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Quantifying seismic structural uncertainty associated with complex near-surface: SEAM Arid model example

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Summary

In regions with complex near-surface conditions, a significant part of the structural uncertainty is associated with the shallow part of the subsurface. This work presents a simplified but practical workflow to quantify the impact of near-surface modeling and imaging scenarios on structural maps. The method is based on a typical processing flow and can be implemented straightforwardly in a processing practice. Using a controlled synthetic example of the SEAM Arid dataset, we focus on the effects of the near-surface complexities of the desert environment. Specifically, we reveal the typical, expected structural uncertainty caused by static corrections approximation and time-to-depth mapping approach.

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Introduction

Seismic imaging is the primary source of structural information about the subsurface. It invariably carries an uncertainty that is well manifested by occasional misidentification of subtle structural traps, for instance, low-relief structures. However, the magnitude of such uncertainty and its dependence on a specific imaging practice often remains unknown. Exploring for and developing low-relief structures demands very accurate structural imaging with reduced uncertainty. Hence, quantitative methods to evaluate the effectiveness of each seismic solution and its uncertainty are of increased importance for such targets. In the past, several methods were introduced for assessing structural uncertainty. Most works focus on velocity uncertainty and the corresponding variations of target horizons. The approaches vary from those based on the Dix equation and stacking velocities to more comprehensive ones based on analyzing residual moveouts after a migration or the reflection tomography operator itself (Thore et al., 2002; Osypov et al., 2013; Jones et al., 2019).

In the arid desert environment with complex near surface, it is commonly believed that a significant part of the uncertainty is associated with the shallow subsurface, particularly with static corrections. Assessing this type of uncertainty is possible with a Bayesian tomography framework (Egorov et al., 2022), but it requires heavy computations. This work presents a simplified but practical workflow to quantify the impact of near-surface statics solutions on structural maps. The method is based on a typical processing flow and can be implemented straightforwardly. Applying the approach to synthetic elastic data from the SEAM Arid 3D model illustrates in a controlled manner the structural uncertainty of a traditional time-to-depth mapping approach that near-surface complexities from the desert environment can cause.

Method

The implemented workflow models multiple scenarios for near-surface static corrections and associated depth maps. We then examine the resulting statistical distribution in depth and time domains. In the first step, refraction tomography or other typical near-surface modeling algorithms are applied to obtain single or multiple plausible near-surface models. Then, several static correction models are derived based on different realistic scenarios. This provides a set of probable corrections to compensate for the near-surface complexities. After this, the conventional seismic processing and interpretation, including velocity analysis and target horizon picking, is applied to seismic data based on each of the derived statics models. This provides sets of time maps for target horizons and root-mean-square velocity models. Finally, time-to-depth mapping is applied to each time map, resulting in several horizon realizations in depth that are used to analyze the uncertainty associated with the near-surface.

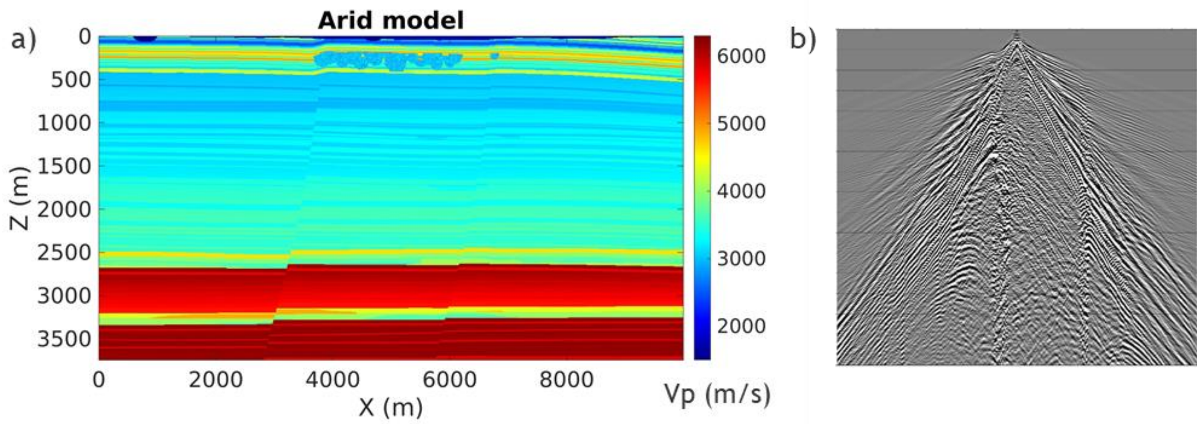

Figure 1 *(a) A vertical slice from the SEAM Arid P-velocity model; (b) an example of a common-shot gather with 9-geophone arrays mimicking realistic field acquisition.*

Examples

We illustrate the workflow using the elastic SEAM Arid 3D model (Oristaglio, 2012). The model (Figure 1a) contains a realistic near surface representing some of the challenges typical to land seismic exploration in arid environments, such as high-contrast layering, velocity inversions, and karsts features in the shallow part. The original dense geometry of the dataset was decimated to 100 m x 50 m intervals for sources and 25 m x 150 m for receivers mimicking a typical modern 3D high channel-count acquisition. In addition, nine adjacent receivers forming a square patch were grouped to emulate field arrays. An example of common-shot gather is shown in Figure 1b, illustrating the complexity of the wavefield dominated by the ground roll and other near-surface arrivals. A conventional 3D travel-time refraction tomography was applied to the dataset providing a near-surface velocity model with a partially resolved deep karstified area in the center of the model (Figure 2). A total of eight realistic statics models were derived from this tomography model by varying intermediate datum levels based on ray-penetration maps, iso-velocity surfaces, or setting a constant depth. Three standard deviations of the static corrections estimated from these realizations (Figure 3a) show smaller statics uncertainty in the southern part of the model (less than 10 ms) and more significant uncertainty in its northern part (up to 50 ms). Based on these statics corrections, eight stacked volumes and root-mean-square (RMS) velocity volumes were obtained following a conventional time processing practice. The stacked section (Figure 4) shows a reasonable quality at the deep target level and a poor quality in the shallower part due to insufficient trace density and weak impedance contrasts (Bakulin and Silvestrov, 2021; Bakulin et al., 2022). Three standard deviations of the picked horizons represent the imaging uncertainty in the time domain, which correlates well with the statics uncertainty (Figure 3b).

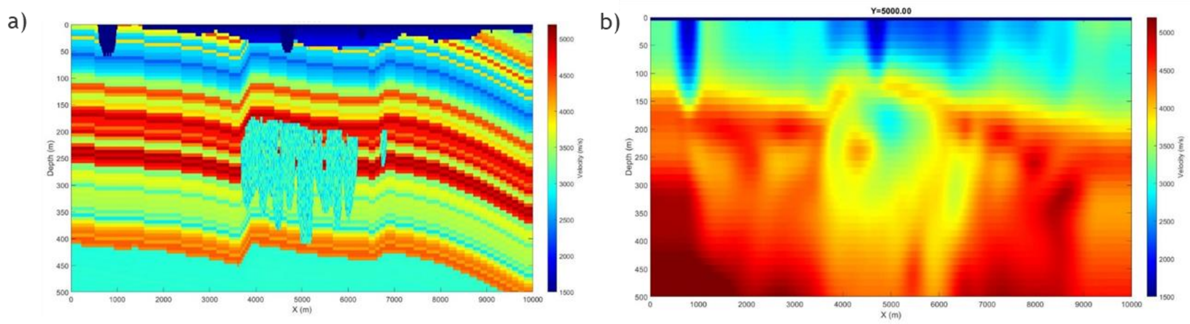

Figure 2 *(a) A vertical slice from the true near-surface model; (b) the near-surface model derived by refraction tomography.*

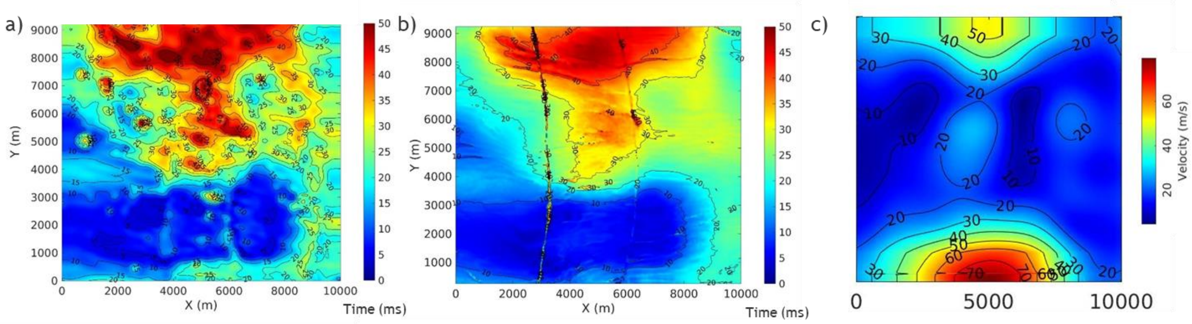

Figure 3 *Uncertainty maps (calculated as three standard deviations over all available realizations) for different quantities: (a) static corrections; (b) target horizon in the time domain; (c) average velocities.*

Several scenarios were considered for mapping the target horizon from time to depth domain. The first case assumes a wildcat scenario without well control. The RMS velocities were recalculated to average velocities for the target, showing a different uncertainty map compared to the time horizon uncertainty itself (Figure 3c). Finally, eight realizations of the horizon's depth maps were obtained after time-to-depth mapping using the estimated average velocities. The horizon map calculated as a mean for all the realizations has some similarities with the true horizon map (Figure 5) but differs in details. The depth uncertainty map (Figure 6a), calculated as three standard deviations, shows the more considerable vertical uncertainty in the northern and southern parts of the volume reaching 60 m and smaller uncertainty below 20 m in the eastern and western regions. The karst field in the model's center results in structural uncertainty up to 30 m. The second and third mapping scenarios introduced time-depth information from two wells. The second case does not use any seismic velocities. The average velocities were estimated based purely on well data propagated using minimum curvature gridding. This results in a smaller uncertainty in the western and central part of the model (Figure 6b) where the wells are located but more significant uncertainty in the eastern region with less well control. In the third and last mapping scenario, the information from wells was combined with the smoothed RMS velocities via cross-plotting and applying the linear relationship between them. This mainly boosts the uncertainty in the whole area reaching 120m in the northern part, apart from a tiny curved region connecting the two wells used as hard constraints (Figure 6c). This apparantely shows a misalignment between the two different sources of the velocity information in this example, meaning that the well information should be used earlier in the processing to guide the velocity picking.

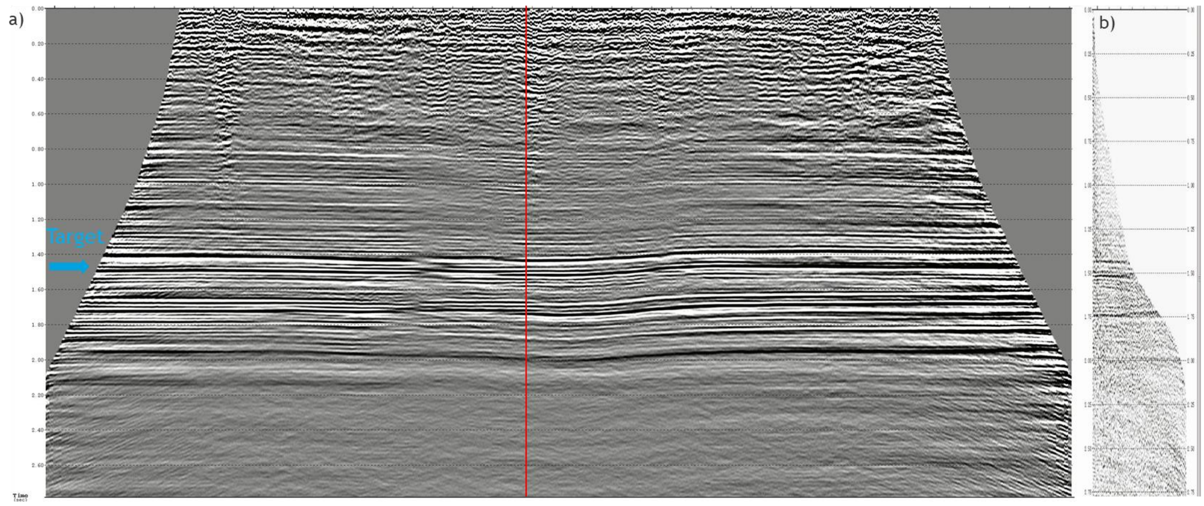

Figure 4 *(a) An example of a stack section for one of the realizations of statics corrections; (b) a common-midpoint gather corresponding to a location shown by the vertical red line in (a).*

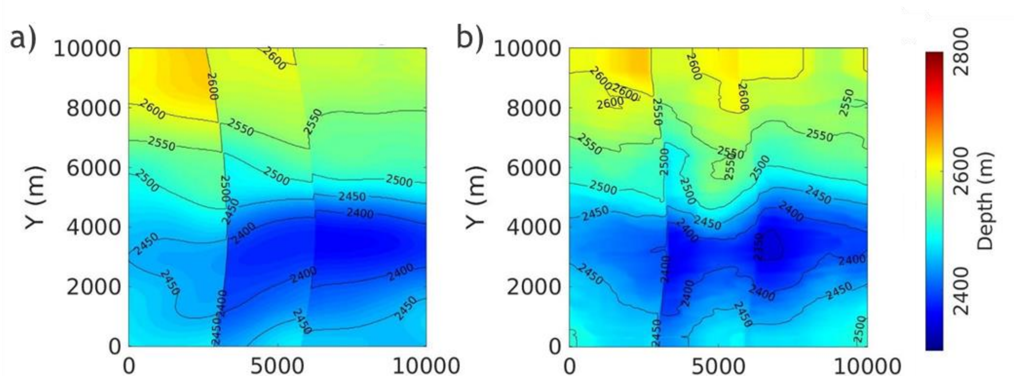

Figure 5 *(a) A true map of the target horizon in depth; (b) an estimated horizon's map calculated as a mean value over all available realizations.*

Conclusion

We presented a practical workflow for quantifying seismic structural uncertainty associated with complex near surface. The workflow constructs multiple versions of realistic plausible static corrections and examines associated imaging scenarios. It can be straightforwardly implemented in a processing practice. We demonstrate this using the synthetic 3D SEAM Arid dataset with realistic near surface typical to arid environments. The constructed maps show the depth uncertainty values varying from 5 m to 120 m in different regions of the model and depending on the time-to-depth mapping scenario. Although the obtained depth uncertainty values might not be considered as severe in the particular example with the target closure larger than 100 m, even in this case, there is still a significant impact on the volumetric resource estimation. In more challenging cases with vertical closures around tens of meters (low-relief structures), such uncertainty values can be critical for decision-making and, therefore, should be exposed and taken into account during processing and interpretation.

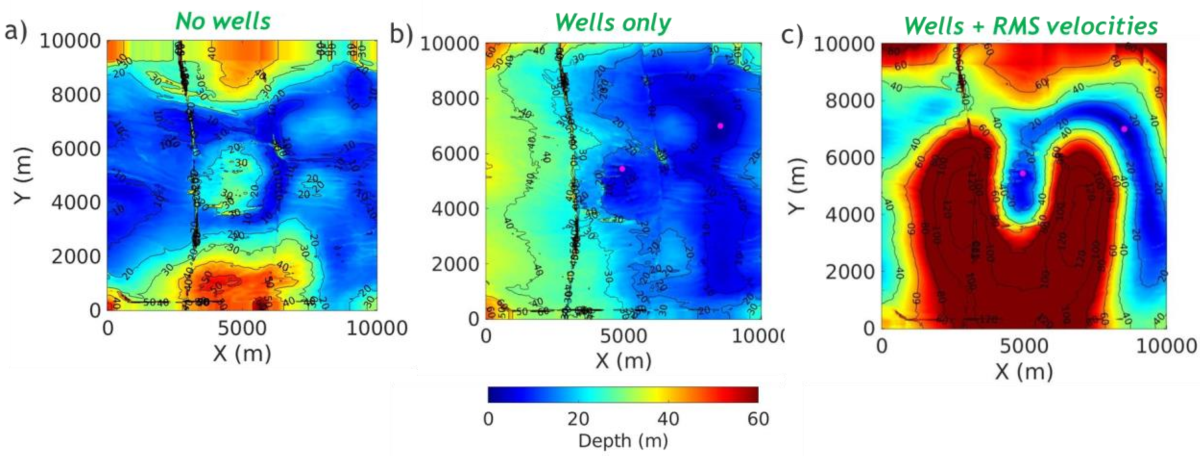

Figure 6 *Depth uncertainty maps (calculated as three standard deviations over all available horizon maps) for different scenarios: (a) a wildcat scenario without well control; (b) a scenario using only well information; (c) a scenario in which information from wells is combined with the smoothed RMS velocities from seismic.*

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