paper presented at the "Microseismicity: Beyond Dots in a Box" workshop, Society of Exploration Geophysicists (SEG) 80th Annual Meeting, Denver, CO, 7-22 October, 2010

DIVERSE APPROACHES TO UTILIZING MICROEARTHQUAKES FOR RESERVOIR RESEARCH

Gillian R. Foulger[1] & Bruce R. Julian[2]

[1]*Dept. Earth Sciences, University of Durham, Durham DH1 3LE, U.K.*, g.r.foulger@durham.ac.uk

[2]*Foulger Consulting, 1025 Paradise Way, Palo Alto, CA 94306, U.S.A.*, bruce@foulgerconsulting.com

1 Introduction

The most useful information in terms of reservoir exploration and exploitation that can be derived from microearthquake observations comes from computed event locations, magnitudes, and source mechanisms and from models of reservoir structure. The last item includes temporal structural changes caused by fluid removal and reinjection during the productive lifetime of a reservoir. In this paper we comment on each of these four issues.

2 Hypocenters

2.1 Absolute Locations

Microearthquake hypocenters are the sites of rock failure and fluid motion, and their locations are the most fundamental information provided by seismology. Furthermore, advanced types of information such as event magnitudes, source mechanisms, and crustal models, require accurate earthquake locations for their derivation. Nevertheless, computed hypocenters are often poorly determined, and have the appearance of diffuse "dots in a box" that do not delineate features such as faults adequately for purposes such as guiding drilling. The situation is sometimes exacerbated because different data sets may produce locations that differ by more than the computed errors, so it is not clear which locations, if any, to believe.

The roots of these problems lie in the fact that traditionally, large-dollar decisions have not depended critically on the accuracy of earthquake locations and thus most commonly used earthquake data processing techniques do not reach industrial standards. We are currently working to develop tools that produce locations that are a) sufficiently accurate to be of use to operators, and b) have realistic error estimates.

In order to obtain the most accurate locations, dense networks of three-component seismometers, well distributed around the earthquakes, are required. Much monitoring is done using inadequate networks with fewer than ten stations, and sometimes inherently weak geometries, *e.g.*, strings of sensors in a single borehole. In order to obtain accurate locations the following are required:

- A dense network of 10 to 20 digital three-component seismometers at a wide range of distances and azimuths around the earthquakes. Numerically tracing rays through local crustal models, if they are adequate, can aid in designing an optimal seismometer network.

- Calibration explosions, yielding direct measurements of travel times along the relevant paths, can eliminate travel-time anomalies, which are the largest source of systematic location error.
- Expert hand measuring of the arrival times of *P*- and *S*-waves.
- Cross-correlating waveforms to measure accurate arrival-time differences.
- Accurate three-dimensional crustal velocity models.
- Correct assessment of the uncertainties in the calculated locations (Section 2.3).

2.2 Relative Locations

Relative hypocenter-location methods can greatly improve the resolution of seismically active structures. These methods use, for each seismic station, differences in arrival times of waves from closely spaced earthquakes. In these data, biases caused by complex geological structure nearly cancel out. An important recent extension of this idea treats a potentially huge network of events, with neighbors closely spaced but the entire network spanning a large volume. The results can be a spectacular improvement in the clarity of delineated structures – a change from "dots in a box" to "faults in a box" [Julian *et al.*, 2010] (Figure 1).

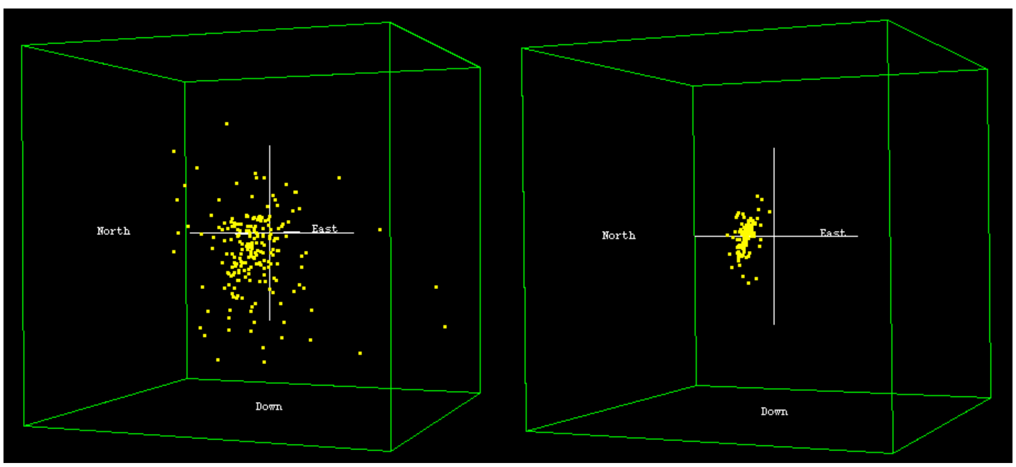

Figure 1: Left: Traditional individual earthquake locations ("dots in a box"), right: relative relocations ("faults in a box"). But do we know the absolute location of the new fault sufficiently accurately to drill through it?

Work is currently ongoing to improve the accuracy of relative locations, and the geological structures such as faults that they define, using improved techniques for waveform cross-correlation. The absolute location accuracy of the structures defined has also been improved by including both relative and absolute arrival times in inversions. Knowing the absolute locations of the relatively relocated clusters is crucial if they are to be used to guide drilling, *e.g.* through new permeable zones created by fluid injection.

2.3 Assessment of Errors

Most hypocenter-location computer programs, if they attempt to assess errors at all, make the serious mistake of assuming that errors in measured arrival times arise primarily from observational uncertainty. They further assume that the errors are statistically independent at different seismometers and from event to event. In truth, the dominant source of error is true variations in travel-times caused by the imperfectly known structure in the Earth. These errors are the same from event to event and, being caused primarily by large-scale structures, are strongly correlated between nearby stations. The result is that arrival times often can be fitted much better by mis-locating events toward regions of higher wave speed. The resulting systematically incorrect locations give artificially good fits to data, and derived confidence regions that are misleadingly optimistic.

A possible solution to this problem is to measure the relevant travel-time anomalies directly using timed explosions. This approach is particularly suitable for the case where microearthquakes are expected near a well in a hydrofracturing experiment. Explosions in the well are not required; times for small explosions at the seismometer sites recorded on a sensor in the well are equivalent because of reciprocity.

If using calibration explosions to eliminate systematic errors is not possible, an alternative approach is to incorporate the statistical estimation of errors into the forward computation of travel times using a (probably *ad hoc*) model of the sizes and strengths of wave-speed anomalies in the Earth. The resulting confidence regions will be much more realistic than ones based on the assumption of statistical independence, and can help to avoid being misled into mistaking artifacts of systematic location error for seismically active structures.

3 Earthquake Magnitudes

There is a great deal of confusion about how to express the size of an earthquake. Traditional magnitude scales are *defined* in terms of seismogram characteristics, not source physics, and are unfit for current needs. Furthermore, the definitions often explicitly ignore the type of seismic wave used, even though *S* waves are about 5 times larger than *P* waves, and specify obsolete instruments, requiring wasteful and error-prone signal processing.

An appropriate quantitative measure of earthquake size is moment magnitude M_W, defined in terms of low-frequency scalar seismic moment M_0 through the relation $M_W = \frac{2}{3}\log M_0 - 10.73$, with M_0 measured in Newton-meters. Seismic moment is defined in terms of physical strain changes at the source, which are directly related to the radiated elastic waves, so this definition anticipates, rather than forbids, improvements in measurement techniques.

The difficulty, however, lies in measuring the scalar moment M_0 at low frequencies. Recordings made using high-frequency sensors such as accelerometers are poorly suited to this task. Earthquake spectra are typically noisy and the amplitude at low frequencies may be difficult to measure accurately. Work is needed to integrate correct procedures into microearthquake processing workflows, and to adopt norms in industry.

4 Source Mechanisms

For precise description of earthquake sources, general physical source models are required; traditional fault-plane solutions designed to represent simple shearing in isotropic media, are not sufficient because they ignore volume changes and more complex shearing, which are crucial for describing physical processes such as tensile cracking. In order to assess these components, a moment tensor description is needed to represent the three-dimensional motions at the earthquake source. For this, again, high-quality data and advanced processing methods are required. Relatively dense networks of 10-20 three-component seismic stations are necessary, and seismic-wave amplitudes or waveforms, in addition to the directions of first motions of *P*- (and possibly) *S*-waves, must be used.

Current advances in source mechanism determination include the addition of lower-order moments, (net forces), which may be important in fluid reservoirs because rapid unsteady fluid flow may be involved in the genesis of earthquakes. This advance is currently in progress, and it may contribute to interpreting the still poorly understood volumetric components known to occur in geothermal and other reservoir-related earthquakes.

5 Reservoir Structure

Because the largest source of error in seismological measurements is our ignorance about the detailed structure of the Earth, accurate models are invaluable in analyses such as hypocenter location and source-mechanism determination. Structural models are also of direct importance for identifying and delineating reservoirs and for monitoring changes that occur during production caused, for example, by progressive fluid withdrawal or injection.

Structural models can be calculated from the earthquakes themselves, using techniques such as seismic tomography. Current advances in tomographic methods, aimed at providing information useful to operators, include:

- the first method for inverting directly for structural change, using datasets collected at different times [Julian & Foulger, 2010], and;
- the extension of local-earthquake tomography methods to include regional earthquakes. Seismic waves from regional earthquakes approach local seismic networks traveling steeply upward and thus sample the Earth beneath the seismically active production zones. Such results may provide information about the heat sources that underlie geothermal reservoirs.

6 Summary

Considerable work remains to be done before the full potential of microearthquake seismology is realized. However, this work is progressing rapidly. Basic techniques already exist to extract first-order information from microearthquake data but refinements and developments currently in progress are needed to deliver results of the accuracy demanded by industry, for example, in hydrofracturing operations. Immediate challenges are for industry to implement the state-of-the-art techniques that are already available, and for a body of documented case histories to accumulate. These will existing, and prototype microearthquake technologies and to guide the direction of current and future developments.

References

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