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# INDUCED MICROSEISMIC ACTIVITY DURING RECENT CIRCULATION TESTS AT THE EGS SITE OF SOULTZ-SOUS-FORÊTS (FRANCE)

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## ABSTRACT

After 20 years of research and development on the geothermal reservoir, a 1.5 MWe power plant has been designed, built and tested at the EGS site of Soultz-sous-Forêts.

One of the major environmental concerns of the project has been for several years the induced microseismicity. During the early phases of the project, the most intense activity occurred during hydraulic stimulation experiments and, to a lesser extent, during chemical stimulation tests. It really became a worrying issue when several earthquakes of magnitude larger than 2 were felt on surface by the population. As the power plant is expected to operate continuously for years, it is of highly importance to study the seismic response of the geothermal reservoir in circulation conditions.

Five circulation tests performed in 2005, 2008 (twice), 2009 and 2010 offered the opportunity to observe the occurrence of microearthquakes in these conditions and will be presented in this study. They were carried out with different experimental setups: 2, 3 or 4 wells involved, artesian or pump-assisted circulation, different durations. The main result is that several hundreds of microseismic events were recorded in all the tests. Among them, earthquakes of magnitude ranging between 2 and a maximum of 2.3 occurred, which were likely to be felt by the population. Location of microseismic activity showed that almost the same zones of the geothermal reservoir were seismically active during all the tests. Moreover, correlations between the observed microseismic activity and hydraulic parameters of the circulation are performed in order to better understand the generation of microearthquakes in relation to hydraulics and to find circulation schemes that minimize the occurrence of microseismic activity for the future exploitation of the power plant.

## INTRODUCTION

The EGS pilot project of Soultz-sous-Forêts has started in 1987 from the will of the European Commission to develop new sources for power production (Gérard et al., 1984; Gérard and Kappelmeyer, 1987). The aim of the project is thus to produce electricity from the heat stored in deep, fractured crystalline rocks. For this purpose, during the first phase of the project (1987-2007), several geothermal and observation wells were drilled; among them, 3 geothermal boreholes reach a depth of 5 km. Because of the low initial permeability of the geothermal reservoir, the geothermal wells have been stimulated, both hydraulically and chemically, in order to improve the connection between the wells and the medium and to enhance the global permeability of the reservoir. In 2005, a 6 months long circulation test was performed between the deep boreholes. During this first phase, extensive research was also performed, so as to get a better characterization of the geothermal reservoir and of the underground fluid circulation.

During a second phase (2007-2009), a pilot power plant was designed and built: a first demonstration module of 1.5 MWe was installed, based on the ORC conversion cycle (Figure 1). Moreover, two downhole production pumps were also installed and tested. During this period, two circulation tests were performed, which lasted 2 months.

The current phase of the project consists in the long-term testing and monitoring of the power plant, together with production of electricity, which is injected directly in the French power grid. A 9-months circulation test was carried out in 2009. In 2010, the circulation test lasted 11 months and was the longest one ever performed at Soultz-sous-Forêts.

*Figure 1: Overview of the Soultz power plant.*

In this paper, a brief description of the Soultz site will be presented. Then, as the induced microseismic activity was monitored during all recent circulation tests, the main seismological results observed during the 2005, 2008, 2009 and 2010 circulation tests will be shown and compared, regarding the hydraulic parameters of each respective experiments.

## THE SOULTZ-SOUS-FORÊTS EGS SITE

### Location and geological settings

The Soultz-sous-Forêts EGS project is located in the northeastern part of France, in the northern part of the Upper Rhine Graben (Figure 2).

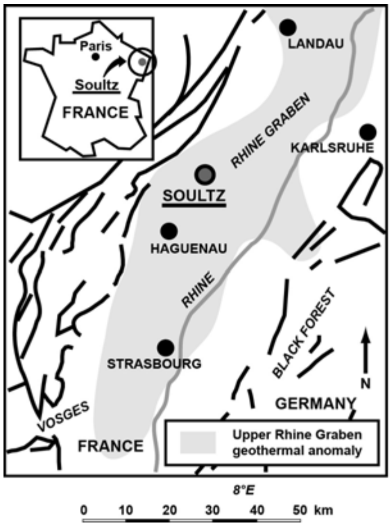

*Figure 2: Location of the EGS site of Soultz-sous-Forêts. The grey area represents the highest geothermal anomaly within the Upper Rhine Graben.*

The site was selected because of the well-known geothermal anomaly (Haas and Hoffmann, 1929) and shallow geology (Schnaebele et al., 1948), both characterized in the frame of oil exploration and exploitation.

The Upper Rhine Graben is a Tertiary Graben. The local geological structure in the Soultz region corresponds to a horst, where a 1400 m thick sedimentary cover overlays the crystalline basement. The basement is made of altered and fractured granitic rocks, which are older than 330 My (Cocherie et al., 2004).

### Temperature settings

Figure 3 shows the temperature profile from the surface down to 5 km depth (Schellschmidt and Schultz, 1991; Pribnow and Schellschmidt, 2000). The thermal gradient exhibits an irregular shape: from surface to 1 km depth, the gradient is very high (~110°C/km) indicating a conductive heat transport; however, between 1 km and 3.3 km depth, the gradient is very low (~5°C/km) and related to a convective circulation system (Le Carlier et al., 1994); below 3.3 km depth, the gradient increases (~30°C/km) and becomes linear again, suggesting a return to conductive heat transport regime.

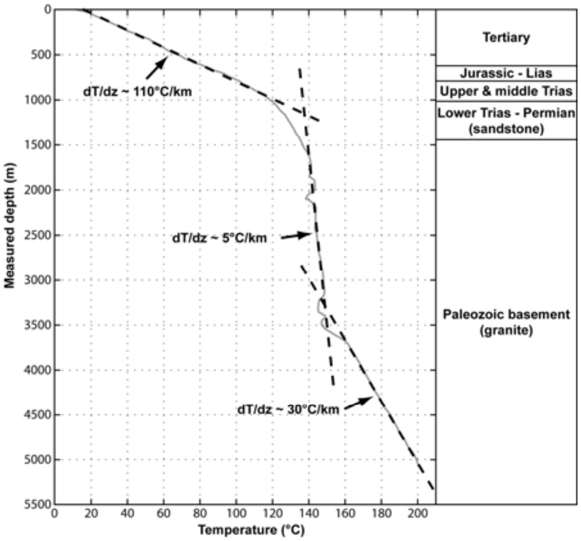

*Figure 3: Equilibrium temperature measured in the well GPK2 (Genter et al., 2010). Values of the thermal gradient are indicated and the main geological units are presented.*

### Fracture network and local stress field

The natural underground fluid circulation is driven by the fracture network and mainly through Hydrothermally Altered and Fractured zones (Evans et al., 2005; Genter, 1989). These fracture zones exhibit a low permeability, due to the presence of altered minerals deposits, such as clays, calcite, secondary quartz and sulfides (Genter and Traineau, 1992). Thus extensive research was performed to characterize the geometry of these fracture zones, mainly from cores, cuttings and geophysical borehole imaging. Most of the fracture zones show an orientation of about N160°E±10° and a high dip (Dezayes et al., 2010). Two secondary sets are also recognized, that strike respectively N20°E±10° and N130°E±10°.

The orientation of the principal components of the local stress field was estimated from wellbore failures (Valley, 2007; Valley and Evans, 2007). The authors found an orientation of N169°E±14° for the maximum horizontal stress $S_{Hmax}$. The maximum stress is vertical, in agreement with the extensive stress regime observed in the Rhine Graben, although its magnitude is close to that of $S_{Hmax}$ (Valley, 2007; Valley and Evans, 2007). This is consistent with the observation of both normal and strike-slip motions on focal mechanisms solutions of induced microearthquakes (Cuenot et al., 2006).

## The deep boreholes

5 deep boreholes were drilled during the project and their trajectory is presented on Figure 4:

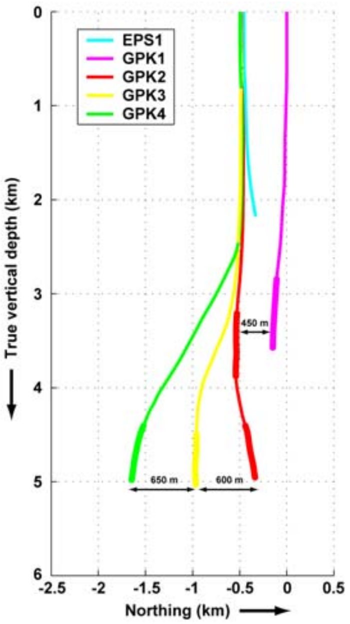

*Figure 4: South-North vertical cross-section showing the trajectory of the wells. The thicker lines indicate the open-hole sections of the geothermal boreholes.*

- EPS1 (in blue on figure 4) is about 2200 m deep (TVD) and was cored from about 900 m depth to bottom hole. It is currently used as a scientific observation well.
- GPK1 (in purple) was the first drilled well of the project. Initially reaching a depth of 2000 m, it was deepened in 1992 to 3600 m and is now a reinjection borehole.
- GPK2 (in red) was drilled to 3880 m depth in 1994, then deepened to 5 km depth in 1999. It is a production well, equipped with a Line-Shaft Pump.
- GPK3 (in yellow) was also drilled to 5 km depth in 2002 and is a reinjection well.
- GPK4 (in green) was drilled in 2004 to 5 km depth. It is the second production well, into which an Electro-Submersible Pump is installed.

## Development of the geothermal reservoir

Because of the low initial permeability of the fracture network that hosts the fluid circulation pathways, each borehole was hydraulically stimulated, once it was drilled. Some complementary chemical stimulations were also performed in several wells. These classical treatments were able to improve the injectivity/productivity index of the wells (Nami et al., 2008).

During the development of the shallow reservoir, GPK1 was stimulated in 1993, GPK2 in 1994 and 1995. Then, the 5 km deep boreholes were also hydraulically stimulated: GPK2 in 2000, GPK3 in 2003 and GPK4 in 2004 and 2005. The chemical treatments were performed in GPK2 (HCl), in GPK3 (HCl, OCA) and in GPK4 (HCl, RMA, NTA, OCA) (Nami et al., 2008; Portier et al., 2009).

During each hydraulic stimulation test, an intense microseismic activity was recorded: several thousands of microseismic events were detected with a downhole seismic network (*e. g.* Jones et al., 1995; Baria et al., 1995; Weidler et al., 2002; Baria et al., 2006) and with a surface seismological network (*e. g.* Cuenot et al., 2008; Charléty et al., 2007; Dorbath et al., 2009). Especially during the development of the deep reservoir, several earthquakes of magnitude larger than 2 occurred and some of them were felt by the neighbouring population, causing some troubles and complaints (Cuenot and Fritsch, 2007). The largest earthquake occurred in 2003, during the stimulation of GPK3, and reached a magnitude of 2.9. This stronger event, as well as several others, occurred during the shut in period, that is, after the end of injections.

The concern about microseismic activity and its implication for the future of the project grew during the stimulation period. Thus, many research works were undertaken to better understand the interactions between the fracture network, the local stress field and the massive fluid injections, that lead to induced microseismicity. Now, it is of equal importance to observe and understand the generation of microseismic activity (and especially of the larger magnitude earthquakes) under circulation conditions, which correspond to exploitation conditions. Thus the observation of microseismic activity during the recent circulation tests at Soultz brought essential information about what could be expected during the lifetime of the power plant.

## 2005 CIRCULATION TEST

The 2005 circulation test was the first test involving the 3 deep geothermal boreholes GPK2, GPK3 and GPK4. It was performed in artesian conditions: GPK2 and GPK4 were the production wells and the

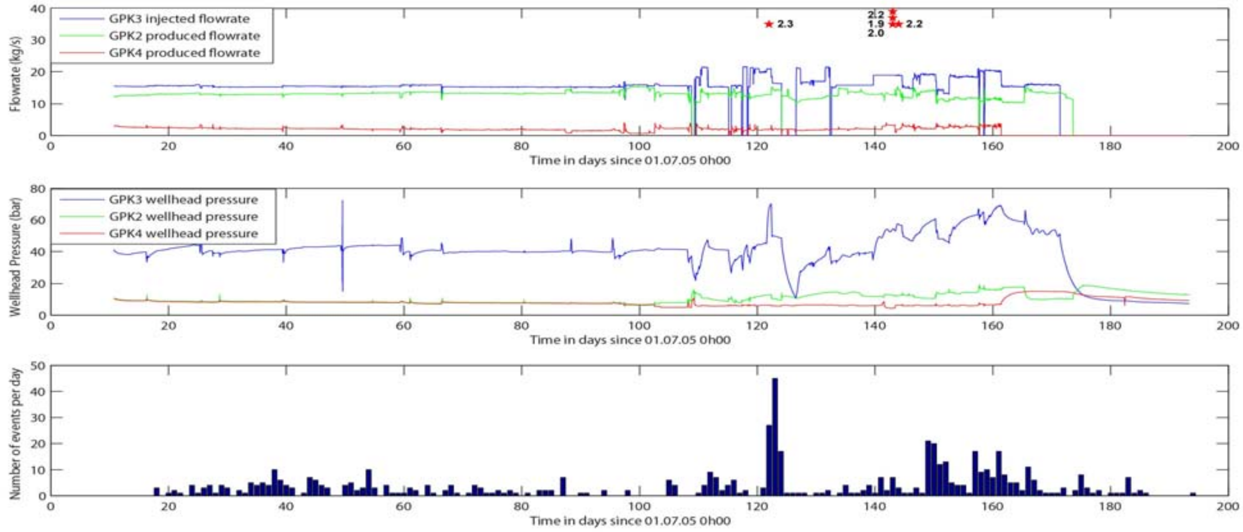

*Figure 5: Hydraulic parameters and microseismic activity during the 2005 circulation test. Top: Production (GPK2 and GPK4) and reinjection (GPK3) flowrates. Middle: GPK-2,-3 and -4 wellhead pressure. Bottom: Microseismic activity. Red stars indicate the occurrence of the largest magnitude events.*

geothermal fluid was reinjected into GPK3 after being cooled through a heat exchanger.

More details about this test can be found in Gérard et al. (2006), Cuenot et al. (2006) and Sanjuan et al. (2006).

## Hydraulic parameters

Figure 5 presents the hydraulic parameters of the circulation, as well as the microseismic activity induced during this test.

Around 165000 $m^3$ of geothermal fluid were produced from GPK2 at an average flowrate of 12 $kg.s^{-1}$. The temperature of the produced fluid was around 160°C. From GPK4, we were able to produce only 40000 $m^3$ at a flowrate of about 3 $kg.s^{-1}$ for a production temperature of 120°C. The sum of GPK2 and GPK4 contributions (i.e. 205000 $m^3$) was reinjected into GPK3 after being cooled down to 60°C by passing through a heat exchanger. The injection was performed at a flowrate of 15 $kg.s^{-1}$, except at the end of the test, when an additional flow of 4 $kg.s^{-1}$ was added to get a total injection flowrate of 19 $kg.s^{-1}$.

The wellhead pressure of both production boreholes was maintained between 10 and 20 bar, so as to prevent scaling. The pressure at GPK3 wellhead was almost stable at around 40 bar during the first part of the test, and then increased to a maximum of 70 bar, when the flowrate rose to 19 $L.s^{-1}$.

## Microseismic activity

Around 600 microseismic events were recorded during this test (Cuenot et al., 2006). The number of microearthquakes per day varied between 0 and a maximum of 45 (Figure 5). During the first 4 months, the activity was moderate and restrained to a maximum of 10 events per day. The most intense seismic activity was observed during the last 2 months of the test, when the injection flow rate had been increased from 15 $L.s^{-1}$ to 19 $L.s^{-1}$ (see Figure 5). The main peak of activity (45 events per day) occurred consecutively to the increase of reinjection rate and the following increase of GPK3 wellhead pressure to 70 bar. Two other smaller peaks are visible (~20 and ~17 events per day), which also corresponds to period of increased reinjection rate.

## Magnitudes

The observed magnitudes range between -1 and 2.3. 32 seismic events reached a magnitude 1.3 or higher; 7 were above a magnitude 1.8 and 4 show magnitude equal or higher than 2. Some of the strongest earthquakes were felt by a part the neighbouring population, but did not create any severe trouble.

During the first 4 months of the test, only 12 earthquakes in the magnitude range 1.3 – 1.8 could be observed. But, as soon as the injection flowrate was increased, a series of larger magnitude events occurred almost immediately, as seen on figure 5. Indeed a series of 7 earthquakes in the magnitude range 1.4 – 2.3 took place between the 29th and 31st of October 2005. Similarly, 4 events of magnitude ranging between 1.9 and 2.2 occurred within a few hours a few days later under the same hydraulic conditions (figure 5).

## Location of microseismic activity

Figure 6 shows the location of the observed microseismic event in plane view and in North-South vertical cross-section.

Three distinct active zones can be noticed. A few earthquakes (mainly in blue and cyan on Figure 6) are located in the vicinity of GPK4 and form the first active area. They occurred at the beginning of the test, but no other seismic event took place within this zone afterwards.

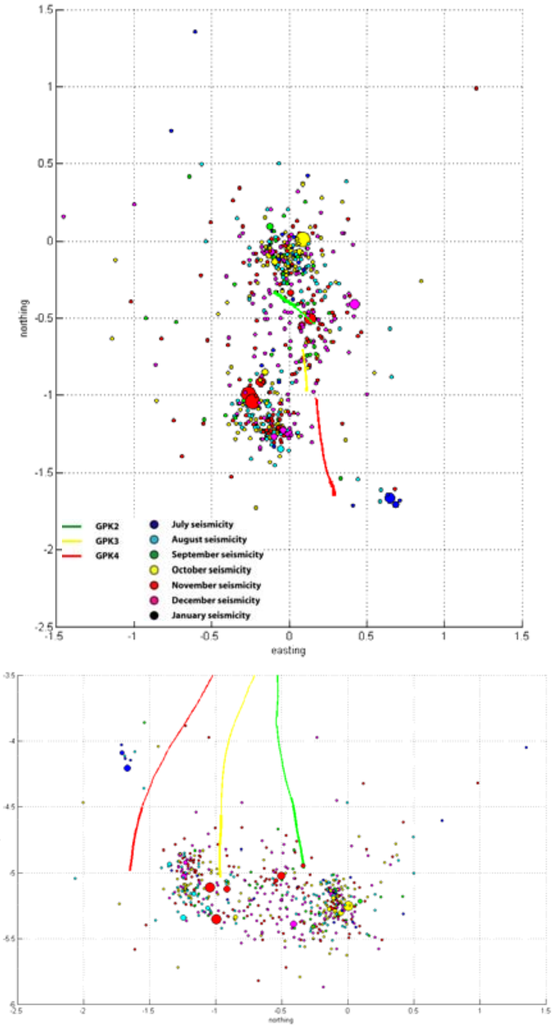

*Figure 6: Location of the 2005 microseismic activity. Top: Plane view; Bottom: South-North vertical cross-section. Earthquakes of magnitude equal or higher than 1.4 are represented by circles which diameter is proportional to the magnitude.*

The second zone is located on the North of GPK2 bottom hole between 5 and 5.5 km depth. The third active area is situated on the South-West of GPK3 bottom hole between 4.8 and 5.4 km depth. Both were active all along the experiment. Several earthquakes are located in the volume between GPK2 and GPK3, but the seismicity does not extend a lot between GPK3 and GPK4 and seems to keep concentrated around GPK3. Both main active areas contain events of small and large magnitude. For instance the M=2.3 earthquake (large yellow circle on Figure 6) is located in the area to the North of GPK2 and the two M=2.2 earthquakes (large red circles) occurred in the vicinity of GPK3.

## 2008 FIRST CIRCULATION TEST

Two 2 months long circulation tests were performed in 2008, following the building of the power plant and the installation of the downhole production pumps.

The test performed in July-August 2008 was aimed at testing the performance of the Line-shaft pump (LSP) installed in GPK2 and of the ORC conversion unit. Thus it involved only GPK2 as a production well and GPK3 as a reinjection well.

### Hydraulic parameters

The longest, uninterrupted circulation period started on the beginning of July and lasted to the 17th of August, when a failure of the LSP led to stop the test.

The hydraulic data of this test are shown on figure 7 (on the left), together with the observed microseismic activity.

The production of geothermal fluid was performed initially at a flowrate of around 17 L.s$^{-1}$, then the flowrate was increased to ~20 L.s$^{-1}$ for a short period, decreased to 18 L.s$^{-1}$. The final production flowrate reached ~25 L.s$^{-1}$. During this last step re-injection was operated at around 22 L.s$^{-1}$. The wellhead pressure of GPK2 was set to about 18 bar and GPK3 wellhead pressure increased continuously during the test to reach a maximum value of about 73 bar (Schindler, 2009).

### Microseismic activity

A total of around 190 microseismic events were detected during the July-August 2008 circulation test (Cuenot et al., 2010). The first observed microearthquake occurred on the 30th of July (Figure 7), when GPK3 wellhead pressure reached around 60 bars (Figure 5). Before, no seismic event could be detected. The activity varies between 0 and a maximum of 26 events per day. Two peaks of activity can be observed, although they cannot be linked with any sharp hydraulic change, as both injection and production flowrates were stable. But the peaks may be correlated with the continuous increase of GPK3 wellhead pressure. This behaviour is quite different from what was observed in 2005 when the peaks of seismic activity were clearly related to significant hydraulic variations.

### Magnitudes

The observed magnitudes are in the interval -0.3 to 1.4. 11 seismic events reached a magnitude equal or higher than 1. None of them was felt on surface. The two strongest earthquakes reached a magnitude of 1.4 and occurred on the 11th and 12th of August (figure 7). It cannot be clearly linked with any significant hydraulic variations.

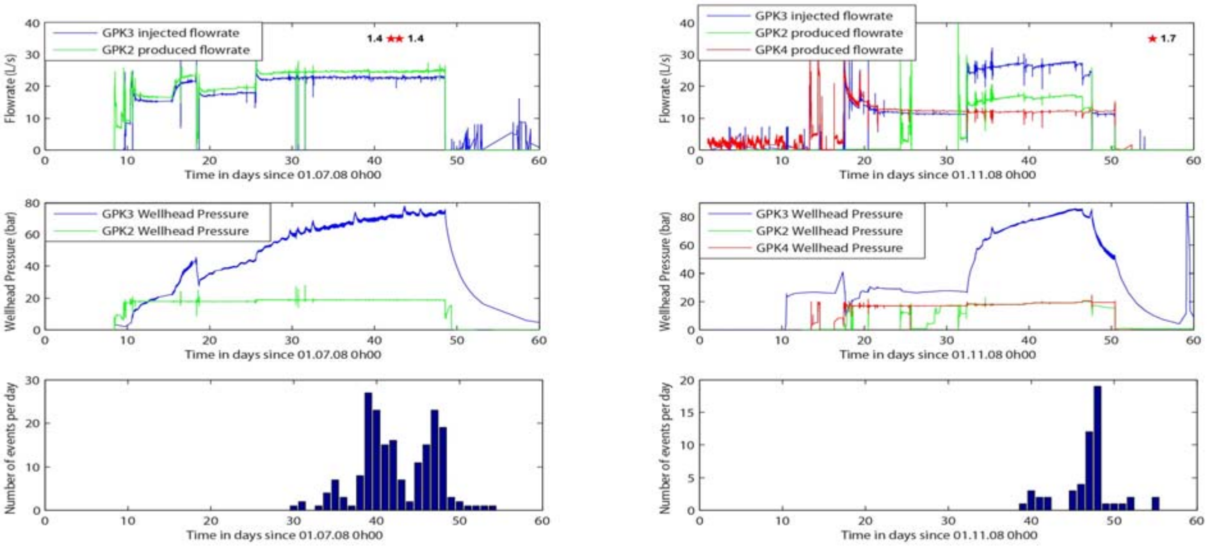

*Figure 7: Hydraulic parameters and microseismic activity during the 2008 circulation tests. Figures on the left correspond to the July-August circulation test and figures on the right to the November-December circulation test. Top: injection and production flowrates; Middle: Wellhead pressure; Bottom: Microseismic activity. Red stars indicate the occurrence of the largest magnitude events.*

## Location of microseismic activity

Figure 8 (plane view) and figure 9 (North-South vertical cross-section) summarize the location of the microseismic activity induced during the 2008, 2009 and 2010 circulation tests. Here the July-August 2008 events appear in blue. Most of the seismicity is located in between GPK2 and GPK3 at a depth ranging between 4.7 and 5.4 km (figures 8 and 9). Several microearthquakes are also situated in the zone on the North of GPK2 bottom hole between 5 and 5.5 km depth and on the South-West of GPK3 bottom hole. However, no earthquake occurred in the vicinity of GPK4, which is not surprising, as this well was not used during the circulation test. A comparison with the 2005 seismicity indicates that the same areas were seismically active during both tests. The early seismicity appears in the zone located north of GPK2, and then propagates toward GPK3. The latest activated area is located on the South-West of GPK3.

Both M=1.4 events are located in between GPK2 and GPK3 at around 5 km depth.

## 2008 SECOND CIRCULATION TEST

The 2008 second circulation test was performed in November-December 2008 after the installation of the second production pump (ESP – Electro-Submersible Pump) into GPK4 and the re-installation of the LSP into GPK2. Thus the test involved GPK2 and GPK4 as production wells and GPK3 as reinjection well. At first, the ESP was started on the 17th of November, then the LSP one week later. Unfortunately, the LSP encountered problems and had to be stopped. It was restarted on the 1st of December. Since this date, the circulation involved the three deep boreholes until the 17th of December: at that time a problem of the automation system caused the LSP to stop. 3 days later, the ESP was also stopped due to a problem on the air cooling system.

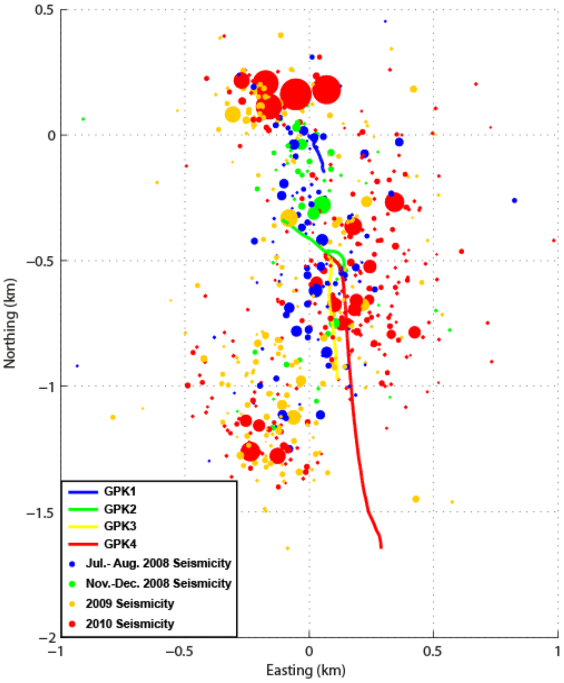

*Figure 8: Plane view showing the microseismic activity induced during the 2008 (blue and green circles), 2009 (yellow circles) and 2010 (red circles) circulation tests. Diameter of the circles is proportional to the event magnitude.*

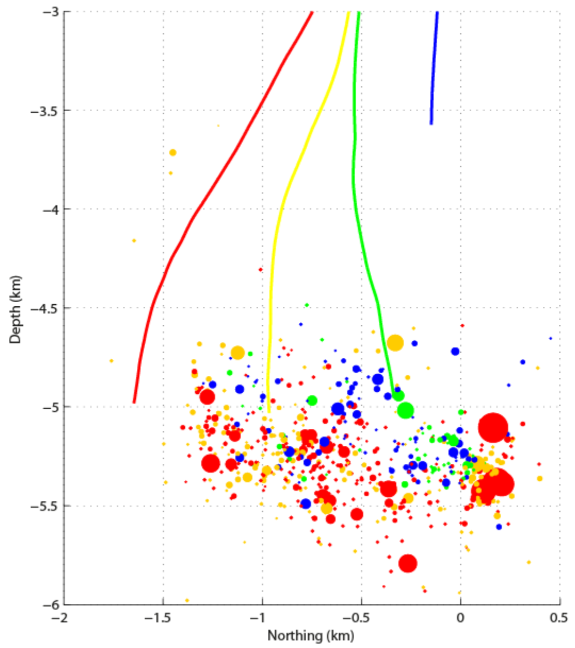

*Figure 9: North-South vertical cross-section showing the induced microseismic activity induced during the 2008, 2009 and circulation tests. Legend is the same as in figure 8.*

## Hydraulic parameters

The hydraulic parameters of the November-December circulation test are presented on figure 7 (on the right) with the associated induced microseismicity. Fluid was extracted from GPK2 at a mean flowrate of around 17 L.s$^{-1}$. From GPK4, the geothermal water was produced at an initial flowrate of ~17L.s$^{-1}$, quickly deceasing to a stable value of around 12 L.s$^{-1}$ (Schindler, 2009). For both production wells, the wellhead pressure was maintained at 18 bar in order to prevent scaling. At the beginning of the test, that is, when only GPK4 was producing, the re-injection into GPK3 was performed at a flowrate of about 17 L.s$^{-1}$, then about 11 L.s$^{-1}$ and the wellhead pressure increased to a maximum of 28 bar. As soon as the second well was put in production, the re-injection flowrate rose to a maximum of 27 L.s$^{-1}$ and the wellhead pressure increased up to 86 bar.

## Microseismic activity

53 microearthquakes were detected during this experiment (Cuenot et al., 2010). The first detected event occurred on the 9th of December, that is, more than 3 weeks after the beginning of the test (figure 7, lower right picture). The onset of seismicity is observed when GPK3 reinjection wellhead pressure reached 60 bar, as already seen during the first 2008 circulation test. Then the number of microseismic events per day varies between 0 and a maximum of 19. While the seismic rate was not higher than 4 events/day during most of the test under stable hydraulic conditions, only two days exhibit a larger rate: the 17th and 18th of December (12 and 19 events per day respectively). This is probably linked with the sudden stop of the LSP, which provoked a sort of mini shut in, as the re-injection pressure dropped quickly from around 90 bar down to 50 bar. Moreover, between 20h00 (17/12/08), that is, a few hours after the stop, and 8h00 (18/12/08), 21 microseismic events occurred; that represents almost the half of the total number of earthquakes recorded during the test. This behaviour is similar to what was observed in 2005: the sudden change of hydraulic parameters leads to an increase of the seismic activity.

## Magnitudes

The observed magnitudes are in the range -0.2 to 1.7. 4 events reached a magnitude 1 or higher: two of magnitude 1.2, one of magnitude 1.3 and the largest one of magnitude 1.7. Among them, one of the M=1.2 events occurred on the 18th of December, a few hours after the stop of the LSP. The M=1.7 earthquake took place on the 25th of December, 5 days after the complete end of the test, that is, during the shut in period. The occurrence of stronger earthquakes during the shut in phase was already observed, mainly during stimulation tests and has become one of the major issues related to induced seismicity on geothermal plant.

## Location of microseismic activity

The location of the microseismic activity induced during this test is shown on figures 8 and 9. Events locations are presented as green circles.

The seismicity is mainly concentrated around the well GPK2 in a zone situated to the North of GPK2 bottom hole (figure 8). It extends between 5 and 5.5 km depth (figure 9). Several earthquakes can be observed to the West of GPK3 well and a few in between GPK2 and GPK3. No seismicity is located around GPK4, although this well was in production and equipped with the ESP downhole pump. Even the sudden stop of the ESP did not induce any earthquake in the vicinity of GPK4.

Around GPK2, the microseismic activity began to develop in the deepest part of the activated area and then migrates to shallower levels. It can be noticed that the microearthquakes occurred during the mini seismic crisis following the stop of the LSP pump constitute a small cluster in the volume to the North of GPK2 (Cuenot et al., 2010). The M=1.7 event is located in the vicinity of GPK2 at about 5 km depth and around 200 m away from the bottom hole. Moreover one can observe that the location of this earthquake is also very close to another larger event (M=1.3) occurred in the early phase of the circulation test.

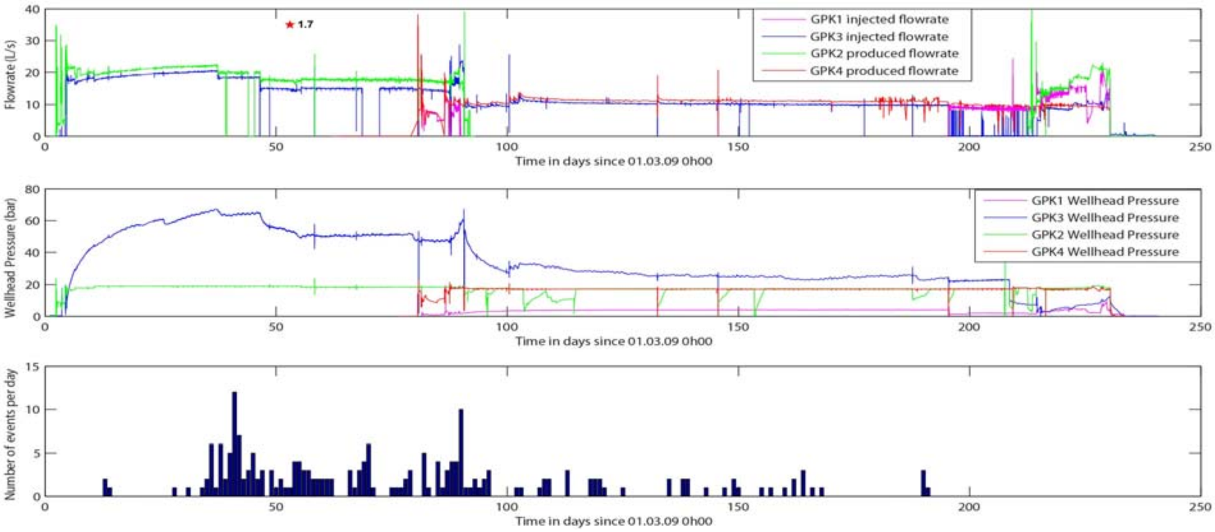

*Figure 10: Hydraulic parameters and microseismic activity during the 2009 circulation test. Top: Injection and production flowrates; Middle: Wellhead pressure; Bottom: Microseismic activity. Red stars indicate the occurrence of the largest magnitude events.*

## 2009 CIRCULATION TEST

The 2009 circulation test was the first involving 4 geothermal wells: geothermal fluid was produced from GPK2 and GPK4, equipped with LSP and ESP respectively. Reinjection was performed into GPK3 as in the previous tests. But in order to avoid a large reinjection flowrate and the resulting high overpressure in GPK3, which could increase the seismicity level both in terms of activity and larger magnitude events, a part of the fluid was reinjected into GPK1.

### Hydraulic parameters

Figure 10 presents the hydraulic data recorded during the test. The hydraulic scheme is rather complex, because of the use of 4 wells and of technical problems that happened during the test. It was conducted over 7 months between March and October 2009. During the first two months, only GPK2 and GPK3 were involved. Production flowrate was increased up to about 22 $L.s^{-1}$, then decreased to 17 $L.s^{-1}$. Meanwhile the reinjection flowrate reached 20 $L.s^{-1}$, then was reduced to 15 $L.s^{-1}$. In May, GPK4 was started and the flowrate reached about 12 $L.s^{-1}$. Consequently, a part of the produced fluid was reinjected into GPK1 at a flowrate of about 8 – 9 $L.s^{-1}$. Unfortunately a technical problem led to stop the test. Only the ESP could be restarted, therefore only GPK4 and GPK3 were used (production: ~11 $L.s^{-1}$; reinjection: ~10$L.s^{-1}$) until September. At that time, GPK2 was also restarted for a production at a maximum flowrate of ~22 $L.s^{-1}$ and reinjection was performed into GPK1 (max. flowrate: ~20 $L.s^{-1}$). The test was stopped on mid-October for a maintenance period.

### Microseismic activity

206 microseismic events were detected during the test. 3 events occurred about 10 days after the beginning of the circulation, followed by a quiet period (figure 10). Then a more continuous activity was observed at a rate between 0 and 12 events per day when the wellhead injection pressure reached about 60 bar. A second peak can be noticed: among the 10 events occurred that day, 8 took place within the few hours following the sudden stop of the circulation. Then from May to October the activity remained at a very low level.

### Magnitudes

We observed magnitude between -0.3 and 1.7. Only 8 earthquakes reached a magnitude larger than 1 over the 7 months of circulation. The M=1.7 event occurred while the hydraulic regime was rather stable, but a few days after a decrease of the circulation flowrate, which also induced a decrease of injection pressure. It is not sure that both are linked. Nevertheless, when carefully observing the hydraulic parameters on figure 10, one can notice that just after the earthquake, a small drop happened on GPK2 production flowrate, followed by an increase of the flowrate. As this earthquake is located in the close vicinity of the well GPK2 (Figure 8 and 9, big yellow circle near GPK2 green trajectory), one may infer that the occurrence of this earthquake had an impact on the underground circulation paths, maybe on a permeable fracture crossed by the borehole open-hole section. This should be further carefully analyzed.

Two other earthquakes of magnitude 1.5 and 1.6 were also detected, which took place in stable hydraulic conditions.

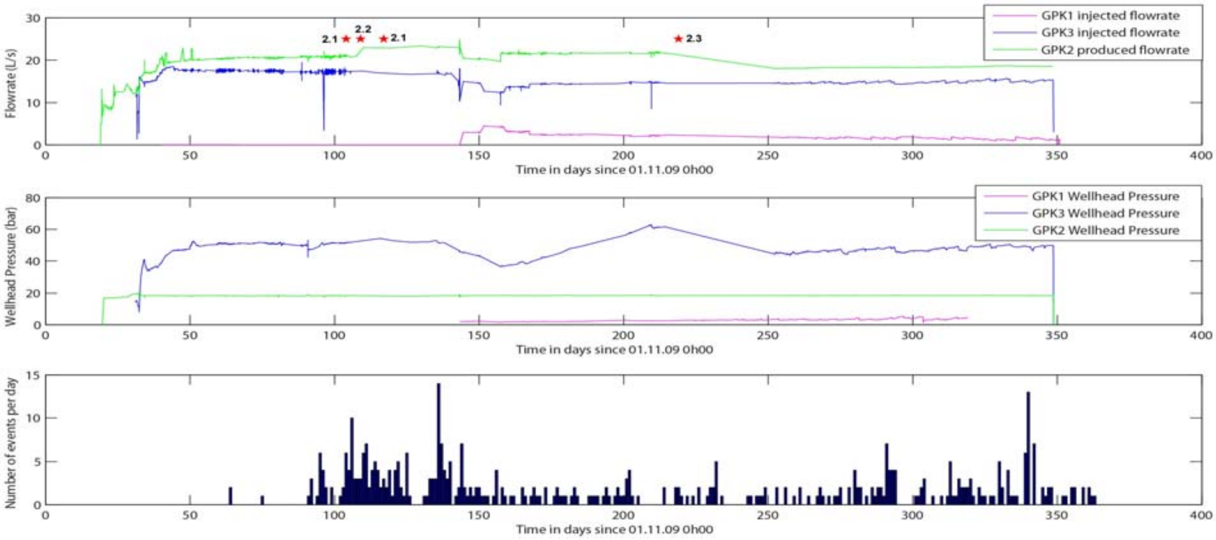

*Figure 11: Hydraulic parameters and microseismic activity during the 2010 circulation test. Top: Injection and production flowrates; Middle: Wellhead pressure; Bottom: Microseismic activity. Red stars indicate the occurrence of the largest magnitude events.*

### Location of microseismic activity

On figures 8 and 9, the 2009 microearthquakes are shown in yellow circles. The spatial distribution of the 2009 seismicity is similar to that of the previous tests. 3 areas are mainly active: a zone on the North of GPK2 bottom hole, where hypocenters are rather deep (below 5.2 km depth), the zone in between GPK2 and GPK3 and a zone on the West/South-West of GPK3 bottom hole at a depth between 5 And 5.4 km. The early seismicity mainly occurred in the zone on the North of GPK2, then this zone was less active, probably because of the stop of production from GPK2. Moreover it should be noticed that no earthquake was located in the vicinity of both GPK1 and GPK4, despite the fact that both were used during the test. The location of the largest earthquake has been discussed above.

## 2010 CIRCULATION TEST

The 2010 circulation test began in November 2009 after a maintenance period and lasted until October 2010, when a new maintenance period was programmed. This 11 months experiment is the longest circulation ever performed on the Soultz project. This test involved only GPK2 (production), GPK3 and GPK1 (reinjection), because the ESP installed in GPK4 encountered a failure and could not be easily and quickly repaired.

### Hydraulic parameters

The hydraulic data are presented on Figure 11. The curves shown here are not very precise, as we experienced several problems with the data acquisition system, causing a loss of data. The missing data are progressively being recovered. The hydraulic regime was very stable all along the test and around 500000 m$^3$ of fluid circulated. Production from GPK2 was performed at an almost constant rate of 18 L.s-1. Note that on figure 11, the production flowrate seems to be higher than 20 L.s$^{-1}$. This is a wrong value, inasmuch as a problem was detected on the flowmeter, leading to an overestimation of the flowrate. The actual value appears from the day 250 on figure 11. The injection into GPK3 was done at a initial flowrate of about 17 L.s$^{-1}$, and then decreased to 15 L.s$^{-1}$, when a part of the produced fluid was injected into GPK1 (flowrate: 1 – 2 L.s$^{-1}$). GPK2 wellhead pressure was kept at 18 bars, while GPK3 wellhead pressure was about 50 bar, then 40 bars when reinjection was performed into GPK1. GPK3 pressure kept slightly increasing until the end of the test.

### Microseismic activity

Observed microseismic activity is shown on figure 11. A few events occurred around 2 months after the beginning of the test and the continuous activity started 1 month later. A total of 411 microseismic events were detected during the circulation. The highest activity was observed during the first phase of the test, when reinjection was performed into GPK3 only: 2 peaks can be distinguished (10 and 14 events per day), although they are not related to significant hydraulic variations. But, one can noticed that after this small seismic crisis, GPK3 injection pressure dropped by about 5 bars, without changing the flowrate. This may indicate an improvement of the injectivity, which could be attributed to a redistribution of the flow paths caused by seismic events. Once a part of the geothermal fluid was reinjected into GPK1, making GPK3 wellhead pressure decreasing, the microseismic activity remained at a low level (between 0 and 5 events per day). Only near the end of the test, the activity seemed to increase a bit, maybe in relation to the continuous rise of GPK3 injection pressure. A small activity had remained for 15 days after the end of the test.

## Magnitudes

Magnitudes are in the range -0.3 to 2.3. Several larger magnitude events occurred during this test. Indeed 25 earthquakes reached a magnitude equal or larger than 1. Among them, 7 were above magnitude 1.8 and 4 reached magnitude higher than 2 (figure 11). The first three earthquakes of magnitude larger than 2 occurred within a few days and are located in the same area (see next paragraph). However, they were quite unexpected, because at that time the hydraulic regime was very stable. Another M=2.3 event happened a few weeks later, again, during stable hydraulic conditions. All the earthquakes of magnitude larger than 1.8 occurred during the first phase of the test, that is, before the beginning of injection into GPK1. Only one earthquake of magnitude 1.1 happened a few hours after the end of the circulation.

## Location of microseismic activity

The location of 2010 microearthquakes is presented in figure 8 and 9. Events are marked as red circles. Again the same zones concentrate the seismicity: in the area on the West/South-West of GPK3, events are located at depths between 4.9 and 5.3 km; in the area between GPK2 and GPK3, hypocenters are located a bit deeper. We can also observe that this zone extends a bit to the East, where very few events occurred during the previous tests. The most striking seismic zone corresponds to the North of GPK2 bottom hole: indeed the four M > 2 earthquakes are located in this area. So they were spatially clustered and for three of them also temporally clustered. Moreover as they occurred during stable hydraulic conditions, they may be associated with a fault, which was activated and followed its own behaviour, almost independently from the hydraulic regime. It should be reminded that during the 2000 and 2003 stimulation experiments, the strongest earthquakes (M=2.6; M=2.9), as well as numerous other larger magnitude events were also located in this zone (Cuenot et al., 2008, Charléty et al., 2007).

As already observed in the previous tests, no seismicity is located around GPK4, which was not used here, and around GPK1, into which reinjection took place at a low flowrate.

## DISCUSSION

It is not easy to directly compare the spatio-temporal evolution of the seismicity from one circulation test to another, as the hydraulic conditions were quite different: duration of the tests, artesian or pump-assisted circulation, 2, 3 or 4 boreholes involved, total volume of fluid having circulated. Nevertheless some common or unexpected behaviours can be deduced from this analysis.

## Microseismic activity

The first major result is that seismicity occurred for all the circulation tests performed in the deep reservoir. In 1997, a 4 months circulation test was conducted in the shallow reservoir (3.5 – 4 km depth) between GPK2 and GPK1 at a flowrate of about 25 L.s-1 (Baumgaertner et al., 1998). No seismicity was detected. This suggests that the stress state at 5 km depth plays a dominant role in the generation of seismicity. But this also implies that a microseismic activity will probably develop more or less continuously during the long-term exploitation of the power plant.

For all the circulation tests, the microseismic activity can be qualified as moderate, especially when the hydraulic regime is stable. In all cases, the onset of seismicity was observed several days after the beginning of circulation. It may be related to the volume of fluid having circulated, but also to the reinjection pressure, as in almost all tests, the continuous seismic activity started when the pressure reached ~60 bar. Moreover, as long as the injection pressure keeps growing, the seismic activity tends to increase. Thus, the injection of a part of the geothermal fluid into GPK1 prevents a too high overpressure in GPK3: in 2009 and 2010, the use of GPK1 and GPK3 for reinjection corresponds to periods of low seismic activity.

However, it was also observed that sharp variations of hydraulic parameters tend to have an immediate impact on seismicity, both in terms of activity and larger magnitude. This includes sudden increase of injection rate as in 2005 for example (figure 5), when a peak of activity was induced and several stronger earthquakes occurred. But a sudden stop of pumping can also have the same consequences as in December 2008: both an increase of activity and a M=1.7 earthquakes were observed after the failure of the LSP and the stop of ESP (figure 7). On the contrary, the end of the circulation tests in 2009 and 2010 did not produce similar results. Moreover in 2010, the observed peaks of activity and the largest earthquakes were not correlated with any significant hydraulic vent. Thus the underlying mechanisms needs to be better understood.

## Larger magnitude earthquakes

In 2005, several earthquakes of magnitude larger than 2 were detected, but none in 2008 and in 2009. Again in 2010, 4 events reached magnitude higher than 2.

The difference between the cases of 2005 and 2008/2009 may be explained by several factors (Cuenot et al., 2010):

- In 2005, the series of $M \geq 2$ earthquakes happened quite lately in the course of the test (around 4 months after the beginning). It means that a large volume of geothermal fluid had already circulated before, compared to the 2008 tests. So the total volume of circulating fluid may have an influence on seismicity and especially on the level of magnitude: some water-rock interactions may develop on the fault planes, as long as water is circulating, and may reduce the resistance to shear of the fractures.
- It is possible that the major part of the seismic energy accumulated on major faults was released by the largest earthquakes of 2005. Until the tests of 2008/2009, the seismic loading may have not retrieved its previous level so that the strongest magnitudes of 2008/2009 are generally lower than those of 2005.
- The enhanced production due to downhole pumping may help limiting the overpressure effect, which is responsible in many cases for the occurrence of the larger seismic events.

For the larger earthquakes of 2010, the situation seems different, as they occurred in the first part of the test and during stable hydraulic conditions. Moreover as they are located within the same zone, they may be associated to a fault, which seismic behaviour could have been triggered by the circulation. An ongoing study on focal mechanisms of these earthquakes may help to better understand their generation, as they were unexpected in these conditions.

### Location of microseismic events

In all the tests, seismicity developed in the same areas. 3 main zones concentrated almost all hypocenters (figures 8 and 9):
- a zone on the West/South-West of GPK3 bottom hole,
- a zone in between GPK2 and GPK3,
- a zone on the North of GPK2, where most of the strongest events are located.

Nevertheless, when carefully observing, one may remark that within each zone, the hypocenters do not overlap so much from one test to the other. It seems that the locations where ruptures took place during a test are not reactivated in the following tests. This is especially true for the 2010 seismicity, which developed mostly at the borders of the previously activated zones.

Another important observation is the absence of seismicity in the vicinity of GPK1 and GPK4, even when the wells were involved in the test. It is not surprising for GPK1, as it is a shallower borehole and as the injected flowrates and the resulting overpressures were rather low. However, we could have expected some seismicity around GPK4, especially in 2005, in November-December 2008 and in 2009, when the well was producing. This may be related to the fact that a poor hydraulic connection exists between GPK3 and GPK4, as highlighted by the tracer test performed during the 2005 circulation test (Sanjuan et al., 2006).

## CONCLUSION

The analysis of the recent circulation tests performed at the EGS site of Soultz-sous-Forêts allowed us to get a good overview of the induced microseismic activity. The different circulation schemes used for these tests give us a broad range of conditions under which seismicity tends to develop. This will greatly help to define the proper circulation parameters of future tests in order to minimize the occurrence of seismicity. This is also very important for the long-term exploitation of the power plant. Nevertheless, a further analysis of the results needs to be undertaken, so as to get a better understanding of the mechanisms responsible for induced seismicity in circulation conditions. Interactions between the local stress field, the fracture network and the circulation of fluids needs to be better understood and modeled. A new circulation period has started in early January 2011, during which careful observation of the seismic activity will continue.

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