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Microseismic Event Relocation Based on PageRank Linkage at the Newberry Volcano Geothermal Site

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ABSTRACT

The Newberry Volcano, a DOE Phase 1 FORGE site in Central Oregon, has been stimulated two times using high-pressure fluid injection to study the Enhanced Geothermal Systems (EGS) technology. Several hundred microseismic events were generated during the first stimulation in the fall of 2012. Initial locations show events occurred in two distinct depth ranges. Within the two depth ranges microseismicity does not clearly outline subsurface structures in part because event location uncertainties for the initial locations are large (Foulger and Julian, 2013). We have initially focused on this stimulation to explore the spatial and temporal development of microseismicity, which is key to understanding how subsurface stimulation modifies stress, fractures rock, and increases permeability. We use an application of PageRank (Aguiar and Beroza, 2014), Google's initial search algorithm, to assess signal-correlation topology for the micro-earthquakes. We then use this information to create signal families and compare these to the spatial and temporal proximity of associated earthquakes. We relocate events within families (identified by PageRank linkage) using the Bayesloc approach (Myers *et al*., 2007). Preliminary relocations show tight spatial clustering of event families as well as a smaller spatial extent than initially implied by catalog locations; suggesting the size of the EGS might be smaller than originally thought. Changes in event location are significant enough in several cases to change cluster affiliation. In every case cluster affiliation determined by PageRank and event relocation agrees. We also find that signal similarity (linkage) at several stations, not just one or two, is needed in order to determine that events are in close proximity to one another suggesting the importance of having good seismic station coverage. We show that indirect linkage of signals using PageRank is a reliable way to increase the number of events that are confidently determined to be similar to one another, which may lead to efficient and effective grouping of earthquakes with similar physical characteristics, such as focal mechanisms and stress drop. We will also apply this analysis to the new stimulation performed in 2014 and compare with clusters found in the initial stimulation. This will allow us to determine whether changes in the state of stress and/or changes in the generation of subsurface fracture networks can be detected using PageRank topology as well as aid in the event relocation to obtain more accurate subsurface structure. Ultimately, automating and applying this method in real time could potentially aid in a more successful geothermal production at any well-instrumented geothermal site.

1. INTRODUCTION

Microseismic events related to enhanced geothermal systems (EGS) play a key role in understanding how these systems work. Finding an effective and efficient method to characterize these events and understand how they are effected by changes in the state of stress will play an important part in the development of this technology. AltaRock Energy and Davenport Newberry selected the Newberry Volcano, located in the Deschutes National Forest in Central Oregon, to test and demonstrate the EGS technology (Cladouhos *et al*. 2012). Following extensive stress, permeability, and temperature studies (Cladouhos *et al*. 2011a; Cladouhos *et al*. 2011b; Davatzes and Hickman 2011), the Newberry EGS site has been stimulated two times to induce hydroshearing.

The initial part of their project consisted in stimulating well NWG 22-29 between October 2012 and February 2013, which resulted in several hundred microseismic events. During this stimulation, a leak developed in the casing of the borehole causing some of the microseismic events to be significantly shallower than expected. Even though the leak in the casing caused problems for the EGS, it produced a highly diverse data set. After initial analyses, locations for the microseismic sequence have large uncertainties and do not clearly outline specific geologic structures in the geothermal system (Foulger and Julian, 2013). After fixing the casing of the well, a second stimulation was performed between September and December of 2014. This stimulation produced about 400 microseismic events, and initial catalog locations show these events to be in the vicinity of the well opening at depth, showing a smaller depth range than the previous stimulation (Cladouhus *et al*. 2016). Given the diversity in the data set as well as the complexity of the location, this is an ideal place to test a new method to characterize microseismicity and explore the possibility of obtaining robust locations within a complex geologic system.

Data mining methods have often been used to explore the similarities of individual seismic events that comprise an earthquake sequence. Here we focus on PageRank, Google's initial search algorithm (Page *et al*. 1999) to characterize the microseismicity. PageRank was originally developed for web searching and later applied in seismology to detect low frequency earthquakes. For seismic data, the PageRank algorithm is based on the number of direct links an event has which are determined by cross-correlation as well as secondary links to other events which were originally missed by direct cross correlation (Aguiar and Beroza, 2014). We expand on this initial application by using PageRank to define signal-correlation topology for micro-earthquakes in Newberry. We apply PageRank to the Newberry data sets to explore whether it can identify a larger number of events with similar physical characteristics, such as focal mechanisms and stress drop, and in turn aid in the relocation of the events helping us understand the properties of the EGS.

2. PAGERANK APPLIED TO MICROSEISMICITY DURING THE FIRST STIMULATION

As mentioned, we initially focused on the analysis of data from the 2012 stimulation which produced 226 microseismic events, by applying the PageRank approach as it was described by Aguiar and Myers (2016). We have identified 5 distinct PageRank families, each associated to one event with high PageRank value which we denote as the reference event. The catalog of epicenters for the 5 reference events are shown in Figure 1 (red stars).

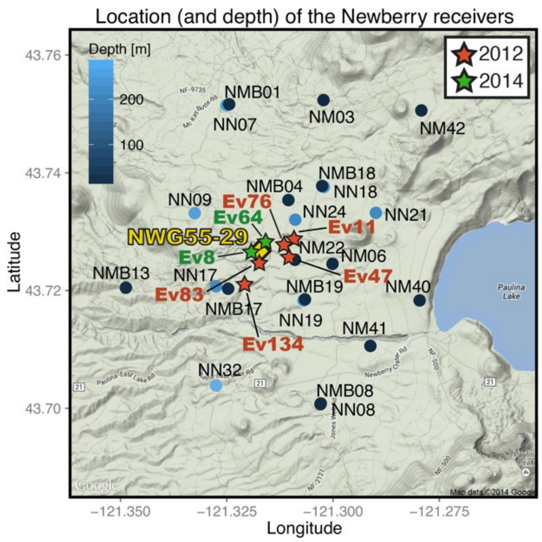

Figure 1: Location Map of the Newberry EGS site and stations used in the analysis. Blue color scale indicates the depth at which the receivers are installed where dark blues are shallow stations and light blues are deeper stations. Yellow diamond represents the location of the stimulated borehole and red and green stars are the locations of the high PageRank events used in this study.

From the PageRank analysis, direct and indirect links to each reference event were identified for each station individually. We then declare all events both directly and indirectly linked to a reference event by at least 6 stations to be a member of the reference event's family. In Figure 2 we can observe all five event families and the associated reference events found during the 2012 stimulation.

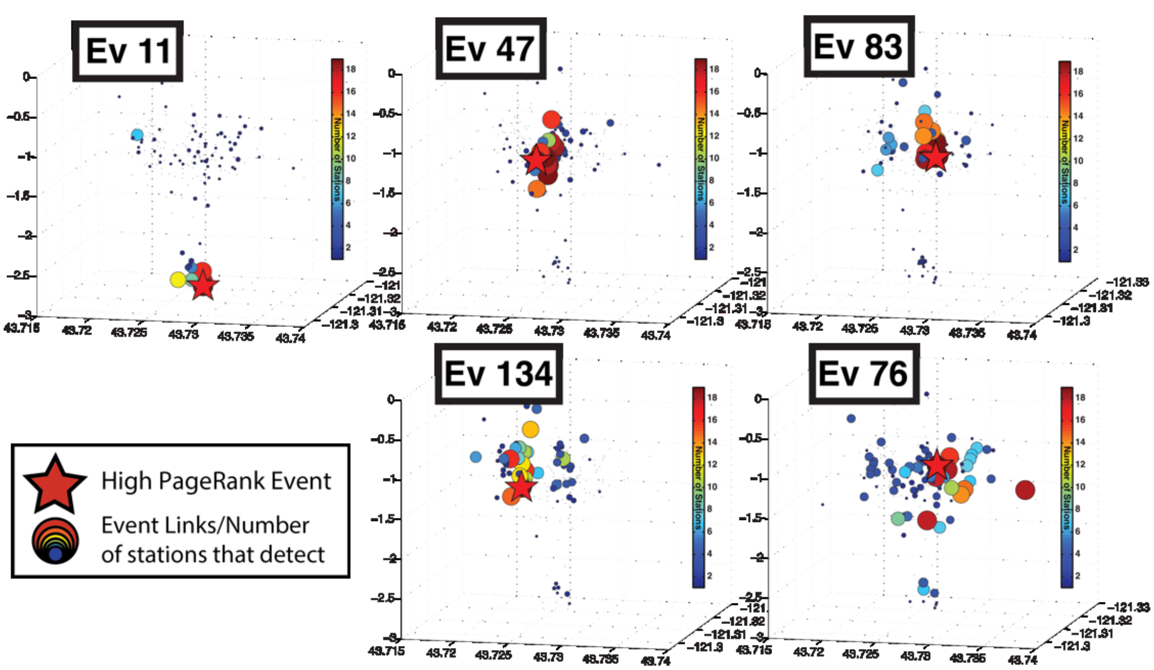

Figure 2: Selected high PageRank events (red stars) that represent unique event families. Warmer colors and larger size both represent a larger number of stations as indicated in the color bar.

Each of these PageRank families define a different volume within the larger cloud of seismicity, which is denoted by the small grey dots in all plots of Figure 2. Here warmer colors and larger size both represent events that were found as a link by a higher number of stations in the analysis. As an example, a large, dark red dot represents an event linked to the reference event by all 19 stations in the analysis. This suggests that linkage at a large number of stations clearly connect the two events but linkage at one or two stations does not. Therefore well instrumented sites are ideal to test the EGS technology.

2.1 Event Relocations

We relocate events within each cluster using the Bayesloc method (Myers et al. 2007) and include differential travel times calculated from cross correlating each event in a cluster with all other events within the same cluster. We relocate the events with all clusters included at once during the iteration sequence.

After relocation we find that event families are tightly clustered spatially. Also, some events determined to be linked by PageRank but not spatially clustered in the initial locations are indeed spatially clustered after relocation. The relocated clusters (red dots in Figure 3) define three distinct depth ranges, as opposed to the two depth ranges suggested by initial catalog locations (black dots in Figure 3). This result potentially suggests three different geologic structures or weaker planes where hydroshearing occurred during the initial stimulation. The two shallower depth ranges shown in the relocations are around 1500 m and 2000 m. Further inspection of well bore lithology analyses identifies a zone of welded tuff between 1966-2057 m (Cladouhus *et al*. 2016). Within the same depth range Davatzes and Hickman (2011) use a high-resolution borehole televiewer (BHTV) log to identify large, well-developed fractures and evidence of bedding, layering, and foliation. In a different report that presents gamma ray logs for the injection well, Waibel *et al*. (2015) identify two different geologic units, one right above 1500 m an a second one just below 2000 m with no units identified between these two depths. We are exploring the possibility that fluid traveled along the casing from the shallow breach then outward at these zones of geologic weakness.

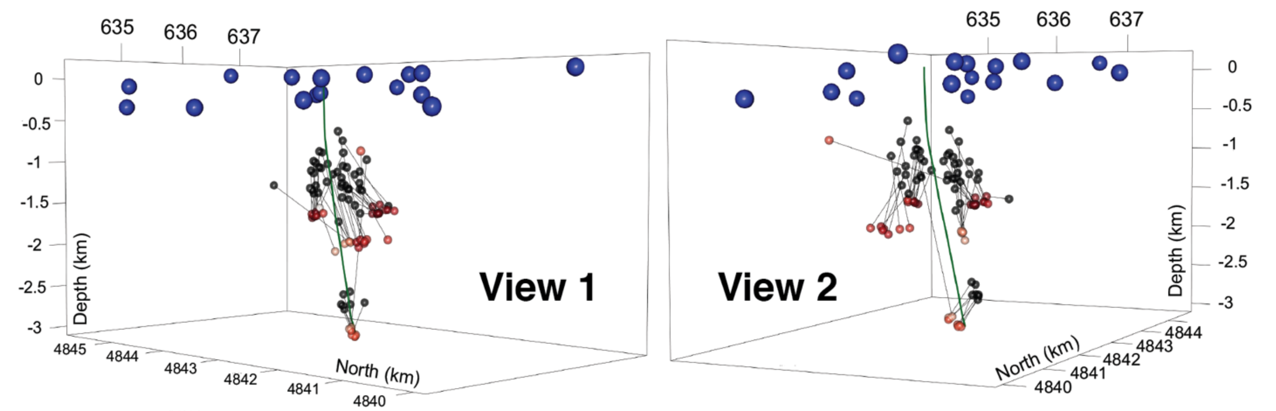

Figure 3: Relocations of the 5 families identified by PageRank shown by two different points of view. The green line represents the borehole parameters and blue dots represent the stations used in the relocation analysis. Black dots are original catalog locations and red dots are the new locations.

We also observe that all events are deeper than originally reported, placing the deep cluster in close proximity to the borehole opening at depth. Focusing on the deep cluster, we also observe how the relocated data separate into two smaller clusters. If this is indeed a true feature in the subsurface, given their close proximity, the seismic signal associated with each cluster would be very similar as well and the most likely reason why PageRank did not determine these to be two separate clusters.

2.2 Inter Event Distance Analysis

Given the tight clustering of each family presented in the relocations, in contrast to initial catalog locations, we calculate the probability density functions (pdfs) of the inter event distance for both the original catalog locations and the relocated events. Standard deviations of the relocated clusters are significantly smaller than previously observed. Figure 4 shows the pdf for all clusters in the analysis where red represents relocated events and black represents original events, with each cluster identified by its number.

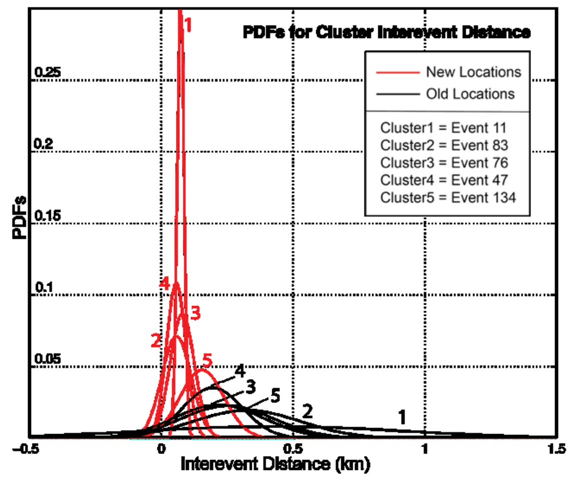

Figure 4: Probability density functions for both initial catalog location (black) and new location (red) inter event distances for each of the clusters associated to the 5 reference events denoted by each number.

This shows that the spatial extent of the microseismic events – which might be a proxy for the fracture network – is smaller than previously thought and these new locations might show the extent of the EGS that was reached during the 2012 stimulation.

3. PAGERANK APPLIED TO MICROSEISMICITY DURING THE SECOND STIMULATION

Following the same analysis presented in Section 2, we now focus on the 2014 stimulation which produced 407 microseismic events. Initial catalog locations for microseismic events during this stimulation covers a smaller volume compared to the 2012 stimulation but still shows a large depth range (Cladouhus *et al*. 2016). During this stimulation, many events were concentrated near the vicinity of the borehole opening near the bottom of the well, which was to be expected as the leaks in the casing were fixed before this stimulation. A large number of the new events also have a similar initial location as the deep events during the stimulation in 2012/2013 and can be used to compare with the cluster found using reference event 11 from the previous stimulation.

Given the proximity of all events to each other in this data set, this stimulation presents a more challenging analysis. From the PageRank analysis, we have identified so far two families within the complete data set. The reference events for these two families are shown in Figure 1 as their epicenters (green stars) and in Figure 5 (large red stars) plotted including all other events linked to each of the two reference events in the analysis.

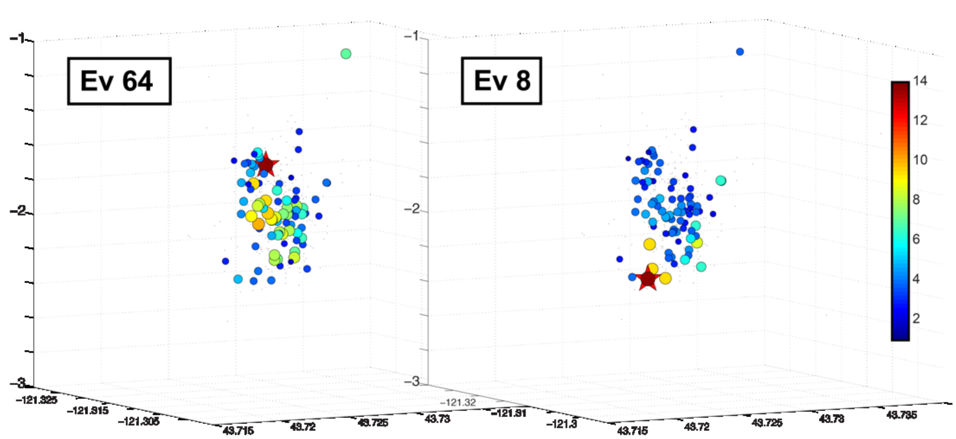

Figure 5: Selected high PageRank events (red stars) that represent unique event families. The number represent the event in the sequence of the total 407 microseismic events generated by the 2014 stimulation. Warmer colors and larger size both represent a larger number of stations as indicated in the color bar.

Again, we see how each reference event and each of their families define a different volume of the original cloud of events, where most events linked to reference event 64 appear to be shallower than events linked to reference event 8 within the 2014 complete microseismic sequence.

Further inspection of the waveforms suggests that reference event 8 and it's family of linked events might be similar to reference event 11 from the 2012 stimulation. If this is the case, then this new PageRank family might also contain two distinct families potentially located in very close proximity to each other, as it appears from new locations of events within the cluster of reference event 11 from the previous stimulation. Relocation of the new data set will allow us to compare this result with the previous simulation as well as analyze the similarities within clusters from each stimulation.

4. CONCLUSIONS

In this study we have shown how applying a data mining technique that exploits the repetitiveness of seismic signals can be an advantage in event location. We show that PageRank successfully identifies unique families of events within the original microseismic sequences, potentially identifying events with similar physical properties, such as location and focal mechanism. We also show that by applying PageRank we can include indirectly linked events to the selected reference events and add these new events to the analysis to obtain a larger number of differential travel times for relocation purposes. Adding this extra information into the location scheme, which would have been ignored by a standard correlation scheme, results in a more robust relocation of events and helps us observe more detail in the subsurface.

After relocation, we have determined that the stimulation during 2012 produced events at three different depths. Also, relocated events show clear clustering within each PageRank family, again suggesting events with similar physical characteristics within the families, as well as a smaller spatial extent of the fracture network in the Newberry EGS.

Preliminary results from the 2014 stimulation data set also show unique PageRank families of events and a possible correlation of one of these families with the deep cluster identified during the 2012 stimulation. Relocating the new events and comparing to the initial stimulation will aid in the understanding of PageRank as a proxy for changes in the state of stress and/or changes in the generation of subsurface fracture networks and ultimately obtain a more accurate subsurface structure.

Given the directness of the method and success in cluster identification as well as the benefits it poses in event relocation, this method should be useful for characterizing microseismicity from any well instrumented area. Eventually, automating the process might potentially aid in real time decision making related to EGS productivity.

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