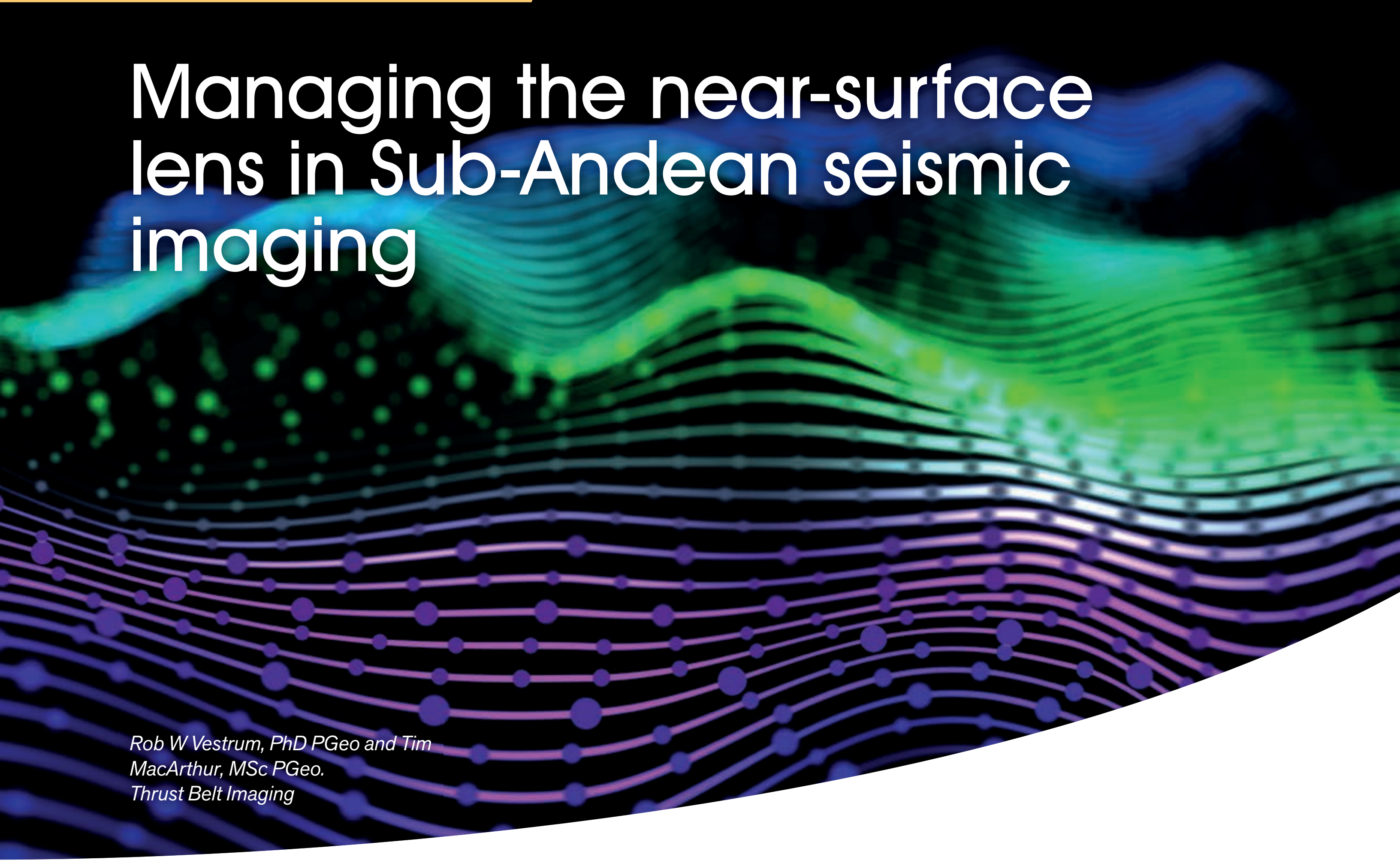
Managing the near-surface lens in Sub-Andean seismic imaging



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Thrust Belt Imaging

Abstract

In structurally complex environments such as the Andes Mountains and foothills, outcropping rocks and differential weathering generate significant variations in near-surface seismic velocities. In time processing, these fluctuations are corrected through weathering statics, which minimize the time delays caused by variations in near-surface velocities associated with weathering. These statics are calculated using first-break energy on shot records (refraction statics), followed by statics derived from the correlation of seismic reflectors (reflection statics).

Correcting near-surface velocity variations through static shifts assumes vertical raypaths through the weathering layer. However, this approximation is no longer valid when high-velocity rocks crop out at the surface.

Seismic imaging in the depth domain provides an opportunity to incorporate refraction velocities derived from first breaks into the PSDM velocity model and to ray trace through low-velocity layers, allowing a more accurate correction for near-surface velocity variations. The refraction solution represents only part of the complete weathering correction, which is typically followed by a pass of reflection statics. During our testing, we found that the reflection statics used in time processing needed to be replaced with depth-domain reflection statics to develop a complete weathering solution for depth imaging.

Before calculating reflection statics, moveout curvature must be corrected. An offset moveout correction, inherently coupled to the PSDM velocity model, provides a complete depth weathering solution (DWS).

We developed a methodology in which all weathering statics from time processing are discarded and all near-surface velocity corrections, including reflection statics, are performed in the depth domain. This workflow was applied to 2D and 3D datasets

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acquired in the Andean foothills and resulted in significant imaging improvements beneath the mountainous portions of the seismic surveys.

Introduction

Seismic data acquired in onshore geological settings are recorded over rugged topography and in areas with significant velocity variations immediately beneath the acquisition surface. The near surface acts as a lens through which the subsurface is imaged; therefore, a better understanding of its effects provides an opportunity to improve corrections for near-surface velocity variations during seismic imaging.

Prestack depth migration (PSDM) offers the possibility of incorporating a greater amount of near-surface velocity information, thereby improving the imaging of subsurface structures. The DWS workflow resulted in enhanced reflector continuity and coherency across several sub-Andean basins.

Weathering velocities in the PSDM velocity model

Velocities derived from first-arrival tomography have proven useful for calculating weathering statics in seismic processing (Lawton, 1989; Cox, 1999; Yilmaz, 2001; Becerra et al., 2009), and there is an opportunity to make better use of this velocity information. By moving beyond the assumptions inherent in time statics, it becomes possible to incorporate deeper portions of the near-surface model and use velocities that are significantly higher than the weathering velocities typically employed in statics calculations.

The initial objective was to remove refraction statics from the input shot gathers and correct for near-surface low-velocity variations by incorporating refraction velocities directly into the PSDM velocity model. However, simply replacing refraction statics with refraction velocities produced mixed results and, in some cases, degraded the seismic image.

One of the test datasets consisted of a 2D line from the Llanos foothills presented by MacArthur et al. (2022). This dataset clearly demonstrates the degradation in image quality resulting from the simple substitution of refraction velocities for refraction statics. Figure 1a shows a PSDM image generated using the traditional workflow, in which time-processing statics were applied prior to migration. When the refraction velocities were incorporated into the PSDM velocity model and the refraction statics were removed from the input data, the resulting image (Figure 1b) exhibited reduced reflector coherency, particularly within the shallow section.

Reflection statics are calculated using seismic data that already have refraction statics applied. Consequently, once refraction statics are replaced by refraction velocities, the inaccuracies associated with the refraction solution change, either positively or negatively. This creates the need for a new method to calculate reflection statics that is fully coupled with the revised refraction approach.

The complete weathering solution in time processing consists of the sum of refraction statics and reflection statics. Therefore, the next step in replacing the conventional time-domain weathering solution was to replace the reflection statics as well, using the model-based moveout technique proposed by Ellison (2018). This example highlights the im-

(a)

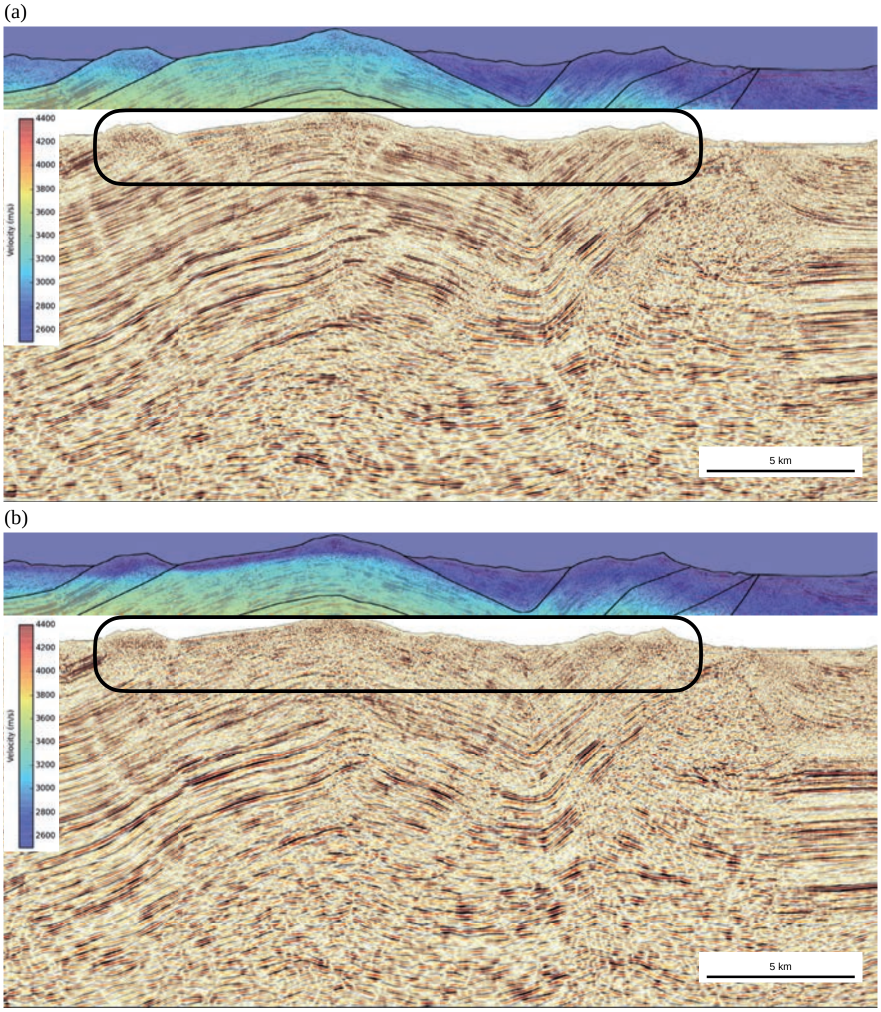


__Figure 1.__ Prestack depth migration of a 2D seismic line with (a) the refraction and reflection statics from time processing applied on input and (b) the refraction velocities in the PSDM velocity model and the reflection statics from time processing applied to the input. The velocity overlay above each section illustrates the differences in velocities with (b) and without (a) the refraction velocities in the model. The boxes indicate the greatest difference between the two seismic images: the degradation of imaging in the shallow section on (b).

portance of calculating reflection statics that are directly coupled to the depth-migration velocity model.

Reflection statics in the depth domain

An essential ingredient in the calculation of reflection statics is the moveout correction. As shown above, in time processing, moveout is corrected using NMO, which relies on the NMO equation and moveout velocities to flatten CMP gathers. The NMO calculation and its associated moveout velocities are based on the hyperbolic assumption and are inherently coupled to the time-processing workflow (Ellison, 2018; MacArthur et al., 2022; Beck et al., 2025). The depth-domain alternative to NMO is model moveout (MMO), which uses travel times from the PSDM velocity model to calculate the moveout correction.

	TWS	DWS
Refraction	statics from first-arrival tomography	velocities from first-arrival tomography
Reflection	statics from cross-correlation of NMO gathers	statics from cross-correlation of MMO gathers

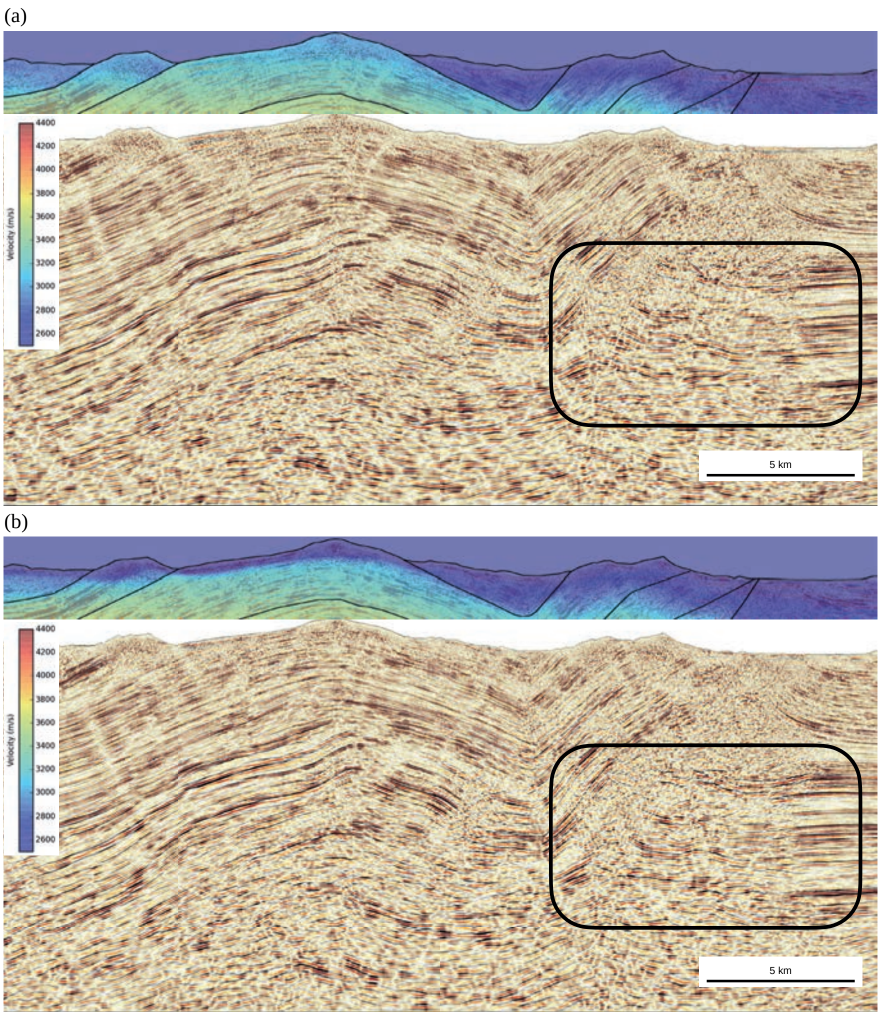


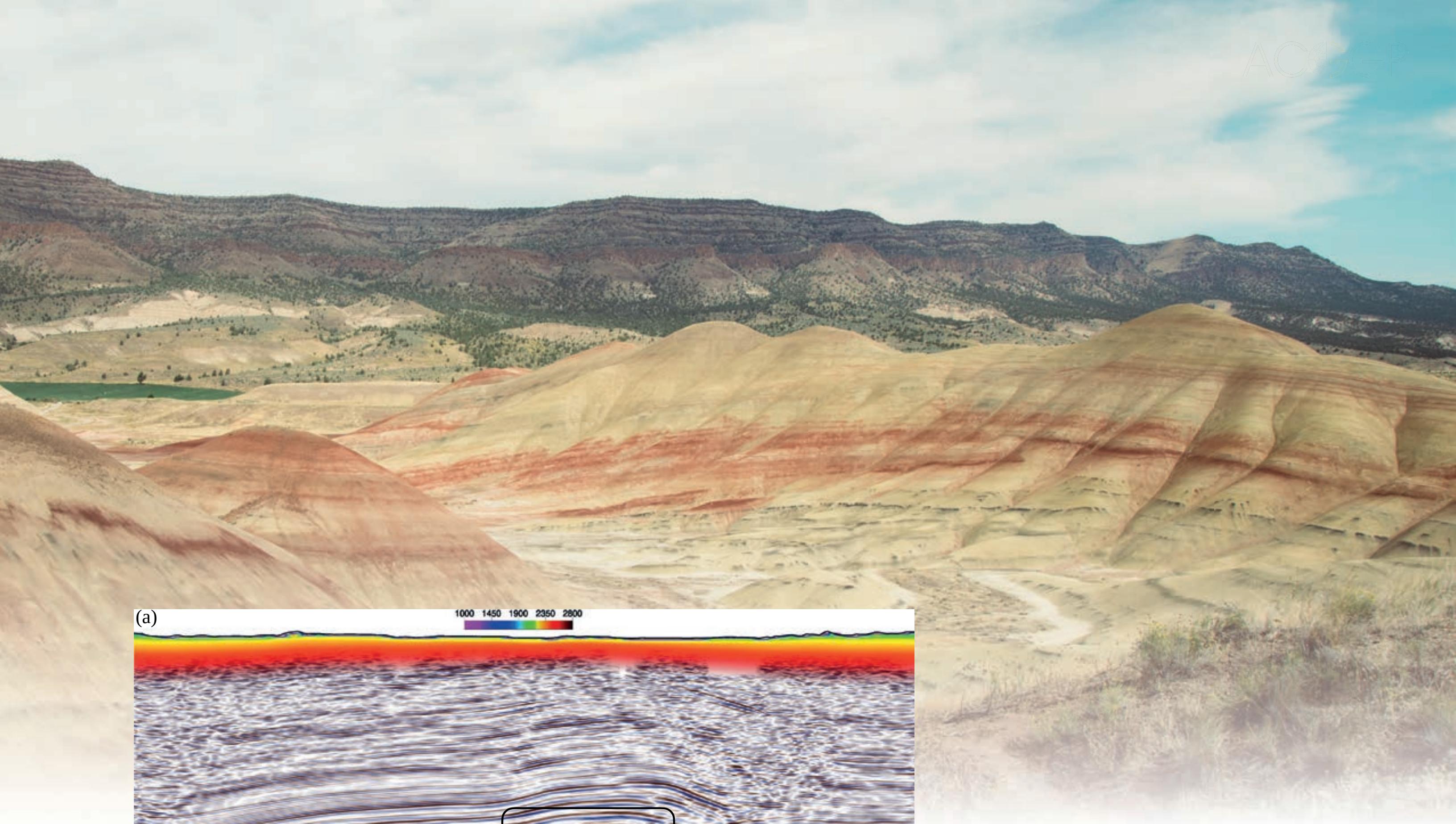
__Figure 2.__ Prestack depth migration of a 2D seismic line (a) with the time weathering solution applied and (b) with the full depth weathering solution applied. The velocity overlay above each section illustrates the differences in near-surface velocities. The boxes highlight the reflectors in the footwall of the overthrust, which show improved reflector coherency and sharper truncations on (b).

Figure 2 shows PSDM images generated using the time weathering solution (TWS) (Figure 2a) and the depth weathering solution (DWS) (Figure 2b). Note that the workflows used to create these two images are identical. The only difference between the two velocity models lies in the low-velocity layer of the shallow section. The table below describes the differences between the two PSDM images.

Including MMO reflection statics in the DWS solution resolved the shortcomings observed in the shallow section of the PSDM image (Figure 1) and resulted in improved imaging of the thrust footwall compared to the TWS solution (Figure 2).

3D data example

Optimized for three-dimensional imaging of subsurface targets, 3D seismic surveys on land have lower data density in the near surface than the single-azimuth acquisition of 2D seismic data (Vestrum & Gittins, 2009). With lower-density coverage in the near surface, weathering corrections for 3D surveys often rely more heavily on reflection statics than those for 2D seismic data.



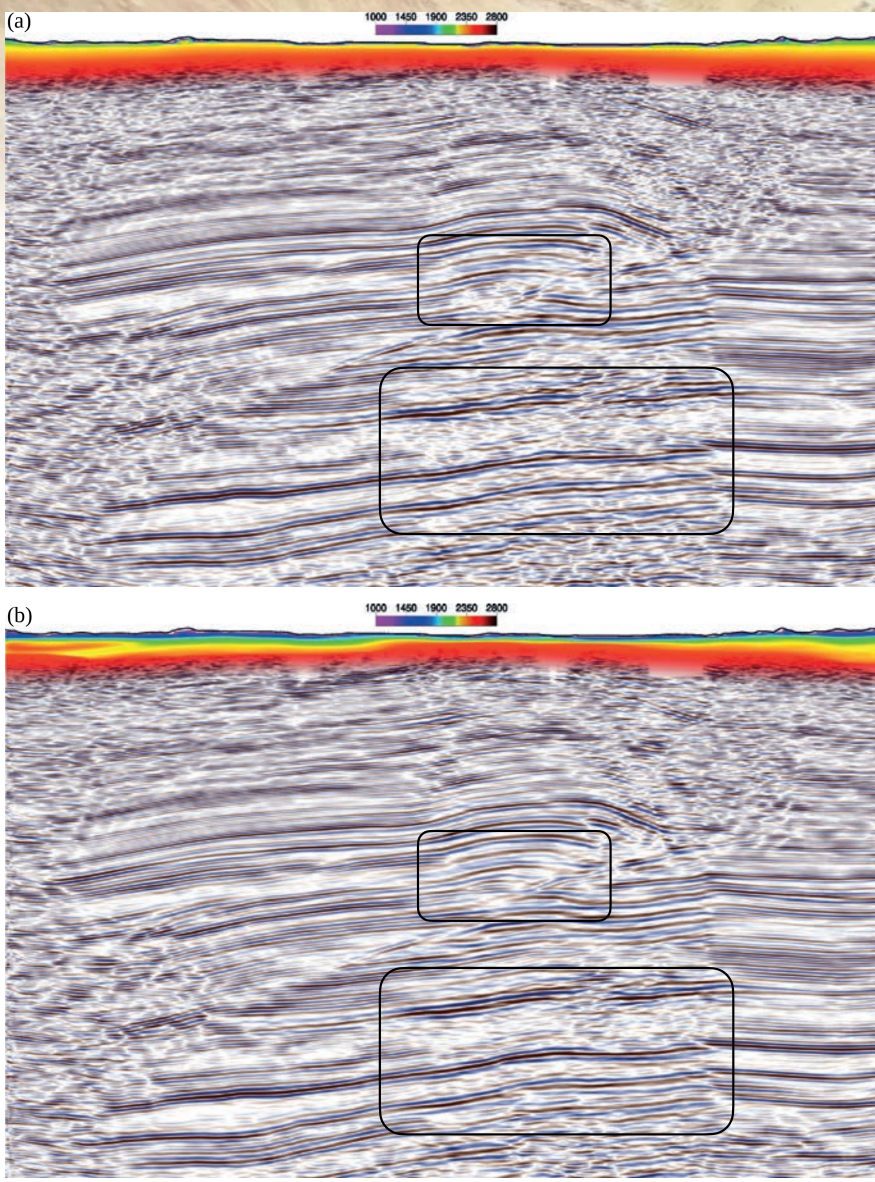


Figure 3. *Inline A near the centre of a 3D PSDM volume with (a) time weathering solution applied and (b) depth weathering solution applied. The velocity overlay near the top of the inline slice shows the shallow velocities in each velocity model. Boxes indicate key differences in imaging between the TWS and DWS versions.*

Figure 3 shows comparisons between TWS and DWS depth images from a 3D survey in the foothills of the Andes. This inline is from the central part of the 3D survey and exhibits strong reflectivity throughout. The small box in this comparison shows improved structural detail and fault-plane imaging in the DWS image (Figure 3b), compared to the TWS result (Figure 3a). The larger box shows overall improved reflector coherency of subthrust reflector:

Figure 4 shows an inline near the edge of the survey that struggles with decreased fold and increased structural complexity subthrust. The DWS (Figure 4a) shows more differences compared to the TWS (Figure 4b), with significantly improved reflector coherency in the foreland reflectors within the tall box on the right side of each image. The central box in this comparison (Figure 4) shows improved coherency and resolution of subthrust reflectors, similar to the result observed on the central crossline.

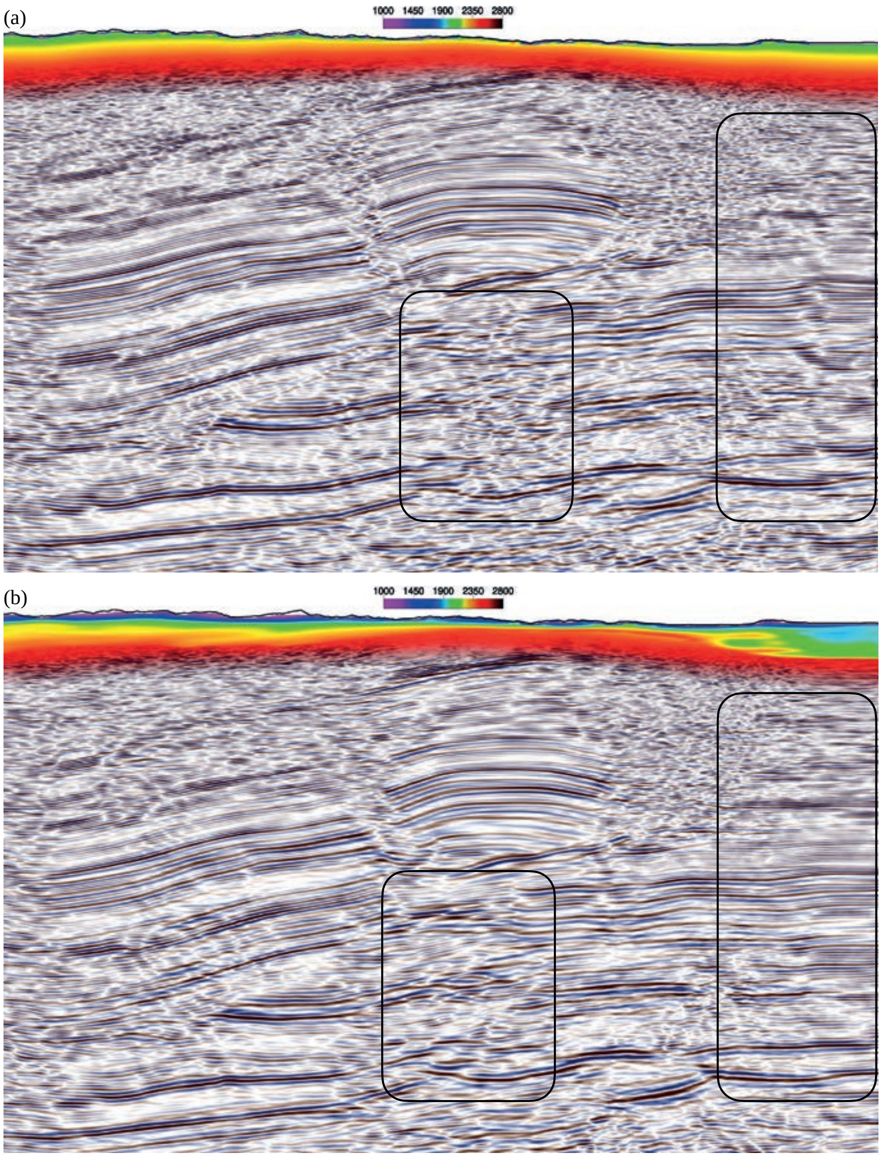


Figure 4. *Inline B near the edge of a 3D PSDM volume with (a) time weathering solution applied and (b) depth weathering solution applied. The velocity overlay near the top of the inline slice shows the shallow velocities in each velocity model. Boxes indicate key differences in imaging between the TWS and DWS versions.*

Discussion and conclusions

In seismic imaging, the near surface is the lens through which we image the subsurface. More accurate correction of these lens effects results in improved seismic imaging in structurally complex areas, such as the foothills and valleys of the Andes Mountains.

During the development of this workflow, we found that simply including first-arrival tomography velocities in the PSDM velocity model did not yield the results we had hoped for. A workflow that incorporates reflection statics coupled to the PSDM velocity model provides a complete depth weathering solution (DWS) that is independent of any weathering corrections or statics solutions derived from time processing.

The results show improved seismic imaging on both 2D and 3D seismic datasets when using DWS, compared to the traditional approach of applying the weathering solution from time processing.

Now that we have a method to correct for the effects of near-surface velocities that is independent of the time-processing solution, we have an opportunity for further workflow optimization. It may be beneficial to pick first arrivals at longer offsets and incorporate more of the first-arrival tomography solution into the PSDM velocity model.

We may also experiment with more advanced techniques. Diving-wave full-waveform inversion may leverage more of the early-arrival energy on shot records to build a subsurface velocity model that has five to ten times more thickness than our current near-surface models from first-arrival tomography.

References

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