Angle-dependent amplitude and AVO/AVA analysis with PSDM

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ABSTRACT

Summary

The paper attempts to illustrate the angle-dependency of amplitude in wave propagation and migration/inversion, and show that the AVO/AVA can be reconstructed in the migration/inversion. The feasibility and accuracy of AVO/AVA analysis with PSDM for structural geology are evaluated with a gas reservoir model inside a complex geology from Mackenzie Delta.

Introduction

Both AVO and PSDM technologies have made great progress in last two decades. Generally, the research and development of the two technologies are taking two parallel paths. AVO analysis is used by interpreters to bridge seismic and rock properties. General research and cases on AVO analysis are based on the assumption that the subsurface is flat-layered or mildly structural. Although less theoretically reasonable than advanced wave theory for seismic experiments, Zoeppritz's equation and its approximations, which many quantitative AVO analyses are based on, are widely accepted by geophysicists. PSDM technologies were built on more advanced wave theory and have great advantages to image complex geological structures over other seismic processing technologies, but AVO-based analysis of the rock properties, lithologies, and reservoir attributes are rarely incorporated into the PSDM imaging technologies. In general, AVO and pre-stack depth migration (PSDM) have been developed by two groups of people with little communication. Processing resources usually master the PSDM technologies, while AVO application and its rock physical links are more used by interpreters, who are not heavily involved into the PSDM development and production. In addition, the high computation costs of PSDM, AVO/AVA preservation issues in PSDM algorithms, and lack of understanding of PSDM by a larger group of geophysicists limit the application of AVO/AVA with PSDM. However, as more structurally complex areas are being explored, imagers and AVOers should exploit the possibilities of combining AVO/AVA and PSDM: PSDM provides more reliable focusing and positioning of gathers for AVO analysis, and AVO will help interpreters to bring in additional rock property information to interpret structural closures in geologically complex areas.

Common image gathers (CIGs) are the byproduct of PSDM. An event on a CIG is from the same reflector at different offsets or angles. CIGs are usually used in the velocity model updating. CIGs are more reliable for AVO analysis than pre-migration CMP gathers even in the mild structures. As imaging was the primary goal in the migration, AVO/AVA preserved CIG was not considered in the early time of the migration developments. Berkhout's research group was among the earliest to investigate the AVO/AVA in the pre-stack migration and design the AVO/AVA preserved CIGs (common shot pre-stack migration by de Bruin et al., 1990). The similar AVO/AVA preserved CIG construction mechanism was investigated with different PSDM algorithms by SEP in recent years (Biondi, Sava, Prucha, Palacharla, Formel, Clapp, etc.). In addition, SEP discussed the incident angles with dipping interfaces in the migration (It can be tracked back to Claerbout and Ottolini in 1980's). The significant development in amplitude-preserving Kirchhoff PSDM was accomplished by researchers at Ecole des Mines de Paris(Xu, Thierry, Chauris, Lambare, and Noble et al.). To understand the amplitude handling in each migration algorithm, wave theory background is required and a few decades of the literature history have to be tracked back. Articles on migration rarely explained the angle-dependent amplitude in the pre-stack migration in a straightforward way to be understood by the geophysicists with various backgrounds.

One attempt of this paper is to explain the angle-dependent amplitude in migration/inversion for the readers with general geophysics backgrounds. In the first part of the paper, the wave propagation forward and inverse processes are illustrated using simple examples. In these examples, acoustic and elastic media with flat and dipping interfaces are used. Shot gathers are generated using wave propagation modeling. AVO responses on the shot gathers are compared with Zoeppritz modeling. For each model, shot gathers are acquired for regularly spaced source locations and a 2D pre-stack dataset is generated. Pre-stack depth migration is performed on the 2D dataset and AVO/AVA preserved CIGs are constructed and compared with Zoeppritz equation solutions. Besides CIGs in the AVO/AVA analysis with PSDM, PSDM provides more reliable background velocity and ray angles than traditional AVO analysis. It is still worthwhile to investigate how to utilize more efficiently the information given by PSDM in AVO/AVA analysis, including QC. In the second part of the paper, the potential and procedure to incorporate AVO with PSDM are explored using the data from a realistic model with complex structures and noises.

Wave propagation and angle-dependent amplitude

Figure 1 (a) shows that one point source generates waves propagating downward in the subsurface homogeneous medium. The circles represent the wave fronts. There is a flat reflection interface at certain depth. The flat interface is composed of reflection points. When wave fronts reach these points, they become the secondary sources to radiate waves downward and upward. In Figure 1 (b), the wave fronts are omitted and rays are used to illustrate the wave propagation directions from the point source to a reflector to the surface detector locations. In Figure 1 (c), the downward and upward wave propagations between surface and reflection interface are illustrated separately using the reflection interface as the mirror. When multi-point sources are acquired, as in Figure 1 (d), the mirrored media illustrate clearly the process of each source sending waves to the reflector and then radiating upward to the detectors on the surface.

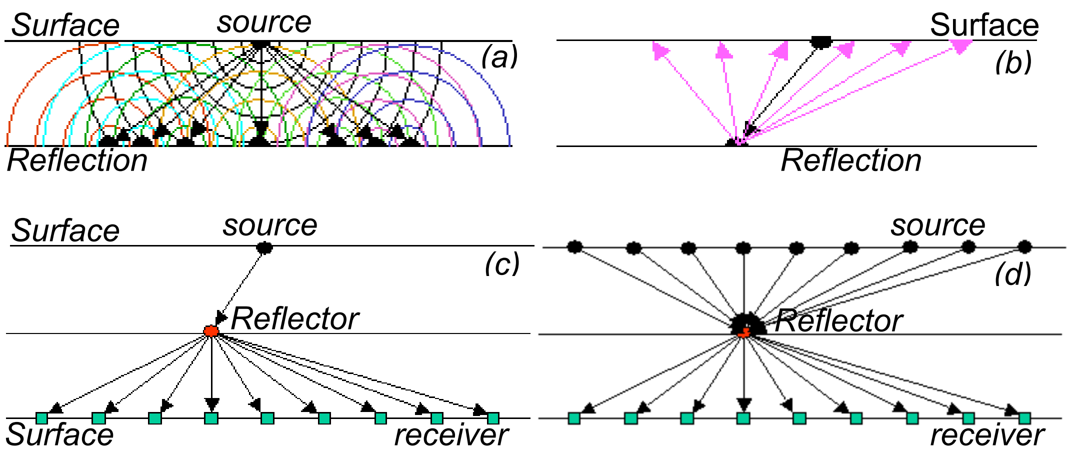

Fig. 1: The process of wave propagation, reflection, and diffraction in subsurface from the point sources.

Amplitude of the waves in the above propagation process is affected by a number of factors:

1. Geometrical spreading and source directivity when the waves downward-propagate from source to the reflector
2. Reflection follows Zoeppritz's equations for every plane wave;
3. Geometrical spreading and directivity when diffracted waves upward-propagate from the reflector to the receivers.

When the media are complex, there are more factors related to the attenuation of the amplitude. In general, geometrical spreading and far-field effect (directivity) are the most basic factors in homogeneous media considered in modeling and migration.

One point source provides limited incident angle plane waves into a reflector (multi-raypath due to structure complexity is not considered at this stage). Multi-point sources at various surface locations generate waves incident at various angles into the reflector as *Fig. 1* (d).

A forward modeling scheme (called wave propagation modeling (WPM) here) can be naturally designed using the wave propagation forward process. Primaries can only be included without other elastic waves (such as multiples, or mode-conversions). This contrasts with Zoeppritz modeling, which is often done in AVO interpretation. In Zoeppritz modeling, Zoeppritz's equations are used to generate a synthetic CMP gather by calculating reflectivities and traveltimes, then filtering with the desired wavelet. The mechanism in WPM is more theoretically reasonable and can be extended to simulate more realistic situations. A few examples are shown here to illustrate the forward modeling and amplitude handling.

The first example uses acoustic media in which there is an interface with only density contrast. The reflection coefficient at the interface is identical for any incident angle. This model was commonly used to test the amplitude in PSDM algorithms. In Fig*. 2 (a)*, the model is shown; in *Fig. 2 (b)*, a shot gather is shown; in *Fig. 2 (c)*, the peak amplitude of the reflection is shown after geometrical spreading and directivity are compensated.

The second example uses the same geometry and structure as in the first example, but now the media are elastic and AVA responses at the reflector are defined by $R(\Theta) = 0.1+0.2*\sin^2(\Theta)$. *Fig. 3 (a)* shows the model; *Fig. 3 (b)* shows a shot gather created by WPM; *Fig. 3 (c)* shows the peak amplitudes after geometrical spreading and directivity are compensated.

In *Figs. 4 and 5*, the dipping reflection interface is used in the model. Acoustic modeling is done in *Fig. 4* using the same density contrast as in *Fig. 2*; elastic modeling is done in *Fig. 5* using the same elastic parameters and reflectivity function as in *Fig. 3*. AVO responses are examined using the peak amplitude of shot gathers and compared with Zoeppritz modeling results.

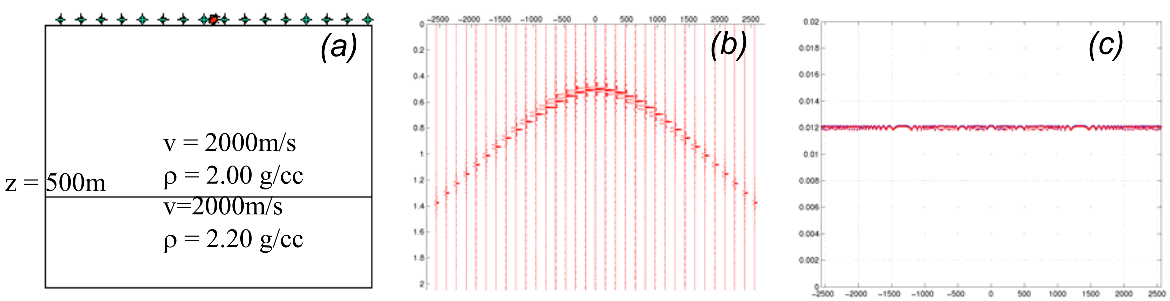

Fig. 2: Acoustic model with only density contrast at the interface: (a) the model; (b) a shot gather from wave propagation modeling with geometrical spreading and directivity effect; (c) peak amplitude of shot gather in (b) after geometrical spreading and directivity correction, compared with Zoeppritz modeling: blue dots for WPM; red for Zoeppritz modeling.

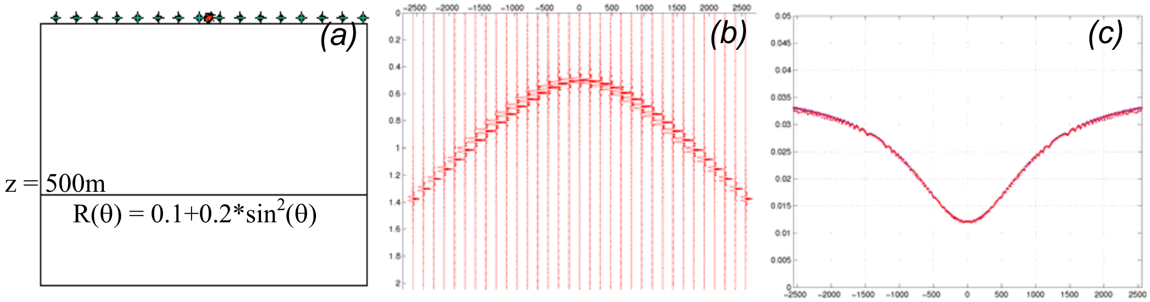

*Fig. 3: Elastic model with an interface with reflectivity function R(Θ) = 0.1+0.2*sin²(Θ): (a) the model; (b) a shot gather from wave propagation modeling with geometrical spreading and directivity effect; (c) peak amplitude of shot gather in (b) after geometrical spreading and directivity correction, compared with Zoeppritz modeling: blue dots for WPM; red for Zoeppritz modeling.*

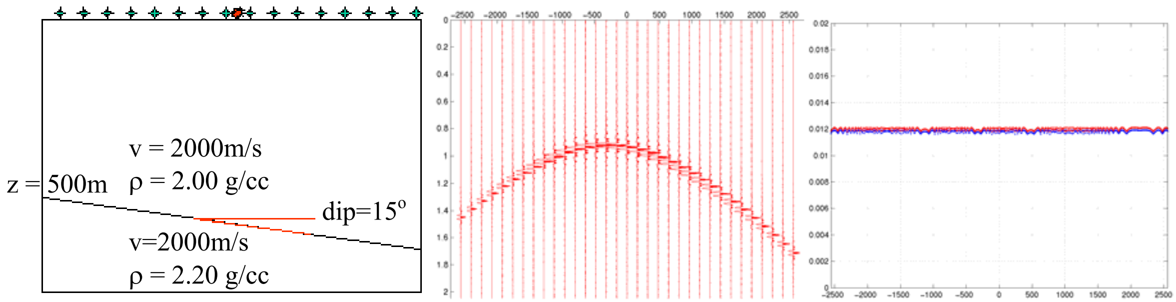

Fig. 4: Acoustic model with only density contrast at a dipping interface: (a) the model; (b) a shot gather from wave propagation modeling with geometrical spreading and directivity effect; (c) peak amplitude of shot gather in (b) after geometrical spreading and directivity correction, compared with Zoeppritz modeling: blue dots for WPM; red for Zoeppritz modeling.

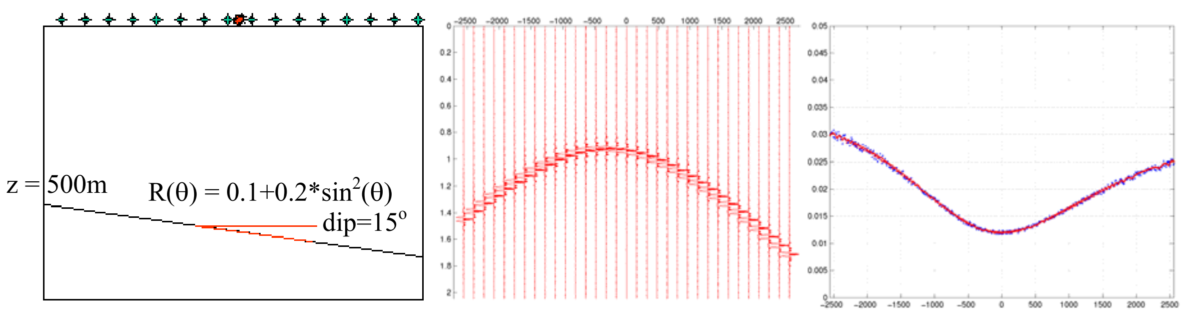

Fig. 5: Elastic model with dipping interface: (a) the model; (b) a shot gather from wave propagation modeling with geometrical spreading and directivity effect; (c) peak amplitude of shot gather in (b) after geometrical spreading and directivity correction, compared with Zoeppritz modeling: blue dots for WPM; red for Zoeppritz modeling.

After geometrical spreading and directivity corrections, the peak amplitude on the shot gathers by WPM matches its counterpart by Zoeppritz modeling. But WPM simulates a more complicated process and seismographs by WPM contain more information than those by Zoeppritz modeling. In next section, it will be shown that the migration/inversion of 2D pre-stack data generated by WPM will produce accurate AVO up to critical incidence. Note that the offset-to-angle conversion is a non-trivial process in both WPM and CIG constructions. Evanescent waves from post-critical incidences are more complicated than primary reflections. They are usually not considered in the migration algorithms. In the examples, evanescent waves are attenuated for both modeling and migration.

Migration/inversion and AVO/AVA reconstruction

Migration/inversion is the inverse process of the wave propagation. In a traditional sense, migration is positioning and focusing the subsurface reflectors – it pursues the correct phase of the wave propagation, while inversion attempts to solve *both* the position and amplitude of subsurface reflectors. With the development of the technologies, migration tends to be the inversion.

In the migration/inversion, the reflectivity at the reflector - the ratio of reflected and incident wave amplitudes - is to be estimated. To do AVO/AVA analysis, a number of reflectivities from different incident angles are required. For one reflector, one point source gather can provide reflectivity at limited incident angle range. Reflectivity at a large angle range is estimated from a number of shot records. Shot-profile migration is a popular industry migration scheme. Migration/inversion is done shot gather by shot gather and final images are produced with all shot records. Given a shot record, the reflectivity estimation process is as follows:

1. As in *Fig. 1 (c)*, the incident wave amplitude at a reflector can be obtained by downward propagating the source signature to the reflector, including the amplitude attenuation and phase updating in the propagation.
2. Collapse the amplitudes diffracting from the reflector to the receivers, including amplitude and phase compensation during the upward propagation. The reflected amplitude is estimated.
3. The ratio of reflected and incident waves can represent the reflectivity at a certain incident angle range.

For all shot records, repeat the above procedure, and a number of reflectivity at multi-incident angles can be estimated.

A 2D pre-stack dataset is generated for each model in *Figs. 2, 3, 4, and 5*. Shot-profile migration is performed on each dataset, and CIG gathers are constructed. In *Figs. 6, 7, 8, and 9*, one CIG and its AVO/AVA are shown for each model. These figures show the AVO/AVA can be preserved fairly well.

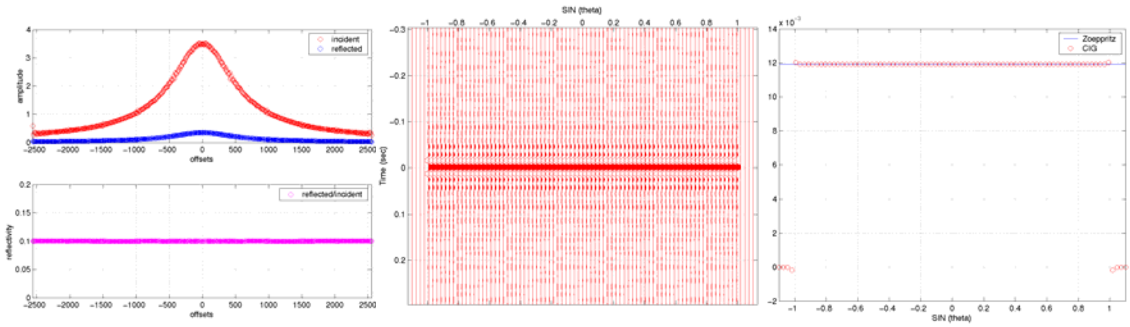

Fig. 6: CIG and its amplitude at a reflector on acoustic model in Fig. 2: (a) amplitude curves along incident waves and reflected waves at different offsets and the ratio of the two amplitude curves. Angle domain CIG gather is reconstructed from two amplitude curves; (b) angle domain CIG – critical incident can be reached; (c) Peak amplitude of CIG compared with Zoeppritz equation – the post-critical is attenuated in the migration.

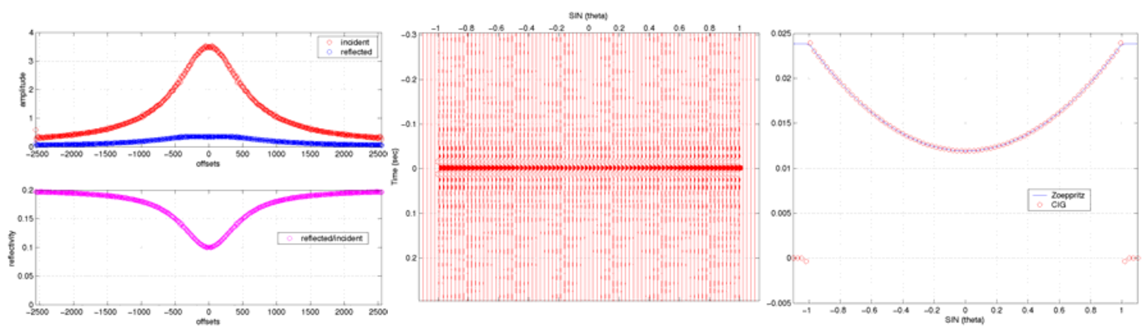

Fig. 7: CIG and its amplitude at a reflector on elastic model in Fig. 3: (a) amplitude curves along incident waves and reflected waves at different offsets and the ratio of the two amplitude curves. Angle domain CIG gather is reconstructed from two amplitude curves. (b) angle domain CIG – critical incident can be reached. (c) Peak amplitude of CIG compared with Zoeppritz equation – the post-critical is attenuated in the migration.

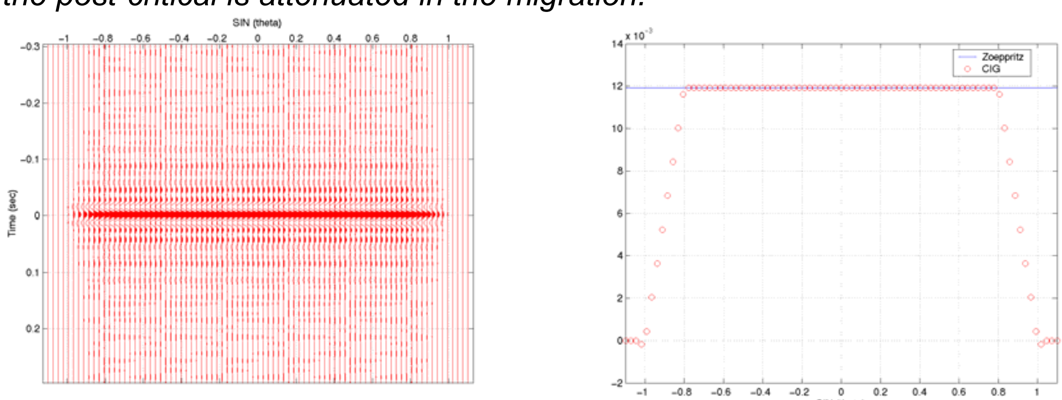

Fig. 8: CIG and its amplitude at a dipping reflector on acoustic model in Fig. 4 (a): (a) The angle domain CIG; (b) Peak amplitude of CIG compared with Zoeppritz equation – the post-critical is attenuated in the migration.

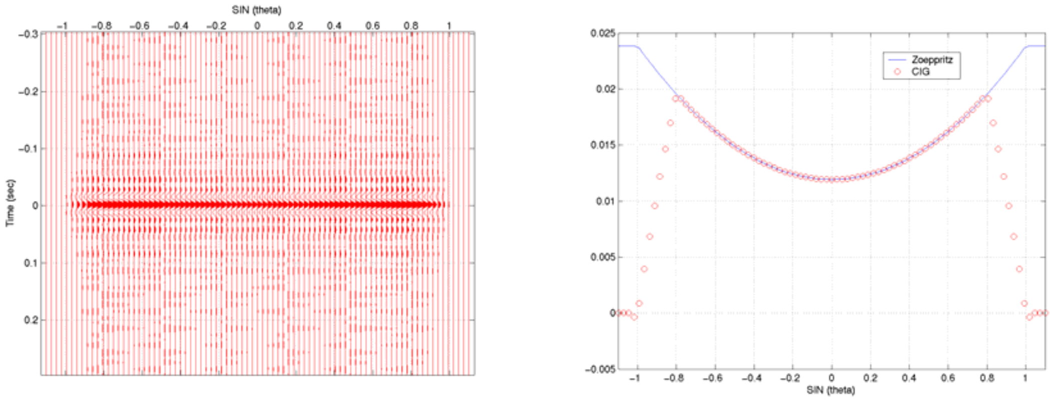

Fig. 9: CIG and its amplitude at a dipping reflector on elastic model in Fig. 4 (a): (a) angle domain CIG; (b) Peak amplitude of CIG compared with Zoeppritz equation – the post-critical is attenuated in the migration.

AVO/AVA with PSDM on model from Mackenzie Delta

Migration/inversion can provide the angle-dependent plane wave amplitude at correctly imaged subsurface reflectors as input to AVO/AVA analysis. This is important in structurally complex geology, where the shadows in the illumination and multi-raypaths are often issues. Strictly speaking, the migration suitable to AVO/AVA analysis has to be an inversion – not only positioning correctly but also compensating amplitude reasonably. In the above description on wave propagation and migration/inversion, much of the details to handle amplitudes are omitted. In the real world, more factors can be added into the above fundamental discussion, such as source arrays, geophone groups, source signature and energy balance, more complex subsurface field. Some of the production PSDM algorithms already considered these factors.

Overall, the primary purpose of migration is to image the subsurface structures. Interpreters look for the structural traps based on migration images, and more important, find out hydrocarbon pool in a number of geological traps. AVO analysis provides an aid to find anomalies due to hydrocarbon saturations. The combination of imaging and AVO analysis is a more powerful approach. There will be more and more research and case histories on the topic of combining AVO and PSDM. Although restoration of correct AVO/AVA with PSDM takes more effort than only structure imaging, it becomes more feasible with the decreasing computation cost and development of modeling/inversion technologies. The rest of this section attempts to evaluate the robustness and accuracy of AVO/AVA with PSDM on real data or realistic model data when noise and processing errors are involved.

Mackenzie Delta (MKD), NWT is a location of considerable seismic exploration activity. Many gas and oil discoveries were made over the last few decades. Large hydrocarbon reservoirs were found in Tertiary and late Cretaceous sequences. The structures in many later sequences with hydrocarbon saturations are mild. AVO responses from CMP gathers or image gathers from time migration have been reliable: AVO analysis on such plays is applicable without PSDM. However a few major faults and related smaller fault systems dominate the structures in early Tertiary sequences and late Cretaceous (Parson Lake area, for example). On the profiles perpendicular to the fault strikes, geological structures are complex and the dips may exceed 20 degrees. PSDM is required for more reliable AVO analysis. In the structural geology and young sediments as MKD, there is also a challenge for an AVO method such as Lambda*Rho^{TM} technology (Goodway et al. 1997). Lambda*Rho^{TM} requires the conversion of seismic reflectivity to impedance. Reliable background impedance constraints are crucial in the conversion. In the Western Canadian Sedimentary Basin, the layered structures and intensive well log control have helped to make Lambda*Rho^{TM} a success. But, in areas such as MKD where well controls are sparse and geology is complex, it is more difficult to estimate a reasonable velocity background. The velocity model built to perform the PSDM is an asset for the application of Lambda*Rho^{TM}.

In this paper, a realistic geological model is created based on the geology and logs from a few production wells from the Taglu field. In the model, a gas reservoir is trapped by the faults, mimicking a Taglu reservoir but with larger dip (20 degrees). This field includes a vast portion of Tertiary sequences filled with unconsolidated clastics. Fig*. 10 (a)* shows the geological model velocity grids. The shallow portion of the model is a permafrost and transitional zone with relatively high velocity. The velocity variation with depth is estimated from a number of well logs from this area. *Fig. 10 (c)* shows this trend. The velocity grid is composed of this trend and the perturbation due to lithology changes and reservoirs.

Finite-difference 2D modeling is applied on this model using typical acquisition parameters to create a 2D line. The calculated dataset includes the full elastic waves. First, the dataset is processed with conventional processing flows to generate the stack section and stacking velocities. Then PSTM is performed to have a reasonable initial velocity model for PSDM. The convergence of modeling updating is investigated in the PSTM and PSDM. PSDM is performed using Core Lab's VIEWS PSDM software suite. We have two objectives: 1) investigate the angle-dependent amplitude reliability of this PSDM package and the ability of AVO/AVA analysis to identify structure-trapped reservoirs; 2) understand the potential of PSDM+AVO/AVA for the typical Mackenzie Delta structures and data acquisitions. The AVO/AVA analysis procedure, angle domain CIG, incorporation of the velocity model from PSDM, and evaluation of the results will be shown in detail in the presentation.

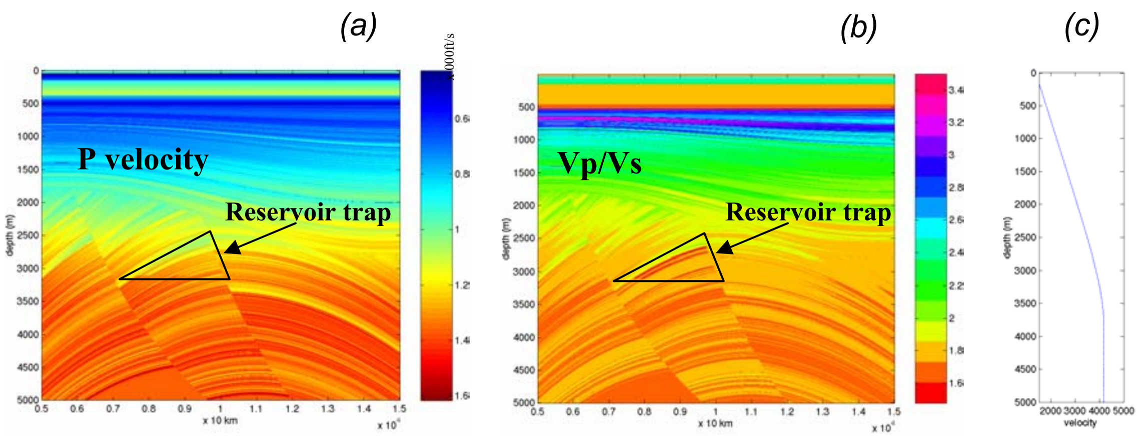

Fig. 10. (a) velocity model; (b) Vp/Vs model; (c) velocity variation depth trend.

Conclusions

Angle-dependent amplitude in the pre-stack depth migration is explored. The AVO/AVA can be reconstructed from migration/inversion. AVO/AVA analysis with PSDM in complex geology is feasible.

Acknowledgements

The author wishes to thank Jan Dewar for comments and editing on the transcripts, Zhengsheng Yao for his discussion and comments and Core Lab for permission to publish this work.

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