Data regularization strategies for azimuth-limited prestack migration of 3D land volumes in fracture detection applications

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Summary

We compare two different approaches to input data regularization for azimuth-limited Kirchhoff prestack migration, namely azimuth sectoring and prestack interpolation via band-limited Fourier reconstruction. We evaluate the performance of both approaches as they are employed in a P-wave fracture detection flow using real and synthetic data. The prestack interpolation gave excellent results in both the real and synthetic cases; moreover we found that a careful implementation of azimuth sectoring also gave good results. By contrast, a naïve implementation of azimuth sectoring produced an unacceptable level of artifacts in the output fracture attribute volumes and we conclude that careful data regularization prior to prestack migration is a critical step in minimizing artifacts in post-migration fracture analysis.

Introduction

P-wave fracture detection tools are enjoying widespread use as interest in unconventional reservoir development continues to surge. P-wave fracture analysis exploits azimuthal variations in stacking velocity (“VVAZ”) and/or amplitude-versus-offset (“AVAZ”). In theory both AVAZ and VVAZ analyses should be performed in the migrated domain, but unfortunately 3D prestack time migration (PSTM) of wide-azimuth land data is known to be sensitive to the effects of irregular and/or sparse spatial sampling. For example, in unstructured data regimes where identification of subtle anomalies requires artifact-free imaging, stacks after PSTM may suffer from more sampling-induced migration noise than their counterparts produced after the relatively simple process of stack plus poststack migration. Unfortunately the stringency of the sampling requirements for avoiding migration artifacts is further heightened if no stacking is performed after PSTM simply because we lose the natural power of the stacking process in eliminating migration noise. This effect was recently explored by Hunt et al., (2008), who sought to minimize migration artifacts on PSTM image gathers generated by common offset migration in order to improve the quality of post-migration AVO inversion. As in the AVO case, post-migration fracture detection analysis is also performed on migrated image gathers (although the associated migration operates on offset-and-azimuth-limited, rather than offset limited, data subvolumes), so we expect a similar sensitivity to the effects of irregular sampling, and correspondingly, the strong possibility that excessive levels of migration noise may completely negate the theoretical advantages associated with operating in the migrated domain.

The traditional approach to forming the offset-and-azimuth-limited data subvolumes appropriate for input to PSTM in migrated-domain fracture analysis is to perform azimuth (and offset) sectoring (Lynn et al., 1996). When carefully implemented, this approach provides a degree of implicit data regularization which can help mitigate some of the migration artifacts related to the imperfect sampling.

In this paper we consider prestack interpolation as an alternative approach for minimizing this migration noise. Specifically, we use a multidimensional Fourier reconstruction technique to synthesize regularly sampled common azimuth and offset data subvolumes which are in turn used as input to PSTM. It is worth noting that common offset vector gathering (also known as “ offset vector tiling”) (Cary (1999); Vermeer (2002)) has recently emerged as another useful approach for forming these offset-and-azimuth-limited data subvolumes (Calvert et al. (2008). Although this abstract focuses on comparing azimuth sectoring to prestack interpolation, examples from COV gathering will be also be included in the oral presentation.

Theory

All three of the above data regularization schemes seek to approximately replicate ideal common-offset-and-azimuth (COA) acquisition which we can never achieve practically in the field, either through binning of the input data (common offset vector gathering and azimuth sectoring cases) or through the manufacturing of synthetic traces at the desired azimuth and offset (prestack interpolation case).

Azimuth sectoring

This approach entails first sorting the data into finite-width azimuth limited sectors, then performing separate industry-standard offset-limited migrations (i.e., so-called “common offset migration”) on each of the sectors. Examination of the underlying continuous-variable COA prestack migration integral suggests that a good strategy would be to choose offset and azimuth bin widths so that the resulting approximate COA volumes provide input data support at each midpoint location (i.e. ensure there are no holes in coverage across the midpoint coordinates). Unfortunately, sparse and irregular acquisition geometries preclude outright satisfaction of this criterion, and attempts at even approximate fulfillment often necessitate the use of very large offset and azimuth bins. Thus we must manage a tradeoff between maximizing resolution in offset/azimuth sampling (such as is required for adequate data support in the downstream AVAZ/VVAZ inversions) and minimizing migration noise. It’s worth noting that common offset migration has been fortified over the years by various industry-strength tricks which can help mitigate sampling-related artifacts (e.g., appropriate normalization of input traces to compensate for local variations in cmp fold; use of variable width offset slots; gap-filling via borrowing of traces from neighbouring offset slots, etc.), and the presence or absence of such tricks may have a significant influence on output image quality.

Prestack interpolation

As an alternative to forming approximate COA ensembles by data binning, prestack interpolation may be used to directly synthesize COA data subvolumes which are in turn input to PSTM. In the idealized scenario of a perfect interpolation algorithm and infinite computational resources, there would be no downside to this approach, since the interpolated traces would provide a perfect replication of the ideal COA experiment at no cost. The practical reality is that no interpolation algorithm gives perfect results, each one being based on its own set of assumptions, and runtimes may be considerable. These concerns notwithstanding, the present algorithm, which is a practical implementation of the Fourier reconstruction technique proposed by Liu and Sacchi (2004) (and later adapted to industry by Trad et al (2008)), is known to produce very good results based on our extensive real and synthetic data testing. The algorithm uses the existing input data to estimate spatial Fourier coefficients in multidimensions (offset, azimuth, cmp-x ,cmp-y) via the solution of an underdetermined inverse problem whose regularization term incorporates a priori information by essentially assuming a smooth distribution of energy across the frequency-wavenumber hyperplane.

Examples

(i) Synthetic experiment

We begin by considering a very simple 1-D synthetic data set whose earth model consists of a single anisotropic (i.e., fractured) layer (Thomsen’s parameter δ^{v}=10%; orientation = 50° E of N) embedded in an otherwise homogeneous and isotropic earth (v=3000 m/s). Top and base of the layer are at 660 and 760 ms, respectively. Because there is no lateral velocity variation, an artifact-free migration would essentially be a “do nothing” operation. Anisotropic amplitudes were modeled using the Rüger equation (Rüger, 1998) and traveltimes were computed based on the azimuthally-dependent moveout equation of Tsvankin (1997). These noise-free synthetic data were projected onto a regularly sampled real (orthogonal) survey geometry from Western Canada with source and receiver line spacings of 200m and 300 m, respectively, and an equal shot and receiver interval of 50 m. In spite of this regular sampling, we anticipate challenges in the imaging of the anisotropic signature because the maximum offset is quite small (1100 m) and the fold at target level is quite low (nominal fold of 12 m).

Figure 1a shows an azimuth limited PSTM stack along an inline together with a representative migrated gather after a naïve azimuth sectoring approach in which the input data volume was sectored into six azimuth-limited subvolumes at 30° increments spanning 0° to 180°. Separate common offset migrations were run on each subvolume, with each migration comprising sixty offset slots of uniform width (50 m). Figure 1b shows the result after a more sophisticated azimuth-sectored migration in which the same six azimuth-limited subvolumes were first formed, but this time all the aforementioned industry-strength tricks were invoked in the individual common offset migrations in order to minimize sampling artifacts. (although the azimuth bin width is fixed at 30°, optimized offset slot widths vary with azimuth and offset and the average width is approximately 300 m). Note that the migration noise is significantly suppressed relative to Figure 1a on both the stack and image the gather. In particular, we are able to discern some of the characteristic sinusoidal “wobble” across azimuths associated with the VVAZ signature (green circle on 900m offset bank of image gather). Figure 1c shows the result after prestack interpolation followed by COA PSTM. The image is superior even to that obtained using the sophisticated sectoring approach. Figure 2 shows the corresponding fracture intensity estimates obtained by applying the VVAZ δ-inversion method of Zheng (2006) to the PSTM image gathers. Recalling that we expect a laterally homogeneous result of $\delta^{(v)}$=10%, we conclude that the migration artifacts in the naïve sectoring approach (Fig. 2c) create unacceptably large errors in the fracture intensity map. The other two approaches give reasonable results, although the optimized sectored result (Fig. 2a) shows more acquisition footprint (though not shown here, both also give good estimates of fracture orientation) . We note with interest that both the optimized sectoring and prestack interpolation (Fig. 2b) approaches underestimate the fracture intensity (i.e., $\delta^{(v)}$ is approx. 7% for both), a consequence of the smoothing across offset and azimuth which is explicitly imposed at the data binning stage for the former technique, and which exists as a fundamental algorithmic assumption (i.e., within the interpolation) for the latter. Finally, the fact that the prestack interpolation approach gives the best result does not necessarily imply that it will always be the best choice for real data; we must remember that these simple synthetic data conform very well to many of the assumptions inherent in the interpolation approach. Still, this successful synthetic test establishes a measure of confidence in the interpolation procedure, and this synthetic test provides an insightful launching pad into the real data example.

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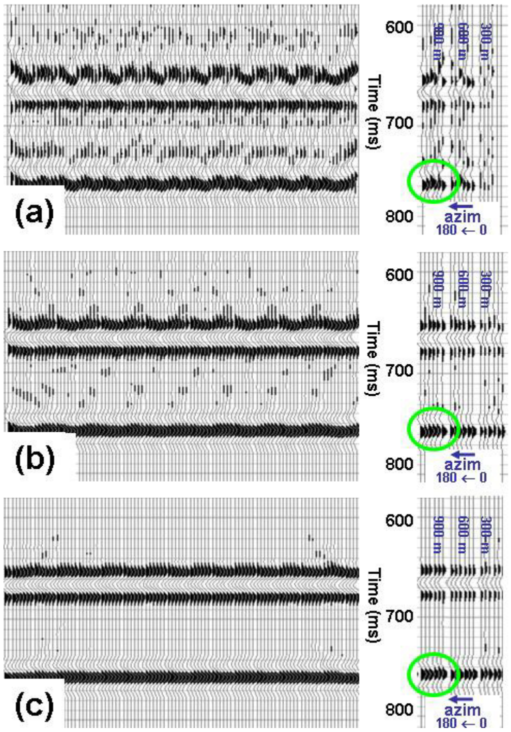

Figure 1: Synthetic data migrations. Left hand panes show images along inline 60 obtained by stacking all common offset PSTMs associated with source-receiver azimuth 80° E of N. Right hand panes show the image gathers at an interior CMP location along this inline with primary sort key offset and secondary sort key azimuth. (a) result after "naïve" azimuth-sectored PSTM; (b) result after optimized azimuth-sectored PSTM; (c) result after interpolation plus PSTM.

(ii) Real data experiment

We now examine a Middle East land data set which features a well-delineated fracture regime whose presence has been confirmed by several wells (Wang et al., 2007). Figure 3a shows an azimuth limited stack along an inline using the same naïve azimuth sectoring approach described in the synthetic test, except this time we used 8 azimuth sectors of width 30° (offset slot size was again set to 50 m). Figure 3b shows the result after running the optimized azimuth-sectored migration. Note that the migration noise is significantly suppressed compared to the result in Figure 3a, both in the shallow events (green box) and in the deeper structure (red arrows). Figure 3c shows the corresponding result after prestack interpolation followed by COA PSTM.

The image quality in Figures 3b and 3c is comparable (arguably the result after prestack interpolation is better) and both images are clearly superior to the one produced by the naïve azimuth sectoring approach. Figures 4a and 4b show the fracture intensity attributes derived from AVAZ and VVAZ analyses, respectively, using the migrated data generated by the sophisticated azimuth-sectored approach. Figures 4e and 4f show the corresponding results after the naïve-sectoring approach, and figures 4c and 4d show the results obtained using the migrated data generated by the prestack interpolation flow. For reference, we have also provided AVAZ and VVAZ fracture intensity attributes generated from the unmigrated data in Figures 4g and 4h, respectively. These figures reveal intriguing similarities and also puzzling differences which lead to the following general comments: (i) all fracture intensity maps show strong fracturing along a NE to SW trend (black boxes, Fig. 4a) which is consistent with the well control; (ii) the migration process seems to have improved both the lateral resolution of the attributes as well as the spatial correlation between the AVAZ and VVAZ results; (iii) the optimized azimuth sectoring flow produces reasonable results, while the naïve sectoring images show severe acquisition footprint, especially for AVAZ; (iv) the prestack interpolation flow appears to produce the best images of all; in particular the background noise is minimized, and the coherent patterns of suspected fracturing appear to be enhanced; (v) it is worth noting that even in the absence of migration noise, result interpretation is complicated by the fact that several factors can conspire to destroy similarity between AVAZ and VVAZ attributes, despite the fact that both techniques are ostensibly aimed at the same objective (Wang et al., 2007; Zheng et al., 2008).

Conclusions

We have reviewed and compared two strategies for minimizing sampling-induced migration noise in post-migration fracture analysis applications. In particular, we are very encouraged by the performance of our prestack interpolation flow, and we note that careful implementation of the azimuth sectoring approach can also give good results. Further studies wll include comparisons with COV migration and also additional synthetic data testing using a more sophisticated numerical modeling algorithm. Finally, although our study has focused on land data we anticipate that our findings will carry over the wide-azimuth marine environment.

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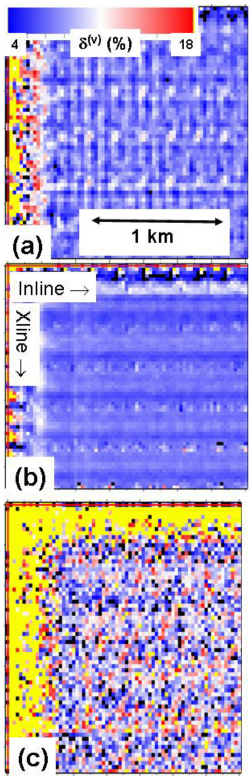

Figure 2: Synthetic data fracture intensity maps after VVAZ. (a) optimized azimuth-sectored PSTM; (b) interpolation plus PSTM; (c) naïve azimuth sectored PSTM.

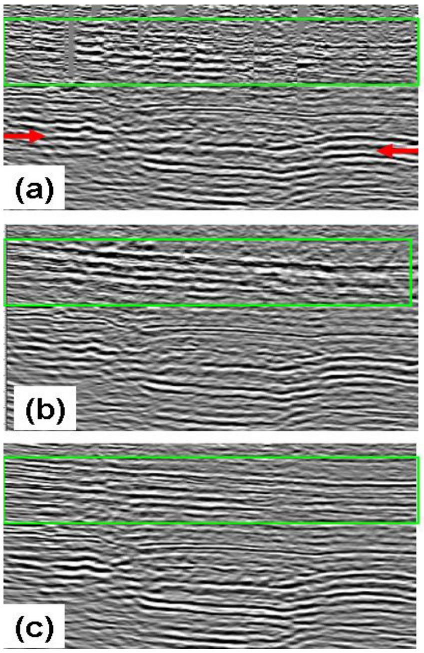

Figure 3: Real data mages obtained by stacking all common offset migrations associated with a single source-receiver azimuth (22.5° E of N). (a) naïve azimuth-sectored PSTM; (b) roptimized azimuth-sectored PSTM; (c) interpolation plus PSTM

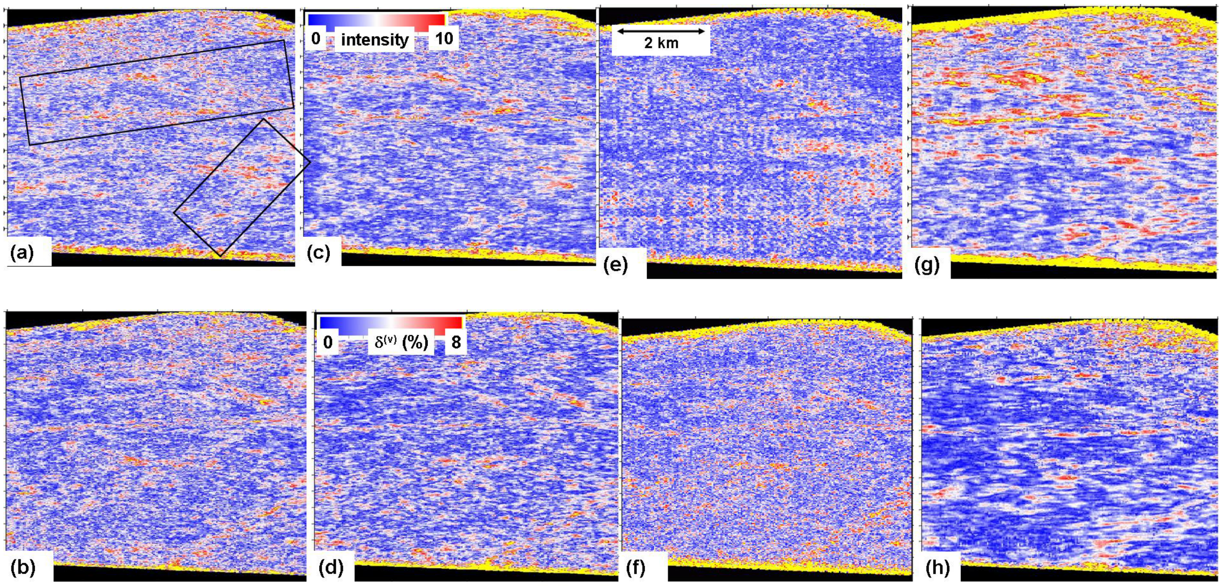

Figure 4: Fracture intensity maps after AVAZ and VVAZ. (a) AVAZ intensity after optimized azimuth-sectored PSTM; (b) VVAZ intensity after optimized azimuth-sectored PSTM; (c) AVAZ intensity after interpolation plus PSTM; (d) VVAZ intensity after interpolation plus PSTM; (e) AVAZ intensity after naïve azimuth-sectored PSTM; (f) VVAZ intensity after naïve azimuth-sectored PSTM; (g) AVAZ intensity from unmigrated data; (h) VVAZ intensity from unmigrated data.

EDITED REFERENCES

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