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Microseismic Activity Induced During Recent Circulation Tests at the Soultz-sous-Forêts EGS Power Plant

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ABSTRACT

After the construction of the Soultz geothermal power plant completed in 2008, several circulation tests have been performed to test electricity production as well as downhole pumping technologies. Different production/injection strategies, involving 2, 3 or 4 boreholes were tested with different production/injection flowrates. Induced seismicity was continuously monitored with a surface seismological network of 8 permanent stations.

In almost all cases, microseismic activity was observed, but at a moderate level as compared to the huge seismicity induced during stimulation experiment. In average, only a few microseismic events occurred per day. Some rare peaks of activity (up to 25 events/day) could be recorded, which usually follow variations of the hydraulic conditions. Several earthquakes reached magnitude higher than 1.7, the maximum recorded magnitude being 2.3. Fortunately, none of them was felt by the population. It has to be noticed that some of the largest magnitude events occurred during the shut-in period and more generally after sharp variations of the hydraulic regime.

The location of the seismic activity is very similar from one test to the other. The events occurred mainly at great depth, between 5 and 5.5 km and 3 main zones are mostly active. However within these 3 zones and from one circulation test to the next, microseismic events tend to take place in previously inactive areas.

Since 2011, it has been decided to split the reinjection between 2 wells in order to decrease the reinjection pressure. By maintaining the reinjection pressure below 20 bars, a spectacular decrease of the seismic activity was observed: in 2010, more than 400 microseismic events occurred over 11 months of circulation, whereas only 5 were recorded during 6 months of circulation in 2011. Thus as the strategy consisting in lowering the reinjection pressure by splitting the reinjected volume between several boreholes was very effective in 2011 in order to reduce the microseismic activity, it has been successfully applied in the following circulation tests.

1. 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. During this phase an very intense induced microseismic activity was observed (Figure 1): 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.

This first phase was concluded in 2005 with a 6 months circulation test performed between the 3 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 2). Moreover, two downhole production pumps were also installed and tested. During this period, two circulation tests were performed in 2008, which lasted 2 months.

The current phase of the project consists in the industrial exploitation of the power plant. Thus long-term testing and monitoring of the power plant have been performed, 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. In 2011, two tests were realized, but both only lasted 3 months because of pump failures. Then two other circulation tests were carried out: a very short one (1 month) in 2012 and a longer one (6 months) in 2013. All the circulation tests will be described in more details below. The 2008, 2009 and 2010 tests were already discussed in Cuenot et al. (2011).

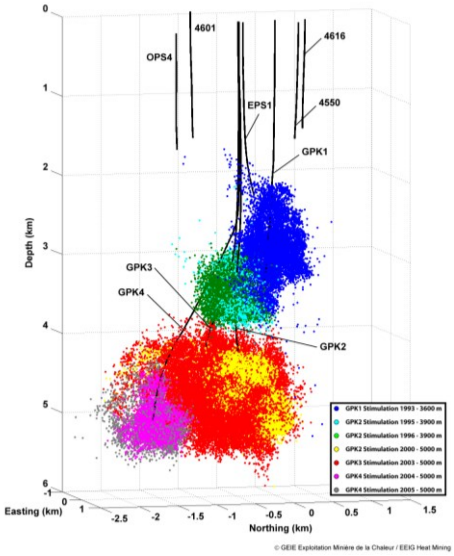

Figure 1: Induced microseismic activity recorded by the downhole seismological network during all stimulation tests performed at Soultz. GPK1, GPK2, GPK3 and GPK4 are the deep geothermal boreholes; EPS1, 4550, 4601, 4616 ans OPS4 are seismic observation boreholes.

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 long-term 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 and also gave new insights about experimental ways to reduce the induced microseismic activity. In the following, hydraulic parameters and seismological observation will be described for each recent circulation tests. Finally the main lessons related to circulation-induced microseismicity will be discussed.

Figure 2: View of the Soultz geothermal power plant

2. 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.

2.1 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 3 (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 and 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).

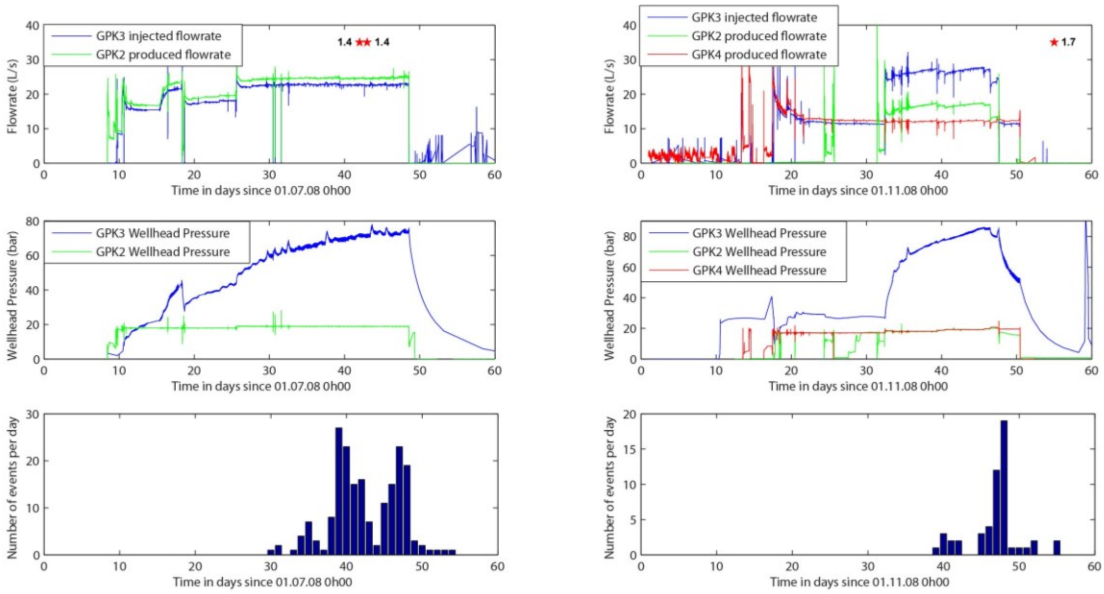

Figure 3: Hydraulic parameters and microseismic activity during the 2008 circulation tests. Figures on the left correspond to the July-August circulation test and figures on the right to the November-December circulation test. Top: injection and production flowrates; Middle: Wellhead pressure; Bottom: Microseismic activity. Red stars indicate the occurrence of the largest magnitude events.

2.2 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 11^{th} and 12^{th} of August (figure 3). It cannot be clearly linked with any significant hydraulic variations.

2.3 Location of Microseismic Events

Figure 4 (left: plane view; right: North-South vertical cross-section) summarizes the location of the microseismic activity induced during the first 2008 circulation test. Most of the seismicity is located in between GPK2 and GPK3 at a depth ranging between 4.7 and 5.4 km. 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. 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.

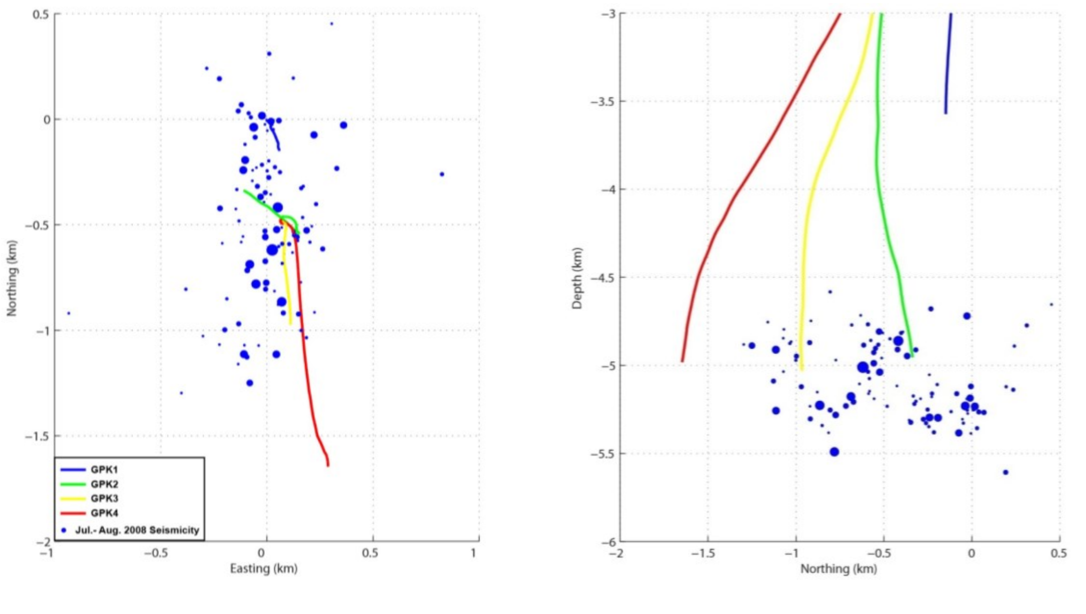

Figure 4 : Microseismic events recorded during the first 2008 circulation test. Left: Plane view; Right: North-South vertical cross-section. Geothermal boreholes are indicated with coloured lines. Diameter of the circles is proportional to the event magnitude.

3. 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.

3.1 Hydraulic Parameters

The hydraulic parameters of the November-December circulation test are presented on figure 3 (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 ~17$L.s^{-1}$, 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.

3.2 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 3, 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 during the 2005 circulation test: the sudden change of hydraulic parameters leads to an increase of the seismic activity (Cuenot et al., 2011).

3.3 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.

3.3 Location of Microseismic Events

The location of the microseismic activity induced during this test is shown on figure 5. 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 5, left). It extends between 5 and 5.5 km depth (figure 5, right). 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.

Although seismicity tends to occur within the same global areas, a closer look shows that the events take place where no previous seismicity was observed, and thus there is no strict overlap between the first and the second 2008 tests.

4. 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.

4.1 Hydraulic Parameters

Figure 6 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.

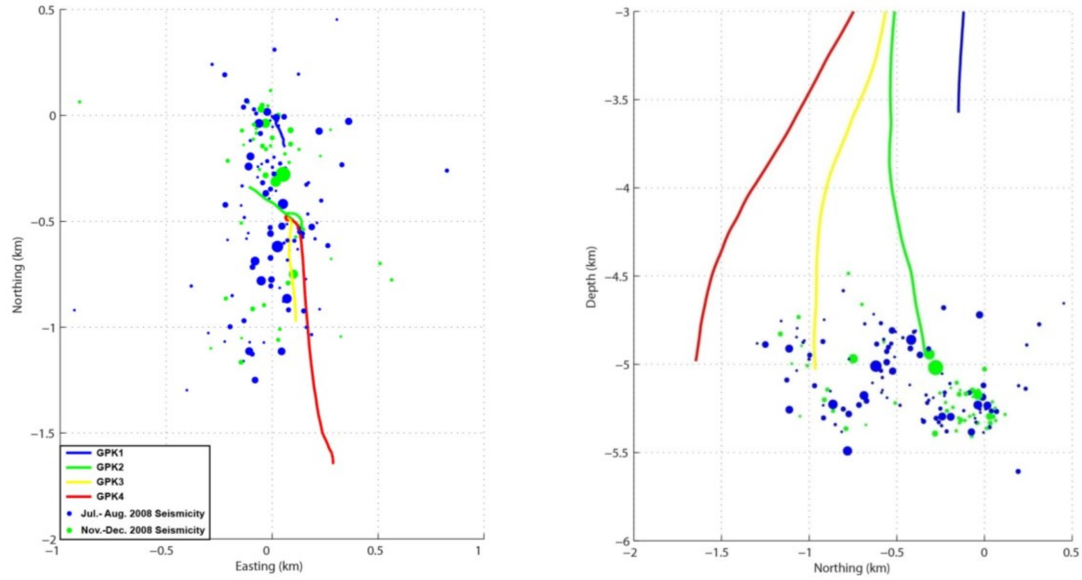

Figure 5: Microseismic events recorded during the second 2008 circulation test (green circles). Left: Plane view; Right: North-South vertical cross-section. Geothermal boreholes are indicated with coloured lines. Diameter of the circles is proportional to the event magnitude.

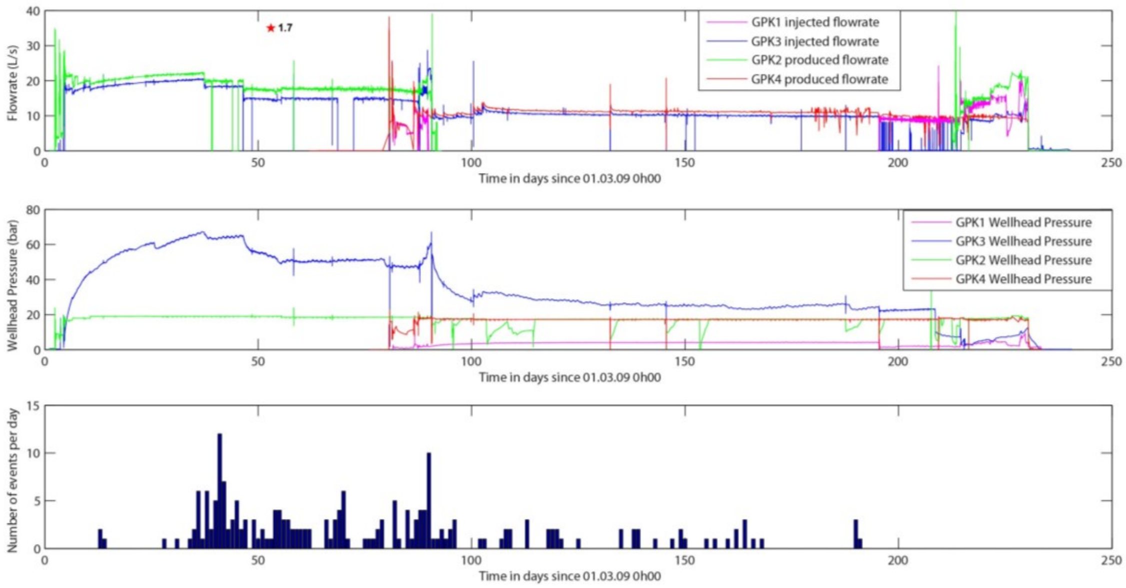

Figure 6: Hydraulic parameters and microseismic activity during the 2009 circulation test. Top: Injection and production flowrates; Middle: Wellhead pressure; Bottom: Microseismic activity. Red stars indicate the occurrence of the largest magnitude events.

4.2 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 6). 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.

4.3 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 6, 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 7, 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. Two other earthquakes of magnitude 1.5 and 1.6 were also detected, which took place under stable hydraulic conditions.

3.4 Location of Microseismic Events

On figure 7, 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. Once again the 2009 seismicity seems to propagate at the rims of the previous observed seismicity, and there is still no overlap with the previous active areas.

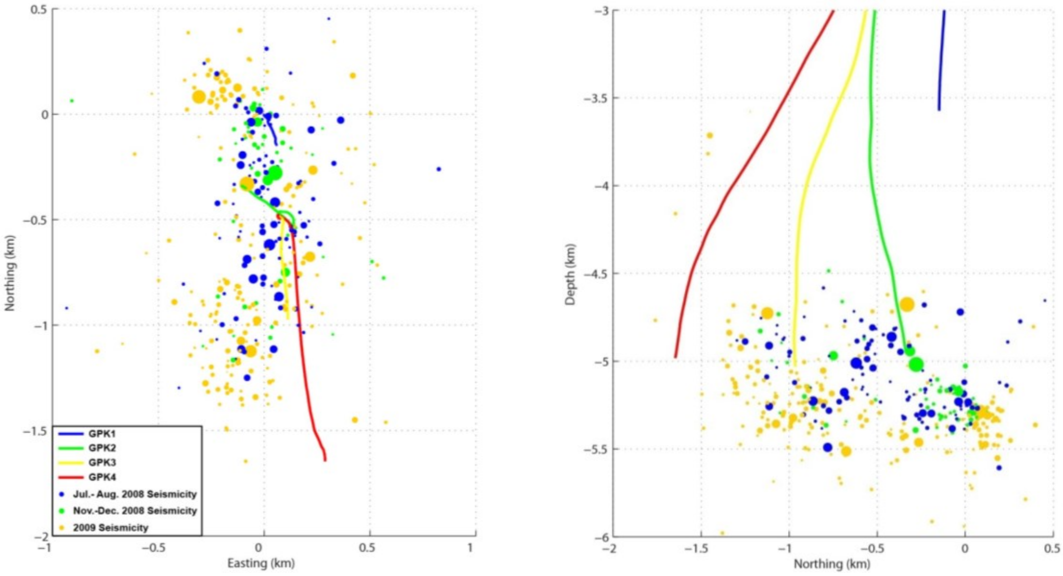

Figure 7: Microseismic events recorded during the 2009 circulation test (yellow circles). Left: Plane view; Right: North-South vertical cross-section. Geothermal boreholes are indicated with coloured lines. Diameter of the circles is proportional to the event magnitude.

5. 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.

5.1 Hydraulic Parameters

The hydraulic data are presented on Figure 8. 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 $L.s^{-1}$. 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 55 bar, then 40 bar when reinjection was performed into GPK1. GPK3 pressure kept slightly increasing until the end of the test.

5.2 Microseismic Activity

Observed microseismic activity is shown on figure 8. 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.

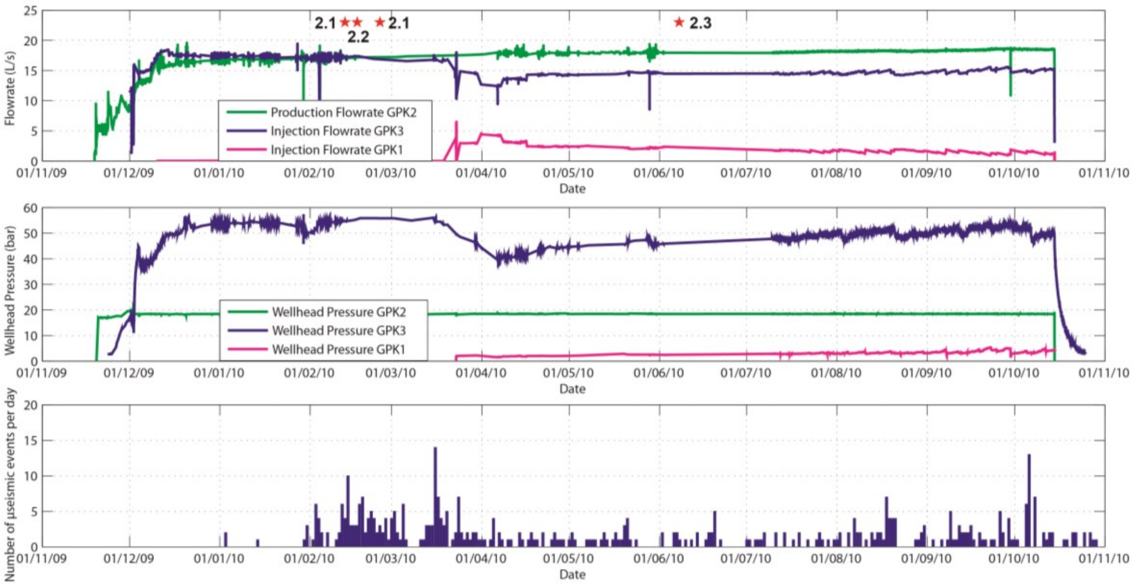

Figure 8: Hydraulic parameters and microseismic activity during the 2010 circulation test. Top: Injection and production flowrates; Middle: Wellhead pressure; Bottom: Microseismic activity. Red stars indicate the occurrence of the largest magnitude events.

5.3 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 8). 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. Only one earthquake of magnitude 1.1 happened a few hours after the end of the circulation.

5.4 Location of Microseismic Events

The location of 2010 microearthquakes is presented in figure 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.

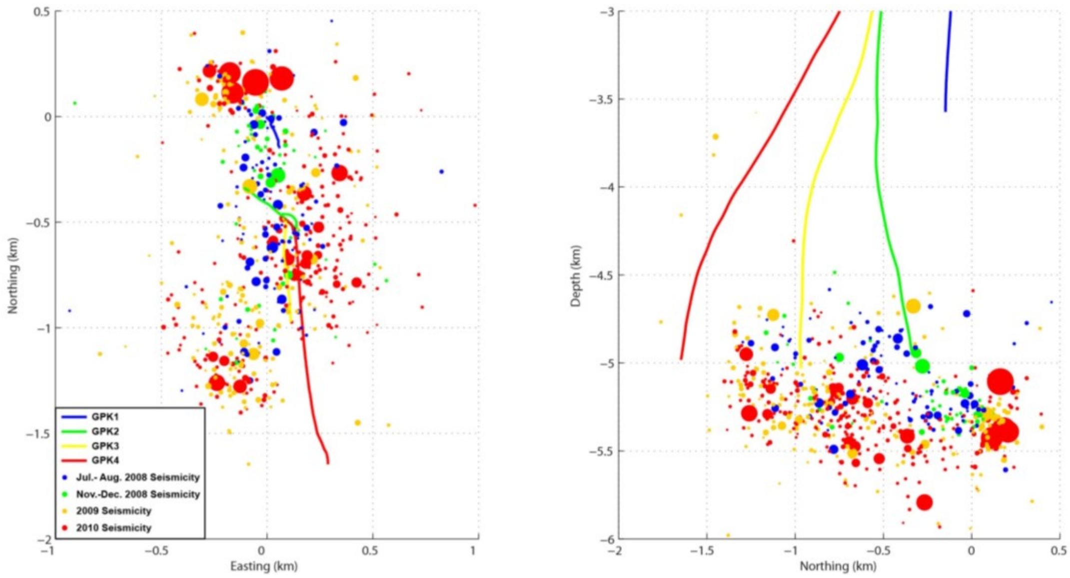

Figure 9: Microseismic events recorded during the 2010 circulation test (red circles). Left: Plane view; Right: North-South vertical cross-section. Geothermal boreholes are indicated with coloured lines. Diameter of the circles is proportional to the event magnitude.

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.

6. 2011 FIRST CIRCULATION TEST

In 2011, the objective of the project was to produce and sell electricity, as the selling contract had been signed in late 2010. Thus the aim of the circulation tests was to increase the production flowrate, in order to maximize the electricity production. Unfortunately app failure led to stop the test after only 3 months. A second circulation period was carried out a few months later, also stopped by technical problems on the pump.

6.1 Hydraulic Parameters

The circulation scheme was similar to the 2010 test, namely: production from GPK2 only and reinjection into both GPK1 and GPK3. The main difference was that a larger volume of fluid was reinjected into GPK1: the reinjection into GPK3 was regulated by the surface pressure (~20 bar). Thus no injection pump was used during this test. The circulation started in January and lasted until April (Figure 10). The production flowrate was initially set up at 19 $L.s^{-1}$ and increased to 22 $L.s^{-1}$. Then it was progressively increased to reach a maximum flowrate of about 26 $L.s^{-1}$. GPK3 reinjection flowrate remained rather stable throughout the test, around 9-10 $L.s^{-1}$, for a reinjection pressure varying between 17 and 19 bar. GPK1 reinjection flowrate increased during the test, following the increase of production. It varied between 7 $L.s^{-1}$ at the beginning to a maximum of 15 $L.s^{-1}$ at the end of the test. GPK1 pressure continuously rose from 1.5 bar to 5 bar.

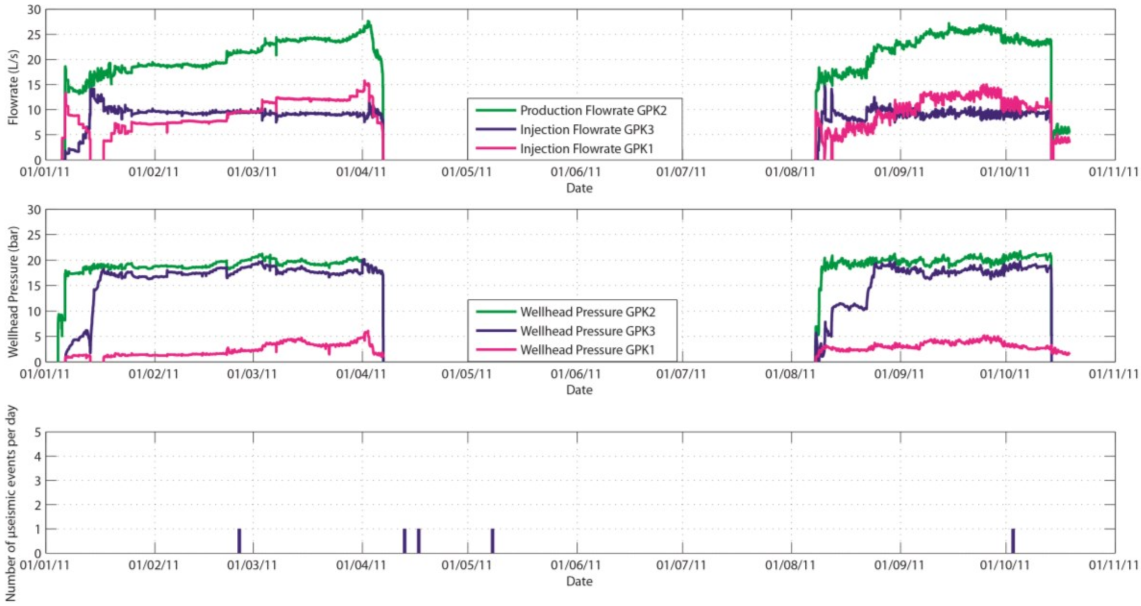

Figure 10: Hydraulic parameters and microseismic activity during the 2011 circulation tests. Top: Injection and production flowrates; Middle: Wellhead pressure; Bottom: Microseismic activity.

6.2 Microseismic Activity

The major result of the present circulation test is the very low induced microseismic activity: only one single event occurred during the test itself and 3 after its end. So it seems that the limitation of GPK3 reinjection pressure to less than 20 bar helped to greatly reduce the microseismic activity, as compared, for example, to the 2010 test, where more than 400 events were induced.

6.3 Magnitudes

Magnitudes varied between 0.1 and 1.7. The largest magnitude event occurred after the end of the test, as well as another event of magnitude 1.3, as already observed.

6.4 Location of Microseismic Events

Figure 11 presents the location of the 2011 microearthquakes (in pink). The 3 events, which occurred after the test are located in the area on the North of GPK2 bottom hole. It has to be noticed that the M=1.7 and M=1.3 events are located within this zone, where most of the largest magnitude events occur. Interestingly, the single event recorded during the circulation period shows a strange location: its depth (~3400 m) is rather shallow as compared to the main seismicity. At that depth we could think that this event may be related to the reinjection into GPK1, as GPK1 depth is around 3600 m. But as seen on the vertical cross-section on figure 11, the event is far from this borehole. Thus the location of this event remains unexplained.

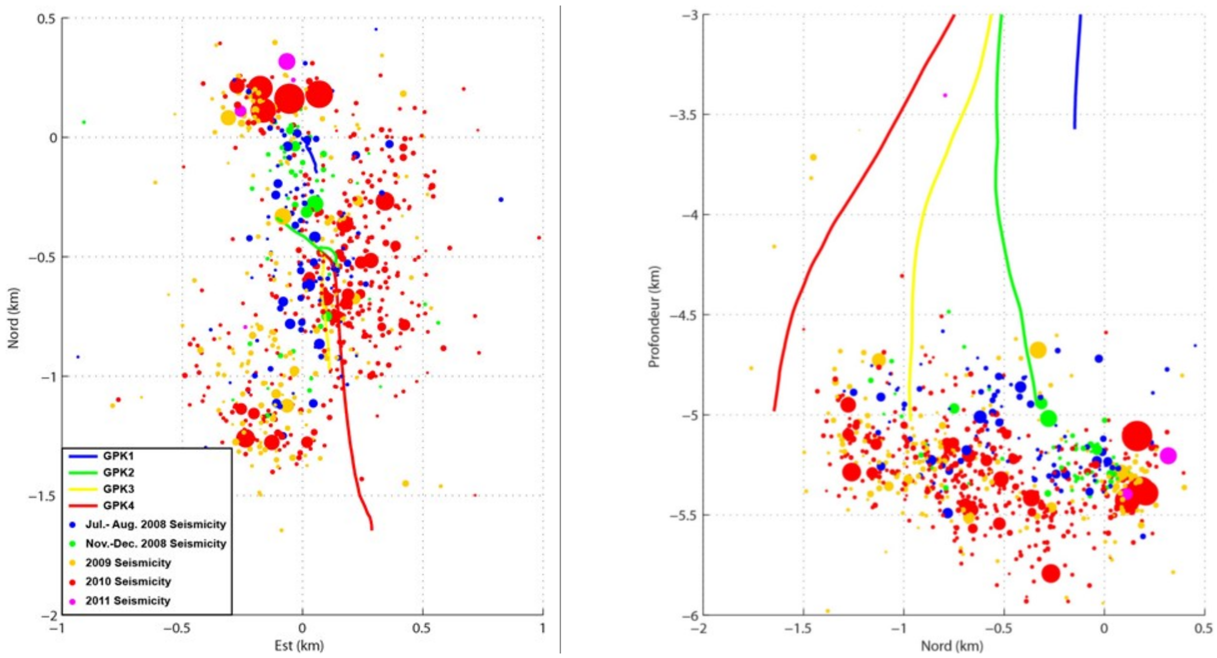

Figure 11: Microseismic events recorded during the 2011 circulation tests (pink circles). Left: Plane view; Right: North-South vertical cross-section. Geothermal boreholes are indicated with coloured lines. Diameter of the circles is proportional to the event magnitude.

7. 2011 SECOND CIRCULATION TEST

After repairing the production pump, a second circulation test was carried out in August 2011. It lasted around 3 months until October 2011 and ended again because of a pump failure (Figure 10). The circulation scheme was exactly the same as for the first 2011 test.

7.1 Hydraulic Parameters

Production started at a mean flowrate of 17 $L.s^{-1}$ and was progressively increased to a maximum flowrate of around 26 $L.s^{-1}$. At that point an increasing level on vibration observed on the pump led to reduce the flowrate at around 23 $L.s^{-1}$ for a few days before the end of the test, caused by the definitive failure of the pump. GPK3 reinjection flowrate varied between 7.5 $L.s^{-1}$ and 10 $L.s^{-1}$, for a maximum pressure of 19 bar. The reinjection was performed into GPK1 at flowrates between 5.5 $L.s^{-1}$ and 14 $L.s^{-1}$. The maximum observed pressure was around 5 bar.

7.2 Microseismic Activity

As for the first 2011 circulation test, the limitation of GPK3 reinjection pressure by avoiding the use of injection pumps was very effective for getting a very low induced microseismic activity, as only one single event was observed during this test (Figure 10). Contrary to the first 2011 circulation, no event occurred during the shut in period.

7.3 Magnitudes

The event was of very low magnitude (M = 0.1).

7.4 Location of Microseismic Events

The event is located on the East of the GPK2-GPK3 interwell zone. Unfortunately it does not appear on figure 11, as it is hidden by other earthquakes.

8. 2012 AND 2013 CIRCULATION TESTS

Both 2012 and 2013 circulation tests will not be too much detailed in this paper. The main reason is the absence of induced microseismic activity during the 2012 test and the single event observed during the 2013 test. Moreover no clear conclusion can be obtained about the microseismic activity, because the operating conditions of both tests were not significant.

8.1 2012 Circulation Test

This test only lasted one month between end of March and end of April 2012. The circulation scheme changed as compared as the previous tests, as GPK4 was, for the first time ever, used as reinjection well, together with GPK3 and GPK1. Most of the circulation was performed at artesian conditions: the production pump only operated for 4 days. Hence the production flowrate remained very low (<10 $L.s^{-1}$). The maximum flowrate reached with the pump was 21 $L.s^{-1}$. Reinjection was performed into GPK1 mainly, during artesian production with flowrates up to 12.5 $L.s^{-1}$. Then once the pump was started, the fluid was reinjected into GPK3 only, then into both GPK3 and GPK4. During the last 3 days, the circulation was again performed in artesian conditions, because of a pump failure. Here reinjection was performed at low flowrate in GPK1 only. As the hydraulic variations were numerous during this test, wellhead pressures were rarely stable and never reached their supposed nominal values: GPK3, GPK4 and GPK1 reinjection pressures reached 15 bar, 8 bar and 2 bar respectively. Figure 12 summarizes the hydraulic parameters of 2012 circulation test.

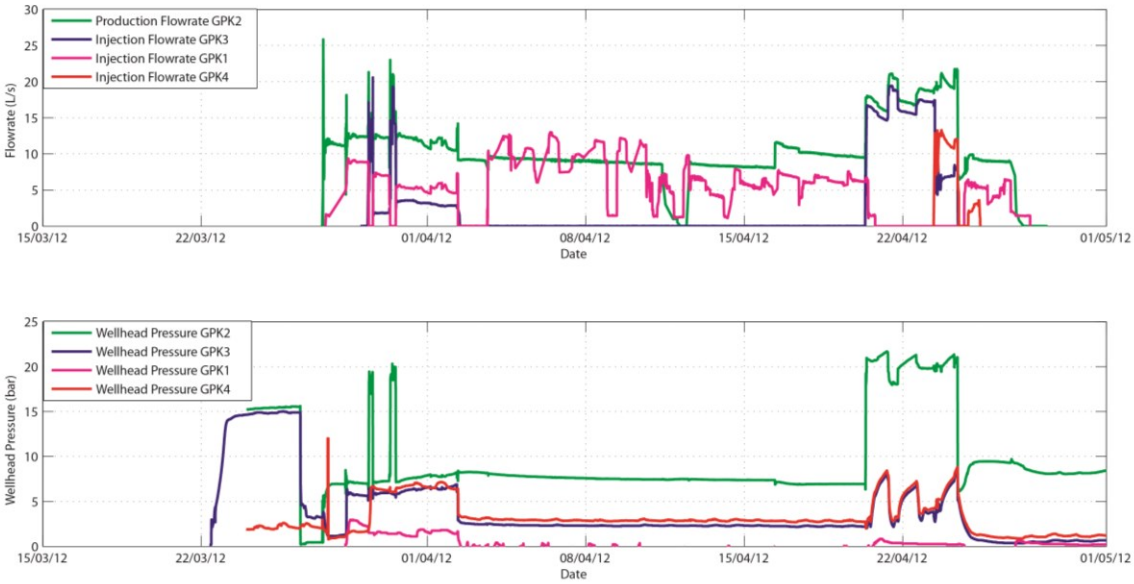

Figure 12: Hydraulic parameters and microseismic activity during the 2012 circulation test. Top: Injection and production flowrates; Bottom: Wellhead pressure.

The absence of microseismicity may be explained by the rather low injection pressures. But this conclusion may not be significant because of the very short duration of the test. Moreover, we cannot conclude about the first use of GPK4 as reinjection borehole and its implication in terms of induced microseismic activity.

8.2 2013 Circulation Test

The 2013 circulation test started in January and lasted 6 months until July. The objective of this circulation was to test a new, redesigned LSP pump. Again it was expected to reinject the geothermal fluid into both GPK3 and GPK4. Unfortunately many technical problems led to severely degrade the conditions of the test: in particular, because of serious problems with heat exchangers, it was impossible to operate the normal, closed geothermal loop. Indeed the cooling of geothermal fluid was done by passing it trough several outdoor pools. Once cooled, it was pumped and reinjected into GPK3 and GPK4 at very low flowrate (~5 $L.s^{-1}$). The normal conditions only lasted a few days (Figure 13), with reinjection into mainly GPK3 and GPK4. Then after heat exchangers failure, it was decided to continue the test in order to check the reliability of the new pump. For about 1 month and a half, reinjection was done into GPK1 only, because surface equipment needed to be adapted to allow reinjection into GPK3 and GPK4 in this new circulation scheme (*i.e.* with the pools). The test was performed in this way from April to July, and GPK3 and GPK4 reinjection pressure never went above 5 bar.

Once again, because of the degraded operating conditions, it is difficult to correlate any hydraulic parameter with the recorded event. The latter was of very low magnitude and occurred 2 days after the problems with the heat exchangers and the beginning of degraded circulation mode. It looks like a kind of shut in event. However the absence of microseismic activity until the end of the test is probably due to the very low injection pressure. Nervertheless, it was once again impossible to get reliable insights about the reservoir's behaviour with reinjection into GPK3 and GPK4.

9. 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 rather different: duration of the tests, artesian or pump-assisted circulation, 2, 3 or 4 boreholes involved, total volume of circulated fluid. Nevertheless some results obtained from these circulation tests can be relevant for estimating the seismic response of the reservoir under long-term exploitation conditions in terms of microseismic activity, occurrence of larger magnitude events and spatial distribution of seismicity.

9.1 Microseismic Activity

The first major result is that seismicity occurred for most of 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 may probably develop during the long-term exploitation of the power plant, implying a mandatory, continuous monitoring.

Nevertheless, the observed microseismic activity can be qualified as "moderate", as compared, for instance, to stimulation-induced seismicity (several tenths of events per hour). One of the major results is the high correlation between GPK3 injection pressure and level of microseismic activity. Firstly, for the 2008, 2009 and 2010 tests when injection pumps were used, the onset of seismicity happened for almost the same reinjection pressure, that is around 50 bars. It may be related with the well-known "Kaiser effect". Moreover, microseismic activity was the most intense when GPK3 injection pressure remained above 50 bars. This is striking from the 2010 test (figure 8): at the beginning of the test, when reinjection into GPK3 only, a higher level of activity can be observed; also, as much as GPK3 injection pressure re-increased throughout the second part of the test, as higher was the level of activity.

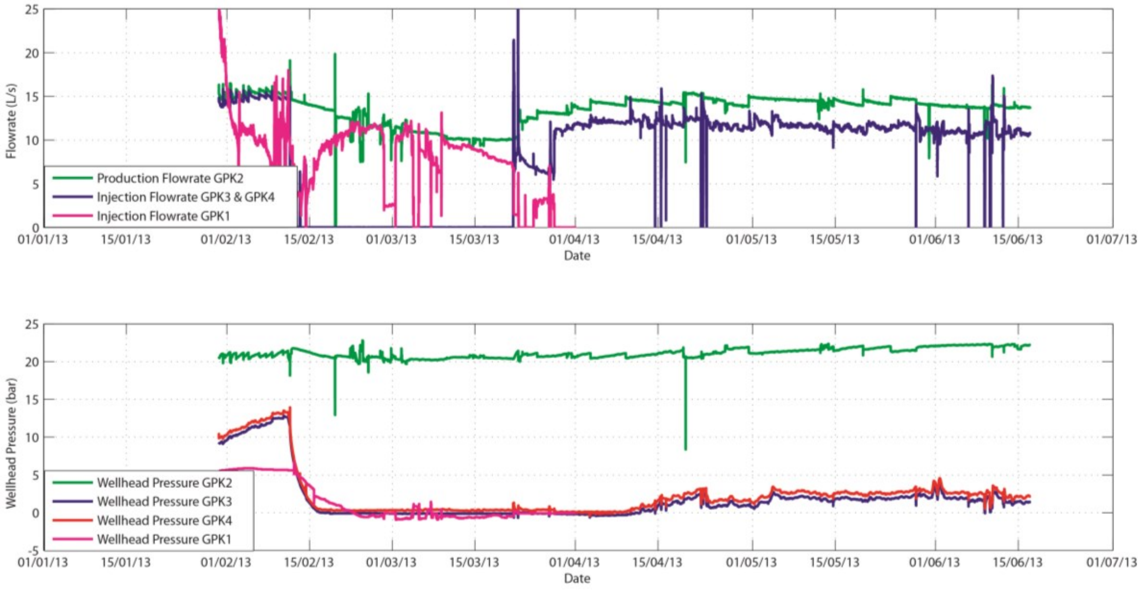

Figure 13: Hydraulic parameters and microseismic activity during the 2013 circulation test. Top: Injection and production flowrates; Bottom: Wellhead pressure.

However, from 2011, 2012 and 2013 tests, when GPK3 injection pressure was kept below 20 bars, the level of seismic activity spectacularly decreased to a few events per month, even no event. But all these tests may not be representative of long-term exploitation conditions, due to their rather short duration or their degraded circulation conditions. Nevertheless splitting the reinjection between several boreholes allowed us to find a way (at least, empirical) to decrease induced microseismic activity.

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. For instance, in December 2008 a sudden stop of pumping led to an increase of activity and the occurrence of a M=1.7 earthquake after the failure of the LSP and the stop of ESP (figure 3). On the contrary, the end of the circulation tests in 2009 and 2010 did not produce similar results.

9.2 Larger Magnitude Events

Larger magnitude events occurred mainly during the 2010 test, with the series of 4 $M \geq 2$ events. However, for the other tests, only a few events of M = 1.7 took place. For the latter, they were mainly associated with sudden variations of hydraulic parameters, as for the second 2008 test and the first 2011 test. In 2009, the M = 1.7 event occurred a few days after the decrease of flowrates, but the correlation is not certain.

For the 2010 events, the situation is rather different, as they occurred during stable hydraulic regime. The first 3 events took place when GPK3 injection pressure was larger than 50 bar, but the M = 2.3 earthquake occurred at lower injection pressure. 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.

9.3 Locations of Microseismicity

In all the tests, seismicity developed in the same areas. 3 main zones concentrated almost all hypocenters (figure 11):

- 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 injection pressures were rather low. However, we could have expected some seismicity around GPK4, in November-December 2008 and in 2009, when the well was producing , and maybe in 2012 and 2013 when it was used as injection well.

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 or not. This will greatly help to define the proper circulation parameters for the long-term exploitation of the power plant in order to minimize the occurrence of seismicity. However, additional data needs to be acquired in longer tests at higher flowrates to really be representative of exploitation conditions. This study also reveals the need to continuously monitor the microseismic activity, as larger magnitude events could occur, that could be felt by the population. Finally, interactions between the local stress field, the fracture network and the circulation of fluids needs to be better understood and modeled. The important conclusion here is that splitting injection between several boreholes, if possible, seems to be an efficient way to limit induced microseismic activity.

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