High-resolution recursive stacking using plane-wave construction[a]

[a]Published in SEG Expanded Abstracts, 4069-4074, (2016)

Kelly Regimbal[*1] *and Sergey Fomel*[1]
[1] *The University of Texas at Austin*

ABSTRACT

We propose an approach to normal moveout (NMO) stacking, which eliminates the effects of "NMO stretch" and restores a wider frequency band by replacing conventional stacking with a regularized inversion to zero offset. The resulting stack is a model that best fits the data using additional constraints imposed by shaping regularization. We introduce a recursive stacking scheme using plane-wave construction in the backward operator of shaping regularization to achieve a higher resolution stack. The advantage of using recursive stacking along local slopes in the application to NMO and stack is that it avoids "stretching effects" caused by NMO correction and is insensitive to non-hyperbolic moveout in the data. Numerical tests demonstrate the algorithm's ability to attain a higher frequency stack with a denser temporal sampling interval compared to those of the conventional stack and to minimize stretching effects caused by NMO correction. We apply this method to a 2-D field dataset from the North Sea and achieve noticeable resolution improvements in the stacked section compared with that of conventional NMO and stack.

INTRODUCTION

In seismic data processing, common midpoint (CMP) stacking is one of the most fundamental processes that combines NMO-corrected traces across a CMP gather to produce a single trace with a higher signal-to-noise ratio (Rashed, 2014). Many problems arise with the assumptions and principles that set the foundation for conventional CMP stacking. Traditional stacking assumes that the NMO-corrected gather has perfectly aligned seismic reflections (Yilmaz, 2001). However, NMO correction is an approximation that assumes the travel-time as a function of offset follows a hyperbolic trajectory in a CMP gather, which may fail in common geologic settings that involve velocity variations or anisotropy. NMO correction also causes undesirable distortions of signals on a seismic trace known as "NMO stretch", which lowers the frequency content of the corrected reflection event at far offsets (Claerbout, 1985). This violates the assumption of a uniform distribution of phase and frequency of seismic reflections across the corrected gather. Common procedures to eliminate this stretching effect involve muting samples with severe distortions. This causes a decrease in fold and may destroy useful far-offset information essential for amplitude variation with offset (AVO) analysis (Swan, 1988). Inaccuracy in stretch muting with residual "stretching" effects may also produce a lower-amplitude and lower-resolution stack (Miller, 1992).

Several algorithms were developed to improve CMP stacking and enhance resolution of stacked sections by reducing stretching effects. Claerbout (1992) described inverse NMO stack, which recasts NMO correction and stacking as an inversion process in the constant velocity case. This approach combines conventional NMO and stack into one step by solving a set of simultaneous equations using iterative least-squares optimization. Sun (1997) extended Claerbout's idea to the case of depth-variable velocity. The inverse NMO stack operator applied depends on hyperbolic moveout relation and can be employed to remove non-hyperbolic events and random noise. Trickett (2003) uses a variation of Claerbout's inverse NMO stack in his stretch-free stacking method to avoid "NMO stretch". Trickett's results tend to be higher frequency but noisier than a conventional stack. Multiple other algorithms have been proposed that aim to reduce NMO stretching effects (Byun and Nelan, 1997; Hicks, 2001; Hilterman and Schuyver, 2003; Rupert and Chun, 1975; Perroud and Tygel, 2004; Masoomzadeh et al., 2010; Zhang et al., 2013; Kazemi and Siahkoohi, 2011). Wisecup (1998) introduced random sample interval imaging (RSI^2), which maps the CMP gather into the "after NMO space" using the exact moveout times and no interpolation. The NMO-corrected values are collected in the stack, rather than summed, where the input sample values are mapped to their correct time values in the stack. Shatilo and Aminzadeh (2000) proposed a constant NMO correction strategy, which applies a constant NMO shift within a finite time interval that is equal to the wavelet length of a trace. This approach eliminates wavelet stretch and preserves higher frequencies than the conventional method, resulting in a higher resolution stack. However, samples that exist in overlapping time windows are used twice during the correction, resulting in an amplitude distortion. Stark (2013) discussed the idea of signal recovery beyond the conventional Nyquist frequency using an approach similar to the RSI^2 algorithm. The method proposed is an output-driven process, where the stack is defined as a merge trace and has a potentially higher sampling rate than the input traces. Using this approach, the final stacked sections are not necessarily limited to the data-collected Nyquist frequencies. More recently, Ma et al. (2015) proposed a stacking technique based on a sparse inversion algorithm that computes the stack directly from a CMP gather by solving an optimization problem using principles of compressive sensing. This method eliminates the stretch effect of conventional CMP stacking and improves resolution in the stacked section. Silva et al. (2015) introduced a recursive stacking approach using local slopes to compute a stack without stretching effects. In our previous work (Regimbal and Fomel, 2015), we proposed a method that computed NMO and stack in an iterative fashion using shaping regularization to achieve a higher resolution stack that avoids the effects of "NMO stretch".

In this paper, we extend the method of shaping NMO stack (Regimbal and Fomel,

2015) further by introducing recursive stacking using plane-wave construction (PWC) (Fomel and Guitton, 2006) in the backward operator of the shaping regularization scheme (Fomel, 2007). PWC stacking is equivalent to computing the zero scale of the seislet transform (Fomel and Liu, 2010). Shaping regularization implies a mapping of the input model to a space of acceptable models. The shaping operator is integrated in an iterative inversion algorithm and provides explicit control on the estimation result. We start by reviewing shaping regularization in the context of NMO and stack and define the operators used in recursive PWC stacking. We test this approach on synthetic examples to demonstrate the algorithm's ability to minimize stretching effects and improve resolution. We then apply this method to a 2-D field dataset from the North Sea and achieve noticeable resolution improvements in the stacked section in comparison with conventional NMO stack.

METHOD

In geophysical estimation problems, regularization is used to solve ill-posed problems by providing additional constraints on the estimated model. Shaping regularization (Fomel, 2007, 2008) implies a mapping of the input model $\mathbf{m}$ to the space of acceptable functions. The mapping is controlled by the shaping operator $\mathbf{S_m}$. In the linear case, the solution of the estimation problem using shaping regularization is defined as:

$$\hat{\mathbf{m}} = [\mathbf{I} + \mathbf{S_m}(\mathbf{BF} - \mathbf{I})]^{-\mathbf{1}}\mathbf{S_m}\mathbf{B}\mathbf{d}, \tag{1}$$

where $\mathbf{F}$ is the forward operator, $\mathbf{B}$ is the backward operator, and $\mathbf{d}$ is the data. We implement the Generalized Minimum Residual (GMRES) algorithm (Saad and Schultz, 1986) to perform the linear inversion in equation 1.

Shaping regularization in the application to NMO stack utilizes signal from different offsets to reconstruct a high resolution stack. The model $\mathbf{m}$ is in this case a seismic trace at zero-offset and the data $\mathbf{d}$ is a CMP gather. We define the linear operators used in the shaping regularization scheme as:

- $\mathbf{F}$ (forward operator) applies predictive painting (Fomel, 2010) to spread information using a known dip field and then subsamples in time.
- $\mathbf{B}$ (backward operator) interpolates the data in time to a denser grid and stacks in a recursive fashion using local slopes.
- $\mathbf{S_m}$ (shaping operator) is a bandpass filter that controls frequency content.

We implement PWC stacking in the backward operator of shaping regularization which follows local slopes of a CMP gather. The key idea of this stacking procedure is to start at the farthest offset trace of the gather and make a local slope prediction of the preceding trace using PWC (Figure 1a). The partially corrected trace is then stacked with the uncorrected neighbor, which is the input for the next local prediction (Figure 1b). The process is repeated in the offset direction until the zero offset trace is reconstructed (Figure 1c). This recursive stacking approach results in higher resolution stacks compared to conventional NMO and stack. The procedure is equivalent to computing the zero scale of the seislet transform (Fomel and Liu, 2010). Advantages of PWC stacking include eliminating the effects of "NMO stretch" as well as the problem of non-hyperbolic moveout. The approximate inverse of PWC stacking is defined by predictive painting (Fomel, 2010). This algorithm is comprised of two main steps, namely estimating local slopes of seismic events using plane-wave destruction (PWD) (Fomel, 2002) and spreading information from a seed trace inside a volume. In this application, we use the updated model to spread information across the CMP gather using the estimated dip field.

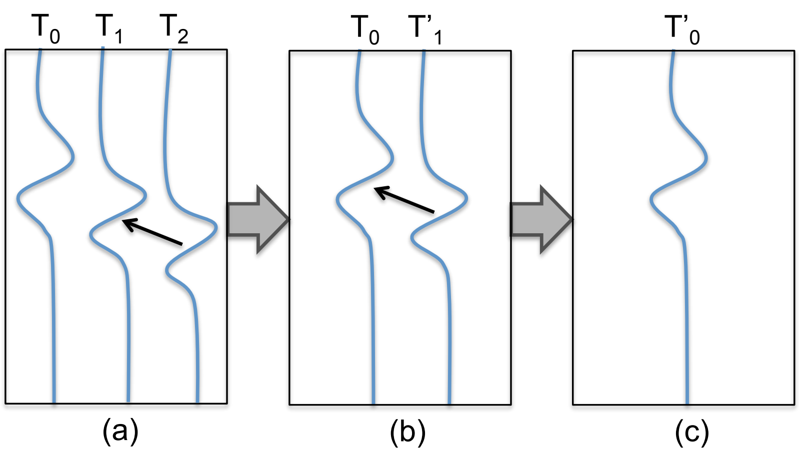


Figure 1: Schematic of the PWC stacking algorithm. (a) Stack far offset trace T_2 with neighboring trace T_1, (b) stack updated trace T'_1 with neighboring trace T_0, (c) final accumulated stack.

In PWC stacking, each seismic trace is predicted from its neighbors that are shifted along the event slopes. Slopes are estimated by PWD, which minimizes the prediction error to estimate optimal slopes. PWD can be sensitive to conflicting slopes at far offsets of a CMP gather when the dip is large and cause PWC stacking to fail in characterizing an optimal stack. To account for this, we first apply a constant velocity NMO correction to the CMP gather, which results in smoothly varying slopes without crossing events. We then estimate the moveout $t(x)$ of the corrected seismic events at offset x as follows:

$$t(x) = \sqrt{t_0^2 + \frac{x^2}{v_0^2} + x^2\left(\frac{1}{v^2} - \frac{1}{v_0^2}\right)}, \tag{2}$$

where t_0 is the zero offset travel-time, v is the NMO velocity estimated by a conventional method and v_0 is a constant velocity. Adding the correction factor due to the constant velocity NMO correction from equation 2, the dip field becomes:

$$p = \frac{x}{t}\left(\frac{1}{v^2} - \frac{1}{v_0^2}\right). \tag{3}$$

We use this estimated dip as the initial model for PWD. This dip estimation scheme follows the velocity-dependent formulation of the seislet transform (Liu et al., 2015) and provides us with a better estimation of the dip field for CMP gathers with large dipping events and conflicting slopes at far offsets. We implement this dip estimation method to compute the PWC stack in an iterative fashion while using shaping regularization (equation 1) to yield a high resolution stack.

EXAMPLES

In our first experiment, we generated a synthetic trace with a sampling interval of 1 ms and used it as a reference trace. This trace was then inverse NMO corrected and subsampled to 4 ms to produce a CMP gather (Figure 2a), which is the input data for PWC stack and conventional NMO and stack. The result of applying a constant velocity NMO correction is displayed in Figure 2b and is used to compute the dip field.

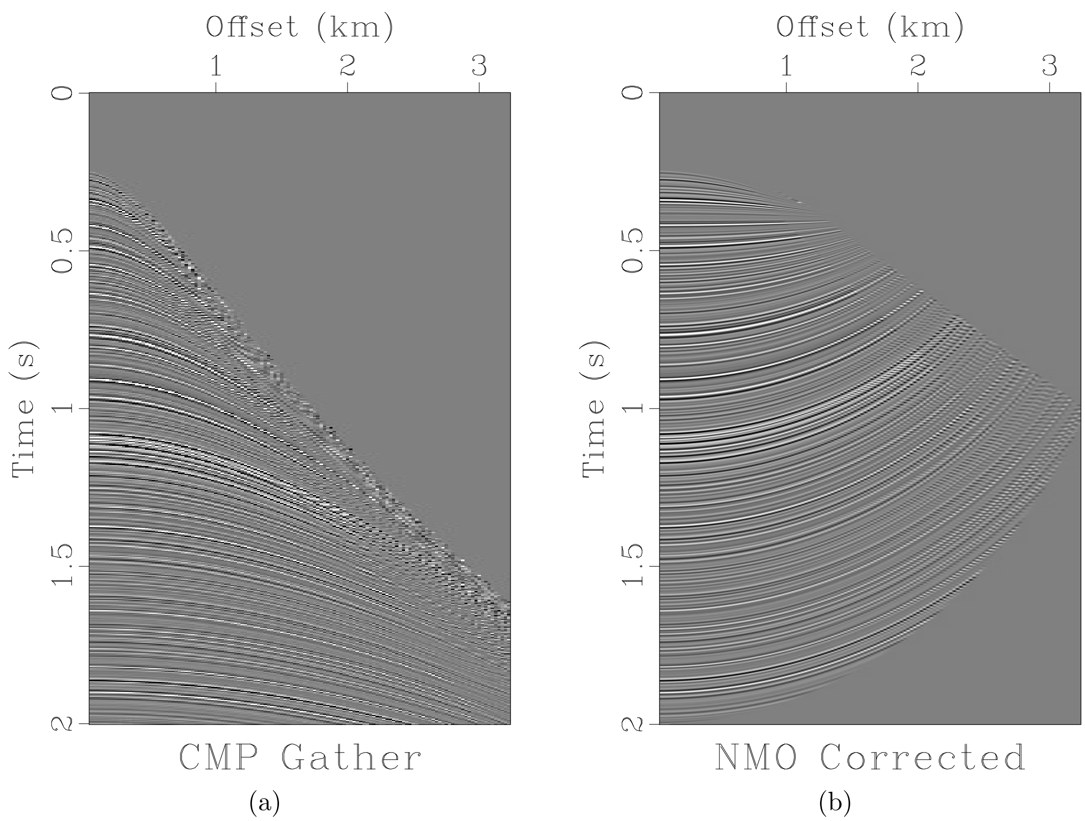


Figure 2: (a) Synthetic CMP gather with 4-ms sampling interval and (b) constant velocity NMO-corrected gather to separate crossing events at far offsets. synseis/ cmp2,nmo0

The convergence of the GMRES algorithm in this example required only 4 iterations to achieve a misfit tolerance of 10^{-5}. The estimated PWC stack is shown in

Figure 3 as a function of iteration, where iteration 0 is the initial model and iteration 4 is the final estimation result using PWC stack. The conventional stack results in lower amplitude and lower frequency content, while the PWC stack achieves results similar to the reference trace (Figure 3). We next compare the frequency content of the PWC stack with the conventional stack (Figure 4a) and the reference trace (Figure 4b). The conventional stack fails to recover useful frequencies ranging from 110 Hz to 175 Hz, whereas the PWC stack contains frequencies up to 175 Hz. Using inversion, we accurately preserve the true amplitude scale and spectrum of the reference trace. One notable observation is the high frequency information recovered beyond the Nyquist frequency of the input data (125 Hz). Ronen (1987) justifies the possibility of such recovery with the idea that a signal can be recovered with the combination of different aliased sequences. Since different offsets correspond to different propagation paths, we obtain different information from each offset. Therefore, the combination of all offsets allows us to reconstruct a higher frequency signal that is not limited by the Nyquist frequency of the input data. In this simple synthetic example, by implementing shaping regularization, we accurately preserve information in the recovered zero-offset trace with a 1-ms sampling interval by using input data with only a 4-ms sampling interval.

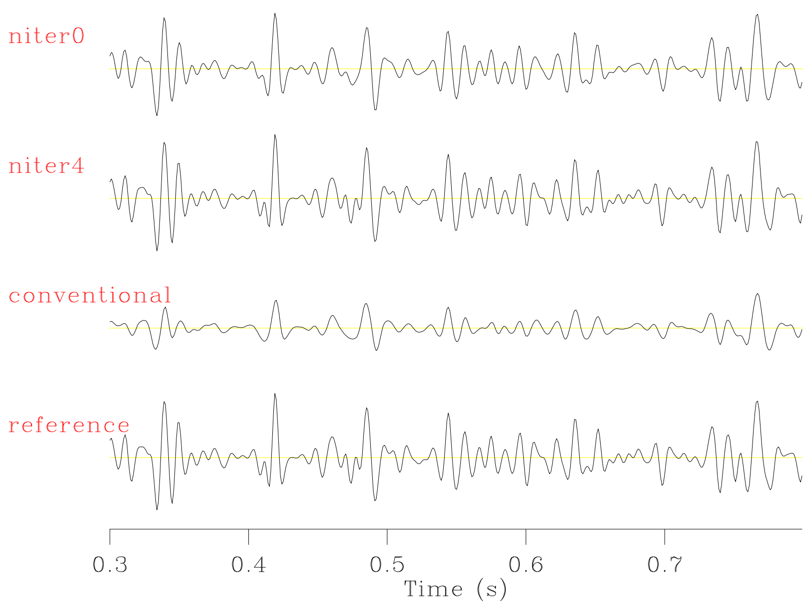
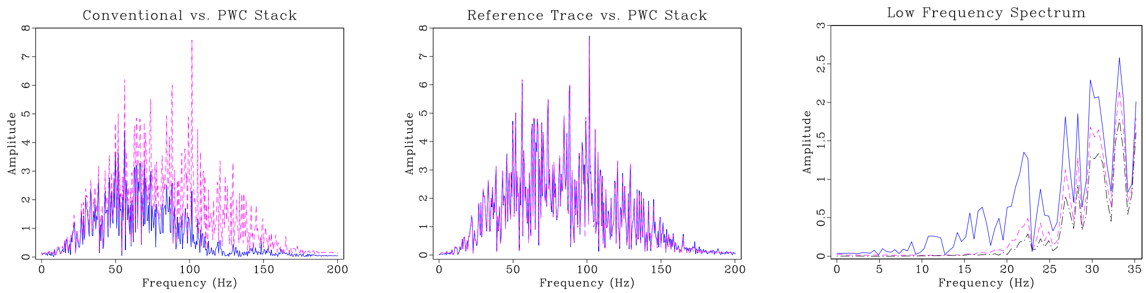


Figure 3: Estimated PWC stack as function of iteration using shaping regularization compared with conventional NMO stack and the reference trace. synseis/ niter

Low frequencies play an important role in seismic inversion for velocity and impedance models (Kroode et al., 2013). We next evaluate the algorithm's ability to recover low frequency information in the estimated stack. We apply a low cut filter to the synthetic CMP gather to remove all of the useful low frequencies below 25 Hz. A spectral comparison of the resulting PWC stack to conventional NMO stack and the reference trace is shown in Figure 4c. We zoom in to the low end of the frequency spectrum to see how well each method does in comparison to the reference



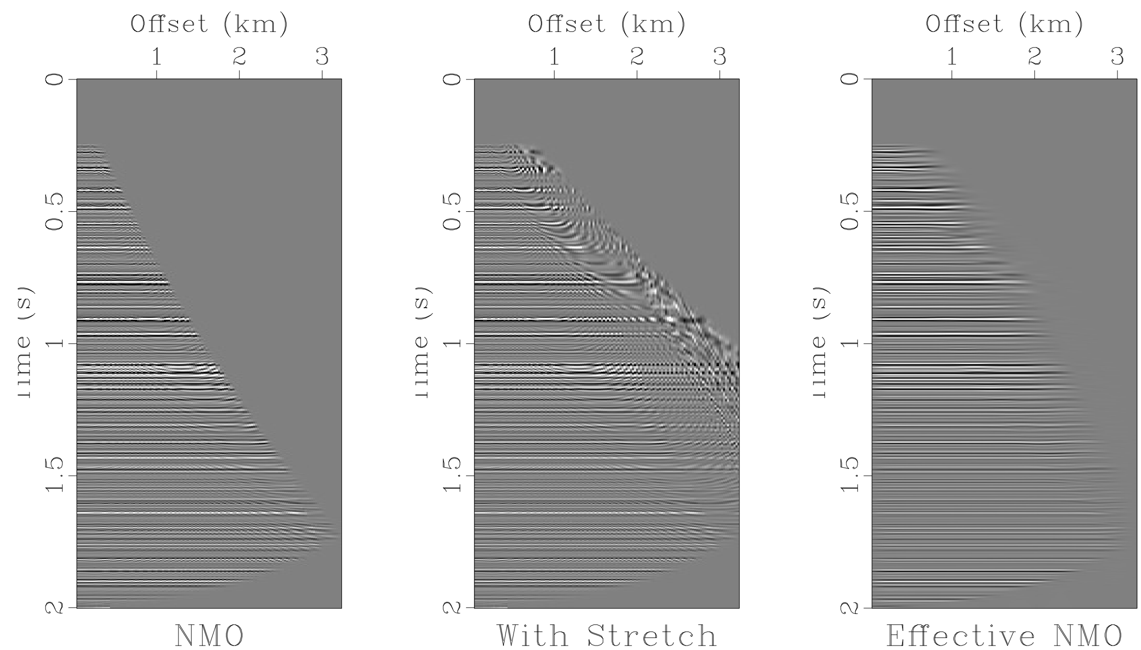
(a) (b) (c)

Figure 4: Spectral comparison of the PWC stack (dashed magenta) with (a) conventional NMO and stack (solid blue) and (b) the reference trace (solid blue) with a 1-ms sampling interval. (c) PWC stack (dashed magenta) recovers lower frequencies in comparison with the conventional stack (dot dash black) and is consistent with the reference trace (solid blue). synseis/ spec5,spec6,speclow

trace. Conventional NMO stack fails to recover frequencies below 25 Hz, while PWC stack recovers more low frequency information that is consistent with the reference trace.

To demonstrate how PWC stack reduces the effects of "NMO stretch", we apply this method to each trace of the CMP gather, setting other traces to zero. After repeating this process for all traces in the gather, we concatenate the output PWC stacks to extract the effective NMO. Figure 5a displays the conventional NMO-corrected gather with a stretch mute applied, where far offset information is lost. Figures 5b and 5c compare the NMO-corrected gather before stretch muting to the effective NMO-corrected gather using PWC stacking. The results indicate that the stretching effects that are prominent at far offsets and early times in the NMO-corrected gather without a stretch mute are effectively reduced by implementing PWC stack.

We next apply this method to a 2-D field dataset from the North Sea and compare the results to conventional NMO stack. This dataset has 1,000 CMP locations and 800 samples per trace with a sampling interval of 4 ms. We use the 4-ms data as a reference for testing the accuracy of our method and subsample the data to 8 ms to provide the input data for PWC stack and conventional NMO stack. The shaping operator used is a bandpass filter ranging from 2 Hz to 100 Hz, which was designed based on the frequency content of the data. The resulting stacked sections are displayed in Figure 6. PWC stack recovers significantly higher frequencies compared to using conventional NMO stack. Thin layers that are unclear in the conventional stacked section become clearly resolved in the PWC stacked section. Overall, events become more continuous and coherent throughout the section using PWC stack, and resolution is noticeably improved.



(a) (b) (c)

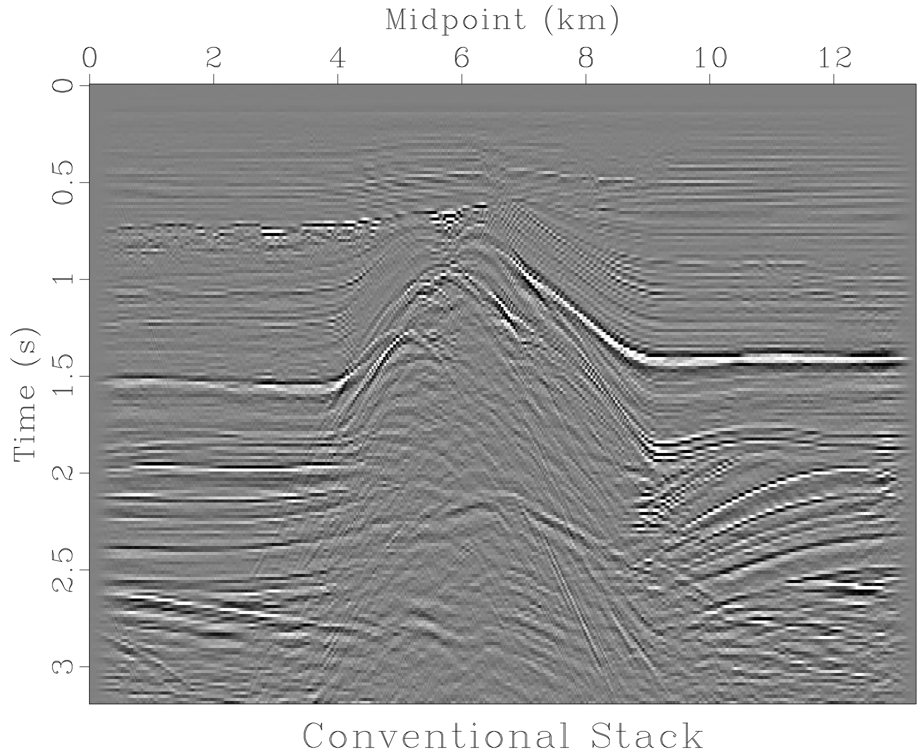
Figure 5: (a) Conventional NMO correction, (b) NMO correction without stretch muting and (c) effective NMO using PWC stack. synseis/ nmo3,nmo2,nsnmo

CONCLUSIONS

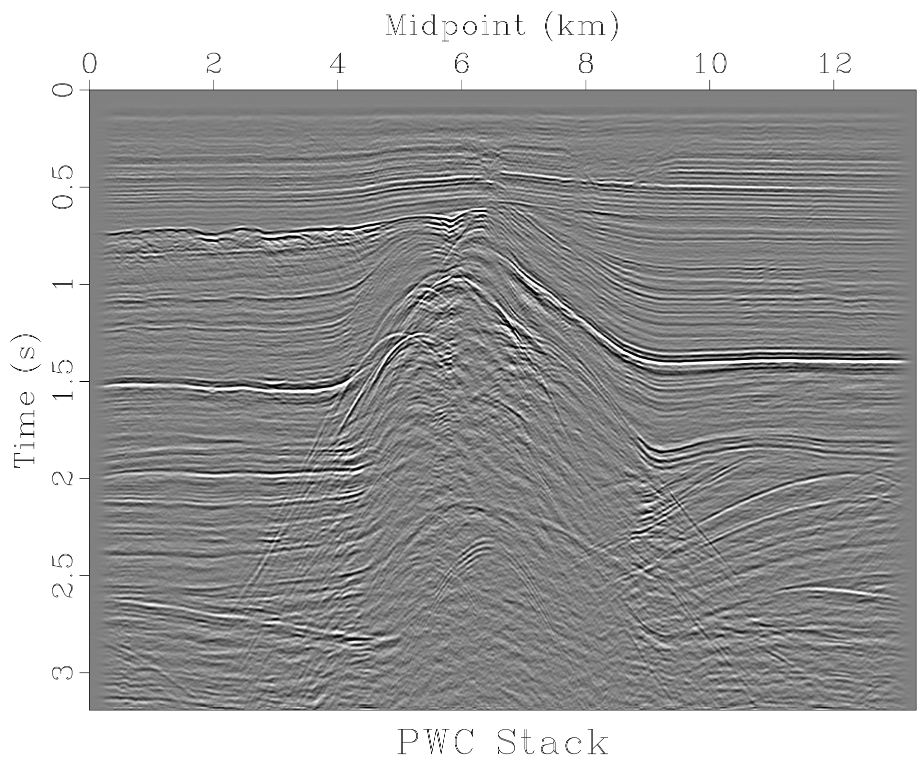
Conventional NMO stack may result in lower resolution stacked sections due to distortions caused by NMO correction and stretch muting. Treating the process of NMO and stack using regularized inversion allows us to compute an optimal stack with higher frequency content. Low frequency content also plays an important role in seismic data processing and imaging. As demonstrated by our numerical examples, PWC stack has the ability to recover both higher and lower frequencies compared to conventional NMO and stack. By implementing PWC stack, we gain resolution by utilizing signal from different offsets and minimizing stretching effects. The final stacked section has improved bandwidth and higher resolution, which may aid in interpretation and inversion of small-scale features such as thin layers and diffractions.

ACKNOWLEDGMENTS

We would like to thank the Texas Consortium for Computational Seismology (TCCS) members for helpful discussions and TCCS sponsors for their financial support.



(a)



(b)

Figure 6: NMO and stack using (a) conventional method and (b) shaping regularization using plane-wave construction. elf/ istack8,ungmres2

REFERENCES

Byun, B. S., and E. S. Nelan, 1997, Method and system for correcting seis- mic traces for normal move-out stretch effects: U.S. Patent, **5**, 684–754.

Claerbout, J., 1985, Imaging the earth's interior: Blackwell Science.

———, 1992, Earth soundings analysis: Processing versus inversion: Blackwell Science.

Fomel, S., 2002, Applications of plane-wave destruction filters: Geophysics, **67**, 1946–1960.

———, 2007, Shaping regularization in geophysical estimation problems: Geophysics, **72**, no. 2, R29–R36.

———, 2008, Nonlinear shaping regularization in geophysical inverse problems: 78th Annual International Meeting, SEG, Expanded Abstracts, 2046–2051.

———, 2010, Predictive painting of 3-D seismic volumes: Geophysics, **75**, no. 4, A25–A30.

Fomel, S., and A. Guitton, 2006, Regularizing seismic inverse problems by model reparameterization using plane-wave construction: Geophysics, **71**, no. 5, A43–A47.

Fomel, S., and Y. Liu, 2010, Seislet transform and frame: Geophysics, **75**, no. 3, V25–V38.

Hicks, G. J., 2001, Removing nmo stretch using the Radon and Fourier- Radon transforms: 63rd Annual Conference and Exhibition, EAGE, Extended Abstracts, A–18.

Hilterman, F., and C. V. Schuyver, 2003, Seismic wide-angle processing to avoid nmo stretch: 73rd Annual International Meeting, SEG, Expanded Abstracts, 215–218.

Kazemi, N., and H. R. Siahkoohi, 2011, Local stretch zeroing NMO correction: Geophysics, **188**, no. 1, 123–130.

Kroode, F., S. Bergler, C. Corsten, J. W. de Maag, F. Strijbos, and H. Tijhof, 2013, Broadband seismic data - the importance of low frequencies: Geophysics, **78**, no. 2, WA3–WA14.

Liu, Y., S. Fomel, and C. Liu, 2015, Signal and noise separation in prestack seismic data using velocity-dependent seislet transform: Geophysics, **80**, no. 6, A25–A30.

Ma, Y., W. Zhu, Y. Luo, and P. Kelamis, 2015, Super-resolution stacking based on compressive sensing: SEG, 3502–3506.

Masoomzadeh, H., P. J. Barton, and S. C. Singh, 2010, Nonstretch moveout correction of long-offset multichannel seismic data for subbasalt imaging: Example from the north atlantic: Geophysics, **75**, no. 4, R83–R91.

Miller, R. D., 1992, Normal moveout stretch mute on shallow-reflection data: Geophysics, **57**, no. 11, 1502–1507.

Perroud, H., and M. Tygel, 2004, Nonstretch nmo: Geophysics, **69**, 599–607.

Rashed, M., 2014, Fifty years of stacking: Acta Geophysica, **62**, no. 3, 505–528.

Regimbal, K., and S. Fomel, 2015, Improving resolution of NMO stack using shaping regularization: SEG, 3859–3863.

Ronen, S., 1987, Wave-equation trace interpolation: Geophysics, **52**, no. 7, 973–984.

Rupert, G. B., and J. H. Chun, 1975, The block move sum normal moveout correction:

Geophysics, **40**, 17–24.

Saad, Y., and M. Schultz, 1986, GMRES: A generalized minimal residual algorithm for solving nonsymmetric linear systems: SIAM, **7**, no. 3, 856–869.

Shatilo, A., and F. Aminzadeh, 2000, Constant normal-moveout (CNMO) correction: a technique and test results: Geophysical Prospecting, **48**, 473–488.

Silva, M., M. Porsani, and B. Ursin, 2015, Recursive stack to zero offset along local slopes: SEG Technical Program Expanded Abstracts, 4323–4327.

Stark, T. J., 2013, Signal recovery beyond conventional Nyquist: The sample rates used for seismic acquisition do not need to limit the maximum recoverable frequencies: The Leading Edge, **32**, no. 11, 1334–1339.

Sun, Y., 1997, Inverse NMO stack in depth-variable velocity: Stanford Exploration Project (SEP) Report 94, 213–222.

Swan, H. W., 1988, Amplitude versus offset analysis in a finely layered media: SEG, 1195–1198.

Trickett, S., 2003, Stretch-free stacking: 73rd Annual International Meeting, SEG, Expanded Abstracts, 2008–2011.

Wisecup, R. D., 1998, Unambiguous signal recovery above the Nyquist using random-sample-interval imaging: Geophysics, **62**, no. 2, 763–771.

Yilmaz, O., 2001, Seismic data analysis: Processing, inversion, and interpretation of seismic data: SEG.

Zhang, B., K. Zhang, S. Guo, and K. Marfurt, 2013, Nonstretching nmo correction of prestack time-migrated gathers using a matching-pursuit algorithm: Geophysics, **78**, no. 1, U9–U18.