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Statistics of microseismic events: implications for geomechanics

Melanie Grob*, University of Alberta, Edmonton, AB, Canada
grob@ualberta.ca
and
Mirko van der Baan, University of Alberta, Edmonton, AB, Canada

Summary

Processes like cyclic steam injection, hydraulic fracturing... are used to increase the permeability of oil and gas reservoirs or geothermal fields. Microseismic events are created during these processes at the injection point due to the local stress changes induced by fluid pressure. The location of events can reveal pre-existing structures whose shape was determined by surrounding tectonic stresses, and weak planes within rocks. The spatial distribution of events is quantified by the *D*-value, a statistical coefficient which reflects the clustering of events. Source properties of microseismic events can be retrieved through the fractal dimension which describes the frequency-magnitude distribution of the events, also known as *b*-value. A combined statistical study of these two dimensions can help infer the variations of local stresses in a reservoir.

Introduction

Finding the link between microseismic events and geomechanics in a reservoir has become a big issue. Microseismic events are the most obvious reactions of the reservoir rock system to the different treatments applied to it (like hydraulic fracturing, steam inejction...). What can these microseismic events tell us about the geomechanics undergone by the reservoir?

The location of events can reveal pre-existing structures whose shape was determined by surrounding tectonic stresses, and weak planes within rocks. Source properties of microseismic events are given by the moment tensor inversion which represents the actual failure mechanism of the rock based on the observed radiation patterns of seismic P and S waves. However accurate locations and failure mechanisms for each microseismic event are difficult to obtain due often to poor signal to noise ratios and small aperture acquisition geometry.

An alternative is to use statistical analyses of microseismic event size and spatial distributions to infer changes in local stresses. The frequency-magnitude and spatial distributions of seismic events have been shown to display a power-law type of behaviour (Gutenberg and Richter, 1944; Grassberger and Procaccia, 1983). Coefficients of these power-laws are called *b* and *D* values respectively. The *b*-value is believed to be an indicator of the stress regime as the latter will influence the size of the rupture and as such the magnitude of an event. *D*-values are a quantification of the shape of clustering of events, thus emphasizing specific rock weaknesses. Studying the temporal variations of these two statistical dimensions can help understand the changes in local stresses within the reservoir.

Concepts

Computing a b-value is a simple task which consists into plotting the number of events with a magnitude larger than a given magnitude on a semi-log plot. The curve displays a fractal behaviour and the slope of the linear part of the curve is equal to -*b*. A small *b*-value indicates a larger proportion of small events whereas a large *b*-value is synonymous of many more bigger events. Schorlemmer et al. (2005) showed that the value of *b* varies according to the tectonic stress regime. They found a *b*-value above 1 for normal (extensional) type of faulting (stress regime where the vertical stress is dominant), *b* around 1 for the strike-slip regime (with an intermediate vertical stress), and *b* below 1 for reverse (compressive) type of stress regime (the vertical stress is minimum).

The statistical quantification of the spatial distribution of events is done by plotting the number of pairs of events separated by a distance smaller than a given distance in a log-log space. This curve exhibits again a power-law behaviour. Fitting the linear part of the curve gives a slope equal to *D*. This *D*-value varies according to the clustering of the events. If *D* equals 0, all events occur at the same place (a point); if it's close to 1, events are aligned; if its value is around 2, events are distributed over a plane; and if it equals 3, then events are spatially uniformely distributed. Given the rock deformation happening in extensional and compressive stress regimes, a *D*-value around 3 is usually observed whereas D is found to be equal or less than 2 for strike-slip regimes.

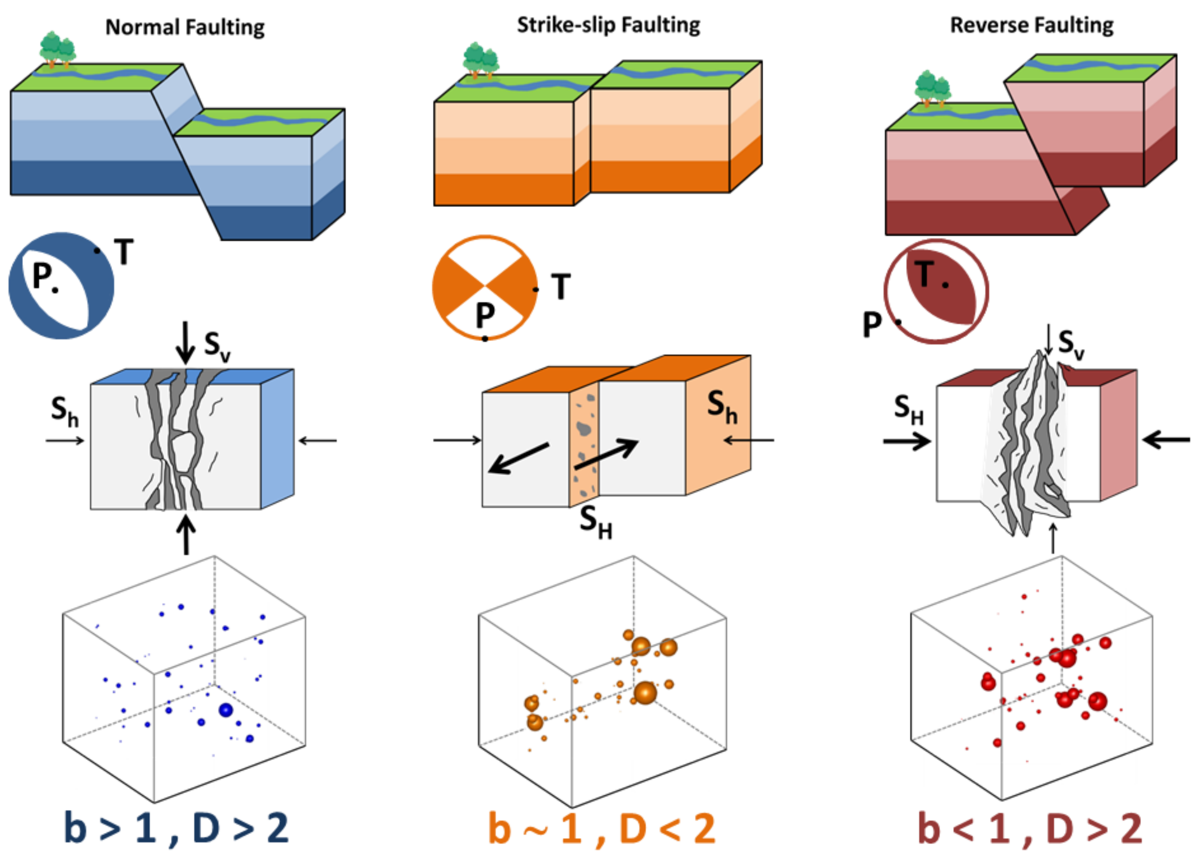

Figure 1: Links between stress regimes, rock deformation and microseismic events. The first line shows the 3 different stress regimes: the left column illustrates the extensional regime; the central column shows the strike-slip stress regime; and the right column represents the compressive regime. The balls below the first line show the common representations of failure mechanism (moment tensors) relative to each stress regime. The second line indicates the rock deformation under the different stress regime. The bottom line shows typical distribution of events, whose size is proportional to their magnitude. The associated b and D values are written underneath (after Grob and van der Baan, 2011).

According to the significance of *b* and *D* values, these statistical coefficients can be used to infer the local stress regimes into the reservoir at the time when the corresponding microseismic events are occurring (Grob and van der Baan, 2011). Indeed a *b* value over 1 coupled with a *D* value above 2 can reveal an extensional stress regime. If *b* ” 1 and *D* < 2, the local stress regime is likely strike-slip. And *b* < 1 and *D* > 2 can indicate a compressive regime. This concept is illustrated in Figure 1.

Examples

Several examples will be shown. The first one deals with cyclic steam injection in a heavy-oil reservoir over a period of 8 months (Grob and van der Baan, 2011). The large number of events allowed to analyze the temporal changes of *b* and *D* values. Three different stages could be seen as a response to the reservoir stimulation. At the beginning both *b* and *D* display high values indicating uniformely distributed and opening fractures (extensional stress regime). The intermediate stage has the characteristics of a strike-slip type of regime with a *b*-value around 1 and low *D*-values. Finally *b*-values decrease below 1 while *D*-values rise again above 2, which means spherically distributed fractures are closing.

Another example comes from the hydraulic fracturing of an oil reservoir. *b*-value temporal variations exhibit a cyclic behavior whereas the spatial dimension *D* stays over 2. The cyclic variations of *b* could indicate alternative periods of opening and closing of fractures or a change in the friction coefficient due to increasing (lower *b*) or decreasing (higher *b*) fracture roughness.

An example from a geothermal field in New-Zealand shows a small decrease in the *b*-value after an episode of injection followed quickly by a large increase (Figure 2). The *D*-value is representative of planar faults in that system. This could mean that some opening occurs in already existing structures due to the injection.

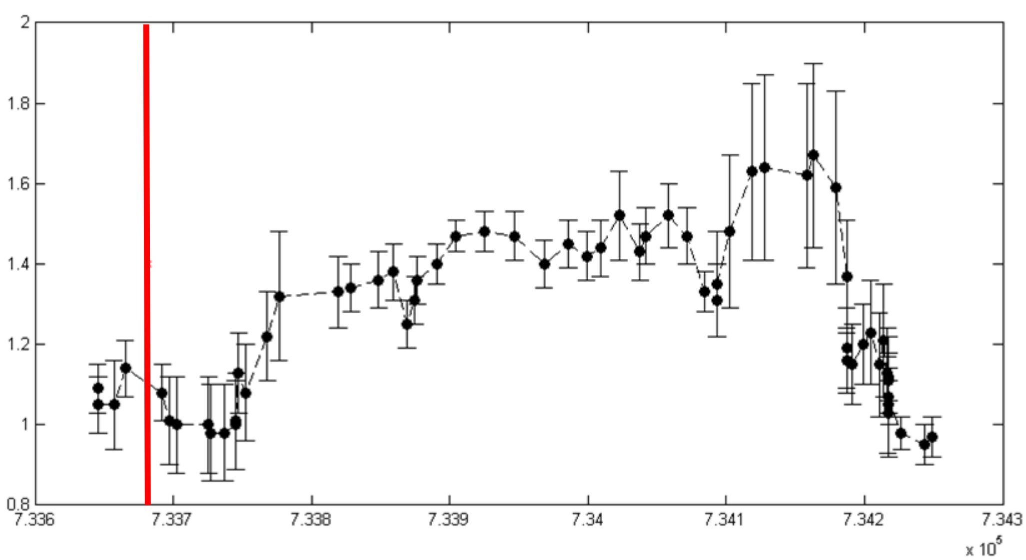

Figure 2: Temporal variations of *b*-values for a geothermal field in New-Zealand from July 2008 to May 2010. The red line shows the time of the injection episode that happens in early October 2008.

Conclusions

Rozhko et al. (2007) developed numerical simulations to understand the interactions between pore-fluid overpressure and failure patterns in rocks and their results show different failure patterns, either with tensile or shear mode, depending on the initial conditions, the geometry and the material properties. Zoback (2007) showed that, at extremely high pore pressure, relatively small stress perturbations are sufficient to change the type of faulting from one stress regime to the other. We therefore postulate that localized pore-fluid pressure can affect the stress regime and hence be responsible for the changes we see in the examples cited in the preceding paragraph.

Computing *b* and *D* fractal dimensions is a simple procedure given a sufficiently large microseismic dataset and can reveal pertinent information on the in situ stress regime (Figure 1). However our analysis is extensively based on the observations of Schorlemmer et al. (2005) and it remains to be established if these observations are also appropriate if more complex rupture mechanisms than double-couple occur, involving for instance significant volume (opening or closing) changes. Our analysis is complementary to results obtained via moment tensor inversions which attempt to infer the actual fracture mechanisms. A comparison between the two methods would establish if *b* and *D* values statistics can trustfully be used to infer stress regime changes.

Acknowledgements

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