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Automatic Moment Tensor Inversion Enables Rapid Real-Time Treatment Optimization

By Michael Kratz

HOUSTON–One of the biggest advantages of real-time microseismic monitoring of hydraulic fracturing operations is that it enables oil and gas companies to evaluate fracture growth as it is occurring and make key treatment decisions or design alterations on the fly to optimize results and mitigate risk.

Real-time treatment evaluation improves stage-by-stage stimulation effectiveness, increases productivity, lowers development costs, and avoids operational risks such as geohazards. Ultimately, the technology leads to enhanced economics and reserves recovery by identifying patterns of fluid movement, fracture development, connectivity, compaction, and determining whether the induced fracture and proppants are staying in the target reservoir zone or propagating out of zone into unproductive intervals.

These critical insights not only enable real-time decision making to allow operators to make refinements to the fracturing plan while a treatment is being pumped, but also provide valuable data for long-term asset management and optimization, such as improved horizontal well spacing and completion design to lower development costs while boosting well productivity. The specific benefits of evaluating hydraulic fracture performance in horizontal wellbores in real time as treatment proceeds include:

- Optimizing completions through clear microseismic correlations of the reservoir's response to each stimulation stage (including estimating event magnitudes, hydraulic fracture growth patterns and stimulated rock volume) while allowing for quick comparisons of different hydraulic fracture design parameters;
- Determining where to drill the next well, and the ideal spacing and wellbore orientation of subsequent wells to maximize production;
- Improving production and recovery through better placement of wellbore landing zones, more effective stage placement throughout the lateral, and keeping the fracture extent within the target zone;
- Reducing overall well costs through real-time monitoring and more efficient well spacing and stage optimization; and
- Avoiding faults, water-bearing formations and out-of-zone fracture growth.

To achieve these benefits, however, fast delivery of the processed microseismic data is fundamental to enabling effective real-time treatment decisions. While traditional approaches use a manual picking method to process source mechanisms and other types of microseismic data, automatic picking methods are much faster and equally accurate.

Full Moment Tensor Inversion

Developing an algorithm that can calculate source mechanisms automatically for the recorded microseismic events and creating a model of the full moment tensor can improve the efficiency of microseismic data processing and the interpretation of a more robust catalog of microseismic events. Automatic moment tensor inversion calculates accurate source mechanisms on all events, and details moment tensor inversion in real time.

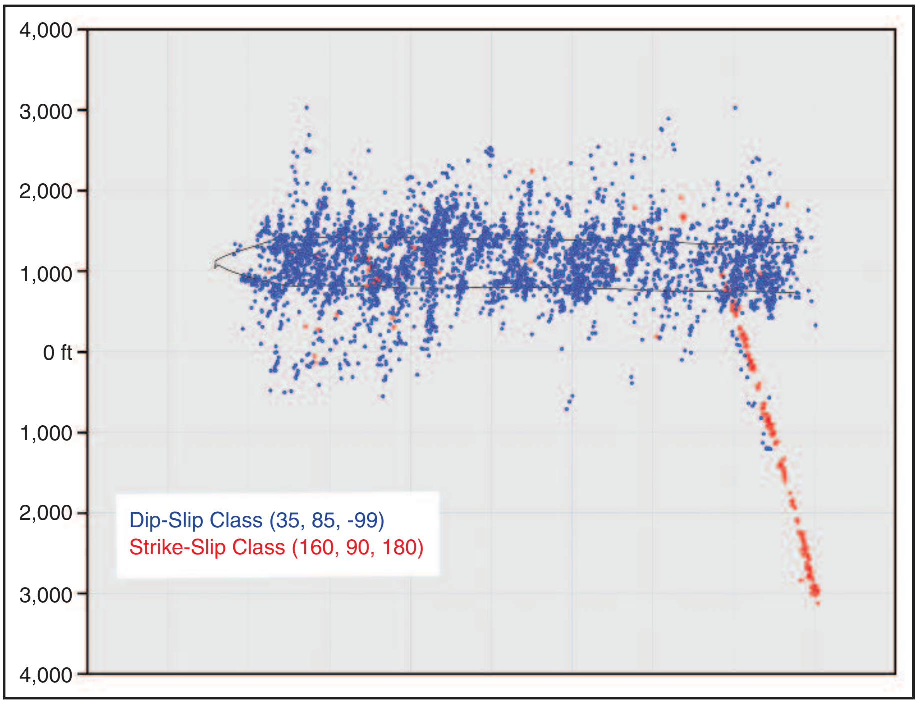
During microseismic event processing, analysts must determine the direction and length of that fracture plane (i.e., the source mechanism) and the associated moment tensor solution (i.e., a mathematical representation of the source mechanism) for each microseismic event. This can be a time-consuming process using manual picking methods to select first-arrival compressional (P)-wave amplitudes, and then determine a source mechanism solution for each individual microseismic event. A computerized algorithm that performs automated calculation of moment tensors requires very little involvement from the analyst, resulting in more efficient data processing.

Being able to automatically calculate estimates of a full moment tensor solution allows for faster identification of changes in the population of source mechanisms, which in turn, dramatically enhances the speed at which real-time microseismic monitoring can reflect large systematic changes in event source mechanisms, and reduces the need for reprocessing in real time. The gains in processing speed can lead to faster identification of obstacles such as geohazards and other valuable information such as stress changes in the reservoir, enabling better and faster treatment decisions.

Automatic moment tensor technology uses a linear inversion to estimate the moment tensor through waveform fitting of the recorded microseismic data and other event-location parameters. The calculation factors in vertical ground motion at the receiver, source-receiver geometry, and wave propagation. The source function

FIGURE 1

Microseismic Events from Original Source Mechanism Analysis



is estimated using the event location and origin time. The estimated moment tensor then is determined by finding the least-squares solution that best fits the data trace at each receiver to the modeled data trace.

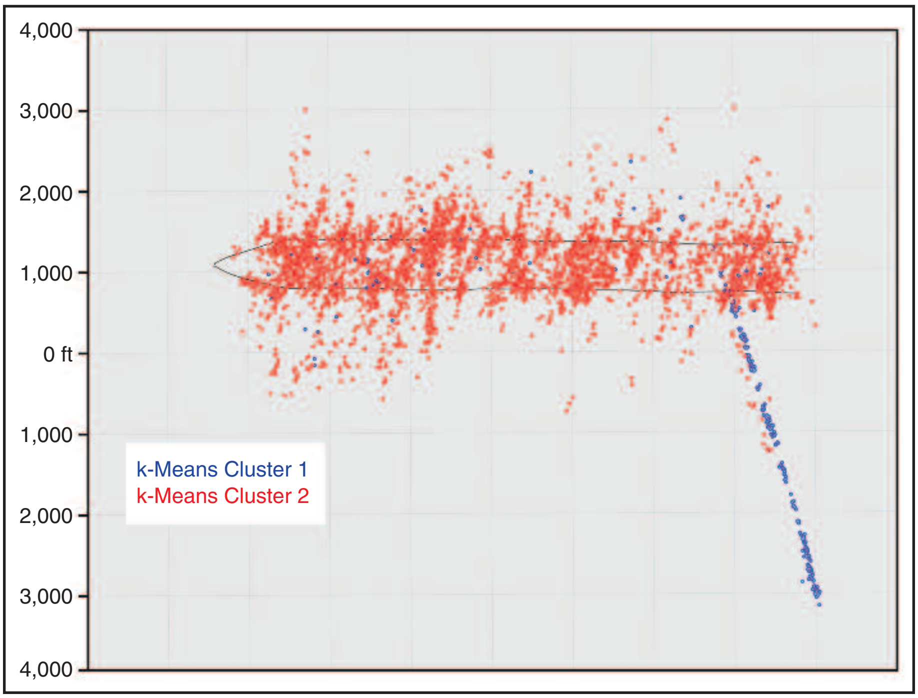
The moment tensor is analyzed further by decomposition into double-couple, compensated linear vector dipole, and isotropic components, which help characterize whether the movement was purely tensile or contained volumetric components. The double-couple component can be analyzed further to determine the orientations of the maximum and minimum compressive stress directions in addition to the strike/dip/rake of the fracture plane associated with the moment tensor. The orientations of compressive stress directions can be used to understand the orientation and relative magnitudes of regional stress, which allows treatments to target fractures of interest and/or avoid potential geohazards.

Theoretically, analysts would hand-pick individual P-wave arrival amplitudes manually to calculate the moment tensor inversion, but this method makes it impractically time-consuming to solve for each event in a large microseismic catalog. Therefore, analysts typically would instead pick a smaller representative population of events and select a set of pure shear solutions that generally described the entire event catalog. The problem with this method is that it can overly simplify the fracture geometry.

Automated moment tensor inversion improves discrete fracture network geometry accuracy and robustness because a fracture plane is modeled for each microseismic event, making the solution deterministic.

FIGURE 2

Microseismic Events from Continuous Full Moment Tensor Inversion Analysis



Eagle Ford Case Study

Using example data from an Eagle Ford Shale horizontal well, Figure 1 shows a map view of the microseismic events from the original source mechanism analysis with manual moment tensor inversion. The events are colored by the source mechanism class from the original processing. The blue events clustered around the wellbore are the dip-slip class, and the red events that extend away from the wellbore in a sharp linear path are the strike-slip class.

The two distinct event classifications make this well a good candidate to test automatic moment tensor inversion techniques. In the original processing, these two pure shear classes were able to describe all events well enough to correct for the radiation patterns necessary to locate the events and distinguish between the two very different fracture styles.

When the same data are calculated by automatic full moment tensor inversion, it should show the same basic solution, but with a more robust continuous catalog of source mechanisms.

A simple k-means clustering technique was applied to the six components of the moment tensor solution to match the original picking method (where only a few classes of source mechanism were calculated in the event catalog) to a fully deterministic source mechanism catalog. The objective of this clustering technique was to determine whether the numerous full moment tensor solutions would group in the same general pattern as that of the original method. If the patterns are similar, it serves to validate the automatic moment tensor solution as being at least as accurate as the traditionally accepted hand-picking method.

Figure 2 displays the results from the same Eagle Ford well using data reprocessed with full automatic moment tensor inversion, again classifying events through a simple k-means cluster algorithm. Note that the blue and red colors have been switched to emphasize distinctions between the two figures, which are essentially identical. Accordingly, in Figure 2, the blue events are the strike-slip class and the red events are the dip-slip class.

The results are similar to the original results from the manual picking method, showing that the automatic method can match the accuracy of the manual picking method in identifying the fault from the standard fracture events. In this case, the k-means cluster matched exactly, with the exception of only two events.

Furthermore, instead of having two moment tensors to describe these two classes of events, the results from the automatic method have 4,500 moment tensors describing every event, which makes it possible to apply additional analysis techniques for a more in-depth evaluation of the recorded microseismic data.

The ability to automatically determine moment tensors in real time can be very helpful when trying to avoid faults and large natural features, such as the one in the Eagle Ford example dataset. Since a source mechanism is needed for a properly imaged location in surface microseismic, it could be difficult to identify this feature immediately in the dataset because erroneous locations would obscure the linearity of the feature. The change would be apparent only by looking directly at raw data for a microseismic event. Once identified, it would have to be pulled, picked and verified before it could be located correctly.

This process takes an analyst 20-30 minutes to perform in real time, and in some cases, an additional 10-20 minutes of reprocessing time before the fault can be identified and operations stopped to assess the best course of action. If the moment tensor was calculated automatically, however, this fault could be identified in a few minutes or even seconds, potentially saving time, energy and completion materials.

Real-Time Stress Analysis

The automatic moment tensor inversion algorithm also allows for real-time analysis of in situ stress conditions during treatment. With a full moment tensor, it is possible to calculate the compression (P) and tensile (T) axes and evaluate their distributions on a stereographic net as the data come in from the field.

In practice, the T axes are used to indicate the minimum compressive stress direction, and the P axes indicate the maximum compressive stress direction. The distribution of the P and T axes should, therefore, reflect the in situ and/or regional stresses during hydraulic fracturing operations, providing valuable information to the operator's decision-making process during treatment.

In the case of the Eagle Ford well, the data indicate that the regional stress field was the dominant factor controlling the strike-slip class events. However, results were less clear for the dip-slip class events, which may be the result of interplay between the in situ and regional stresses. Further analysis could define full stress inversions of the focal mechanism data and evaluate temporal variations in the stress field during treatment.

The ability to model source mechanisms automatically in real time is a critical component for real-time operational decision making. Automatic source mechanism calculation has been shown to accurately describe source mechanisms while also enabling automatic modeling of a full moment tensor in real time. This enables rapid identification of geohazards, allowing treatment decisions to avoid such features, saving time and resources.

Determining full moment tensors also provides stress information in real time, which allows an operator to more efficiently and confidently make on-the-fly changes to treatment plans. Having a deterministic moment tensor for each event in a microseismic catalog enables smarter reservoir modeling and greater recovery optimization. ❒

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