Brute force analysis of residuals arising from the near surface

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ABSTRACT

Variations in the elastic properties of the near surface are known to cause issues with seismic imaging and inversion, with velocity, density, and thickness variations resulting in statics problems. In particular, in contemplating FWI on land, the sensitivity of amplitude and phase information to changes in the near surface is known to be complex, but we have little quantitative information to guide us here. In this paper, an initial model with a complex near surface and deeper reflectors is studied. Piece by piece, a single characteristic (velocity, density, or thickness) is altered for a single layer or unit. The resulting shot record is compared to the original, to gauge the effect that that rock property change or geometry change has on the recorded events, for both surface waves and reflections. By subtracting the original shot record from the result, we can quantify this effect in a residual, which is used to calculate the ℓ_2 norm. Velocity changes in shallower layers are found to have the greatest effect, with changes in thickness having a lesser effect. With increasing depth, property changes have a reduced effect on the ℓ_2 norm. It is shown that a minor change in the near surface has an effect on the ℓ_2 norm orders of magnitude greater than the same change made at greater depth, demonstrating the importance of understanding the properties of the near surface.

INTRODUCTION

Variations in composition and uniformity of the near surface result in statics time shifts, which cause imaging problems for deeper layers (Henley, 2004). Understanding the make-up of the near surface layers, and how their properties affect propagation and recording of seismic energy is key to mitigating negative near surface effects in seismic data. In this paper, an original model containing a complex near surface and deeper reflectors is built, and a synthetic shot record is generated over it. This shot record will be the standard to which shot records generated from modified models will be compared. Sequentially, a single property (shear wave velocity, layer thickness, model geometry) is altered for a single layer, and a new synthetic shot record is generated and compared to the original. Changes from the original model shot record are quantified in the ℓ_2 norm of the residual, $\|r\|_2$. The residual is the difference between the altered model data and the original data. This paper will be a collection of examples demonstrating the effect and magnitude that each property change, at each location in the model has on the $\|r\|_2$. The $\|r\|_2$ will be compared for each alteration to the model, to quantify the alteration's effect on the recorded data. Through this study, we will be able to directly observe and quantify the effect of each property (velocity, geometry) on shot records.

DATA AND RESULTS

Synthetic modelling

The geologic Vp, Vs, and ρ models used in this study are built in MatLab, and are 5000m wide by 2500m deep. Models represent a complex near surface in the shallowest 100m, including a vertical discontinuity at x=2500m offsetting the three near surface layers, with three deeper layers to a maximum reflector depth of 1510m (Figure 1). The model in Figure 1 will be the original data model, which will be altered incrementally to conduct a data comparison.

The synthetic modelling is carried out using SOFI2D, a 2D finite difference elastic modelling engine. The top of the model is set as a free surface, meaning that Rayleigh waves can be generated and recorded, which is necessary to observe the effect the changes have on ground roll (Mills et al., 2016). Absorbing boundary conditions are on the sides and bottom of the model, however some artificial reflections from these boundaries still appear. An explosive point source is placed at 10m depth, at x=1500m. Placing the shot at 1000m offset from the near surface discontinuity will bias the results to be more influenced by impedance changes in the left side of the model. However, by placing the shot away from the discontinuity we will be able to observe the effect these lateral changes will have on the residuals. A Fuchs-Muller minimum-phase wavelet with a central frequency of 12 Hz is used for the source. Receivers are placed at 10m depth across the model at 10m receiver spacing. Once SOFI2D has run using the input models and specified receiver locations, a 2 second shot record is generated with a time sampling rate of 1ms. These shot records can then be analyzed in seismic unix (SU) format in Vista or Matlab.

Original data

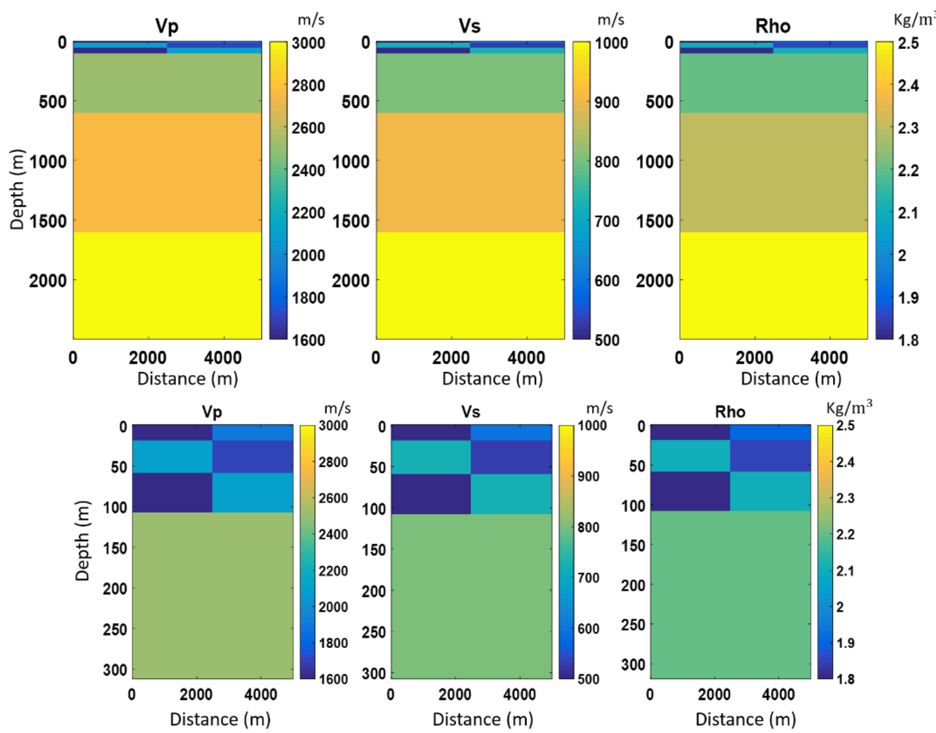

FIG. 1. Initial geologic models used for synthetic modelling. Top: Full model. Bottom: Near surface zoom.

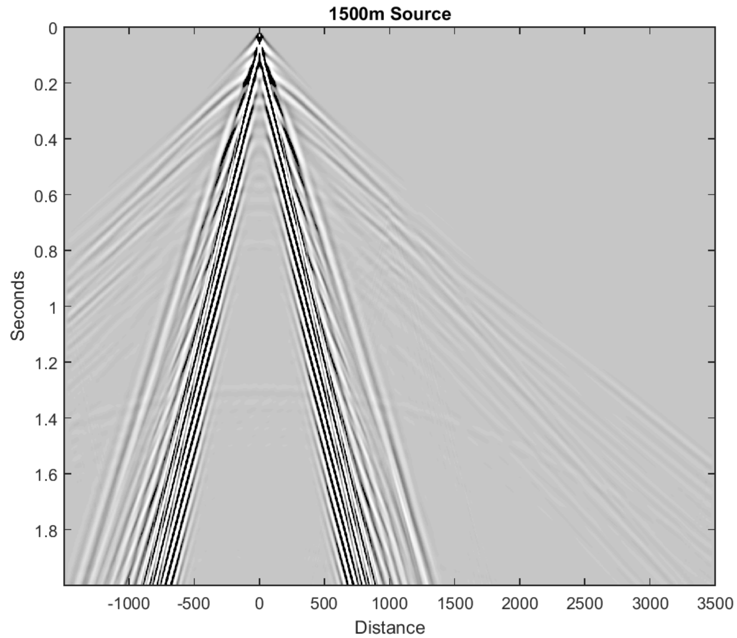

FIG. 2. The shot record over the original model. Altered model shot records will be compared to this shot record. Distances are in m, and are measured from the source location.

Altered models

The perturbed models will be presented in descending order of the magnitude of their residuals. The changes that have the greatest effect on the original shot record will be presented first. The models will be presented with model name, the property changes, and the square root of the residual for comparison to different models.

The ℓ_2 norm, $\|r\|_2$ is calculated from

$$r = s_{mod} - s_{alt} \tag{1}$$

$$\|r\|_2 = \sqrt{r * r} \tag{2}$$

where r is the residual, s_{mod} is the original modelled shot record, and s_{alt} is the altered model shot record.

Nsv1: The change that generated the greatest residual was increasing the shear velocity of the second layers by 100m/s, from 725m/s (left) and 525m/s (right). This change increases velocity contrasts both above and below this layer on the left side of the model, and decreases the contrasts on the right. The shot record from this altered model is shown in Figure 3 (left), with the residual shown in Figure 3 (right). As can be expected, an increase in Vs affects mainly the ground roll component of the record, with some effects seen in the refractions. The $\|r\|_2 = 0.0303$.

Nsv8: Increasing the first layer shear velocity by 50m/s from 500m/s (left) and 600m/s (right) has the second greatest effect, resulting in a $\|r\|_2 = 0.0300$. This change decreases the velocity contrast on the left, and increases it on the right side of the model. The altered model shot record and it's residual are show in Figure 4 (left, right). Again, changes are observed mainly in the ground roll component of the record.

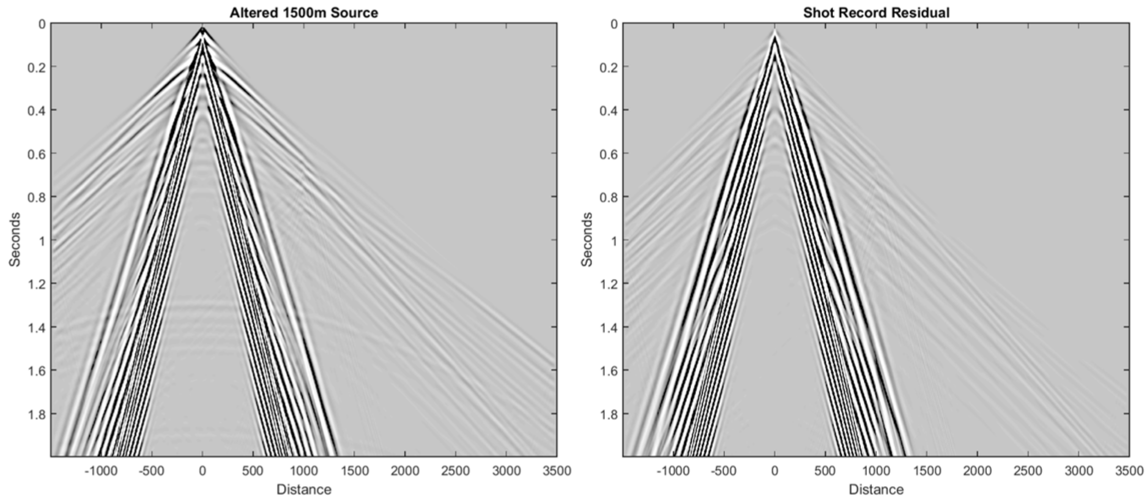

FIG. 3. Nsv1: Left: Shot record with second layer Vs increased by 100m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.0303$.

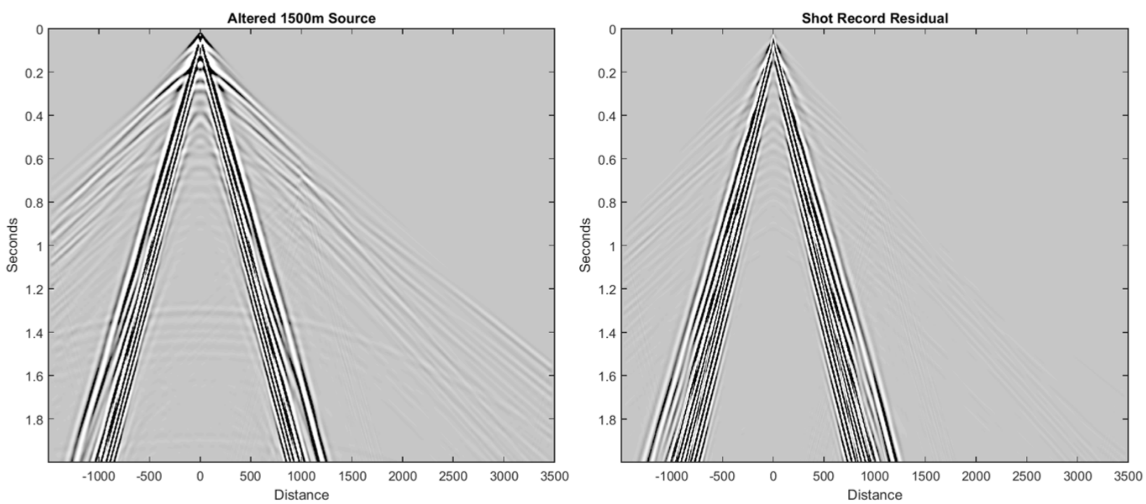

FIG. 4. Nsv8: Left: Shot record with first layer Vs increased by 50m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.0300$.

Nsv7: Decreasing the first layer shear velocity by 50m/s from 500m/s (left) and 600m/s (right) results in a $\|r\|_2 = 0.0286$. This change decreases the velocity contrast on the left, and increases it on the right side of the model. The altered model shot record and it's residual are show in Figure 5 (left, right).

Nsv10: Decreasing the second layer shear velocity by 100m/s from 725m/s (left) and 525m/s (right) results in a $\|r\|_2 = 0.0283$. This change decreases the velocity contrast on the left, and increases it on the right side of the model. The altered model shot record and it's residual are show in Figure 6 (left, right).

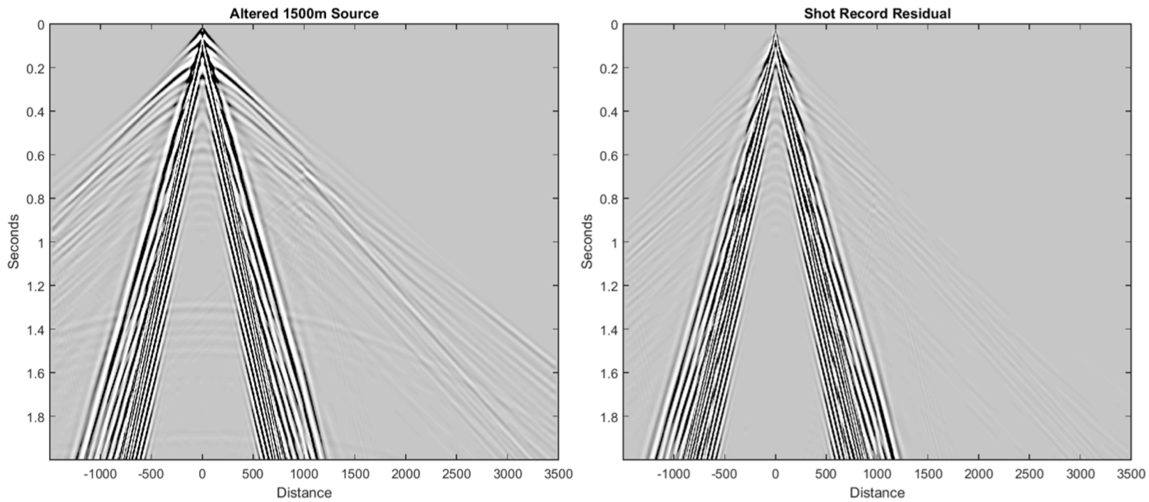

FIG. 5. Nsv7: Left: Shot record with first layer Vs decreased by 50m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.0286$.

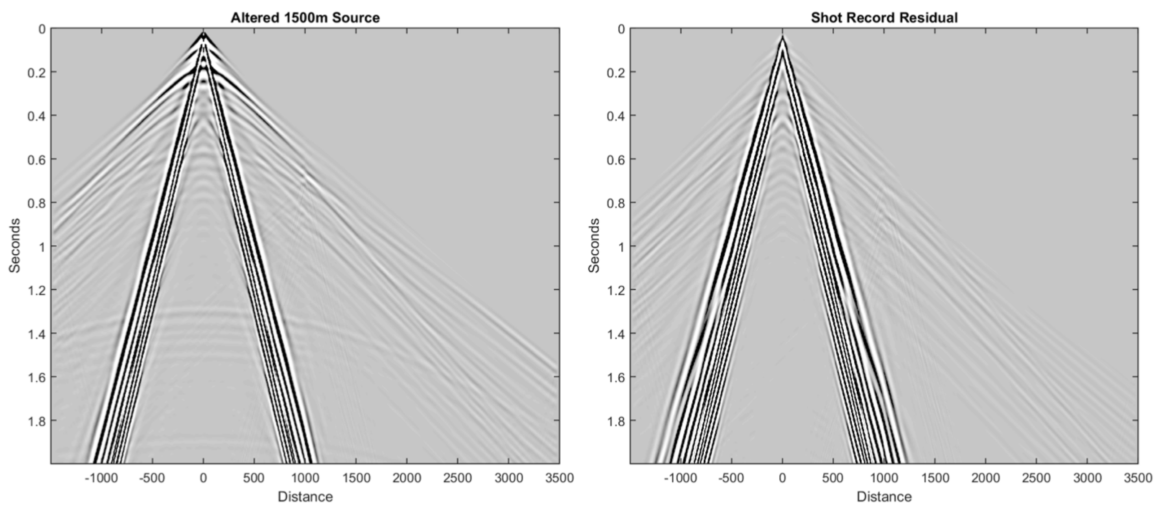

FIG. 6. Nsv10: Left: Shot record with second layer Vs decreased by 100m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.0283$.

Nsv4: Increasing the second layer shear velocity by 50m/s from 725m/s (left) and 525m/s (right) results in a $\|r\|_2 = 0.0251$. This change increases the velocity contrast on the left, and decreases it on the right side of the model. The altered model shot record and it's residual are show in Figure 7 (left, right).

Nsv3: Increasing the second layer shear velocity by 50m/s from 725m/s (left), left side only results in a $\|r\|_2 = 0.0251$. This change increases the velocity contrast on the left, and decreases it on the right side of the model. The altered model shot record and it's residual are show in Figure 8 (left, right). In the last two examples, the same change was made on the left side of the model, while the right side was changed in nsv4, and unchanged in nsv3. The square root of the residual is the same (to four decimal places) for both, demonstrating that changes in laterally adjacent layers have minimal effect on the residuals.

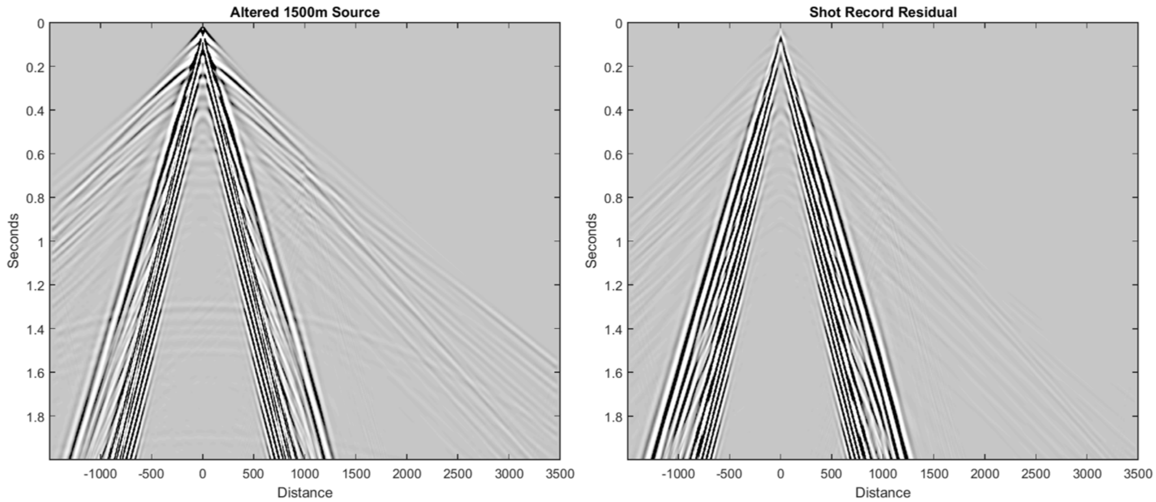

FIG. 7. Nsv4: Left: Shot record with second layer Vs increased by 50m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.0251$.

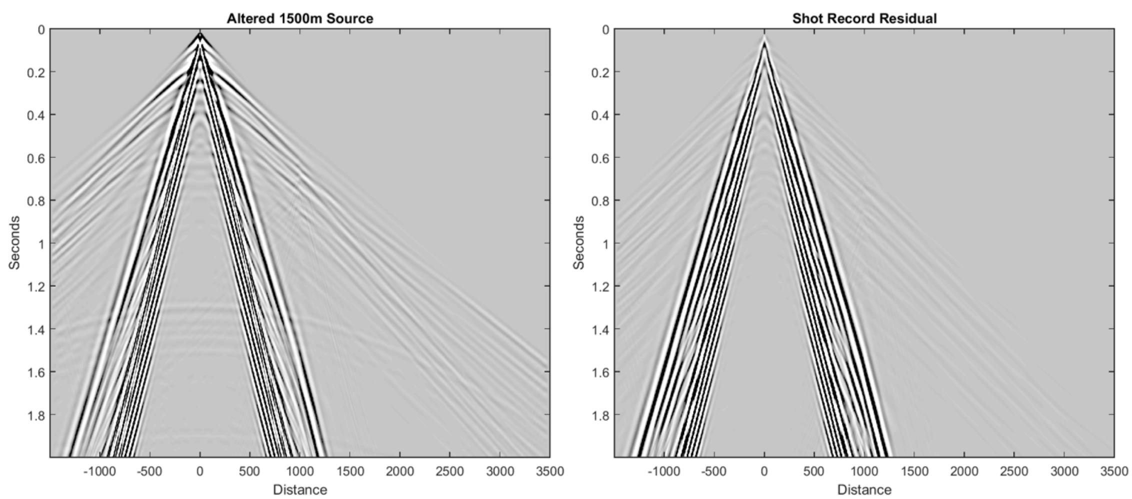

FIG. 8. Nsv3: Left: Shot record with second layer (left side only) Vs increased by 50m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.0251$.

Nsv6: Decreasing the second layer shear velocity by 50m/s from 725m/s (left) and 525m/s (right) results in a $\|r\|_2 = 0.0251$. This change decreases the velocity contrast on the left, and increases it on the right side of the model. The altered model shot record and it's residual are show in Figure 9 (left, right). In the last three examples (nsv4, nsv3, nsv6) the second layer Vs has been increased or decreased by 50m/s, and all three have had very similar residual values. From this series, and the relation between nsv1 and nsv10, we can see that increasing the velocity has a greater effect on the residual than decreasing it. This effect increases with an increase in velocity, but at around 50m/s it appears that either an increase or decrease in Vs at this depth has the same effect on the residual.

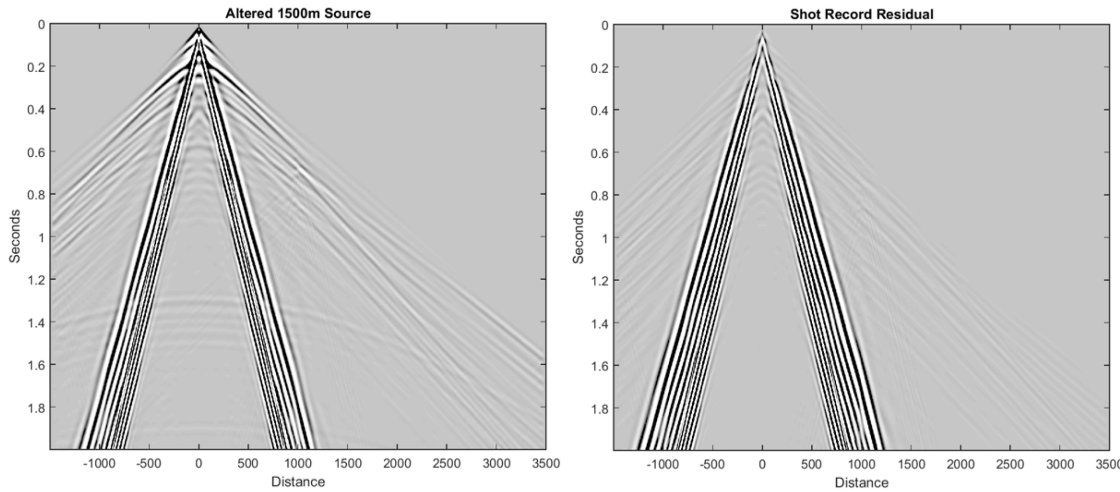

FIG. 9. Nsv6: Left: Shot record with second layer Vs decreased by 50m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.0251$.

Nsv2: Increasing the third layer shear velocity by 100m/s from 500m/s (left), and 725m/s (right) results in a $\|r\|_2 = 0.0112$. This change decreases the velocity contrast on the left, and increases it on the right side of the model. The altered model shot record and it's residual are show in Figure 10 (left, right). The effect on the square root of the residual at this depth is half of that of changes in the layer above, confirming that changes have decreasing effect as distance from the receivers increases.

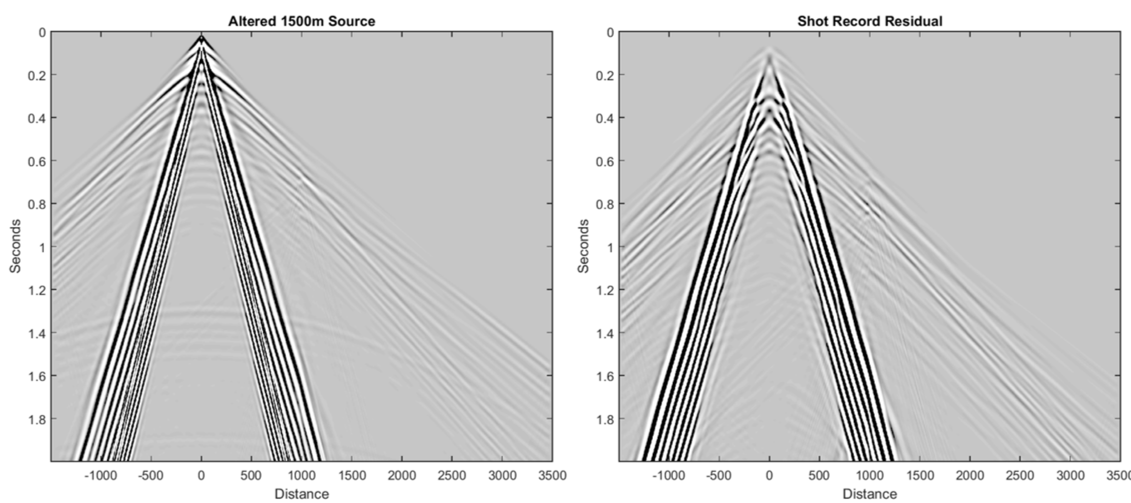

FIG. 10. Nsv2: Left: Shot record with third layer Vs increased by 100m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.0112$.

Nsg2: Decreasing the thickness of the second layer by 10m from 40m thickness results in a $\|r\|_2 = 0.0109$. This change reduces the amount of time the waves spend in the second layer, and also moves the third layer impedance contrast closer to the receivers. The altered model shot record and it's residual are show in Figure 11 (left, right). Now that the geometry of the model has changed (all reflectors below the second have shifted up by

10m), the residual includes changes in reflections, refractions, and direct arrivals. The ground roll residual still dominates the residual.

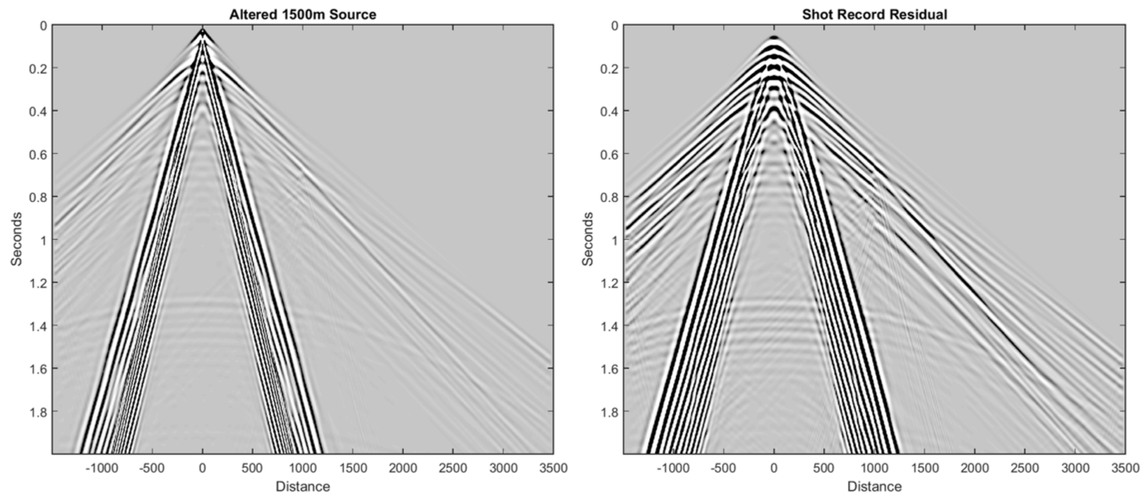

FIG. 11. Nsg2: Left: Shot record with second layer thickness decreased by 10m. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.0109$.

Nsg1: Increasing the thickness of the second layer by 10m from 40m thickness results in a $\|r\|_2 = 0.00079$. This change increases the amount of time the waves spend in the second layer, and also moves the third layer impedance contrast further from the receivers. The altered model shot record and it's residual are show in Figure 12 (left, right). Now that the geometry of the model has changed (all reflectors below the second have shifted down by 10m), the residual includes changes in reflections, refractions, and direct arrivals. The ground roll residual still dominates the residual.

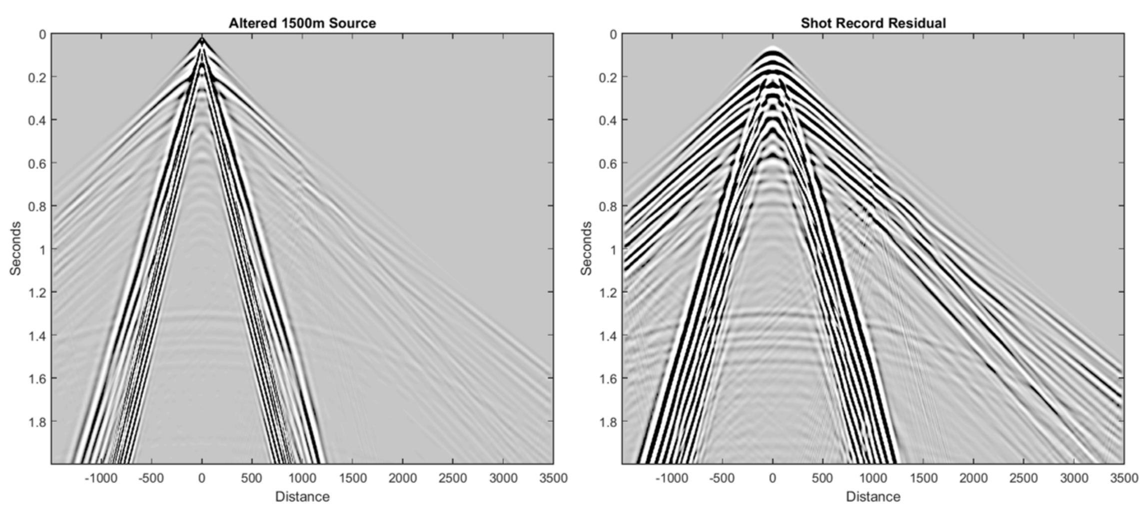

FIG. 12. Nsg1: Left: Shot record with second layer thickness increased by 10m. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.00079$.

Further modelling was conducted, in which the velocities and thickness of the fourth layer were altered. Decreasing its Vs by 50m/s (Model Drv3) resulted in a $\|r\|_2 =$

0.00034. The altered model shot record and it's residual are show in Figure 13 (left, right). Note in this figure that the residual is still dominated by ground roll, meaning that some surface waves are sampling this deeper layer. Increasing its Vs by 50m/s (Model Drv2) resulted in a $\|r\|_2 = 0.0030$. The residuals for these changes were dominated by higher velocity Rayleigh waves. The altered model shot record and it's residual are show in Figure 14 (left, right). Increasing its thickness by 100m (Model Drg1) resulted in a $\|r\|_2 = 0.00011$. The residuals for this change included only the reflections from the deeper layers, with no contribution from surface waves, as can be seen in Figure 15 (right). These alterations show that changes made at depth (>100m) have a minimal effect on the residual when compared to changes in the near surface (<100m).

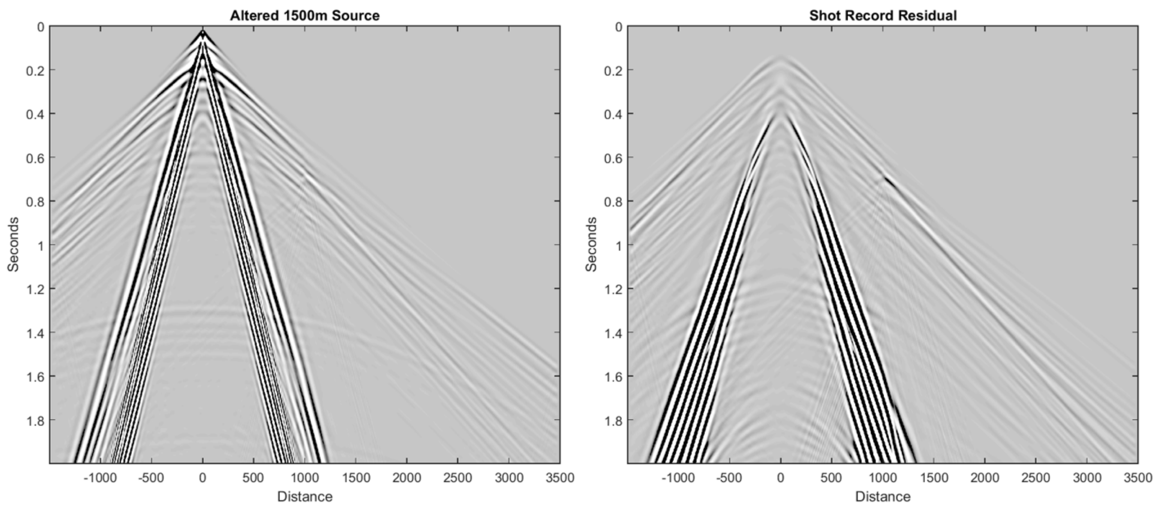

FIG. 13. Drv3: Left: Shot record with fourth layer Vs decreased by 50m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.00034$.

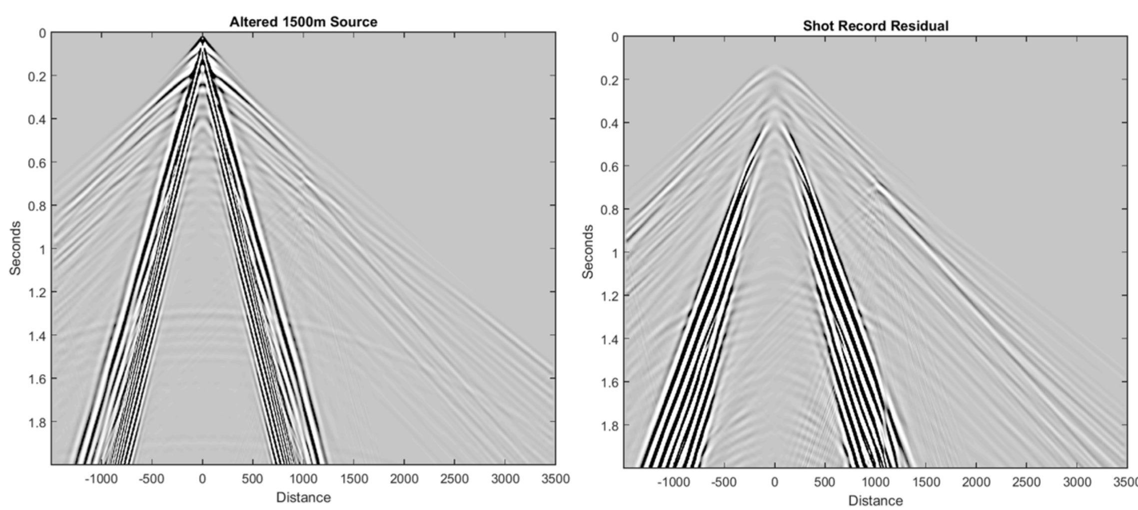

FIG. 14. Drv2: Left: Shot record with fourth layer Vs increased by 50m/s. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.00011$.

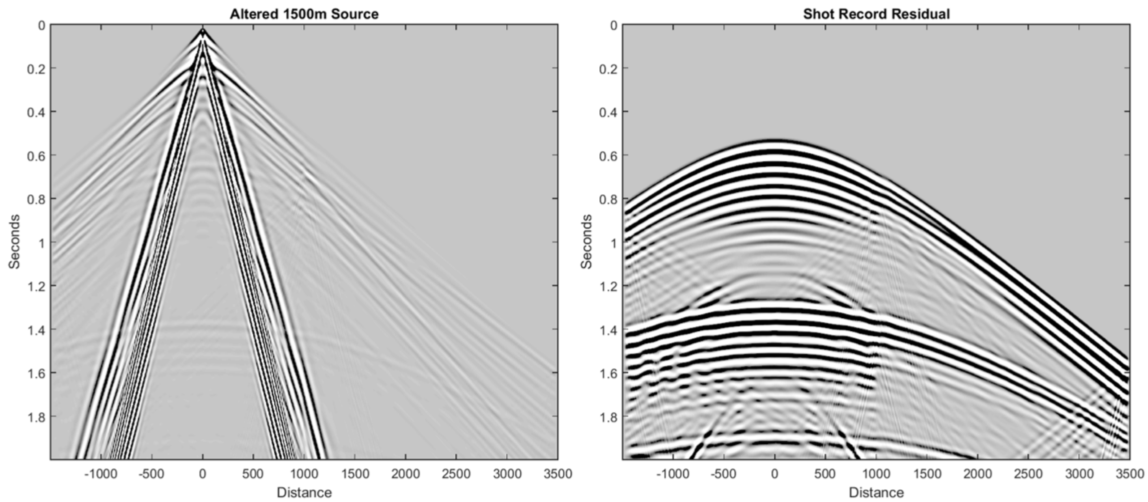

FIG. 15. Drg1: Left: Shot record with fourth layer thickness increased by 100m. Right: Residual between this shot record and the original model. $\|r\|_2 = 0.00030$.

SUMMARY

Model Name	Property Changes	r*r	$\|r\|_2$
Nsv1	Second layer Vs increased 100 m/s	9.15 E-06	0.00303
Nsv8	First layer Vs increased 50m/s	8.98 E-06	0.00300
Nsv7	First layer Vs decreased 50m/s	8.20 E-06	0.00286
Nsv10	Second layer Vs decreased by 100m/s	7.98 E-06	0.00283
Nsv4	Second layer Vs increased 50m/s	6.32 E-06	0.00251
Nsv3	Left side of second layer Vs increased 50m/s	6.31 E-06	0.00251
Nsv6	Second layer Vs decreased 50m/s	6.30 E-06	0.00251
Nsv2	Third layer Vs increased 100m/s	1.26 E-06	0.00112
Nsg2	Second layer thickness decreased 10m	1.19 E-06	0.00109
Nsg1	Second layer thickness increased 10m	6.22 E-07	0.00079
Drv3	Fourth layer Vs decreases 50m/s	1.13 E-07	0.00034
Drv2	Fourth layer Vs increased 50m/s	8.77 E-08	0.00030
Drg1	Fourth layer thickness increased 100m	1.18 E-08	0.00011

DISCUSSION

Starting with an initial geologic model and a simulated shot record over it, we have proceeded through altering its layer properties individually. At each alteration, another shot record was produced, and the residual (difference) between it and the original was calculated, and quantified with the ℓ_2 norm, $\|r\|_2$. The results show that changes closer to the free surface, and thus source and receivers, have a substantially greater effect on the resulting shot record than changes at depth. The effect on the residual is mostly impacted by the ground roll component of the shot record. This is due to the alterations being made in the near surface layers, which causes a difference in the propagation through these layers of ground roll, or Rayleigh waves, which have a much higher amplitude than reflections. The largest residuals are generated from velocity changes in the near surface, which change the propagation velocities of the ground roll. Moving layer boundaries closer to the free surface (decreasing layer thickness) has a greater effect on the residual than increasing this distance (increasing thickness). This is due to the Rayleigh waves interacting with a larger number of, or portion of near surface layers. From the models nsv4,3,6, and the relation between nsv1 and nsv10, we can see that increasing the layer velocity has a greater effect on the residual than decreasing it. This effect increases at increased velocity, but at and below around 50m/s, it appears that either an increase or decrease in Vs at the second layer depth has the same effect on the residual. Although changes at depth have a substantially smaller effect on the overall residual than near surface changes, at depth velocity alterations have a greater effect than model geometry changes.

The most impactful outcome from this study is that a minor change in the near surface has an effect on $\|r\|_2$ orders of magnitude greater than the same change made at depth. This shows the scale of influence a complex near surface has on seismic data targeting deeper structures. These results could be applied to guiding the perturbation of initial near surface velocity models in FWI, based on the ground roll component of residuals. For example, if it is observed that the ground roll velocities are higher in the data than in the model, then increasing near surface velocities would result in a smaller FWI residual. By comparing the scale of $\|r\|_2$ of the ground roll components at each iteration in FWI, we may be able to direct the model perturbation to preferentially alter the model velocities or geometry at appropriate depths.

CONCLUSIONS

In this paper, we have studied the effect that a change to velocity or geometry at one point in a geologic model has on the shot record residual. Through making incremental changes, we have built a catalogue of ℓ_2 norm, $\|r\|_2$, values associated with a particular alteration, and ranked these alterations in order of their $\|r\|_2$ magnitude. Velocity changes have the greatest effect on residuals, with this effect increasing with increased proximity to the free surface. Geometry changes, such as depth to boundaries and layer thicknesses have a lesser effect, but the residual is still apparent. We have shown that a minor change made in the near surface has an effect on $\|r\|_2$ orders of magnitude greater than the same change made at greater depth. This demonstrates the influence that a complex near surface can have on seismic data, and emphasizes the importance of understanding the near surface properties when attempting to build or perturb initial velocity models for FWI.

ACKNOWLEDGEMENTS

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