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Wave-equation prestack depth migration for sub-basalt P and converted wave imaging

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ABSTRACT

We apply 2-D wave-equation prestack depth migration to a North Sea basalt dataset. High velocity and impedance contrasts across a basalt layer causes low P-wave reflection signal-to-noise ratio under the basalt. We first migrate the P-wave data with a provided depth velocity model, and then replace sub-basalt P-wave velocity with a simple estimate of shear wave velocity and migrate locally-converted shear waves. Angle domain common image gathers assist our interpretation of a sub-basalt converted wave.

INTRODUCTION

Layers of high-velocity sediments, such as basalt, salt, and carbonates, impede conventional P-wave reflection imaging when the velocity contrast between the high-velocity layer (HVL) and overburden is large. In particular, there are considerable challenges associated with imaging below the flood basalts of the Faeroes-Shetland Basin in the North Sea, though the potential returns generate considerable exploration interest (Ogilvie et al., 2001; Sweetman, 1997). The large velocity and impedance contrasts across the sediment/top-basalt interface seriously hamper traditional time imaging, and decrease available velocity information due to poor coverage in P-wave incidence angle. Based on the quality of current published imaging results over basalt in this region, the key questions on which further investment hinge–basalt thickness, tertiary sediments under basalt, and sub/intra-basalt fault distribution–remain largely unanswered.

For incidence angles greater than the P-wave critical angle, and when the overburden compressional wave velocity is similar to the shear wave velocity in the HVL, a relatively large amount of locally-converted S-wave energy penetrates into the HVL (Ogilvie and Purnell, 1996). In some cases, these locally-converted reflections are energetic enough to be recorded at the further offsets of conventional streamer data. In theory, the "symmetric" converted modes (energy travels as S through the same layers on the source and receiver legs of the raypath) can be imaged by off-the-shelf P-wave algorithms. In practice, however, many factors inhibit the success of sub-basalt converted wave imaging. Strong multiple reflection and refracted waves with complex raypaths (Longshaw et al., 1998) and low signal-to-noise ratio (Hanssen et al., 2000) render identification of converted modes in the prestack domain

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difficult. Additionally, the basalt flows often exhibit a highly complex structure, both laterally (rugose) and vertically (multiple flows, thin layering), the result of which is degradation of the coherency of converted modes (Lafond et al., 1999).

In this paper, we apply 2-D prestack wave equation depth migration to long-offset streamer data recorded in the Faeroes-Shetland Basin by WesternGeco and discussed previously by Kostov et al. (2000). The migration program produces angle domain common image gathers (ADCIG) (Prucha et al., 1999; Sava and Fomel, 2000). Because it is parametrized in terms of an actual physical parameter, we show that the angle domain clearly illustrates critical angle as a function of depth, and is thus well-suited to the task of discriminating between converted wave reflections and other modes. After making appropriate substitutions for *S*-wave velocity in a depth velocity model, we migrate the symmetric and asymmetric converted wave modes in the data and interpret an event on the PSSP section as the base basalt reflection. We then discuss the evidence in support of that interpretation.

DATA BACKGROUND

The data were recorded by WesternGeco in 1999, as part of a multi-client (non-exclusive) survey which acquired a coarse grid of ten 2-D lines. A single 2-D line, consisting of 2943 shots covering roughly 120 km, was donated to SEP. The survey used the following acquisition parameters:

- Shot interval: 25 m
- Group interval: 12.5 m
- Number of channels: 912
- Active array length: 11.4 km
- Near offset: 185 m
- Record length: 9.8 sec at 4 msec

Of the 2943 total shots, we chose to limit our experimentation to the 960 from the center of the survey that were processed by WesternGeco using the Delft Surface Related Multiple Elimination (SRME) technique (Verschuur et al., 1992). Before demultiple, the subset underwent the following preprocessing:

- Swell noise removal.
- Source signature deconvolution using nominal signature.
- Bandpass filtering and subsampling to 8 msec in time and 25 m group interval.
- Truncation to 9 km maximum offset.

After sorting into CMP gathers with 353 traces, the study area covered 26 km of midpoints. Cable feathering over the 120 km line was variable, but unfortunately quite strong over the subset that we studied. Differences between actual and nominal positions reach 2 km at 9 km offset. The SRME demultiple technique assumes nominal geometry, so the feathering issue in this case likely was a first order contributor to the incomplete suppression of multiples at far offsets (Kostov et al., 2000). As we explain later, success of multiple suppression over the entire offset range is a crucial prerequisite to the successful identification of converted waves in both the prestack data and migrated images, since converted waves and multiples have similar apparent velocities. Other factors, such as 3-D effects and source/receiver directivity, also contribute to poorer performance of the SRME method.

WesternGeco also provided a depth velocity model, shown in Figure 1. The basalt layer exhibits a complicated vertical structure. A thin "transition zone" (perhaps interbedded basalt-sediment layers) with interpreted velocity of 3000 m/s gives way to more basalt-like velocities near 4500 m/s. The base of basalt is interpreted as a relatively flat reflector at roughly 3000 meters depth, underlain by a basement assigned a velocity of 5000 m/s.

MIGRATION ALGORITHM

We use a 2-D Extended Split-Step prestack depth migration algorithm (Stoffa et al., 1990) with three so-called "reference velocities" to handle lateral velocity variation. Image sampling in depth is 16 meters, which is probably a bit coarse for the regions of the image above the basalt, but adequate for sub-basalt imaging.

The migration algorithm outputs angle domain common image gathers (ADCIG) for velocity analysis. in fact, the "angle" axis here is parameterized in terms of offset ray parameter, p_h, which is linked to reflection opening angle θ by the following relationship (Prucha et al., 1999).

$$\frac{\partial t}{\partial h} = p_h = \frac{2\sin\theta\cos\phi}{V(z,\mathbf{m})} \tag{1}$$

ϕ is the reflector dip angle, and $V(z,\mathbf{m})$ is the interval velocity in the neighborhood above the reflector point. Sava and Fomel (2000) show an efficient method for direct computation of ADCIGs as a function of opening angle. In both cases, the ADCIGs are easier to interpret for angle-dependent phenomena than are offset-domain common image gathers, a fact that we feel will improve our ability to identify converted waves in the presence of complex multiples and refracted waves.

We summarize some important parameters for the migration below:

- Input data CMP spacing: binned to 25 m (from nominal of 12.5 m).
- Image CMP sampling: 1024 samples @ 25 m (26 km total).
- Image Depth sampling: 325 samples @ 16 m (5.2 km total).
- Frequencies imaged: 3-34 Hz.

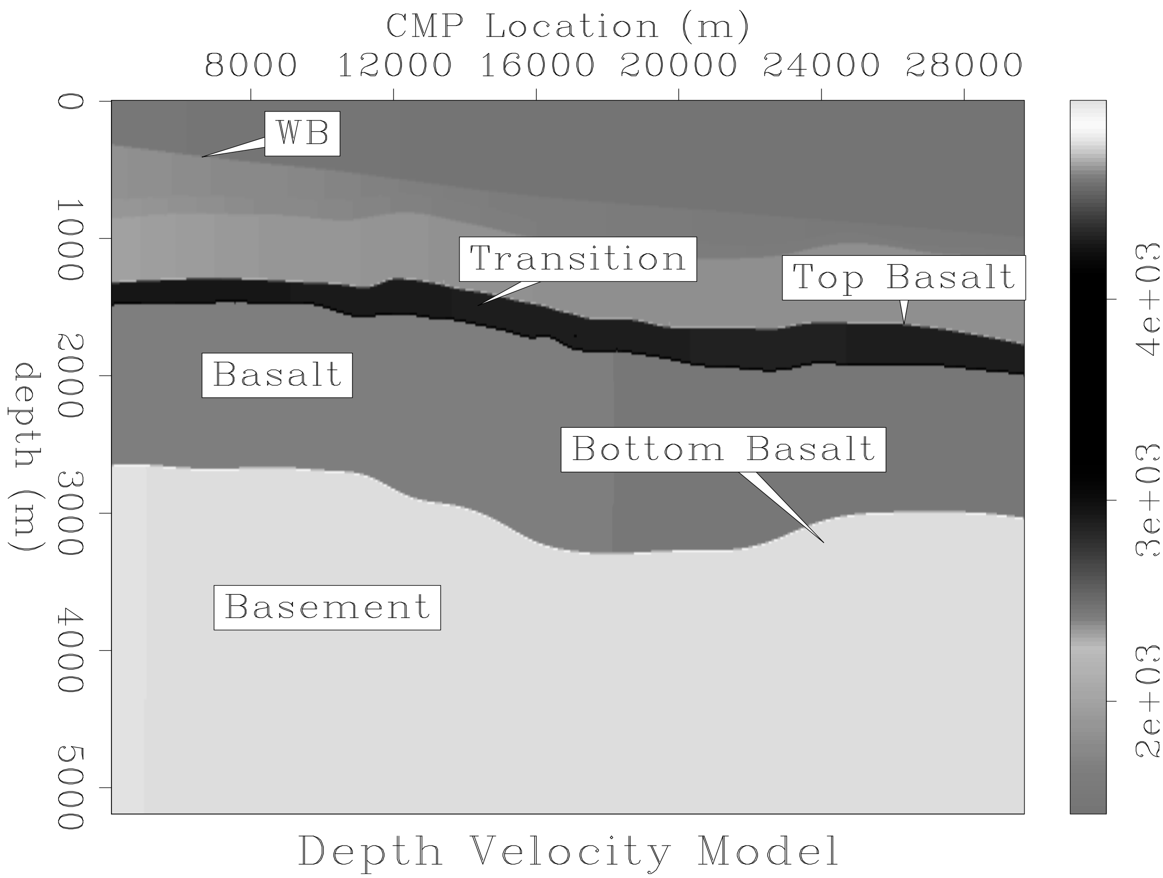

Figure 1: Depth migration velocity model provided by WesternGeco. We used the non-intuitive color scale shown because with the large velocity range (1400-5000m/s), it is impossible to resolve the layer boundaries on a simple grayscale intensity paper plot. Water depth ranges from 300-800 meters. The strongest reflection among the near surface sediments comes from the flat reflector at roughly 1000 meters depth. The transition zone consists of a package of reflectors from the basalt top. Base basalt interpretation is questionable, due to very low interpretable reflection energy. morgan2-vel-p [ER]

- ADCIG sampling: 120 samples @ 8×10^{-6} sec/m.

EVENT IDENTIFICATION

In theory, the maximum transmission of locally converted S-wave energy across a HVL occurs at P-wave critical angle. The reflected P-wave also exhibits an amplitude “bloom” at its critical angle. While this P-wave bloom should be readily visible on ADCIGs, Ogilvie and Purnell (1996) show that it is not visible as a function of offset. We observe this amplitude bloom on depth slices of a constant p_h migration cube, and use it as an indicator of critical angle in our search for converted waves. We also believe that overturned, or diving waves may be present on the ADCIGs as events with a high apparent velocity. Fliedner and White (2001) show the utility of diving waves in estimating the thickness and vertical velocity gradient of the basalt.

When identifying converted waves on ADCIGs, we expect to see events with a lower apparent velocity than primary reflections, and which occur only at larger p_h. Multiples will be seen for all p_h (and similarly have a lower apparent velocity than primaries), while primaries will appear below basalt for small p_h only. If the multiple suppression is incomplete at far offsets, we lose the ability to discriminate between multiples and converted waves via their respective amplitude-versus-p_h dependence. As mentioned earlier, this 2-D survey suffered from strong cable feathering, and we have reason to expect that the SRME demultiple method may not fully attenuate multiples at far offsets. For these reasons, we feel that the raw data should be migrated at some point in the future.

RESULTS

We ran four prestack depth migrations, one for four possible permutations of converted waves. For the “PPPP” migration, we image the usual P-wave reflections, using the velocity of Figure 1. In the “PSSP” migration, we image waves which convert from P to S at the top of basalt, reflect as S, then convert back to P at the top of basalt. The PSSP waves are “symmetric”, meaning that by simply replacing compressional wave velocity with an estimate of shear wave velocity below the basalt, we can image these waves with conventional methods (Gratwick, 2000). We simply scaled the velocity model shown in Figure 1 by 0.6 (corresponding to a V_p/V_s ratio of roughly 1.7) below the top basalt. The last two migrations image the “asymmetric” converted waves, “PSPP” and “PPSP”, or waves for which only one leg of the source-to-receiver raypath contains a sub-basalt conversion. Our migration code can accept different velocity functions for the source-to-reflector and reflector-to-receiver legs of the downward continuation.

Since in all migrations, we assume P-wave propagation from source to top of basalt and from top of basalt to the receiver, we datumed the prestack data to 1200 meters, just above the top of basalt.

Figure 2 shows a `Cubeplot` view of a constant-p_h PPPP migration. The interpreted base basalt reflection is just below 3000 m at this CMP (see Figure 1). On the p_h gather, we see a strong reflection around 3000 m, although it has quite a bit of curvature, meaning it is imaged with too high a velocity. On a time-migrated section (not shown), we interpret this as a likely internal multiple; one that takes an extra bounce between the top basalt and water bottom (event 2 on Figure 3). The depth slice is taken through the top basalt reflection; notice critical angle behavior around $p_h = 0.0004$. Given the velocity of 2800 m/s just under top basalt, the predicted critical angle ($p_h = 1/2800 \approx 0.00036$) is consistent with the estimate. Thus we can use critical angle as a rough means of validating the velocity model.

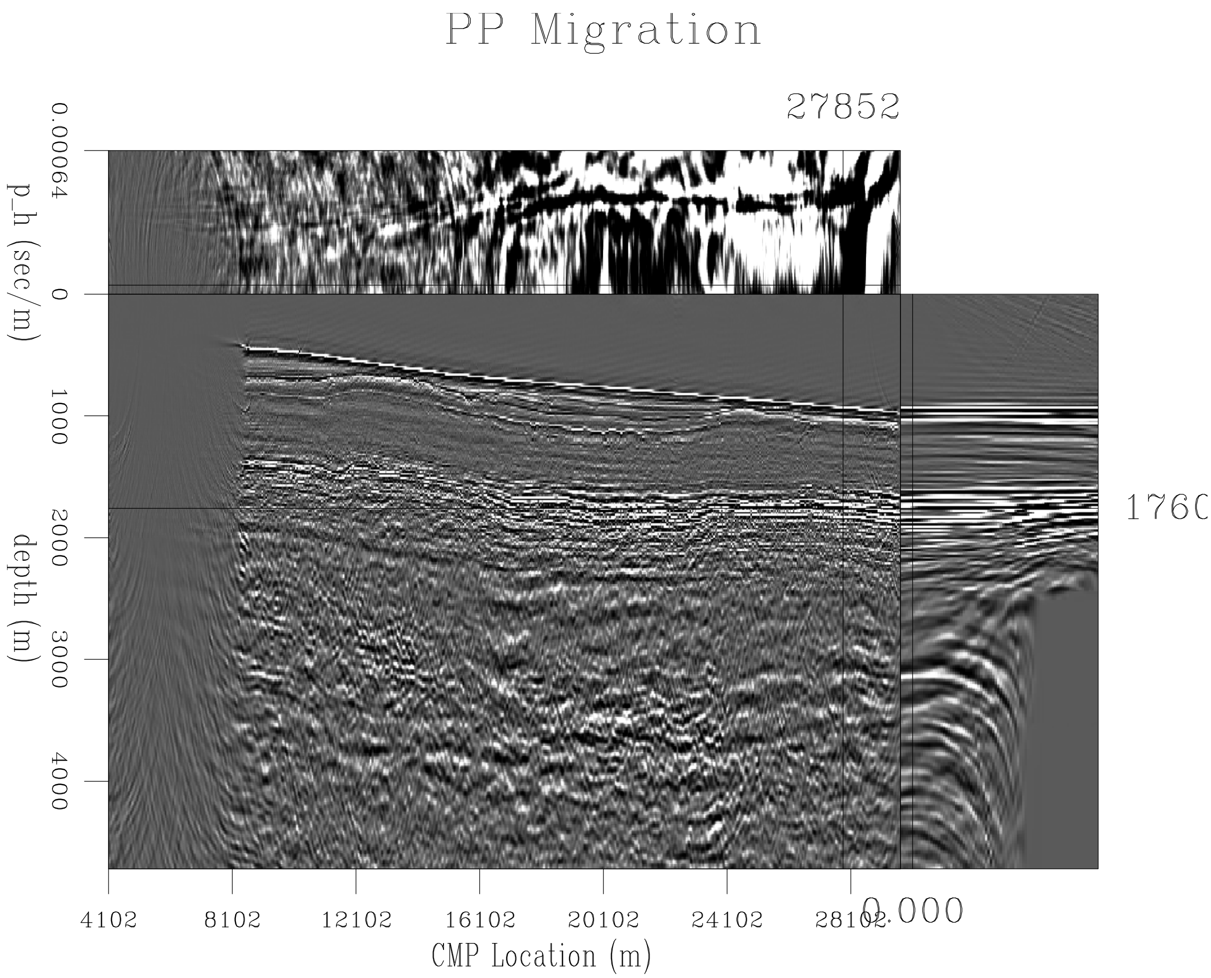

Figure 2: Cubeplot view of PPPP migration. The three axes on the figure are depth, CMP, and p_h. morgan2-mig-cube [CR]

Figure 4 shows five selected ADCIGs from the PSSP migration, from CMP 19352 m to 24477 m. The package of strong, low-velocity events is interpreted as the top basalt water layer multiple (one bounce). However, at a depth of about 2700 m on all gathers we notice two persistent, fast events which occurs only at high p_h. The deeper of the two (marked “C”) is fairly flat, while the shallower one (marked “*”) has a higher apparent velocity, and thus curves upward. At CMP 24477, notice a package of strong events (marked “M”) with higher velocity than the obvious multiples below, but still not flat. Initially, we thought these events

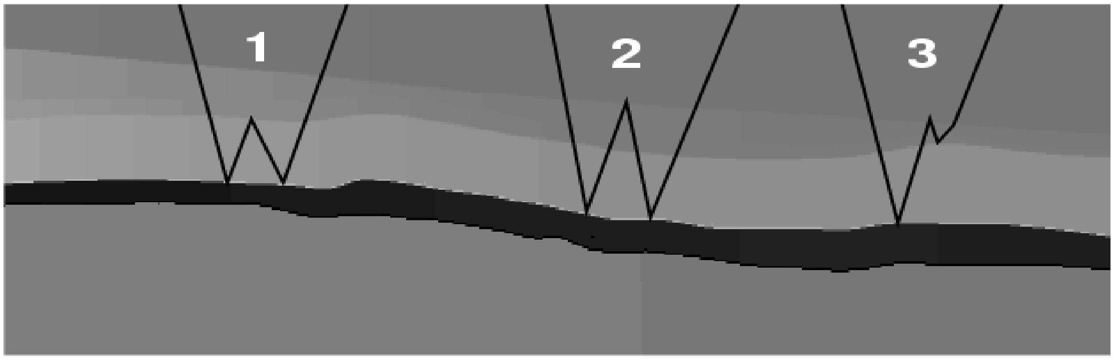

Figure 3: Three possibly energetic internal multiples with a faster apparent velocity than water layer multiples. Because they do not reflect at the free surface, the SRME method is not designed to attenuate them. morgan2-mult2 [NR]

might be converted waves, but on a time-migrated section, we noted that the events have the same character as top basalt and the correct time delay to be a top basalt/water bottom internal multiple (event 2 on Figure 3). Since the events marked “C” seem to be independent from these probable internal multiples, we are confident in our interpretation of these events as real PSSP reflections.

Figures 5-8 show near-angle stacks (for PPPP) and far-angle stacks (for PSSP, PSPP, and PPSP) of the four constant-p_h migrations. The PPPP migration near-angle (p_h = [0.0, 0.00016]) stack (Figure 5) appears to have little interpretable coherent energy below the top basalt. The signal-to-noise ratio appears highest on the right hand side of the image, and we can see a coherent event just below 3000 meters, which has been interpreted as base basalt (compare with Figure 1). A preliminary base basalt has been annotated onto the figure, but the uncertainty is quite high.

The PSSP far-angle (p_h = [0.00040, 0.000696]) stack (Figure 6) has more interpretable energy, but much of it is likely due to un-suppressed multiples. The first top basalt water bottom multiple (TBM1) is readily visible, dipping down from 2000 m depth on the left to 4000 m depth on the right. The second multiple (TBM2) is visible near the bottom of the section. On the right side of the image, we have an interesting package of events, which we believe are internal multiples (labeled “IM2”; event 2 on Figure 3), and which appear convex between CMP 24000-28000 m, and then appear to dip down between CMP 20000-24000 m. The possible sub-basalt PSSP event that we interpreted in Figure 4 is annotated with the CMP location (in kilometers) of the gathers.

Time constraints prevented us from more fully interpreting the results of the far-angle (p_h = [0.00016, 0.000408]) stacks of the asymmetric mode migrations (Figures 7 and 8). Still a few comparative features merit attention. We note that the first top basalt water bottom multiple focuses differently on each plot, and also a slight relative horizontal shift between the two panels. In perfunctory viewing of the migrated gathers, we saw no obvious candidates for PSPP or PPSP waves. We may not be looking in the right places, or our lack of success may

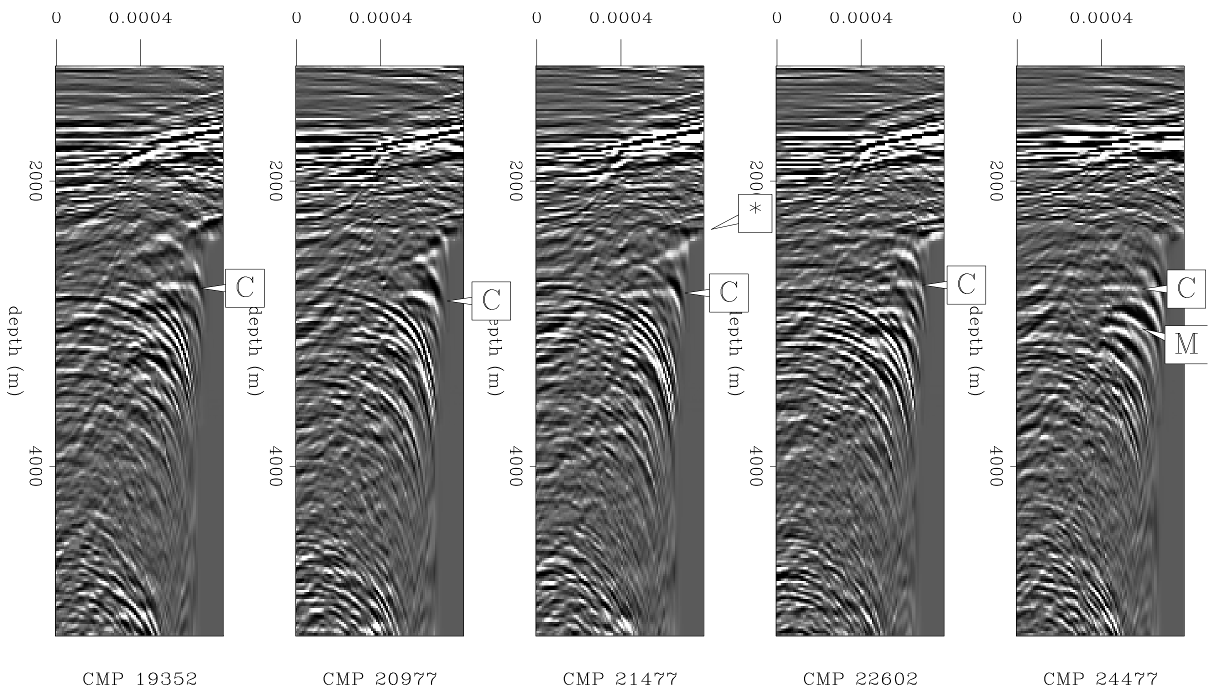

Figure 4: ADCIGs for five CMPs between 19352-24477 m. “C” labels a probable PSSP sub-basalt reflection, possibly the base basalt. “*” denotes a persistent faster event. “M” denotes probable top basalt internal multiple interpreted as base basalt. morgan2-migc-gathers [CR]

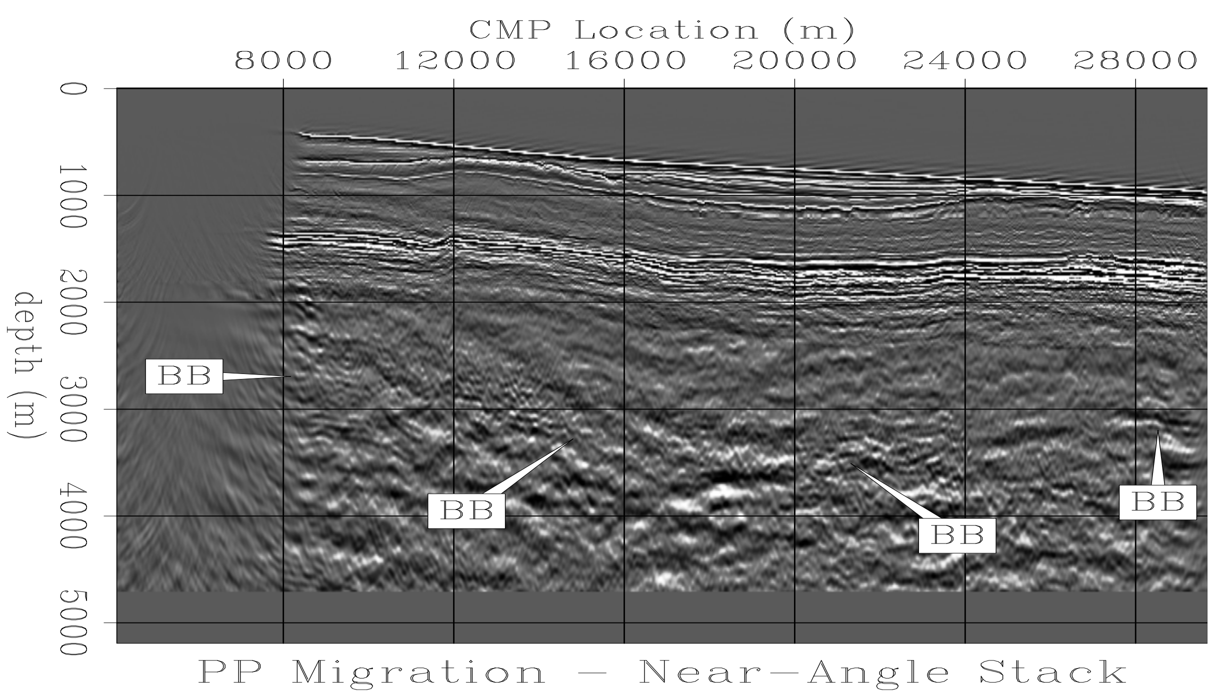

Figure 5: PPPP Migration–near-angle stack. Approximate location of interpreted base basalt labeled “BB”. morgan2-mig-nang [CR]

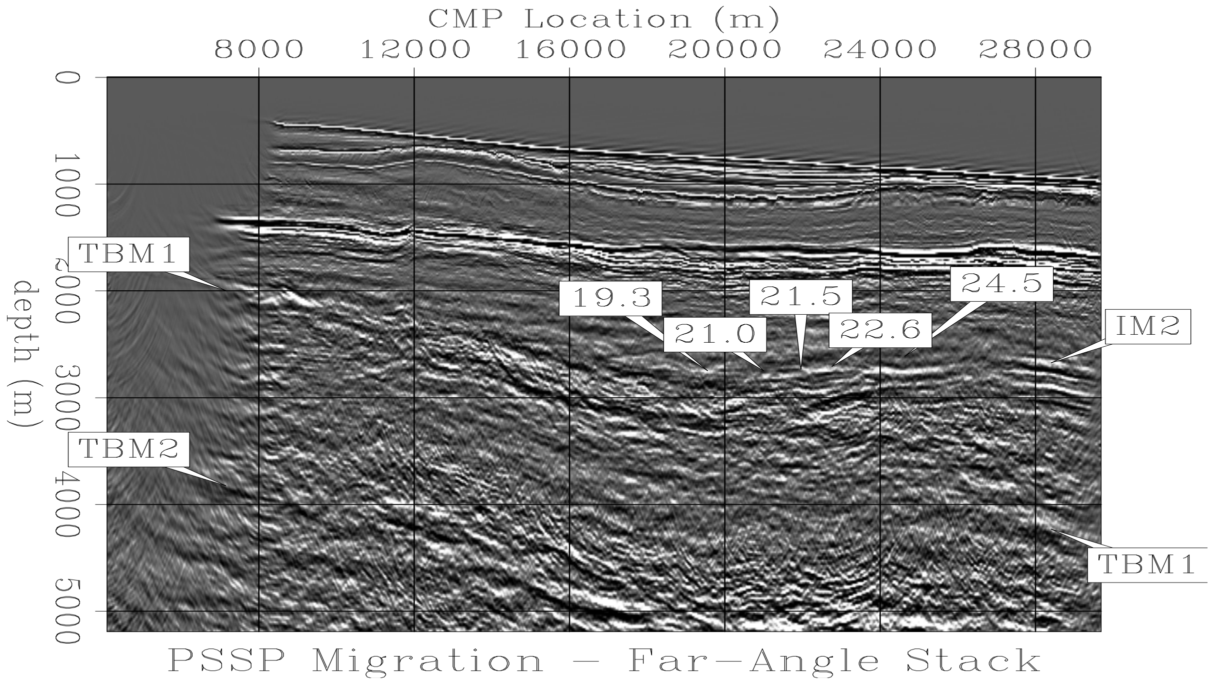

Figure 6: PSSP Migration–far-angle stack. Numeric labels denote CMP locations (in km) of interpreted PSSP waves in Figure 4. "TBM1,TBM2" = first and second top basalt multiples. "IM2" possible internal multiple (event 2 on Figure 3). morgan2-migc-fang [CR]

underscore our need for more serious velocity analysis, or both.

DISCUSSION/FUTURE WORK

We have applied 2-D wave equation prestack depth migration to a long-offset dataset acquired over the flood basalts of the Faeroes-Shetland Basin. We attempted to migrate PSSP, PSPP, and PPSP converted modes by making a suitable replacement of compressional wave velocity with shear wave velocity. In spite of very low subsalt signal-to-noise ratio, we demonstrate that our use of angle domain common image gathers (ADCIGs) facilitated the successful discrimination between a probable PSSP converted wave and multiples in the migrated domain. Still, more investigation and careful processing is required to determine the validity of that interpretation.

Looking to the future, we see many avenues toward improvement. As noted by Kostov et al. (2000) the strong cable feathering in the acquisition of this data contributed to incomplete suppression of multiples at far offsets. Since we used the theoretical amplitude-versus-angle behavior to discriminate between converted waves and multiples, it is crucial either to suppress multiples at all offsets or to image with the raw data.

To improve the performance of the SRME algorithm, we plan to apply azimuth moveout (AMO) (Biondi et al., 1998) to correct for the cable feathering. Although AMO is designed

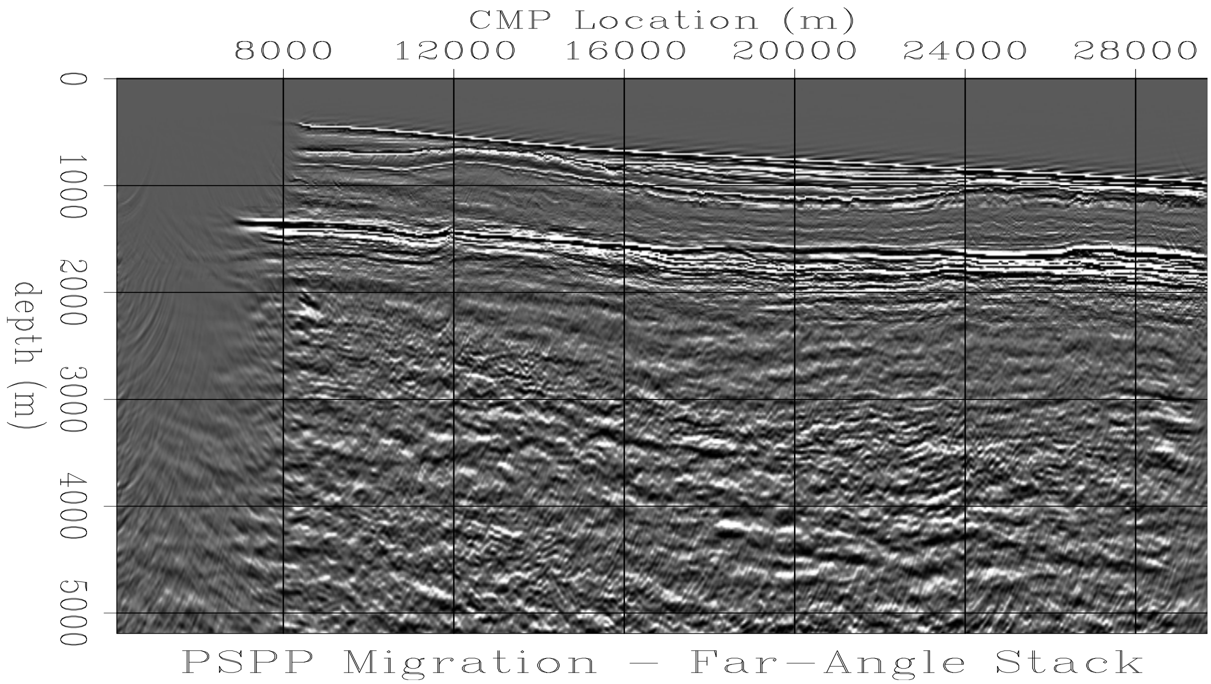

Figure 7: PSPP Migration–far-angle stack. morgan2-migpspp-fang [CR]

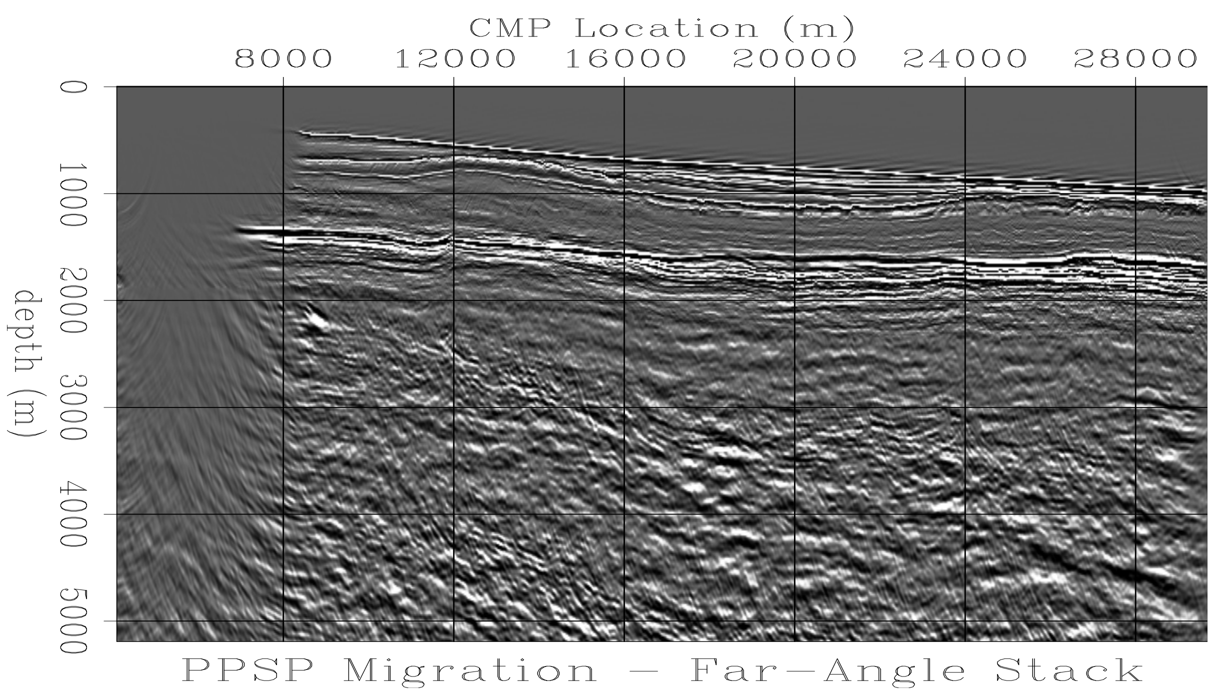

Figure 8: PPSP Migration–far-angle stack. Similar to Figure 7, only shifted slightly laterally. morgan2-migppsp-fang [CR]

for use with 3-D acquisition geometries, we can make a first order correction for the feathering by assuming a 2-D earth.

As normally applied in the industry, SRME attenuates multiples from the free surface only. As mentioned in the body of the paper, we noted that the timing of an energetic internal multiple may have been misinterpreted as the base of basalt. At the very least, we need to time-migrate the raw data, as this domain is superior for interpretation of multiples. Next, we believe that careful wave equation or ray-based modeling is crucial to the identification of these more complex multiples. Alternatively (or additionally), if we construct an excellent velocity model of the region above the top basalt, we should be able to migrate the internal multiples.

The strong velocity contrast over the top basalt makes prestack depth migration a must. Unfortunately, the same velocity contrast also seriously inhibits construction of a velocity model, on which depth migration is notoriously dependent. In order to obtain rough bounds on sub-basalt velocity and structure, we may make use of refracted modes. Fliedner and White (2001) demonstrate the use of diving waves (overturning rays), in conjunction with reflection data, to determine basalt thickness and velocity gradient. We also need to investigate the validity of the simplistic substitution we made for shear wave velocity (constant V_p/V_s ratio). While the simplicity of a single-parameter model is appealing, it is likely unrealistic, given the complexity of most basalt flows. Lastly, migration velocity analysis for the asymmetric modes is poorly defined. The recent work of Rosales and Biondi (2001) on Ocean Bottom Cable PS data shows promise to this end.

Although we record a single wavefield, the individual modes within that wavefield may be viewed as multiple, possibly independent, sources of data. Lu et al. (2000) demonstrate excellent results from the prestack separation, then depth imaging, of converted waves under salt. Taking this philsophy beyond validation of interpretation of base basalt, we can think of having multiple data sources (prestack separation of converted waves and multiples) which produce a single, self-consistent image (obtained by least squares optimization).

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