Depth imaging velocity estimation by layer-stripping Dix update and dip-constrained tomography in a compressional tectonic regime

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Two major issues that give rise to seismic imaging challenges in California are near-surface propagation effects and complex velocity structure. We describe a case history exhibiting both of these challenges. In this case history, a deep target has been imaged by a 50,000' 2D seismic line with 535 shots and 1072 receiver locations. The maximum offset is 20,000'. The topographic relief is about 800' with up to 400' change in elevation over a distance of 3000'. The imaging target is about 20,000' deep under a faulted anticline. The main imaging problem is a package of low-velocity "air sands" at the top of the anticline that lets little seismic energy penetrate vertically and severely distorts the raypaths of non-vertically traveling seismic energy (Figure 1). This setting poses a particular challenge to depth imaging because of its sensitivity to errors in the velocity model compared to time imaging. The dip of the sedimentary strata in the SW flank of the anticline is know from a borehole down to a depth of about 12,000'; this information provides some quality control of the deeper sections of the depth image.

In order to build a reliable velocity model for prestack depth migration, we employed two different approaches of iterative migration velocity analysis: (1) a layer-based vertical update based on Dix's equation that proceeds from the surface downward, freezing the model in shallower layers when a satisfactory solution has been reached ("layer-stripping"), and (2) a whole-model tomographic update which is constrained by dip steering filters obtained from analyzing the slopes present in the seismic image; these steering filters ensure that the tomographic solution makes geological sense. The tomographic method employed here eliminates the need for manual reflector picking by automatically selecting back projection points based on dip coherency and semblance strength. The layer stripping and tomographic approaches described in this case history complement each other, as the Dix update performs better in the shallow section (to about 5000' depth), whereas the tomographic update works better for the deeper parts of the model (Figure 2).

Layer-stripping velocity analysis

The objective of migration velocity analysis is to horizontally align events along offset in common image gathers. Given an initial approximate velocity model and input seismic data, common image gathers at analysis subsurface locations are generated from Kirchhoff prestack depth migration. Migrated events in the image gathers may exhibit deviations in depth along with offset due to incorrect migration velocity. A residual moveout analysis is performed at each depth location. In addition, geologic horizons are picked from the stacked image volume. To improve reliability, residuals are tied to and smoothed along horizons prior to updating. Updates can be performed using an increasingly sophisticated portfolio of techniques, starting with a completely automatic approach for initial velocity models and simple structures, to horizon-based vertical updates, horizon-based normal ray updates, and tomography for the most challenging structures. The process can be iterated for all layers at once, or as in the case described here, performed in a layer-stripping fashion (Deregowski, 1990) until all events are aligned horizontally with offset.

Tomographic velocity analysis without picking

In traditional ray-based migration velocity analysis, picking reflectors is an integral and painful part of the process. The general methodology is to pick a series of reflectors from a migrated image. Sets of rays are then calculated that reflect at the picked interfaces. A major problem is the human intensive nature of reflector picking, especially for 3-D data. Automatic pickers can help, but significant human quality control (QC) is still necessary. A high level of quality control is required because inaccurate reflector picks lead to inaccurate reflector dip estimates, which in turn leads to back projecting information to the wrong portion of the model space, seriously hampering the inversion.

In this case history, we present a method to eliminate, or at least significantly reduce, the need for reflector picking. The method calculates a dip field (Figure 3) and coherency from a migrated image by first using the plane-wave estimator from Claerbout (1992) and later used by Bednar (1997). The dip estimate is then refined using the methodology described in Fomel (2000), and back projection points are automatically selected based on dip coherency and semblance strength. The turn around time is reduced significantly.

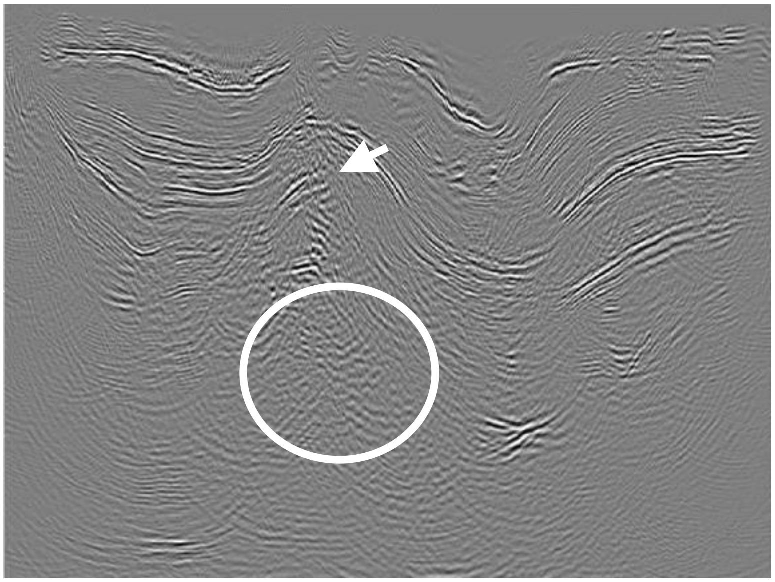

Figure 1: Poststack time migration of imaging target (circled). "Air sands" marked by arrow.

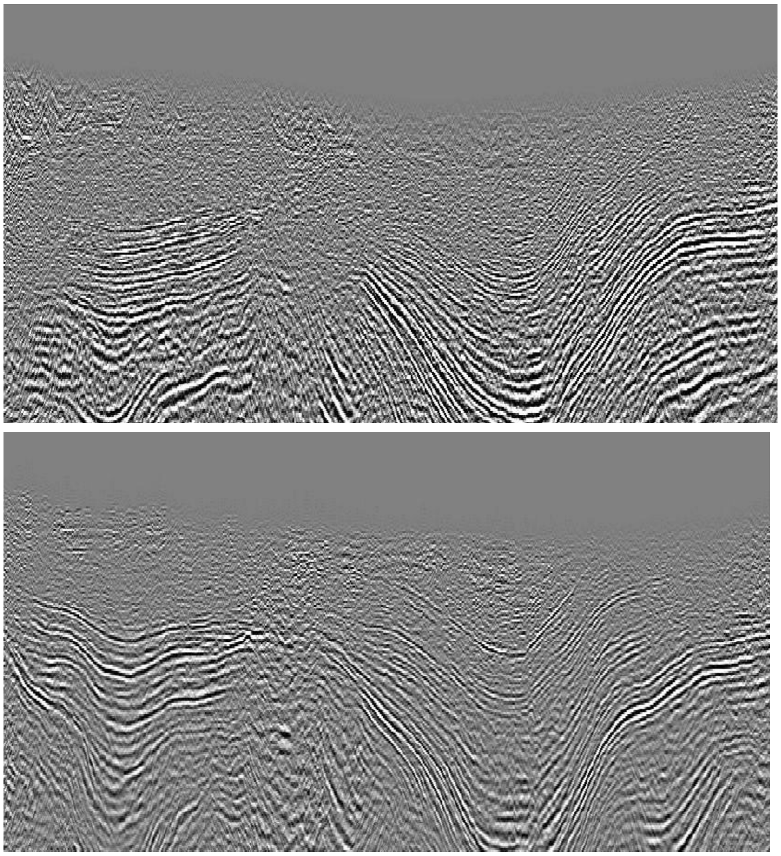

Figure 2: Prestack depth migration of shallow section after (top) tomographic velocity update and (bottom) layered Dix update.

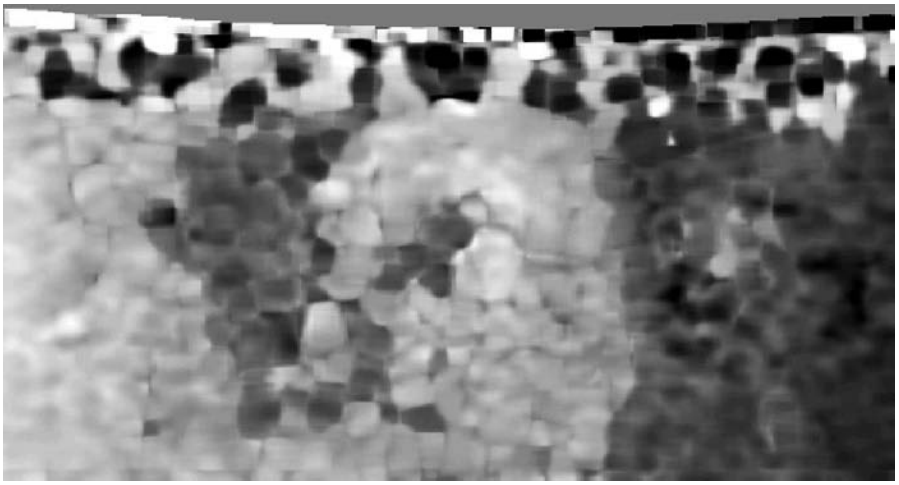

Figure 3: Automatically calculated dip field for the construction of the tomographic steering filters. Dips to the left are displayed in dark shades, dips to the right in light shades. No dips have been calculated above the topography.

Likely back projection points are then automatically selected by finding model locations that meet some specified dip coherence, amplitude, and distance from other selected points. To get the 'best' points in each region, these criteria are slowly relaxed (e.g. the first pass might look for points above the 90th percentile in amplitude and dip coherence, while the last pass might drop both these criteria to the 50th percentile.) At each initially selected point semblance analysis is performed. Points that do not have good semblance (large semblance value and a definite maximum) are discarded. The remaining points are then used.

The selected points are used in a regularized residual migration reflection tomography inversion. The tomographic operator simultaneously accounts for reflector movement (Stork, 1992). The model is preconditioned with a steering filter (Clapp, 1998; 2001), which tends to create velocity variations consistent with geologic dip. The resulting tomographic update produces an image with better coherence at deeper events where the signal to noise ratio is low.

Prestack depth imaging

The layer based migration velocity analysis performs best in areas with continuous well-defined reflectors. It is therefore well suited for building a velocity model for the shallow section. In the lower two-thirds of the section dips become steeper and therefore a vertical velocity update invalid. Updating along normal rays alleviates this problem. The more serious obstacle is the lack of clear, coherent reflectors with unambiguous semblance maxima. The layer-stripping procedure becomes unstable and produces spurious velocity estimates from localized coherent reflectivity. In this case, the tomographic approach without picking is clearly superior.

For the final velocity model, we combined both approaches by building a first a global tomographic model and then refining it especially in the shallow section with a few iterations of layered Dix velocity updates (Figure 4). A final round of residual moveout correction further improves the sharpness of reflectors.

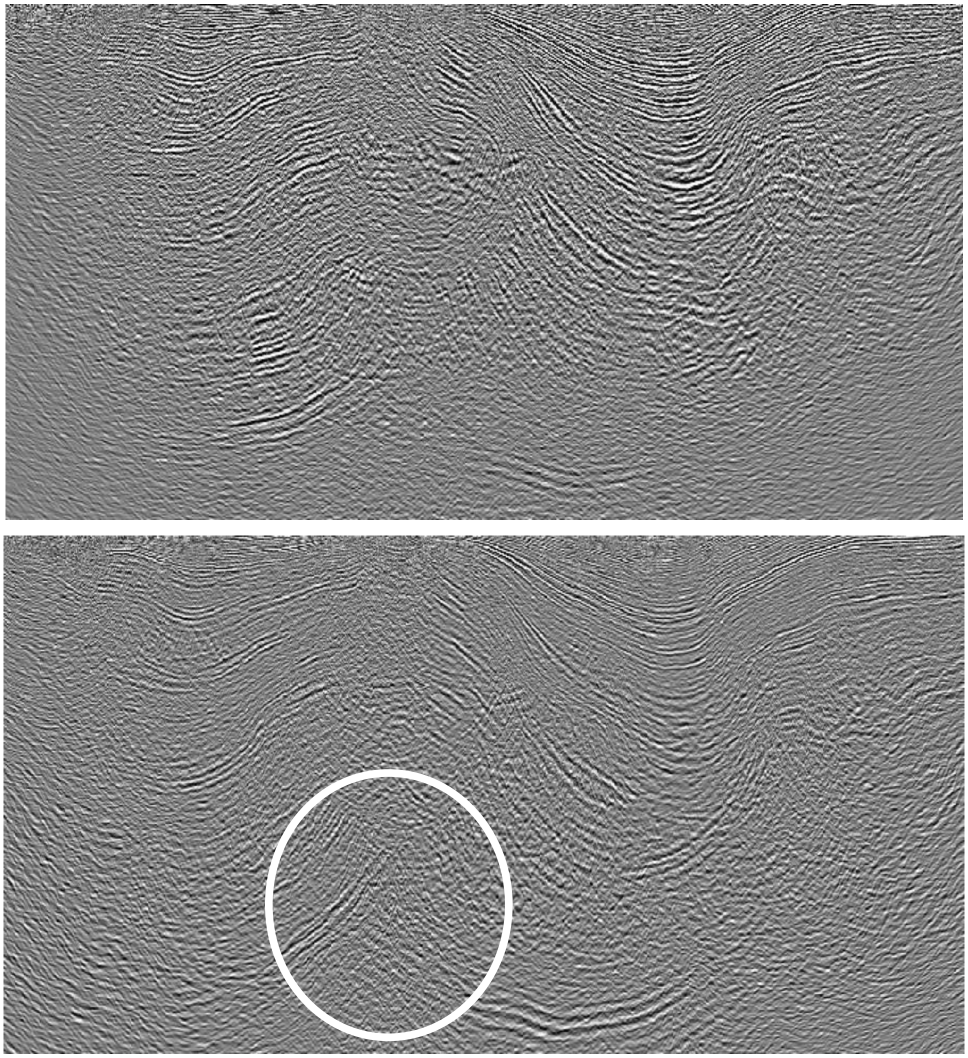

Figure 4: (top) Prestack depth migrated image using the tomographic velocity model and (bottom) image after additional iterations of layered migration velocity analysis and Dix update. Note the improvement in reflector coherence in the target area (circled).

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