# Tutorial: Time conversion of depth migrated data

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## Abstract

Many data processing and interpretation procedures are performed on time domain data. If such procedures are to be applied after a depth imaging project has been conducted, it is necessary to convert the data to the time domain from the depth domain. Although there will be a velocity-depth model available that was used for the depth migration, in this tutorial note I show why it is inappropriate to use the depth migration velocity model for depth-to-time conversion if additional processing is to be performed on the prestack data in the time domain. The situation is less clear-cut if the objective is to compare the time-converted depth image to checkshot or interval times. It should be noted that time conversion of depth migrated data is subtly different from depth conversion of time migrated data. For time migration, the velocity field is inherently smooth: this is not the case for depth migrated data, and as I show in this tutorial, this lack of smoothness is the issue.


## Introduction

Many studies have been performed in the past concerning the most appropriate ways of representing velocity fields and of converting a time image to geological depth (e.g., Al-Chalabi, 1994; Armstrong, 2001; Armstrong et al., 2001; Bartel et al., 2006; Cameron et al, 2008; Iversen and Tygel, 2008). In these cases, the velocity fields were inherently smooth because they were designed for performing time migration and subsequent depth conversion of these time images. The velocity field associated with a depth migrated image is not usually smooth. It is this lack of smoothness, especially in the lateral sense, which concerns us here.

Following prestack depth migration (preSDM), which uses a model of arbitrary complexity, we often have to apply various processes in the time domain, typically residual moveout (RMO) correction, Radon demultiple, and spectral shaping. In addition, if the interpreter requires a time-converted deliverable, such as a stack for interpretation, then the product must be fit for purpose. The issue is then raised as to how best to convert the depth-domain data back to time for these processes to be applied.

Under the high frequency approximation, migration simply moves energy along raypaths. Conversely, depth-to-time conversion, or its inverse, is achieved via a purely vertical stretch. This latter procedure has no physical justification, and there is no theoretically correct way of doing it. How we approach depth-to-time conversion depends on what we hope to achieve. In the context of post-migration processing, we most often want to estimate and apply RMO using time-domain tools, perform residual multiple suppression, and apply spectral balancing. Consequently, we need to consider what the depth-time stretch does to the seismic wavelet and to the moveout behaviour across the gather, because this moveout behaviour will affect any subsequent multi-channel transform process. Furthermore, in the case of a preSDM image converted to time for interpretation purposes, we must ensure that the stretching does not introduce aliasing of steep events that could hinder automated picking of horizons, nor create spurious pull-down or pull-up imprints at deeper target levels.

In this note, I first demonstrate the effects of time conversion of depth gathers on subsequent multi-channel transforms, and then consider the effects of a vertical stretch on the preSDM image itself when converted to time with a highly structured (i.e. non-smooth or blocky) velocity model. For the pre-processing aspects considered here, we can summarize the conclusions of this note with the following rule of thumb: *convert from depth to time with a smooth velocity field*. This velocity field could be a smoothed version of the depth migration velocity field or, if there was also a time migrated product, its velocity field could be used. For interpretational purposes, conversion to time with a smooth model is probably also desirable if horizon autopickers are to be used. Exceptions to this approach would be the cases where we want to compare the image to checkshot times or to compare interval-time maps to those from previous time migrated data. Even then, the checkshot mistie error may be more acceptable to the interpreter than the image distortion associated with rapidly changing velocity structure.

## The pitfalls

*Effects on gathers and transforms*

At first sight, we may think that all offsets are treated equivalently by the vertical stretch, as the velocity model boundary does not change with offset. However, this view is

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only correct when the events in the common reflection point (CRP) gathers are all flat. When we have residual moveout, whether due to an incorrect model for a primary or the presence of multiples, then the residual curvature in the moveout trajectory will tend to cut across the velocity boundaries in the model. Hence the wavelet at different offsets will be subjected to different amounts of stretch and the smooth curvature of the moveout trajectory, which is approximately parabolic in the depth domain CRP gathers, will be distorted by this differential stretch.

Figure 1a shows a simple synthetic depth CRP gather with two events: one flat, and one with residual curvature. The velocity model to be used for depth-to-time conversion has two layers: the velocity is 2500 m s$^{-1}$ in the upper layer and 5000 m s$^{-1}$ in the lower layer with the boundary between them at 3840 m. The wavelet in the second event has a black-to-white zero-crossing just above the boundary at near offsets. This second event could represent a multiple, or a primary migrated with a velocity which is too high. After depth-to-time conversion with a smooth velocity model, the wavelet is almost unchanged with offset (Figure 1b). However, with

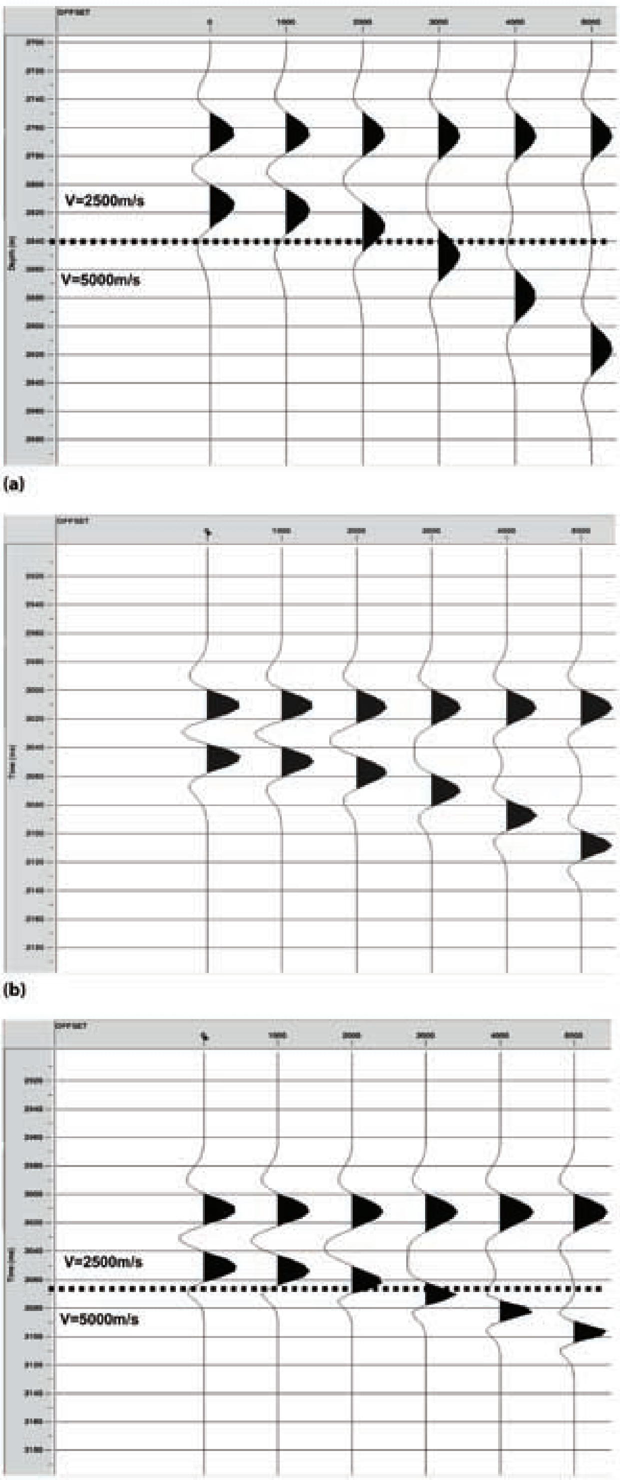


*Figure 1* (a) PreSDM CRP gather (51-fold, but only six traces shown). The second event has 100 m residual moveout at 5 km offset. (b) Same CRP gather after depth-to-time conversion with vertically smooth velocity boundary. (c) Same CRP gather after depth to time conversion with a sharp velocity boundary at 3840 m = 3067 ms.

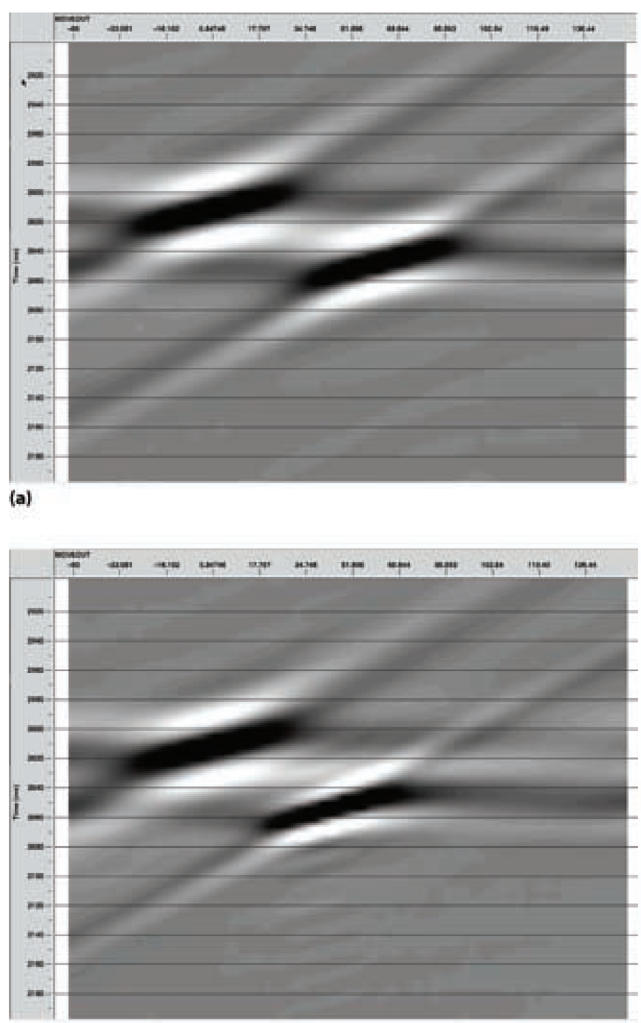


*Figure 2* Parabolic Radon transform of CRP gather converted to time (a) with smooth velocity boundary model, and (b) with sharp velocity boundary at 3840 m. The Radon transform modelled far-offset shifts from –50 ms to +150 ms, using 60 p-values.

depth-to-time conversion using a blocky velocity model with a sharp boundary at 3840 m, the wavelets in the far-offset half of the gather are located in the deeper faster medium, and so are stretched differently (Figure 1c).

The consequence of this differential stretch is that the residual curvature on the far traces is reduced, for an increase in velocity with depth, and there is less separation of events both in the parabolic Radon domain and in the hyperbolic Radon domain for velocity analysis. This reduced separation adversely affects the Radon de-multiple process and our ability to estimate and apply RMO corrections. Figure 2 shows the parabolic Radon transform of the synthetic data for the smooth and blocky models. In the Radon transform domain, the events converted with the smooth model are completely separated laterally; hence picking a near-vertical tau-p mute would work well if we were trying to separate these events, say, for multiple suppression. However, converting to time with the sharp boundary in the velocity model at 3840 m reduces the apparent curvature, due to differential wavelet stretch, and causes the individual events to overlap laterally in the tau-p domain. Hence event separation would be difficult.

The same type of effect is manifest in the velocity spectra (Figure 3), which are a type of hyperbolic Radon transform. Whereas the events are well separated after conversion with a smooth model, they are closer together and thus more difficult to pick in the data converted to time with a sharp model boundary.

*Effects on images*

Synthetic data are used here to summarize the effects. Finite difference (FD) synthetic data were generated for a salt-lens model and migrated with both post-stack time migration (postSTM) and post-stack depth migration (postSDM) algorithms, and the depth image was then converted to time with two different velocity fields. The first velocity field used for conversion was the postSDM velocity model with the salt-lens feature included (Figure 4a), and the second was a smooth salt-free velocity model (Figure 4b) as used for the postSTM. Figure 4c shows the postSDM result and Figure 4d the postSTM result. The depth-to-time conversions are shown in Figures 4e and f for the structured and smooth velocity models, respectively. The distortion seen in Figure 4e would cause an autotracker to fail, and would impose an unacceptable imprint on deeper horizons.

The next example is taken from a real project where the issues discussed actually occurred. Figures 5a and b show a velocity model and preSDM from an area with small-scale shallow channels that have high-velocity fill, which have been incorporated into the depth model to resolve pull-up distortions. These distortions would be present to some extent in a time migration, as seen in the preSTM result in Figure 5c. It is often the case that a time-converted version of the preSDM migration is required for interpretation, after RMO corrections. Converting to time with a highly structured model can introduce unacceptable artefacts, as the wavelet stretch near, say, a salt boundary may cause an autotracker to fail, so this issue can be more than cosmetic.

Converting the preSDM result to time with the preSDM velocity model introduces a pull-up distortion down the entire section below the channel velocity anomaly (Figure 5d), whereas the actual time migration only has a pronounced anomaly immediately below the channel, and the pull-up effect diminishes further down in the section. In a salt province, this effect could be worse, leading to severe aliasing on the edges of the feature. The degree of pull-up distortion seen in the time converted preSDM image is worse than in the preSTM image! This is because it has been inserted over the entire trace length below the anomaly. Converting the preSDM result to time using a single laterally invariant velocity function (Figure 5e) or, better, a laterally smooth velocity field (Figure 5f) avoids the distortion and actually looks more like the time migrated result. The time converted data were compared to checkshot information, and the error

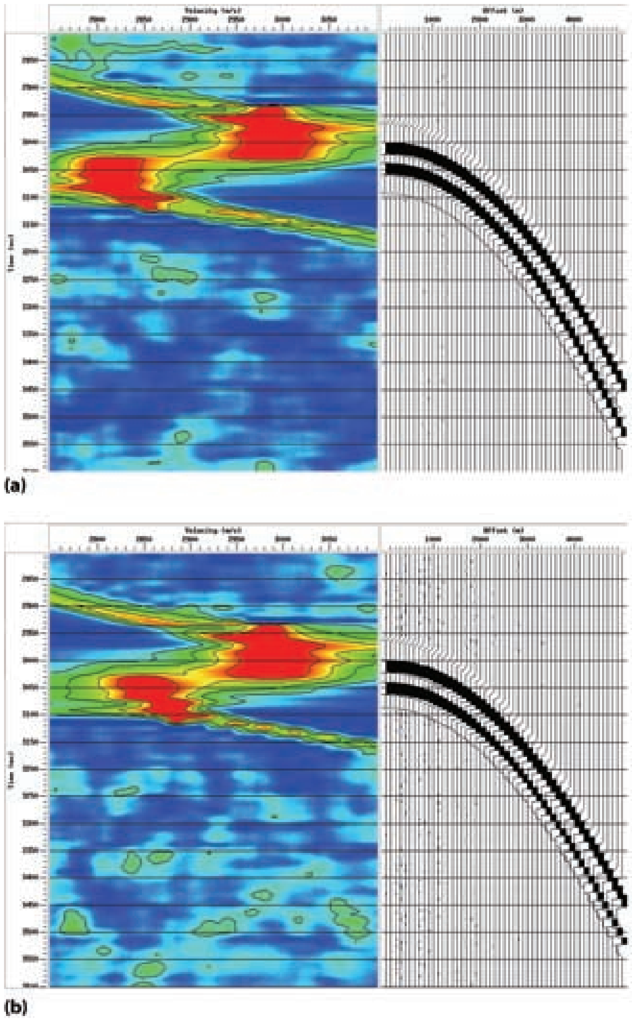

***Figure 3*** *Velocity spectrum and 51-fold CRP gather. Depth-to-time conversion (a) with smooth velocity boundary, and (b) with sharp velocity boundary at 3840 m. In both cases the inverse reference NMO velocity is 3000 m s-1.*

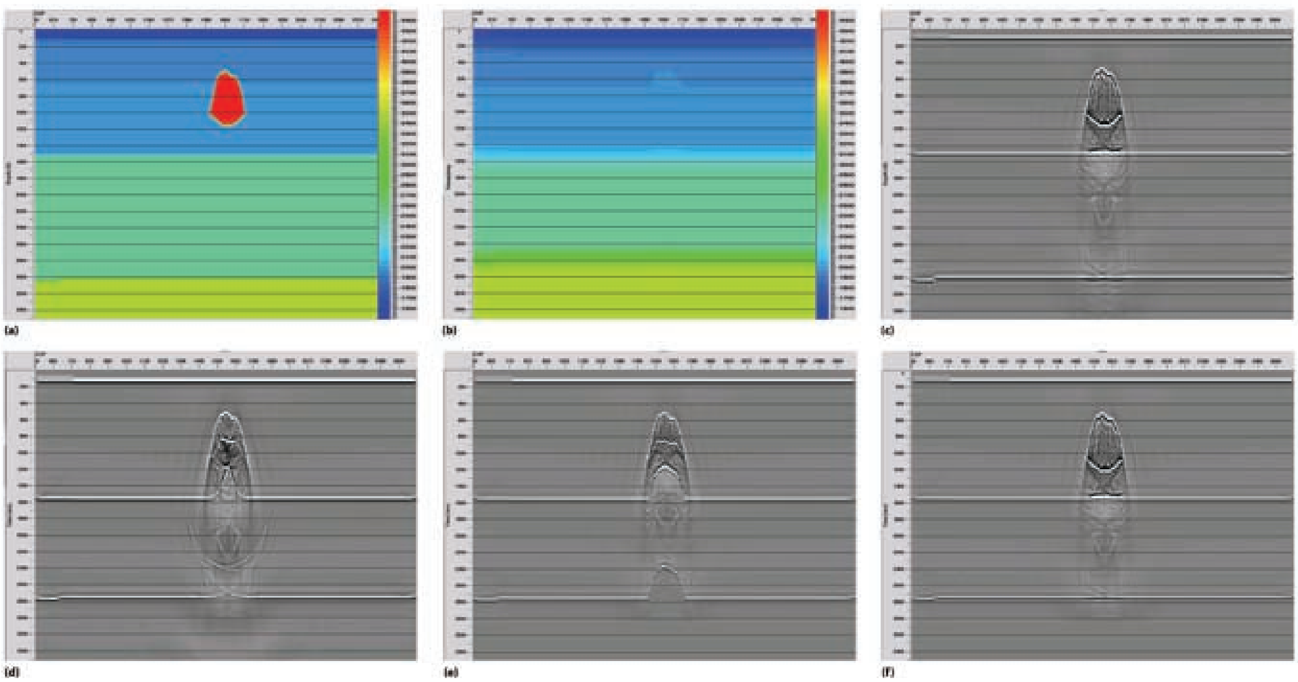

***Figure 4*** *(a) Salt velocity model in depth. (b) Smooth no-salt velocity model in time. (c) FD postSDM result using salt velocity model. (d) FD postSTM result using no-salt velocity model. (e) FD postSDM result using salt velocity model after conversion to time with the same velocity model. (f) FD postSDM result using salt velocity model after conversion to time with smooth no-salt velocity model.*

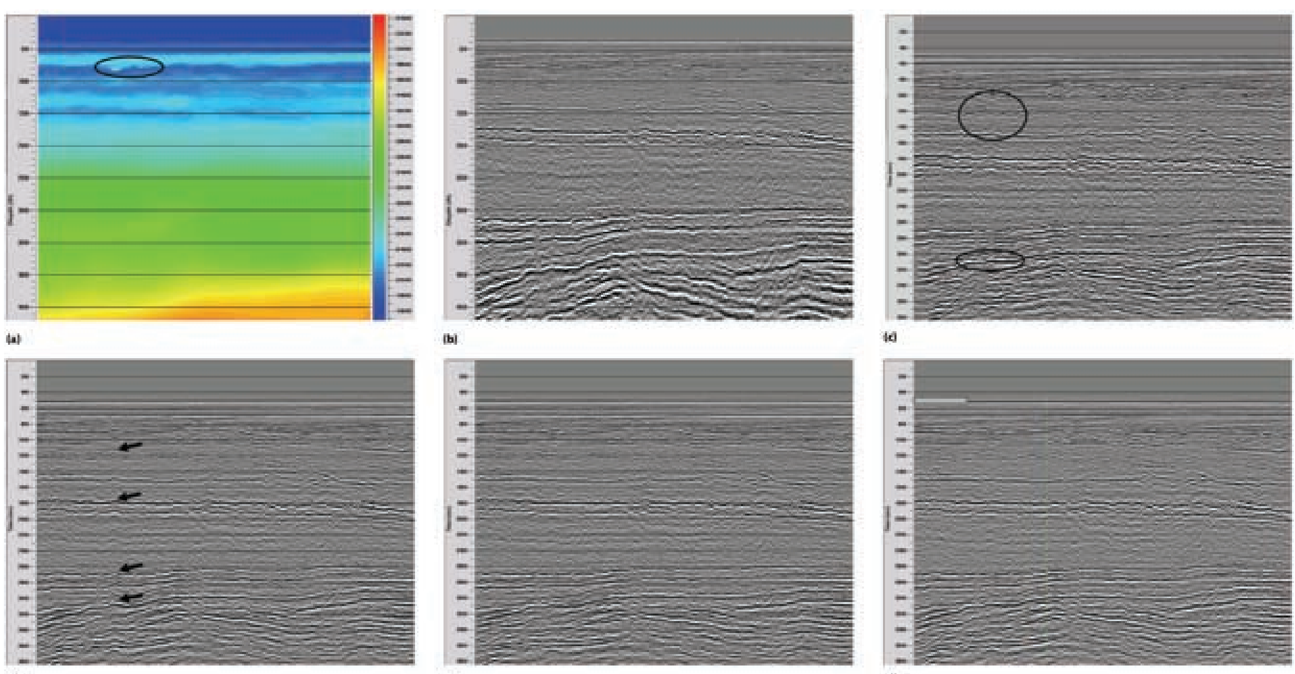

***Figure 5*** *(a) 3D preSDM velocity model. (b) 3D preSDM result in depth. (c) 3D preSTM result in time. (d) 3D preSDM result converted to time with preSDM velocity model. (e) 3D preSDM result converted to time with smooth single velocity function. (f) 3D preSDM result converted to time with smooth velocity function. This model was smoothed laterally only in a vertical window containing the channel.*

resulting from conversion with a smooth model in this case was only ~3ms.

However, if we want to compare horizon interval times of the high velocity layer with those from a previous time migration, we should not perform the conversion with a smooth model.

## Problems with smooth model conversion

In suggesting use of a smooth model for conversion, I have mentioned some of the legitimate problems of taking this route. If the objective is to compare seismic horizons with checkshot information, then we need to be careful. Usually well ties would be

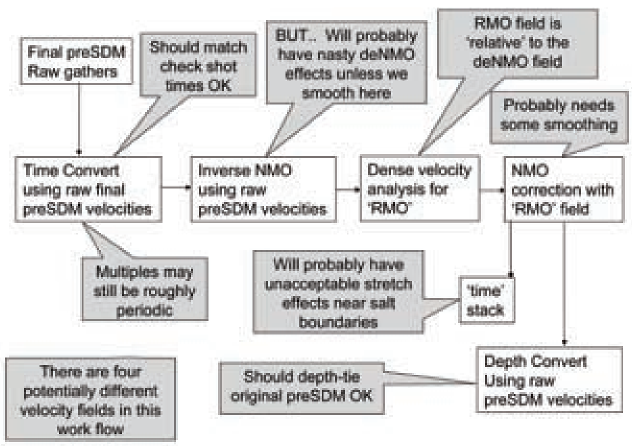


***Figure 6*** *Pros and cons of depth-to-time conversion using raw preSDM velocity field.*

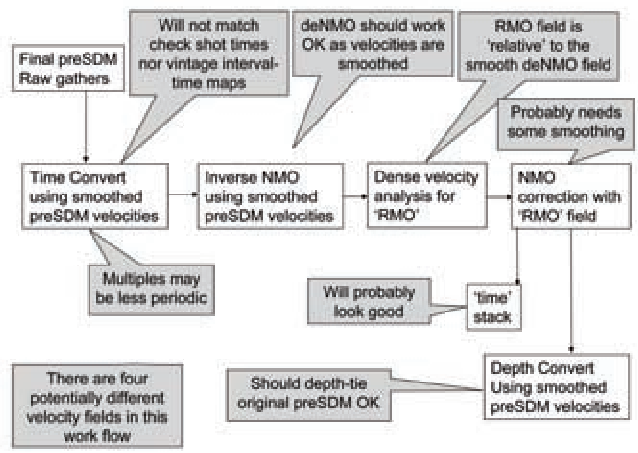


***Figure 7*** *Pros and cons of depth-to-time conversion using smoothed preSDM velocity field.*

done with depth domain data, so a problem does not arise, but if the interpreter wants to compare checkshot times with the time converted preSDM image, then converting to time with a smoothed model will probably introduce a mistie error.

Comparison with vintage time images might also be easier if the depth-to-time conversion was performed with the actual preSDM velocity model. In addition, if we intend to perform several trial time-to-depth conversions with differing velocity functions, then the initial conversion from depth to time should be done with the actual preSDM model.

If we wanted to apply a de-multiple deconvolution, before or after stack, we would have the issue that the period of the multiples may be less regular after conversion with the smooth model. However, if the geology is sufficiently complex for this smooth-versus-blocky discussion to be an issue, the chances are that multiples are not very periodic after preSDM anyway. And for deconvolution before stack, the wavelet would change with offset following conversion with a blocky model.

For residual moveout correction, we are often asked to supply the RMO field which was derived and applied to the gathers. If we use smoothed velocities, and take the route of converting to time by backing out an NMO correction and then estimating a dense velocity field for RMO purposes, this RMO field will be referenced to both the smoothed field used for conversion and the field used for the inverse NMO. As long as this is understood, there will not be a problem, but if the interpreter wants to use the RMO stacking field as a correction to the original preSDM field, then we will have a problem. The RMO correction field derived from the smooth route could be re-calibrated to the unsmoothed velocities by assessing the squares of the differences between smooth and RMO fields: but this is probably not worthwhile. It does, however, raise a theoretical question for pore pressure prediction calibration, but the error is probably insignificant. The flow diagrams in Figures 6 and 7 summarize the possible routes, and highlight the pros and cons of each.

## Conclusions

We have seen that, on balance if we intend to apply post-migration prestack processing to preSDM data, it is preferable to time-convert the depth data using a smooth velocity model. In general, this will not be the preSDM model itself because it tends to include sharp velocity boundaries. Hence we need to introduce a new, separate velocity field for the purpose of depth-to-time conversion. If, however, the objective is solely to compare to checkshot times, or horizon interval times, or to perform a suite of trial time-to-depth conversions, then the depth image could be time-converted with the actual preSDM model.

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