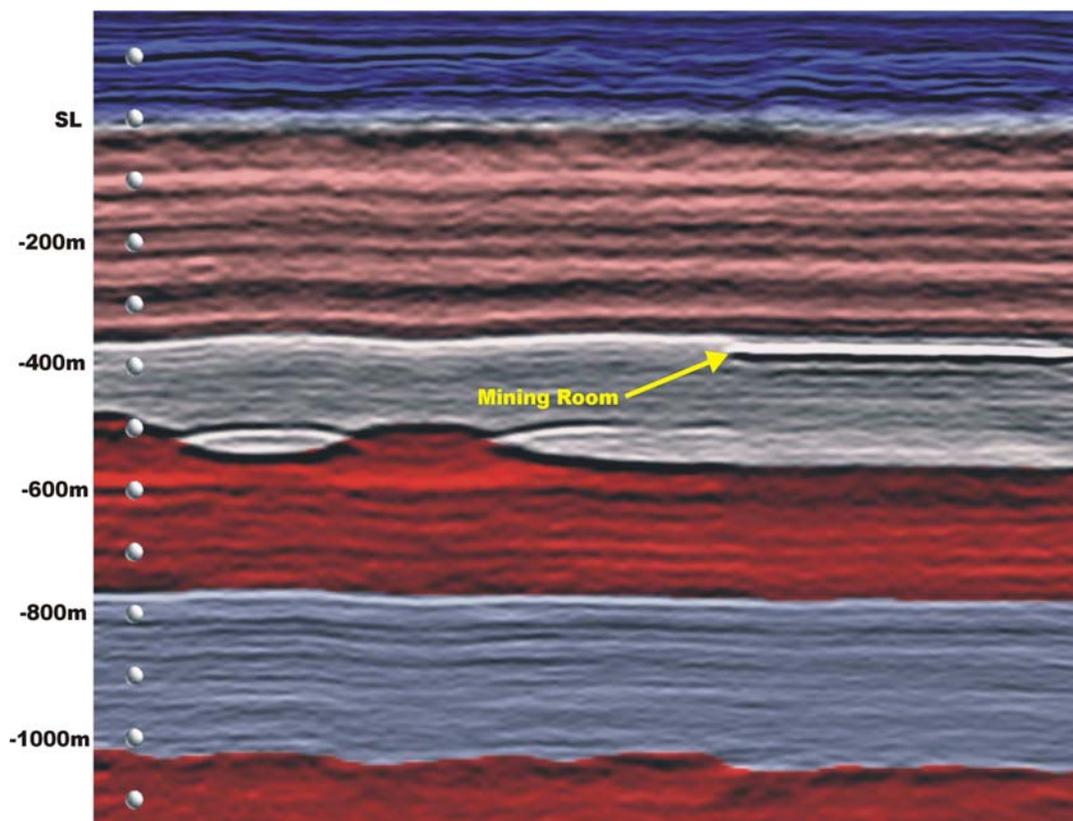


Figure 1: PSPI depth-migrated seismic section in metres below Sea Level (SL); this section has a 2X vertical exaggeration. The arrow marks a “cultural” reflector, Allan mine Panel N2E.

Salts of the Middle Devonian Prairie Evaporite Formation extend over much of the Williston Basin region of west-central North America. Saskatchewan potash producers mine ore (used as fertilizer) at 20 – 30 m from the top of the 100 – 200 m thick salt unit, at about 1000 m depth; for more information about potash mining in Saskatchewan see Fuzesy, (1982). “Normal” stratigraphy for most geological units in this region means sub-horizontal layers of uniform thickness, as shown in Figure 2. The notable exception are carbonate reefs of the Middle Devonian Winnipegosis Formation, which vary in both thickness and height. Winnipegosis carbonates, the stratigraphic equivalent of the Keg River Formation in Alberta, form the geological base for the Prairie Evaporite Formation.

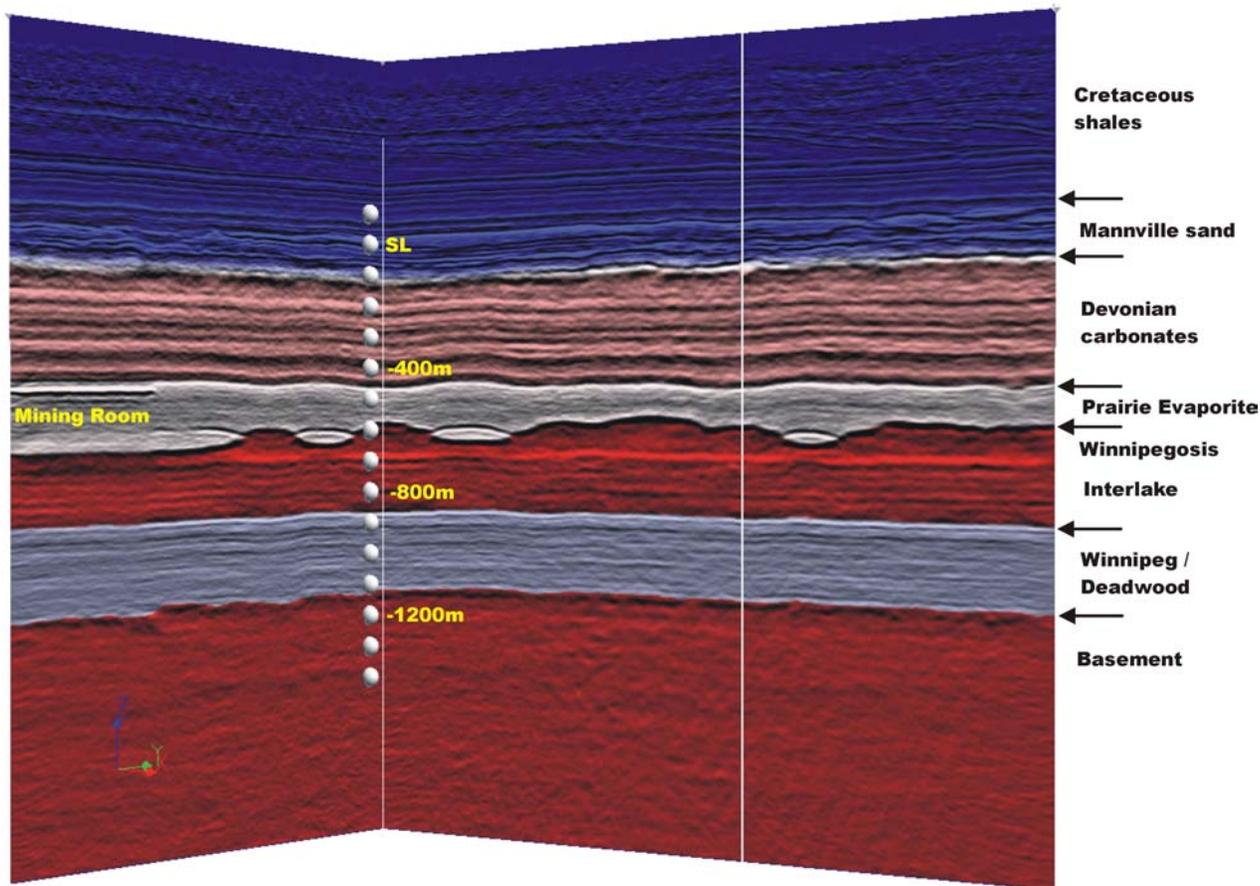


Figure 2: PSPI depth-migrated seismic section showing normal central Saskatchewan stratigraphy (from the Allan area); section has a 2X vertical exaggeration. This is a different view of the data shown in Figure 1. Fence sections are painted with velocity from the model derived during the migration: blue is slow (shales & sand), red is fast (carbonates & basement), and grey is intermediate-speed (salt & sand).

The most striking disruption to normal Phanerozoic stratigraphy in the Williston Basin is the collapse structure. Collapse structures are localized regions of considerable, sometimes complete, destruction of original geological layering. Historically these features were thought to result from dissolution of Prairie Evaporite salts at depth, with associated brecciation and collapse of overlying (mostly carbonate, then shale) strata into the resulting washout caverns (eg.- Gendzwill, 1978; Gendzwill and Lundberg, 1989). Collapses are often assumed to take the shape of sub-vertical cylinders, 100 – 1000 m in diameter, extending from depths of over 1000 m right to surface. In Saskatchewan, the most famous of these are the Crater Lake collapse (south of Yorkton) and the Colonsay Collapse (east of Saskatoon). Earth Scientists working in the Saskatchewan potash industry have a strong interest in mapping collapses because of the hazard these disruptions pose to mining operations. Any fracturing of normally impermeable carbonate rocks could 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 (Prugger and Prugger, 1991; Gendzwill and Martin, 1996; Danyluk et al., 1999). This is the main reason that Saskatchewan potash mining companies routinely utilize seismic surveys to map the subsurface in advance of mining.

The recent practice of depth migration of 3D seismic data has resulted in a more detailed view of the shape of these features than ever seen before. With depth migration, disturbed zones become much smaller and more focused than previously thought. While some collapses are consistent with the existing washout/brecciation model, others are not. 3D images of some disturbances look more like carbonate-karst features than collapse washout-breccias (Halabura et al., 2002; Prugger et al. 2002). Some of these disturbances are underlain by washouts in the Prairie Evaporite, but some are not, as shown in Figure 3.

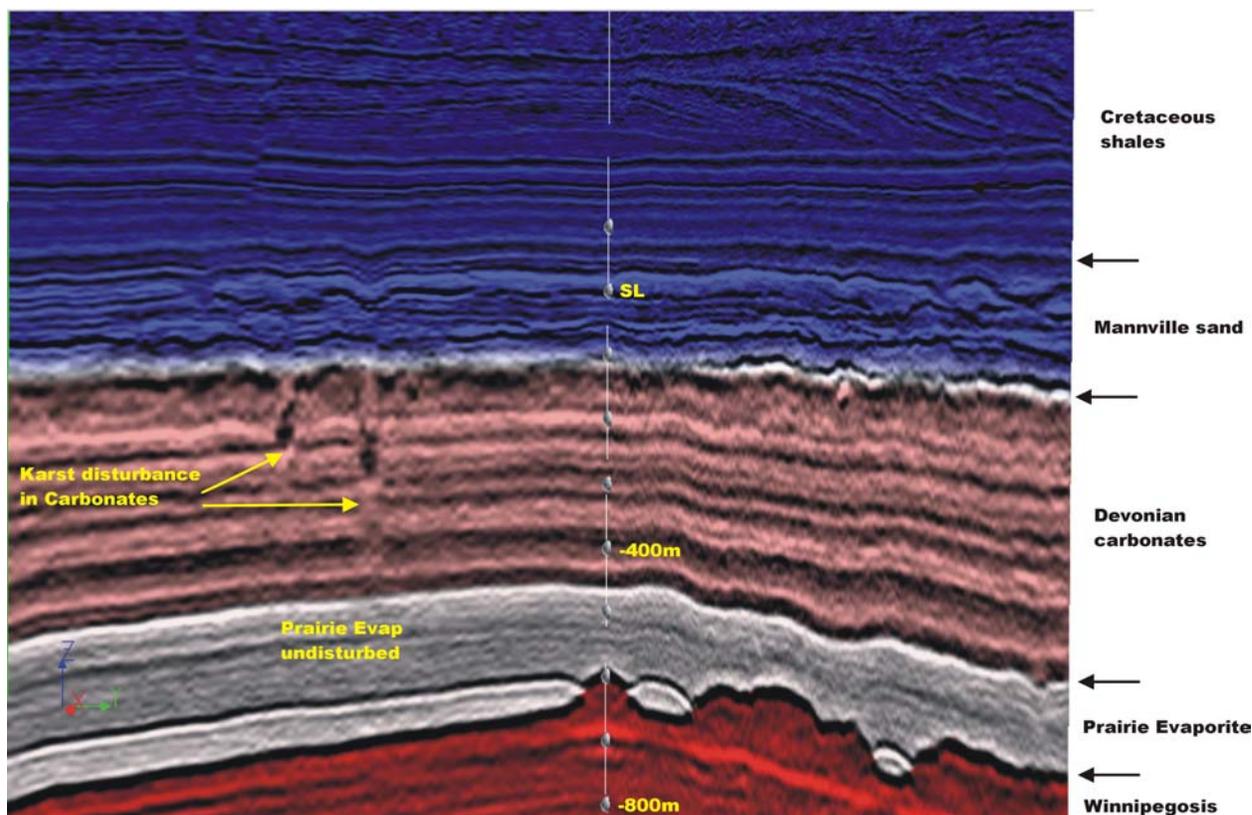


Figure 3: Another fence from the Allan data volume; this section has a 2X vertical exaggeration. Two Karst-type disturbances are marked; these features are about 130 – 150 m wide.

The absence of any disruption within Prairie Evaporite salts below a disturbed zone in overlying carbonates is inconsistent with the historic washout/breccia model for how these carbonate “collapses” are formed. One of the disturbances in Figure 3 extends no more than 200 m below the top of the Phanerozoic unconformity, “stopping” about 200 m above the Evaporite. The other disruption is about 400 m high, extending all the way down to the Prairie Evaporite. But the salts underlying both features appear to be undisturbed; these disturbed zones might have nothing to do with underlying salts. This observation is consistent with existence of porous Karst zones in these carbonates, not traditional washout collapses.

Any relationship between these postulated zones of Karstification and disruption of underlying Prairie Evaporite salts is currently unclear. We have attempted to relate Karst and collapse disturbances to other geological features. An example of this is shown in Figure 4: the two Allan Karst disruptions are plotted in map view with respect to the underlying basement structure surface (which is about 700 m below the base of the larger Karst). The disruptions are located above a basement structure-edge, and some lineament patterns in the basement unconformity surface align with these disruptions. Is this a real relationship, or is this a strange coincidence? Comparisons to spatial trends in everything from Cretaceous faults to Winnipegosis mound patterns have also been attempted (and will be shown).

For us, the application of PSPI depth migration was a real breakthrough. Application of the technique has increased the practical value of our 3D seismic data tremendously at each of our four Saskatchewan minesites: Cory, Allan, Lanigan, and Rocanville. We feel that we are now able to see much finer detail to much greater depth in our 3D seismic data sets than ever before. This is detail that matters when attempting to predict potash ore zone disruptions and hazards in advance of mining.

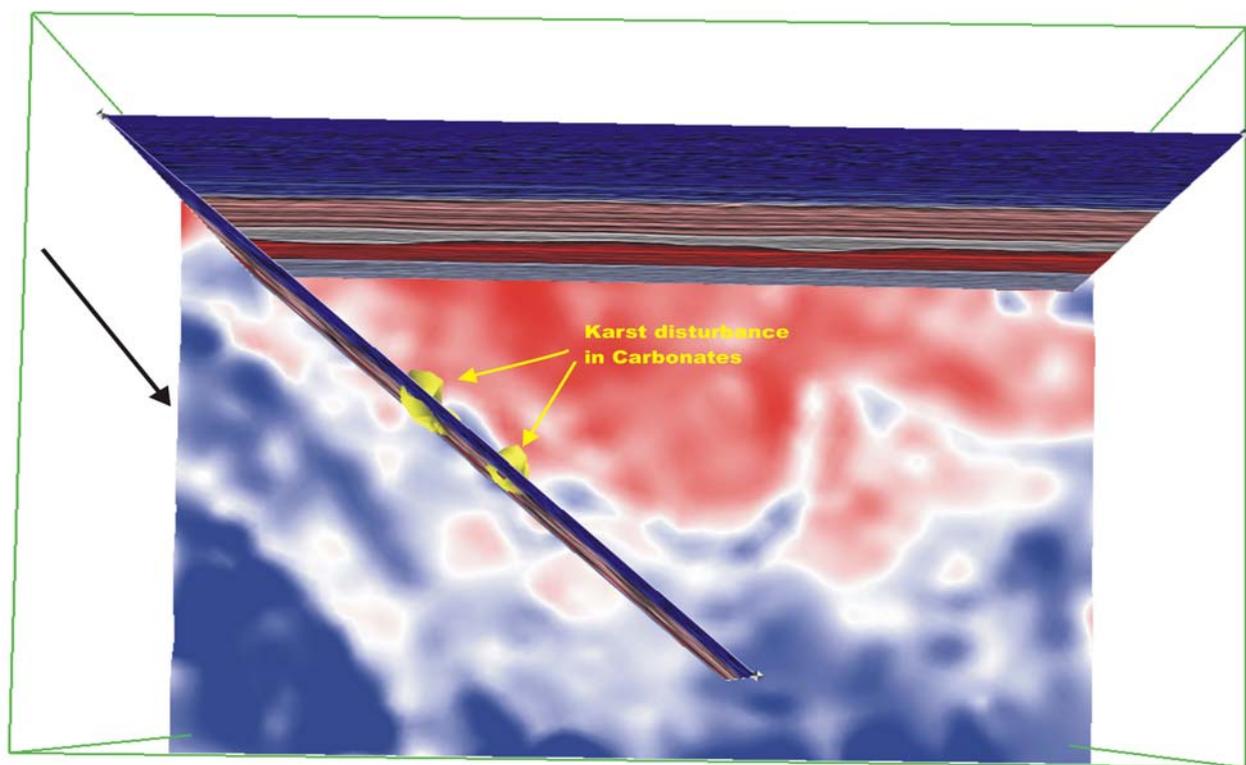


Figure 4: Map view of fence data from Allan (shown in earlier figures) along with the basement structure map picked from these data. Colour contours range from -1100m BSL (red) to -1150m BSL (blue). Karst model outlines picked from seismic data are marked. Black arrows mark a basement lineament. This 3D seismic data set measures about 3.4 by 2.3 miles.

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