Residual-moveout analysis in presence of strong lateral velocity anomalies

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ABSTRACT

The analysis of a simple synthetic data set recorded above a strong velocity anomaly and a flat reflector illustrates the challenges that can be encountered when performing residual-moveout analysis using a family of curves described by a single parameter. Overcoming these challenges is important if we want to use automatic velocity analysis methods that rely on the derivative of the stack power with respect to the residual-moveout parameter to compute velocity gradients. My analysis shows how, at some reflector locations, the stack-power may have a poorly defined peak because the residual moveout is more complex than the one-parameter model assumes. At other reflector locations, the peak of the stack-power is sharp but it is too far from the value of the parameter corresponding to no residual moveout. Consequently, the derivatives are unreliable, and possibly have even the wrong sign. More robust information could be provided by migrating data with lower frequencies, when available. A more general solution is smoothing the stack power along the residual-moveout parameter before evaluating its derivatives.

INTRODUCTION

Methods to perform wave-equation migration velocity analysis without requiring velocity-spectra picking are attractive and have been the focus of substantial effort at SEP (**???**). Robustness should be an important characteristic of these methods. Therefore, we have focused on algorithms that extract velocity information from migrated angle-domain common image gathers (ADCIG) using a one-parameter residual-moveout analysis. One-parameter moveout analysis has the advantage of being more robust to noise, imaging artifacts, and cycle skipping than alternative methods for measuring residual moveout. It has been extensively used for ray-based migration velocity analysis where it has proven to provide useful information for velocity updating when the moveout parameter is picked from stack-power, or semblance, scans. However, it has not been extensively tested when the velocity information is extracted by computing the derivative of the focusing measure (e.g. semblance or stack power) around the origin of the moveout-parameter axis, as is required by the automatic methods we have been developing.

A one-parameter moveout cannot accurately describe the actual moveout of the

Figure 1: Central part of the velocity model used to model the data. [**ER**]

migrated gathers in some important cases, such as in the presence of strong lateral velocity anomalies and anisotropy. When the velocity errors are large and the migrated gathers display a significant (i.e. larger than the dominant wavelength in the image) moveout at wide angles, numerical differentiation of stack-power scans can be prone to errors caused by cycle skipping.

To test the robustness of one-parameter moveout analysis for automatic wave-equation migration velocity analysis, I performed numerical experiments on a simple synthetic data set. I started from the angle-domain image generated from data that were modeled assuming a strong velocity anomaly, but migrated with a constant background velocity. In the migrated image there are areas that illustrate both the challenges described above (complex residual moveout and cycle skipping caused by large velocity errors). At the original frequency band of the data (25 Hz dominant frequency) the straightforward computation of the gradients would likely result in poor convergence. After I applied a low-pass filter to the data (high cut at 8 Hz) the gradient becomes better behaved. However, seismic data are not currently recorded with sufficient signal-to-noise ratio at arbitrarily low frequencies. Smoothing the velocity spectra along the moveout parameter axis is a simple remedy that does not require low-frequency data. This smoothing is sufficient to overcome the problems identified from the test data set. Numerical differentiation of smoothed stack-power scans provides useful information to be used for a tomographic update even when the data are migrated at full bandwidth.

TEST DATA AND IMAGE

I performed my test on a simple synthetic data set. The data were modeled assuming a strong, and fairly localized, velocity anomaly above a flat reflector. Figure **??** shows the central part of the model. I modeled 400 split-spread shot gathers with offsets ranging from -2 km to 2 km. The source function was a Ricker wavelet with central frequency of 25 Hz.

The localized velocity anomaly caused clear non-hyperbolicity in the data common-midpoint (CMP) gathers. Figure **??** shows two typical CMP gathers in the data set. Figure **??**a shows the CMP gather at horizontal location X=0 km; that is, in the middle of the model, and Figure **??**b shows the CMP gather at X=.55 km. The non-hyperbolicity in the CMP gathers makes this a challenging data set for velocity methods that characterize moveout with one-parameter curves.

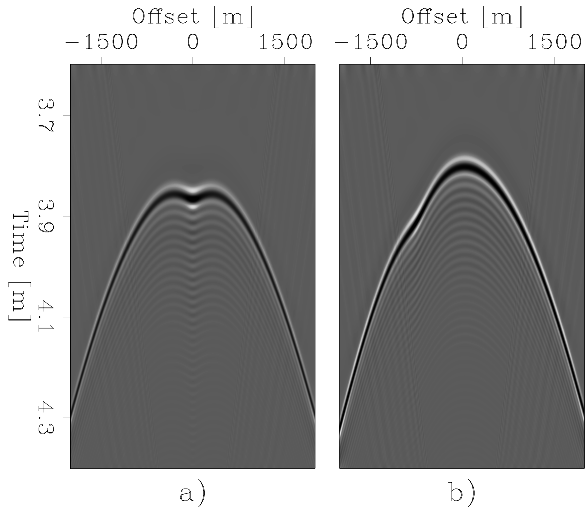

Figure 2: Two typical CMP gathers in the data set: a) X=0 km, and b) X=.55 km. [**CR**]

Migrated image with background velocity

I migrated the data set introduced above by using reverse time migration and assuming a constant background velocity of 1 km/s. Figure **??** shows the angle-domain image produced by this migration. Figure **??**a shows the stacked section (i.e. zero subsurface-offset section). The strong residual moveout prevents a coherent stack in the central area of the reflector, approximately between X=-.8 km and X=.8 km. The three panels on the right of the stacked section display the ADCIGs taken at three midpoint locations, identified by the vertical lines superimposed onto the stacked section; that is, at: b) X=0 km, c) X=.55 km, and d) X=1.1 km.

The one-parameter residual-moveout analysis conducted on this image is based on approximating the vertical shifts as being directly proportional to the square of the tangent of the aperture angle (?). The ADCIG shown in Figure **??**b obviously does not fulfill this approximation because the velocity error is quickly changing along the horizontal direction. Furthermore, because the cumulative kinematic error caused by the anomaly is large, the moveout at wide angles in the ADCIG shown in Figure **??**c is sufficiently large to cause cycle-skip problems even when using a supposedly robust one-parameter moveout analysis.

Figure **??** shows panels equivalent to the ones shown in Figure **??** after the data were drastically low passed before migration. The peak frequency of the data was reduced to 5 Hz, from the original 25 Hz of the full-bandwidth data. Because of the lower frequency, the wide angles in the ADCIG at .55 km (Figure **??**c) do not suffer from cycle-skip problems. Consequently, the stack (Figure **??**a) is now coherent over the majority of the reflector, except in the very central part approximately located between X=-.2 km and X=.2 km.

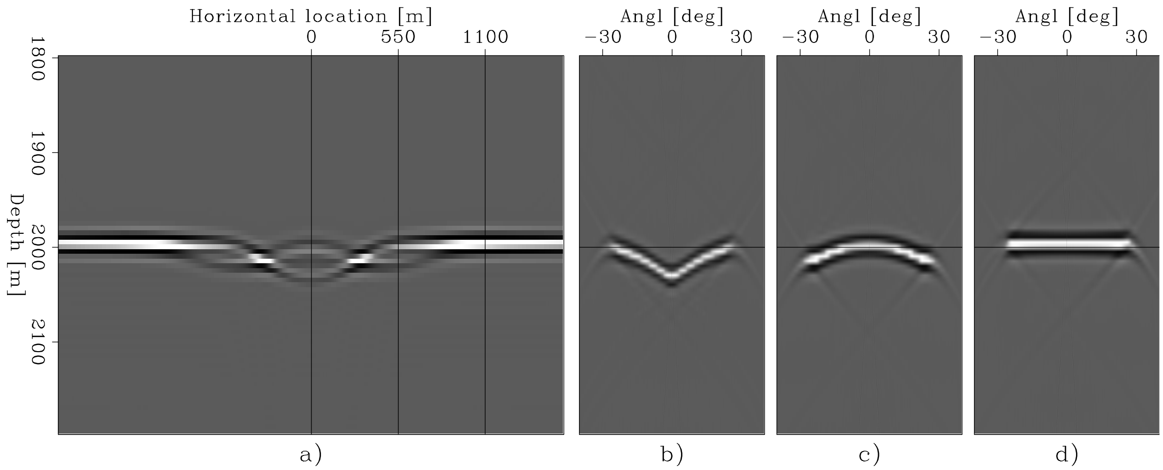

Figure 3: Angle-domain prestack image obtained from the full-bandwidth data set: (peak frequency at 25 Hz) a) stacked section, b) ADCIG at X=0 km, c) ADCIG at X=.55 km, and d) ADCIG at X=1.1 km. [**CR**]

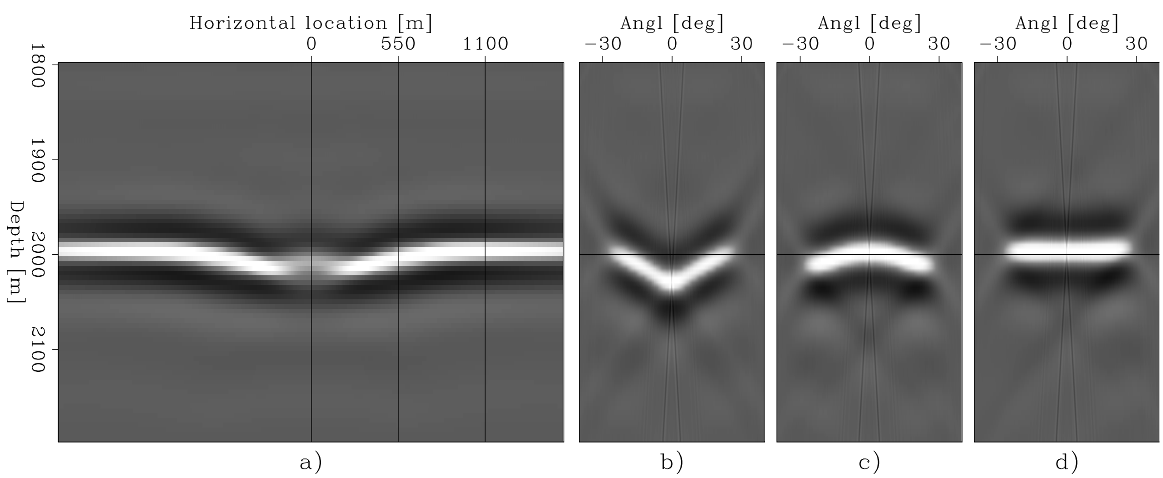

Figure 4: Angle-domain prestack image obtained from the low-passed data set (peak frequency at 5 Hz): a) stacked section, b) ADCIG at X=0 km, c) ADCIG at X=.55 km, and d) ADCIG at X=1.1 km. [**CR**]

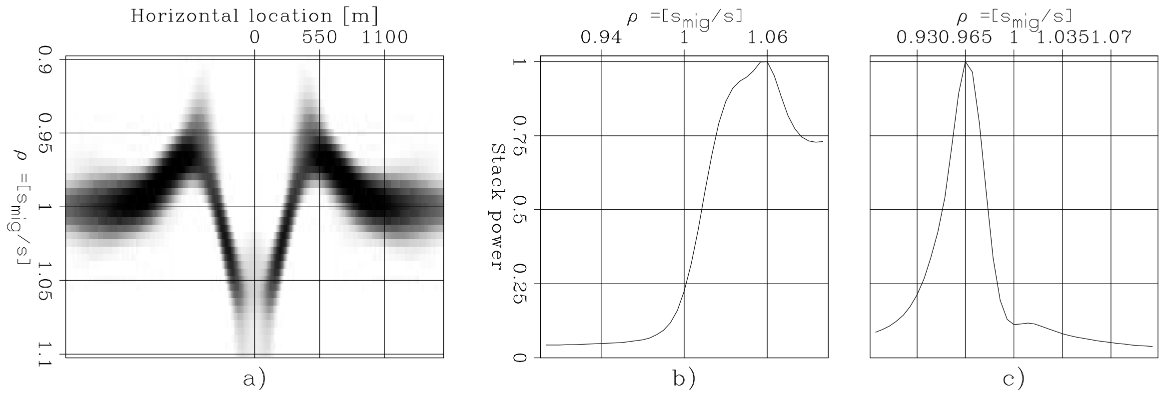

Figure 5: (a) Stack power as a function of horizontal location X and the moveout parameter ρ, corresponding to the full-bandwidth image shown in Figure **??**. Graphs of the function in panel a) at (b) X=0 km, and (c) X=.55 km. [**CR**]

RESIDUAL MOVEOUT ANALYSIS

Starting from the images shown in the previous section, I performed a conventional residual moveout analysis by applying the following angle-domain moveout

$$\Delta z = (1 - \rho) \tan^2 \gamma, \tag{1}$$

over a range of values for ρ, and then computing the stack power from the moved-out ADCIGs. For constant velocity errors in the half space above the reflector, the parameter ρ is approximately related to the ratio between the current migration slowness s_{mig} and the true slowness s; that is, $\rho \approx s_{\mathrm{mig}}/s$ (**?**).

Figure **??**a shows the stack power as a function of horizontal location X and moveout parameter ρ, averaged over the depth interval of the reflector. The panels in Figure **??**b and **??**c show the graphs of this function at (b) X= 0 km and (c) X=.55 km.

In the middle of the reflector the residual moveout is not well described by a one parameter curve, and thus in Figure **??**b the stack power peak is broad and not well defined. Figure **??** shows the central ADCIG before (a) and after (b) residual moveout with ρ=1.06. Whereas the power of the stack is maximum for ρ=1.06 (see Figure **??**b), the gather shown in Figure **??**b is far from being flat.

In contrast, at X=.55 km, the residual moveout is well described by a one-parameter curve and the stack power peak is sharp and well defined in Figure **??**c. However, at $\rho = 1$ the stack power curve is almost flat. If we relied on the numerical derivative of this curve to compute the velocity gradient, we might be relying on the wrong information. The power of the stack is maximum for ρ=.965 (see Figure **??**c) and indeed the ADCIG moved-out with this value of ρ is flat, as shown in Figure **??**b.

A simple solution to the problems identified above could be to image only the low frequency component of the data. Figure **??** shows the stack-power function when

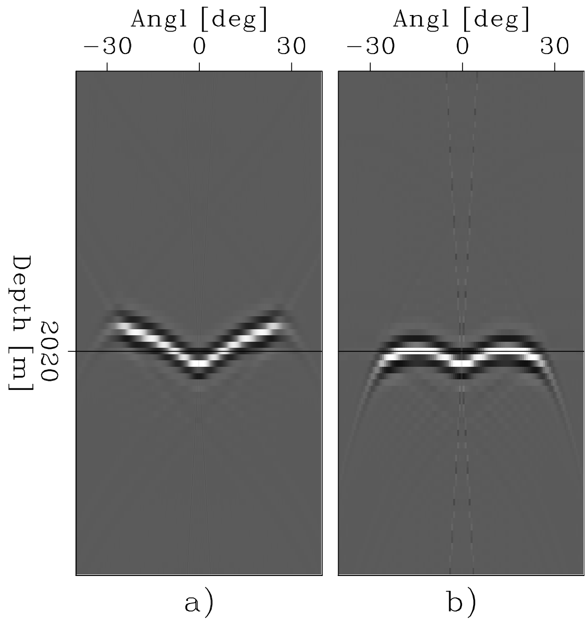

Figure 6: ADCIGs at X=0 km before (a) and after (b) residual moveout with ρ=1.06. [**CR**]

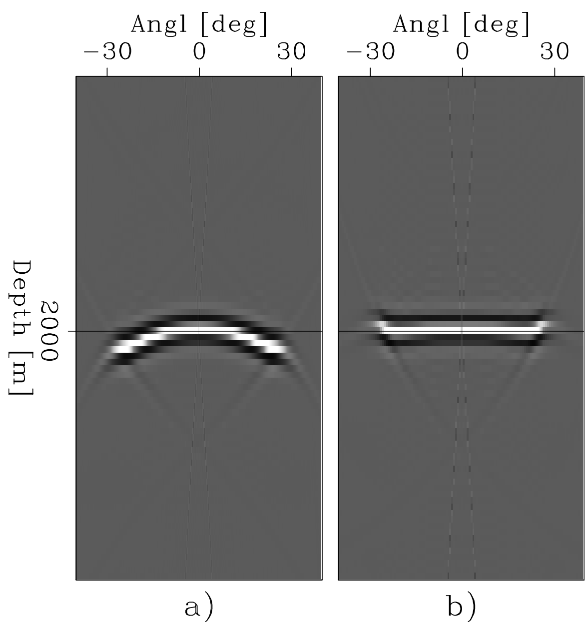

Figure 7: ADCIGs at X=.55 km before (a) and after (b) residual moveout with ρ=.965. [**CR**]

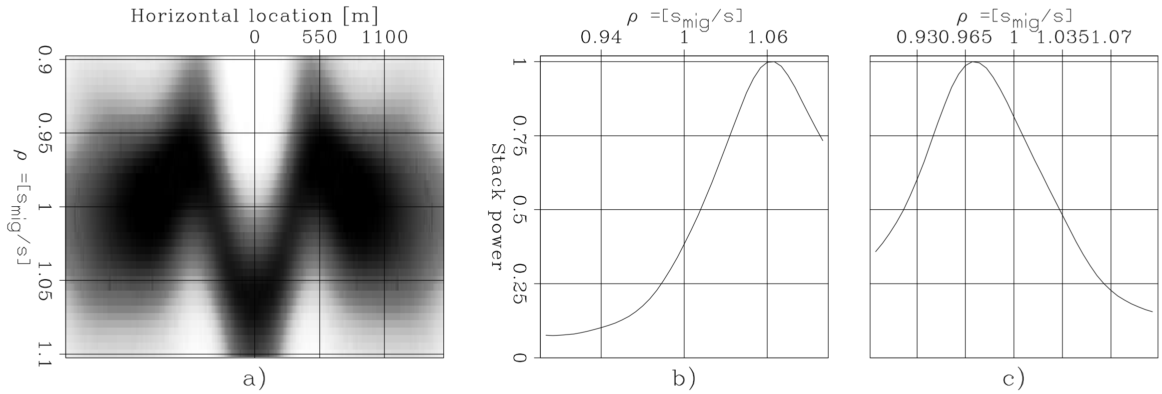

Figure 8: (a) Stack power as a function of horizontal location and moveout parameter ρ corresponding to the low-passed image shown in Figure **??**. Graphs of the function in panel a) at (b) X=0 km, and (c) X=.55 km. [**CR**]

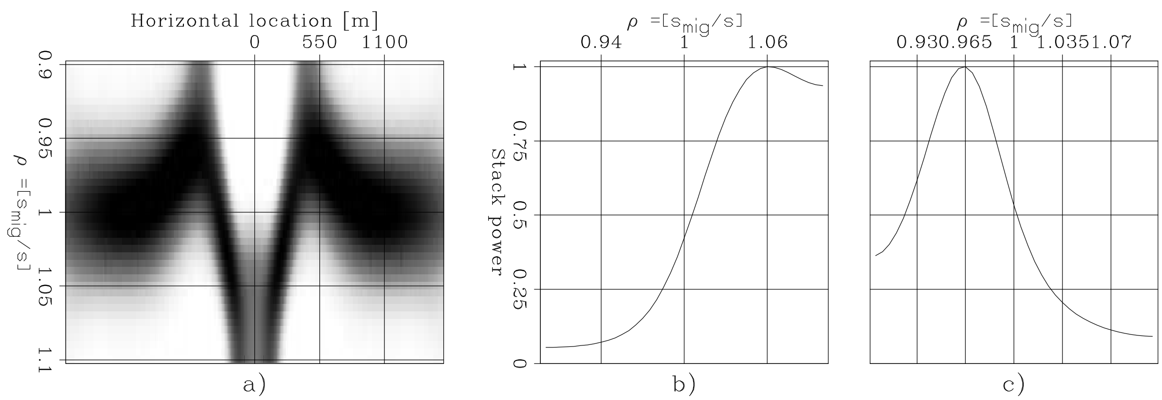

Figure 9: (a) Stack-power function resulting from smoothing along the ρ axis the function shown in Figure **??**. Graphs of the function in panel a) at (b) X=0 km, and (c) X=.55 km. [**CR**]

computed from the low-frequency image shown in Figure **??**. In this case the stack-power peaks are well defined at both X=0 km and X=.55 km, and they are sufficiently broad that the derivative of the stack-power with respect to ρ, evaluated at $\rho = 1$, would provide useful information for the computation of the velocity gradient.

However, seismic data are not always available with sufficient signal-to-noise ratio at low frequencies. In these cases, the challenge can be tackled by smoothing the stack-power function along the moveout parameter before evaluating the derivatives. Figure **??** shows the stack-power function when computed from the full-bandwidth image and then smoothed along the ρ axis. This function has many similarities to the low-frequency one shown in Figure **??**, but does not require data with good signal-to-noise ratio at low frequencies.

Finally, Figure **??** shows the derivatives of the stack-power functions shown in the previous three figures, evaluated numerically at $\rho = 1$. These functions would be

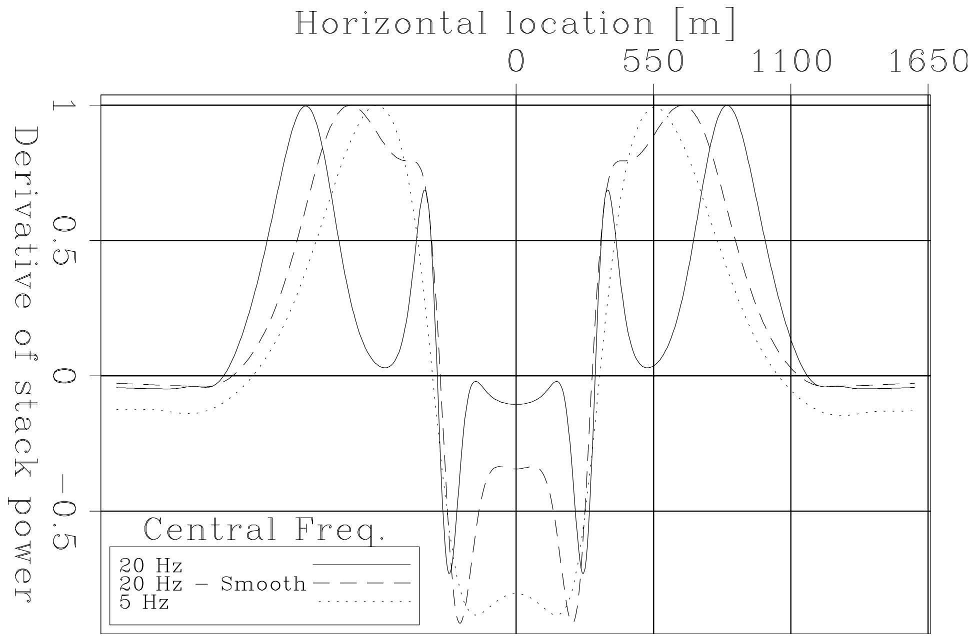

Figure 10: Derivatives of the stack-power functions evaluated numerically at $\rho = 1$: solid line - full-bandwidth data (Figure **??**), dashed line - full-bandwidth data with smoothing (Figure **??**), dotted line - low-passed data (Figure **??**). [**CR**]

the starting data from which the velocity gradient is computed in a wave-equation migration velocity analysis method (**???**). The solid line, which corresponds to the full-bandwidth data without smoothing, would provide misleading information and possibly would prevent proper convergence of the velocity estimation algorithm. On the contrary, both the curve computed from the low-frequency data (dotted line) and the one obtained by smoothing the stack-power along ρ (dashed line) would provide useful information for the computation of the gradient.

CONCLUSIONS

Strong lateral velocity anomalies are challenging for one-parameter residual-moveout analysis. The migrated ADCIGs may display complex moveouts that are not accurately described by a a one-parameter family of curves. Furthermore, when the residual velocity error is large enough, the moveout at far angles may be larger than the dominant wavelength, and thus stack-power spectra may display local maxima. The negative effects of these phenomena can be avoided by imaging only the low-frequency components of the data, when they are available. A more general solution is to smooth the stack-power function along the residual-moveout parameter axis.