

## Special Section

### Microseismicity: Beyond dots in a box — Introduction

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This special section of *GEOPHYSICS* is a consequence of a very successful SEG workshop titled *Microseismicity: Beyond dots in a box*. The workshop was held 22 October 2010, following the SEG Annual Meeting that was held in Denver. More than 120 people attended the meeting, and nine oral papers and 22 posters were presented.

Small microseismic events, or acoustic emissions, occur naturally and a result of anthropogenic influences in reservoirs. Sudden stress release leads to elastic rock failure, which serves as an effective seismic source. These microearthquakes may be the result of production or hydraulic stimulation, but they also may be a consequence of natural tectonic activity. They are usually detectable using only sensitive sensors and after careful data processing. Such passive seismic monitoring has been used in mining settings for more than 100 years, but its application in petroleum setting is relatively new. As such, it is a rapidly advancing field of technology, where the challenges are manifold and span issues associated with data acquisition, processing, and interpretation. Much can be learned from methods and case studies developed for microseismic monitoring in volcanological, geothermal, and mining settings, but one of the key advantages in oilfield monitoring is that a great deal is ordinarily already known about the reservoir. Comparatively good velocity models exist, and production or injection information is available — the same is obviously not true for a volcano.

The microearthquake or microseismic event location is useful in itself. Clusters of events delineate faults and fracturing, highlighting reactivation or the generation of new zones of failure. This has been very effective in helping assess the efficacy of hydraulic stimulation (i.e., frac monitoring). Longer term monitoring will no doubt provide an early warning system for detecting top seal leakage and fault reactivation in CO<sub>2</sub> sequestration projects, for example.

Until recently, most microseismic monitoring studies in petroleum settings have concentrated on detecting and locating events. An aim of the SEG workshop was to highlight progress in a wealth of other applications — ‘beyond dots in a box.’ For example, source characteristics and mechanisms provide helpful information about the stress field, especially as multiwell monitoring and surface arrays become more common. Magnitudes help quantify stress drop and focal mechanisms and provide insights into the magnitude and orientation of the stress tensor. Furthermore, microseismic events can be used to image the surrounding media. They can help refine velocity models, study attenuation, and are ideally suited to estimating anisotropy parameters. Insights into the nature of faults, estimates of the stress tensor, and velocity model refinement are all valuable inputs for reservoir simulators.

The breadth of potential applications of microseismic monitoring can be summarized as follows:

- estimating magnitude and orientation of the stress tensor
- predicting stress build-up and potentially mitigating well-bore failure
- imaging fault and fracture orientations and their reactivation
- characterizing seismic anisotropy, which can be used to determine anisotropy parameters but also can be used to assess lithology and fracture-set properties including orientation, density, and size.
- studying fluid-properties using frequency-dependent wave characteristics (e.g.,  $Q$  estimation and frequency-dependent shear-wave splitting)
- monitoring injection fronts such as water, CO<sub>2</sub>, and steam
- monitoring hydraulic fracturing, especially in tight-gas shales and sands
- studying compaction effects around reservoirs
- studying cap-rock integrity

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- studying sealing faults and reservoir compartmentalization
- identifying seismically active and potentially hazardous zones
- calibrating geomechanical models.

The papers presented in this special section summarize recent developments in six aspects of passive seismic monitoring: survey design and processing considerations, improving event locations, interpreting event magnitudes, source mechanisms, anisotropy estimation, and reservoir geomechanics.

### Survey design and processing considerations

Microseismic event location and source mechanisms offer a rich source of information about a reservoir, but the accuracy of any such analysis needs to be treated carefully. It is easy to make meaningless estimates of such event attributes. Foulger and Julian describe factors affecting the typical accuracy of source locations and discuss methods to compute more precise relative locations. They also describe the various magnitude scales used to report source strength. Finally the accuracy of source mechanism studies using moment tensor inversions is discussed.

Zimmer provides a tutorial on the content and application of modeling and design studies for microseismic surveys with downhole geophones. Using only the information available prior to the microseismic survey, these studies provide a tool to optimize the acquisition, processing, and interpretation of microseismic data and to assess the potential of a given acquisition geometry to meet the survey objectives.

### Improving event locations

Any subsequent data analysis is strongly influenced by the quality of event locations. Single-well monitoring is the norm, rather than the exception, so it is important to use as much information as possible to refine event location. Interferometry offers a new approach, and Poliannikov et al. consider a problem of localizing hydrofracture microseismic events using previously localized events in a reference fracture. They propose the use of single-well interferometry and show how event localization uncertainty can be reduced by averaging over a large number of reference events.

Another approach is to use seismic multiplets (recurring events whose waveforms are essentially identical) to refine locations. Moriya proposes a phase-only correlation of time-varying spectral representations of waveforms to identify similar microseismic events. The author tests its application to earthquake aftershock events and demonstrates the feasibility of this technique for identification of similar seismic waveforms.

### Interpreting event magnitudes

Event magnitude is related to energy release and the stress drop associated with rock failure. The relationship between event magnitude and frequency is well known to be sensitive to the style of rock failure and can be described by the so-called Gutenberg-Richter '*b*-value'. Haney et al. calculate the magnitudes of several thousand small earthquakes at the German Deep Drilling Site (KTB) during an injection phase in 2004–2005 using data from a single three-component borehole geophone and extrapolating a scale determined for a much smaller number of events using near-surface stations. They determine a *b*-value for all events of

0.78. They find that the event distribution with time is consistent with prediction from theory assuming pore pressure diffusion as the underlying mechanism to trigger the events. The seismogenic index of  $-4$  shows that the seismic hazard potential at the German Deep Drilling Site (KTB) is comparatively low.

Shapiro et al. discuss seismic hazard associated with fluid injections. The authors investigate the relationship between the geometric size of the cloud of microseismicity induced by fluid injection and magnitude of induced earthquakes, and they propose a relationship between the dimension of the fluid stimulated volume and discontinuities that controls the probability of triggering earthquakes.

### Source mechanisms

The signature of the seismic source is held in the recorded seismic waveform. Microseismic data can be used to infer fault geometry and failure mechanism. With a good velocity model and favorable recording geometry, the entire moment tensor can be estimated, but practical considerations usually mean that neither is generally available.

Du and Warpinski discuss the accuracy of fault plane investigations. Uncertainties in inferred fault plane orientations and the associated slip directions are examined using moment tensor inversion of synthetic data sets. The authors add white noise to the theoretical seismic radiation pattern for typical downhole hydraulic fracture monitoring geometries and examine the errors in the resulting fault plane solutions.

Microseismic moment tensors have the potential to reveal important details of fracture processes that occur during hydraulic fracture treatments of tight reservoirs. Eaton and Ferozideh show that careful survey design is required to be confident in inversion results. The paper reveals a simple design consideration, namely that the stability of the inversion is related to the solid angle subtended by the receiver array, and it shows that ill-conditioned inversions may produce biased results.

Li et al. describe a moment tensor inversion method and apply it to a case study of surface and downhole recording of microseismicity associated with oil production. A full waveform inversion method is used to compare the orientations of the seismically active faults with known faults in the reservoir.

Song and Toksöz discuss a new methodology for estimating source mechanisms of induced microseismic events. They show that full waveform inversion improves stability of the inversion; in particular, including the near-field terms enables inversion of the complete moment tensor even from a single vertical monitoring borehole. They demonstrate that such inversion is practical for events in close vicinity of the monitoring borehole and investigate methods of stabilization at greater distances.

### Anisotropy estimation

Due to the recording geometry and distribution of sources, microseismic data generally are well suited to estimating anisotropy parameters. Furthermore, microseismic events normally are rich in S-waves and are therefore ideally suited to study shear-wave splitting. Such information is valuable input for data processing that considers anisotropy, but it also provides valuable information about rock properties.

Gei et al. use P-wave arrivals recorded by surface monitoring arrays to invert for a best fitting homogeneous transversely isotropic model with a vertical axis of symmetry (i.e., VTI symmetry). The Thomsen parameter  $\delta$  and the anellipticity coefficient  $\eta$  are estimated from traveltimes picks. They explore the sensitivity of this inversion to picking errors and uncertainties in the P-wave vertical velocity and source depth.

Grechka and Duchkov develop a technique for estimating seismic anisotropy from perforation-shot data acquired in narrow-angle geometries. They apply their methodology to build a triclinic model that allows them to fit the traveltimes and simultaneously locate perforation shots recorded in a shale-gas field. Grechka et al. then present a case study in which they build an effective anisotropic model simultaneously with locating microseismic events. They show that anisotropy is necessary to explain the recorded data and its variation is suggestive of opening fractures in the course of hydraulic well stimulation.

Wuestefeld et al. present an analysis of seismic anisotropy using shear wave splitting measurements made on microseismic events recorded during hydraulic fracture stimulation. They then use an assumed rock-physics model to invert the splitting measurements for fracture parameters. They show a temporal variation in anisotropy that mimics fluid pumping volumes and present evidence for induced fracturing that follows preexisting fractures that are oblique to the general trend of the main frac.

### Reservoir geomechanics

The long-term management of any reservoir requires a reliable geomechanical model that considers stress changes and the development of faults and fractures. This is a grand challenge, and microseismic monitoring provides a valuable means of calibrating

and verifying geomechanical models. Numerical models of seismicity and its relation to fluid and mechanical properties provide a valuable link to observations.

Zhao and Young present a numerical modeling study using a 2D distinct element particle flow code that offers insights into fracture mechanisms in naturally fractured reservoirs. They compare the geometry of hydraulic fractures with seismic source information (locations, magnitudes, and mechanisms). The numerical results qualitatively agree with laboratory and field observations and suggest possible mechanics for new fracture development and their interaction with a natural fracture (e.g., a tectonic fault).

McClure and Horne present an approach to modeling induced seismicity due to hydraulic fracturing through coupled rate and state friction with fluid flow. Their simulation focuses on fluid-only injections (no proppant) and understanding injection parameters that control the maximum magnitude of the induced seismicity. While the model is relatively simple, the authors show that decreasing injection pressure over time was a successful strategy for reducing the maximum magnitude.

The papers compiled in this volume illustrate the diversity in applications of microseismic monitoring. The technology has rapidly gone from a subject of abstract curiosity to a staple in the exploration seismologist's toolbox. The number of research papers in this field is growing rapidly; the reader is also referred to the recent special issue of *Geophysical Prospecting* (vol. 5, 2010) and two review papers in the 75th anniversary issue of *GEOPHYSICS* (Maxwell et al.; Duncan and Eisner, vol. 75, no. 5, 2010). Passive seismic monitoring will no doubt help address many of the future challenges facing the petroleum industry, including optimizing enhanced oil recovery (EOR), heavy oil extraction, CO<sub>2</sub> storage in geologic reservoirs, exploiting unconventional hydrocarbons targets, and drilling hazard mitigation — to name a few.