

MICROSEISMIC MONITORING OF NEWBERRY VOLCANO EGS DEMONSTRATION

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ABSTRACT

Hydraulic stimulation of an existing deep, hot well on the west flank of Newberry Volcano was performed in the fall of 2012 as part of the Newberry EGS Demonstration. A microseismic array of 15 stations was installed in the summer to monitor the EGS growth. Eight geophones were installed in 213-246 m deep boreholes, four drilled in the summer of 2012, in order to reduce noise due to scattering in the attenuating volcanic deposits near the surface. Seven surface geophones were installed to further improve locations and allow determination of source mechanisms by enhancing focal sphere coverage. Each station is equipped with a cell phone modem which sends data in real-time to an acquisition server in Seattle

After onsite assembly of moderate pressure pumps and piping, injection of cold groundwater into the EGS target well head began October 17 and continued until December 7. 174 microearthquakes with moment magnitudes between 0.0 and 2.4 were located within 1 km of the injection well, defining the EGS reservoir. Multi-zone stimulation was carried out by injecting thermally-degradable zonal isolation materials to plug stimulated fractures and shift stimulation to new fractures.

The Newberry Volcano EGS Demonstration will allow geothermal industry and academic experts to develop, validate and enhance geoscience and engineering techniques, and other procedures essential to the expansion of EGS. Successful development will demonstrate to the American public that EGS can play a significant role in reducing foreign energy dependence, and provide clean, renewable, and safe baseload geothermal power generation.

INTRODUCTION

Newberry Volcano is a shield volcano located in central Oregon, about 35 km south of the city of Bend and 65 km east of the crest of the Cascade

Range. The Newberry EGS Demonstration is being conducted on federal geothermal leases and National Forest Service lands located in the Deschutes National Forest, adjacent to Newberry National Volcanic Monument (NNVM).

The goals of the demonstration include (Osborn et al., 2010):

- Create an EGS reservoir,
- Stimulate multiple zones in existing well NWG 55-29 using AltaRock's proprietary thermally-degradable zonal isolation materials (TZIM) and associated technologies,
- Test single-well tracers,
- Confirm EGS reservoir viability through a flow-back test of the injected water,
- Drill one or two production wells to intersect the EGS reservoir (scheduled for 2013), and
- Using well NWG 55-29 as the injector, demonstrate EGS viability through a three-month circulation test.

The stimulation of NWG 55-29 began October 17, 2012 and injection ended December 7, 2012, achieving the first two goals. This paper focuses on the microseismic monitoring and results. See Petty et al. (2013) in this volume for more details related to flow rate, injectivity improvements, and temperature profiles.

HYDROSHEARING

AltaRock uses the term hydroshearing (Cladouhos et al., 2009) to describe the process of injecting water at moderate pressure, below the minimum principle stress (S_{hmin}), to cause existing fractures to dilate and slip in shear. A byproduct of shear-slip is the generation of seismic waves that can be used to map fracture location and size. In contrast, tensional fracturing, or hydrofracking, commonly used in the oil and gas industry requires fluid pressures well above S_{hmin} . Permeability enhancement occurs at

lower fluid pressures during hydroshearing because hydroshearing relies on displacement along preexisting fractures, as opposed to hydrofracking that creates entirely new fractures. Hydroshearing opens natural fractures that will dilate and remain open, even when fluid pressure is reduced, because of the irregularities of natural fracture surfaces.

It should be noted that hydroshearing is a simplified conceptual model with assumptions that are likely broken in the real-world. For example, an existing crack may open, close or shear depending on its orientation, cohesive strength and local stresses. The important distinction is that the stimulation equipment is designed to remain below S_{hmin} in hydroshearing, while in hydrofracking it is designed exceed S_{hmin} .

Another implicit assumption of EGS/hydroshearing is that microseismicity illuminates flow paths of the injected fluid that can be traced back to the injection well. However, because microseismicity is thought to be induced by a change in fluid pressure, fluid movement may not always be needed. Rather seismic events located away from the well could be related to fluid pressure connection only. This is one reason why tracers were injected as part of the EGS Demonstration, to eventually evaluate connectivity.

PHASE II 55-29 STIMULATION PREPARATION

Phase II of the Newberry EGS Demonstrations began in April 2012 after a Finding of No Significant Impact (FONSI) was issued by the Bureau of Land Management on the project's Environmental Assessment. Phase I planning and permitting is described by Osborn et al. (2011), AltaRock (2011), BLM (2012), and Cladouhos et al. (2012).

MSA Installation

In Phase I, a microseismic array (MSA) of 5 stations was proposed in order to map the EGS reservoir and provide real-time monitoring required by the project-specific Induced Seismicity Mitigation Plan (AltaRock, 2011; BLM, 2011; Cladouhos et al, 2012). Starting in late May, after snow melt, four new MSA monitoring holes (NN17, NN19, NN21, and NN24 on Figure 1) were drilled to depths between 213 and 246 m. The depth of these holes was chosen so that the geophones could be installed below the water table, in sections of competent rock at least 30 m long, and below the highly attenuating, cinders and debris flows on the flanks of the Newberry Volcano. The holes were drilled using the air hammer and casing-while-drill technique and were completed with 5" steel casing cemented from TD to the surface.

On average the new holes took 11 drilling days to complete. In addition, one existing water well (NN18) was deepened to improve coupling to the bedrock for the geophone. The holes were drilled by a Foremost DR-24 drill rig owned and operated by Tacoma Pump & Drilling of Graham, Washington. It took 3 months to drill all five holes. In addition, three holes drilled in 2009 and 2010 (NN32, NN09, and NN07 on Figure 1) by a DOE-funded exploration project awarded to lease-holder Davenport Newberry, were used as monitoring holes.

Seismic equipment installation began in early August 2012. Two-Hz geophones were installed at 7 surface sites and 8 borehole sites. The surface equipment (Figure 2) at each site included two 80-Watt solar panels, a GPS antenna and one or two cell phone antennas mounted in a tree to ensure that snow would not cover equipment that needed to stay exposed. In a Hoffman box at the base of the tree, we installed a digitizer, wireless cell modem, solar charge controllers, and two 12-V batteries.

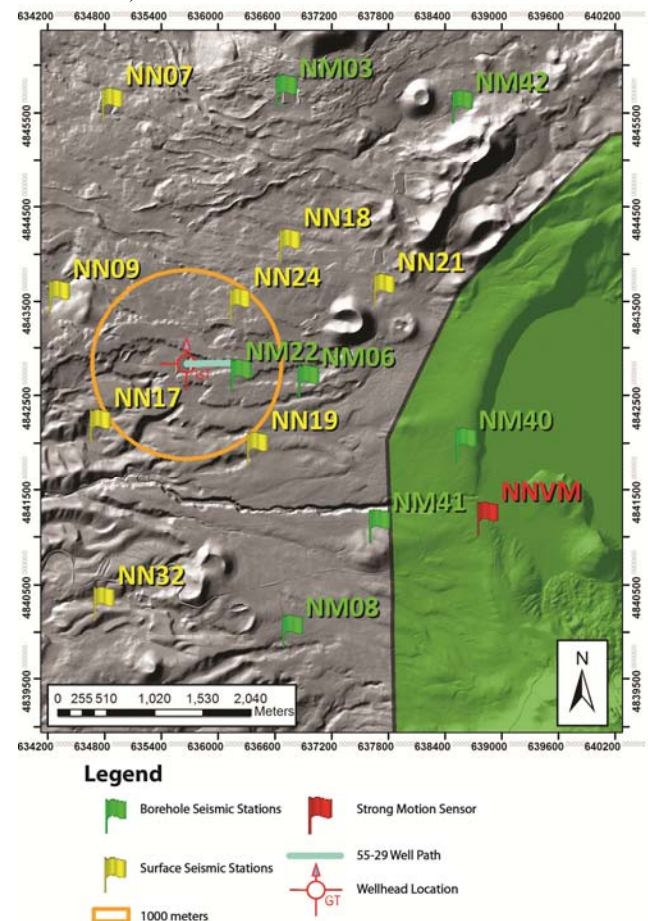


Figure 1: MSA locations, EGS well 55-29, and Newberry National Volcanic Monument (green shading).



Figure 2: Typical Newberry surface MSA equipment.



Figure 3: Borehole geophone with hole-lock adapter.

At each of the borehole stations an orientable hole-lock was installed near TD. Knowledge of the orientation of the horizontal components was required in order to maximize location accuracies and determine source mechanisms for the earthquakes.

The borehole geophones were equipped with an adapter that fit into the hole locks (Figure 3).

The 15 stations stream continuous data to a server running acquisition software at AltaRock's office in Seattle. All continuous data are saved and archived by AltaRock. Triggered waveforms are sent to Lawrence Berkeley National Lab (LBNL) for locating and publishing to the public website (LBNL, 2013).

Strong-Motion Sensor

In order to monitor any potential shaking at the nearest buildings due to injection-induced seismicity, a strong-motion sensor (SMS) was installed, bolted to the concrete floor of a USFS building near Paulina Lake. This site was connected to the Pacific Northwest Seismic Network (PNSNa, 2013) by cell modem and coded as NNVM (Figure 1).

Background Seismicity

The regional network at Newberry Volcano has improved greatly in the past two years. In 2009, the only station was NCO, a single-component, short-period seismometer on the east flank and only four microearthquakes were detected on Newberry in the prior 25 years. In 2011, the USGS installed six three-component broadband seismometers and one three-component short-period sensor (PNSNa, 2013). In late August 2012, three of the borehole stations in the AltaRock Newberry MSA (NN19, NN17, and NN21) were also added to the PNSN network. The seismic coverage on Newberry Volcano is now very good,

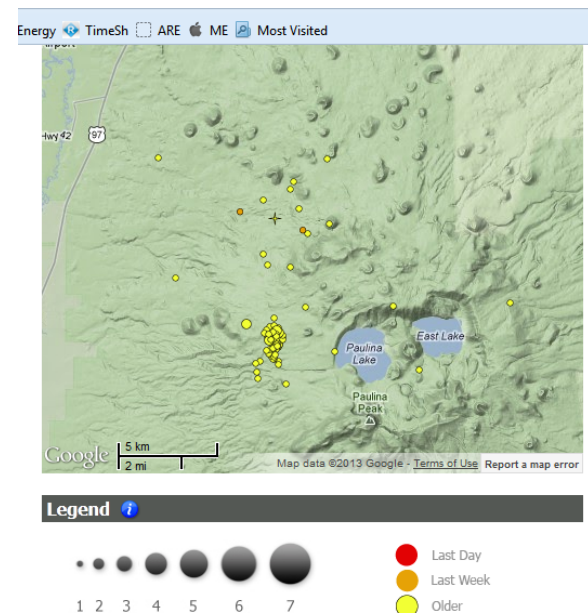


Figure 4: Five months of microseismicity on Newberry located by the regional network (PNSNb, 2013).

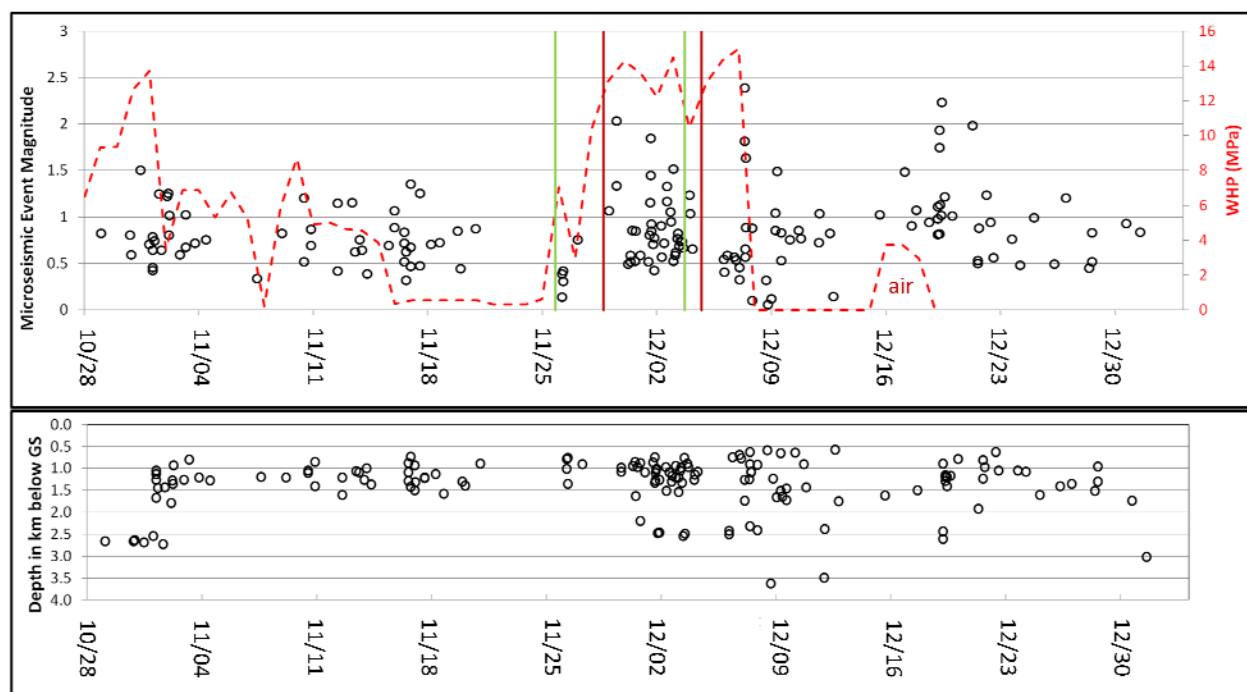


Figure 5: Magnitudes (top) and depths (bottom) of microseismic events with time compared to WHP (dashed red line). Prior to 11/25 WHP changes were due to stimulation pump issues. After 11/25, WHP changes were intentional. The vertical bars delineate the begin (green) and end (dark red) times for the two TZIM batches.

with events smaller than M_L 0.0 being locatable. In September and October, prior to stimulation, three natural microearthquakes were located using the improved network, compared to four in the prior 25 years. During and after the stimulation, in addition to locating 86 events in the EGS swarm (within 1 km of the well), 22 events were detected outside the swarm (Figure 4).

STIMULATION AND PRELIMINARY SEISMIC RESULTS

Injection into NWG 55-29 began October 17 and the first microearthquake located in the EGS stimulation zone occurred October 29. Microseismicity in the EGS zone continued for 2 months, with the last confirmed event January 2, 2013. Preliminary locations were determined for 174 microseismic events, usually within 8 hours of the event's occurrence. The results discussed below and shown in Figure 5 are preliminary; quality control and advanced analysis of the data is currently ongoing.

WHP and Hydroshearing

During step-rate testing October 18-20, the well head pressure (WHP) exceeded 12 MPa for just 3 hours. This was insufficient time or pressure to initiate hydroshearing. Due to stimulation pump problems,

the WHP did not exceed 9 MPa again until October 28. After 12 hours at 9.3 MPa, the first definite microearthquake in the EGS stimulation zone occurred near the injection well bore at a depth of ~2.4 km bgs, consistent with a temperature deflection on the DTS (Petty et al., 2013). Forty-two hours passed until the next event occurred, by which time the WHP had been increased to 12.5 MPa. Six events followed, indicating that sustained pressure over 12 MPa is required to cause sustained hydroshearing at depth in this well. There was no evidence from the pressure and flow-rate logs or the continuously recorded temperature profile (Petty et al., 2013), that the minimum principle stress (S_{hmin}) had been exceeded, i.e., no hydrofracking occurred.

After November 1, problems with one of the stimulation pumps necessitated lower pressures, ~ 5 MPa for two weeks and ~0.5 MPa for 10 days (Figure 5). During the lower WHP period, microseismicity continued for 19 days after WHP dropped below 12 MPa. When the stimulation pumps were fully repaired, November 25, seismicity re-initiated at the lower pressure of 7 MPa.

A maximum WHP of 16.7 MPa was reached December 7, and the well was shut in that same day. The seismicity rate dropped over the following week.

After the well was pressured up to 3.9 MPa with an air compressor on December 16, in an attempt to flow the well, seismicity increased, similar to the re-initiation of seismicity on November 25.

Size Distribution and Cumulative Moment

The size distribution of 114 events located during the stimulation period (10/29-12/7) is shown in Figure 6. The curvature away from a linear fit at small magnitudes indicates that most events down to M_w 0.5 were located. The rest of the curve is remarkably linear (especially given that the data set is small) with a negative slope, or b-value, of ~ 1.1 . It remains to be seen whether this same fit will remain when post-stimulation events are included.

The cumulative injected volume and cumulative logarithmic seismic moment are correlated (Figure 7). The M_w 2.39 event at the end of the Stage 3 stimulation accounted for 29% of the total seismic moment. The total cumulative moment of 14.6×10^{12} N m (Table 1) would correspond to a single M_w 2.75 event. Compared to predictions (AltaRock, 2011) and EGS projects in Basel, Switzerland (Haring et al., 2008), and Soultz, France (Dorbath et al., 2009), the cumulative moment is at least an order of magnitude lower for similar injected volumes. The Newberry site appears to have a much lower seismogenic index (Shapiro et al., 2010) than other sites.

Table 1: Injected volume and seismic moment, by Stage

Phase	Injected volume (m ³)	Cum. Moment (10 ¹² N m)	Max. mag. (M_w)
Stage 1	26,225	1.5	1.51
Stage 2	9,795	4.7	2.04
Stage 3	5,305	10.4	2.39
Shut-in	0	14.6	2.23

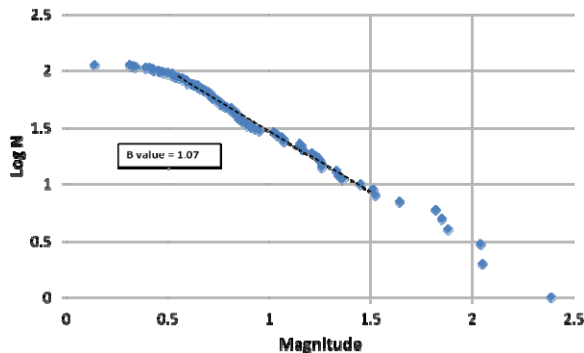


Figure 6. Size distribution of events during stimulation showing a b-value of ~ 1.1 .

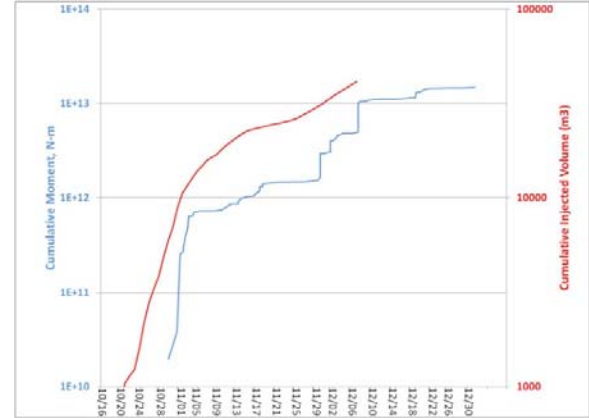


Figure 7: Cumulative injected volume and cumulative seismic moment.

Locations

The maps in Figure 8 show locations of seismic events by Stages defined by TZIM use and the postulated stimulation of a new set of fractures. The locations were calculated using the program *hypoc* (Julian, unpublished), a program that improves upon the relative relocation approach of Waldhauser and Ellsworth (2000).

During stimulation of Stage 1 (10/17-11/25), the microseismicity initiated near the well bore at a depth about 2.4 km bgs (Figure 8a). With time the events became shallower (Figure 5), and occurred mostly in the northeast quadrant (relative to the well head).

Stage 2: The first batch of TZIM was injected between November 25 & 28. The seismic response was a shift from the northeast quadrant to the southwest quadrant (Figure 8b). Additional events in northeast quadrant would be expected, as TZIM diversion was gradual, occurring over a four-day period (Petty et al., 2013).

Stage 3: The second batch of TZIM was injected December 3 & 4. After this treatment the majority of microearthquakes occurred in the southwest quadrant, indicating new connections to the southwest were enhanced. There is a ~ 300 m gap in seismicity between the southwest cluster of seismicity and the well bore.

In map view, the overall cloud of seismicity (Figure 7d) is 1.5×0.7 km with a NE-SW long axis and an area about 1 km^2 . The depth range (Figure 5) is currently uncertain, but appears to be at least 1 km and could easily be 1.5 km. Thus the total volume over which the seismicity occurred is between 1 and 1.5 km^3 .

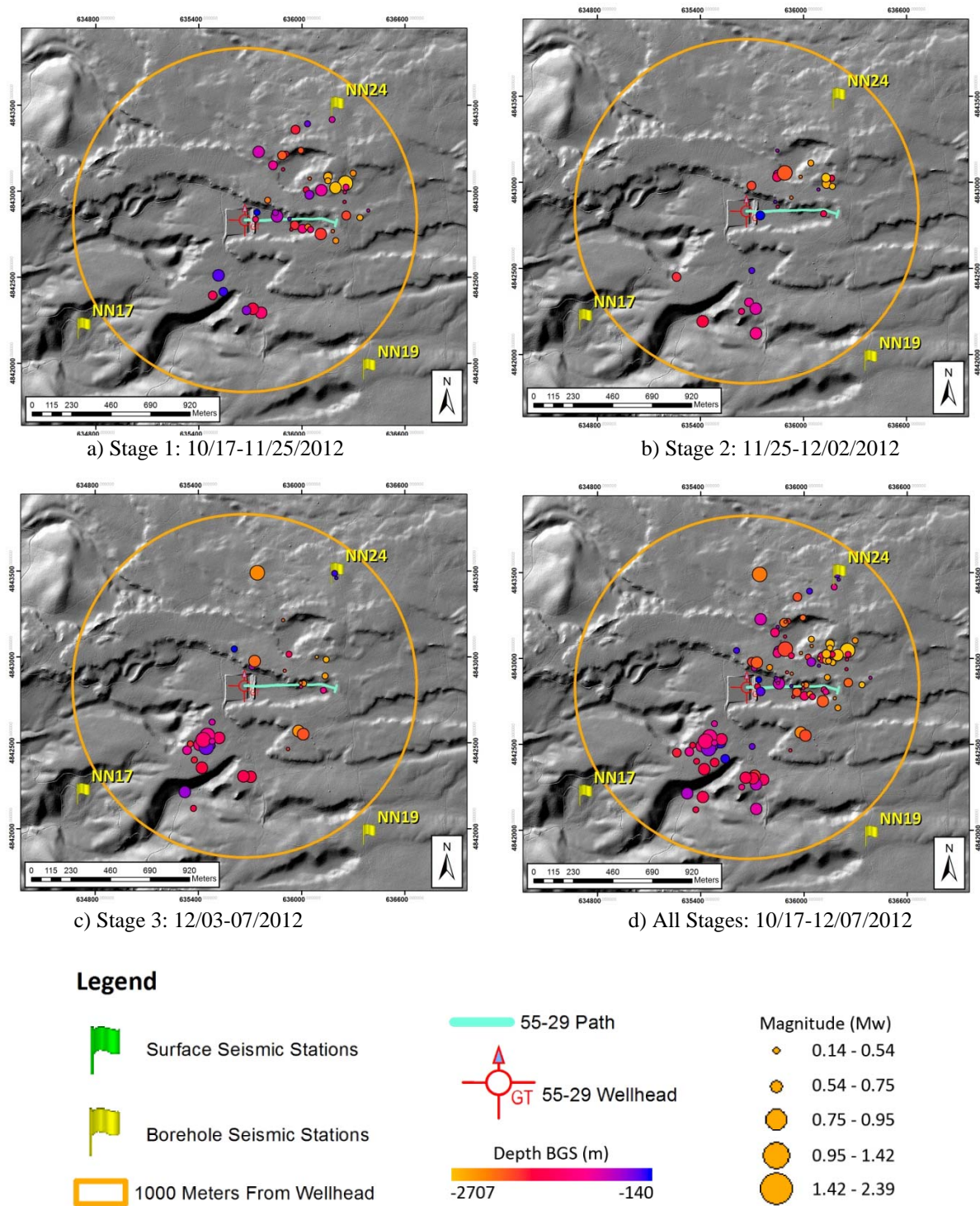


Figure 8: Maps of microseismicity during EGS stimulation. Location shown are preliminary relative relocations.

Lineaments within the cloud form a conjugate set with the same trends as the boundaries of the overall cloud, NE-SW and NW-SE. These lineaments appear to be sub-vertical and would be strike-slip faults in the stress regime, E-W S_{hmin} , determined from

regional studies and borehole breakouts in 55-29 (Davatzes and Hickman, 2011).

We anticipate that ongoing work will provide less diffuse event locations, which will provide the basis

for a conceptual model for the stimulation away from the well bore.

Performance of MSA

The hardware and software of the microseismic array performed very well, apart from some limited downtime on non-critical stations during cloudy periods in December. Most importantly, the borehole seismometers were far more effective than the surface seismometers. Below $M_w \sim 0.8$ there were very few usable arrivals on the surface stations, while most borehole stations did have usable arrivals. If the network had consisted of surface sensors only, the number of event located would have dropped by at least 2/3

Moment Tensors

Microseismicity in geothermal reservoirs can involve several different physical processes (Julian et al., 1998; Miller et al., 1998a). These include:

1. simple shear slip on planar faults
2. tensile cracking
3. rapid fluid motion

Understanding these processes is critical to understanding hydroshearing in EGS demonstrations. Traditional 'fault-plane solutions' assume that only Process 1 occurs, thus ignoring processes associated with opening and closing cracks, and fluid flow. For this reason, such an approach is inadequate for EGS work. Instead, a moment-tensor approach must be used. In order to determine moment tensors, more information than simply P -wave polarities is needed. The most effective and readily obtained information is the amplitudes of P - and S -phases (Julian and Foulger, 1996).

The preferred way of displaying moment tensors graphically is to use source-type diagrams (Hudson et al., 1989). This has been applied to many natural and industrially induced microearthquake sequences, including geothermal and hydrocarbon reservoirs and EGS stimulations (Julian and Foulger, 1996; Julian et al., 1997; Julian et al., 2010a; Miller et al., 1998). A source-type diagram (Figure 9) illustrates the deviation from a pure earthquake double-couple (DC) source at the center in terms of a volumetric component; explosion on top and left or implosion on bottom and right. Tectonic earthquakes typically fall near the center point of the plot (labeled DC). Injection-induced seismicity, which involves an underground change in volume, may *require* non DC source-types.

Moment tensor solutions have been calculated for 23 Newberry events. The source-type plot (Figure 9)

indicates a wide variety of source mechanisms ranging from double couple to opening cracks (+Crack) to closing cracks (-Crack). This variety may be due to a relatively low differential stress and wide variety of volcanic features (dikes, flow boundaries, ring fractures) that were stimulated. Interestingly, a source-type plot of the Geysers shows a similar range of mechanisms (Julian and Foulger, 2004).

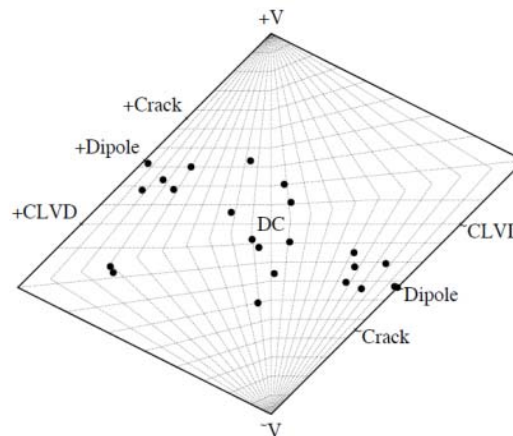


Figure 9: Source-type plot of 23 Newberry EGS events.

ISMP

AltaRock developed a project-specific Induced Seismicity Mitigation Plan (AltaRock, 2011; BLM, 2011) for the EGS demonstration that satisfied the requirements of the Induced Seismicity Mitigation

Protocol adopted by the DOE (Majer et al, 2008, 2011). This included predicting the largest possible induced microearthquake and developing predefined thresholds of event magnitudes and ground motion accompanied by appropriate mitigation actions.

The biggest event (M_w 2.39) which occurred on the last day of stimulation (12/7/2012) exceeded the initial limit, M_w 2.0, on magnitude. The mitigation action for this limit was to wait 24 hours before increasing well head pressure or flow rate. Since the event occurred on the last day of planned stimulation, no modification to operational plans was necessary, and the well was shut-in later that day.

Ground motion at the NNVM SMS due to the M_w 2.39 event was estimated PGA of 0.1% g, far below the action threshold set in the ISMP (AltaRock, 2011) of 1.4% g. From the seismometer closest to the event, a borehole seismometer at NN17, a PGA of 0.3% g was estimated. That level of ground motion would not necessarily have occurred at the surface, due to the highly attenuating cinders blanketing the volcano flanks. In any case, there were no reports of any felt seismicity from the field crews on-site for this or any

other microearthquake. Due to winter conditions, no visitors were near the site.

CONCLUSIONS AND FUTURE WORK

The installed MSA network met performance expectations throughout the Newberry stimulation. Results showed borehole stations were crucial for locating smaller events ($M_w < 0.8$) at Newberry. An EGS reservoir was created at Newberry Volcano as evidenced by the cloud of microearthquakes extending 500-800 m from the injection well. The stimulation occurred at well head pressures between 12 and 16.7 MPa. Shifts in seismic response corresponded with TZIM injection as multiple zones were stimulated. The total seismic volume was 1-1.5 km³ elongate in NE-SW direction. Lineaments within the seismic cloud are parallel to the cloud boundaries and sub-vertical, consistent with strike-slip fault movement in the measured stress field.

Preliminary moment tensor analysis showed a wide variety of source mechanisms due to the relative low differential stress and wide variety of volcanic features present at Newberry. Further analysis of the seismic data is ongoing to determine the optimal drilling path and target for the planned production well.

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Intellectual property statement

AltaRock holds a portfolio of patents, patent applications, licenses and related proprietary

intellectual property regarding its thermally-degradable zonal isolation materials, TZIM, and stimulation technology, materials and methods.

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