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Application Areas Driving Microseismic

By Peter M. Duncan

HOUSTON–A resurgence of hydrocarbon production in North America, reversing a 20-year decline, is being driven by the development of unconventional reservoirs. Producing these reservoirs economically has been enabled by the development of horizontal drilling, hydraulic fracturing and microseismic monitoring.

Long laterals expose more of the reservoir to the well bore, increasing drainage area and rates of production. Fracturing creates new fractures or opens old fractures in the low-permeability rock. This network of connected, open fractures provides pathways for hydrocarbon flow back to the well bore, once again increasing drainage area and rates of production.

Microseismic monitoring allows for mapping the fractured drainage area so the operator can most efficiently plan well spacing and infill drilling. As experience with the technique has grown, more uses for microseismic data are being discovered.

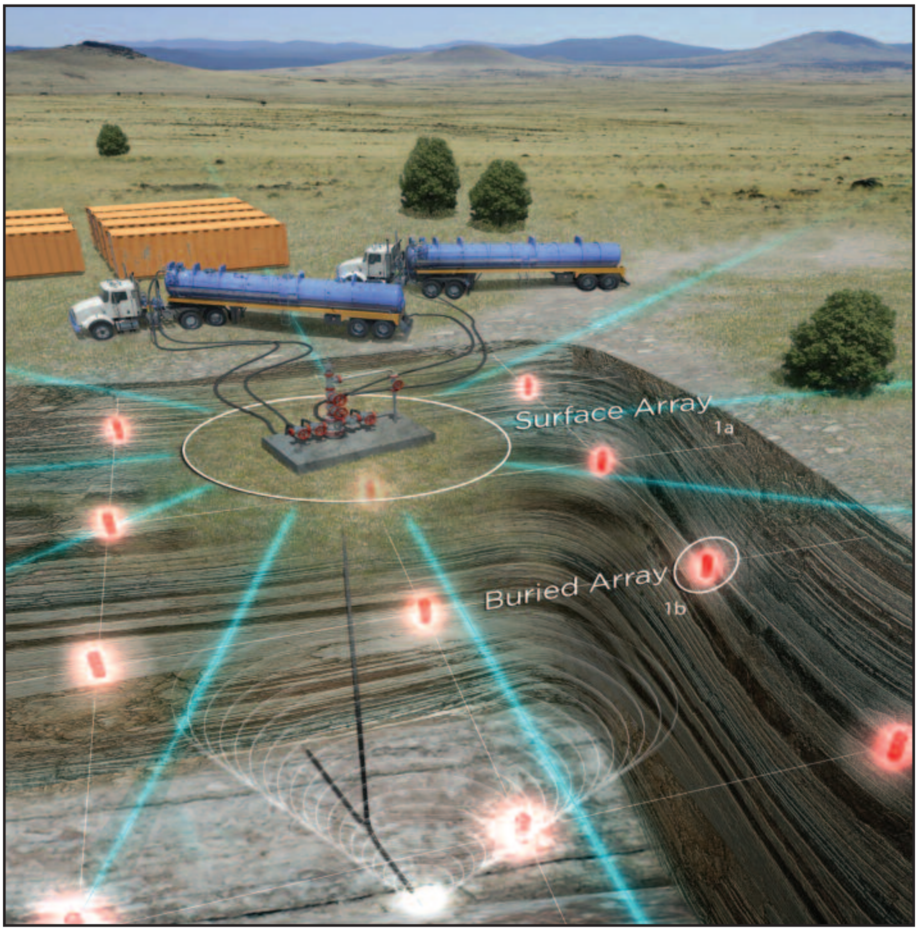
When fractures open or move during well stimulation, an acoustic signal is emitted that is captured by microseismic monitoring to locate the source event in time and space, and to extract other information about the way the rock broke and the stresses that caused the breakage.

There are two prevailing methods for locating the source of a microseismic event. The first is an adaptation of the way government agencies and academics locate large earthquakes around the world. This procedure employs an array of listening stations that are always on. When a signal is detected, the arrival time of the compressional (p) phase and the shear (s) phase signal is "picked" to a high degree of precision.

By knowing the difference between the arrival times of the phases and the velocity that each phase travels (often only an estimate), one can calculate the distance from the station to the source location. By plotting that distance from an array of stations, distributed around the event, one arrives at the likely source location. The accuracy of this location

FIGURE 1

Surface Receiver Array versus Near-Surface Permanent Array



estimate is driven by the precision to which one can pick the arrival times. Typically, the events created by fracturing are minuscule; several orders of magnitude below that which can be felt at the surface.

With such small signals, it is rare that one would be able to pick arrival times with sufficient precision using surface-located geophone stations. The solution has been to place the geophones at near reservoir depth in monitoring wells located within 1,000 feet of the treatment well.

The cost of providing monitoring wells usually limits the deployment of these arrays to one, or at most, three strings of geophones. This limited sample of the signal does put some limitations on the accuracy of the location estimates, particularly as the distance between the events and the geophones increases. It also limits the ability to image how the rock broke.

Nevertheless, this downhole approach to monitoring is responsible for the majority of microseismic work done to date.

Full-Waveform Stacking

The second method for estimating event location uses a full-waveform stacking process very similar to what is used in conventional seismic imaging to locate reflecting horizons in the earth. One can think of this as searching for the source position by finding the location that causes the signals at each of the receiving stations to align in time, once they have been shifted for the travel time between the suspected source location and the receiving location. This alignment is not just that of the signal arrival, but of the entire waveform. The statistical power of using many samples from each signal rather than only the first arrival allows for the recovery of smaller signals at a given level of noise.

As with telescopes and dish antennae, the resolving power of this approach depends on having a large aperture and a well-sampled signal over that aperture. Economics dictate that for this beam-steering approach to event location, the receivers must be placed on the surface, or at most, in relatively shallow holes. Otherwise, the sampling demand would make the process prohibitively expensive.

For short-duration projects, a purely surface array (labeled "1a" in Figure 1) is the method of choice. For longer, multiwell or life-of-field monitoring projects, a near-surface permanent array (labeled "1b" in Figure 1) is generally more cost effective, since it employs fewer receiving stations spread over the same area.

Fracture Mapping

The primary commercial use of microseismic monitoring has been for hydraulic fracture mapping. Rocks subjected to pressure often break along lines of pre-existing natural microfractures, generating microseismic events as they break. By determining the location of the "hypocenters" of these events, it is possible to construct a map of the area of the reservoir stimulated by the treatment. As shown in Figure 2, the microseismic events are mapped conterminous with the well bore.

The mapped fracture half-length and trend orientation are commonly used to plan well direction and spacing, ensuring that future well drainage areas do not overlap. This approach provides a more definitive analysis than is possible with alternatives such as pressure transient testing and tracer logs. Delineating the fracture network can form the basis of a stimulated rock volume calculation, and ultimately, an estimated ultimate recovery.

Fracture geometry helps operators understand whether the stimulation remained within the producing zone, went out of zone, or perhaps was lost to thief zones such as large faults that can be reactivated during a fracture treatment. Fracturing unproductive rock is not only an expensive and fruitless endeavor, but it could result in watering out a well. Microseismic monitoring, especially if done in real time, can provide a "quick look" evaluation sufficient to modify treatment plans to avoid these deleterious outcomes.

Hydraulic fracture mapping is used to better understand the effect of stimulation treatments and improve completion techniques from one well to another. Operators are able to evaluate frac efficiency for different fluids, proppant concentrations, pump rates, durations, etc. Fracture mapping allows comparison between sliding sleeve, plug-and-perf, and open-hole completions. Multilateral completion methods such as the "zipper frac," "inside-out," and "outside-in" methods can be diagnosed for efficacy. Taken together, these optimizations can save cost on completions, improve field development, and increase hydrocarbon recovery.

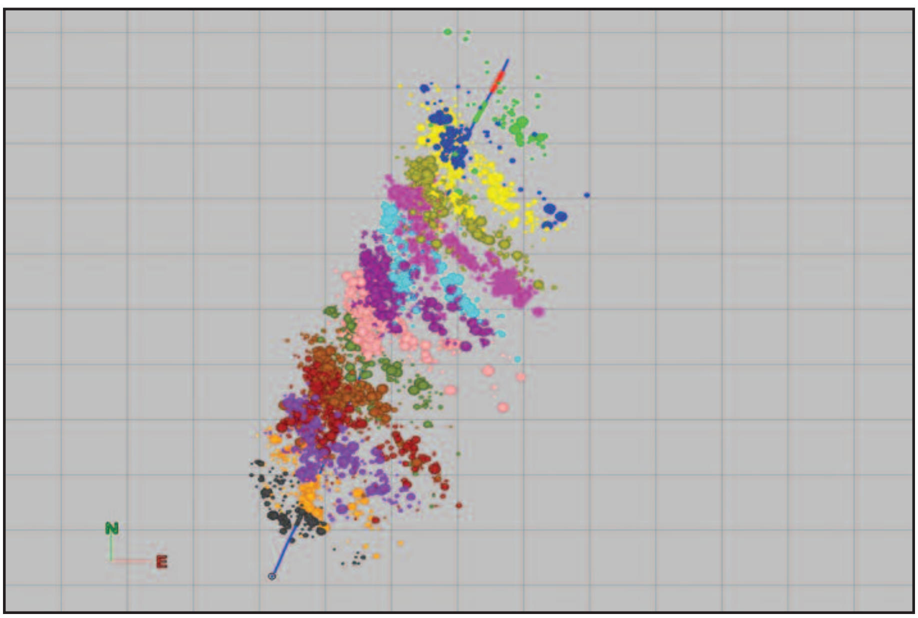
Reservoir Monitoring

Microseismic monitoring can be applied to other interactions with the reservoir that result in stress changes and seismic emissions. One such application of high interest today is monitoring steam injection in heavy oil deposits.

Steam can migrate large distances from the injection site, preferentially moving through faults and fractures, causing slippage that results in seismicity. Thermal expansion also may result in seismic event generation. In rare cases, especially where there is no cap rock (such as in the shallow diatomite reservoirs

FIGURE 2

Reservoir Near Well Bore Following Hydraulic Fracture Treatment



near Bakersfield, Ca.), dangerous surface expressions can occur. Locating these events can be trickier than standard hydraulic fracturing projects, since the events are small and the time window for occurrence is usually less constrained than it is for fracs.

When the purpose of monitoring is preventing any near-surface contamination or blowouts, real-time alerting when significant upward migration is detected allows the operator to cease injection, relieve the pressure and prevent further damage. The large area requiring monitoring in these cases makes this an ideal application for buried, near-surface arrays.

Other activities or events that have been observed to create mapable microseismic events include reservoir compaction as a result of depletion, stress realignment as a result of injection for pressure maintenance, cap rock failure during sequestration or other injection, and casing failure, whether as a result of mechanical issues or fault shearing. All these situations present value-added opportunities for deploying long-term monitoring in fields over their active lives.

Induced Seismicity Monitoring

An application of microseismic monitoring is to detect anthropogenic, low-magnitude tremors resulting from wastewater disposal or hydraulic fracturing. New studies in British Columbia, the United Kingdom, Oklahoma and Texas suggest that, in rare cases, events as high as local magnitude (M_L) 4.0 have been triggered by oil and gas activities. In the United Kingdom, it was shown that fracturing activity in a well near Blackpool likely triggered a swarm of small seismic events along a pre-existing fault that were felt at the surface.

This and other studies have shown that induced seismicity, usually at a very low, but perceptible level, can occur when injection takes place near a fault. The fault is usually under tectonic stress, aligned in such a way as to predispose the fault to move. The injection rate must be sufficiently high, compared with the leak-off rate such that fluid pressure builds up enough along the fault plane to offset friction.

It has been observed that the larger events often are preceded by smaller events, which build over time to a peak in stress relief. It appears that the seismic activity can be shut down if the injection is terminated and the well is flowed back to release the pressure in the failure zone.

Following on protocols developed in relation to enhanced geothermal systems projects, the industry is moving toward a "traffic light" system (green, yellow and red) that builds on the following workflow:

- Avoid injecting into active faults.
- Minimize pore pressure changes at depth.
- Install local seismic monitoring arrays.
- Establish modification protocols in advance (green, yellow and red), depending on observed seismicity.
- Be prepared to alter plans or abandon wells.

The traffic light system was implemented in the United Kingdom using the three warning levels, with green denoting magnitudes smaller than 0.0 M_L (regular operation), yellow denoting magnitudes between 0.0 and 1.7 M_L (calling for continued monitoring after the treatment until the seismicity rate fell below one event a day) and red denoting magnitudes greater than 1.7 M_L (requiring pumping to stop and the well to be flowed back while monitoring is continued).

Some operators have been installing microseismic monitoring systems around each of their well sites, including an adaptation of the traffic light early warning system. Elsewhere, operators are evaluating using microseismic monitoring for similar applications. Numerous regulatory bodies are evaluating including microseismic monitoring as a routine part of well safety evaluations. California has released a draft on hydraulic fracturing safety rules, which included an allusion to these protocols.

Microseismic monitoring is an important technology whose utility is growing. Microseismic monitoring can lower costs and improve initial production through hydraulic fracture mapping, minimize geohazards, improve secondary recovery efforts when used for reservoir monitoring, and demonstrate compliance with environmental safeguards during recovery and disposal operations. Microseismic monitoring can ensure that the oil and gas industry will continue to provide for global energy needs safely and cost effectively. ❒

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Peter M. Duncan is founder and chief executive officer of Houston-based MicroSeismic Inc. He began his career as an exploration geophysicist with Shell Canada before joining Digicon Geophysical. In 1987, he helped Digicon found ExploiTech Inc., an exploration and production consultancy. He was named president of ExploiTech in 1989 when it became a subsidiary of Landmark Graphics. In 1992, Duncan was one of three founders of independent exploration company, 3DX Technologies Inc., where he served as vice president and chief geophysicist. He is a former president of the Society of Exploration Geophysicists, and established the SEG Challenge Bowl, a quiz contest designed to encourage high school students to pursue degrees in the geosciences. After his term as SEG's vice president in 1994, he developed a distinguished instructor short course program that sends one outstanding instructor each year around the world to lecture at colleges, universities and local associations. He holds a Ph.D. in geophysics from the University of Toronto.