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Spatio-temporal Complexity of Microseismic Events in a Hydraulic Fracturing Experiment: A Graph Theory Approach

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Summary

The main goal of hydraulic fracturing is to cause fracturing of the host rock along specific orientations based on the available knowledge of the prevailing stress field at and around the target formation so as to enhance oil/gas production. Such fracturing generates microseismic events. Understanding the spatio-temporal complexity of them provides a basis for gaining an insight into the behaviour and properties of the poro-elastic medium. Here, we model the microseismic events of a multi-stage hydraulic experiment to a complex network of their spatio-temporal recurrences. In this presentation, we use graph theory to glean new insight into the statistics and properties of the spatio-temporal recurrences to infer the dynamics of the fracturing of a poro-elastic medium under modified stress.

Introduction

Naturally-occurring fractures and induced fractures influence processes such as formation of ore deposits, changes in fluid pressure and stress states during earthquake cycles, flow in hydrothermal systems, and performance of hydrocarbon reservoirs (Hickman et al., 1995; Sibson, 1997, 2000; Bosl and Nur, 2002; Rothert and Shapiro, 2003; Fischer and Horalek, 2005; Edelman, 2006; Fischer et al., 2008; Maxwell et al., 2010; Barnhoorn et al., 2010; Sayers and Le Calvez, 2010). Induced fracturing in formation rocks has been the main stay to enhance oil and gas production in exploration industry for several decades, as was initially documented in the middle of the twentieth century (Clark, 1949; Hubbert and Willis, 1957).

Formation rocks in different sedimentary basins are under different stress states and fluid pressures. Changes in both can lead to the formation of new fracture networks. During hydraulic fracturing, the poro-elastic stress changes do not only nucleate a new fracture network but also cause its growth in the formation. A closely associated phenomenon is the occurrence of microseismic events. In recent years, with sophisticated monitoring techniques, storing the location information, the time of occurrence, the magnitude and full waveforms of the microseismic events in a catalogue is a common exercise. We access one such catalogue (Figure 1) for a statistical study of the microseismic events. This catalogue resulted from a multi-stage (six-stage) hydraulic fracturing experiment done in Central Alberta.

Similar to earthquakes, microseismicity has spatio-temporal recurrence complexity. A statistical analysis of earthquakes within the framework of complex networks (Davidsen et al. 2008; Vasudevan et al. 2010) has been shown to shed light on the behaviour of recurrences at different scales. Here, we undertake to study the statistics of spatio-temporal recurrences of the microseismic events with directed graphs resulting from a complex network (Albert and Barabasi, 2002; Newman, 2003).

Method

Microseismic events from an event catalogue of a multifracturing experiment as shown in Figure 1 form the basis to generate a directed graph by linking each event to its recurrences, following the definition of recurrences given by Davidsen et al., 2008; Vasudevan et al., 2010). The distance-intervals of recurring events with respect to any event should form a record-breaking process with respect to the shortest distance.

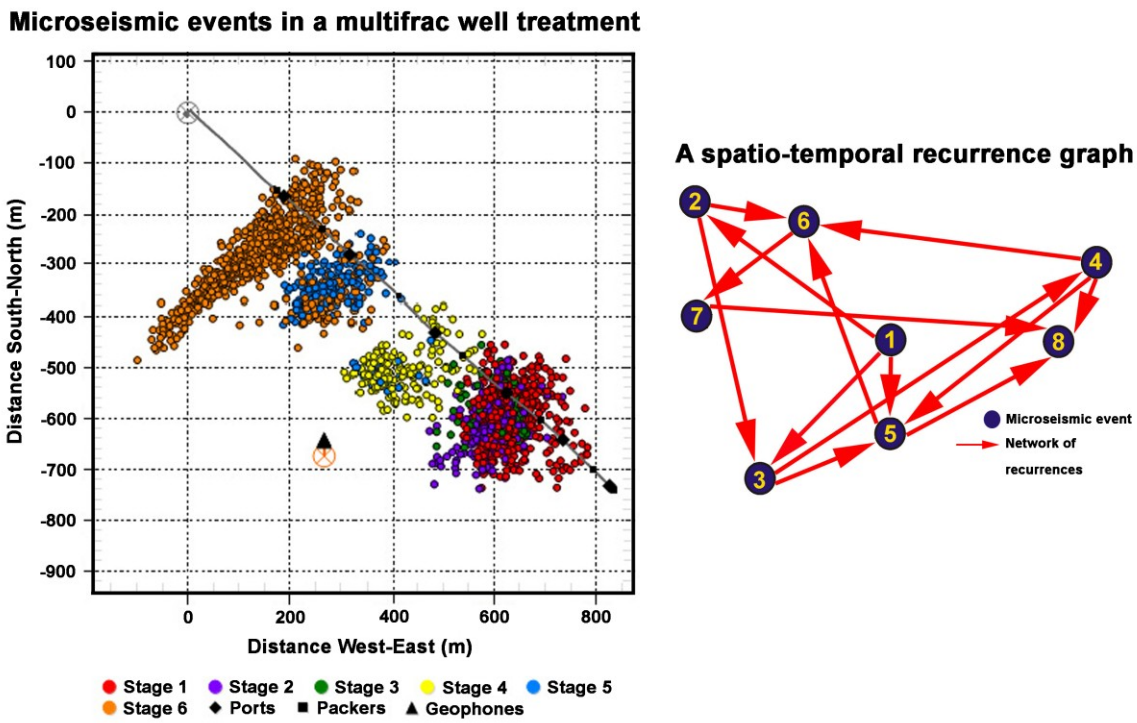

Figure 1: Left: Map view of the locations of the microseismic events from a multi-stage hydraulic-fracturing experiment; Right: An illustration of directed, spatio-temporal recurrence graph of an eight-event catalogue. We build this graph from microseismic events in 3D space.

Using the microseismic catalogue, we extracted the number of events and their spatio-temporal recurrences for different stages of the experiment. For the analysis reported here, we used the stage 6 data set and its several subsets. We used the time-quartile constraint (**S6p25, S6p50, S6p75** and **S6full**) and the user-specified signal to noise ration constraint (**6SNR**). For the catalogue containing spatio-temporal recurrences, we examined the distance-interval and time-interval statistics. In this catalogue, each event represented as a node in a directed graph (Figure 1) spawns other events ("out-degree" of an event) and also, can be an event that is spawned ("in-degree" of an event). This allowed us to study both clustering around each node using the approach of Fagiolo (2007) and also, the in-degree – out-degree distributions. We present all of the results in summary form, as shown in Figures 2 and 3.

Results

Probability density function (pdf) curves of distance intervals derived from spatio-temporal recurrences for stage 6 of the multi-stage fracturing experiment reveal a maximum in the population of distance intervals (Figure 2). The curve building to a maximum from very short distance intervals do not show any scaling behaviour. For distance intervals greater than that corresponding to the maximum in the pdf function, distance interval dependent scaling behaviour is present. Furthermore, the maximum in the pdf curve shifts from a large distance interval to a small distance interval as one goes from the first time-quartile data set to the full data set. As far as the pdf curves of time intervals go (Figure 1), we observe Omori-law-like scaling behaviour. The pdf curves also strike an interesting oscillatory behaviour between 2 and 4 seconds.

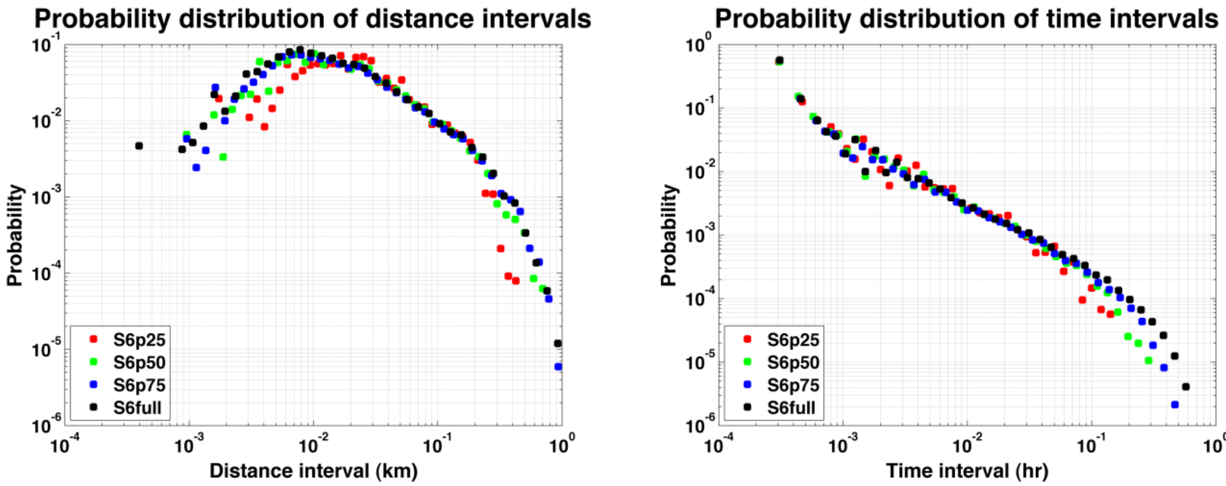

Figure 2: Left: Probability distribution of distance intervals of recurring microseismic events from a hydrofracturing experiment at different times for stage6; Right: Probability distribution of time intervals of recurring microseismic events from a hydrofracturing experiment during different stages

Large value for the clustering coefficient (>0.15) for nodes is indicative of the dynamics of the complex network of fractures (Figure 3). For nodes with large clustering coefficients exceeding 0.2, we suggest that they are likely to constitute the main junctions of the fracture network resulting from hydraulic fracturing.

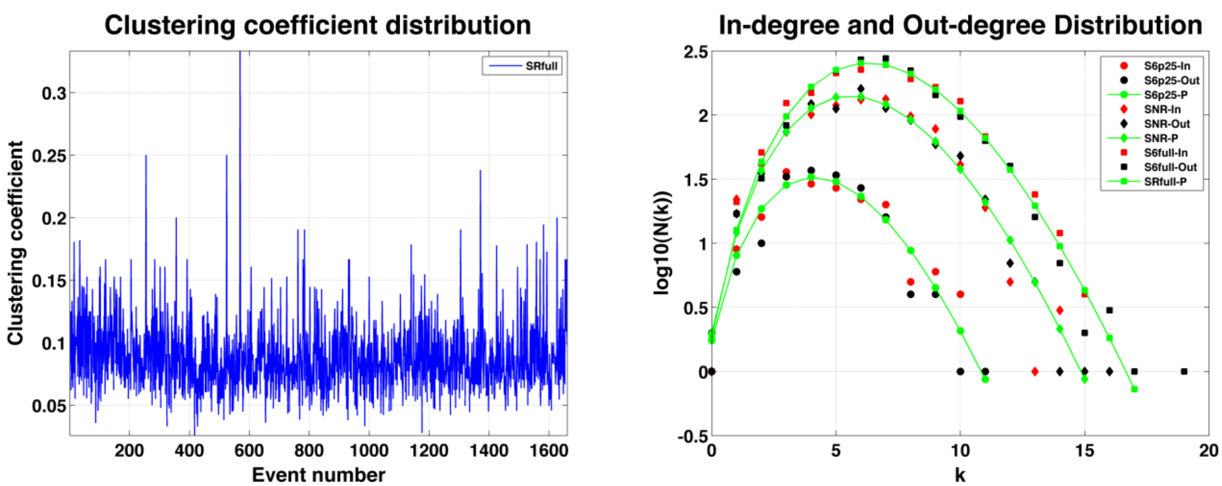

Figure 3: Left: Clustering coefficient of spatio-temporal recurrences for each microseismic event from the stage 6 catalogue; Right: In-degree and Out-degree distributions for three different sets of microscopic events. Also, included in these graphs are the Poisson degree distribution for each data set.

Whether we take a subset of the data or the full data (Figure 3), we observe certain deviations from the Poisson distribution in each case. They are significant for small in-degree (or out-degree) and for large in-degree (or out-degree) values.

Conclusions

For the work presented here, we assume that the location and magnitude information is complete and correct. If there were to be significant errors in the location information, they would affect the distance-interval probability density function curves. However, the shapes of distributions will remain unaffected.

(a) Constructing and working with complex network of spatio-temporal recurrences to understand the properties of induced fracture networks is intuitive in that each microseismic event results in a rupture geometry that is closely tied to it. Although we do not know the exact rupture geometry for each microseismic event, the location provides an anchor point for a node in a complex network representation of induced fractures. Also, the magnitude information adds weight to each node in the network definition.
(b) Each record-breaking recurrence defined in this paper is an edge in the complex network. We treat all of the edges as being equal in influencing the dynamic properties of the network. However, with both the acquisition and processing technologies improving, it is quite conceivable that the edges would assume weights. For example, each edge could be looked at as a stress vector with an associated magnitude.
(c) Distance-interval pdf curves of the microseismic spatio-temporal recurrences show similarities to such curves generated for earthquakes along the San Andreas fault (Davidsen et al. 2008).
(d) The in-degree and out-degree distributions mark deviations from the Poisson behaviour that we usually attribute to a random network of fractures.
(e) The clustering coefficient profiles suggest that there are certain locations preferred to certain other locations within the complex network of fractures suggesting their stress states under pore-pressure induced seismicity.

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