Importance of Seismic Diffractions for Fractures Imaging

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Abstract. The use of diffraction imaging is important and rapidly gaining momentum in the oil and gas industry as the need of the industry moves toward exploiting smaller and more complex structures to find hydrocarbon. Illumination of these small-scale discrete transmissivity structures such as faults or fracture zones prior to exploration offers substantial benefits for all phases of field development. We have established a new way of seismic imaging through diffractions study using reflection seismology. A subsurface geological model is developed from one of highly productive field located in the southern part of the Malay Basin. To study the seismic component in reflection seismology, a Finite difference modelling is used to generate synthetic seismic data. Both velocity and density models are used for the explanation of wave propagation, intimating the subsurface from side to side in both one-way and two-wave propagation. One-way wave equation migration methods are tested to image the faults in the synthetic seismic section of the Malay basin and we demonstrated the need of diffraction imaging for highly dipping faults and complex structure.

1. Introduction

The Malay Basin is a mature Tertiary extensional basin with a later inversion regime in the late Miocene. The overall geology is a simple “layer cake” seismically, with compressive anticlinal inversion structures [1]. Extreme tectonic activity is a cause of a compressional structure like complex faulting with steep dips and over-thrust.

The spectral practices of migration are well known to have a Wavefield extrapolation achieved in the Fourier domain (frequency and wave number)[2]. Seismic data is recorded in the space-time domain (x-t) and transformed into the Fourier domain (k-w) are undergoing converted namesake. The algorithms which belong to the categories of fundamental migration are Stolt [3], Phase Shift [4], Split Step [5], Phase Shift Plus Interpolation -PSPI [6], and the Fourier Finite Difference –FFD [7]. We describe the migration in the form of the wave equation in figure 1 that is an enlightenment of all migration algorithms which are being rummage-sale by the processors in all over the world.

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Figure 1: Classification of Seismic migration on the basis of wave equation techniques, from simple to advanced methods [8].

These methods mentioned in Figure 1 are reasonably vary from low computational power to high computational power, and implement the Wavefield extrapolation based on the derivative of the Fourier transformation and properties of the translation in time [2]. However, every algorithm has some inherent inadequacies by way of its own, which prevent the imaging of small-scale and high-sloped structures, whose reflections have trajectories with reflections on more than one interface of the seismic data.

2. Methodology

2.1. Geological Model

The model presented in this paper is taken from one of the fields in the Malay Basin. The model comprises four superimposed layers of different velocities, with major faulting because of uplifting of the sub layers. The synthetic seismic data of this model was obtained from a well-known seismic modeling technique as given below.

The finite difference methods (FDM) have been widely used in seismic modeling and migration. One of the disadvantages of FDMs is inadequate computational cost. The FD approximations give a numerical solution of a partial differential equation. The precision of this solution is reliant on the order of approximation. Eventually, all the finite difference methods are based on Taylor Series approximation [9]. Therefore, a discrete version of wave equation that includes the Initial situation or preliminary point, where the wave field to starts propagate, is required.
The modeling was conducted in a grid of 10x2 m (dx=10, dz=2) and with Ricker wavelet, which is defined by its dominant frequency of 50 Hz. These constraints were respectable enough to avoid numerical dispersion and unpredictability in finite difference modeling. The modeling was performed by ignoring multiples and absorption edge in the physical limit of the model.

The modeling was performed using the same model with different velocity and density parameters.

![Figure 4: Zero-offset synthetic seismic section using finite difference modelling, showing alterations in parameters of velocity (left) and a constant velocity (right).](image)

### 3. Discussions and obtained Results

The extrapolation of the Wavefield in the frequency domain is computationally highly efficient and numerically stable, which is contributing to make the use of spectral techniques attractive in the migration of seismic data[2]. However, ignoring the down-going Wavefield, the most important limitation in the imaging of high dipping structures are imposed to these algorithms. The result obtained with the imaging of data from the above geological faulted model clearly demonstrates the limitations of conventional spectral techniques imaging and the competency of two-way wave migration.

The comparison of dissimilar wave equation migration techniques reveals data with similar structural imaging; however, these techniques consider that using the same processing capability and faster implementation provides optimum imaging results.

One-way-FK-Reverse-Time migration can be distributed into FK, Phase shift methods, and phase shift plus interpolation method.

We started the solution for the scaler wave equation for the zero-offset Wavefield. If the medium velocity is constant, migration can be expressed as direct mapping form temporal frequency \( \omega \) to vertical wavenumber \( k_z \). In mid-1970’s, R. H. Stolt invented what has become known as Stolt or FK migration.

\[
k_z = \mp \sqrt{\frac{\omega^2}{v^2} - k_x^2}
\]

(1)

\[
P(k_x, k_z, t = 0) = \left[\frac{v}{2 \sqrt{k_x^2 + k_z^2}}\right] P\left[ k_x, 0, \omega = \frac{v}{2 \sqrt{k_x^2 + k_z^2}} \right]
\]

(2)

where \( P(k_x, z=0, \omega) \) is zero-offset section and \( P(k_x, k_z, t=0) \) is the migrated section in the frequency-wavenumber domain.
Figure 5: A zero-offset section that contains a set of faults and reflectors (left), F-k spectrums of unmigrated data, showing high amplitude in the central part and low amplitudes away from the sides (right).

Figure 6: migrated data using Stolt’s constant velocity algorithm (left) and f-k spectrum of the migrated data which showing low amplitude distributed on the true position of reflection (right).

Phase shift method was based purely on the reverse-time modeling approach. In this technique, the approach of constant velocity criteria was successfully removed, as which was imposed by the Stolt method. It was also the earliest and, conceivably until very recently, the only method that was capable of imaging steeply dipping reflectors. The phase shift approach was developed by Jeno Gazdag shortly after the Stolt method appeared [4]. The starting PDE is the Helmholtz equation given by:

$$\nabla^2 P(x, z, \omega) + \frac{\omega^2}{v^2} P(x, z, \omega) = 0$$

Since the starting exploding reflection is at t=0, the location of the reflector is therefore given by inverse transforming the solution in k_x and w and evaluating at t=0:

$$r(x, z) \approx p(x, z, t = 0) = \sum_{k_x} \sum_{\omega} P^-(k_x, 0, \omega) e^{-i(k_x x + k_z z)}$$

The above condition of $r(x, z) = p(x, z, t=0)$ is known as the zero-offset migration imaging condition.

Phase Shift Plus Interpolation –PSPI method is a phase-shift like method for dealing with strong lateral velocity variation [6]. The initial impression of PSPI is to familiarize several reference velocities in order to describe the lateral velocity in each extrapolation step, and obtain the multi-reference Wavefield in the f-k domain. Based on the relationship of the local velocity and reference velocity, the final
migration results are obtained by interpolating the reference Wavefield in the f-k domain. The basic formulas are:

\[ P_0(x, y, z, \omega) = P(x, y, z, \omega) e^{i\frac{\omega}{v(x,y,z)}dz} \]  

(5)

and

\[ P'(k_x, k_y, z + dz, \omega) = P_0(k_x, k_y, z, \omega) e^{i\left(k'_z - \frac{\omega}{v_{\text{ref}}}\right)} \]  

(6)

where \( k'_z \) is obtained using the reference velocity. After the reference wavefield is Fourier-transformed back to the frequency-space domain, the final migration result is obtained by linear interpolation[6].

Figure 7: Comparison of migration algorithm operators. (a) Gazdag (b) Phase Shift and (c) Stolt migration.

Figure 7 shows the recovery of all the seismic reflection properly and illuminates the horizontal reflections, but none of these migration algorithms are capable of compensating for all the component of faults as shown above. For these types of structure we need diffraction imaging by to separate diffracted and reflected waves and image it separately [10]. Figure 8 shows the separated diffraction using plane-wave destruction filter, which calculates the slope of the data on the basis of reflection and then separates the diffracted event.
Figure 8: Diffraction separation process (a) input model; (b) zero-offset synthetic shot gather data; (c) diffraction separation using dip frequency filtering; and (d) separated diffraction using plane-wave destruction filtering.

These highly dipping faults have an illumination problem in the reflection data imaging. Figure 8(b) is the zero-offset section of the model data after finite difference modelling. Diffractions are caused by the irregular fault boundaries and preserved in the section. Figure 8 (c) shows separated diffractions using DFF and Figure 8(d) is the separated diffractions section using PWD, which shows better results for the diffraction separation. The arrows clarify the reflections which are suppressed from the given data. Both filtering techniques are able to eliminate upper straight reflections, but if we look at the flanks below of the anticline, our DFF is eliminating those reflections from the data which do not originally belong to the diffraction data. On the other hand, the PWD filtering technique is sophisticated enough to remove the reflection seismic data and preserve the diffractions.

4. Conclusions

Diffractions give us valuable information about subsurface structures; the objective of this paper is to show that, when we migrate our data, most of the diffracted events cannot collapse correctly. Consequently, we lose information from the diffracted waves. In order to prove the importance of diffractions, dissimilar wave equation techniques are applied to the synthetic data for imaging faults. Application of one-way wave equation migration using F-K, PS, and Gazdaz migration is used to image the data but none of them were able to image the dipping components of fault. Therefore, the best way to image these events is to preserve these diffractions by separating the reflection and diffraction. We have proposed two methods for diffraction separation: Dip Frequency Filtering (DFF) and Plane-wave Destruction filtering (PWD). The possibilities of using these methods are dependent on the complexity of the subsurface structure. The results demonstrate the effectiveness of the desired objective to preserve the diffraction for Imaging. Future work can be extended to apply these methods on real seismic data, especially carbonate fields for Karsts imaging.
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