

Seismicity Associated with the Stimulation of the Enhanced Geothermal System at Habanero, Australia

Andrew McMahon¹ and Stefan Baisch²

¹Geodynamics Limited, Level 3, 19 Lang Parade, Milton 4064, Australia

² Q-con GmbH, Markstr. 39, D-76887 Bad Bergzabern, Germany

baisch@q-con.de

Keywords: enhanced geothermal system, EGS, seismicity, Habanero, hydraulic stimulation.

ABSTRACT

Geodynamics Limited has been developing an Enhanced Geothermal System (EGS) at Habanero in the Cooper Basin, Australia, since 2002. Prior to the hydraulic stimulation of Habanero 4 in 2012, the system had produced over 44,000 seismic events, of which over 31,000 events could be located.

In November 2012, a large hydraulic stimulation was carried out in the Habanero field. The intent of the stimulation was to expand the existing EGS geothermal reservoir and to gain a better understanding of the geothermal system, through the seismic response caused by the stimulation. The stimulation was conducted through Habanero 4, situated approximately 680 m North East of Habanero 1, which had been used for the original stimulations in 2003 and 2005. Over 34 ML of water was injected into the existing “Main Fracture” at a depth of 4,077 m true vertical depth (TVD) over a 3 week period.

During stimulation, seven seismic stations were used to transfer data in real time to the central processing office with an additional 17 stations recording in an offline mode and incorporated into the workflow in post-processing. In this three week stimulation period, over 27,000 events were recorded, of which over 20,700 events were located. Event magnitudes calibrated against recordings of the permanent network of Geoscience Australia were in the range of M_L -1.6 and 3. Hypocenter locations and fault plane solutions indicate that seismicity occurred on the same sub-horizontal layer structure identified in previous stimulations. The seismic cloud growth is consistent with the previous 2003 stimulation performed through the Habanero 1 well. However, it exhibits some different characteristics compared to the 2005 re-stimulation through Habanero 1 where a pronounced Kaiser effect was observed near the injection well (Baisch et al, 2009).

This paper aims to provide an overview of the seismicity produced through the 2012 stimulation of Habanero 4 and how its growth relates to previous stimulations of the Habanero field.

1. PROJECT AND LOCATION

The Habanero geothermal field is located in the northeast of South Australia, near the Queensland border (Figure 1). Drilling and related fieldwork began in 2002 and is spread across the company’s Geothermal Retention Licenses (GRLs) 3 to 12, which have a total area of 985 km². To date, six deep wells have been drilled into the granite ranging from a depth of between 3,629 m TVD at Savina 1 to 4,852 m TVD at Jolokia 1. The majority of work has been confined to the Habanero field where four wells have been drilled to depths between 4,200-4,400 m TVD.

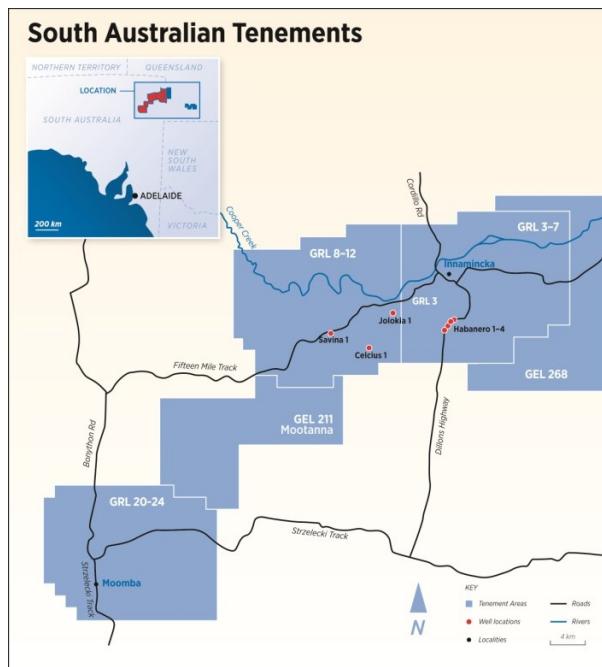


Figure 1: Location of Habanero Project.

McMahon and Baisch.

2. SEISMIC MONITORING SYSTEM

The initial seismic monitoring system for the 2003 Habanero stimulation was installed and jointly operated by Tohoku University and the Central Research Institute of Electric Power Industry (CRIEPI), Japan (Soma et al, 2004) and included seven shallow borehole arrays and one deep seismometer. The system was significantly upgraded in 2005 (Baisch et al, 2009) with all stations equipped with 24 bit SMART24 digitizers produced by Geotech, recording continuously at a sampling rate of 500 Hz.

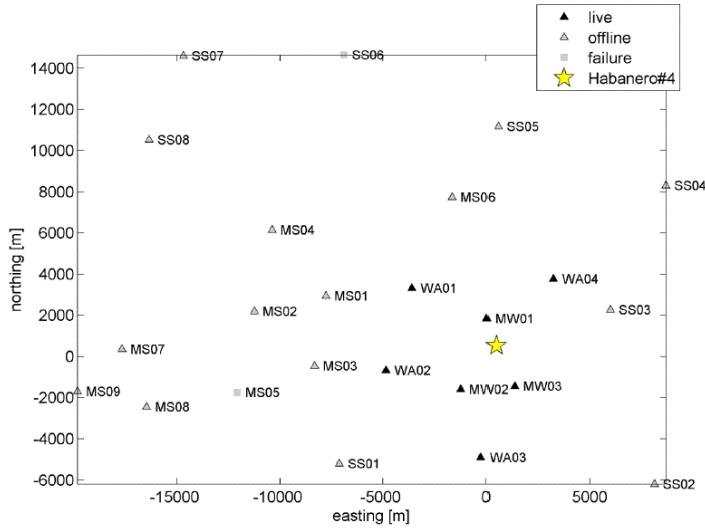


Figure 2: Map of seismic station locations. Live stations are denoted by black triangles, offline stations by grey triangles. Coordinates are given relative to the Habanero 1 well head.

With the development of operations in nearby wells, additional seismic monitoring stations were installed in 2008 and 2009, extending the existing seismic network towards the west. For the Habanero 4 stimulation, 9 additional mobile stations were installed in order to improve the coverage of the focal sphere when determining fault plane solutions. Fifteen seismic stations were operated with downhole geophones (depth range in the order of 90 m to 370 m). The 9 mobile stations installed most recently were equipped with LE3D 1-Hz three-component surface seismometers. Continuous waveform recordings were stored locally on a hard disk with the seven principal stations also transmitting during stimulation by a wireless local area network to the central data acquisition office located at Habanero 1. The seismic network configuration around Habanero 4 is shown in Figure 2 with a typical station shown in Figure 3.



Figure 3: Typical seismic station used in monitoring seismic activity.

3. METHOD

During stimulation activities, data from the seven principal seismic stations around Habanero was processed in near real time in the central acquisition office. Data was processed with Q-con's in-house software package QUBE and results cross-checked manually. The automatic event detection was based on the STA/LTA method which calculates the ratio of two averages of energy between a short-term window and long-term window. The peak of the energy ratio is very close to the time of first arrivals. A seismic event was declared whenever coincident STA/LTA detections on at least 3 trigger channels occurred.

After event detection, P and S-phase onset times were automatically determined with the QUBE autopicker. All onset times were then quality controlled by visual inspection and manually adjusted whenever necessary.

After P and S-phase onset times were determined, hypocenters were located using a linearized inversion method (Baisch et al, 2002). Hypocenter locations determined during real time operations utilised a velocity model which was adapted from previous studies, where average velocities have been calibrated by associating the location of early seismicity with the flow exit at the well bore from previous stimulations at Habanero 1 and Habanero 3. A more detailed analysis of the single station impact on hypocenter locations and a re-calibration of the seismic velocity model were performed after the monitoring operations, resulting in minor adjustments only.

For each event detected, the local magnitude M_L was automatically determined using the following equation:

$$M_L = \log_{10} \left(\frac{\overline{PGV}}{\overline{PGV}_{cal}} \right) + M_{cal}$$

With \overline{PGV} denoting the peak ground velocity determined by averaging the measured maximum signal amplitude over all recording channels. Correspondingly, \overline{PGV}_{cal} denotes the network averaged peak ground velocity of a calibration event of magnitude M_{cal} . The calibration event data was taken from a previous stimulation campaign in the same reservoir (Baisch et al, 2009), where several of the largest magnitude events were also recorded by Geoscience Australia. Note that \overline{PGV}_{cal} was measured by the same local seismic monitoring stations used during the current monitoring campaign.

4. HYDRAULIC STIMULATION OF HABANERO 1

In 2003 and 2005, Habanero 1 was hydraulically stimulated by injecting large amounts of water at high pressures. The stimulation in 2003 involved the injection of over 20 ML of water at varying time periods and pressures. This resulted in over 28,000 micro earthquakes (Figure 4) being recorded. Initial processing located over 11,000 events (Sumo et al, 2004) and subsequent reprocessing was able to locate an additional 12,000 events (Baisch et al, 2006).

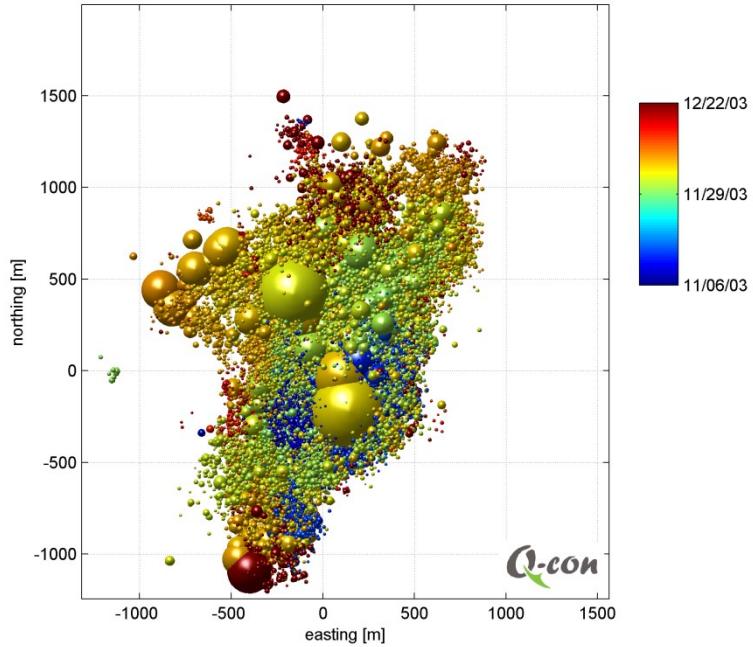


Figure 4: Hypocenter locations of the induced seismicity from the 2003 stimulation of Habanero 1. Each seismic event is displayed by a globe scaled to the event magnitude. Colour encoding denotes occurrence time according to legend.

The objective of the subsequent re-stimulation in 2005 was to extend the previously stimulated reservoir and to further enhance the hydraulic permeability. Re-stimulation of Habanero 1 commenced mid-September 2005 and continued for 13 days with a total volume of 22 ML. Over 16,000 seismic events (Figure 5) were recorded during stimulation with over 8,000 events located.

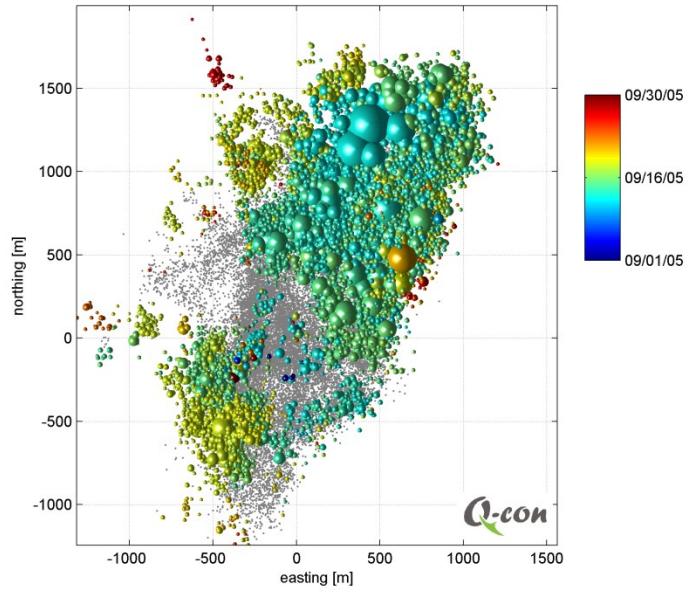


Figure 5: Hypocenter locations of the induced seismicity from the 2005 stimulation of Habanero 1. Each seismic event is displayed by a globe scaled to the event magnitude. Colour encoding denotes occurrence time according to legend. Previous seismic activity is indicated by grey dots.

5. HYDRAULIC STIMULATION OF HABANERO 4

Following a small local stimulation of Habanero 4, an extensive stimulation commenced on 17 Nov 2012. Injection commenced at 2 L/s for 12 hours to slowly cool the well. Thereafter, injection rates were stepped up every six hours before long-term injection at constant well-head pressure.

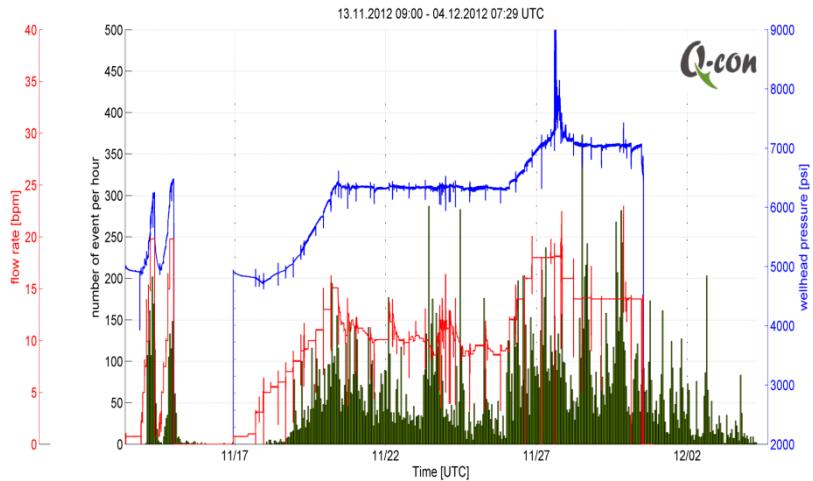


Figure 6: Injection pressure, flow rate and seismicity data for the extended stimulation.

The first seismic event occurred at 12:00 on 18 November whilst pumping at 32.8 MPa (4,757 psi). Initially, injection pressures were limited to 43.4 MPa (6,300 psi) on the C annulus (9 7/8" to 13 3/8" annulus). When this limit was reached, injection rates were adjusted (reduced) to maintain 43.4 MPa (6,300 psi) on the C annulus. This resulted in several days of injection at an injection pressure of ~43.6 MPa (~6,330 psi) at rates reducing from 31 to 23 L/s (11.7 to 8.6 bbl/min).

The pressure limit on the C annulus was lifted to 48.3 MPa (7,000 psi) and injection rates were again stepped up until the limit was reached. The injection rate was as high as 48 L/s (18.1 bbl/min) before the pressure limit was reached and rates were reduced. Injection continued at an injection pressure of ~48.5 MPa (~7,040 psi) at a rate of ~37 L/s (14 bbl/min).

Towards the end of the extended stimulation the annulus pressure limit was lifted briefly and an injectivity test was conducted. The maximum sustained rate achieved was 60 L/s (22.7 bbl/min) but only for a few minutes at an injection pressure of ~50.4 MPa (~7,310 psi).

The extended stimulation ended on 30 November after pumping inhibited brine in the well to prevent corrosion. The total volume pumped, including the inhibited brine, was 34 ML (215,000 bbl). The real-time seismic data collection continued until 18:00 on 4 December (ACDT).

During this period, real-time monitoring was performed by Q-con with two seismologists in the field supported by two seismologists working from the Q-con office in Germany. Remote access from the German offices was provided by satellite link.

6. HABANERO 4 STIMULATION RESULTS

The connection between the wellbore and fault was well established, shown by short duration flow tests and further enhanced by the short stimulation prior to the extended stimulation. Seismicity started approximately three hours after the beginning of the stimulation. Throughout the stimulation, seismic event rates correlate with injection pressures in the sense that an increase of the injection rate (and associated increase in injection pressure) resulted in an increase of the seismicity rate (Figure 6). Hypocenters were highly organised in space with seismic activity expanding outwards from the injection point in Habanero 4 with time (Figure 7). There was a steady decline in seismic activity after the conclusion of hydraulic operations, with nearly all post-stimulation activity located on the outer rim of the reservoir. This type of “post-injection” seismicity reflects an ongoing hydraulic diffusion process at the outer rim of the reservoir (Baisch et al., 2006b). During real-time monitoring, a total of 27,445 reservoir events were detected with sufficient signal-to-noise ratio for 20,734 of these events to be accurately located. Averaged formal location errors on a $1-\sigma$ level are 41 m, 38 m, and 68 m into eastern, northern, and vertical direction, respectively.

The largest event recorded was a magnitude 3.0 event which occurred on 27 November, 2012, with the largest post-stimulation event a magnitude 2.8 event occurring on 26 February, 2012. This was nearly three months after the conclusion of hydraulic activities.

7. COMPARISONS TO PREVIOUS STIMULATIONS

The processing of seismic data from the 2003 stimulation showed a distribution of the absolute hypocenters along a distinct, sub-horizontal layer structure. The vertical extent of the hypocenter distribution is 100-150 meters which is in the order of the observed vertical location accuracy. Taking into account the relative hypocenter locations and the tendency of the events inside each cluster to align along planes, it was concluded that a single fracture zone had been stimulated with a vertical extent at the meter scale (Baisch et al, 2006). The seismic activity was characterized by a strong degree of spatiotemporal ordering where the activity was moving away from the injection well with increasing time.

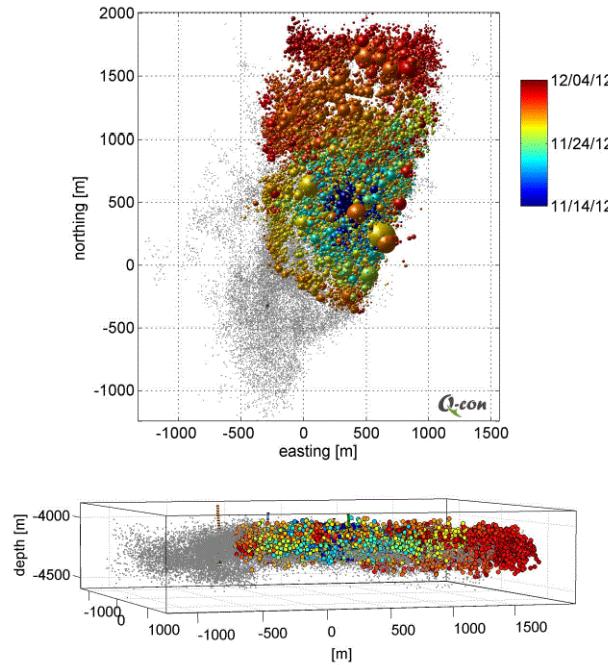


Figure 7: (top) Hypocenter locations of the induced seismicity from the 2012 stimulation in Habanero 4. Each seismic event is displayed by a globe scaled to the event magnitude. Colour encoding denotes occurrence time according to legend. Previous seismic activity is indicated by grey dots. **(bottom)** Hypocenter locations in side-view looking from ESE. Seismic events are displayed as dots with colour encoding denoting the origin time.

It was noted during stimulation that the seismicity did not propagate in all directions equally. In some directions, it appears blocked by linear temporary barriers. These barriers were later broken through, usually associated with an event on the outside of the barrier as pressure built up (Figure 8). These may not represent actual physical barriers, but might reflect small scale, lateral changes in the fracture properties, resulting in a slightly larger “triggering pressure” and thus a delay of the seismicity. This style of seismic cloud growth was seen in all stimulations.

Seismic activity during the re-stimulation of Habanero 1 in 2005 reinforced the view that the stimulation was occurring over a single fracture zone. The activity was constrained in the south and east of the previously stimulated zone but there was significant

growth of the seismic cloud to the north and west. There was also a distinct NNE-SSW boundary to the seismicity on the eastern side of the stimulation reservoir. Unlike the previous stimulation, there was little seismic activity around the injection zone with seismicity starting at the outer rim of the previously stimulated reservoir and subsequently migrated both towards the injection well and away. This was explained by the “Kaiser Effect” where regions of previous seismic activity remain seismically quiet as long as the previously applied hydraulic stimulation pressures are not exceeded (Baisch et al, 2009).

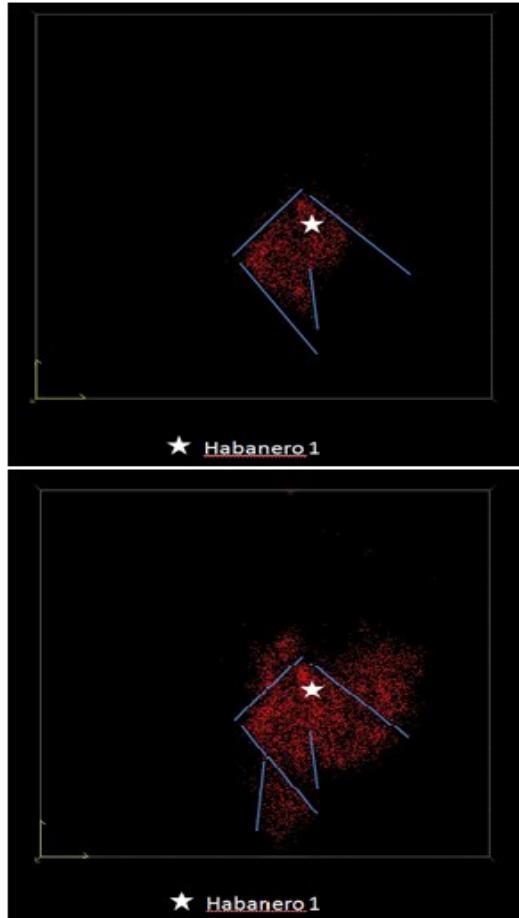


Figure 8: Seismicity from 2003 Habanero 1 stimulation showing temporary barriers in blue. Top picture includes seismicity from 6/11/03 to 12/11/03. Bottom picture includes seismicity from 6/11/03 to 30/11/03.

Based on the results of the 2005 stimulation of Habanero 1, an objective of the extended stimulation of Habanero 4 was to enlarge the existing fracture zone to maximise the development opportunities through a long term hydraulic injection of Habanero 4.

Seismicity over the duration of the extended stimulation in Habanero 4 was relatively constant. There was a strong degree of spatiotemporal ordering, with activity moving away from the injection point over time. Once again, seismicity did not propagate equally. There was a strong North-South trend with apparent temporary barriers which were overcome as the pressure increased as shown in Figure 9.

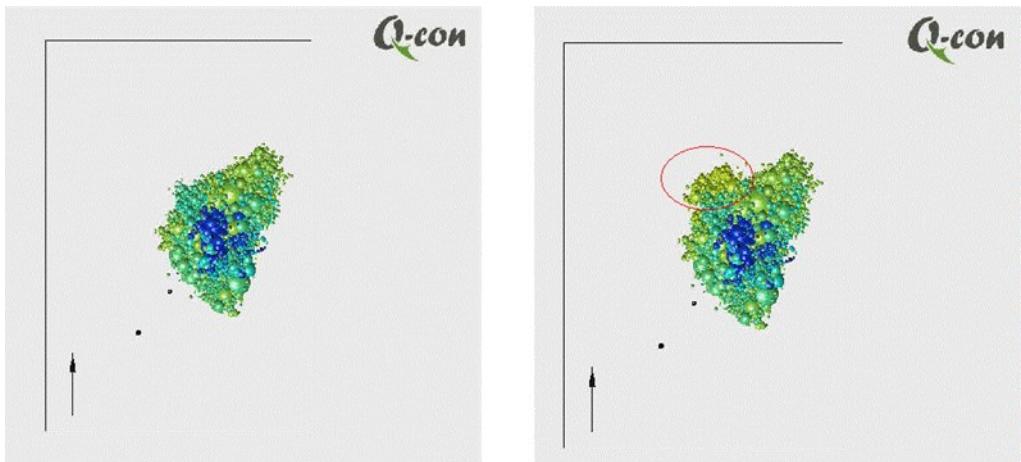


Figure 9: Seismicity from 2012 Habanero 4 stimulation showing temporary barriers. Top picture includes seismicity from 14/11/12 to 23/11/12. Bottom picture includes seismicity from 14/11/12 to 24/11/12.

However, the seismicity growth did not replicate what had been seen with the stimulation of Habanero 1 in 2005 but was consistent with the spatiotemporal evolution of the seismicity seen in the stimulation of Habanero 1 in 2003. Although the Habanero 1 and Habanero 4 wells are separated by ~ 700 m, it is noted that the evolution of the seismicity is very similar as shown in Figure 10. Once the seismic cloud reached the edge of the previously stimulated zone to the North, nearly all seismic activity concentrated to the North. Post-stimulation seismic activity has been primarily located on the eastern rim of the previously stimulated zone, indicating highly unstable stress conditions on what appears to be a hard boundary and which could be a steeply dipping fault.

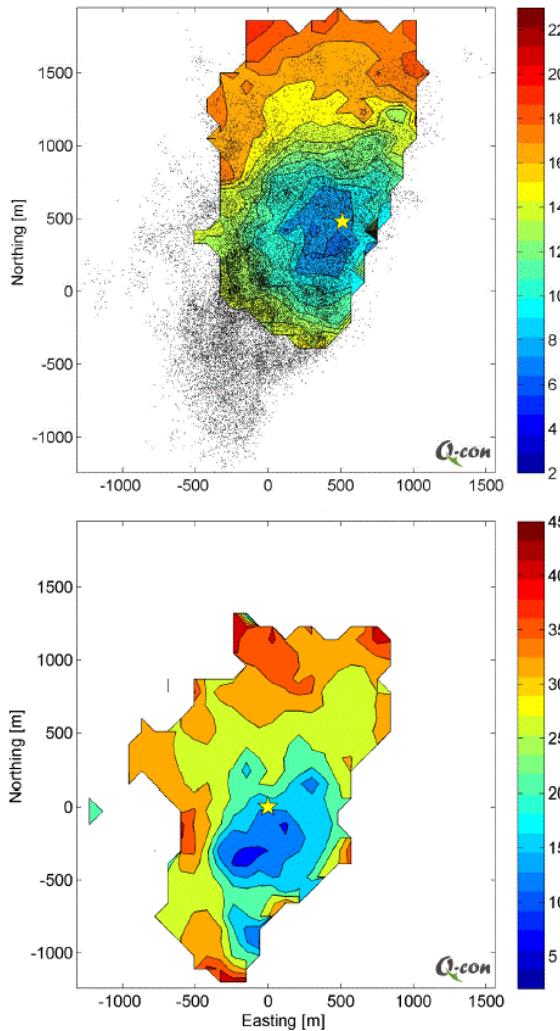


Figure 10: (Top) Spatiotemporal distribution of the induced seismicity of Habanero 4 (yellow star) in map view displayed by contours of the occurrence times according to the colour map in days. Previous seismic activity is indicated by grey dots. **(Bottom)** Same type of display for seismicity induced during the Habanero 1 (yellow star) stimulation in 2003.

8. FAULT PLANE SOLUTION ANALYSIS

Fault mechanisms were previously determined for the Habanero reservoir by analyzing P-wave polarities of induced events from the Habanero 1 re-stimulation (Baisch et al, 2009). Two main fault mechanisms were identified, named type I (strike = 157° , dip = 9° , rake = 65°) and type II (strike = 74° , dip = 20° , rake = 150°). These mechanisms were consistent with the regional stress field. However, in this previous analysis, only seismic stations immediately around Habanero 1 could be used, causing limitations to the azimuthal coverage of the focal sphere. Therefore, only compound fault plane solutions could be determined using data from multiple events.

For the Habanero 4 stimulation, additional seismic stations were deployed (“SS” prefixed stations Figure 2) and stations from outer networks were used in post processing (“MS” prefixed stations Figure 2). This was to constrain individual fault plane solutions during stimulation.

From all events recorded from the Habanero 4 stimulation, 571 events were initially analyzed. The dataset included all events of magnitude $M_L \geq 1.0$ (321 events) and 250 events with $0 \leq M_L \leq 1.0$. The selection criteria was designed in order to achieve an even (spatial) distribution of the events. Subsequent processing reduced the number of events to 560.

The results of the analysis are shown in Figure 11 and Table 1, which shows the fault plane solutions for the final 560 events analyzed. The polarity pattern of the majority of events is consistent with the previously determined type I fault mechanism of Baisch et al, 2009. However, fault mechanisms of 65 events are neither type I or type II events. Most of these events exhibit a

predominant strike-slip component in the best fitting solution. These events might indicate local fracture complexity and/or local deviations of the fracture orientation.

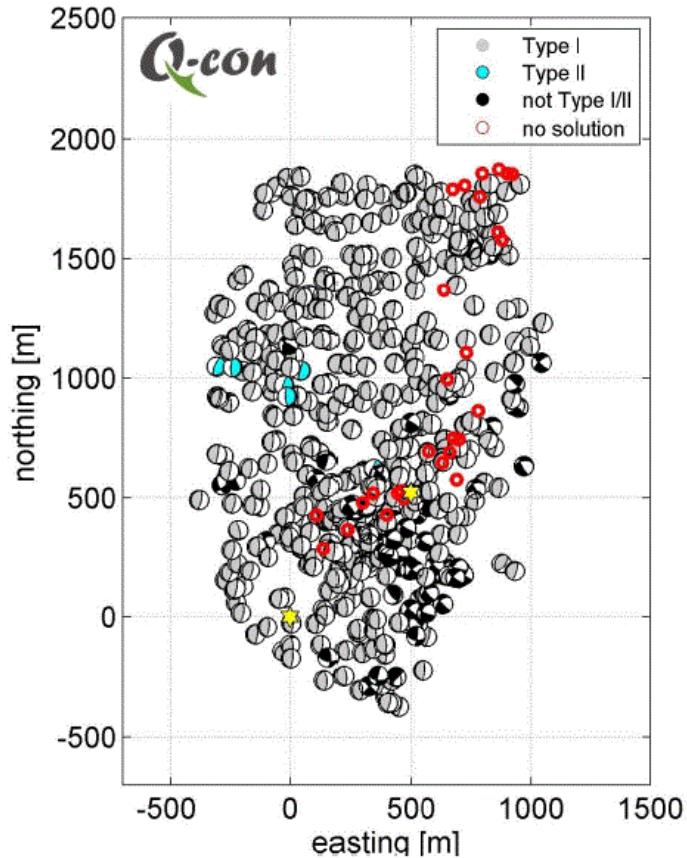


Figure 11 – Fault mechanisms (beachballs) for 560 events in map view. Grey beachballs denote events with a fault mechanism compatible with the previously determined type 1 solution. Blue beachballs denote events with a fault mechanism compatible with the previously determined type II solution. Black beachballs denote events which are not compatible with type I/II solutions. Red circles denote events which are not consistent with a pure double couple. Yellow stars indicate locations of the Habanero #1 and #4 well, respectively.

Table 1 - Number and percentage of events compatible with different types of fault plane solutions.

Type of FPS	Number of events	%
compatible with type I	453	81 %
compatible with type II	7	1 %
not type I/II, strike-slip	65	12 %
no solution	35	6 %

The mean values determined for type I and type II events by averaging all possible solutions are given in Table 2. Strike values are found to be slightly larger for type I compared to previously determined values and mean strike values for type II solutions are found to be significantly smaller.

9. OUTCOME FROM EXTENDED STIMULATION

One of the objectives of the stimulation of Habanero 4 was to extend the existing fracture zone to maximise the development opportunities in the Habanero reservoir. A causal relationship between induced seismicity and permeability increase based on self propping of fractures is commonly assumed (Baisch et al, 2006). Any further development planning would be based on the spatial distribution of induced seismicity. Figure 12 shows the seismic cloud growth between the 2012 stimulation and previous stimulations. Image 1 shows the seismic events recorded during the stimulation of Habanero 4 in 2012 in blue. Image 2 shows all seismic events recorded between 2003 and 2008 in red. By comparing the areal extent of these two images (Image 3), there was only a growth of approximately 0.35 km^2 or approximately 10% as shown by the yellow bounding box in Image 4. Cloud growth has occurred solely to the north of the previously stimulated zone.

Table 2 - Mean strike, dip and rake values for type I and type II events. Previous compound fault plane solution of Baisch et al. (2009) is shown in brackets.

Type of FPS	mean strike [°]	mean dip [°]	mean rake [°]
type I (well constrained)	197 ± 19	14 ± 4	101 ± 22
type I (all events) (previous solution)	197 ± 22 (157)	20 ± 6 (9)	103 ± 28 (65)
type II (previous solution)	29 ± 16 (74)	17 ± 4 (20)	107 ± 18 (150)

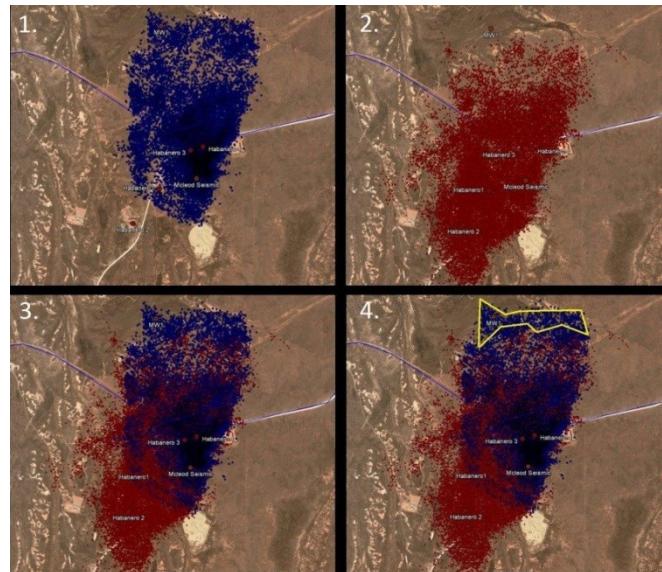


Figure 12: Difference in seismic cloud between the Habanero 1 stimulation and Habanero 4 stimulation.

10. SUMMARY

The stimulation of the Enhanced Geothermal System reservoir through Habanero 4 was successfully completed in November 2012. From this stimulation, over 27,000 seismic events were detected with over 20,600 events located. Hypocenter locations indicated that seismicity occurred on the same sub-horizontal layer structure identified in previous stimulations. It was noted that the evolution of the seismicity in 2012 was very similar to that seen in the original stimulation of Habanero 1 in 2003.

REFERENCES

Baisch, S., Bohnhoff, M., Ceranna, L., Tu, Y., and Harjes, H.P.: Probing the crust to 9 km depth: Fluid injection experiments and induced seismicity at the KTB super deep drilling hole, Germany , Bull. Seismol. Soc. Am. 92, 2369-2380. (2002).

Baisch, S., Weidler, R., Voros, R., Wyborn, D., and DeGraaf, L.: Induced seismicity during the stimulation of a geothermal HFR reservoir in the Cooper Basin (Australia) . , Bull. Seismol. Soc. Am. 96, 2242-2252. (2006).

Baisch, S., Weidler, R., Vörös, R., and R. Jung.: A conceptual model for post-injection seismicity at Soultz-sous-Forêts. Geothermal Resources Council, Trans., Vol. 30, 601-606. (2006b)

Baisch, S., Voros, R., Weidler, R. and Wyborn, D.: Investigation of Fault Mechanisms during Geothermal Reservoir Stimulation Experiments in the Cooper Basin, Australia. Bull. Seismol. Soc. Am Vol. 99, p148-158. (2009).

Soma, N., Asanuma, H., Kaieda, H., Tezuka, K., Wyborn, D., and Niitsuma, H.: On site mapping of microseismicity at Cooper Basin, Australia HDR project by the Japanese Team., In Proceedings, 29th Workshop on Geothermal Reservoir Engineering, Stanford University, Standford, California, 26-28 January, SGP-TR-175, 240-245. (2004).