LONDON2007

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Duplex Wave Migration – A Practical and Effective Tool for Imaging Vertical Boundaries

N. Marmalevskyi* (Ukrainian State Geological Prospecting Institute), B.H. Link (Kelman Technologies Inc.), Y. Roganov (Ukrainian State Geological Prospecting Institute), A. Kostyukevych (Tetra Seis Inc.) & Z. Gornyak (Ukrainian State Geological Prospecting Institute)

SUMMARY

Reverse time migration (RTM) has recently become available on a commercial basis. This two-way wave equation method is theoretically capable of imaging vertical boundaries by virtue of the fact that it can use reflection energy that has undergone two bounces (duplex wave energy (DWE)) to image vertical boundaries. However, RTM has a number of inherent problems that limit how effective and practical the tool is to solve a whole series of common E&P problems. This paper describes a Kirchhoff implementation of Duplex Wave Migration (DWM) to address these problems and to illustrate how DWM can provide an entirely new methodology for determining more accurate depth models. A 3D data set from the Western Canadian Basin (WCB) will be used to illustrate the ability of DWM to image a well known normal fault, a vertical dyke that is detectable using an aeromagnetic survey but invisible on 3D seismic data and additional parallel and orthogonal vertical faulting that is invisible to both aeromagnetic surveys and 3D seismic surveys.

Introduction:

The imaging of vertical boundaries has become extremely important for solving a whole host of exploration and production challenges; salt wall imaging, zero or near zero throw faults within the reservoir (fault compartmentalization), zones of fracturing, locating diagenetic reservoirs formed by basinal hydrothermal fluid flow along vertical faults (Hickman and Kent 2005), identification of bypassed reserves (enhanced recovery) and the delineation of the edge boundaries of oil (or gas) to water interfaces.

Hail et al. (1992) illustrated that it is possible to image vertical boundaries using turning waves provided sufficient vertical velocity heterogeneity (VVH) exists. Under these conditions the refracted waves will return to the surface, however the required size of recording aperture is large and for accurate lateral positioning a very accurate depth model over a very wide area is a must. However, if we use duplex wave energy (DWE) to image the vertical boundary no VVH need be present and the recording aperture can be quite small. The DWE is produced when a primary event that has been reflected from a deeper event reflects again off of the vertical boundary and then returns to the surface. The path of the DWE may also be reversed – first bouncing off the vertical boundary and then the deeper base boundary. This means that even if our 3D is relatively small in area we can still extract information about the vertical boundaries. The properties of DWE have been investigated by Lutsenko (1987) and Kostyukevych et al. (2001) and it has been clearly shown that the strength of these waves is sufficient for imaging vertical boundaries.

The first paper that described the use of DWE to image vertical boundaries on synthetic data was by McMachan (1983). Reverse time migration (RTM) was used in this case, however the inability of RTM to attenuate the primary energy was problematic because its strength was so much greater than that of the DWE that it masked the image of the vertical boundary. McMachan got around this problem by attenuating the primary energy on the shot gathers before the application of RTM. Yoon et al. (2004) offered a similar solution for primary refracted waves. This method, which relies on the attenuation of the single bounce, primary energy on real seismic data is not practical particularly in structurally complex areas.

Yoon et al. (2004) and Flatcher et al. (2005) offer methods for attenuating diffracted and refracted energy with a RTM implementation in an effort to allow the DWE to be imaged. This RTM method can be put into a class of algorithms based on a non-reflective principle for waves that strike a boundary at a steep angle of incidence. This principle is not suitable for the imaging of DWE because the DWE is formed by upward propagating energy that has been reflected from a deeper base boundary (or vise versa).

Jin et al. (2006) suggested a duplex wave migration (DWM) implementation using two passes of one-way wave equation migration – the second pass computes the upward reflected wave from fixed base boundaries. This method is faster that RTM, however the correlation based imaging condition has difficulties dealing with the hindrance waves, that is the primary, refracted and diffracted wave energy. This energy obscures the image that would have been produced by the correct imaging of the DWE.

Farmez et al. (2006) presented the results of RTM applied to a 3D data set to produce a cube of the vertical boundary images from a salt dome. In this case the problem of the hindrance waves was solved by using a reference velocity for the salt that was considerably different from the velocity in the area of the salt dome. This limits the applicability of DWM. The essential characteristic that is necessary for this method to work is the significant difference in travel time inside the salt versus its travel time in the sediments surrounding the salt. Faults and fracture zones in reservoir country rock usually have thickness in the order of one seismic wavelength. Defining a substantially different velocity to this narrow interval around the fault will not produce a significantly different travel time for the purpose of attenuating the hindrance wave energy.

Marmalyevskyy et al. (2005) presented a Kirchhoff method for DWM that successfully imaged vertical boundaries from salt walls and subtle zero throw faults within the sedimentary section while at the same time automatically attenuating all energy other than the DWE. In this paper we will present an example of 3D DWM on a 3D data set from the

Western Canadian Basin (WCB) to identify otherwise seismically invisible vertical boundaries.

Method:

We have developed a Kirchhoff depth migration that is based on the Green's function using the kinematics of DWE. A primary event (that must be deeper than the vertical boundaries we wish to image) is defined in depth by the user. It is assumed that a conventional prestack depth migration (PSDM) has been run prior to running DWM, therefore we use the depth model generated from that process as a starting point. The depth model can be either isotropic or TTI anisotropic. The TTI travel time calculations are generate using an eikonal solver as described by Roganov (2006).

The DWM algorithm is designed to image the DWE that will arrive at a time greater than that of the primary base boundary. A beam tube construction eliminates the migration noise that would result from including the base boundary primary reflections in the migration summation. Tight control of the aperture is also key to suppression of artifacts from primary reflections. Each DWM run produces four separate and distinct views of the vertical boundaries based on two possible bounce orders – base boundary then vertical boundary or vice versa and traces input to the migration are either to the right of the shot or to the left of the shot.

This means that in the case of a vertical boundary we can examine the reflections from the same boundary using data that has bounced off of each side of the boundary. If the velocities are too slow then the vertical boundary will be positioned too close to the shot and if they are too fast then the positioning of the vertical boundary will be too far from the shot. Since we have an image of the same vertical boundary from both sides of the boundary they will only focus at the same location in 3D space if the velocities are correct. This means we no longer have to rely solely on the flatness of migrated gathers criteria for velocity model building. It is hoped that further research will indicate that this is a powerful method for obtaining more accurate anisotropic parameters.

This method for the suppression of artifacts can be used without restrictions on the geologic structure of the medium through which the DWE travels. This method enables the identification of all types of vertical boundaries including salt walls, subtle vertical faults within the reservoir, vertical zones of corrosion that exist above the oil to water contacts etc. The fact that we use a Kirchhoff implementation means that the data need not be regularly sampled in space. Also, the Kirchhoff implementation allows for efficient and targeted velocity analysis by generating a series of migrated DWM 3D view cubes. Modern 3D visualization technology is used to integrate the additional information about vertical boundaries into the pre-existing PSDM depth model. If the changes in structure or velocities are significant then we may wish to rerun the PSDM.

Real 3D data example from the Western Canadian Basin:

It is well known that NW to SE trending lineaments, and a near orthogonal set of NE to SW trending lineaments exist throughout the WCB (K.S. Misra et al., (1991)). These vertical faults originate from block faulting in the Precambrian basement and they often have little or no vertical throw, therefore they are generally invisible to conventional seismic imaging. In some areas the faults have been intruded by igneous lava flow that in some cases outcrops at the surface. A NW to SE linear dyke has been revealed by an aeromagnetic survey in the north half of the example 3D survey. The dyke is invisible on the coherency cube of the conventional PSDM product.

Figure 1 shows two cross sections from the interpreted 3D PSDM data cube. Five horizons are interpreted and several wells were drilled in this area into a thin gas sand play above horizon 2 and a few wells were also drilled into an oil play above horizon 3. We ran 3D DWM on horizons 2 through 5. The DWM images generated from all four horizons showed faulting that matched the known normal fault (which was clearly identified on the PSDM coherency cube), and the aeromagnetic evidence of a dyke (which was invisible on the same coherency cube). Also, a set of faults parallel to the dyke was revealed and a set of parallel faults in the NE to SW direction was identified.

Figure 2 shows vertical boundary imaging in a 3D DWM data cube 100 meters above horizon 5 and Figure 3 shows the structure map of horizon 5 generated during conventional PSDM model building. Figure 4 shows the vertical boundaries identified in the interval 100 meters above horizon 2 and figure 5 illustrates that the only producing gas well from this interval is at the crossing point of high amplitude orthogonal faults.

Conclusions:

3D DWM is a practical and more effective method than RTM to delineate vertical boundaries that are invisible to conventional PSDM. Vertical faulting and fracturing is thought to be much more prevalent than we realize today. Diagenetic reservoirs that develop where hydrothermal flow is vertically directed were previously found only by accident but now we have a direct imaging technology to aid in a targeted search for these traps. Corrosive plumes above oil to water contacts can now be used to delineate reservoir boundaries. Perhaps the most significant potential of this technology is enhanced recovery through accurate delineation of fault compartmentalization, fault characterization, fault seal analysis and the identification of bypassed hydrocarbons within the reservoir.

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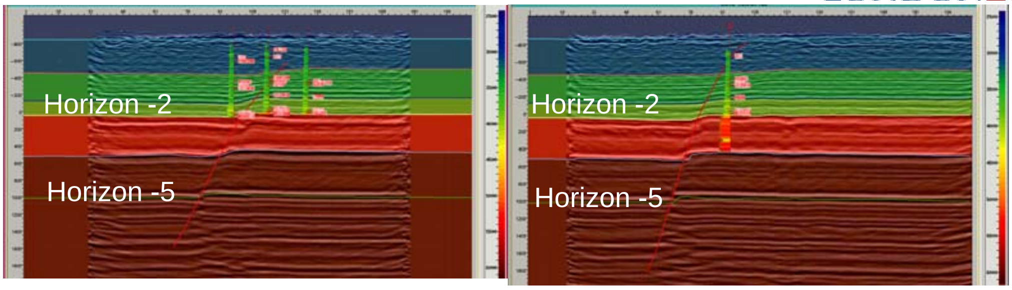

Figure 1 PSDM Stack Section with Velocity and Horizon: Xsline80 (left), Xsline190 (right)

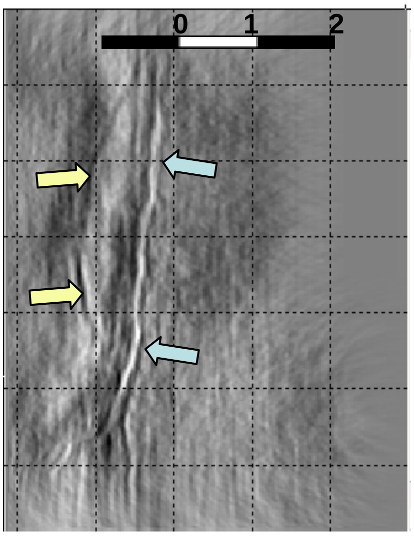

Figure 2 Horizontal slice of DWM cube 100 meters above horizon 5.
Blue arrows – known regional fault.
Yellow – subtle fault

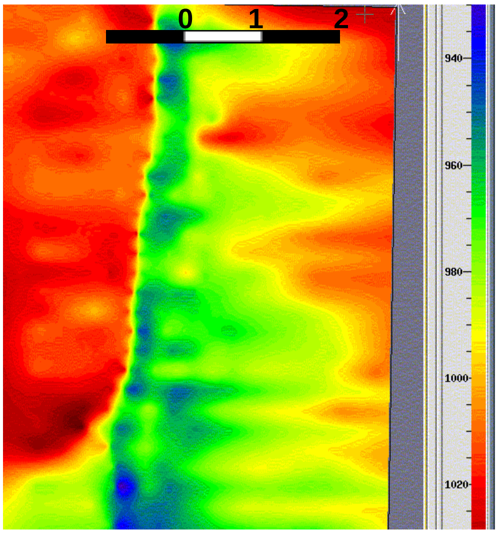

Figure 3 Structural map of horizon 5 from PSDM model building.

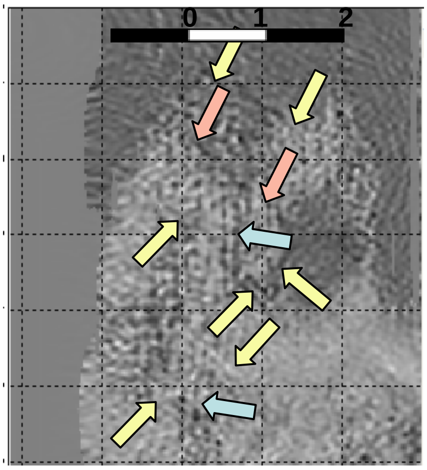

Figure 4 Horizontal slice of DWM cube 100 meters above horizon 2.
Blue arrows – known regional fault.
Yellow and red – faults imaged by DWM only. Red arrows – fault corresponding to dyke, delineated by aeromagnetic survey data.

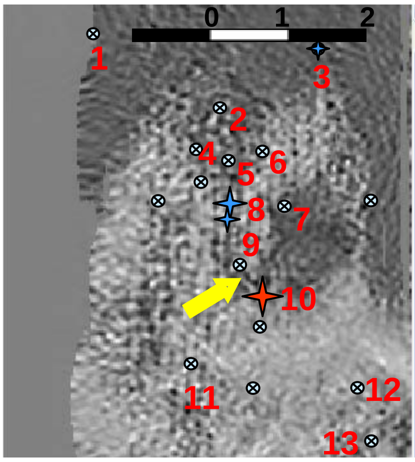

Figure 5 Horizontal slice of DWM cube 100 meters above horizon 2 with marked well positions.

- Well with industrial gas production
- Oil wells
- Dry wells
- Fault, controlling gas deposit