Acoustic emission — an ear to the ground

Hydrofracturing is one of the most commonly used methods of increasing production from low reservoir permeability reservoirs. It is crucial for siting producing wells, predicting water breakthrough and planning of waterflood and enhanced oil recovery (EOR) projects. But until recently, there has been no way of predicting how the induced rock fractures will propagate away from the well.

The Formation MicroScanner* tool can be run into open holes before and after hydrofracturing to investigate the fractures. In cased hole, analysis of a full waveform sonic log from the Array-Sonic* tool may provide some fracture information. Variations in the quality of casing cement, however, may affect the data making interpretation difficult. Both these measurements cannot “see” more than a few inches into the formation and thus cannot indicate the direction and extent of fracture development far from the borehole.

However, a more comprehensive fracture analysis may now be possible using the acoustic emission (AE) technique. This method has recently been used successfully in several different parts of the world at depths up to 11,000 feet (3,350 meters). Basically, the technique involves listening to the sounds emitted from rocks during hydrofracturing. Low-frequency sound, generated when rock cracks, is detected by geophones placed in the well being fractured or in nearby wells.

Three-component borehole seismic tools with triaxial geophones are necessary for AE work. During openhole surveys, the tool is clamped to the wall by mechanical locking arms. In cased holes, either locking arms or strong magnets are used. Clamping couples the sensors tightly to the formation and permits the cable to be slackened, thus eliminating noise transmission from the surface.

During rock fracturing, cracks open perpendicular to the earth’s minimum stress direction (above). The

* Mark of Schlumberger
Acoustic wave motion generated by the fracturing has characteristic particle motion directions and frequencies which can provide fracture information. The compressional wave, with most of its particle motion in the fracture plane, indicates the induced fracture’s direction. Shear waves, if detected, can give a better determination of the fracture’s extent.

Finding the fracture’s direction of propagation depends on knowing the geophone’s orientation. This can be found by setting off check shots at known surface locations and observing the directions of the incoming compressional wave arrivals recorded by the triaxial sensors. The seismic source is offset from the well to ensure production of horizontal wave motion measurements. With this procedure, fracture orientation can be determined to within 3 degrees (above). A compass-pendulum system and a downhole gyroscope have been also used for this purpose; but the additional tool mass, however, may degrade the geophone response. This problem can be avoided by using the recently introduced Combimable Seismic Imager (CSI) tool whose geophones are relatively unaffected by changes in the configuration of the main tool.

A three-part schematic demonstrates the directions of wave fronts from a seismic source and the acoustic emissions from induced fractures. The left portion shows hydraulic fracturing in operation and also depicts a seismic pulse traveling from an offset surface source toward a three-component downhole seismic tool. The central plots show the geometry of shear and compressional wave fronts emanating from the fracturing operation and the surface source, in relation to the triaxial geophones. The hodogram on the right shows how the wave front arrival angle is determined from a pair of horizontal geophone signals (x and y).

Acoustic waves arrivals at the geophones are crossplotted to determine their incoming direction. Plotting the geophone response to the compressional wave on the x axis against that for the y axis at simultaneous times produces a hodogram. Compressional waves are shown with the rock particles moving in the wave’s direction (above, left). On the horizontal axes, the crossplot of the signals indicates the horizontal component of the compressional wave’s direction. The angle with respect to the vertical component (z) can be found in a similar way. Once the angle of the x and y axes relative to the known source position has been determined, the source of the fracture’s acoustic emissions can be similarly defined.
A continuous recording of signals from the triaxial receiver in the injection well. Identifying the direction of wave front motion, is difficult since the first wave arrivals of the events are not clear.

In single-well experiments, using only the injection well, this technique can indicate the orientation of the induced fracture plane. Data obtained from the triaxial receivers during the fluid injection phase of a hydrofracturing job show considerable background noise in signals from all three axes (below). The rose diagram, or polar plot, for these data, compiled from hodogram directions of selected events on the x and y axes, is shown (right). The postulated fracture direction coincides with the most frequently observed azimuth direction. Data from an observation well about 160 feet (50 metres) away (next page) is less affected by environmental and borehole noise.

Discrete events appear on all three axes, and their origins are in a plane through the injection well. The direction of the first motion in these events depends on the position of the acoustic emission source relative to the receiver. But because this direction of motion is difficult to identify in the data, an ambiguity of 180 degrees remains in the directional results (above, right). This ambiguity can be resolved by taking data in two or more wells and extending the directions indicated by their respective rose plots until they intersect.

If, in addition to compressional wave motion, shear modes are also detected (previous page), the arrival time delay between the two waves indicates the distance from the well at which the fracturing is occurring. The velocity of both compressional and shear waves can be measured in the wells using full waveform sonic tools such as the Array-Sonic tool. These velocities and the measured arrival time differences can thus add distance to the azimuth data.

AE location methods are based on the assumption that both compressional and shear waves propagate in a straight line. Since this is not true for heterogeneous or anisotropic media, a more reliable method
has been developed based on calibrations of the system using perforation shots in nearby wells. By knowing the distances and observing the time difference between compressional and shear arrivals from the same shot, it is possible to measure velocity factors associated with the wave propagation directions between the fracture well and observation well. These factors can then be used to calculate the distances to microseisms in various directions, thus essentially taking anisotropy into account.

There is still much to be learned about microseism-induced acoustic emissions and the relationship of the detected sound to fracture propagation. Specifically, more research needs to be carried out on an array of topics: acoustic emissions and their mechanism of generation; how emission energy separates into compressional and shear waves; how and why the wave train character changes with the nature of the fractured rock and the observation period; and how to better relate the detected acoustic emissions to the fracture parameters, especially in anisotropic and inhomogeneous formations. More detailed answers to these questions will lead to improved data acquisition methods and interpretation procedures.—JT, GC

Further Reading and Acknowledgements


For assistance in preparing this focus, thanks to Carl Poster, Dubai, UAE.

Continuous triaxial geophone recordings in the observation well. Although the same kind of recordings as in the injection well (previous page), these are much clearer.