Statistical Analysis of Microseismic Event Locations and Magnitudes, and their Geomechanical Implications

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Summary

It is often postulated that many naturally occurring processes are characterized by power-law distributions and exhibit thus fractal properties. Two commonly estimated fractal dimensions in earthquake and rock-fracture experiments are the so-called *b* and *D* values, representing statistical characteristics in the distribution of magnitude sizes (*b*) and spatial hypocenter locations (*D*), respectively. We analysed microseismic events recorded in a heavy-oil field drained using cyclic steam stimulation. We infer that the measured temporal variation in fractal dimension *b* is most likely due to significant changes in the local stress regime over an 8-month period, ranging from extensional faulting (fractures opening), via a strike-slip regime, to finally compressive faulting (fractures closing). The fracture dimension *D* indicates spatially predominantly planar to spherical hypocenter distributions in the first and last stage, but changes to a more linear to planar spatial pattern in the intermediate strike-slip regime when the vertical stress is anticipated to be in between the maximum and minimum horizontal stresses.

Introduction

Geomechanics in a reservoir depends on three factors. The first factor is the in situ stress regime which relates to the magnitude and ratio of the vertical stress S_v and the maximum and minimum horizontal stresses S_H and S_h. The second one is the pre-existing fractures which induce zones of weakness most likely to break. And finally the third factor is the local rock properties defined by the Young's modulus and Poisson's ratio (both related to the Lamé parameters). These three factors can be studied with microseismic data through statistical and deterministic analyses. Here we focus our study on the first factor, the in situ stress regime, via statistical analyses focusing on two characteristic fractal dimensions. The so-called b-value defines the frequency-magnitude distribution of microseismic events. The D-value describes the spatial distribution of event hypocentres. These two kinds of distributions have been shown to follow the same power law for events in laboratory rock fracturing experiments and at a much larger scale for earthquakes, indicating the universality of these laws and their applicability to microseismicity.

Fractal dimensions *b* and *D*

The b-value can be determined by plotting the distribution of event magnitudes on a semi-log plot. This distribution, also called the Gutenberg-Richter relation (Gutenberg and Richter, 1944), usually shows a power law behaviour (represented by a linear curve):

$$\log N(m>M)=a-bM$$

where $N(m>M)$ is the number of events with a magnitude m more than M. The slope of the linear part of the curve gives the b-value. Schorlemmer et al. (2005) have shown that this b-value changes depending on the stress regime (Table 1). For a b-value less than 1, the vertical stress is minimum and we are in a compressive regime. If the vertical stress is intermediate, the b-value will likely be around 1, indicating strike-slip faulting. And if it exceeds 1, then the stress regime is extensional.

b-value	Stress regime	Fault type
$b < 0.9$	$S_H > S_h > S_v$	Reverse (compressive)
$b \sim 0.9$	$S_H > S_v > S_h$	Strike-slip
$b > 1$	$S_v > S_H > S_h$	Normal (extensional)

Table 1: Summary on how b-values might be linked to stress regime and dominant faulting type, based on work by Schorlemmer et al. (2005). SH : maximum horizontal stress, Sh : minimum horizontal stress, Sv : vertical stress. High b-value: relatively more smaller-sized earthquakes occur, small b-value: relatively more larger-sized earthquakes happen.

The spatial distribution of event hypocenters can be studied through the correlation integral which computes the number of pairs of events $N(R<r)$ separated by a distance R smaller than r (Grassberger and Procaccia, 1983):

$$C(r)=\frac{2}{N(N-1)}N(R<r)$$

where N is the total number of events. When plotting the integral value $C(r)$ versus a range of distances r on a log-log plot, a part of the distribution appears linear. The coefficient of the corresponding power law is called the fractal dimension D:

$$C(r) \propto r^D$$

This dimension is equal to 0 if the cloud of events maps onto a point, 1 for a line, 2 for a plane, and 3 if events are uniformly distributed. Lahaie and Grasso (1999) have shown that the relation between the D value and the stress rate during a gas field monitoring is rather complex.

Several authors tried to find relations between b and D values, and therefore between the size of events and the shape of event clouds. Some found no relation (Hirata et al., 1987), others found a positive correlation (Huang and Turcotte, 1988), and some a negative one (Hirata, 1989; Henderson et al., 1992; Amitrano, 2003). To explain the positive and negative correlations found, many authors insisted on fracture interactions (Huang and Turcotte, 1988; Henderson et al., 1992; Helmstetter et al., 2005). For instance, Main (1992) used a model based on fracture mechanics and showed that a positive correlation could be found in the case of first uniformly distributed events which align along a plane, but a negative relation between b and D is found if events first aligned along a plane concentrate around some zones like jogs to reduce the local stresses.

Case study

We analyzed microseismic data from a heavy-oil reservoir drained using cyclic steam stimulation. Injection lasted from August 2009 to April 2010, and production started in December 2009. Microseismic data were acquired with three-component receivers on vertical and deviated wells. 3139 events were recorded over 8 months. A statistical analysis on all the events gives a b-value about 1.35 (Figure 1a), indicating an extensional stress regime, and a D value equal to 2.72 (Figure 2a), indicating a rather spherical distributions of all the events.

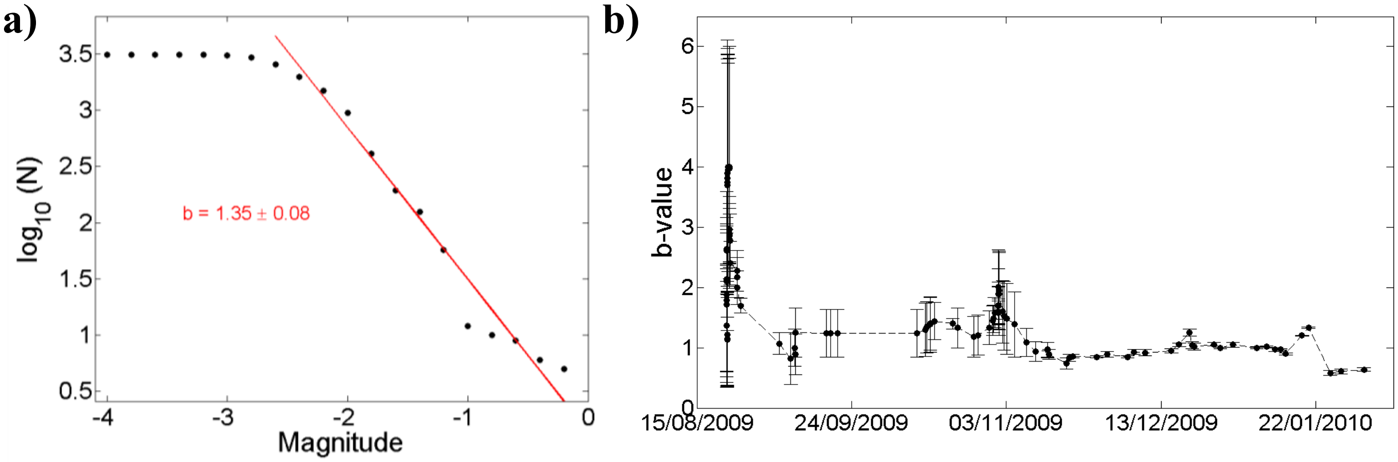

Figure 1: a) Distribution of event sizes for the whole dataset. A fit on the linear part of the curve gives a b-value of 1.35. b) Temporal evolution of b-values for a heavy-oil dataset. Four stages are visible: at the beginning high b-values with high variations, then a plateau with b-values larger than1 (extensional faulting or opening of fractures) until November 2009, followed by b-values around 1.0 and finally a last stage with values around 0.65 (closing of fractures or compressive faulting), starting end of January 2010.

We then analyzed the changes in b and D values over time. These values were computed over 300 events with a 30 event overlap. Four stages can be seen for the b-value (Figure 1b). The first stage shows high b-values with high variations. The second one from September to November 2009 comprises b-values over 1. Then b-values around 1 are found for the third stage. And after January 2010 b-values lower than 1 define the last stage. Three stress regimes can be deduced from these variations: an extensional regime at the beginning, certainly due to the opening of fractures, followed by a strike-slip regime, and at the end, a compressive stress regime corresponding to closing of fractures.

Changes in D values show three stages (Figure 2b). D values around 2.5 from August to November 2009 imply a uniform distribution of events. Then a drop in D values around 1 indicates an alignment of events along a plane. And in January 2010 a spherical distribution of events again can be deduced from D values around 2.

Geomechanically our analysis has the following implications. At the beginning, the high b and D values indicate opening of fractures which are uniformly distributed, due to dominating vertical stress. Then there is an intermediate stage with a lineation of events along vertical fractures with a strike-slip movement, due to a vertical stress magnitude which is in between the two horizontal stresses. And at the end, uniformly distributed fractures are closing corresponding to a stress regime where the vertical stress has become the smallest stress.

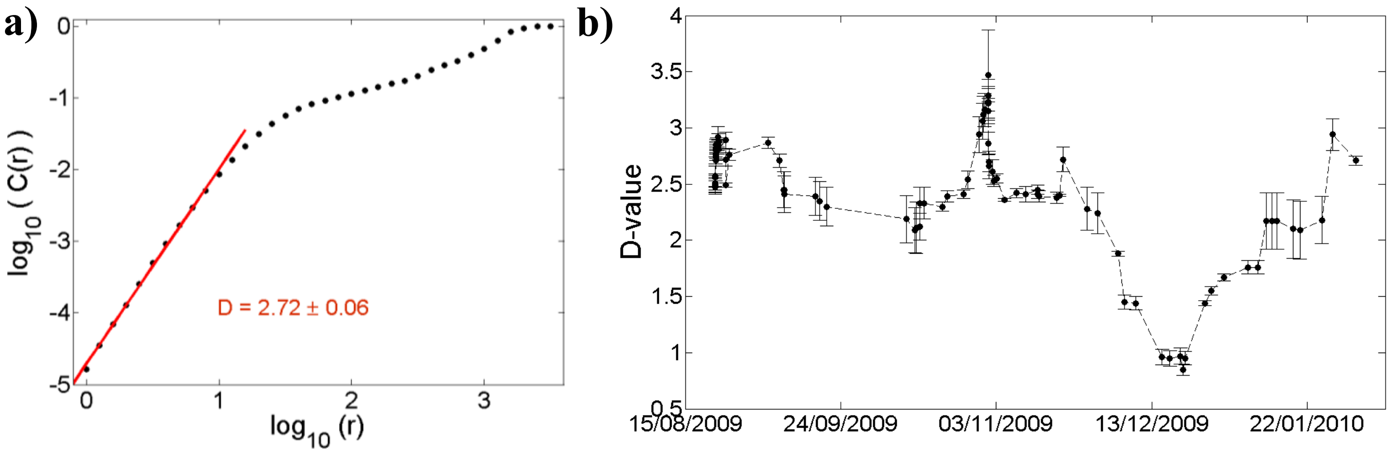

Figure 2: a) Integral correlation values versus distances *r*. A fit on the linear part of the curve gives a D value of 2.72. b) Temporal evolution of D-values for a heavy-oil dataset. No clear correlation exists with the b-values shown in Figure 1, except that the lowest D-values occur in the middle of the second stage, indicating the possible presence of strike-slip faulting.

Conclusions

Geomechanics in a reservoir depend on several factors. These factors can be studied via a statistical analysis of microseismic event-size and hypocenter-shape distributions through the fractal dimensions b and D. These dimensions are simple to compute at low cost. The fractal dimension b is linked to the amount of damage and hence gives some information about permeability and new fracture densities. The fractal dimension D deals with the shape of event clouds and is therefore related to the shape and extent of the damage zone. Statistical analysis of micorseismic events can thus help interpret the geomechanical behaviour of a reservoir. For instance, our analysis on microseismicity recorded over a heavy-oil field implies that the stress state changed from extensional to compressive with an intermediate strike-slip regime, indicating initial opening and then closing of fractures.

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