Analysis of multimode seismic conversions from high-velocity layers

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ABSTRACT

The seismic imaging of targets lying beneath or within a high-velocity sequence can be unsuccessful when using conventional techniques. We study a model based on log data from the northeastern area of Ireland which is covered by high-velocity basalts over a large area. The Zoeppritz response at the top and bottom of the high-velocity layer of the given model predicts strong multimode conversions for an incident P wave. Raytracing demonstrates the complicating effect that the high-velocity surface has on the recording of vertical and horizontal component data. Synthetic seismograms of the various multimode arrivals from the high-velocity layer of the model give an idea of the complexity of the problem. When offsets are large, the effect of wave conversions is even more important, and the possibility of confusing converted waves with multiples of primary P-wave reflection increases.

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 makes seismic surveying of limited use in imaging exploration targets that lie beneath or within the high-velocity sequence. Permafrost regions, carbonate outcrops and volcanic layers which have very 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. Similarly in the foothills of the Rockies and areas in the Middle East, high-velocity carbonate outcrops at surface often contribute to poor seismic recording. In addition, an analogous problem is encountered in the permafrost regions of 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) and Pujol et al. (1989) 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). Young and Lucas (1988), and Withers et al. (1994) suggest an integrated approach to the problem, that is interpretation combining seismic, gravity, magnetotelluric and log data.

In this paper, we consider a model based on log data from Ireland, which is covered by large extent of high acoustic impedance basalts on the surface. The Zoeppritz response at the top and bottom of the high-velocity layer of the model are used to determine energy partitioning among wavetypes. In the present work, we consider only the case of incident P wave at the top of the high-velocity layer. Raytracing is used to estimate the raypaths for the various multimode propagations under a given source-receiver geometry and surface conditions. Synthetic seismograms are constructed to study the pattern of various multimode arrivals. Finally, we outline the course of our future work in this direction.

ANALYSIS OF ZOEPPRITZ RESPONSE

Use of the Zoeppritz equations requires the P-wave and S-wave velocities and densities of media on each side of the interface. Log data from a well in northeastern Ireland provided information on the sub-surface lithology. P-wave velocities and density values are estimated for the layers from the P-wave and density logs. Various authors give a V_P/V_S value of 2 for basalts (Papworth, 1985 ; Pujol et al., 1989; Purnell, 1992). The variation of the P-wave and calculated S-wave velocity with depth for the model is shown in Figure 1. We have used a FORTRAN routine for calculating the Zoeppritz response of the model.

Analysis of the transmission coefficients for a P-wave incident on the mudstone-sill interface (Figure 2a) reveal significant conversions from P-wave to the S-wave mode even at incident angles less than the P-P critical angle (23 degrees) for the interface. Incident P, at angles greater than the critical angle for P-P transmission, are converted to the S-mode with an efficiency equalling that of pre-critical P-P transmissions. The close match between V_S within the high-velocity sill layer (HVL) and V_P within the relatively low-velocity mudstone layer (LVL) enables efficient coupling between S-waves within and P-waves outside (Purnell, 1992). 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.

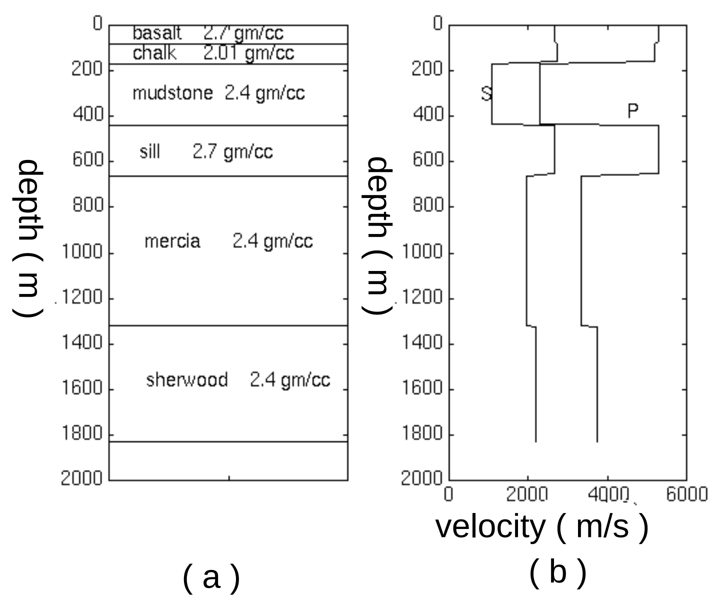

Fig. 1.Sub-surface depth model for the area. (a)Lithology of the subsurface, and density values blocked from the density log. (b)Variation of P-wave and S-wave velocities with depth.

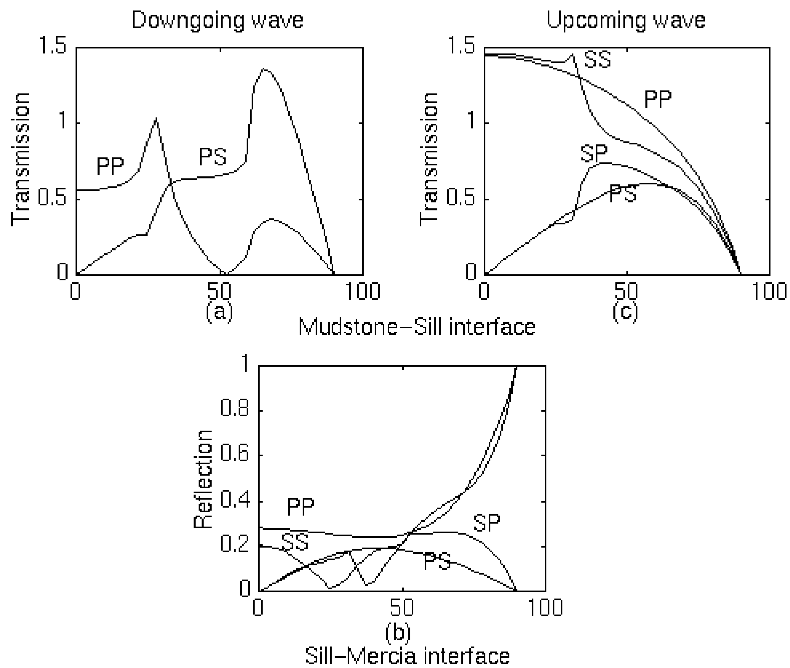

Fig. 2.Calculated Zoeppritz response at the top and base of the high-velocity sill layer (HVL). (a)P-P and P-S transmission coefficients for downgoing incident P-wave at the top of the HVL. (b)Reflection coefficients for all possible modes at the base of the HVL. (c)Transmission coefficients for upgoing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

Thus, various combinations of strong wave propagation are possible for incident P-wave at the top of the HVL. In particular, the cumulative energy associated with each of the PPPP, PSSS and PSSP paths through the HVL for incident P are estimated to be high enough to be recorded as an event of high amplitude on the seismic trace. The PSSP is slower compared to the PPPP event and may be misinterpreted when recorded on the vertical geophone. The PSPP is another significant event which could add to the confusion. Using physical-model experiments, Purnell (1992) has shown that a sub-HVL reflection from a low-velocity layer that travels through the HVL in the S-mode and elsewhere in the P-mode can be significantly strong relative to the unconverted P-wave arrival at the surface. Consequently, one would expect the PSPPSP event from the sub-HVL mercia layer (Figure 1) to be stronger than the unconverted PPPPPP event. This further complicates the problem. Thus we see that converted waves play a important role in areas where high-velocity layers are present at or near the surface.

RAYTRACING AND SYNTHETIC SEISMOGRAMS

From the Zoeppritz response we get the various strong multimode paths for the HVL. Raytracing of the various multimode paths are used for a better understanding of the problem. The raytracing was primarily divided into two categories. One involved the simulation of a particular raypath for two distinct surface conditions, and the other involved tracing of the various multimode paths. Strong multiples, expected from the large contrast in acoustic impedance across the chalk-mudstone boundary, have also been simulated.

We used the GXII modeling package for computing the raypaths and synthetic seismograms for the model. The common-shot gather geometry is used for raytracing.

A single simulated impulse source is shot with a receiver interval of 100m. The near offset is 100m and the far-offset is 2900m, with receiver numbers increasing from left to the right. Raytracing of the unconverted P-wave from the mercia layer (Figure 3) shows that the P-wave arrival at far-offsets is far away from the normal. This would lead to recording of significant amount of P-wave motion on the radial component geophone as well. Figure 4 displays the effect of the presence/absence of a weathering layer at receiver locations. It is noted that receivers located over a weathering layer receive near-vertical wave propagation and hence vertical-component geophones should record the P-wave motion almost completely. However, in the absence of a weathering layer at receiver locations and at far-offsets, the P-wave motion can be far from the normal as seen before in Figure 3 as well. Similar results are obtained in the presence of a weathering layer at source location for a P-P reflection. In addition, a shadow-zone is observed in the case of a P-S reflection, and this may complicate interpretation of a horizontal-component section. Therefore, any analysis involving a combination of vertical-component and radial-component sections should consider the surface conditions prior to any conclusions.

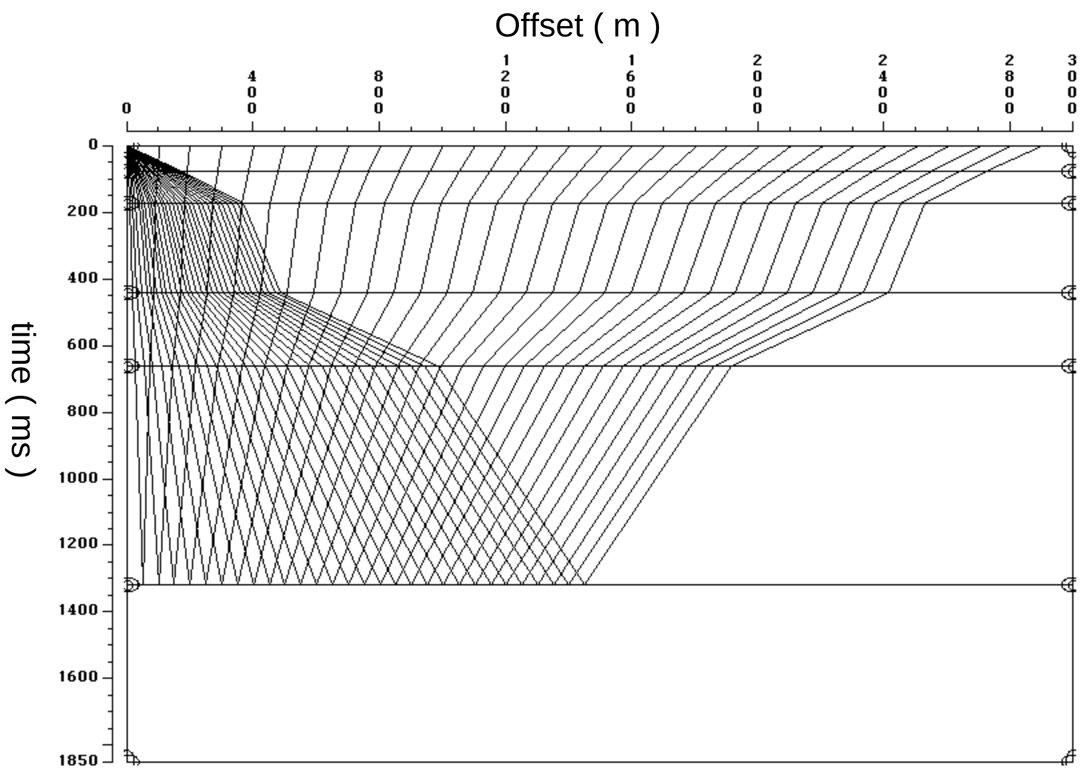

Fig. 3.Raypath of unconverted P-wave reflected from the top of the sub-HVL low-velocity mercia layer.

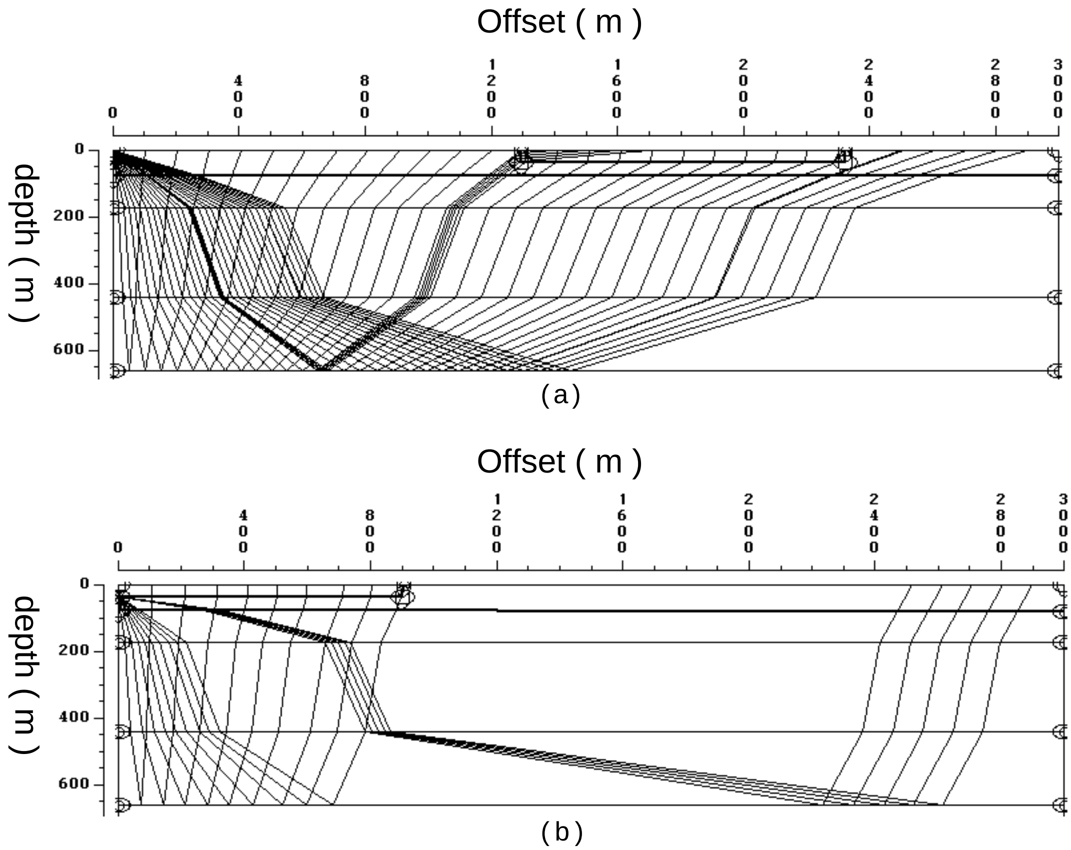

Fig. 4.Raypaths for incident P at the base of the HVL for different surface conditions. (a)Receivers fixed over a weathering layer, P-P reflection. At far offsets, the P-waves are seen to arrive at great angles away from the normal in the absence of a weathering layer. (b)Source over a weathering layer, P-S reflection. Occurence of a shadow-zone for intermediate offsets.

After testing the raypaths for different surface conditions, ray-generation was initiated for the strong multimode paths estimated from the Zoeppritz response of the HVL. Event **1** in Figure 5 is the unconverted P-wave arrival from the base of the HVL. Events **2** and **3** are the converted waves PSSP and PSSS respectively. The event intermediate between **1** and **2** is the PSPP mode. It is observed that waves reflected at the base of the HVL and which travel entirely in the S-mode in the HVL may be detected on the seismic section by a reversal in polarity after a certain offset (events **2** and **3**). Events **4** and **5** are the PPPPPP and PSPPSP reflections from the sub-HVL mercia layer. Although these are events from the same reflector, they would be misinterpreted due to the equally strong converted mode propagations.

The radial component geophone section (Figure 6) is observed to record the P-wave arrivals significantly. In fact, a comparison of the radial and vertical component sections reveal that the unconverted P-wave arrival (event **1**) is recorded in equal strength on both the sections at small offsets. At larger offsets, the amplitude of the unconverted P-wave arrival is observed to be more on the radial component than on the vertical component section. P-wave arrivals and multiples from the base of mudstone, chalk and basalt, that is arrivals before event **1**, are observed to record more strongly on the radial component geophone than on the vertical one as the wave arrivals are far from the normal.

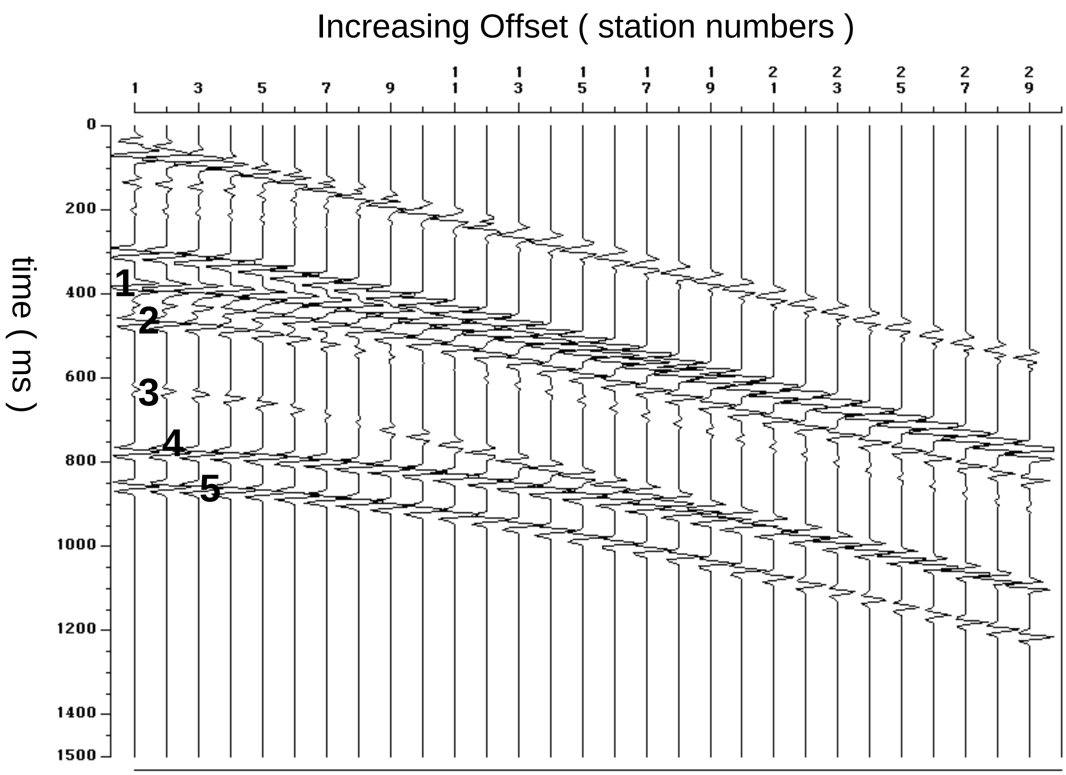

Fig. 5.Vertical-component synthetic seismic trace with AGC, for all unconverted P-waves of the model and the various strong multimode paths estimated from the Zoeppritz response of the HVL.

FUTURE DIRECTIONS

As part of our continuing effort to understand and propose solutions to the problem, we will be testing model data with new processing algorithms. Filter design will involve testing the data for response to a predictive deconvolution operator and the effects of f-k velocity filtering. Possibilities of correlating the horizontal component data with that of the vertical will also be examined. This might be used for modal suppression or combination into a total reflectivity section. Development of a technique accounting for the geometry of the reflection path will be pursued. Path-specific pre-stack migrations will also be attempted. We also intend to consider any statistical analysis that could pick up a converted wave based on the departure from a true hyperbola.

CONCLUSION

Several strong multimode propagation paths are feasible through a high-velocity layer. Surface conditions have an important role in the recording of component data. The multimode arrivals can severely distort the vertical component data and make interpretation difficult. Arrivals from the same event can be misinterpreted due to equally strong converted mode propagations from the event. Multimode paths having an S-S reflection component at the base of the high-velocity layer may be identified by polarity reversals with increasing offset on the component data.

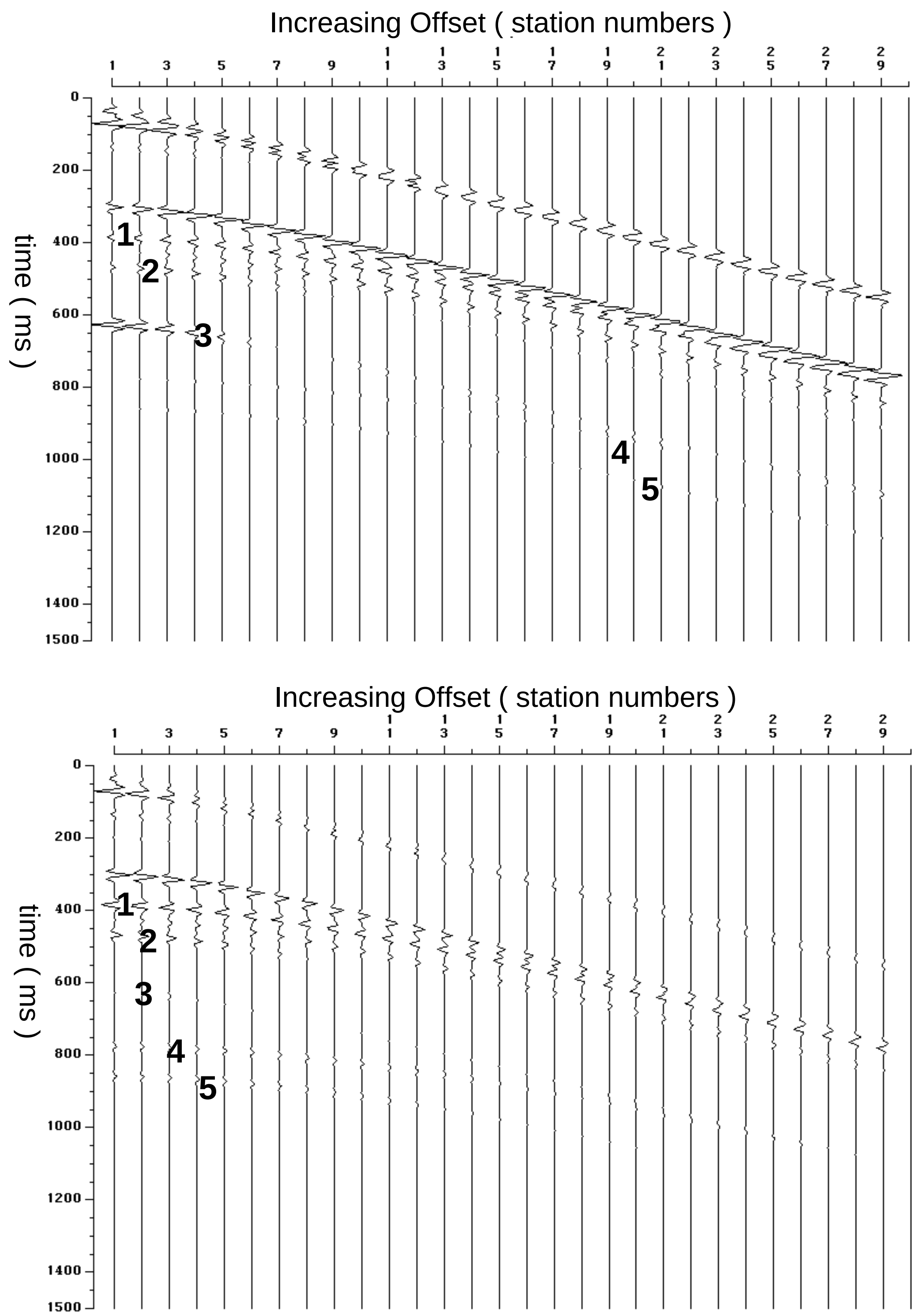

Fig. 6.Radial (Top) and vertical (Bottom) component seismic sections without any gain, for the unconverted P-waves of the model and the various strong multimode paths estimated from the Zoeppritz response.

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. We would also like to thank the CREWES Sponsors for their generous support of the work. The first author would like to thank the CREWES Sponsors for providing financial aid for his graduate studies. The authors would also like to thank Mr.Foltinek and Mr.Bland for continuous technical help during the tenure of the present work.

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