Shallow land PSDM velocity model building for unconventional plays

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Summary

Various strategies for populating the shallow portion of the prestack depth migration (PSDM) velocity model are explored in a carefully-controlled synthetic environment which mimics a real-world Permian Basin unconventional play. Key findings from the synthetic experiments are corroborated by analogous observations on real data, suggesting that the experiments are capturing realistic effects. These synthetic experiments clearly demonstrate that gather flattening improves dramatically with application of the more sophisticated shallow model building approaches. In the case of the most primitive approaches (e.g, migration-from-flat-datum or migration from topography while populating the shallow model with a spatially homogenous "replacement" velocity), the migrated gathers exhibit significant residual moveout, and applying a tomographic velocity update to improve flattening leads to a significant error in event depth location (i.e, "depthing"), a finding that in turn suggests that downstream anisotropic parameter estimation will be compromised unless a more sophisticated shallow model building approach is employed. The concept of differential statics is introduced and is demonstrated to be a useful tool which can provide good gather flattening, accurate event depthing, and also improved lateral continuity of events in the common case where the near-surface velocity estimate from refraction statics analysis is not suitable for verbatim insertion into the shallow PSDM model.

Introduction

Traveltime distortion due to near-surface heterogeneity poses a major challenge in land seismic imaging. Addressing this problem is particularly important in unconventional plays, where accurate depthing of subtle features is crucial for applications such as steering optimization and hazard avoidance. While the processing industry continues to struggle with the challenge, some notable advances have been made in recent years including the use of novel refraction statics techniques (Diggins et al., 2016), application of full-waveform inversion (e.g., Roy et al., 2017), as well as incorporation of potential field/EM data (Colombo et al., 2012), all of which seek to better elucidate complexity in the near-surface velocity field. At the same time as these shallow-velocity-estimation improvements are unfolding, prestack depth migration for unconventionals is gaining popularity to the point of becoming commonplace in many North American shale plays (Rauch-Davies et al., 2018).

Despite this routine use of PSDM, confusion abounds among practitioners on the topic of how to best incorporate these improved near-surface velocity estimates into the PSDM model-building process. Evidence for the confusion is largely anecdotal, and tends to assume one of the following forms: (i) a common belief that inserting the near-surface velocity information derived from refraction statics directly into the shallow PSDM model does not work well in practice, despite this being a theoretically pleasing process; (ii) puzzlement over the question of which elements of the shallow velocity estimate ought to be directly inserted into the shallow PSDM model versus which elements should be applied to the data prior to migration in the form of a static correction; (iii) a conviction in direct contravention to (ii) above, but held by many practitioners, that the action of migrating from topography (i.e, rather than from flat datum) poses the primary control on good PSDM image quality, and that considerations related to the proper apportioning of statics and shallow velocities are of secondary importance.

In the present work, we seek to eradicate this confusion through use of synthetic experiments in which the (known) near-surface velocity distribution mimics typical Permian Basin shallow geology. While the problem of PSDM shallow velocity model building has been studied to a certain degree in the context of thrust-belt plays (Zhu et al., 2000), unconventional plays impose very different requirements on PSDM image quality than their thrust-belt counterparts. First, PSDM in unconventional shale environments places heavy emphasis on accurate depthing of events and resolution of subtle stratigraphy and faults rather than on the imaging of complex structures. Second, both migrated stacks and gathers (as opposed to migrated stacks alone) are of key interest in the unconventional world as the gathers are often used as input to prestack inversion. Finally, there is typically much more well data available to constrain the model building process in the unconventional world. To our knowledge the present work is the first-ever shallow PSDM velocity building study explicitly tailored to unconventional plays.

Theory and Method

A shallow velocity grid was created which contains realistic near-surface geological features typical of the Delaware Basin (i.e, a major component basin of the Permian Basin), including a shallow low-velocity salt collapse zone. This shallow grid was superimposed atop a realistic deeper velocity grid which contained four synthetic reflection horizons (Figure 1). A realistic topography profile was created by extracting surface elevation information from a real Delaware Basin seismic survey. Isotropic 2D-finite

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difference acoustic modeling was then performed from topography, and the resulting noise-free synthetic data set was submitted to a simple time processing flow comprising first-break picking and refraction statics analysis, picking of stacking velocities, and application of surface-consistent residual statics.

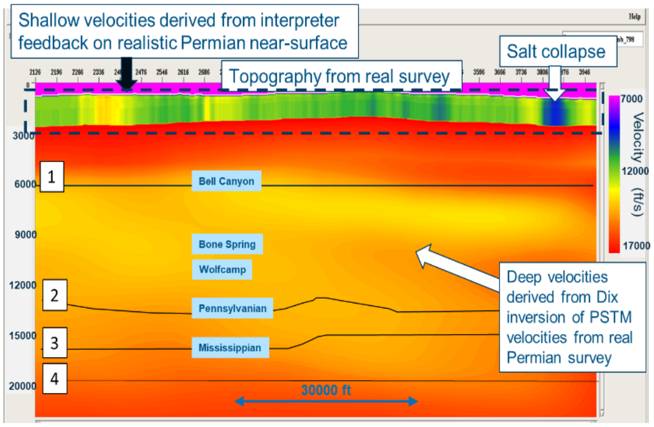

Figure 1: Velocity model used in finite-difference modeling. Shallow velocity model, which is the focus of the present paper, is shown by dashed box. Four reflectors have been inserted into the model. Reflector 1 (Bell Canyon proxy, at 6000 ft depth) is examined in Figure 2.

Two independent refraction statics approaches were tested, namely diving ray tomography using first-break picks from all offsets and the single-layer delay-time inversion technique proposed by Diggins et al. (2016). The latter scheme, which uses only far-offset first break picks from a single deep refractor, is preferable in the case where near-to-mid-offset first breaks are difficult to pick (a situation commonly encountered on Permian Basin data sets). Significantly, the shallow velocity estimates produced by these two independent first break inversion algorithms, though both reasonably accurate in terms of their long-wavelength structure, were observed to be lacking in short-wavelength detail. Therefore, a pass of surface-consistent residual statics was required for optimal event alignment in both cases, a requirement which we view as a happy finding in the context of the present testing as it simulates the real-world situation where residual statics are routinely applied.

Once the above time processing steps were performed, the resulting data set was input to several trial PSDM scenarios, each one corresponding to a different level of sophistication in its treatment of statics and shallow velocity model definition (Table 1). Sophistication ranged from the primitive (migration from flat datum while flooding the shallow model with a uniform replacement velocity) to the complex (migration from topography incorporating geologically-plausible velocities into the shallow model definition). Care was taken to apply the appropriate statics prior to migration for the test-at-hand. For example, in the case of migration from flat datum all statics were applied before PSDM, while in the case of migration from topography using the shallow velocities derived from diving ray tomography only surface-consistent residual statics were applied. Table 1 lists the various near-surface model building approaches studied in our synthetic experiments,

Both of the sophisticated shallow model building schemes (rows 2 and 7, Table 1) involve injection of spatially-varying near-surface velocity information into the model grid. In our synthetic environment, we found that this insertion was straightforward in the case that velocities were derived from diving ray tomography (such velocities being inherently smooth and therefore naturally matching the heterogeneity scale of the deeper velocities in our ideal model). However, in general the near-surface velocity estimate produced by refraction statics analysis will not be suitable for direct (i.e, “as-is”) population within the shallow PSDM velocity model. There are two main reasons for the lack of suitability: first, the refraction-based estimate may contain abrupt velocity changes (e.g, at internal layer-boundaries and/or at the transition between the base of the refraction-based estimate and the deeper velocity field) which can pose problems for the PSDM ray tracer; second, the refraction-based estimate may lack geological plausibility because of simplifying assumptions within the first-break inversion process (e.g., use of a single-layer model when the actual geology is known to exhibit severe vertical inhomogeneity).

Scenario description	Shallow velocity model construction	Sophistication level
Ideal PSDM with exact (known) velocities	Ideal velocity field	N/A
PSDM from topography using velocities from diving ray tomography	Diving ray tomography velocity field	high
PSDM from topography	Uniform replacement velocity flood from topography to base of tomo model	low
PSDM from flat datum using statics from diving ray tomography	Uniform replacement velocity flood from flat datum to base of tomo model	very low
PSDM from flat datum using statics from delay-time inversion	Uniform replacement velocity flood from flat datum to base of delay time model	very low
PSDM from topography using smoothed Dix-inverted stacking velocities	Dix-inverted stacking velocity field after smoothing	very low
PSDM from topography using smoothed Dix-inverted stacking velocities after application of differential statics	Dix-inverted stacking velocity field after smoothing	high

Table 1: Description of various PSDM model building scenarios.

In either case, a practical difficulty arises in PSDM shallow model construction because any perturbation applied to the refraction-based estimate (i.e, in order to increase suitability for shallow PSDM model population) tends to decouple the underlying statics solution from the data, thereby degrading event continuity after migration. Such perturbations include smoothing operations, as well as operations aimed at injecting additional "non-refraction-based" velocity information into the shallow PSDM model (e.g, inclusion of information from shallow sonic logs, checkshots, shallow PSTM/stacking velocities, potential field and/or EM data). To address this difficulty, we have introduced the use of an intermediate statics correction which we term "differential statics". Differential statics account for the difference in vertical traveltimes between the refraction-based velocity estimate and the "perturbed" PSDM shallow velocity model and are applied in a surface-consistent fashion prior to migration. As will be shown in the next section, this approach can provide very good migration results.

Results

We show a few representative results in Figure 2; a more complete suite of results will be shown in the oral presentation. As a general statement, the more primitive the shallow model building scenario, the greater the residual curvature in the migrated image gathers, with the most sophisticated (and theoretically valid) schemes yielding excellent gather flatness and image quality. Figure 2a shows migrated image gathers under the relatively primitive scenario where the data were migrated from topography with the shallow PSDM model containing a uniform replacement velocity (Table 1, row 3); note the significant residual curvature at far offset (red box in lower pane). By contrast, the image after PSDM from topography using a relatively sophisticated approach including application of differential statics (Table 1, row 7) shows very good gather flattening (Figure 2c) and compares favorably to the ideal result where the data were migrated using the exact velocity field (Figure 2b). Interestingly, migrated stacks show only minor degradation under the more primitive model-building scenario, such degradation being most pronounced across the salt collapse (Figure 3a, red box), where we also note the presence of some significant modeling noise, even for the ideal case shown in Figure 3b.

Figure 4 shows a real data analog from the Delaware Basin in which virtually identical model building steps were employed relative to the synthetic test shown in Figure 2, the only subtle difference being that a smoothed version of the refraction-based velocity estimate was used in conjunction with differential statics rather than a smoothed version of the Dix-inverted stacking velocity field. Just as in the synthetic case, significant residual curvature is observed on the real data after PSDM using the primitive shallow model approach (blue box, Figure 4a; note that the apparently under-corrected "events" in the overburden above blue box likely correspond to coherent noise), suggesting that our synthetic tests embody a high degree of realism.

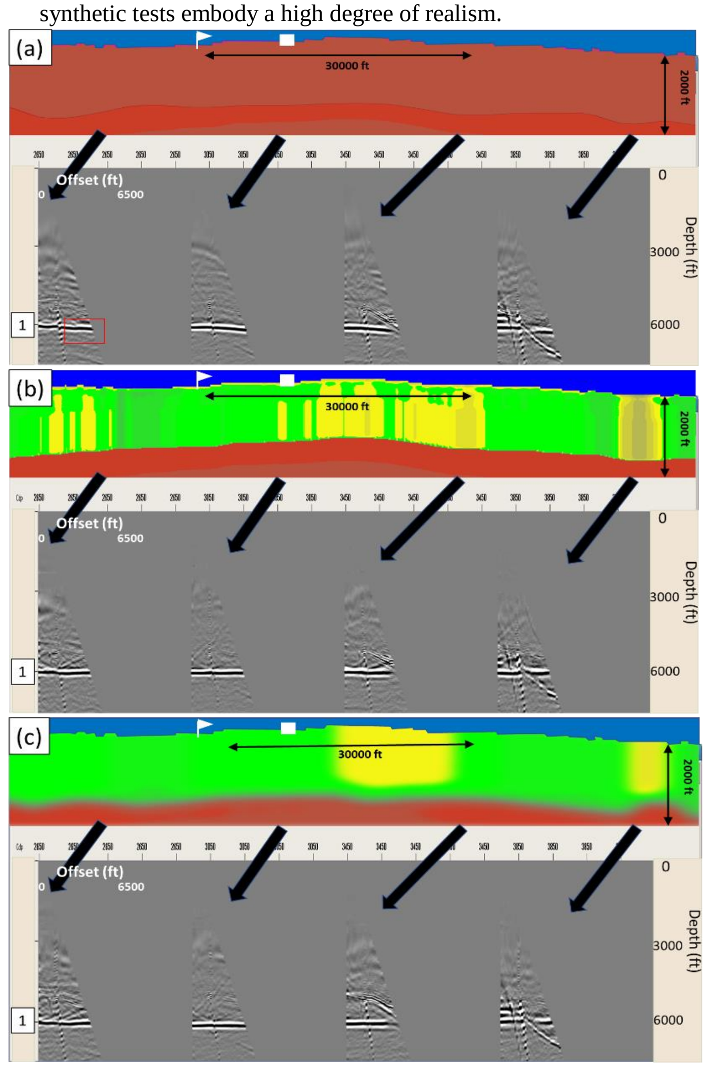

Figure 2: Three representative synthetic results. Top portion of each of the three panes (denoted a,b,c) shows the shallow velocity model used for PSDM and bottom portion shows four migrated image gathers extracted from arbitrary locations along line as indicated by bold, black arrows. Event 1 at 6000 ft depth is Bell Canyon reflector proxy. (a) after migration from topography using a shallow velocity model populated with a single, uniform replacement velocity as per row 3 of Table 1; (b) ideal result after migration from topography using exact velocities (row 1, Table 1); (c) after migration from topography using smoothed Dix-inverted velocities where differential statics were applied to input (row 7, Table 1).

The significant residual curvature observed after PSDM based on the primitive model-building approach shown in Figures 2a and 3a raises the obvious question of what would be the impact of applying industry-standard residual

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curvature tomography to improve gather flatness. A numerical analysis based on concepts discussed in Woodward et al. (2008) and Stork (1992) was performed in order to estimate the interval velocity update after tomography as a function of observed far-offset residual curvature. This analysis suggests that residual moveout observed on the shallow event in Figure 2a can give rise to a velocity update error of 6%, an error which in turn leads to a 5% mismatch in event depthing (i.e., relative to the known ideal depth) after the next iteration of PSDM. This analysis suggests that use of a primitive shallow model-building approach will significantly compromise downstream earth model updating, especially estimation of anisotropic Thomsen parameter δ (this parameter being highly sensitive to errors in event depthing).

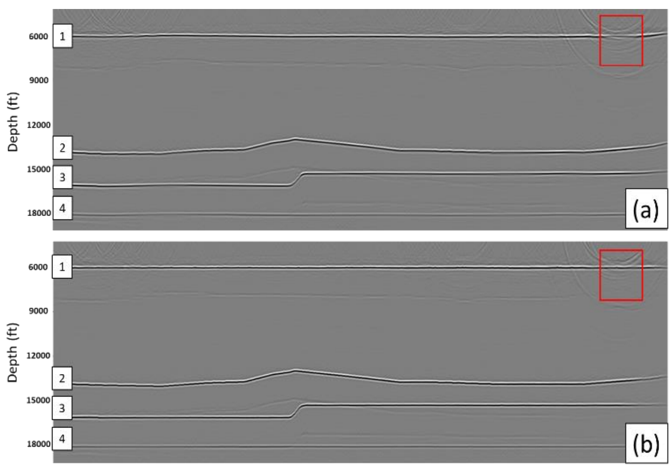

Figure 3: Stacked PSDM images. Panes (a) and (b) correspond to gathers shown in Figures 2a and 2b, respectively.

Conclusions

Our synthetic experiments show that it is possible to obtain a high quality PSDM result by incorporating a smooth, but otherwise geologically plausible, velocity field directly into the PSDM velocity model and applying appropriate statics before migration. Application of differential statics, a statics correction which seeks to couple a smooth shallow velocity PSDM model to the refraction statics solution, is demonstrated to be a robust tool providing good event continuity and good gather flatness after PSDM. One of our key tests shows that the simplistic scheme of migrating from topography while flooding the near-surface with a uniform replacement velocity leads to an unacceptably large amount of residual moveout in the output image gathers. Numerical analysis suggests that attempting to flatten this residual moveout through application of post-migration tomography leads to erroneous velocity updates which can compromise downstream anisotropic model building. It follows that the action of migration from topography alone does not suffice to ensure good image quality, and that careful consideration of shallow velocity model population and corresponding statics treatment is paramount. Companion experiments conducted on real Delaware Basin data sets show similar findings to those observed in our synthetic world, lending a high amount of confidence to our analysis.

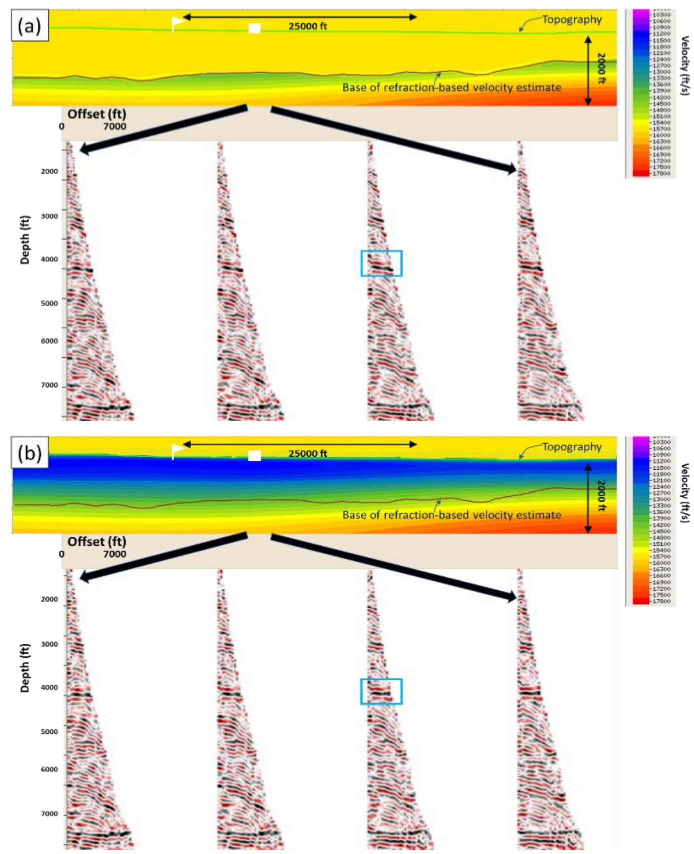

Figure 4: Real Delaware Basin data example from TGS' West Lindsey 3D survey. Top portion of each of the two panes (denoted a,b) shows the shallow velocity model used for PSDM and bottom portion shows four migrated image gathers extracted from an area along line as indicated by bold, black arrows. (a) after migration from topography using a shallow velocity model populated with a single, uniform replacement velocity as per row 3 of Table 1; (b) after migration from topography using a shallow velocity model populated with a smoothed version of the refraction-based velocity estimate, together with application of differential statics (minor variant of row 7, Table 1). Data courtesy TGS.

Acknowledgments

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