Improvement of sub-basalt imaging using parabolic tau-p transformation

R Spitzer and RS White, Bullard Laboratories, Cambridge University, and*
PAF Christie, Schlumberger Cambridge Research.

Summary

Imaging prospective structures lying beneath thick basalt flows presents a key technical challenge in the Faroe-Shetland region. The FLARE-2 profile, recorded in 1996 southeast of the Faroe Islands by the Amerada Hess Ltd. Partner group, was used to test a new approach toward better resolution of sub-basalt structures. In this study, we demonstrate that appropriate re-scaling of seismic data in the parabolic *tau-p* domain has the potential to enhance significantly intra- and sub-basalt reflections. Processing the entire FLARE-2 data set twice, once using conventional time processing and a second time including the new *tau-p* strategy, illustrates the benefits of the proposed scheme.

Introduction

A major problem in the Faroe-Shetland Basin is the presence of basalt flows covering potential hydrocarbon exploration targets. Such basaltic layers (up to several kilometers of stacked flows) create enormous problems for imaging underlying structures using conventional seismic acquisition and processing methods. Scattering from the highly reflective top of the basalt and short-period multiples from intra-basalt boundaries may completely mask reflections from the base of the basalt. Long-period multiples and the generally high attenuation of seismic energy in basaltic rocks may obscure or weaken sub-basalt reflections and images from the basement.

Recent investigations have shown that wide-angle acquisition (e.g., Fliedner and White, 2001; Fruehn et al., 2001) combined with a broad-band, low-frequency source (White et al., 2002) has the potential to overcome some of the aforementioned difficulties. Further, development of processing techniques based on modeling (e.g., Hansen et al., 2001) and converted wave energy (e.g., Barzaghi et al., 2002) enhances our ability to extract sub-basalt information from seismic reflection data.

In this paper we present the results of a new technique for sub-basalt imaging based on the treatment of seismic data in the parabolic *tau-p* domain (slant stack; Gardner and Lu, 1991). In our proposed processing sequence (Figure 1), we "re-scale" the sub-basalt data in the parabolic *tau-p* domain to increase significantly primary reflections relative to multiples and non-reflected seismic energy. We demonstrate that a composite result from post-basalt sediments obtained from conventional seismic processing, and sub-basalt features obtained from optional *tau-p* processing, yields a more comprehensive image compared to conventional processing alone. To test and verify this method, the data recorded within the Faroe Large Aperture Research Experiment (FLARE; White et al., 1999 and 2003) have been revisited and subjected to the new approach.

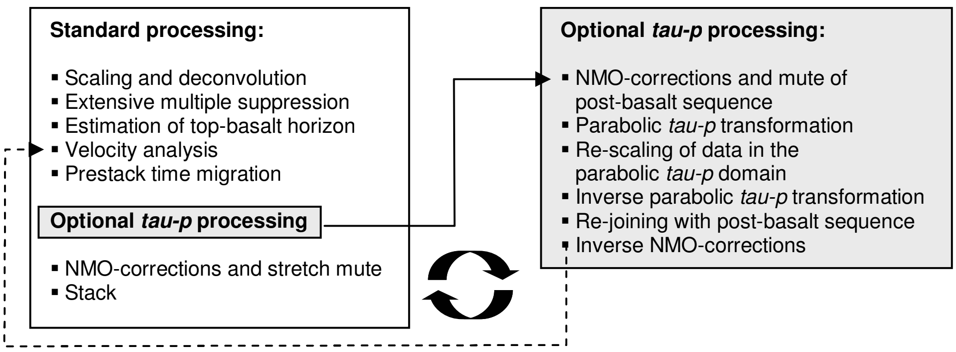

Figure 1. Iterative processing sequence applied to FLARE-2 seismic data set east of Faroes, which includes optional *tau-p* processing for substantial improvement of reflected signal in the sub-basalt part of the seismic data.

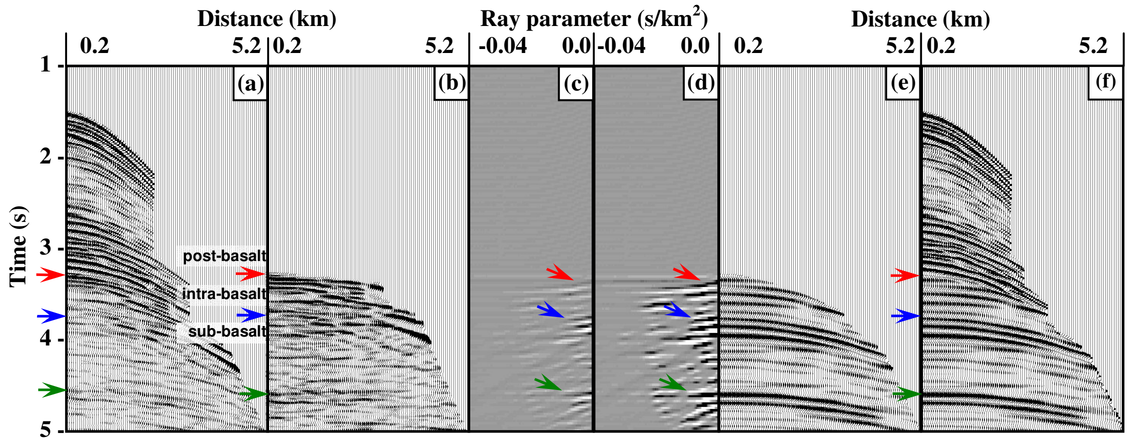

Figure 2. (a) Detailed view of typical CMP gather recorded along FLARE-2 line after prestack time migration (Figure 1). Trace spacing is uniformly 50 m. Relevant top-basalt horizon (marked with red arrow) becomes evident at ~3.3 s. (b) As for (a), except NMO-corrections and top-mute (i.e., based on top-basalt horizon) applied. Identical trace balancing applied to Figures 2a, 2b, 2e and 2f. (c) Result of parabolic *tau-p* transformation applied to (b), where ray parameter $p = \Delta T / x^2$ (ΔT = moveout, x = offset). (d) As for (c), except amplitude of each sample is squared (sign is preserved). Same plot scaling applied to (c) and (d); for display purposes, each trace normalized with respect to mean energy of the entire section. Note reduced noise (i.e., non-reflected signal) level in (d) relative to (c). (e) Result of inverse parabolic *tau-p* transformation followed by inverse NMO-corrections applied to (d). (f) Merged (a) post-basalt sequence and (e) sub-basalt data yields final CMP gather used for updating the velocity field (Figure 1); intra-basalt reflections, base-basalt horizon (marked with blue arrow) and sub-basalt events (marked with green arrow) are markedly enhanced.

Processing strategy

Careful suppression of multiples is critical for the successful imaging of sub-basalt features. Incomplete elimination of multiples may lead to mis-processing and their mis-interpretation as primary reflections. After extensive testing, we decided to apply a 3-step sequence for the suppression of multiple reflections recorded along the FLARE-2 line, which consists of (i) wave-equation modeling, (ii) deconvolution in the linear *tau-p* domain and (iii) muting in the parabolic *tau-p* domain. Figure 2a shows a typical trace-normalized CMP gather recorded along the FLARE-2 profile after the demultiple-sequence and prestack time migration were applied (Figure 1). Strong events from post-basalt sediments (~1.5 s to 3.3 s) and the basaltic sequence (~3.3 s to 3.7 s) are observable. Amplitudes of reflections from interfaces below the basalt are relatively weak and partly covered by remaining multiple energy. Thus, a method capable of enhancing primary reflections relative to multiples and non-reflected energy in the sub-basalt part of the data can be beneficial.

First, we map the top-basalt horizon (red arrow in Figure 2; separates post-basalt sediments from intra- and sub-basalt events) and perform velocity analyses along the entire data set. It is straightforward to estimate stacking velocities within the post-basalt sequence but it is difficult to obtain reliable velocity estimates within and below the basaltic sequence. Therefore, below the top of the basalt, we define constant velocity functions based on estimated stacking velocities at the top-basalt boundary. Although these time-invariant velocities have no physical meaning to the sub-basalt reflections, NMO-corrections using these velocity functions convert all hyperbolic sub-basalt events into approximately parabolic events (Yilmaz, 2001).

This simple processing step followed by muting the post-basalt sequence (Figure 1) yields sub-basalt data with slightly overcorrected parabolic events in the *t-x* domain (Figure 2b), which map approximately to “points” after parabolic *tau-p* transformation (Figure 2c). Since we are interested only in primary reflections, the range of slowness for the *tau-p* transform was limited such that multiples are largely eliminated from further consideration. Multiples show relatively large positive moveout compared to reflections and, would therefore map to positive regions in the parabolic *tau-p* domain. Due to strong attenuation of high-frequency components within the basaltic layer, the received sub-basalt signal along FLARE-2 is dominated by low frequencies. Therefore, we have also restricted the range of frequencies to 0 – 15 Hz for the parabolic *tau-p* transformation, which yields a clearer image of reflected events in the parabolic slant stacks.

The signal-to-noise (S/N) ratio (i.e., reflected energy to non-reflected energy) in the parabolic slant stack

(Figure 2c) is ~10, which means that the summed amplitudes of parabolic events (i.e., reflections) are about one order of magnitude larger than the summed amplitudes of non-coherent events. Squaring each sample value in the *tau-p* domain markedly enhances the reflections relative to other events (Figure 2d). The S/N is ~100 after re-scaling the parabolic slant stack. Inverse parabolic *tau-p* transformation followed by inverse NMO-corrections yields a CMP gather with prominent primary intra- and sub-basalt reflections (Figure 2e). The re-scaling process has markedly increased the sub-basalt signal compared to conventionally processed data (Figure 2a). Finally, Figure 2f shows the joint CMP gather composed of standard post-basalt data (i.e., top part of data shown in Figure 2a) and *tau-p* processed sub-basalt data (Figure 2e), which can either be stacked or subjected to another velocity analyses before final migration (dashed line in Figure 1).

At this point it is important to mention that some amplitude information is changed during the processing in the parabolic *tau-p* domain. Even though generalized discrete Radon transforms have been used (i.e., minimizes differences between input and output data sets in a least-squares sense; Thorson and Claerbout, 1985), squaring the data in the parabolic *tau-p* domain results in alterations of absolute amplitude values. However, relative amplitude variations along sub-basalt reflections are preserved, as we would expect.

Results

We have shown that processing applied in the parabolic *tau-p* domain has the potential to improve significantly sub-basalt signal-to-noise ratios in CMP gathers (compare Figure 2a with Figure 2f). To examine the effects of these improvements on final seismic images, we have processed the entire FLARE-2 data set twice, once using conventional time processing and a second time including the proposed new *tau-p* strategy for the sub-basalt part of the data. Except for the optional items in Figure 1, we have used the same processing sequence with identical processing parameters for the two stacks. Differences between the stacks in Figures 3a and 3b are solely a function of the optional items in Figure 1.

Figure 3a shows the stacked section obtained with standard processing. Figure 3b shows the result of applying the new strategy with the parabolic *tau-p* processing scheme (Figure 1). Sub-basalt reflections on the section of Figure 3b are uniformly more continuous than those on the section of Figure 3a. The advantages of the new strategy for mapping sub-basalt structures are particularly evident: the basement at ~4 s in Figure 3b is hardly recognizable on conventionally processed data in Figure 3a and portions of the intra- and sub-basalt features become more visible after *tau-p* processing (Figure 3b).

Conclusions

Our ability to image seismically the sub-basalt subsurface at many locations worldwide is limited by the fact that basaltic layers are generally characterized by poor seismic penetration for various reasons (e.g., high reflectivity contrast, scattering and attenuation). To address this issue, we propose an efficient processing strategy that enhances reflected energy in sub-basalt seismic data. We have shown that parabolic *tau-p* transformation followed by re-scaling may strongly improve the appearance of sub-basalt reflections. Although we have only described the application of the proposed *tau-p* processing strategy to near-offset data (<6000 m), it is a relatively trivial matter to extend the procedure to handle wide-angle seismic reflection data.

Acknowledgements

The FLARE data used in this article were collected by Amerada Hess Limited and its partners LASMO (ULX) Limited, Norsk Hydro a.s., DOPAS and Atlantic Petroleum. We acknowledge the help of colleagues in the iSIMM (integrated Seismic Investigation and Modelling of Margins) study group which, with the authors, comprises N.J. Kusznir, A.M. Roberts, N. Hurst, Z.C. Lunnon, C.J. Parkin, A.W. Roberts, L.K. Smith and V. Tymms. iSIMM is supported by the UK's Natural Environment Research Council and Department of Trade and Industry, Agip UK, BP, Amerada Hess Ltd., Anadarko, ConocoPhillips, Shell, Statoil, and WesternGeco. The views expressed here are those of the authors, who are wholly responsible for any errors.

References

Barzaghi, L., Calcagni, D., Passolunghi, M., and Sandroni, S., 2002, Faeroe sub-basalt seismic imaging: a new iterative time processing approach: First Break, **20**, 611-617.

Fliedner, M., and White, R.S., 2001, Sub-basalt imaging in the Faeroe-Shetland Basin with large offset data: First Break, **19**, 247-252.

Fruehn, J., Fliedner, M.M., White, R.S., 2001, Integrated wide-angle and near-vertical subbasalt study using large-aperture seismic data from the Faeroe-Shetland region: Geophysics, **66**, 1340-1348.

Gardner, G.H.F., and Lu, L., 1991, Slant-stack processing: Soc. Expl. Geophys.

Hansen, J.O., Tjøstheim, B.A., and Sønneland, L., 2001, Analysis of Long Offset Sub-Basalt Data using Model-based Processing: 71st Annual Internat.

Meeting. Society Expl. Geophys., Expanded Abstracts.

Thorson, J. R., and Claerbout, J. F., 1985, Velocity-stack and slant-stack stochastic inversion: Geophysics, **50**, 2727-2741.

White, R.S., Fruehn, J., Richardson, K.R., Cullen, E., Kirk, W., Smallwood, J.R., and Latkiewicz, C., 1999, Faeroes Large Aperture Research Experiment (FLARE): imaging trough basalt: *In*: Fleet, A.J. & Boldy, S.A.R. (eds) Petroleum Geology Northwest Europe: Proceedings of the 5th Conference, 1243-1252.

White, R.S., Christie, P.A.F., Kusznir, N.J., Roberts, A., Davies, A., Hurst, N., Lunnon, Z., Parkin, C.J., Roberts, A.W., Smith, L.K., Spitzer, R., Surendra, A., and Tymms, V., 2002, iSIMM pushes frontiers of marine seismic acquisition: First Break, **20**, 782-786.

White, R.S., Smallwood, J.R, Fliedner, M.M., Boslaugh, B., Maresh, J., and Fruehn, J., 2003, Imaging and regional distribution of basalt flows in the Faeroe-Shetland Basin: Geophysical Prospecting, **51**, *in press*.

Yilmaz, O., 2001, Seismic data analysis, Vol. 1: Soc. Expl. Geophys.

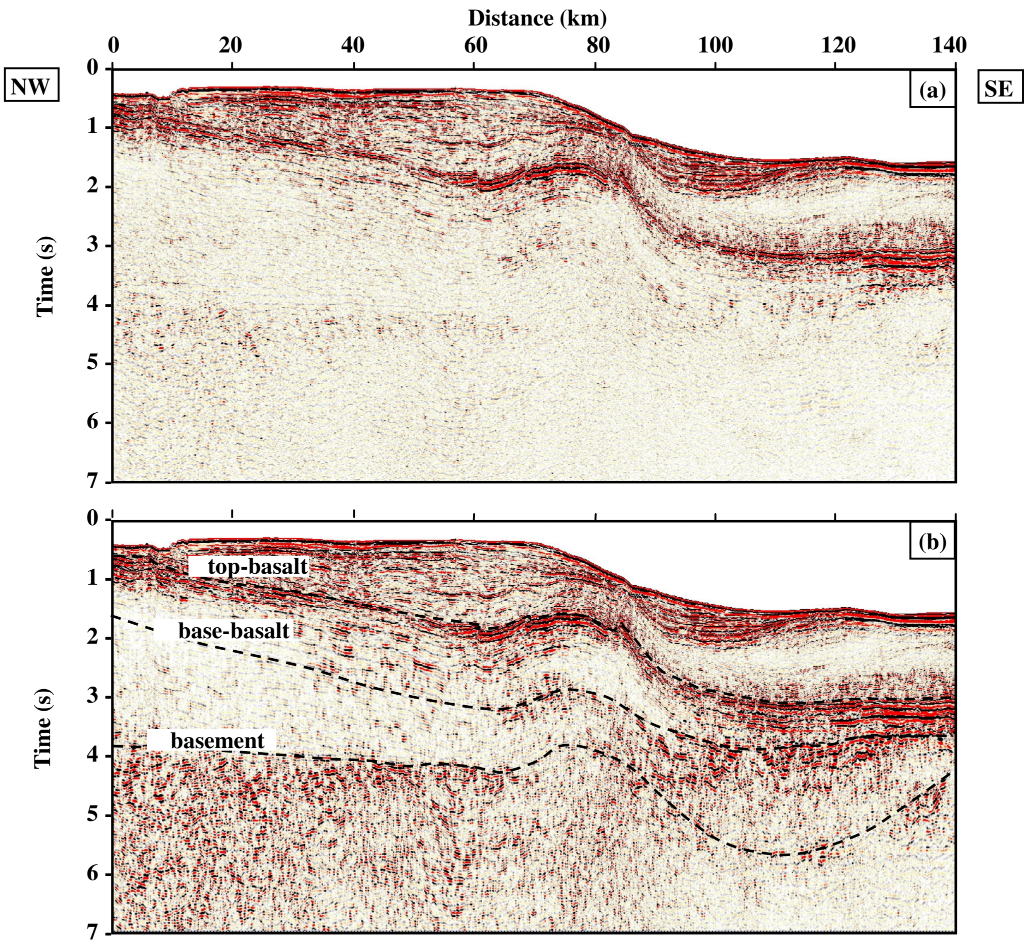

Figure 3. Prestack time migrated sections obtained by (a) applying standard processing, and (b) merged with sub-basalt data obtained from optional *tau-p* processing, with preliminary interpretation superimposed. Identical trace balancing applied to both sections. Except for the *tau-p* processing, the same processing sequence with identical parameters was employed for both sections. Note enhancement of sub-basalt signal, especially reflections indicating the basement around 4 s.