Analysis of mode conversions over high-velocity layers

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ABSTRACT

A seismic model based on log data from northeastern Ireland is used to study seismic imaging problems over high velocity layers. Zoeppritz responses at the top and base of a high-velocity layer of the model are used to predict strong modal conversions for an incident P-wave Synthetic seismograms demonstrate that the presence of the various mode-converted (multimode) arrivals leads to complicated reflection events. Separation of various arrivals is important prior to interpretation. The P-S reflection equation is modified to a form which gives physical insight into the amplitude variation with offset of converted waves. Finally, this equation is shown to isolate the multimode arrivals and can be the basis of a modal filter.

INTRODUCTION

Seismic reflection data are often of poor quality when recorded in areas where high-velocity layers are present at or near the surface. This compromised data makes it difficult to explore for targets that lie beneath or within the high-velocity sequence. Permafrost regions, carbonate outcrops and volcanic layers with high acoustic impedance are all examples of the problem. Places such as the Columbia Plateau in North America and the Parana Basin in South America have hydrocarbon potential, but exploration in these places is hampered by the presence of volcanic layers (Purnell, 1992). Similarly in the foothills of the Rockies and areas in the Middle East, high-velocity carbonate outcrops at the surface often contribute to poor seismic recording. In addition, an analogous problem is encountered in the permafrost regions of the North America Arctic.

Previous experiments show that the problem is partially caused by abrupt vertical discontinuities in the elastic parameters, which affect wave propagation substantially. Papworth (1985), Pujol et al. (1989) and Purnell (1992) each identify strong S-wave arrivals associated with P-to-S conversion at basalt surfaces encountered in land surveys. Intense field effort can make an improvement in the quality of data (Papworth, 1985;Withers et al., 1994). Application of residual statics using a detailed near-surface velocity model also can improve the data quality (Papworth, 1985). Acoustic migration tailored for selected families of converted-wave arrivals may also image a range of dips underlying a high-velocity layer (Purnell, 1992).

In this paper, we use the Zoeppritz equations and raytracing to study the wave propagation at the HVL interface. Synthetic seismograms are used to show the pattern of various multimode arrivals. The P-S reflection equation is modified to a new form. We propose a framework to use a ‘sine’ function in the filtering of the multimodes.

ENERGY PARTITIONING

The elastic model (Figure 1) used for the study is based on well-logs and geologic information from northeatern Ireland. The Zoeppritz responses at the top and bottom of the high-velocity sill layer of the model are used to determine energy partitioning among wavetypes.

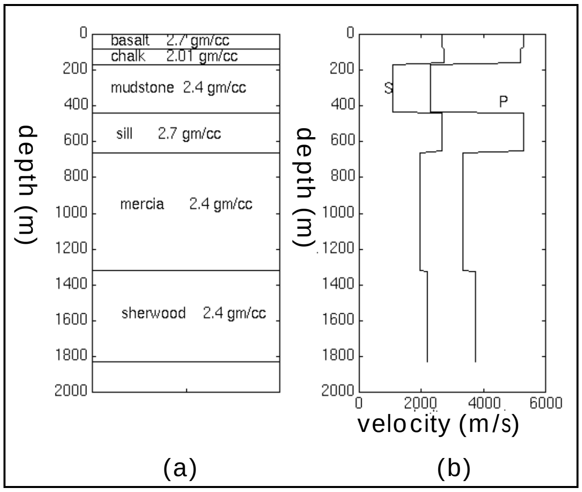

Fig. 1. (a)Sub-surface depth model for the area of study. Lithology of the subsurface, and density values blocked from a density log are shown. (b)Variation of the P-wave and S-wave velocities with depth.

Analysis of the transmission coefficients for a P-wave incident on the mudstone-sill interface (Figure 2a) reveals significant conversions from P-wave to the S-wave mode even at small incident angles. Incident P energy, at angles greater than the critical angle for P-P transmission, is converted to the S-mode with an efficiency equalling that of pre-critical P-P transmissions. P-P and S-S reflection coefficients (Figure 2b) for the sill-mercia interface are nearly the same except for intermediate incident angles between 25 and 40 degrees. We also observe strong P-S and S-P reflections at the interface. Figure 2c reveals high coefficient values associated with all types of mode transmissions at the sill-mudstone interface. In particular, the cumulative energy associated with each of the PPPP, PPSS, PSSS and PSPP paths through the HVL for incident P are estimated to be high enough to be recorded as a significant event on the seismic trace.

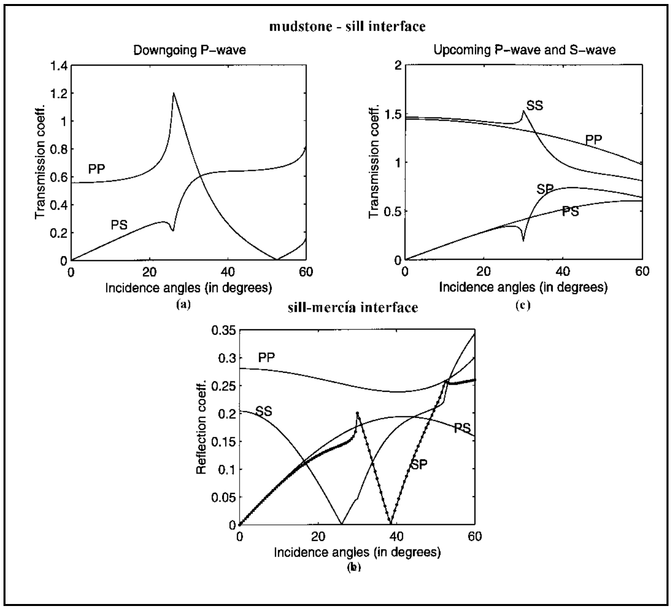

Fig. 2.Calculated Zoeppritz response at the top and base of the high-velocity sill layer (HVL). (a) P-P and P-S transmission coefficients for downgoing incident P-wave at the top of the HVL. (b) Reflection coefficients for all possible modes at the base of the HVL. (c)Transmission coefficients for upgoing waves at the top of the HVL.

Raytracing (Figure 3) demonstrates that the close match between V_S within the sill layer (HVL) and V_P within the relatively low-velocity mudstone layer enables a near-straight path between S-waves within and P-waves outside. This leads to an efficient coupling between the P-wave mode and the S-wave mode across the interface (Purnell, 1992).

Synthetic seismograms (Figure 4) show the complications introduced by the various multimode arrivals. Events **1** and **2** are the P-wave and the converted-wave PPSS arrivals from the base of the HVL respectively. The events intermediate between **1** and **2** are the PSPP and the PSSP and the event immediately after **2** is the PSSS multimode. Another event (not annotated) is the PSSP arrival after the PSPP event. Events from the same reflector can be misinterpreted to present a distorted image of the sub-surface geology. Later events (from **3** onwards) are the pure P and the multimodes from the sub-HVL mercia layer.

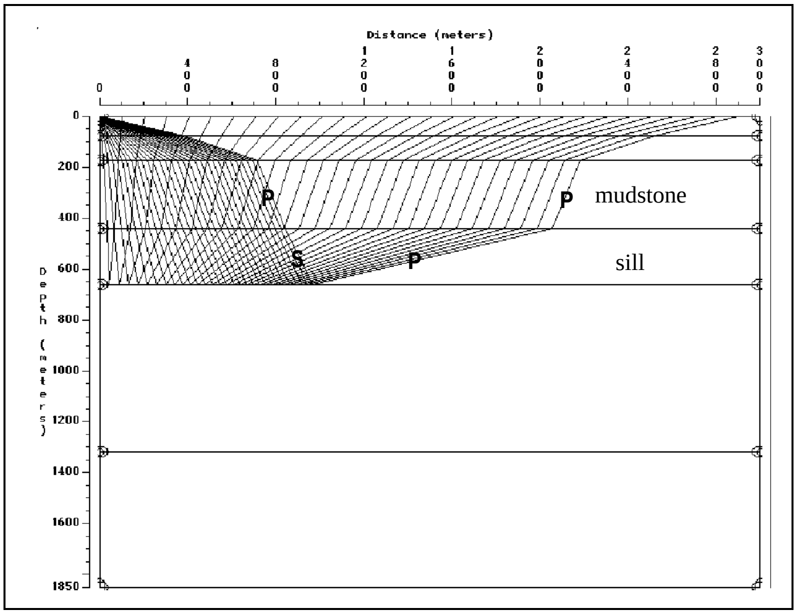

Fig. 3.Ray trace plot of a P-wave event with an S-wave leg. There is efficient coupling between the P-waves in the mudstone layer and S-waves within the high-velocity sill layer.

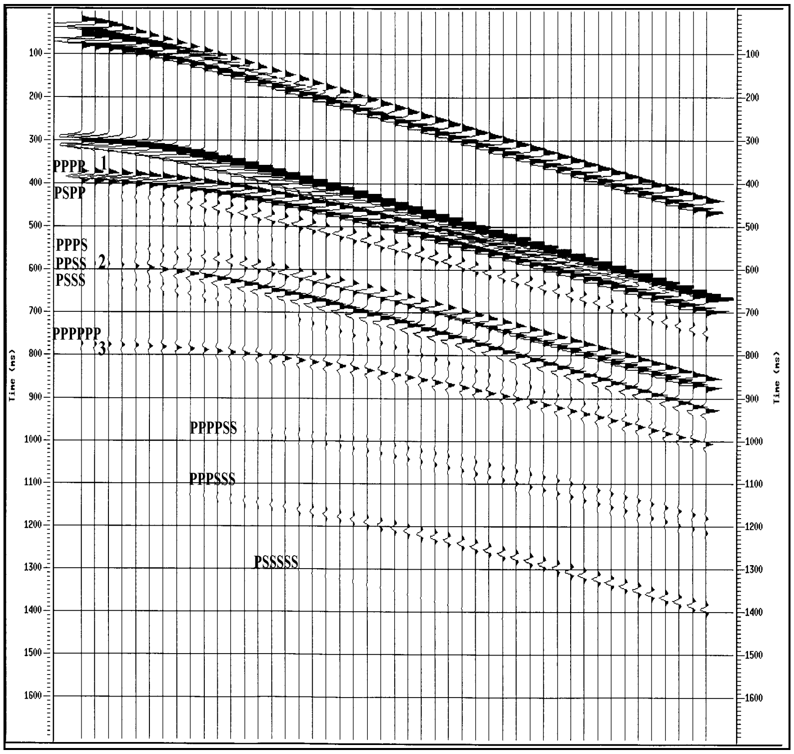

Fig. 4.Synthetic seismogram for the model. Unconverted P-wave arrivals from the different layers and the multimodes from the sill and mercia layer are annotated. Multiples are not generated.

SIMPLIFIED P-S REFLECTION EQUATION

The Aki and Richards(1980) approximation, for small changes in elastic parameters, for the P-S reflection amplitude $R^{PS}(\theta)$ is given as

$$R^{PS}(\theta) \approx \frac{-\rho\alpha}{2\cos\varphi}[(1-2\beta^2p^2+2\beta^2\frac{\cos\theta\cos\phi}{\alpha\beta})\frac{\Delta\rho}{\rho}-(4\beta^2p^2-4\beta^2\frac{\cos\theta\cos\varphi}{\alpha\beta})\frac{\Delta\beta}{\beta}] \qquad (1)$$

where

$$\rho=(\rho_1+\rho_2)\big/2,\ \Delta\rho=\rho_2-\rho_1,$$
$$\alpha=(\alpha_1+\alpha_2)\big/2,\ \beta=(\beta_1+\beta_2)\big/2,\ \Delta\beta=\beta_2-\beta_1,$$
$$\theta=(\theta_1+\theta_2)\big/2,\ \varphi=(\phi_1+\phi_2)\big/2,$$

and p is the ray paramter given by

$$p=\frac{\sin\theta_1}{\alpha_1}=\frac{\sin\theta_2}{\alpha_2}=\frac{\sin\phi_1}{\beta_1}=\frac{\sin\phi_2}{\beta_2}.$$

Using the approximations,

$$p\approx\frac{\sin\theta}{\alpha},\ and\ \frac{1}{\cos\phi}\approx 1+\frac{1}{2}\frac{\beta^2}{\alpha^2}\sin^2\theta,$$

the trigonometric identity

$$\sin 3\theta = 3\sin\theta - 4\sin^3\theta$$

and neglecting the term with the fifth power of sine, the Equation (1) can approximately be written as

$$R^{PS}(\theta)\approx a'\sin\theta+b'\sin 2\theta+c'\sin 3\theta \qquad (2)$$

where

$$a'=3[A-\frac{\Delta\rho}{6\rho}],\ b'=\frac{-\gamma k}{2},\ c'=-A,$$

$$A=\frac{1}{4}[\gamma^2k-\frac{\gamma^2\Delta\rho}{4\rho}],\ \gamma=\frac{\beta}{\alpha},\ and$$

$$k=\frac{\Delta\rho}{\rho}+\frac{2\Delta\beta}{\beta}.$$

From Equation (2), we see that the amplitude of the P-S reflection is a sine function of the angle of incidence of the P-wave, i.e. amplitude variation of the converted wave follows a sinusoidal function with increase in offset. Thus, Equation (2) consolidates the well-known observation of the amplitude variations of converted-waves with offset. A comparision of theoretical amplitudes calculated from the Zoeppritz equations, Aki-Richards' approximation and Equation (2) is made in Figure 5. The reflection amplitudes have been calculated at the sill-mercia interface (large change in elastic paramters) of the model (Figure 1). The difference between the reflection coefficients at larger angles of incidence as calculated by the Aki-Richards approximation and that calculated using Equation (2) is due to neglecting the fifth power term. Also, the large discrepancy from the Zoeppritz calculations is due to the violation of the assumption of small change in elastic parameters across the interface.

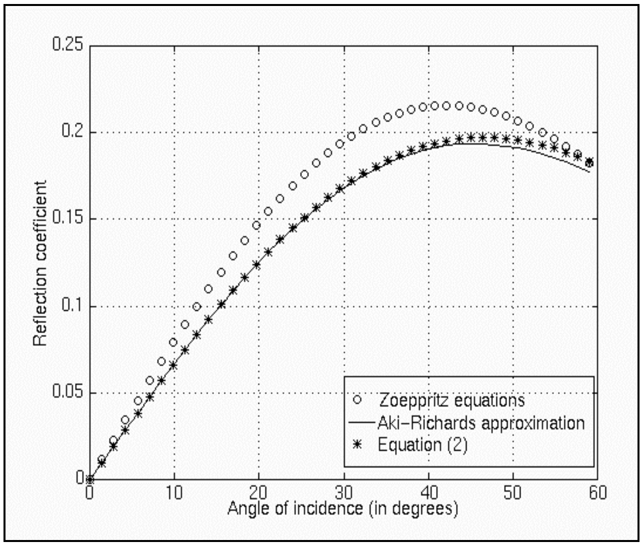

Fig. 5.Comparision of the displacement reflection amplitudes as calculated using the Zoeppritz equations, the Aki-Richards' approximation and Equation (2) for the sill-mercia interface of the model.

ALGORITHM FOR THE FILTERING OF MULTIMODES

Equation (2) implies that a sine function can be used to fit the amplitude variations with offset for converted-wave arrivals. Multimodes show a similar amplitude variation with offset i.e. zero at zero offset and increasing with offset (a sine function) and this suggests that a similar approach can also be adapted to isolate them. We will, however, use the original form of Equation (2) as one need not calculate the angles of incidence when using this equation. A arbitrary set of angles of incidence suffices in the least-squares fit as any under-estimation of the angles is offset by higher values of b' and c'. The following flow-chart shows the steps, where TOL is a pre-determined error tolerance, that were followed to isolate the multimode arrivals in Figure 4.

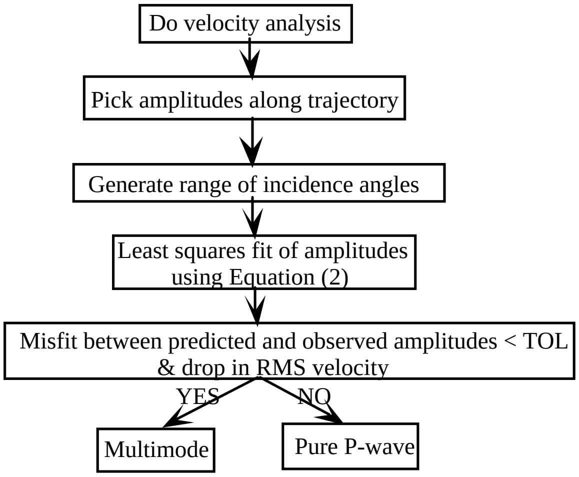

Figure 6 shows that most of the multimodes were effectively isolated using the above methodology. However, the multimode PSSS could not be isolated. It appears that the algorithm may fail in the case of polarity reversal of amplitudes with offset Also, any successful implementation of the method demands that the picking of the amplitudes be as accurate as possible.

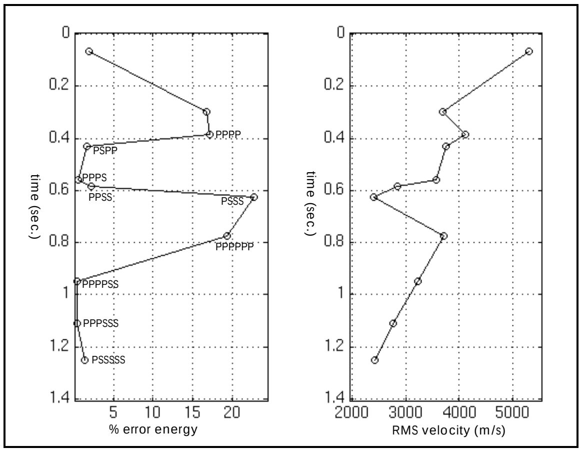

Fig. 6.A combined analysis of percentage error energy and RMS velocity plots show that the multimodes can effectively be isolated. Events studied here are the same as those annotated in Figure 4.

CONCLUSIONS

Several strong multimode propagation paths can occur through a high-velocity layer. The multimode arrivals can severely distort the data and make interpretation difficult. Representation of the same interface by different mode arrivals present a complicated picture of the sub-surface geology. Results of filtering technique based on a combined analysis of least-squares fit of amplitudes using the modified P-S reflection equation and velocity analysis show promise in isolating the multimode arrivals and thereby enhance interpretation.

ACKNOWLEDGEMENTS

The authors would like to thank Rigel Energy Inc., and in particular Mr. Mark Smith for providing log data and a geologic model for this work. The authors would like to thank Mr. Gerry Schlosser and Mr. Andy Maycock at Sensor Geophysical for their continuing help in processing real data from the Ireland area. We would also like to thank the CREWES Sponsors for their generous support of the work.

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