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Induced Seismicity Patterns in the Paralana Geothermal Reservoir, South Australia

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SUMMARY

We are presenting the results of the analysis of seismicity induced by the first main stimulation of the geothermal reservoir at Paralana (south Australia) in July 2011. More than 7000 events were detected and processed automatically. A 3D velocity model was built from active seismic data and used to locate the events. Well-located microearthquakes were relocated using differential travel-times improved by waveform cross-correlation. Focal mechanisms of the four largest events (two Mw 2.4 and one 2.5) are all in thrust with a strike-slip component, consistent with the stress regime in the area.

Introduction

Exploring deep geothermal resources requires generally enhancing fluid circulation into the ground through hydraulic stimulation, which can induce thousands of microearthquakes. Location and source parameter of induced seismicity are in turn used to monitor the geothermal reservoir, for risk assessment purpose or to map the fracture network. Accordingly, the latter have to be determined precisely which will depend strongly on the quality of the passive seismic data (network configuration, signal-to-noise ratio,...) and on the knowledge a priori of the elastic properties of the medium (velocity, poisson ratio,...), unfortunately not always available.

Paralana is an Enhanced Geothermal System (EGS) that is being developed in South-Australia (Reid et al., 2010). The objective is to recover the energy generated by the radioactive decay of high heat producing basement rocks, buried under several layers of sediments. Recently, in July 2011, about 3 million litres of water were injected in the 4-km depth well (Paralana-2), inducing ~7000 microearthquakes (Hasting et al., 2011). Active seismic methods were applied to build a 3D velocity model used afterwards to compute accurate initial earthquake locations (Albaric et al., 2012).

We present here further work we performed on these data to image the reservoir in more details in order to better understand its evolution during injection relatively to the pre-existing fracture network and local stress field.

Methods and results

In total, 20 stations were deployed around the well Paralana-2 to get continuous seismic recordings during the five days of injection (surface and borehole stations at 40, 60 and 1800-m depth). The seismic network configuration is illustrated in Figure 1 together with the traces of the two main normal faults mapped on seismic reflection profiles (Hasting et al., 2011; Albaric et al., 2012).

Figure 1 Map view of the seismic network deployed around the Paralana-2 injection well (P2). The blue and green lines represent the traces of two main normal faults at surface and 4-km depth respectively.

Data were processed automatically in near-real time (Oye and Roth, 2003) and results cross-checked manually. Synthetic travel-times were computed with the 3-D Eikonal solver of Podvin and Lecomte (1991) and residuals minimised using the method of singular value decomposition (SVD). Initial location is presented on Figures 1 and Figure 2A (zoom): induced seismicity clusters around Paralana-2, in-between the two faults. The seismic cloud is growing in a general NE-SW direction.

Figure 2 Map view (top) and cross-section (bottom) of induced seismicity at Paralana (circles coloured and sized according to time occurrence and moment magnitude M_w , respectively) before (A) and after (B) relocation. Focal mechanism of the largest event is represented on box B. P2: Paralana-2 well.

Travel-time differences (P and S phases) were computed for all pairs of earthquakes recorded at the same stations and improved using waveform cross-correlation. Then, the double-difference method of Waldhauser and Ellsworth (2000) was applied to these differential times to relocate the events. The results are presented in Figure 1 B. The same pattern in terms of migration outward from the injection point is observed with relocated events. Location of induced seismicity is dramatically improved and the cluster sharpen into structures oriented NNE-SSW and $\sim$ NE-SW. According to the N-S cross section (Figure 1, *bottom*), the hypocentres tend to deepen towards North.

Moment magnitudes (M_w) were computed from the integrals of the S -waves squared displacement, assuming Brune's model (Andrews, 1986). Magnitudes range between -0.6 and 2.5 and more than 90% of the events have a magnitude larger than 0. The four largest events (M_w 2.4 to 2.5) were also recorded by the Australian national network (www.ga.gov.au), dominate the total seismic moment and occurred while fluid was injected. The focal mechanism of this event, computed from P -wave first motions, indicates a reverse movement on a fault oriented $\sim$ NE-SW (Figure 1 B). The comparison with the distribution of the induced seismicity allows identifying the nodal plane dipping towards NNE as the fault plane.

The b -value was estimated with the maximum likelihood method (Aki, 1965). We found a quite high b -value ($b = 1.32 \pm 0.02$), as it is commonly observed in volcanic and geothermal areas (Wyss et al., 2001; Cuenot et al., 2008), which can be related to the effect of elevated pore pressure.

Conclusion

We have studied the microseismicity induced by the first large scale hydraulic stimulation at Paralana (July 2011). The Azimuthal Image Density log performed into Paralana-2 well indicates two main clusters of fractures oriented ~N-S and NE-SW. We observe similar directions in the distribution of induced seismicity, suggesting the injection has activated pre-existing structures. The relocated cluster is like an *en echelon* fracture system limited to the West and East by ~N-S faults comparable to the main normal faults surrounding the well (Figure 1). Reverse faulting is expressed in the focal mechanism of the largest event, which is consistent with the regional stress-regime, between strike-slip and reverse (Clark and Leonard, 2003).

A frequent observation in EGS and it that the largest events occur after shut-in (e.g., Soultz-sous-Forêt, France, 2000, Dorbath et al., 2009; Basel, Switzerland, 2006, Häring et al., 2008). In the case of Paralana, the four largest events occurred during injection. One plausible explanation is the geology of the site, considered as hybrid with the combination of crystalline rocks and sediments.

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