Velocity estimation for seismic data exhibiting focusing-effect AVO

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Summary

Small-scale velocity heterogeneities can create amplitude variation with offset (AVO) effects by focusing the seismic wavefields. Such effects can impede AVO analysis. They are arranged in spatially consistent patterns. We present the method used until now for detecting focusing-effect AVO (FEAVO) and advance a new method. This transmission-related AVO can be eliminated by prestack depth migrating with the correct velocity model. To find the velocity model, we develop a specific adaptation of wave-equation migration velocity analysis.

Introduction

AVO is commonly interpreted as being caused only by the petrophysical properties of the reflecting interfaces. However, amplitude can also vary with offset due to focusing through velocity anomalies that are too small to give full triplications. Such anomalies can be related to gas-filled lenses or channels (Kjartansson, 1979; Harlan, 1994) or to truncations of thin layers by faults (Hatchell, 2000). FEAVO can be much stronger than interface-related AVO, rendering amplitude analysis impossible.

FEAVO can be eliminated from the seismic image by prestack depth migrating with a velocity model that contains the "lenses" that cause it. The FEAVO problem can be thus reduced to the more familiar one of velocity analysis – albeit with a special target. The spatial extent of these velocity anomalies is close to the seismic wavelength, and their magnitude is only a few percent of that of the velocity background. Although the amplitudes are seriously distorted, the traveltime delays they produce are at the limit of the detectable. A classic approach based on traveltime inversion with infinite-frequency (ray-based) imaging operators is not well-suited to this problem. We will use instead a finite-band ("wave-equation") iterative inversion method that optimizes the quality of the migrated image, with a fitting goal geared specifically for FEAVO.

FEAVO – description and detection

In many cases FEAVO is detected in the interpretation stage, when picked amplitudes vary in a fashion inconsistent with plausible values of physical parameters at the rock interface. This is especially the case when, as in the dataset presented by Kjartansson (1979), the geology is flat and there is no visible need for illumination studies. However, FEAVO effects are spatially correlated in the prestack volume. We will describe the shape of the effects in the data, the classic, manpower-intensive detection procedure, as well as the automatic one that we propose.

If present, FEAVO anomalies are easiest to notice on a time slice from a prestack 2-D data volume acquired in an area with flat reflectors. After performing normal move-out and taking the absolute value of the amplitudes, we can see V-shaped patterns such as those exhibited in Figure 1.

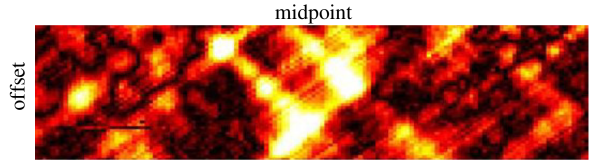

Figure 1: FEAVO effects, midpoint-offset space, before migration

Figure 2 explains how the "V" shapes appear. The upper panel of the figure shows a section through a constant-velocity 2-D earth with one reflector and three small velocity anomalies (in white) at three different depths: at the reflector, between the reflector and the surface, and at the surface. The bottom panel shows the amplitudes at the reflector, in the midpoint-offset space.

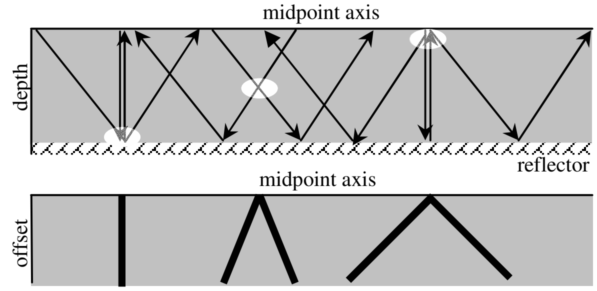

Figure 2: The formation of spatially consistent FEAVO patterns

The anomaly at the reflector will affect only its midpoint, producing a single line of anomalous amplitudes in the midpoint-offset space. The anomaly at the surface will affect, like a static, all midpoints that are closer to the anomaly than the length of the maximum half offset, producing a "V" with a 90^o opening. The intermediate anomaly will produce a "V" shape with an opening between 0^o and 90^o. When multiple reflectors are present, we can notice the V's opening gradually. The same holds true for angle-domain common image gathers (ADCIGs; Biondi, 2003), after prestack depth migration. In the depth-midpoint-angle space, in constant velocity, the path of the anomalies is:

$$z = z_a + | m\text{-}m_a | \cot \theta, \qquad (1)$$

where z_a is the depth of the anomaly and m_a its midpoint. Figure 3 shows an example of such a tent-like, "inverted boat keel" surface for z_a=20m.

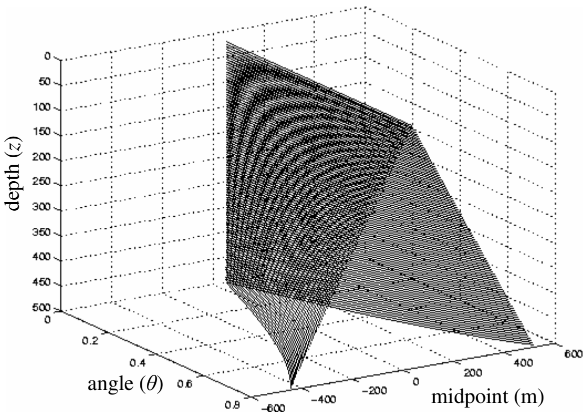

Figure 3: FEAVO path in the depth-midpoint-angle domain

Synthetic examples of enhanced anomalies are shown in Figure 4. The ADCIGs in the figure have been generated in the following way. First, we produced a 2-D velocity model with a background velocity of 2000 m/s and three smoothed, 20m-in-diameter, velocity anomalies. The peak anomalies, as departures from the background, from left to right, were: -153 m/s, -188 m/s, +231m/s (Figure 8A). We used this model to generate a synthetic dataset with six flat reflectors. The dataset was migrated with the correct velocity model, to produce a FEAVO-free image, and with only the background velocity, to produce a FEAVO-affected image. The two images were subtracted, producing ADCIGs that only contain FEAVO effects (Figure 4).

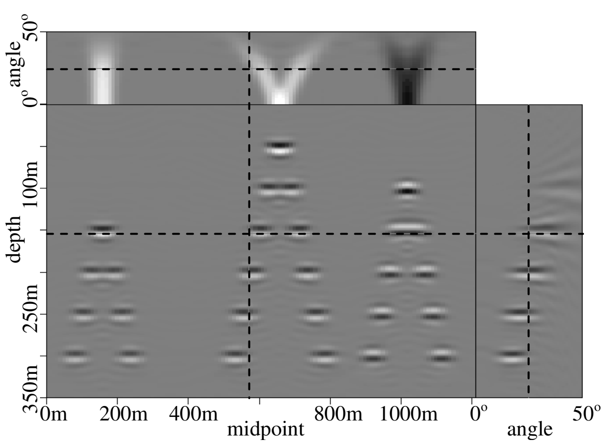

Figure 4: Enhanced FEAVO effects in ADCIGs

Detecting FEAVO by having a person look for "V" shapes in the prestack domain is not feasible for the volumes of data used nowadays. We need a computationally cheap method that would reduce the volume of data to be examined by orders of magnitude and will specifically highlight the presence of FEAVO. We present such a method below.

The reflection amplitudes for incidence angles under 30^o are modeled by Shuey (1985) as

$$R(\theta) = I + G \sin^2(\theta), \qquad (2)$$

where I and G are scalar values depending on the rock properties. This means that if we pick the amplitudes for all angles at a given midpoint-depth location and plot them as a function of the squared sine of angle, the points will arrange in a straight line. Numerical experiments with the FEAVO-affected image used to produce Figure 4 showed that the linear dependence of amplitude from the squared sine of angle breaks significantly when FEAVO is present.

To detect FEAVO, we proceed as follows. At each midpoint-depth location in ADCIGs we compute the best-fitting linear trend in the sin^2-amplitude space, and then we subtract it from the amplitude values. The residuals thus obtained will be close to zero where FEAVO is not present, and will depart from zero in FEAVO-affected areas. For each midpoint-depth location, a large value in the variance of the residual at that point is a direct flag for the presence of FEAVO. Figure 5 illustrates this process.

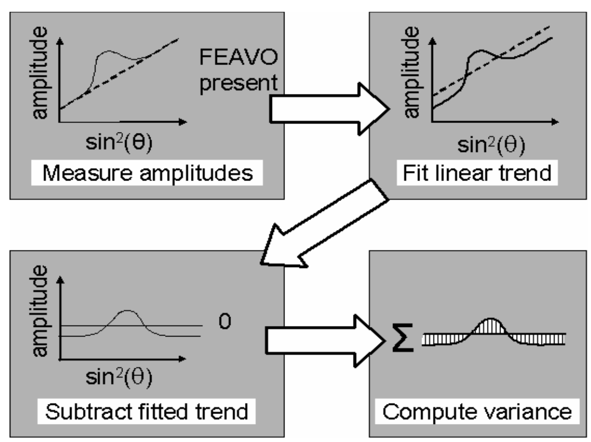

Figure 5: Detecting FEAVO with the variance of the residual

Where FEAVO is present, a measurable deviation from zero will exist even if the subtracted linear trend is not close to the reflector-caused AVO. Using the variance of the residual as a flag for the presence of FEAVO reduces the number of dimensions of the volume to be examined from five to three and specifically highlights only FEAVO. Figure 6 shows the result of applying this process to the FEAVO-affected image used to produce Figure 4. The presence of FEAVO is signaled at once by spatially coherent high values (dark) in the variance of the residual. The stars pinpoint the FEAVO-causing velocity "lenses".

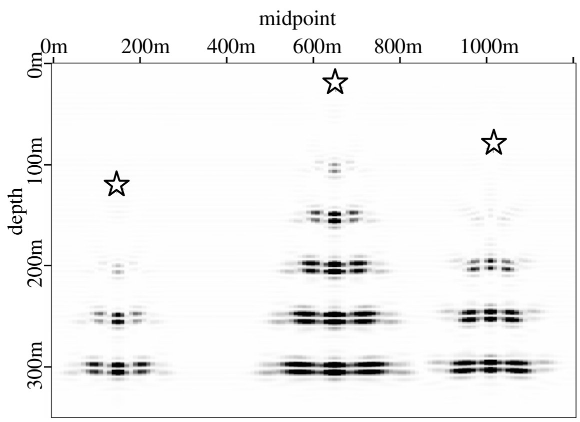

Figure 6: Detected FEAVO effects, as an intensity plot of the variance of the residuals. The velocity lenses are pointed by stars.

This FEAVO detection process is computationally cheap and does not have data-dependent parameters. It can be applied routinely on the prestack migrated image, requiring only a cursory examination of a stack-sized variance-of-the-residuals volume. If FEAVO is detected, it needs to be removed. Image processing techniques risk removing "legitimate" AVO too, or require complicate procedures that involve picking the amplitudes for each reflector separately (Harlan, 1994). The best way to eliminate FEAVO is to improve the velocity model so that the migrated image is focusing-free. Given the small dimensions and magnitudes of the velocity anomalies, we will use a special procedure to find them.

Wave-equation migration velocity analysis

Like tomography, migration velocity analysis (MVA) is based on iterative inversion. While tomography finds the velocity model that fits best the unmigrated data, MVA finds the one that optimally focuses the image after migration. The quality of focusing can be assessed from the flatness and amplitude distribution of ADCIGs. MVA can be done with infinite-frequency (ray-based) operators, or with finite-band ("wave-equation") operators. In particular, ray theory breaks down if its high-frequency assumption does not hold, as is the case with velocity anomalies small enough to generate FEAVO instead of full triplications. Wave-equation migration velocity analysis (WEMVA) was first proposed by Biondi and Sava (1999), which contains the mathematical developments of the method. We present below an adaptation of WEMVA to the specific of the FEAVO problem.

Since the traveltime effects associated with FEAVO are negligible, we assume that a background velocity model that flattens the ADCIGs has already been obtained. We proceed then to refine the velocity model by performing WEMVA's iterative inversion with a fitting goal specifically designed to detect FEAVO patterns in the image. Figure 7 presents the adapted WEMVA flowchart.

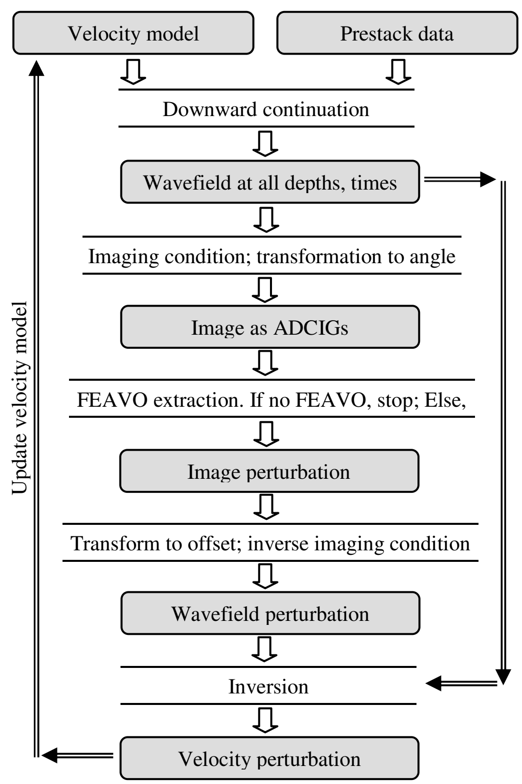

Figure 7: WEMVA with a FEAVO-oriented fitting goal

When working with a synthetic dataset, the FEAVO extraction step can be done in an error-free manner by subtracting the image migrated with the correct velocity from the one migrated with the background velocity. Eliminating error in this step allows testing the accuracy of all the other steps in the iterative inversion. We performed WEMVA with perfect FEAVO extraction (Figure 8B) on the synthetic dataset used in Figures 4 and 6. After two WEMVA loops, each inversion comprising ten linear solver iterations, we obtained a velocity model practically identical in morphology with the correct one, and with peak individual anomalies of two thirds of the correct ones

(Figure 8C). After migrating with the updated velocity, the FEAVO effects are no longer visible in the image. In the required conditions (ADCIGs already flattened), WEMVA works. The only step left is constructing an operator that will correctly extract FEAVO effects in the image domain.

Extracting FEAVO in the image domain

To extract FEAVO we will use both its local characteristics (departure of amplitudes from linearity as in Figure 5) and its global ones (characteristic shape – Figure 3). We plan to employ a "discriminate-focus-filter-mask" strategy. First we will perform FEAVO discrimination by extracting the existing linear AVO trends, with much more care than in the case of detection. We plan to formulate the extraction as an inverse problem, imposing constraints on the plausible range of the intercept and gradient, and on the lateral continuity of their values. We will then take the absolute values of the amplitudes and focus the anomalies by summing, Radon-style, along precomputed surfaces such as the one in Figure 3. We will then filter to keep only the "bright stars" and backproject the result in ADCIGs. We will use the result of backprojection as a mask that will highlight the presence of the anomalies.

While these are all future work plans, we implemented a very simplified version, by inverting into velocity just the output of the first three detector steps presented in Figure 5. Figure 8D shows a depth slice from the result of running the first three steps of the FEAVO detector. Figure 8E shows the velocity update produced by WEMVA. The results are encouraging given the very simple procedure used to construct the image perturbation.

Conclusions

Focusing effects impede AVO studies, but are eliminated by migrating with the proper velocity model. We have devised a cheap and quick FEAVO detector, as well as a way to compute the path of the effects in ADCIGs, with an analytical formula for the constant-velocity case. We have adapted WEMVA to find the FEAVO-causing velocity anomalies and found that it performs well if the underlying assumptions are satisfied and the image perturbation can be extracted with no error. We showed that even when the extraction is done in a very simple manner, the overall shape of the anomalies is recovered. We devised a strategy to accurately extract the image perturbation and we are currently working on implementing it.

Acknowledgments

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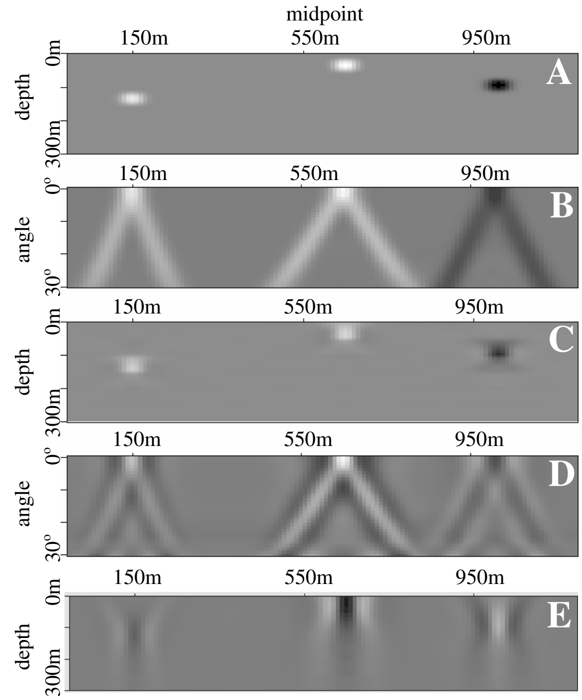

Figure 8: **A** – correct velocity; **B** – depth slice from the optimal image perturbation; **C –** velocity by WEMVA using the optimal image perturbation; **D** – depth slice from the image perturbation extracted using only the FEAVO detector; **E** – velocity from the image perturbation extracted with the FEAVO detector.

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