Fracture detection via azimuthal analysis of seismic data: snake oil or silver bullet?

Mike Perz*, Peter Cary, Xinxiang Li, Satinder Chopra, Arcis Seismic Solutions, A TGS Company, Calgary, AB, Canada

mperz@arcis.com

Summary

We examine the performance of three azimuthal fracture detection techniques: P wave azimuthal velocity analysis (VVAZ), P wave azimuthal AVO analysis (AVAZ), and converted wave shear wave splitting analysis (SWS). Fundamental algorithm limitations are studied in an attempt to explain observed differences between fracture attributes generated from the three approaches. Given the large number of limitations, we believe that simultaneous analysis of diverse attributes generated from all three techniques, as well as from curvature analysis, should help improve reliability of interpretation.

Introduction

Although fracture estimation via analysis of surface-seismic data is enjoying increasing use in resource play development, dissenting opinions exist regarding the efficacy of the VVAZ/AVAZ/SWS techniques. Those on the "silver bullet" side of the argument claim good results in most cases, while others residing in the "snake oil" camp say the techniques never work and have been oversold. Such strong polarization of opinion obviously underscores our industry's need to better answer the fundamental, and difficult, question of how well these techniques are working in practice. While we are unable to provide a definitive answer in the present paper, we do make the recognition that the answer must come in two parts: (i) a wellbore verification element in which azimuthal fracture attributes must be compared to FMI logs, core, and production data across a wide range of surveys and (ii) an algorithm analysis element in which fundamental assumptions and limitations must be examined in light of the successes and failures observed in part (i) in order to better establish which techniques work well and under which conditions.

Regarding part (i) of the answer, while ground-truthing studies are now emerging with increasing frequency, the reality is that they still do not exist in sufficient number to provide a good statistical sampling of most of the popular plays. In the absence of wellbore-based validations, we believe focus should shift towards the second part of the answer (i.e., analysis of algorithm limitations) in order to help determine which of the tools, if any, is likely to produce useful results for the project at hand.. Accordingly, the main purpose of this paper is to provide the interpreter with a complete and easy-to-understand list of the assumptions underlying the three approaches. Our paper is motivated in part by the fact that most of the existing literature tends to focus on a small fraction of the totality of effects influencing algorithm performance (notable, broader-scoping exceptions include a recent paper by Delbecq et al. (2013) and also Zheng et al., 2008).

Theory

The two P wave azimuthal fracture methodologies are well-documented in the literature. The AVAZ technique is based on the work of Rüger (1998) and the VVAZ technique is based on the Zheng inversion (Zheng, 2006) The converted wave SWS technique follows the method outlined by Li (2012). All three approaches produce independent estimates of fracture intensity and orientation. The theory described in these references gives rise to many algorithmic limitations which we review below.

Data quality and noise issues

All three techniques are sensitive to noise and to the effects of sparse spatial sampling. Although the advent of 5D interpolation has helped mitigate issues related to imperfect sampling, the field acquisition must still possess a sufficiently rich distribution of offsets and azimuths to allow the interpolation to identify multi-dimensional coherent signal trends. Strong noise, both random and linear, can lead to poor results in the case of all three techniques. AVAZ in particular requires an AVO compliant processing flow which can heighten sensitivity to noise. Also, azimuth-dependent noise linear noise and/or multiples may leak into the final migrated common offset vector ensembles which form the input to AVAZ and VVAZ. Finally, well-known imaging issues in converted wave processing (low signal-to-noise, lack of high frequency content, large statics) may adversely affect SWS success.

Data Resolution Discrepancies

The fact that the three approaches carry inherent differences in resolution can lead to significant differences in the computed attribute maps. The AVAZ approach is an interface technique and therefore standard reflection processing resolution paradigms apply (i.e., lateral and vertical resolution$\approx$ $\lambda/4$—note that both AVAZ and VVAZ are typically performed after migration). By contrast, both VVAZ and SWS are layer-based techniques, and vertical resolution is therefore governed by the thickness of the layer of interest. For various reasons in practice, the minimum thickness will always be larger than the seismic wavelength (a representative value might be 100 m for Western Canadian plains data).

Lateral resolution is a somewhat murky topic for both VVAZ and SWS. In the case of the VVAZ Zheng inversion, it is likely governed by the horizontal smear within the target layer of the various ray segments swept out by the incident angles sampled in each migrated gather (a typical range is 0° to 30°, and a simple geometric argument suggests a resolution limit equal to thickness*0.577). In the SWS case, the topic is complicated by the fact that the analysis is typically performed on unmigrated data (although Simmons (2009) shows a migrated-domain SWS example) for which the Fresnel zone has not yet been collapsed. We believe that lateral resolution is likely controlled by the maximum of the Fresnel zone and the asymptotic conversion point supergather size (a representative value might be 300 m)**.** Despite our struggle to precisely quantify lateral resolution, we are confident in asserting that both techniques yield inferior resolution (both lateral and vertical) compared to AVAZ. Note that in the case of extremely thin fractured beds where reflection events are obscured by wavelet tuning, even the relatively high resolution AVAZ technique will produce erroneous results (Liu et al, 2001).

Overburden effects

While both SWS and VVAZ offer natural protection from the confounding effects of an anisotropic overburden, AVAZ enjoys no such safeguard. Although several authors have examined the AVAZ overburden issue (e.g., Alhussain and Sen, 2012; Liu et al.,2011), the industry still lacks robust solutions. Another overburden complication arises in the case of shallow lateral velocity heterogeneity in an isotropic earth. Jenner (2009; 2010) shows how lateral velocity anomalies in the overburden create phantom VVAZ responses which masquerade as anisotropy. Although never studied to our knowledge, such heterogeneity would likely produce similar phantom signatures for SWS.

 AVAZ reflection interface assumptions

The underlying AVAZ theory imposes stringent requirements on the types of reflection events which admit accurate inversion. Specifically the theory assumes an isotropic layer overlying an HTI layer (HTI defined below), or vice-versa (it also includes the case of two HTI layers possessing identical fracture orientations). It follows that AVAZ will produce erroneous results in the case of two abutting layers possessing differing fracture orientations. Even when the interface assumptions *are* satisfied, the AVAZ measurement may be distorted if the reflection event is weak or obscured by noise. By contrast, this same problem can be avoided for VVAZ and SWS techniques if the user is able to pick clean reflection events which lie a small distance outboard from the true layer of interest (the resulting degradation in vertical resolution may be offset by the benefits associated with inverting cleaner data).

Rock physics considerations and AVAZ orientation ambiguity

Delbecq et al. (2013) give a good description of both of these issues. The AVAZ technique is sensitive to two Thomsen parameters, $\gamma^{(v)}$ and $\delta^{\backslash(v)}$ (parameters describing layer-localized shear wave splitting

and P wave NMO velocity differences parallel and perpendicular to fractures, respectively), while the VVAZ and SWS responses depend on $\delta^{\backslash(v)}$ alone and $\gamma^{(v)}$ alone, respectively. The fact that the three techniques are measuring different properties will obviously lead to differences in the attribute maps. The AVAZ 90 degree orientation ambiguity is well documented (e.g., Zheng et al., 2004) and stems from the fact that the industry-standard Rüger equation is a small incident angle truncation of a higher order expression as discussed in Goodway et al. (2006). Note that a recent alternative AVAZ approach based on azimuthal Fourier analysis can overcome this orientation ambiguity (Downton et al., 2011).

The HTI anisotropy assumption

The AVAZ and VVAZ inversions are based on the horizontal transverse isotropy (HTI) anisotropic theory. The HTI model in turn assumes the existence of locally mono-oriented fracture sets. Unfortunately fracture sets in the real world don't always conform to this simple configuration: Figure 1a shows a case where the HTI assumption appears to be valid while Figure 1b shows a case where it is clearly invalid. Although we may still measure azimuthally varying AVO and/or velocity effects in this latter case, it would not be appropriate to relate the computed fracture intensity attribute to $\gamma^{(v)}$ and $\delta^{\backslash(v)}$ (nor to alternative formulations of HTI parameters), and the orientation estimate cannot be related to a single fracture set. In the SWS case, various classes of anisotropy are known to induce fast and slow polarized shear waves. Although the HTI class gives rise to a particularly simple interpretation of SWS intensity and orientation, other interpretations exist for more complicated classes (Winterstein, 1999).
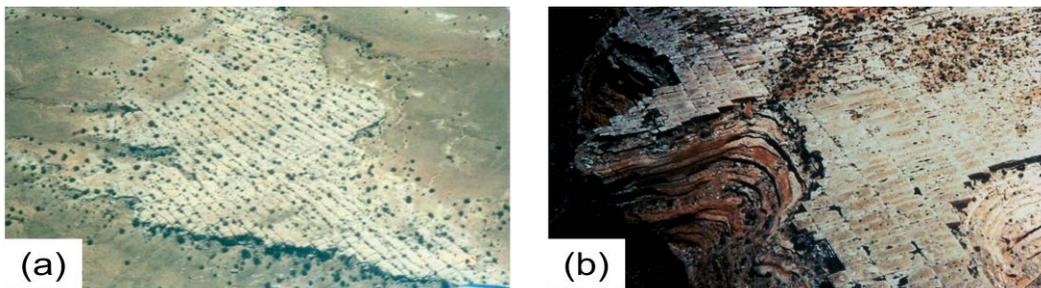
Figure 1: Aerial photos of fracture outcrop. (a) mono-oriented vertical extension fractures, San Juan Basin; (b) two sets of vertical extension fractures in sandstone, Cedar Mesa Fm. Photos courtesy of Scott Cooper and John Lorenz.

Example

Figure 2a shows VVAZ attribute maps for an upper Devonian shale unit, and Figures 2b and 2d show the AVAZ intensity maps at top and base of the unit, respectively. While the VVAZ intensity map shows some correlation with the AVAZ map from the top-of-unit reflector, it reveals poor correlation with the AVAZ map from the base-of-unit reflector. Figure 2c shows the VVAZ map for the middle Devonian carbonate interval immediately underlying the interval of interest. Note that the orientations appear "flip-flopped" approximately 90 degrees in the zones of strong fracturing compared to the VVAZ image from the overlying unit in Fig. 2a). This orientation flip-flop was also observed on the FMI log from a nearby vertical well, suggesting that the VVAZ technique is giving a reliable fracture characterization. In light of the above discussion, it seems likely that the base-of-unit AVAZ map is unreliable because the Rüger equation is violated in the case of two abutting fractured layers with differing orientations.

Discussion/Conclusions

We have reviewed the various limitations associated with the AVAZ/VVAZ/SWS tools. A real data example containing both successful and unsuccessful elements of fracture characterization suggests that the usefulness of the tools lies somewhere inside the spectrum defined by the "snake oil" and "silver bullet" end-members, and that a keen awareness of algorithmic limitations should always accompany result interpretation. One of the main challenges, both in attribute interpretation and in applied research aimed at improving the algorithms, is to determine the relative importance of the various limitations. Although this is not an easy task, we are confident that data quality issues rank among the most significant problems, and much of our research is directed towards improving data
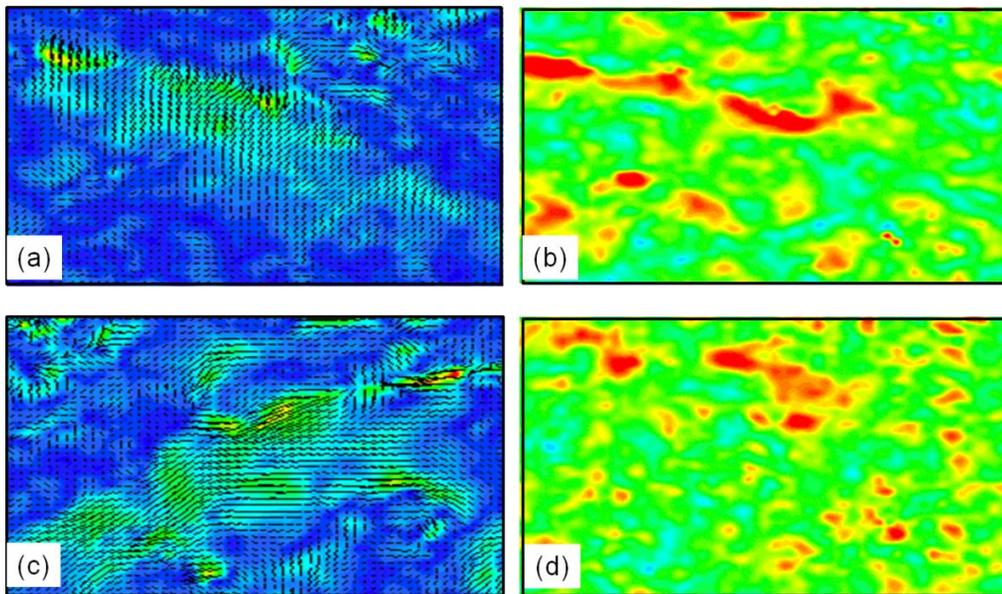
Figure 2: VVAZ/AVAZ comparison. (a) VVAZ fracture intensity (colour) with orientation vector overlay for upper Devonian shale; (b) AVAZ fracture intensity at top upper Devonian; (c) VVAZ fracture intensity for middle Devonian carbonate; (d) AVAZ fracture intensity at base upper Devonian.

preconditioning in processing. In addition, we are working on providing a convenient framework for co-displaying fracture attributes generated from all three approaches in conjunction with those generated from poststack curvature analysis.

Acknowledgements

References

Alhussain, M., and M. Sen, 2012, Removing anisotropic overburden effect for reliable reservoir fracture characterization: 82nd Annual International Meeting, SEG, Expanded Abstracts, 1-5.

Delbecq, F, J. Downton, J., and M. Letizia, 2013, A math-free look at azimuthal surface seismic techniques: CSEG Recorder, **38**, no.1, 20-31.

Downton, J., B. Roure, and L. Hunt, 2011, Azimuthal Fourier coefficients: CSEG Recorder, **36**, no. 10, 22-36.

Goodway, W., J. Varsek and C. Abaco, 2006, Practical applications of P-wave AVO for unconventional gas resource plays, Part 2: CSEG Recorder, **31**, no. 4, 52-65.

Jenner, E., 2009, Data example and modeling study of P-wave azimuthal anisotropy potentially caused by isotropic velocity heterogeneity: First Break, **27**, February, 45-50.

Jenner, E., 2010, Modelling azimuthal NMO in laterally heterogeneous HTI media: First Break, **28**, September, 89-94.

Li, X., 2012, A stable criterion for shear wave splitting analysis: 2012 CSEG Annual Convention, Expanded Abstracts.

Liu, E., G. Zelewski, C.P. Liu, J.M. Reilly, and Z.J. Shevchek, 2011, Mitigation of overburden effects in fracture prediction using azimuthal AVO analysis: An example from a Middle East carbonate field: The Leading Edge, **30**, 750-756.

Liu, Y. J., A. Ziolkowski, E. Liu, and X.Y. Li, 2001, Characterization of azimuthal anisotropy in the presence of thin layers using P-waves: 71st Annual International Meeting, SEG Expanded Abstracts, 169-172.

Rüger, A., 1998, Variation of P-wave reflectivity with offset and azimuth in anisotropic media: Geophysics, **63**, 935-947.
Simmens, J., 2009, Converted-wave splitting estimation and compensation: Geophysics,. **74**, D37–D48
Winterstein, D., 1992, How shear-wave properties related to rock fractures: Simple cases: The Leading Edge, **11**, No 9, 21-28.

Zheng, Y., 2006, Seismic azimuthal anisotropy and fracture analysis from PP reflection data: Ph.D. dissertation, the University of Calgary.

Zheng, Y., G. Larson, 2004, Seismic fracture detection: Ambiguity and practical solution, 74th Annual International Meeting, SEG, Expanded Abstracts, 1575-1578.

Zheng, Y, J. Wang, and M. Perz, 2008, Pitfalls and tips for seismic fracture analysis: 78th Annual International Meeting, SEG, Expanded Abstracts, 1531-1534.