Microseismic Network Design: Estimating the Number of Detected Events During Hydraulic Fracturing

Shawn Maxwell*
Schlumberger
smaxwell@slb.com

Summary

The rapid expansion of microseismic monitoring, particularly to image hydraulic fracture geometry, has resulted in increased awareness of pre-survey design studies in attempt to optimize the microseismic data. These design studies typically include estimates of the expected source location accuracy and the minimum expected magnitude of a microseismic event that could be recorded. However, a critical but often overlooked factor is the number of microseismic events that are expected to be recorded, which will impact the confidence of the interpreted hydraulic fracture geometry. This paper describes a method of predicting the number of events based on average relationships between magnitude and frequency of microseismic events as well as published seismic injection efficiencies, defined as the ratio of seismic energy to hydraulic energy of the injection. A test using hydraulic fractures in various fields showed that the prediction was well within an order of magnitude of the actual observed number of recorded microseismic events. The predicted number of events can be used in design studies to ensure adequate data for hydraulic fracture interpretation.

Introduction

Microseismic design studies attempt to select the position of sensor arrays, within logistical constraints, in such away as to allow acquisition of high quality data (e.g. Maxwell et al., 2003). A common component of such a design study is an estimation of the expected location uncertainties assuming certain data quality and ray tracing between expected source and sensor arrays. Also common is the estimation of minimum magnitude microseismic source strength that can be expected to be detected at different locations (Raymer and Leslie, 2010). While both components are important in an attempt to acquire microseismic data with the best possible location accuracy and sensitivity, a generally overlooked component is the expected number and magnitude range of microseismic events that will be recorded. The number and magnitude range is highly variable from project to project, but is a critical aspect that will define the effectiveness of the monitoring, in terms of the data quality and if sufficient data will be recorded to statistically describe the fracture geometry. While the number of detected events is a somewhat subjective parameter depending on the minimum detectable signal strength, for a specific minimum detectable magnitude the corresponding number of recorded events above that level will be a well defined number.

The number of events and magnitude range are actually related parameters, since microseismic events generally follow the Gutenberg-Richter power law between frequency and magnitude. The magnitude of microseismic events generated during the hydraulic fracture stimulation depends on both the injection and the site conditions. The pressure and rate of injection appear to be significant factors, although the characteristics of the injected fluid also play a role (Maxwell et al., 2009). The geomechanical site conditions including stress, fractures, stiffness and possibility of triggering tectonic induced deformation are also important factors. Maxwell et al., 2009 describe an analysis of the seismic injection efficiency (SIE:

defined as the ratio of total cumulative seismic energy release of all recorded microseismic events to hydraulic energy of the injection) which appears to account for the injection characteristics and also potentially formation permeability. Figure 1 shows a plot of SIE versus frac gradient (depth normalized fracturing pressure associated with the minimum principal stress). Based on these results compiled from diverse North America reservoirs and from subsequent SIE investigations it appears that the SIE is proportional to the frac gradient for a specific site. The exception being scenarios where the hydraulic fracture activates tectonic deformation on a pre-existing fault, in which case a higher SIE is observed. McGarr (1976) hypothesised that the total strength of the seismic activity would be proportional to the injected volume. While the constant of this proportional relationship appears to be approximately constant for a given project, it has been found to vary both within a single monitoring project as well as between projects even for the same site (Maxwell et al., 2009).

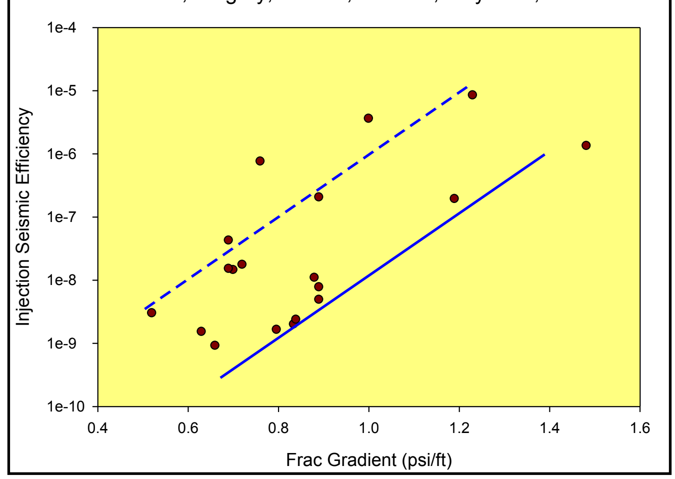

Figure 1. Plot of seismic injection efficiency versus frac gradient (after Maxwell et al., 2009). Solid blue curve represents a low SIE "conservative" trend and dashed a high SIE trend.

In this paper, a workflow is described to estimate the number of events that would be recorded during a hydraulic fracture. Exact estimation of the number of events would intuitively be a difficult, if not impossible task. The objective here is to provide a conservative estimate to avoid a scenario where a monitoring project would result in too few microseismic events to characterize the hydraulic fracture.

Method

The number of recorded microseismic events is estimated from the SIE, using the following steps:

1. Compute the hydraulic injection energy, or range of values based on possible injection schedules
2. Estimate the SIE based on frac gradient and site conditions
3. Compute the released seismic energy and corresponding total seismic moment
4. Compute the number of events relative to an estimated minimum detectable moment magnitude assuming a Gutenberg-Richter distribution

Typically the planned injection volume and rates will be defined based on the stimulation engineering design. The injection pressure can depend on site conditions but can either be estimated numerically or based on local site experience. The hydraulic energy is then equivalent to the work done during pumping given by the time integral of the pressure and rate. While the actual executed injection could vary from the plan for various logistical reasons, the injection plan(s) are generally available beforehand.

Estimating the SIE can be done using local SIE information from previous monitoring projects in the same formation. An estimate of the expected frac gradient is also required or an average value can be assumed. In cases where no previous microseismic data are available the most conservative trend in Figure 1 can be assumed, or results from a formation analogue can be used. However, the site characteristics that would serve a basis for selecting an analogue are not well understood. Here the use of the conservative trend is considered advantageous in light of a producing a conservative microseismic monitoring scenario. If more events are recorded beyond a conservative estimate it allows more aggressive filtering of a subset of high quality/ high signal-to-noise ratio events for interpretation. Once the total released seismic energy is estimated, the Kanamori (1978) relationship between seismic energy and moment can be used to estimate seismic moment. Alternatively other energy-moment relationships can be used such as a local relationship from previous projects.

Finally the number of events relative to the estimated total seismic moment is computed. Typical hydraulic fracture microseismicity results in a frequency-magnitude power law distribution with an average b-value slope of 2 (e.g. Maxwell et al., 2010). Other frequency-magnitude relationships are possible although the main variation appears to be fault activation related activity, which as described above also leads to an increased SIE. Therefore the frequency-magnitude characteristics do not appear to result in significant biases in the estimation compared to other aspects of the estimation.

Calibration

This workflow has been tested against several projects in various formations. Figure 2 shows a comparison of estimated and observed number of events from several fracs in various fields, representing a range of reservoir types (tight sands and shales) and hydraulic fracture designs (high and low rate, large and small volumes). Observed and predicted number of events show a reasonable agreement over three orders of magnitude, with the majority of data points well within an order of magnitude. However, the data points with a largest number of observed events are underestimated using the conservative estimates (circles) with the low SIE trend in Figure 1. The data points correspond to reservoirs which plot along the higher SIE trend, and recalculating the predicted number using the higher efficiency (triangles) results in significantly improved agreement. Notice that the prediction is advantageously biased towards being conservative or under-estimating the observed number of events.

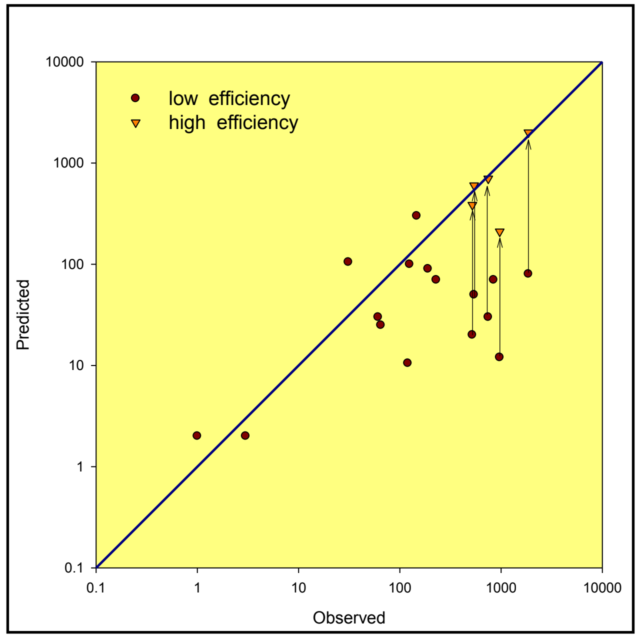

Figure 2. Comparison of predicted and observed number of microseismic events.

Application

The main application of the method is pre-acquisition survey designs to predict the number of events that are expected to be recorded. However, as implied with Figure 2, accurate prediction requires an assessment of the SIE. Previous experience is the best indicator of a realistic SIE trend, although not always available. The underestimated data points in Figure 2 represent a fault activation example (Maxwell et al., 2010) and select data from the Barnett Shale in the US. While fault activation tends to increase the SIE (Maxwell et al., 2009) in is sometimes difficult to predict beforehand. Furthermore, it is unclear for the Barnett Shale what geomechanical properties lead to high SIE in that formation. While additional work is needed to be able to predict the SIE for a given site, the low SIE trend provides a conservative design criterion. High and low SIE values can also be used to estimate a range for the predicted number of events for a given frac plan.

Estimating the number of recordable events as part of a survey design, leads to a question: how many microseismic events are required for an effective microseismic monitoring project? Clearly too few events will lead to a low level of confidence in interpreted fracture geometry and dimensions. Many events are obviously better, and in addition to better measurement statistics allow events to be filtered based on quality control attributes like signal-to-noise ratio or low location uncertainty estimates. Many events also allow interpretation of the temporal fracture growth in addition to interpretation of the final fracture geometry. While subjective, the following has been adopted as suggested design criteria:

< 10 events: low confidence in terms of fracture geometry and dimensions
10-50 events: improved confidence in geometry but low confidence in dimensions
> 50 events: improved confidence in geometry and dimensions

To demonstrate other application scenarios, consider a hypothetical example where 5 microseismic events are acquired die to high background noise levels. Elevated noise reduces the number of recorded events. The data set of 5 events would be considered questionable in terms of interpreting geometry and could lead to three questions for effective future monitoring projects: What is the impact of using a closer observation well? What is the impact of reducing the background noise? What is the impact of changing the injection?

Estimating the number of events at different distances is relatively straight forward by combining observed or assumed magnitude-frequency relationships with estimates of the minimum detectable magnitude. While managing background seismic noise is a challenge that is beyond the scope of this paper, the number of recorded events that would be detected at other noise levels can be extrapolated. The complete workflow described above can also be used to estimate the impact of alternate injection scenarios, such as increasing injection rate. Figure 3 shows a graphical representation of these three scenarios, including doubling the rate for the same total pump time. Also superimposed are three statistical categories of ability to confidently interpret fracture characteristics, which allow assessment of various operational scenarios.

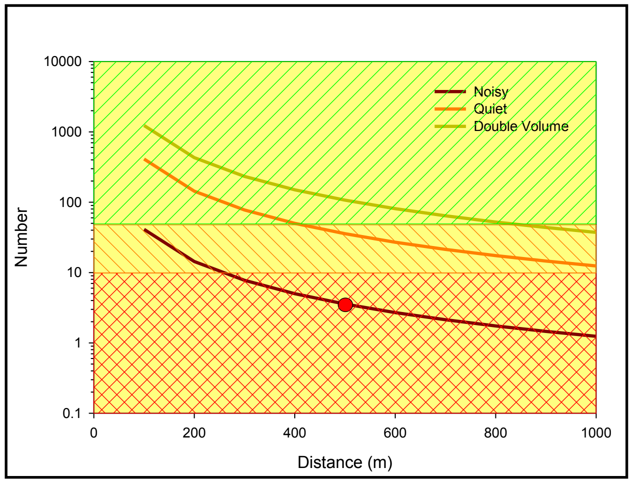

Figure 3. Predicted number of events at different source-sensor distances for various hypothetical scenarios. Red dot represent hypothetical scenario discussed in the text.

Conclusions

The described workflow results in a prediction of the number of events that would be recorded for a given monitoring geometry of a specific hydraulic fracture injection. A comparison of the predicted and observed number of microseismic events showed that the prediction was biased towards underestimating the number. Accounting for calibrated trends for specific reservoirs, the predicted number of events was well within an order of magnitude of the observed number. The predicted number of events can be used in pre-survey design studies to attempt to ensure adequate microseismic data for hydraulic fracture interpretation.

References

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