Pitfalls in seismic processing: An application of seismic modeling to investigate acquisition footprint

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Abstract

The term acquisition footprint is commonly used to define patterns in seismic time and horizon slices that are closely correlated to the acquisition geometry. Seismic attributes often exacerbate footprint artifacts and may pose pitfalls to the less experienced interpreter. Although removal of the acquisition footprint is the focus of considerable research, the sources of such artifact acquisition footprint are less commonly discussed or illustrated. Based on real data examples, we have hypothesized possible causes of footprint occurrence and created them through synthetic prestack modeling. Then, we processed these models using the same workflows used for the real data. Computation of geometric attributes from the migrated synthetics found the same footprint artifacts as the real data. These models showed that acquisition footprint could be caused by residual ground roll, inaccurate velocities, and far-offset migration stretch. With this understanding, we have examined the real seismic data volume and found that the key cause of acquisition footprint was inaccurate velocity analysis.

Introduction

Acquisition and processing procedures can greatly affect the reliability of seismic data leading to the occurrence of the acquisition footprint. The term acquisition footprint refers to the imprint of acquisition geometry on the seismic amplitude time and horizon slices. An acquisition footprint can obstruct not only classical seismic interpretation but it can also affect interpretation based on seismic attributes (Marfurt et al., 1998; Marfurt and Alves, 2014). Seismic attributes, especially coherence and curvature, often exacerbate the effect of acquisition footprint, masking the more subtle underlying faults and fractures, thus making their effectiveness diminish. Seismic attributes are a popular method to accelerate interpretations. Acquisition footprint on such volumes can lead to pitfalls by less experienced interpreters (Marfurt and Alves, 2014; Verma et al., 2014).

Although acquisition footprint is a common problem, its occurrence and formation are often poorly understood (Chopra and Larsen, 2000). Although several methodologies have been proposed to remove linear coherent noise and acquisition footprint (Marfurt et al., 1998; Cvetkovic et al., 2008), little has been done in the way of illustrating its occurrence via seismic modeling with one exception being Hill et al.'s (1999) analysis of acquisition footprint caused by inaccurately picked normal moveout (NMO) velocities. Furthermore, although it is accepted that ground roll is one of the prime causes of acquisition footprint, the footprint pattern caused by the presence of ground roll has not been modeled and documented. Seismic modeling can be an invaluable tool in evaluating alternative seismic processing procedures, with a particular emphasis on the calibration of tomographic analysis, migration, and full-waveform inversion algorithms. In a recent example, Ha (2015) uses seismic modeling in an attempt to better understand the response of a fractured granitic basement. He uses elastic modeling to identify coherent seismic noise, such as ground roll and reverberating refractions that masked his shallow basement target. With the insight gained from seismic modeling, he is able to better identify and eliminate coherent noise during seismic processing.

We hypothesize that there are three main factors that cause acquisition footprint: (1) coherent noise that is not attenuated when stacked; (2) factors that affect the flatness of reflectors on gathers, such as velocity analysis and NMO or migration stretch; and (3) amplitude anomalies. However, amplitude anomaly affects are not examined here.

We are able to make an analog between the responses seen in the stacked prestack Kirchhoff time-migrated modeled seismic data set and that seen in the stacked prestack Kirchhoff time-migrated real

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seismic data set. Using seismic models, we are able to better understand how common pitfalls in processing steps can generate acquisition footprint and affect the subsequent geologic interpretation.

We begin by laying forth the motivation of this study. We describe the acquisition footprint observed on the real seismic data and hypothesize three possible sources. We then tested these hypotheses, generating prestack synthetic gathers via seismic modeling. We analyzed the generated synthetics using seismic attributes for the different hypotheses to decide which is most likely.

Motivation

Upon reprocessing the 3D legacy seismic Jean survey (Figure 1) in the Fort Worth Basin with a conventional workflow, Cahoj (2015) realizes undulating features in the shallow section after stacking and computing seismic attributes (Figures 2 and 3). Although these features appeared to be geologic suggesting karst or collapse structures in the Palo Pinto Limestone, they did not match the a priori geologic model confirmed by hundreds of wells in the adjacent area drilled over five decades of oil and gas exploration. This led us to conclude that the cause of these interpretation artifacts was due to errors in processing giving rise to acquisition footprint due to the relatively shallow depth of the target and the low fold of the 1995 vintage survey.

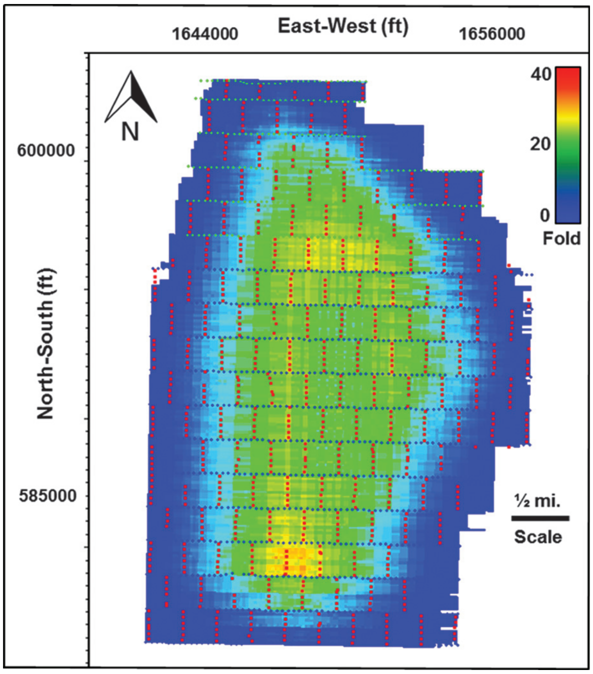

Figure 1. Acquisition geometry of the Jean survey overlain on a fold map. Sources are red and receivers are blue and green. The green receivers are those turned on for the current shot or patch. The nominal fold of the survey is 17 with a maximum fold of 36 using 33.5 × 33.5m (110 × 110 ft) bin size. The Jean survey acquisition geometry is used for generating the 3D models used for investigating the occurrence of acquisition footprint.

We hypothesize that this acquisition footprint has three potential sources:

1) improper velocity analysis causing the reflectors to be under/over corrected
2) far-offset stretching of the wavelet caused by NMO and migration
3) inadequate removal of ground roll by f-k filtering.

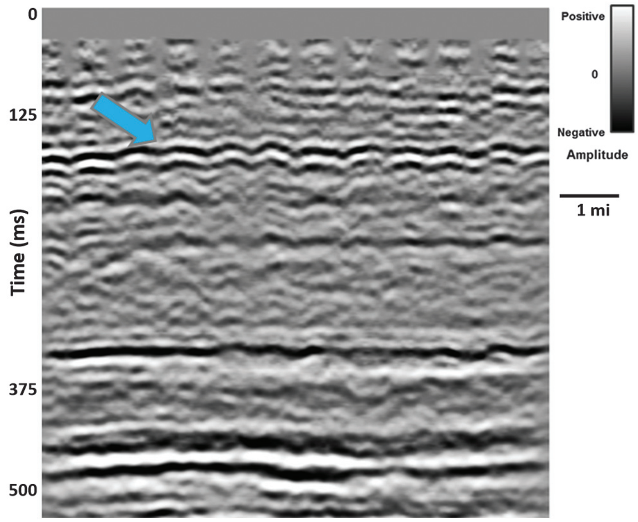

Figure 2. Stacked prestack time Kirchhoff migrated real seismic data set. Note the undulations in the shallow section (blue arrow) that could easily be mistaken for geology.

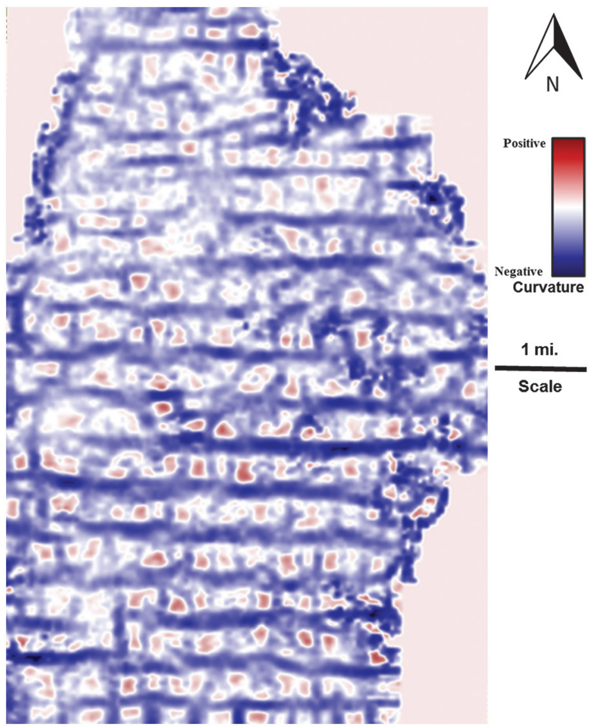

Figure 3. Most negative curvature time slice at $t = 420$ ms through seismic data (courtesy of TameCat LLC.) acquired over the north Texas Jean survey. We see strong acquisition footprint, aligning with the receiver and shot lines shown in Figure 1.

We generate a 3D model with the geometry of the Jean survey (Figure 1) to evaluate these three potential sources of footprint.

Methodology

Seismic acquisition template

The acquisition and processing flow for the real Jean survey is done using a conventional workflow for 3D land seismic surveys. The acquisition geometry and fold coverage for the Jean survey is shown in Figure 1 and exhibits a relatively low fold with the nominal fold of 17 with a bin size of 33.5×33.5 m (110×110 ft). The source and receiver spacing is 67 m (220 ft) with 5 kg dynamite sources buried at 24.3 m (80 ft). This acquisition array was the same used for generating the 3D models for investigating the source of acquisition footprint.

Seismic modeling

Full-wave equation elastic modeling is significantly more computationally expensive than prestack depth migration, limiting its use for problems like ours. However, simpler models often answer questions of interest. Because our objective is to understand how noise leaks into seismic data to cause acquisition footprint, we do not need to provide any structural complexity. Instead, we generate a simple layer cake elastic model that includes P-, S-, and converted Rayleigh waves, which provides an impulse response (Green's function) that we can move laterally across the survey. Mechanically, we take a source-receiver pair described by the headers plotted in Figure 1, compute the offset, and extract the appropriate trace, thereby generating a 3D synthetic survey.

The objective of this model is to see how processing procedures affect stacked seismic data after migration and its relation with reflectors. Our impulse response was created from two different models with the real seismic data's acquisition array. The first model has no ground roll and consists of four isotropic layers. The four interval's velocities were extracted from a P-wave sonic well log within the survey. The S-wave velocity was computed from P-wave velocity by assuming a constant Poisson's ratio of 0.25 for all the layers, whereas density was estimated using Gardner's

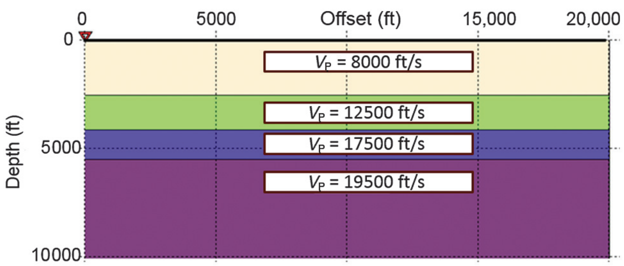

Figure 4. Acoustic model built from a p-sonic well log within the Jean survey to approximate the seismic reflection response within the study area.

equation. Figure 4 shows the geologic model used to generate the seismic reflection model. This model was used for studying velocity analysis and the far-offset stretch effect.

A second model was used to create the near-surface ground roll response. The dispersive ground roll was generated using an elastic model with four thin layers in the shallow section increasing in velocity with depth (Figure 5). The seismic response of this model was bandlimited (0–25 Hz) to match the frequency content of ground roll in the real seismic survey. The impulse responses of the two models (Figures 4 and 5) were added to form a synthetic subjected to subsequent *f-k* filtering, ground roll removal, and velocity analysis.

Model processing

The models were processed using similar workflows as the real seismic data set. In the first case, we investigate the effects of velocity analysis and far-offset stretching. The seismic processing for velocity analysis can be broken into the following six steps:

1) import the synthetic seismic data
2) define the geometry
3) perform velocity analysis
4) generate a 3D velocity volume
5) perform prestack Kirchhoff time migration and stack the synthetic data
6) compute geometric attributes.

Figure 6 shows the raw synthetic seismic data sorted in shot versus absolute offset, clearly showing the three hyperbolic reflectors. Figure 7a shows the velocity picks, and Figure 7b shows the corresponding NMO

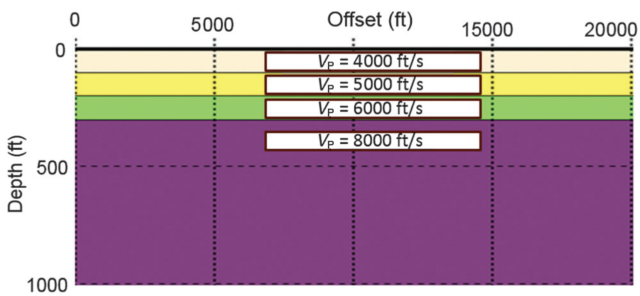

Figure 5. Elastic model built to generate ground roll similar to that seen within the Jean survey.

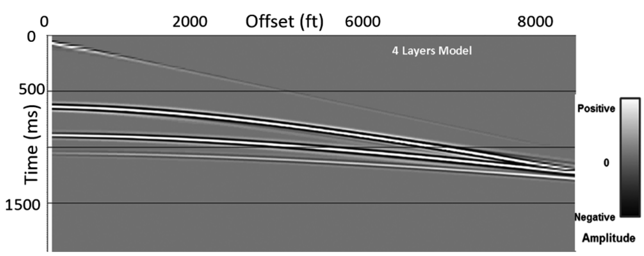

Figure 6. Three reflectors generated from the acoustic model sorted by absolute source-receiver offset.

corrected gather of the picked semblances (in white). In this figure, we have picked the velocities used to generate the synthetic on the semblance panel resulting in flattened reflectors. We picked the velocities on the semblance panel to be 5% too fast for the first reflector resulting in an undercorrection. Figure 7d is the associated gather. In Figure 7e, we have selected the semblances to be 5% too slow in the first reflector resulting in an overcorrection (Figure 7f). After velocity analysis, we prestack Kirchhoff time migration and stack these synthetic seismic models.

In the second model, we attempt to remove ground roll and other coherent seismic noise by f-k filtering. The seismic processing for removing ground roll can be broken into the following seven steps:

1) import the synthetic seismic data
2) define the geometry
3) window the noise with a mute and finding its linear moveout velocity
4) model the muted noise in the f-k domain
5) inverse linear moveout and subtract the f-k modeled noise
6) perform prestack Kirchhoff time migration and stack the synthetic data
7) compute geometric attributes.

Figure 8a shows the synthetic model sorted by shot versus absolute offset. Low-frequency, high-amplitude ground roll crosscut and mask the underlying reflectors based on their different moveouts. Figure 8b shows the ground roll modeled by a standard f-k filtering

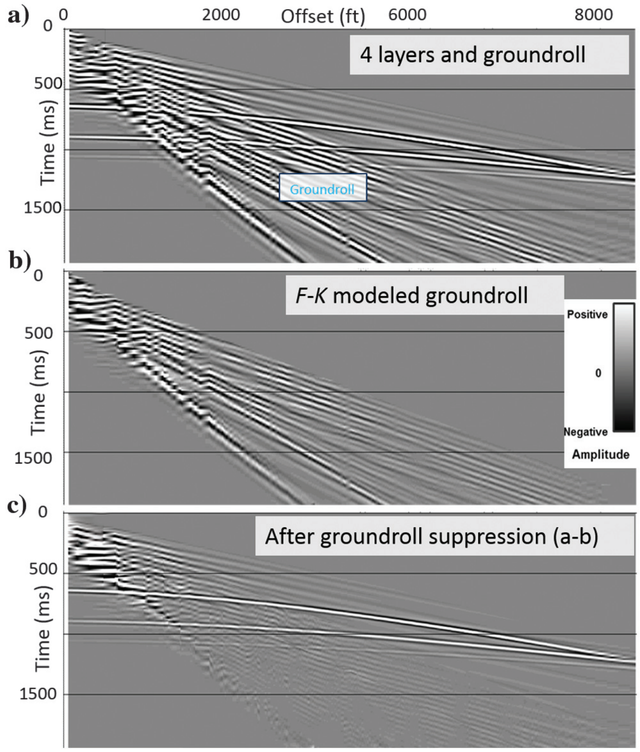

Figure 8. (a) Four-layer model plus ground roll. (b) f-k modeled ground roll to be subtracted from panel (a). (c) Result of subtracting panel (b) f-k modeled ground roll from panel (a) four-layer model with ground roll. We can observe that most of the coherent noise crosscutting the seismic reflectors have been removed leaving only some residual noise in the shallow section.

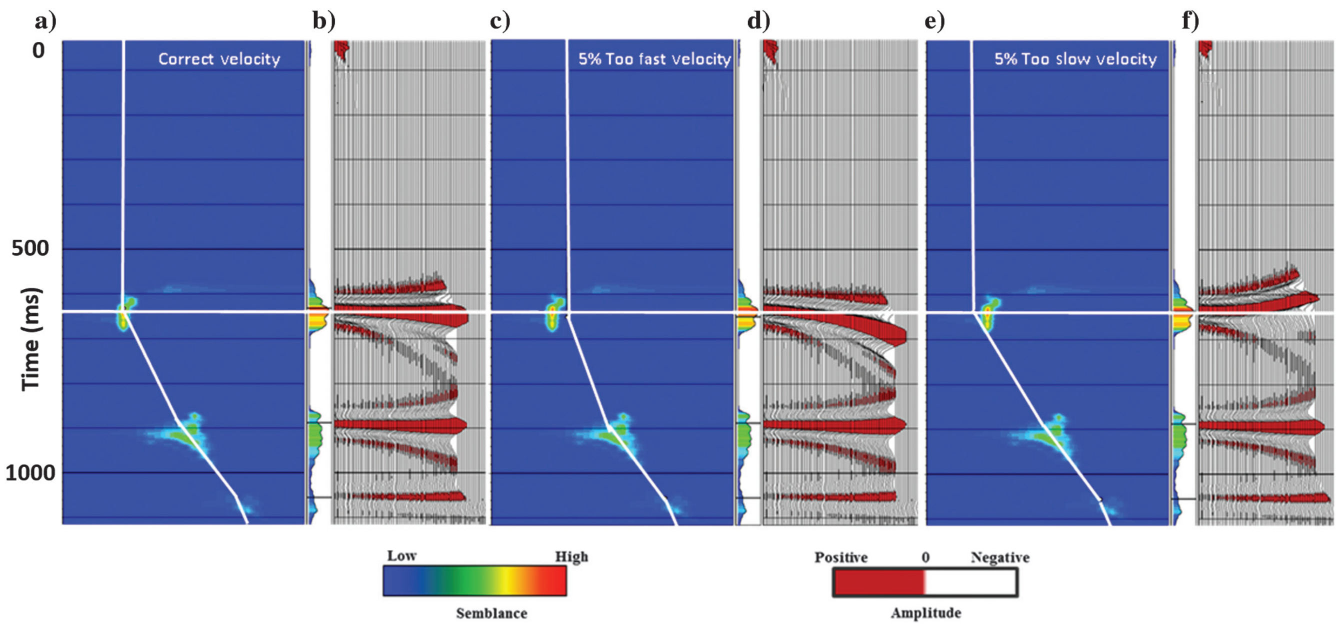

Figure 7. (a) Semblance panel with correct velocities picked by processor (white line) (b) and its corresponding NMO corrected gather. (c) Semblance panel with velocity picked 5% too fast for the first reflector and (d) its corresponding NMO correct gather. The result in the gather is an undercorrection. (e) Semblance panel with velocity picked 5% too slow for the first reflector and its corresponding NMO correct gather. The result is an overcorrection as seen in panel (f). The velocities shown in the above image were used for subsequent prestack time Kirchhoff migration.

procedure. Figure 8c shows the results after the modeled ground roll is subtracted from the input model. In this figure, we see that most of the high-amplitude ground roll has been removed and the reflectors, once overprinted, are now visible. Upon partial ground roll removal through use of f-k filtering, the synthetic data were prestack Kirchhoff time migrated and stacked (Figures 9 and 10). Artifacts are created due to inadequate f-k filtering.

Attribute computation

After processing and prestack Kirchhoff time migration, we computed a suite of seismic attributes on the modeled synthetic seismic data and the actual seismic data. Such attributes included dip and azimuth, energy ratio similarity, and structural curvature (Figure 10). With these attributes, we were able to determine the footprint's response from improperly removed ground roll, improper velocity analysis, and far-offset stretching. Seismic attributes were computed over the synthetic data without any ground roll, using the correct velocity to offer an artifact-free data set to serve as a baseline for comparison. Using the modeled seismic data, we were able to make an analog to the actual seismic data to compare inadequacies in the processing procedures response and how it could affect subsequent interpretation. Due to the fact that our model was made with flat layers to simplify the geology, we flattened the real data set on a shallow geologic horizon before we computed attributes. Furthermore, by flattening we ensure that artifacts remain in plane when we take a time slice through the attribute volume. Figure 11 is a time structure map of the horizon used to flatten the seismic survey. The acquisition footprint imprint on the geologic horizon can be` seen (gray arrow).

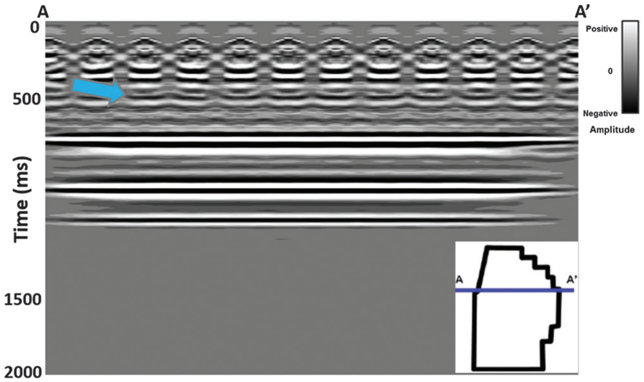

Figure 9. Stacked prestack time Kirchhoff migrated four-layer synthetic model with residual ground roll from f-k filtering. The result is undulations and an appearance of a reflector in the shallow section above the first reflector.

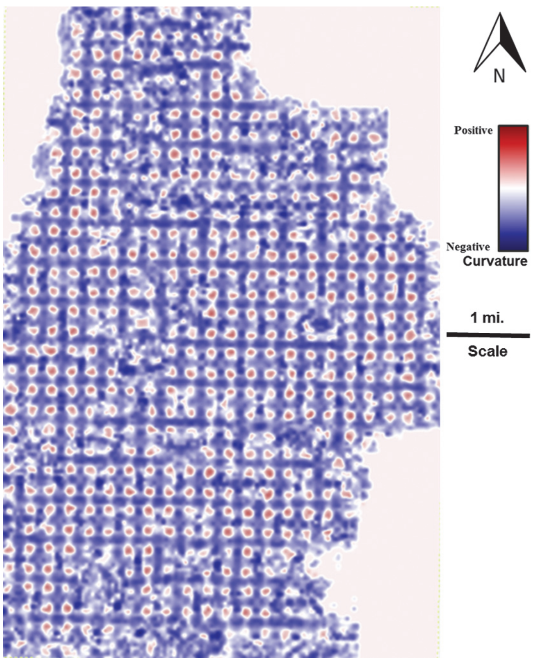

Figure 10. Most negative curvature time slice at $t = 420$ ms through the four-layer model with ground roll not properly removed by f-k filtering. We see strong acquisition footprint present that does not seem to align with either shot or receiver lines.

Results

Correct velocity, no ground roll — "Ideal model"

Figure 12 shows a vertical section through the stacked synthetic seismic data after prestack Kirchhoff time migration without any ground roll and the correct velocity chosen to flatten the reflectors. The result is

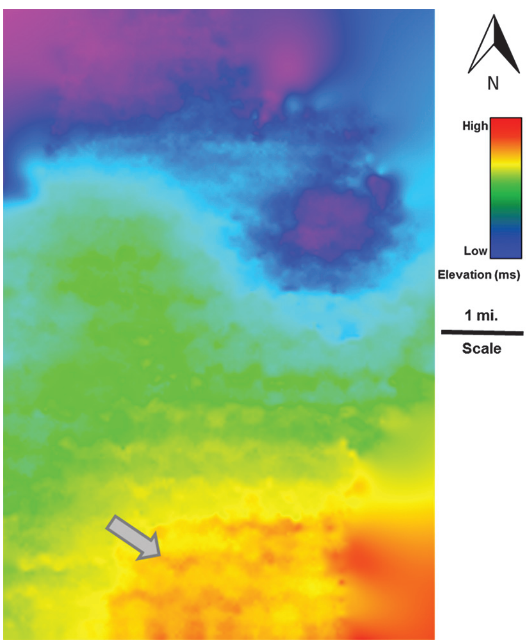

Figure 11. Horizon tracked through the real seismic data set in the shallow section of the Jean survey. Before attribute computation of the real data, the seismic survey was flattened with respect to this survey to mitigate any effects of geology. This allowed for acquisition footprint to remain in plane, while visualizing the intersection of time slices. The gray arrow highlights the effect of acquisition footprint on conventional interpretation utilities, such as horizon tracking.

three flattened reflectors that are not contaminated by artifacts. We can further examine the "ideal model using seismic attributes. Figure 13 is a time slice at $t = 616$ ms through most negative curvature. The strong patterns associated with acquisition footprint are subtle suggesting the ideal model serves as an accurate baseline for further investigation. Some small nuances in the curvature values do appear, which we attribute to small misalignments due to Snell's law that are only approximated by hyperbolic moveout.

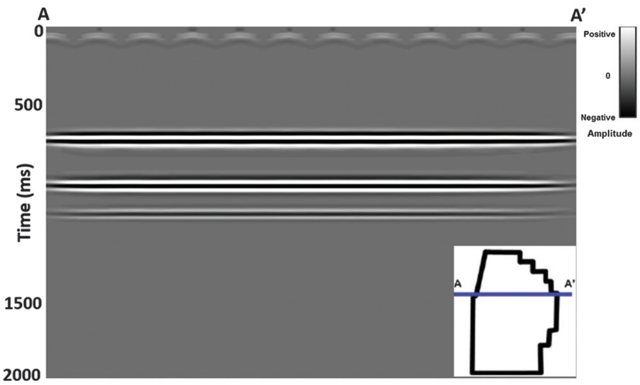

Figure 12. Four-layer synthetic model with correct velocities chosen and no ground roll serving as the ideal case to serve as a baseline for further investigation.

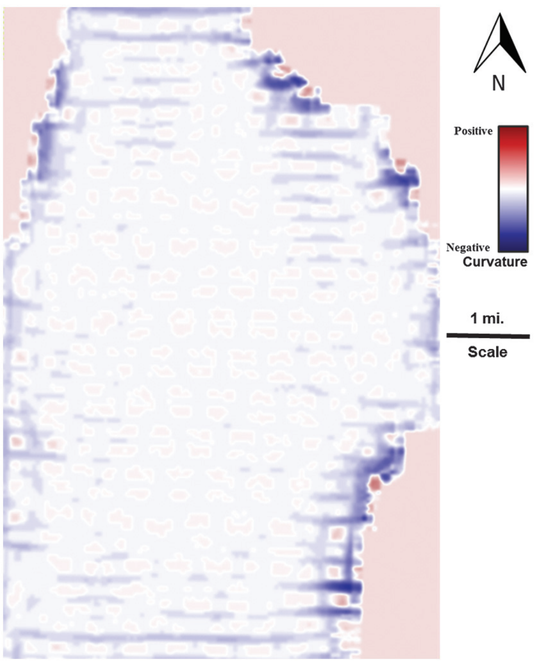

Figure 13. Most negative curvature time slice at $t = 616$ ms through the four-layer model with no ground roll and the correct velocity picked by the processor. We see that there is no acquisition footprint present although some small nuances in the curvature values do appear. This is probably due to irregularities in the survey design or inherent to the curvature attribute.

Far-offset stretch

Figure 14 shows a vertical section of the stacked synthetic seismic data after prestack Kirchhoff time migration without any ground roll and the correct velocity chosen to flatten the reflectors. However, in this model, we intentionally selected an improper prestack mute on the migrated gathers. This mute result in far-offset stretch is not being properly removed. Upon stacking the data, we see the destruction of high frequencies in the first reflector (blue arrow) when compared with the ideal model (Figure 12).

Inaccurate velocity analysis

In our next perturbation, we intentionally pick seismic velocities that are 5% too fast and 5% too slow, resulting in an under- and overcorrection, respectively.

Figure 15 shows a vertical section of the stacked synthetic seismic data after prestack Kirchhoff time migration with the velocity intentionally picked 5% too fast. We can see quasi-hyperbolic artifacts caused by the constructive and destructive interference of reflectors not properly flattened during velocity analysis. The blue arrow points to the artifacts on reflector 1. However, the most identifiable feature in the stacked section is the loss of frequency content in the first reflector when compared with the ideal model. This inline is constructed from the velocity panel and NMO corrected gather shown in Figure 7c and 7d. Figure 16 shows a time slice at $t = 616$ ms through most negative curvature. We see a weak curvature anomaly aligning with the receiver lines.

Figure 17 shows a vertical section of the stacked synthetic seismic data after prestack Kirchhoff time migration with the velocity intentionally picked 5% too slow. The quasi-hyperbolic artifacts caused by the constructive and destructive interference of interfaces not properly flattened during velocity analysis. These are similar to the case with the velocity picked 5% too fast,

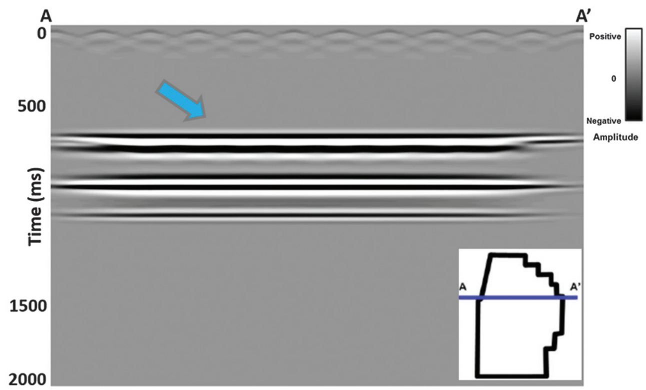

Figure 14. Stacked prestack time Kirchhoff migrated four-layer synthetic model with correct velocities and no ground roll. However, an inadequate prestack mute was applied to the prestack migrated data leaving the far-offset stretching of the wavelet not being removed. The result in the stacked section is a loss of frequency content around reflector one (blue arrow).

however more pronounced. The blue arrow points to the artifacts on reflector 1. This inline is constructed from the velocity panel and NMO corrected gather shown in Figure 7e and 7f. Figure 18 shows a time slice at $t = 616$ ms through most negative curvature. We see a strong curvature anomaly aligning with the receiver and shot lines.

It is important to note that it is unlikely, although possible, that the seismic processor would incorrectly pick the velocities from semblance analysis to be wrong for the entire 3D seismic survey in the systematic way that we did for this experiment.

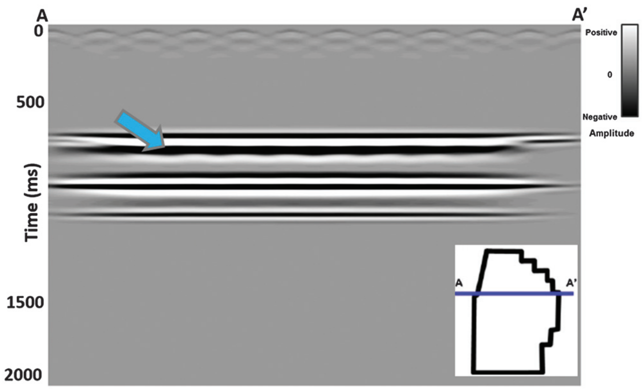

Figure 15. Stacked prestack time Kirchhoff migrated four-layer synthetic model with velocities intentionally picked 5% too fast for the first reflector, resulting in an overcorrection. The result is, similar to an improper stretch mute, a loss of high frequencies. The blue arrow indicates a slight undulation forming in the lower trough of the reflector.

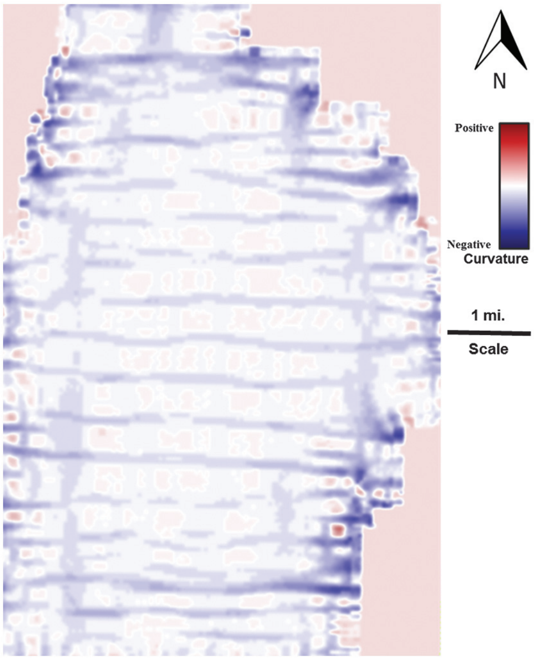

Figure 16. Most negative curvature time slice at $t = 616$ ms through the four-layer model with the velocity picked 5% too fast by the processor. We see weak acquisition footprint, aligning with the receiver lines.

Ground roll

In this section, we show the results of the model with ground roll that was not properly removed by f-k filtering. Figure 9 shows a vertical section of the stacked synthetic seismic data after prestack Kirchhoff

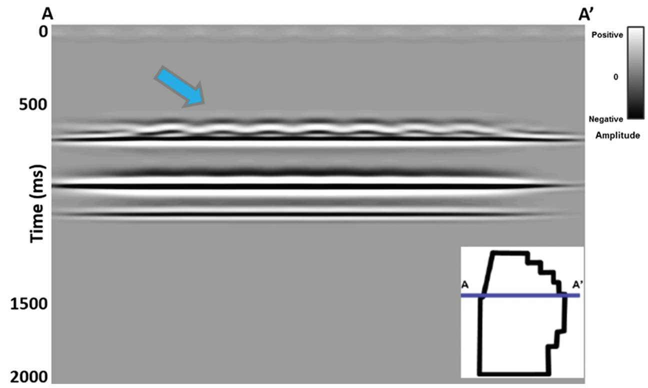

Figure 17. Stacked prestack time Kirchhoff migrated four-layer synthetic model with velocities intentionally picked 5% too slow for the first reflector, resulting in an undercorrection. The result is undulations on the top of the first reflector similar to those seen on the real seismic data. The blue arrow indicates strong undulations forming on the top of the reflector.

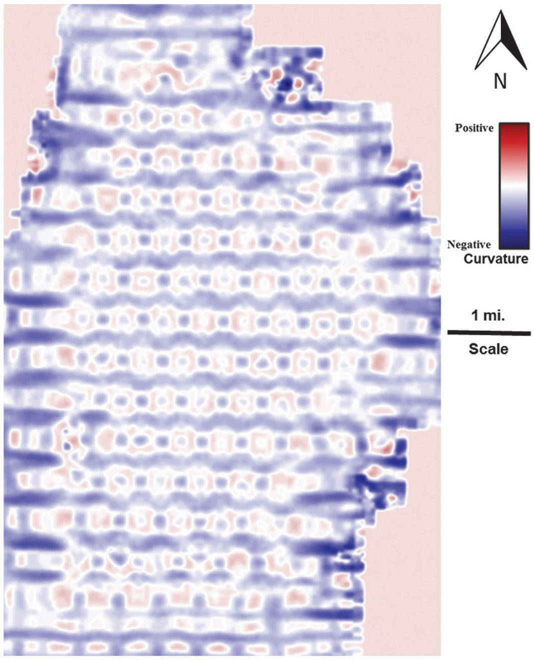

Figure 18. Most negative curvature time slice at $t = 616$ ms through the four-layer model with the velocity picked 5% too slow by the processor. We see strong acquisition footprint aligning with the receivers and shot lines.

time migration. It is evident that the interferences of out of plane, therefore hyperbolic, ground roll can result in the appearance of a piecewise continuous flat reflectors after Kirchhoff time migration (blue arrow). Figure 10 shows a time slice at $t = 420$ ms through the most negative curvature volume. We find that the response of curvature, an attribute used to quantify the morphology of a surface, is greatly contaminated by the inadequately removed ground roll. Although the time slice has a strong most negative curvature anomaly, it does not appear to align with the source of receiver lines, as well as that associated with velocity analysis sourced acquisition footprint.

Real seismic data

Figure 2 shows a vertical section of the stacked real seismic data after prestack Kirchhoff time migration. Undulatory patterns in the shallow section are strong (blue arrow). Figure 3 shows a time slice at $t = 420$ ms through most negative curvature of the real seismic data. Most negative curvature anomalies are visible aligning with the source and receiver lines.

Conclusions

Our analysis indicates that velocity analysis, not removing NMO stretching and residual ground roll can cause artifacts to be present on the seismic. These artifacts can often look geologic and can hinder classical and attribute interpretations.

Not adequately removing ground roll using f-k filtering can result in the appearance of artificial flat reflectors after migration caused by constructive and destructive interference of the hyperbolic events thrown on an ellipse by the Kirchhoff operator. This could lead to erroneous interpretations and difficulties in well to seismic ties. Artifacts caused by residual ground roll will have the strongest amplitude near to zero offset and attenuate with distance. However, by analyzing the stacked section and attribute volumes, it does not appear that artifacts caused by ground roll have a similar appearance as those seen in the real seismic data.

While looking at a vertical section, it appears that our real seismic data set suffers from NMO velocities picked to be too slow. This can be seen as the undulations in the shallow sections that could be interpreted as karst features or pock marks. By further analysis using structural curvature, it appears that either velocity analysis error could result in the features seen in the real seismic data. Combining the conventional and attribute interpretation of the model leads us toward the conclusion that picking velocities too slow may be the source of our footprint in the real data set. However, inaccurate velocity analysis will only display features within the interval that the velocity is mispicked. Picking a correct velocity in the vertically adjacent section will result in reflectors with no artifacts.

Finally, it is important to note that seismic attributes, often used by less experienced interpreters to accelerate their interpretations, are not immune to acquisition footprint and in many cases seismic attributes exacerbate the effects of this noise.

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