The effect of the near surface on internal multiples: a test of 1.5D prediction on synthetic examples

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ABSTRACT

Internal multiples occur in seismic data when incident energy reflects downwards within a geological layer, and are recorded at the surface as a unique reflection event. These multiples must travel at least twice (downward and upward) through a low velocity, unconsolidated near surface, possibly with different properties at each raypath location. In this paper, various geological models are tested, in which at least one internal multiple is produced from a deeper low velocity layer. These internal multiples are compared for different complexities of near surfaces, and a 1.5D multiple prediction in the plane wave domain is tested on the produced seismic data. For simple models, the 1.5D prediction is accurate, but for a laterally heterogeneous near surface, the 1.5D prediction is insufficient to correctly predict the multiples.

INTRODUCTION

Internal multiples (IMs) in seismic data create issues for seismic interpretation, as they may be mistaken for primary arrivals, or may obscure primaries of interest. Internal multiples arise when a wave reflects within a layer of the earth and is recorded as a discrete event. IMs in a laterally homogeneous, horizontally layered medium can be easily removed by predicting the arrival time of the multiple. A near surface with sufficiently low velocity and complex geometry may affect how IMs appear in shot records. This holds the potential to alter the arrival time of the multiple at offset, enough that the prediction fails, leaving multiples in the seismic record. In this paper, various models with a near surface component overlying an internal multiple generator (IMG) will be tested to observe this effect. A 1.5D multiple prediction in the plane wave domain will be tested on shot records generated from these models to gage whether the near surface effect has consequences to multiple prediction and attenuation.

BACKGROUND

Near surface effects

The near surface of the earth is defined as the shallowest 10's-100's of metres of sediment and material (Yilmaz, 2015). This sediment is composed of the soil-column, and low-velocity, often unconsolidated, heterogeneous, and weathered rock layers. The velocity of this layer is generally lower than the underlying consolidated, sedimentary and crystalline rocks. Because the seismic energy must travel through this near surface layer twice, possibly at different locations, the effect on traveltimes could be substantial. Combined with lateral velocity changes, the travel times could be substantially different than normal moveout (NMO) predicted traveltimes, which could create problems for IM prediction.

Internal multiple prediction

1D IM prediction predicts the arrival time of an IM at zero offset, for a single trace. 1.5D prediction does this as well, but extends the prediction to other traces for a medium that is the same as the 1D medium, but extended over a 2D profile. A 1.5D inverse scattering series IM prediction algorithm will be tested on various modelled shot records. Some shot records will be modelled over a true 2D medium, with lateral changes in the near surface. For large scale changes, 1.5D prediction would be expected to fail, but the IM prediction may be effective at some offsets.

The formula for 1.5D multiple prediction in the plane wave domain as proposed by Coates and Weglein (1996) is

$$b_{3IM}(p_g,\omega) =$$

$$\int_{-\infty}^{+\infty} d\tau e^{i\omega\tau} b_1(p_g,\tau) \int_{-\infty}^{\tau-\epsilon} d\tau'\, e^{-i\omega\tau'} b_1(p_g,\tau') \text{ X } \int_{\tau'+\epsilon}^{+\infty} d\tau'' e^{i\omega\tau''} b_1(p_g,\tau'') \qquad (1)$$

where $p_g = p_s$ are the receiver and source horizontal slowness respectively, which are equal in 1.5D problems. The time variables τ are the intercept times of three events (the primaries and IM), which satisfy the lower-higher-lower relationship of a triplet of events. The IM prediction process and algorithm of Sun and Innanen (2015) is utilized for this test.

In a laterally homogeneous, horizontally layered known model, the arrival times of reflections and IMs from a single IMG can be predicted at offset using normal moveout (NMO), which is given by

$$t_{NMO}^2 = t_0^2 \frac{x^2}{v_{RMS}^2} \qquad (2)$$

where t_0 is the zero offset two way traveltime, and x is the offset. v_{RMS}^2 is used because the medium is horizontally layered. The *small-spread approximation* (offset is small compared to depth) is employed to use this form of the NMO calculation (Yilmaz, 2001). In the case of these experiments, the depth of the IMG is only 400m, whereas offsets are up to 2500m. It can be seen in Figure 1 that this approximation is only accurate for offsets up to 1000m, where the actual arrival times of all events are sooner than the predicted NMO times.

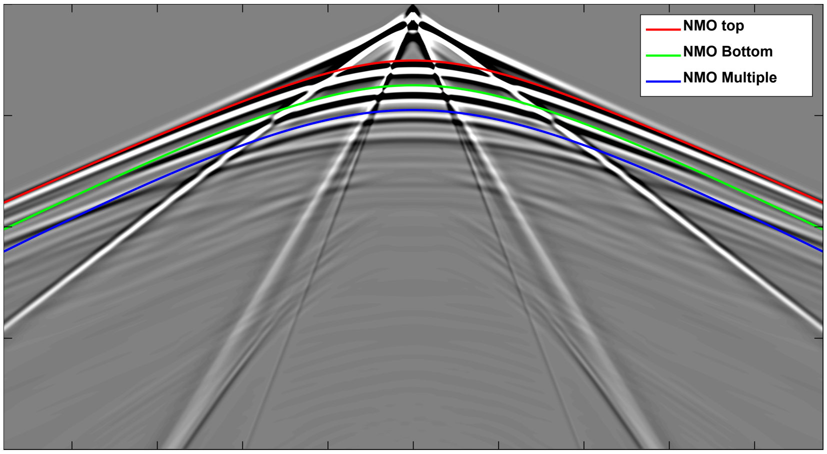

FIG. 1. Shot gather of Model 1 with NMO curves overlain of reflections from the IMG, and the first IM.

INTERNAL MULTIPLE MODELLING

Modelling software

In this study, all seismic modelling is done using SOFI2D, which is a 2D finite difference seismic modeling engine. Various velocity (Vp and Vs) and density models were built in Matlab, and used as input into SOFI2D (Cova, 2016). The models are 5000m wide by 1000m deep, with the near surface confined to the top 100m of the model. An explosive point source is used in all shot record simulations. The source and receivers are placed at 50m depth, to avoid the 40m absorbing boundaries that surround the computational grid. Receivers are placed from 100m to 4900m, with a receiver spacing of 2m. Models with increasing velocity contrasts and geometry complexity will be analyzed. Shot records will be generated at different points along the model, in order to observe the effect of offset from lateral changes on IM traveltimes. A low velocity, low density layer, similar to a coal seam (reflection coefficient of -0.45) lies at 400m depth, and is 100m thick. It is overlain and underlain by the same higher velocity rock layer. The impedance contrast between the surrounding material and this IMG is great enough to generate a visible IM ~100ms after the primary arrivals.

Model 1: Laterally Homogeneous, Layered Near Surface

The first model to be analysed is a laterally homogeneous, horizontally layered medium (Figure 2). This will be the reference model for this study, as all reflections should be symmetric about the shot point, and exhibit predictable NMO, as seen in Figure 1.

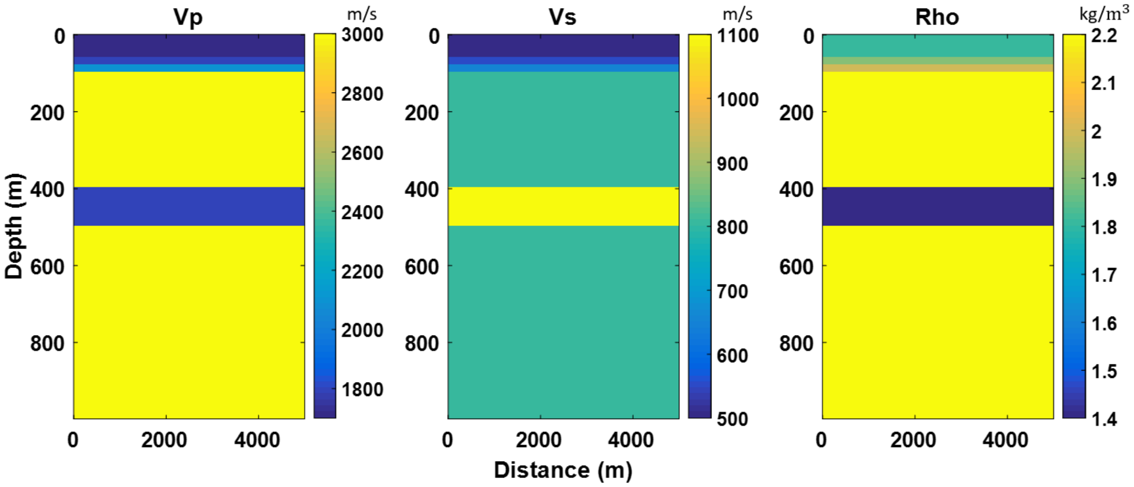

FIG. 2. Velocity model 1, with simple symmetric geometry.

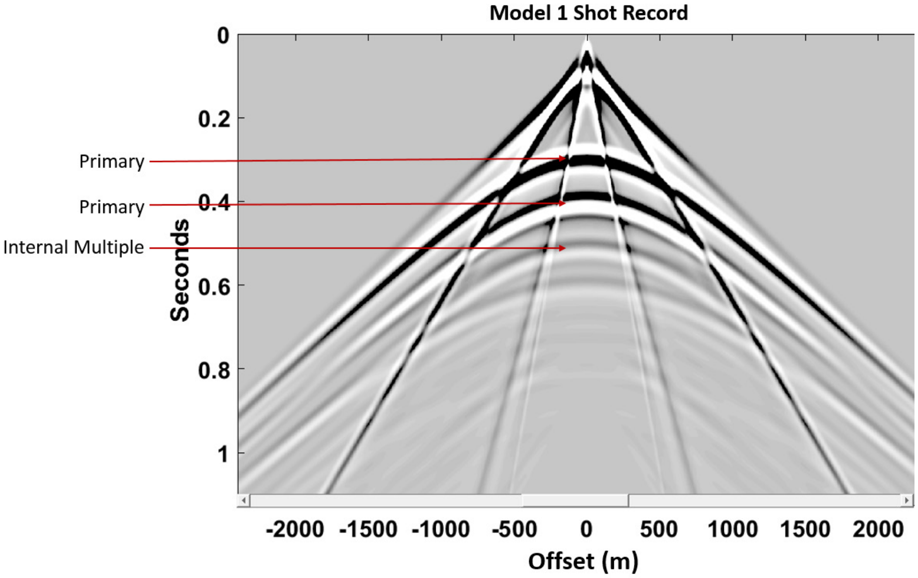

FIG. 3. Raw shot record of model 1, with labelled events.

The raw shot gather (Figure 3) is tau-p transformed to filter out the direct arrivals, refractions, and slower linear events. Then, a mute is applied above the first primary to remove artefacts remaining from the tau-p transform, leaving only the reflections and IMs (Figure 4). These steps are necessary because otherwise direct and refracted arrivals will be interpreted as reflection events by the IM prediction algorithm. The 1.5D IM prediction code is run on this shot record, and correctly predicts the IM, as shown in Figures 4 and 5. This is expected, since the model is a 1.5D medium.

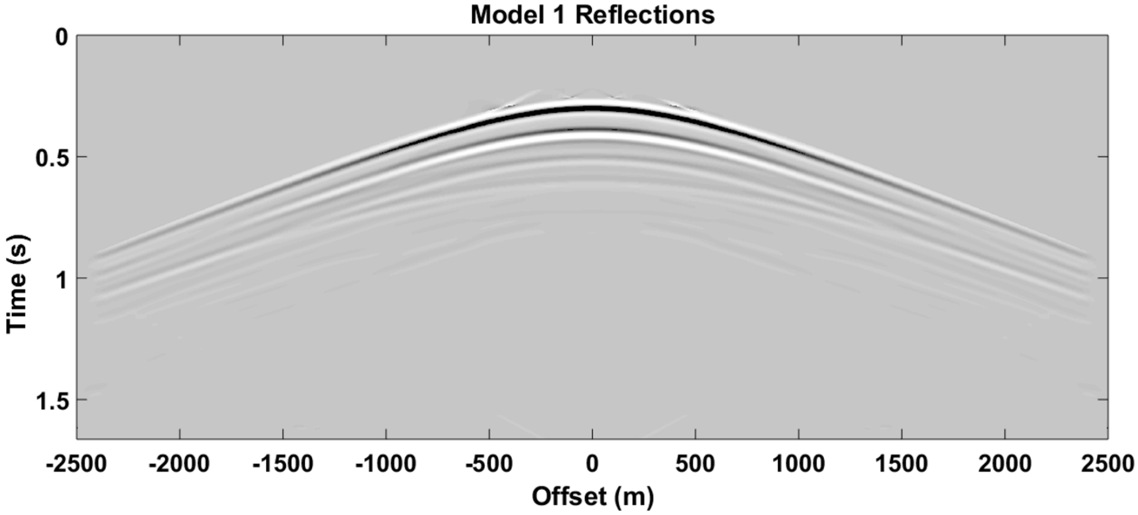

FIG. 4. Model 1 shot record, with reflection events and IM's only.

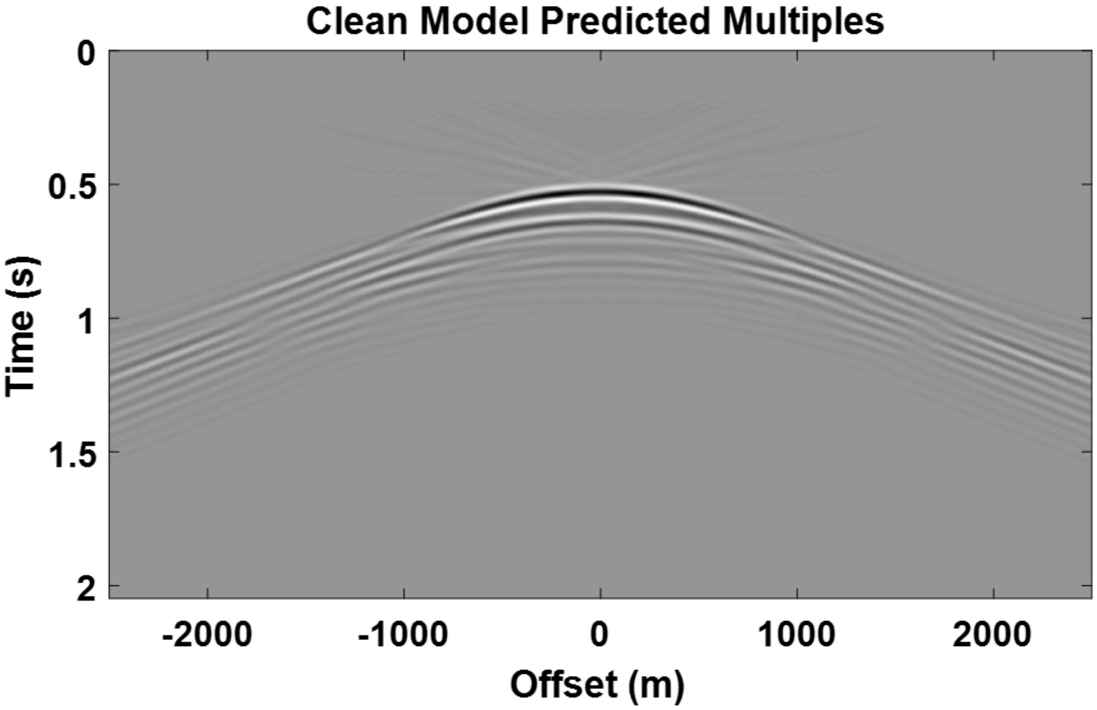

FIG. 5. 1.5D predicted internal multiples

Model 2: Vertical Near Surface Discontinuity

The second model to be studied has a vertical contrast in the centre, where the source is located. Events on opposite sides of the discontinuity could be expected to have different arrival times, but on the shot record (Figure 7a) only slight differences are visible. At farther offsets, earlier arrivals occur on the right side of the model (Table 1), so there are slight differences in the multiple that increase with offset. The predicted multiples (Figure 7b) appear to match the multiples in the shot record at near offsets, but with asymmetric character would not match at far offsets. Therefore, attempting IM removal in this case would remove near offset multiple arrivals, but leave artefacts at farther offsets.

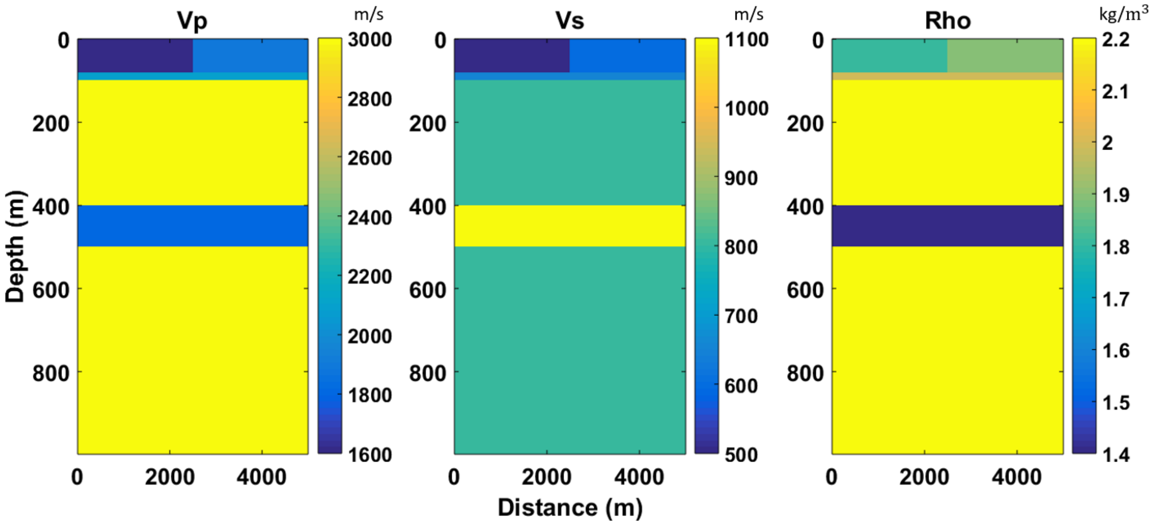

FIG. 6. Model 2, with a vertical discontinuity in the centre of the model.

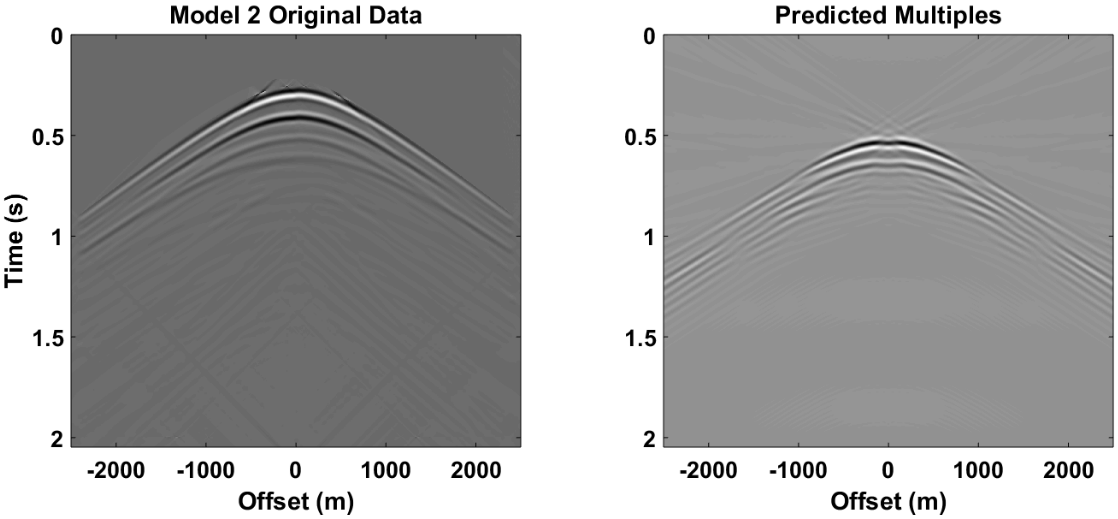

FIG. 7. Left (a): Original data for Model 2. Right (b): Predicted internal multiples from the data in FIG. 7a.

Model 3: Multilayer Near Surface with Vertical Discontinuity

The final model to be examined has three different layers with different velocities on either side of the model (Figure 7). The IM produced from a shot in the center of the model (Figure 7a), has slightly earlier arrivals at positive offsets, due to higher velocities on the right side of the model. The multiples predicted (Figure 7b) appear to be uniform and symmetric, which is different than the observed multiples.

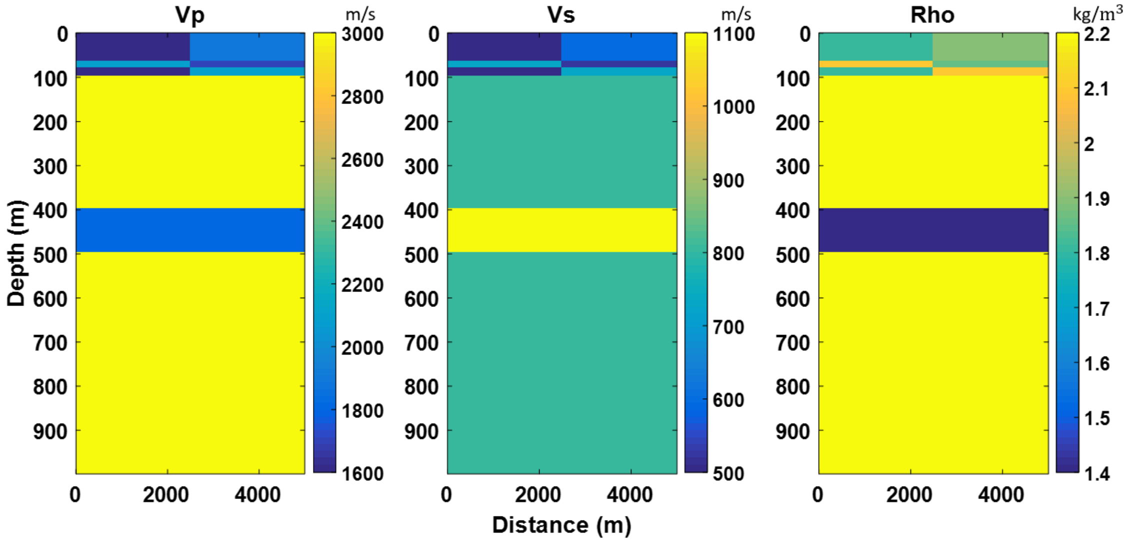

FIG. 8. Model 3 velocity and density models.

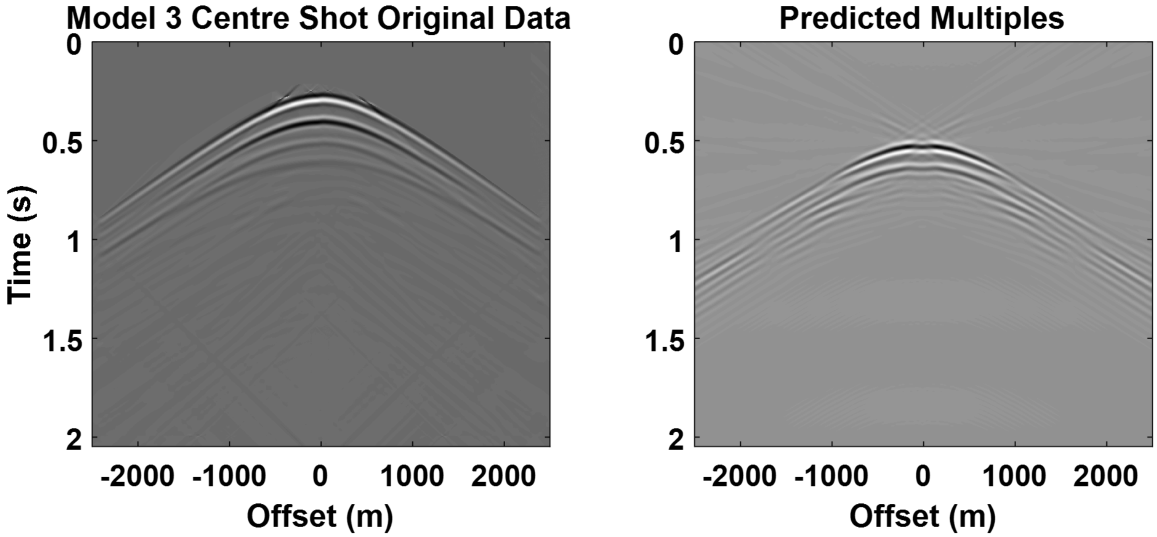

FIG. 9. Left (a): Original data for central shot in Model 3. Right (b): Predicted internal multiples from the data in FIG. 9a.

If these multiples were to be subtracted from the data, there would be at least partial removal. However, because there are changes in the multiple character in the data, artifacts would remain in the data.

For a shot 300m to the left of the vertical discontinuity (at 2200m) (Figure 10a), similar multiples to Figure 9a are observed. At the discontinuity, there is a clear boundary visible in the IMs on the reflections-only shot record (Figure 10a). As expected with a 1.5D prediction method, this change in character is not accounted for. There is a slight change in the hyperbolic shape of the prediction at the location of the discontinuity (Figure 10a), but this change also appears on the opposite side of the prediction. Again, subtracting these multiples would likely lead to a partial removal, but artefacts would remain.

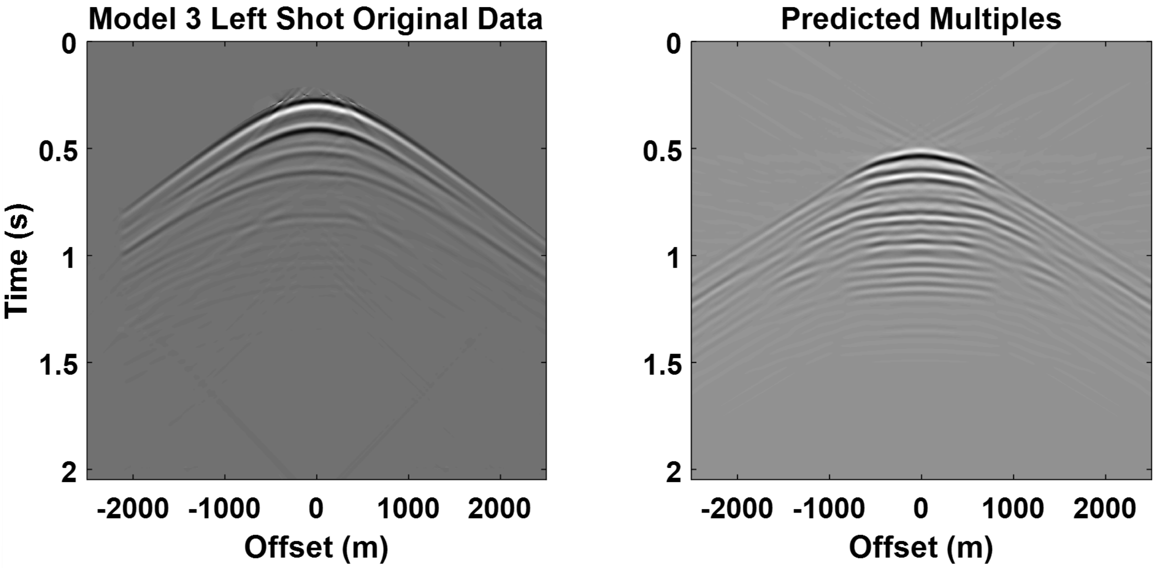

FIG. 10. Left (a): Original data for left shot of Model 3. Right (b): Predicted internal multiples from the data in FIG. 10a.

SUMMARY

Offset	-1000 m	-600 m	0 m	600 m	1000 m
Model 1 IM Arrival Time (s)	0.660	0.571	0.512	0.571	0.660
Model 2 IM Arrival Time (s)	0.660	0.573	0.513	0.569	0.635
Model 3 IM Arrival Time (s) (Centre Source)	0.660	0.570	0.515	0.572	0.635

Table 1. Arrival times of the internal multiples for all models, at various offsets from the source.

In Table 1, the observed arrival times of the IM for all models are compared. These arrival times were extracted from individual traces in each shot record. Model 1 is a laterally homogeneous, true 1.5D medium, and the arrival times are symmetric, and can be predicted by NMO calculation. In the other models a slight asymmetry of arrival times appears. Models 2 and 3 produce an IM with very similar arrival times, due to an averaging of the near surface velocities in Model 3. The IMs predicted by the 1.5D prediction are symmetric about the shot point, which would result in partial removal depending on offset.

CONCLUSIONS

Various near surface velocity models were tested, with the goal of detecting how complexity in the near surface affects the production and detection of IMs from deeper layers. A laterally homogeneous, horizontally layered near surface was initially tested as a standard for a model with a near surface and IMG. The IM produced from this model was successfully predicted by 1.5D prediction. In more complex models with a vertical discontinuity, the IM produced had an arrival time difference of ~30ms at 1000m offset, due to higher near surface velocities on one side of the model. These IMs were not successfully predicted by the 1.5D prediction at all offsets. Removing the IM prediction from the data would only achieve partial multiple removal, leaving artefacts in the data. A 2D IM prediction would be required in these cases to successfully predict and completely remove any internal multiples. In all the models tested, the near surface was effectively 50m thick. A thinner near surface would increase the effectiveness of 1.5D prediction. A thicker near surface system would reduce the accuracy of predictions by increasing the influence of these velocities on the waves. In these cases, 2D multiple prediction would be necessary.

ACKNOWLEDGEMENTS

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REFERENCES

Coate, R.T., and Weglein, A.B., 1996, Internal multiple attenuation using inverse scattering: results from prestack 1D & 2D elastic synthetics, SEG Technical Program Expanded Abstracts, **13**, 1039-1041.

Sun, J., and Innanen, K., 2015, 1.5D Internal multiple prediction in the plane wave domain, Geoconvention 2015 Expanded Abstracts.

Yilmaz, O., 2015, Engineering seismology with applications to geotechnical engineering, Society of Exploration Geophysicists.

Yilmaz, O., 2001, Seismic data analysis: processing, inversion, and interpretation or seismic data, Volume 1, Society of Exploration Geophysicists.