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The St. Gallen Project: Development of Fault Controlled Geothermal Systems in Urban Areas

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ABSTRACT

In areas of average geothermal gradients and conduction dominated heat transport, coupled heat-power generation is the most efficient way of geothermal energy utilization. Since heat for district heating cannot get efficiently transported over large distances, viable geothermal resources should be located close to the point of end-use as it is the case in urban areas. The city of St. Gallen in northeast Switzerland matches these requirements: St. Gallen is located in the Molasse Basin, i.e. the northern foreland basin of the Alps with viable deep geothermal resources, and has an installed and expandable district heating system.

The project in St. Gallen started in 2008 with a feasibility study considering different target horizons and different concepts of utilization including hydrothermal and petrothermal resources applying conventional and EGS technologies. An extensive 3D seismic survey in 2010 was followed by a public poll about the geothermal project in 2010. After overwhelming advocacy throughout the voting citizens of St. Gallen, planning of the first well started in 2011. In 2013, drilling operation started and the first target horizon in 4 km deep Upper Jurassic carbonate rocks was successfully achieved. After an injection test and well cleaning, a gas kick and subsequent work-over operation caused a seismic event of ML 3.5. Among other approaches, stress field analysis applying the concept of limiting stress ratios, the concept of effective stresses, and the slip tendency technique helped to decide further steps. After a short interruption, the project continued with a 4-weeks production test, which evidenced a gas reservoir of hitherto unknown extend. One of the main conclusions drawn from the project is the existence of dormant faults, which have to be considered in fault-controlled regions with historic seismicity. Dormant faults may have experienced fault healing and strain hardening evolving to a strong fault with high friction coefficient as indicated from geomechanical parameters gained from the St. Gallen well. A focus on dormant fault investigation and their geomechanical characterization might therefore play an important role on future geothermal research topics.

With this article we demonstrate best practices of geothermal project development in urban areas, and delineate concepts and critical data required to guide efficient decision making.

1. INTRODUCTION

More than 25 years ago, the city of St. Gallen (NE Switzerland) developed a district heating system fed by a municipal waste combustor plant. In 2007, the city decided for modernization of its energy provision leading to the new sustainable model referred to as the Energy Concept 2050. This concept aims to reduce the emission of greenhouse gases, the consumption of fossil fuels, and a growing use of renewable energies. One of the goals within this concept is to develop geothermal resources for district heating and possibly electricity production.

In 2009, a feasibility study delineated potential hydrothermal resources in predominantly carbonate rocks of Upper Jurassic (Malm) and Middle Triassic (Muschelkalk) formations in about 4 km depth beneath St. Gallen. NE Switzerland is located in the prominent North Alpine Molasse Basin where geothermal energy is already successfully produced from Malm formations in Bavaria and Austria. Temperatures of 130–150°C were expected in the Malm carbonates beneath St. Gallen. An extensive seismic campaign covering more 300 km^2 and including 37 municipalities in four cantons ended up in the largest 3D-seismic survey of Switzerland to date. A large fault zone dominated by graben tectonics was identified and selected as a target to achieve high flow rates through fractured rock in presumably tight carbonates. The project preparation incorporated the installation of a seismic monitoring network managed in cooperation with the Swiss Seismological Service (SED) within the research project GEOBEST. A contract conclusion for a risk insurance financed by the federal government of Switzerland should cover 50% of allowable drilling and testing expenditures.

In 2008, an extensive education campaign about geothermal energy utilization was initiated by the municipality of St. Gallen. An informative webpage was set up and continuously updated, the appearance on local exhibitions and events was intensified and a comprehensive stakeholder management was implemented. In a 2010 referendum, citizens voted for the start of a geothermal project consisting of a well doublet in the urban area of St. Gallen and a massive expansion of the district heating system. The poll included a framework credit of CHF 159 Mio with a maximum expenditure of about CHF 35 Mio (~ 29 Mio EURO or ~ 40 Mio $US) for preparation and realization of the first well including testing.

2. GEOLOGIC SETTING

The drill site of the geothermal project is located at the site of the river Sitter in the urban area of St. Gallen (Fig. 1). Geologically the drill site is positioned at the southern edge of the eastern Swiss Molasse Plateau where the Molasse is increasingly inclined, dipping NW towards the foreland basin due to backthrusting of the Aquitanian upper freshwater Molasse. The successions in the footwall of the backthrust are dipping in SE direction towards the orogenic belt. The frontal thrust fault of the Subalpine Molasse crops out about 6 km SE of the drill site. The backthrust and a décollement at the base of the anticlinal Molasse form the prominent Triangle Zone where compressional deformation accumulated at the front of the Alpine Orogeny (Fig. 1). The base of the clastic to shallow marine Molasse sediments is built up by gently SE dipping Mesozoic strata hosting potential geothermal aquifers in the carbonate formations of the Malm (Upper Jurassic) and the Muschelkalk (Middle Triassic).

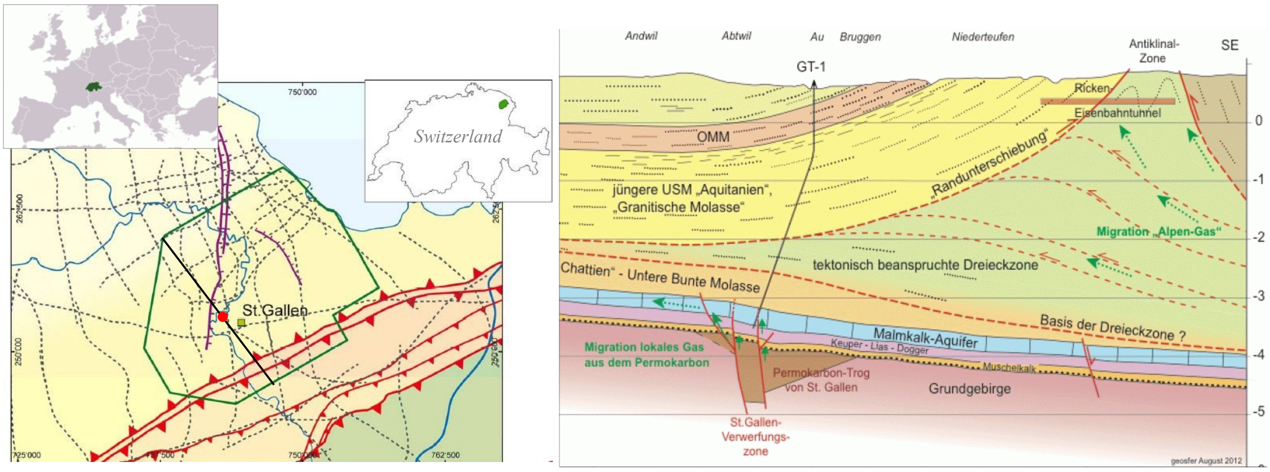

Figure 1: Left: Location of St. Gallen in NE Switzerland; the red dot is the drill site; the black line is the profile line of the cross section in the right image. The green line shows the area of the 3D seismic survey. Dashed grey lines are pre-existing 2D seismic lines. Purple is the normal fault zone identified in the 3D seismic survey. Right: Schematic geological cross section and well trajectory of the geothermal well GT-1 in St. Gallen (modified from Naef et al., 2014).

2.1 Structural geology

The dominating structure in the St. Gallen prospect is a NNE–SSW-oriented fault zone dipping steeply to the SE. To the north of the exploration area antithetic normal faults complete this fault zone to a graben structure. The normal faults of this NNE–SSW-trending graben structure are restricted to the Mesozoic and Paleozoic strata and die out in the lower Molasse Formations. The faults may root in a Permo-Carboniferous trough (Fig.1, right) indicating an initial Paleozoic formation of the St. Gallen fault zone. The main activity of these normal faults is probably related to Jurassic rifting in the Piemont-Liguria Tethys and presumably continued during the Cretaceous related to normal faulting in the Helvetian shelf (Weissert & Bernoulli, 1985; Stampfli, 1994). Jurassic and Cretaceous normal faulting related to rifting in the Piemont-Liguria Ocean and at the Helvetian shelf is evidenced by major ENE- to NE-striking normal faults in the western Bavarian Molasse Basin as well (Moeck et al., submitted). Likewise in the Bavarian Molasse Basin, the Mesozoic faults in the Swiss Molasse Basin have been reactivated by Cenozoic foreland basin formation (causing local extension) and during reverse faulting and folding in the Subalpine Molasse (caused by compression) (Moeck et al., submitted). The structural interpretation of the reflection seismic data focused on the Mesozoic strata where faults could be clearly identified. In contrast, the signature of faults in the partly highly deformed Cenozoic Molasse is weak and faults can hardly be traced. Some fault segments however truncate parts of or the entire Molasse indicating fault activity at least until the middle to late Miocene (approx. 12 Ma). The possible recent kinematic state of the St. Gallen fault zone can be delineated from its position related to the present-day stress field.

2.2 Stress field and slip tendency

The stress field of the St. Gallen area was determined after the project oriented approach for *stress model determination for deep reservoirs* (Moeck, 2012). The steps for stress field determination include regional, local, and estimated (later measured) in-situ data:

- Delineation of the direction of the maximum horizontal stress S_H from the World Stress Map and regional seismicity maps
- Estimation of the stress regime based on regional seismicity maps and local structural geology
- Estimation of the in-situ stress field applying the concept of limiting stress ratios (Jaeger, Cook & Zimmerman, 2007; Zoback, 2007; Moeck et al., 2009a)
- Calculation of the fault reactivation potential using the slip tendency technique (Morris et al., 1996; Moeck et al., 2009b)

In a step-by-step approach the stress field was continuously updated by new data obtained from well tests (e.g., formation integrity tests, fracture density index from image logs). The applied failure criterion is the Mohr-Coulomb failure criterion extended by the Hoek-Brown parameters to incorporate the integrity and strength of rock (Moeck et al., 2009b).

The stress regime is a strike-slip regime with a direction of the maximum horizontal stress S_H in NNW-SSE (160±12°). The well trajectory is placed into the damage zone of the St. Gallen fault zone which exhibits estimated present-day left-lateral strike-slip kinematics with respect to the current stress field. With the left-lateral strike-slip faulting regime, the St. Gallen fault is considered as fossil fault in a present-day stress regime that has changed since the formation of the fault. Fossil normal faults are also known from the western Bavarian Molasse Basin (Moeck et al., this volume).

The in-situ stress regime was estimated as pure strike-slip stress regime with a possible critical fault stress state under transtensional stress regime conditions. The possible critical fault stress state has been regarded in any drilling and testing operations. The in situ stress regime is calculated for two different lithologies and testing horizons in the Malm Fm. (Fig. 2). The transtensional stress state is confirmed with the seismic event. The friction coefficient and the cohesion were determined by tri-axial tests on drillcore plugs from the respective horizons. The lower Malm (Felsenkalk horizon) exhibits a high friction coefficient indicating strong rock that can accumulate high stresses. It should be noted that the test body size of 1 cm diameter and 2 cm length reflects the geotechnical standard ratio (diameter/length) of test body but does not correspond to the absolute standard size (after American Society for Testing Materials, ASTM).

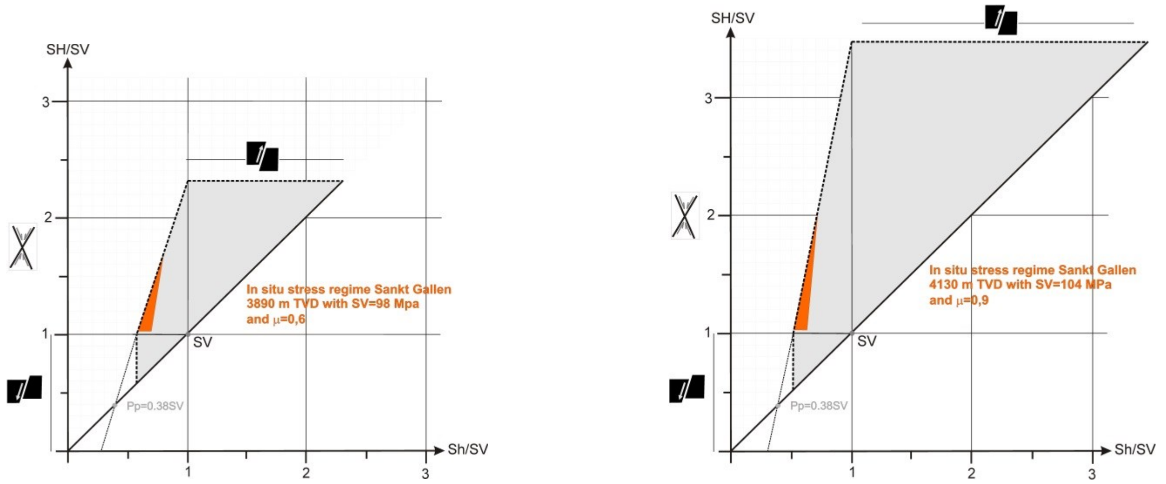

Figure 2: Left: In-situ stress ratios for 3890 m TVD. The orange field illustrates the in-situ stress regime of the St. Gallen Malm fm. Right: In-situ stress ratios for 4130 m TVD. The orange field illustrates the in-situ stress regime of the St. Gallen Malm fm. The friction coefficients for both horizons are measured by tri-axial tests on sidewall core plugs.

3. PROJECT DEVELOPMENT

The project development was initiated with the Energy Concept 2050 of the city of St. Gallen. The project plan focused on hydrothermal resources and was not planned as an ESG project as misleadingly stated (e.g., Breede et al., 2013). Petrothermal resources or EGS technology (i.e., hydraulic stimulation) were subordinately considered as an option for a later stage of the project in case of dry well in the hydrothermal formations. From 2007 onwards the project passed through the following phases:

- 2007 – Energy Concept 2050 of St. Gallen includes the geothermal project as one of its key components
- 2008/2009 – Feasibility study for deep geothermal utilization, focusing on hydrothermal resources
- 2009/2010 – 3D seismic survey
- 2010 – Popular vote with 53% voters participation and 82% advocacy for a CHF 159 Mio credit for a geothermal project
- 2011-2012 – Selection, preparation and construction of the drill site
- 2012 – Start of planning, design, and installation of local seismic monitoring of the St.Gallen region
- 03/2013 – Start of drilling with target horizon in the Malm Fm. in 3.8–4.2 km depth
- 07/2013 – Hitting the target horizon with end of well in 4253 m TVD (4450 m MD)
    - 06.07/2013 – Hitting the target horizon with in-situ temperature of 145°C
    - 8.-10.07/2013 – Logging of target horizon
    - 14.07/2013 – Careful step-rate injection test in 15 steps
    - 16.-19.07/2013 – Cleaning of well including acidizing
    - 19.07/2013 – Gas kick (95% CH_4), well control operation to overcome gas kick
    - 20.07/2013 – Seismic event of ML 3.5
    - 24.07/2013 – End of well control operation
- 08/2013 – Decision for project continuation with a high feeling of solidarity from the public
- 09/2013 – Fishing operation and cleaning the well
- 10/2013 – Well-Production test (drill stem test)

The region around St. Gallen experienced recent seismicity over the past 500 years, but not particularly along the fault in the target region. The most recent seismic event was an earthquake in 1987 with a magnitude of ML 3.2 located near Abtwil SG, WNW of St. Gallen (Kraft et al., 2013). The distance between the epicenter of the 1987 earthquake and the 2013 St. Gallen earthquake is about 2 km with a normal faulting regime at the 1987 earthquake. The focal mechanism of the St. Gallen event indicates a strike-slip faulting regime with S_1 (maximum principal stress) in NNW-SSE (Kraft et al., 2013). The seismic response was intense compared to the injected volume of ~700 m^3 during injection test and cleaning operation. The depth of the seismicity is still under debate, however, the stress and faulting regime is different between the 2013 St. Gallen event and the 1987 Abtwil SG event, indicating two different faults activated. Likewise, the origin of the gas is still under debate although an upward migration from the Permo-Carboniferous trough seems most reasonable.

4. DECISION MAKING PROCESS AFTER SEISMICITY

With the occurrence of the seismic event on July 20, 2013, the project team had to decide on further steps. At the time of the gas kick the gas pressure, volume (whether it is only a small occurrence or a larger commodity), and the ratio of brine to gas was unknown. For any safe future operation or conservation of the well, a production test was required to gain these critical reservoir data.

The concept of effective stresses predicts a stabilization of the fault zone with production because the ratio of normal to shear stress increases with the drop of fluid pressure through production. The critical fault stress state would be reduced by production and by the subsequent increase of normal stresses acting on any fault surfaces (Fig. 3, left). New seismicity is not expected during production. Following the concept of effective stresses, the project team decided for a production test. While seismicity occurred during work-over activities in the well before the production test indicating an instantaneous response of the reservoir to any hydraulic pressure changes in the well, the seismicity decayed with the production test (Fig. 3, right). The concept of effective stresses can be applied for fractured reservoirs at least on the short-term perspective because poro-elastic effects may play a subordinated role in extreme tight reservoirs. The permeability k of the Malm Fm. ranges between < 1e-17 to 5e-17 with a porosity of 2–6%.

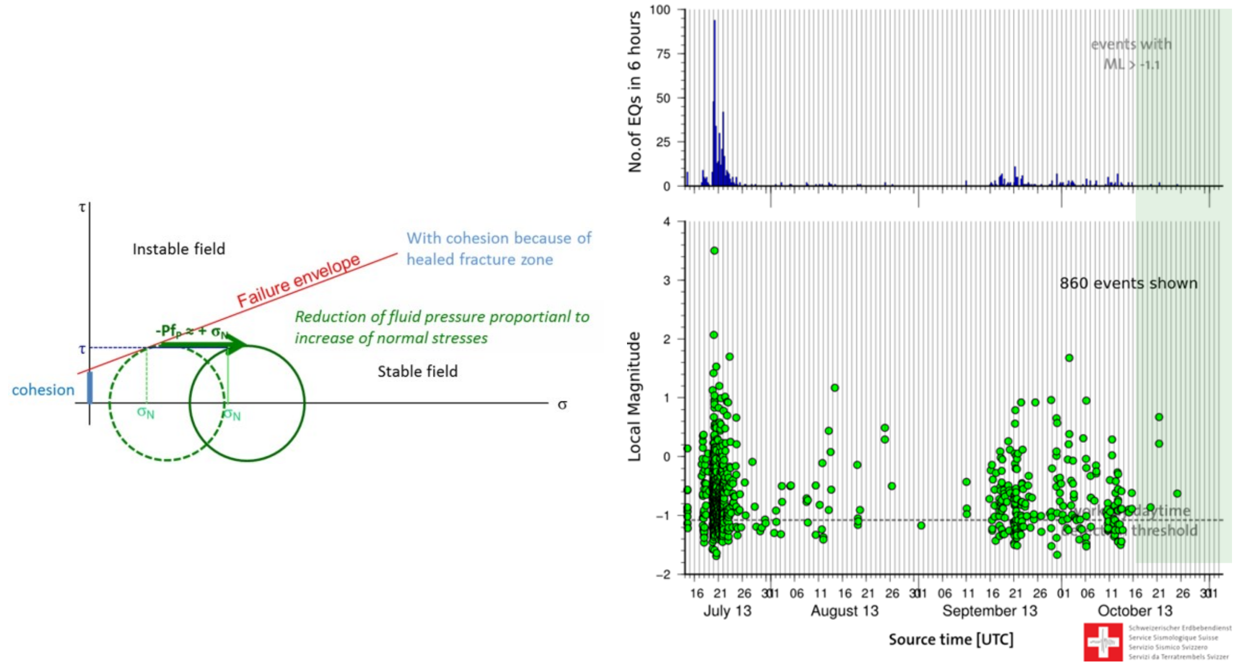

Figure 3: Left: Concept of effective stresses illustrating the decrease of the ratio shear stress/normal stress τ/σN. Right: Seismicity activity in the St Gallen area (from Swiss Seismic Survey, SED). The production test started on October 16, 2013 (green transparent bar).

The production test results in only 10% of the expected minimal flow rate of 50 l/s (brine) with a significant portion of natural gas. The size of the producible gas volume needs to be determined by a long term production test. Meanwhile, various scenarios for a possible future path of the project were analyzed under these new circumstances. The installation of a well doublet including an optional deepening the well would require repeated injection and the application of EGS technology (hydraulic stimulation) to increase the flow rate. The risk of new seismic events associated to large volume injection would be high, and this scenario is therefore not an option. The installation of a deep heat pump in the existing well connected to a heat exchanger is neither economic nor efficient under the present-day conditions. The use as gas production well implies the change of the project goal from geothermal to gas production. This third option seems the most reasonable option among the analyzed scenarios.

5. THE PROJECT AS A BENCHMARK

Although data interpretation is complex due to the presence of natural gas in a supposedly fractured hydrothermal reservoir, two key messages can be derived from the St. Gallen project: (I) A geothermal project in urban areas starts with work on public acceptance, and – if achieved – seismicity does not necessarily turn down the project; (II) Critically stressed dormant faults may be present in areas of low natural seismicity. Dormant faults may need to be considered in any geothermal projects encountering fractured reservoirs when historical seismicity is known from the vicinity of a prospect.

The St. Gallen project might change its destination now by switching from a geothermal to a natural gas production site. However, although not achieved the geothermal goals, the project can draw a number of positive results upon geothermal field development:

- The largest 3D seismic campaign of Switzerland covering 300 km^2 with partly challenging topography but excellent data quality.
- Successful application of different seismic processing methods to countervail the lack of a detailed velocity model for the St. Gallen area. Eventually, the prediction uncertainty for the depth of the top Malm could be reduced to about 50 m.
- A well-section of 1200 m drilled with one single bit.
- More than 37 sidewall core plugs (intact and broken) were drilled into the target zone.
- One of the most extensive wireline logging data sets of the reservoir section in a geothermal well in the Molasse basin.
- More than 80% of St. Gallen citizens voted for the geothermal project, the largest measured public advocacy for a geothermal project worldwide.

The project has demonstrated how public acceptance can be achieved through transparency and continual public communication. The time and budget plan of the project until the gas kick could be attained through extensive exploration incorporating detailed geological expertise. The geological prognosis was correct including the occurrence of natural gas. The extreme short time and scale of events described with the gas kick, however, was un-predictable. With the decision for a production test after the seismic event, a critical data and knowledge base could be achieved in addition to logging and core data. Only this data base enabled the project team to decide for the best-case future scenario of the project. St. Gallen is located at a critically stressed but strong dormant fault zone where – at the current state of knowledge - geothermal production and injection might not be the best solution for energy production.

Ultimately the St. Gallen project has not been stopped because of the seismic event only – even after the seismic event public claimed for a continuation of the geothermal project. The reasons for stopping the geothermal project are affected by the low flow rate of brine, by the occurrence of high volumes of natural gas, the low produced temperature caused by the expansion cooling of the natural gas, and the project's financial framework combined with a future risk of triggered seismicity during injection. Possibly natural gas can be produced. Technology, however, can and will evolve, and it might be a feasible vision that with new technologies or concepts the St. Gallen project might switch back to a geothermal production site: The well – in case of lacking gas productivity - will be conserved and not completely plugged. Potentially it could be re-opened, newly tested or deepened.

Summarizing the lessons learned, the expertise gained, and decision making process demonstrated before and after a seismic event, the St. Gallen project is and will be a benchmark project for geothermal development worldwide.

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