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Duplex Wave Migration Based AVO for Determination Properties of Vertical Boundaries

G.B. Dubrova* (Ukrainian State Geological Research Institute), I. Khromova (LUKoil), A. Kostyukevych (Tetrale Technologies Inc.), D. Luo (CNOOC Ltd Shenzhen), W. Liang (CNOOC Ltd Shenzhen) & B. Li (CNOOC Ltd Shenzhen)

SUMMARY

Modification of the application methods for duplex wave migration (DWM) has enabled us to obtain seismic images of sub-vertical boundaries which are formed by the waves having the fixed incidence angle ranges (partial DWM cubes). It allows the AVO analysis for sub-vertical objects (AVO-DWM) and on that basis the classification of the vertical boundaries and their properties. The role of the full-wave modeling for calculation of corrections needed for the creation of amplitude corrected AVO-DWM curves on vertical boundaries is shown. Example of the AVO - DWM on a real 3D data set is demonstrated.

Introduction

Duplex wave energy is defined as energy that has undergone two reflections, one of which is from a sub-vertical boundary. Duplex wave migration (DWM) is a type pre-stack depth migration that images duplex wave energy only to produce images of vertical boundaries, for example, salt dome walls, low throw faults, vertical fracture zones etc.

An image of a vertical boundary was first obtained with the use of duplex waves by McMechan (McMechan, 1983) with reverse time migration (RTM).

Farmer e.a. (Farmer e.a., 2006), showed that it is possible to form the images of a salt stocks sub-vertical boundaries with use of the duplex waves and 3D RTM.

Marmalevskyy e.a. has shown examples of salt stocks boundaries (Marmalyevskyy et al., 2005) and low throw faults (Marmalyevskyy et al., 2007) imaged with the use of DWM based on Kirchhoff integrals.

Khromova (Khromova, 2008) has shown a real data case-history illustrating the delineation of fracture zone systems using DWM amplitude cubes. The DWM predictions were correlated with well results and this provided a means by which she could perform fracture permeability characterization.

Seismic-based methods to delineate low throw faults and fracture zones are now a key element of the exploitation process for oil and gas companies. Such tectonic elements may act as seals of tectonic traps, or as delivery channels and as traps themselves. DWM by itself is capable of locating these fault/fracture zones, and providing a good estimate of the intensity of the fracturing. However, if we use DWM as a tool with which we conduct an AVO analysis on these vertical fault/fracture systems then this will provide the possibility to further classify the fault/fracture fluid properties etc.

In this article, a case study is presented for the main tasks needed to be solved for performing AVO based on duplex wave migration (AVO - DWM) and a real 3D data example is shown for evaluation of fractured zone properties with use of AVO - DWM for a 3D offshore marine carbonate fractures play.

Method

DWM used for analysis of AVO-dependency, is based on the Kirchhoff integral. DWM considers two possible ray paths; in the first case (HV), the first wall incidences to a sub-horizontal (base) boundary, and then to the target sub-vertical boundary; in the second case (VH), the reflection sequence is reversed. For the DWM implementation, the same depth velocity model is used as for the standard depth migration, but additionally the user must define the base boundary in depth that will act as a mirror under the zone of interest. Since DWM is a second type of pre-stack depth migration, conventional depth migration will have already been performed and therefore the interpretation of the base boundaries will be readily available for us in the DWM process.

To perform AVO – DWM analysis we need to take the following steps:

a) Implement the DWM scheme, for which the waves will arrive the sub-vertical boundary within a given range of incident angles.
b) Take into account the transmission effects, which in the simplest case will be reduced to application of the AVO corrections for the base boundary and the divergence corrections.
c) Introduce a correction for the angle of emergence to the land surface against the measured component of the wave field, and for the intensity of the incidence wave.

The Kirchhoff integral is a convenient tool for the creation of seismic images characterized by the fixed range of the angles of incidence to the boundary. In the Figure 1, the scheme that enables us to define a range of incident angles on the vertical boundary is shown. If the image aperture R is determined by the distance from the source position to its middle, under a constant L, then such distance will determine the angle of the seismic wave incidence to the vertical boundary.

The set of the seismic images for the fixed angles of the wave incidence to a vertical boundary, obtained after the DWM will need to undergo the amplitude corrections mentioned above. The reflection coefficient at the base boundary should be determined during inversion process or by modeling based on well data.

It is not a simple task to take into consideration the geometrical divergence. In particular, for a homogeneous earth where the duplex wave is propagating, the task to keep on the amplitudes is reduced to correction of the geometrical divergence. In case the Kirchhoff integral is used, and especially for the 2D variant, it is important to evaluate its characteristics in terms of the true-amplitude imaging.

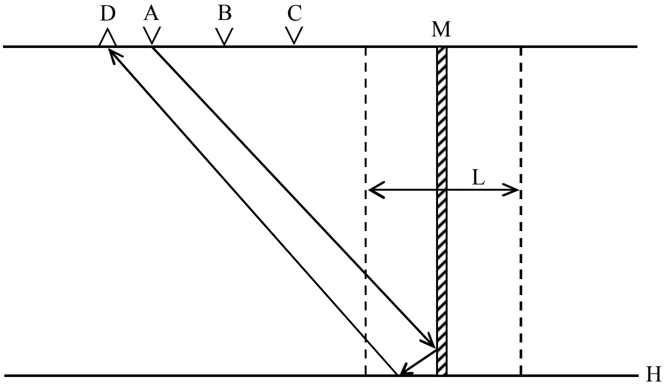

Figure 1 Scheme of the AVO - DWM at the vertical boundary
L – aperture value; A, B, C – location of the wave sources; D – receiver location for shot point A for the ray path shown by arrows; M – projection of the target sub-vertical boundary to the surface; H – the horizontal based boundary

By Goldin (Goldin, 1985), the migration operator of the following type was proposed:

$$U(M,t) = \frac{1}{2\pi}\int_s W(M,N)[U]ds, \tag{1}$$

where $U(M,t)$ - is the wave function in the image domain, $[U] = U(t-\tau(M,N))$ - is the delayed function in the source data domain, $\tau(M,N)$ - is the wave travel time from the point M of the medium to the point N of the observation surface; $W(M,N)$ is the weight function.

Shape of the weight function W is mainly determined by the properties of the relevant migration, but locations of the boundaries in the image do not depend on the W type. Due to this fact, these operators are named «kinematic-equivalent» (K - equivalent) one, and they are considered as various approximations to the Kirchhoff integral which convergence to the exact solution. In a homogeneous media, the true-amplitude imaging is reduced to correction of the geometrical divergence. In case $W = \frac{1}{r}$, that in this particular case may be considered as the Green function, where *r* is the MN distance, the expression (1) may be considered as the hyperbolical summation (Nakhamkin, 1977), the frequency characteristics of which for the 2D case away from the source is equal to

$$\mathrm{H}(\mathrm{K_x},\mathrm{w}) = \sqrt{\frac{2\pi}{\beta}}\exp(\mathrm{i}(\beta + \frac{\pi}{4})), \tag{2}$$

where K_x - is the spatial frequency,
w - is the time frequency,

$$\beta = Z_0\sqrt{\left(\frac{w}{v}\right)^2 - K_x^2},$$

here Z_0- is the object depth, v – is the propagation velocity.

Division of the right part of the expression (2) by $\sqrt{\beta}$ modifies the frequency characteristics of the hyperbolical summation for the 2D case to the shape relevant to decomposition of the spherical wave to the plane wave (Brekhovskikh, 1973). To take into account the whole geometrical divergence, it is needed to carry out the integrating (reciprocal to the inverse Fourier transformation) of the modified frequency characteristics for all spatial frequencies related in this case to the angles of wave incidence to the boundary. The limitations, for the AVO-analysis purposes, of the spatial frequencies range will cause the dynamic distortions of seismic images.

It is proposed to use full-wave modeling for introduction of the mentioned corrections. After the modeled seismic images are obtained corrections are made to obtain the final AVO curve for the vertical boundary.

Example of the AVO-DWM correction

Let's consider a 2-layer model complicated by a vertical boundary. In such model, the elastic parameters for the horizontal and vertical boundaries are chosen to be equal. Such parameter equality simplifies introduction of corrections.
Figure 2 shows the model AVO for the target vertical boundary in the incident angle range of 30-60° (curve 4) and the AVO values obtained by amplitude readings from the DWM seismic images (curve 1). The seismic

image was calculated for the VH scheme. It is seen from the figure that the inclination angle for the AVO curve obtained by the DWM data differs markedly from the model AVO. Curve 2 corresponds to curve 1 with corrections for reflection coefficient on the horizontal boundary. Curve 3 corresponds to the additional correction for difference in intensity of the incident signal. As mentioned previously, the geometrical divergence correction is computed from the difference between the model AVO curve (curve 4) and the AVO curve obtained by the DWM with corrections (curve 3).

Example of the AVO - DWM on a real 3D data set

Conventionally processed 3D pre-stack data was input to the 3D DWM process and this produced a DWM amplitude cube which clearly identified vertical boundaries within the carbonate zone of interest. A stratigraphic slice of the cube above the base boundary of the target interval is shown in the Figure 3. In the figure, the vertical boundaries can easily be identified. The most intensive vertical boundaries are interpreted as oil-saturated highly permeable zones (shown with arrows).

Examples of the stratigraphic slices for the partial DWM cubes obtained with fixed range apertures for the angles of incidence of the P-wave to the sub-vertical boundary from 30° to 45° were generated and some of them are shown in Figure 4. It is possible to see that with increasing aperture (parameter R), the intensity of the target sub-vertical boundaries increases significantly. The AVO curve obtained by the partial cubes within the limits of the most intensive vertical boundary (shown with red arrow in Figure 3) is shown in Figure 5. By the a priori information related to the based boundary the AVO-effect was calculated. The relevant AVO-curve is shown in Figure 6.

The carbonate rock including the fracture zone under study is characterized by the following parameters: Vp=4700 m/s, Vs=2700 m/s, ρ = 2200 kg/m^3, where Vp, Vs, and ρ are velocities of P, S waves, and the density, accordingly. On the base of the AVO curves shown in the Figure 5 and Figure 6 after corrections, the AVO curve on the target vertical boundary was computed (Figure 7). The prognostic medium parameters within the fractured sub-vertical zone are evaluated as follows: Vp=3500 m/s, Vs=1700 m/s, ρ = 2150 kg/m^3. Based on this observation of AVO response of the vertical boundary, we predict that this vertical boundary represents a zone of intense and significant fracturing.

Conclusion

Modification of the application methods for DWM has enabled us to obtain seismic images of sub-vertical boundaries which are formed by the waves having the fixed incidence angle ranges (partial DWM cubes). It allows the AVO analysis for sub-vertical objects and on that basis the classification of the vertical boundaries and their properties. The role of the full-wave modeling for calculation of corrections needed for the creation of amplitude corrected AVO curves on vertical boundaries is shown.

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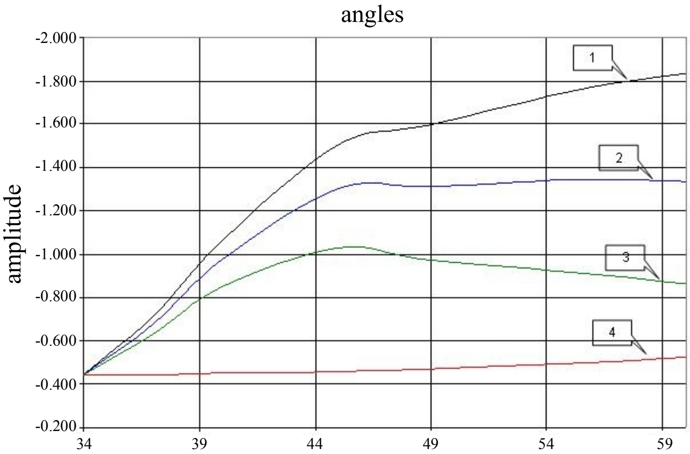

Figure 2 *Example of the AVO-DWM correction*
The model AVO-curve for vertical boundary (curve 4) normalized to the minimal value of the AVO-curve obtained by seismic images of the vertical boundary, which were formed under various apertures of transformation (curve 1); AVO-curve with correction for reflection coefficient of the key boundary (curve 2): AVO-curve with an additional correction for intensity of the incidence wave (curve 3)

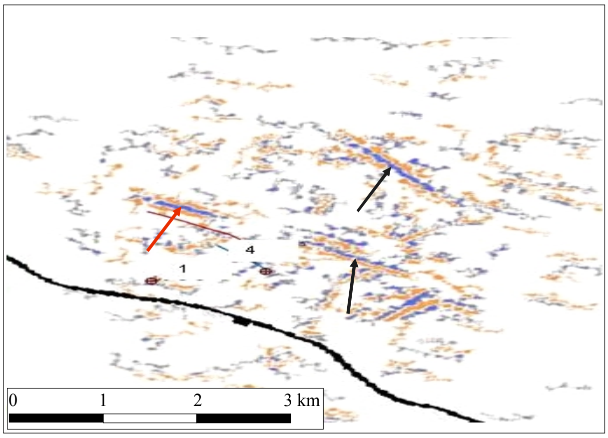

Figure 3 *The stratigraphic slice of the DWM cube obtained above the bottom of the target interval*

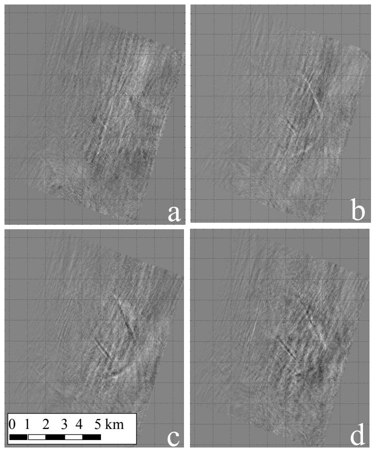

Figure 4 *The stratigraphic slices of the partial DWM cubes obtained above the target interval boundary with apertures relative to the source points in the intervals*
a) 1500-1600 m *b) 1600-1700 m*
c) 1700-1800 m *d) 1800-1900 m*

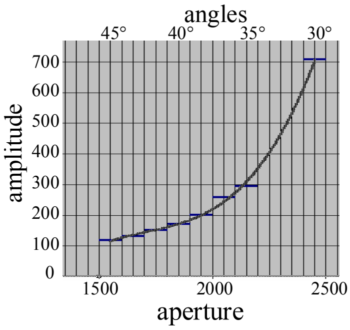

Figure 5 *The AVO-curve obtained by partial cubes within the lineament shown by the red arrow in the Figure 3.*

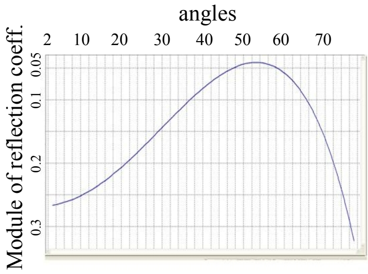

Figure 6 *The AVO-curve obtained by the base boundary by a priori geological data*

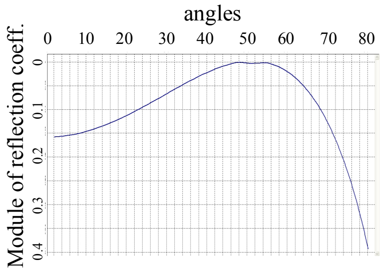

Figure 7 *The prognostic AVO-curve on the target sub-vertical boundary*