Pitfalls and tips for seismic fracture analysis

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Summary

P-wave fracture analysis provides a means to extract fracture density and orientation of an underground reservoir. Good methods are important for fracture analysis, and moreover, careful handling of some practical issues is crucial. These issues include, but are not limited to, avoiding cycle skipping when applying dynamic trim statics, the confounding effects of an anisotropic overburden, and also consideration of the boundaries between two fractured zones. Any improper treatment on any of these issues can lead to incorrect outcomes of the analysis and/or misinterpretation of the analysis results.

Introduction

Much work has been done in seismic fracture analysis on P wave data (e.g. Lynn et al., 1996; Teng and Mavko, 1996; Li, 1999; Gray and Head, 2000; MacBeth and Lynn, 2001; Zheng and Gray, 2002; Chapman and Liu, 2004; Chi et al., 2004; Parney, 2004; Zheng et al., 2004). Typically, a fractured zone is mathematically simplified as a **H**orizontally **T**ransverse **I**sotropic (HTI) layer, which implies all fractures are vertical and oriented in one direction. There are two categories of methods for fracture analysis. One detects the **A**mplitude **V**ariation with offset and **AZ**imuth (AVAZ), and another detects the **V**elocity **V**ariation with **AZ**imuth (VVAZ). We have experimented with both categories on synthetic and real datasets, and have achieved successful results (Wang et al., 2007). For AVAZ we use Rüger's method (Rüger, 1998), and for VVAZ, use the δ inversion (Zheng, 2006) which is a horizon based, layer stripping method.

Obviously the use of a good algorithm is a must for good fracture analysis. However, there are also some practical issues which may degrade the quality of fracture analysis if they are not handled properly. Some of these issues are related to processing procedures, and some of them are due to the intrinsic limitations of the method employed. Here, we are going to talk about four of these issues.

1. Dynamic trim statics

It is a common practice to calculate dynamic trim statics on key horizons to obtain the **R**esidual **M**ove**O**ut (RMO) for VVAZ, and also to apply those dynamic trim statics to flatten seismic gathers prior to AVAZ inversion. The trim statics may be calculated by cross correlation between each individual trace in the gather and a pilot trace, using a short correlation window in order to focus on a particular horizon. One obvious approach to forming the pilot trace is to simply stack traces within a CMP gather (using either a full or partial offset stack). However, a problem arises when the reflection shows a polarity reversal with increasing offset. Specifically, the trim statics computation may cause misalignment of the seismic event if the trace has a different polarity or phase from the pilot trace. In other words, the short window trim statics process may do more harm than good for class II AVO if a stacked trace is used as a pilot trace.

Figure 1 shows an NMO corrected common offset stack of a supergather with three events (i.e. some partial stacking was performed within offset bins). These events simulate wave propagation in a layered medium in which the first and third layers are isotropic, the second layer exhibits HTI anisotropy, and all the above three layers lie atop an isotropic half space (Figure 1, left hand side). Anisotropic amplitudes were modeled using the Rüger equation and traveltimes were computed based on the azimuthally-dependent moveout equation of Tsvankin (1997). The first event (event A at 1420 ms), which is the reflection from the top of the fractured layer (i.e., anisotropic/HTI), shows class I AVO behaviour. The second event (event B at 1522 ms) simulates a reflection from the base of the fractured layer. This event exhibits class II AVO behaviour, as evidenced by the polarity reversal around the offset of 2200 m. Note that the main lobe of event B is a peak at near offsets and changes to a trough at far offsets. Finally, there is a class IV event (event C) at 1654 ms emanating from the interface between the third (isotropic) layer and the infinite isotropic half space. Note the presence of subtle anisotropy-induced RMO on events B and C that is more obvious at far offsets. We have displayed the associated stacked trace on the same figure. Because event B is class II AVO, it appears as a weak peak on the stacked trace.

To demonstrate the potential problem, dynamic trim statics were calculated from the gather in Figure 1 using a stacked trace as a pilot trace. The dynamic trim static computation focused on all three events A, B and C, and all three correlation windows were chosen to be 80 ms. Figure 2 shows the common offset stack of the same supergather used in Figure 1 after applying dynamic trim statics (the dynamic statics were computed and applied prior to partial stacking). It works very well for events A and C, but not for event B, where erroneous static shifts are visible at far offsets as evidenced by the red circle in Figure 2. The far offset traces were shifted upward to line up the trailing positive side lobe of event B on the far offset trace with the main peak of event B on the pilot trace (Figure 2). Thus, false statics were introduced by using the stacked trace as a pilot. With this unexpected behaviour of the dynamic trim statics, there is no doubt the subsequent fracture analysis will yield erroneous results. A better approach is needed to avoid this problem.

One obvious approach to partially solving the misalignment problem is to create offset-dependent pilot traces via partial stacking of select traces within the supergather. However, such an approach would require much user experimentation with offset binning, and ultimately may still fail depending on various factors such as the offset distribution and the magnitude of the class II gradient. Instead, we propose a new method for forming the pilot trace for correlation. In particular, we use the isotropic AVO intercept and gradient (Shuey, 1985) to project a pilot trace at the same offset as the trace to be correlated, thereby avoiding correlating two traces of different phases/polarities. In practice, we run AVO inversion first to extract the AVO intercept and gradient using the same gathers which are used for fracture analysis. Then, when we calculate the trim static for a trace (target trace), we generate a pilot trace on-the-fly by forward modeling of the Shuey equation using the previously computed intercept and gradient, as well as the offset of the target trace and the local velocity. The fact that our pilot trace construction assumes an isotropic theory, while our data traces are presumed to exhibit HTI-type anisotrpoy does not seem to represent a serious inconsistency from the viewpoint of dynamic trim statics computation, presumably because the isotropic component of the amplitude gradient is typically larger than the anisotropic component, and therefore the pilot trace typically has the same phase/polarity as the target trace. Figure 3 shows the common offset stack after applying dynamic trim statics using the AVO projected pilot trace (note that the waveform of event B is not a verbatim replication of that in Figure 2 due to the partial stacking in each offset bin). All events, including event B, are flat after applying dynamic trim statics. Clearly, this method has successfully avoided the trouble of polarity reversal or phase difference between the pilot trace and the gather.

To further verify the advantage of the AVO projected pilot trace, we built a synthetic dataset with two interfaces. The top interface is a class I AVO reflection at 1470 ms. The second is a class II AVO at 1522 ms. The layer between these two interfaces is isotropic everywhere except within a circular anomaly of anisotropy centred at inline 200 and cross line 105 with a radius of 50 CDPs. We used both the stacked trace and the AVO projected trace as pilot traces followed by the δ inversion. The results of the δ inversion are shown in Figure 4. When the stacked trace is used as the pilot trace, the δ inversion result is erroneous. The image of the anomaly is barely visible (left panel) and the false statics caused by cycle skip (Figure 2) have introduced “false” anisotropy all the way across the survey. However, when the AVO projected pilot trace is used, the VVAZ result matches the input model, and the circular anisotropic anomaly is properly resolved (right panel).

2. Importance of far offset traces

All traces with different offsets contain anisotropic information to some degree. However, in the presence of noise, there is no doubt that far offset traces contain more discernable anisotropic information than the near offset traces, and therefore provide an important constraint to the inverse problem for either AVAZ or VVAZ. Therefore, it is important to utilize as many offsets as possible, up to the theoretical limit of the particular method employed. Figure 5 shows horizon maps of the fracture density obtained from the AVAZ method on a real dataset with different maximum offsets. When the maximum offset was “accidentally” limited to 18 degrees of incident angle during the AVAZ inversion (simulating, say, an overly-aggressive choice of mute), it yielded a poor result (left panel of Figure 5) which is contaminated by obvious acquisition footprint (the linear anomalies coincide with shot/receiver lines). Once the maximum offset was opened to 30 degrees, the AVAZ inversion produced a reasonable result (right panel of Figure 5).

3. Overburden influence

The amplitude of the reflected wave from the boundary of a fractured zone varies with azimuth, and so does the transmitted wave. Therefore, in general, the amplitude of a reflection wave from the interface below a fractured zone will vary with azimuth, even this interface is between two isotropic layers. In other words, the influence of a fractured zone will be carried over from the shallow section down to the deep section. Therefore, the result of AVAZ on a particular horizon contains the fracture information accumulated from the surface all the way down to this horizon. In general, AVAZ suffers from the problem of overburden impact, even though it ostensibly carries localized information at the reflection interface. Interpreters should pay close attention to the overburden impact when interpreting the fracture attributes from AVAZ.

Conventional traveltime-based VVAZ (i.e., azimuthally-dependent velocity analysis) has a similar overburden impact as AVAZ, but fortunately the δ inversion is able to strip off the impact by using the difference of RMOs on the top and base horizons (Zheng, 2006). Since this method considers traveltime variations which are isolated to a specific layer, the resulting inversion yields an interval estimate of fracture density and orientation. Although our intuition suggests that this traveltime difference approach is capable of perfectly localizing the fracture characterization attributes to within the layer of interest, further testing using full waveform HTI modeling will be carried out in order to assess the method's robustness in practice with respect to the overburden influence.

4. Boundary between fractured layers

The industry-standard AVAZ method is based on Rüger's equation (Rüger, 1998). This equation expresses the amplitude variation with offset and azimuth for a reflected wave from an interface between two HTI layers with same orientation. As a special case, one of the HTI layer may be isotropic. However, in the real world, the fracture orientations of different layers may not be the same, thereby leading to a violation of the assumptions underlying the equation. In such a case the amplitude variation of the reflected wave from the interface between two fractured layers with different orientations will be influenced by both layers. If we use Rüger's equation for AVAZ inversion, the resulting estimates of fracture density and orientation will be erroneous as they will contain the confounding influence of the combination of the properties of both layers.

Since the δ inversion scheme we use for VVAZ can effectively remove overburden impact, it can still produce useful results when reflections emanate from the interface between two fractured layers.

Conclusions

The quality of fracture analysis largely depends on the data preparation. In the case of class II AVO, the seismic traces may shift half a cycle if a stacked trace is used as a pilot trace, thereby resulting in erroneous fracture attributes. By using the AVO projected pilot, the problem can be avoided.

Interpreters should pay attention to the overburden impact on fracture analysis. The fracture anomaly may not be a vertically localized anomaly, but rather it may carry the influence from the shallower layers, depending on the method used for fracture analysis.

AVAZ may yield incorrect results if the interface is between two fractured zones and the fractures are oriented in different directions. The δ inversion used for VVAZ removes the overburden impact and is still valid for the interfaces between fractured layers (at the expense of a loss of vertical resolution)

Far offset traces are important for fracture analysis. One should ensure they are included in the inversion, provided their offsets illuminate angles which are within the limit of the method being used.

Acknowledgements

The authors would like to thank the anonymous sponsor for providing the real data for test, and also thank Divestco Inc. for the permission to publish this paper.

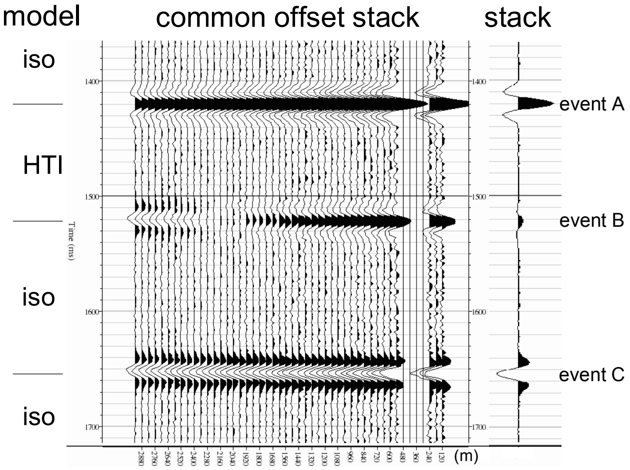


Figure 1. A seismic common offset stack of a supergather and its stack. There are three events and one of the events is class II (event B). There is some residual moveout on events B and C due to the presence of the fractured layer (more obvious at far offsets). The stacked trace shows reversed polarity compared to the far offset traces in the gather for event B.

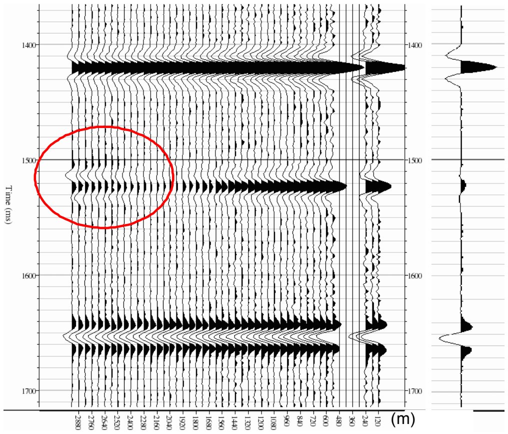


Figure 2. The common offset stack after applying dynamic trim statics using the stacked trace as a pilot trace (left side of the figure). The far offset traces were erroneously shifted upward (highlighted by the red circle).

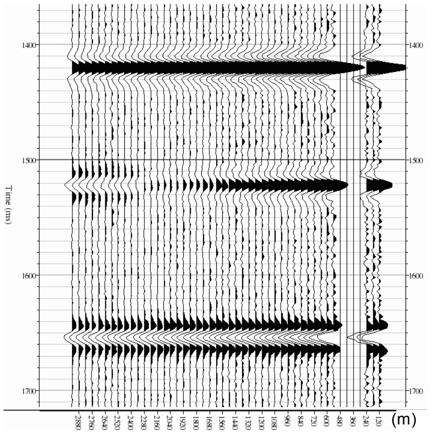
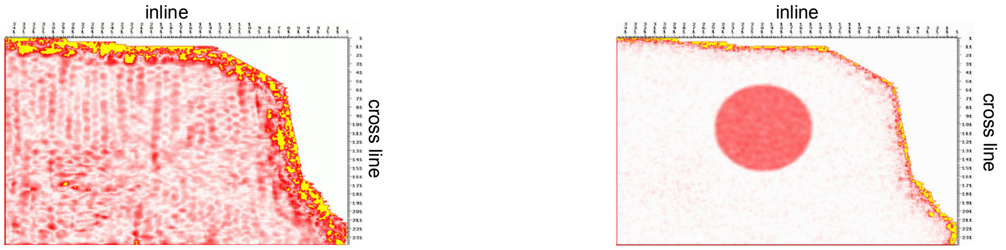


Figure 3 The common offset stack after applying dynamic trim statics using the AVO projected pilot trace. All events, including the class II event, are flat after applying dynamic trim statics.



δ inversion using stacked trace as a pilot

δ inversion using AVO projected pilot trace

Figure 4. Synthetic test of fracture analysis using different pilot traces. An anomalous fractured zone, centred at inline 200, cross line 105 with a radius of 50 CDPs, is embedded in an otherwise isotropic medium. The reflection from the base of the target zone exhibits class II AVO behavior. When a stacked trace is used as a pilot trace for trim statics, the result from the δ inversion is not correct, because there is a problem of cycle skip and the statics are not correct (left panel). When the AVO projected pilot trace was used, the δ inversion is correct (right panel), because the polarity changes at different offsets was handled properly.

offset up to 18°

offset up to 30°

Figure 5. Horizon maps of the fracture density obtained from AVAZ method with different maximum offsets. When the maximum offset was accidentally limited to 18 degrees during AVAZ inversion, it yielded a poor result (left panel) with obvious acquisition foot prints. The linear anomalies coincide with shot/receiver lines. Once the maximum offset is opened to 30 degrees, the AVAZ inversion produced a reasonable result (right panel).

EDITED REFERENCES

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