Induced Seismicity at the Geothermal Project Schlattingen, CH

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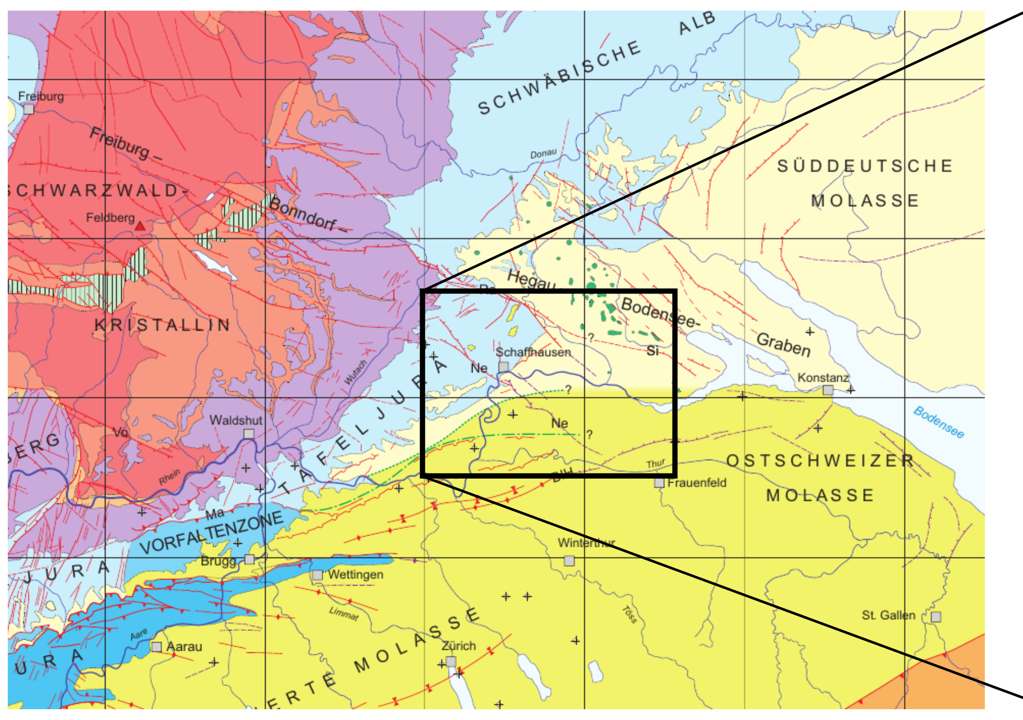
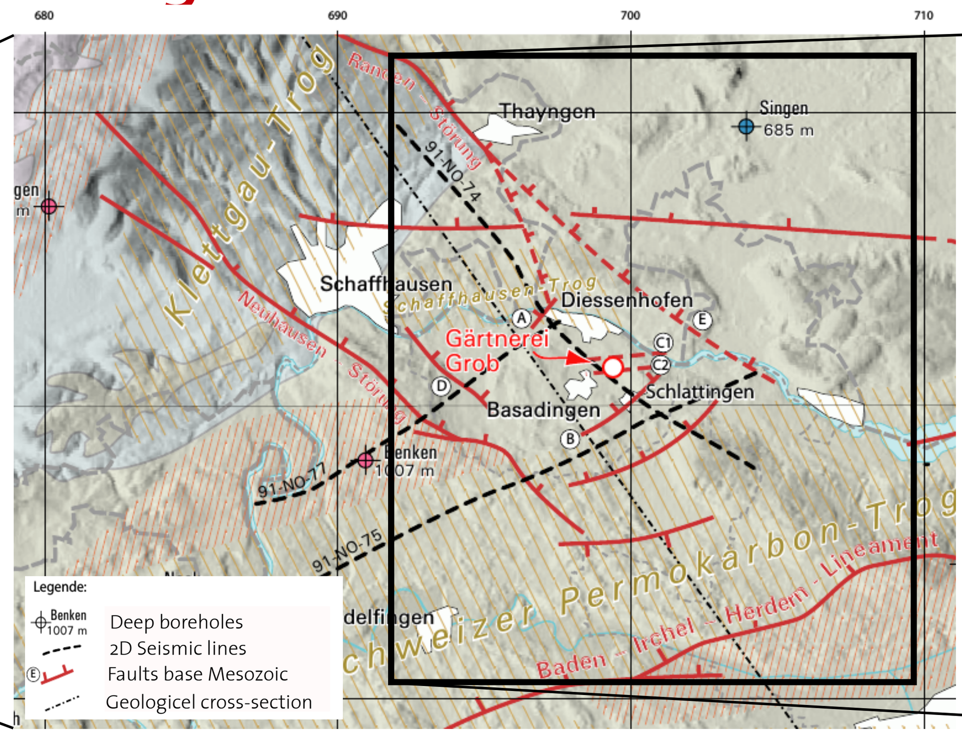
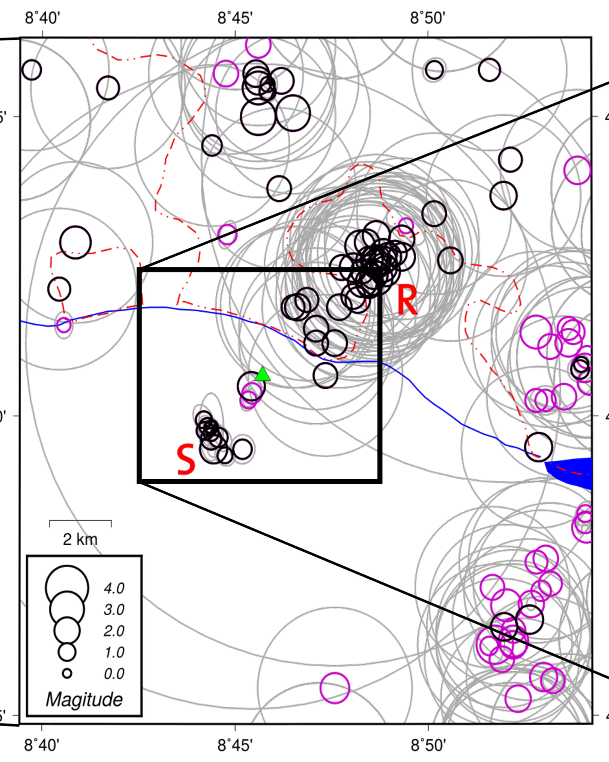
Seismotectonic Background / Monitoring network

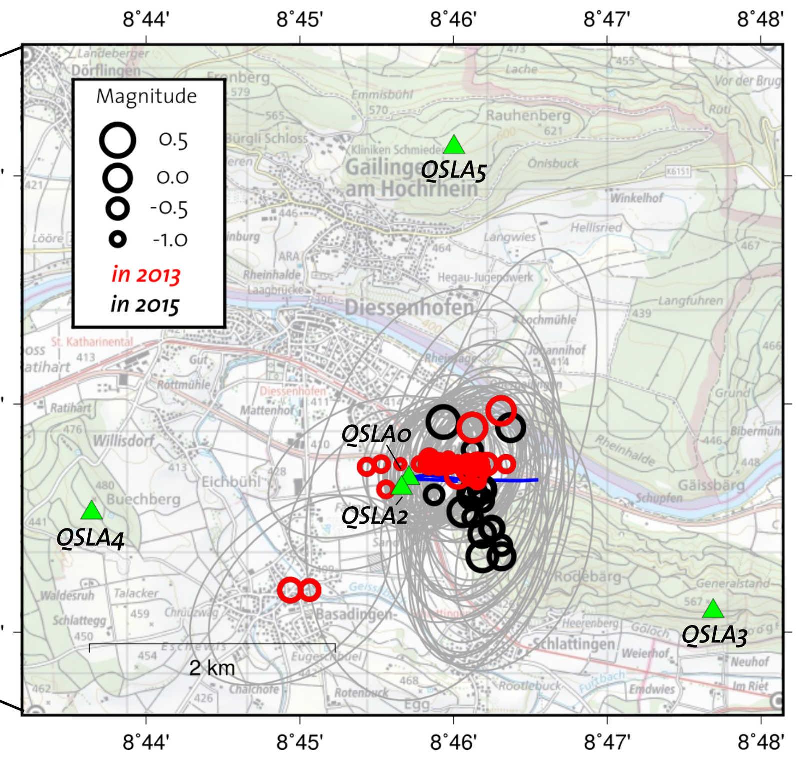




Geological map of the wider surrounding of the study area. The Schlattingen site is located at the northern rim of the Swiss Molasse Basin and at the SW corner of the Freiburg-Bonndorf-Hegau-Bodensee Graben between the well-documented Randen and Neuhausen Fault Zones. The NS-striking Albstadt Shear Zone is postulated to extend into the study area. The Hegau Volcanic Field marks the postulated intersection of these two crustal-scale fracture zones. Dominant basement structure is the Swiss Permo-Carboniferous Trough striking EW.



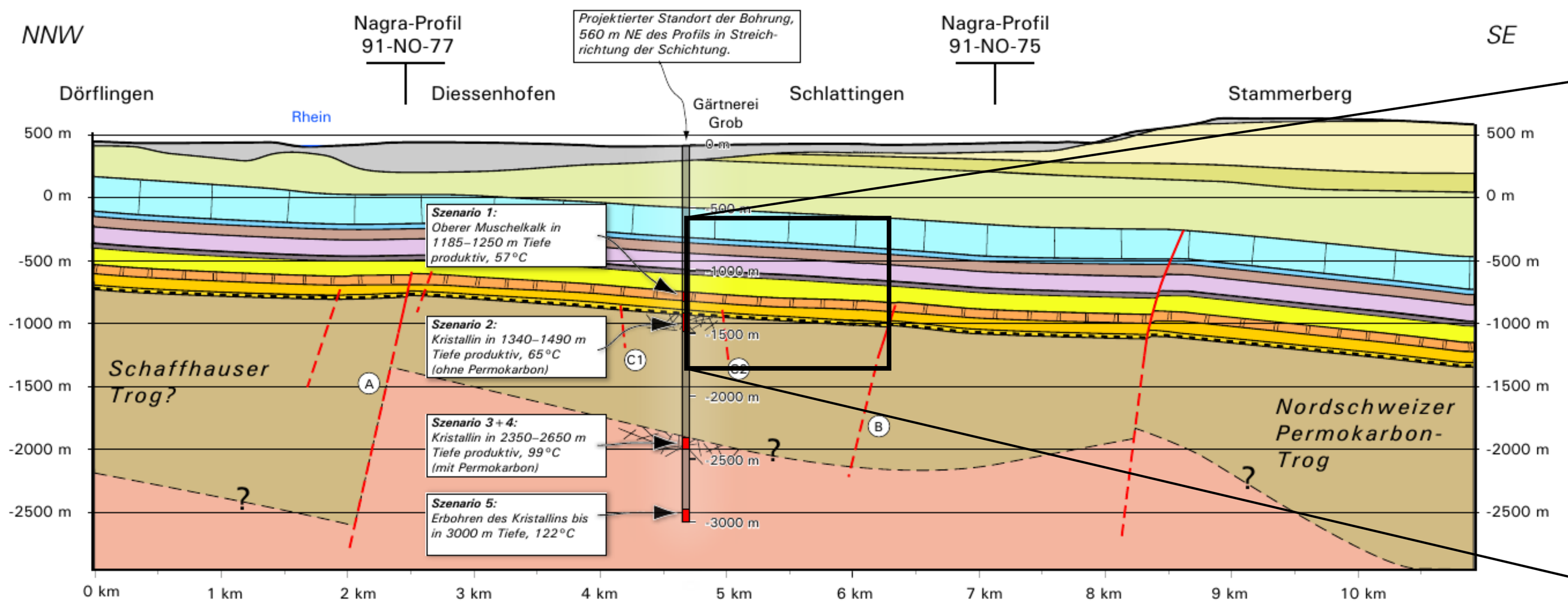
Natural seismicity in the vicinity of the study area. Black: >1983; magenta: <1983; (Uncertainties in gray). Swarms at **S**chlattingen (2015) and **R**amsen (1983).

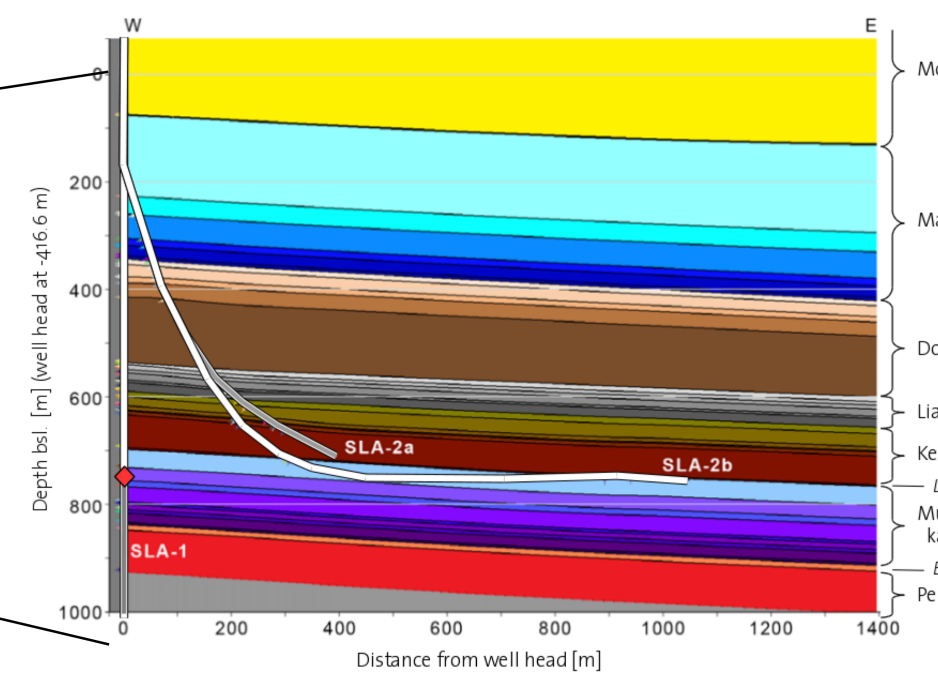


Monitoring & induced seismicity. 4 surface and 1 deep borehole stations (QSLA0) installed between Apr 2013 and July 2015. Borehole sensor at 1185m_{MD} in the first vertical well SLA1 drilled in 2011. Trajectory of SLA2 in blue.

The Schlattingen geothermal project

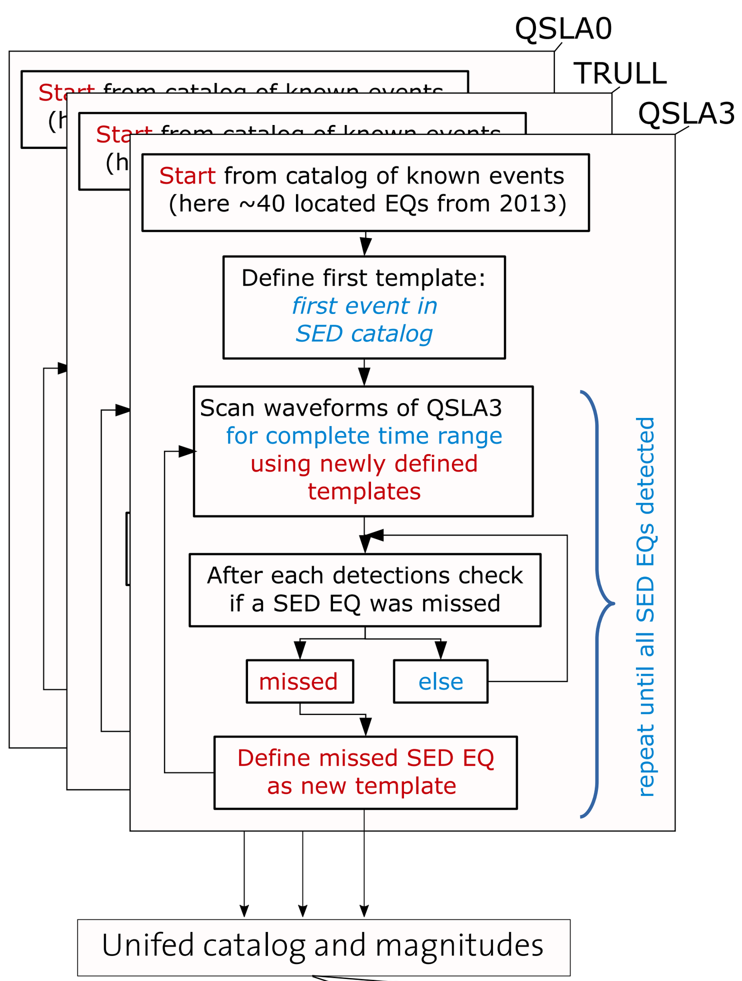
The geothermal project in Schlattingen was privately initiated by a vegetable farmer in 2007 aiming to reduce the heating costs for his greenhouses. A first vertical borehole (SLA-1) was drilled to a depth of 1508 m (TVD) into the crystalline basement by Jan. 2012. After an extensive testing and well-logging campaign, the well was back-cemented to a level of 1185 m (TVD) and the selected target aquifer in the Upper Muschelkalk chemically stimulated in Oct. 2012. A long-term pumping test confirmed a successful increase of the transmissivity in the aquifer by one order of magnitude and yielded flow rates of about 6 l/s and water temperatures around 62 °C. After an evaluation and planning period, a second deviated well (SLA-2b) with a 735 m long sub-vertical section was drilled into the Muschelkalk aquifer. Massive mud losses which occurred when the deepest part of the well was drilled between 19-24. Apr., 2013, were confirmed to be related to a high-permeable fault zone with fracture apertures of up to 1 cm in the subsequent welllogging program. Acid stimulations of the open-hole section in May 2013 and February 2015 only slightly increased the pre-stimulation flowrates to 8 l/s, since most of the injected fluids(deluded dichloridic acid) may have gone into the high-permeable fracture zone in the deepest wellbore section. Geothermal greenhouse heating started in test operation in December 2016.

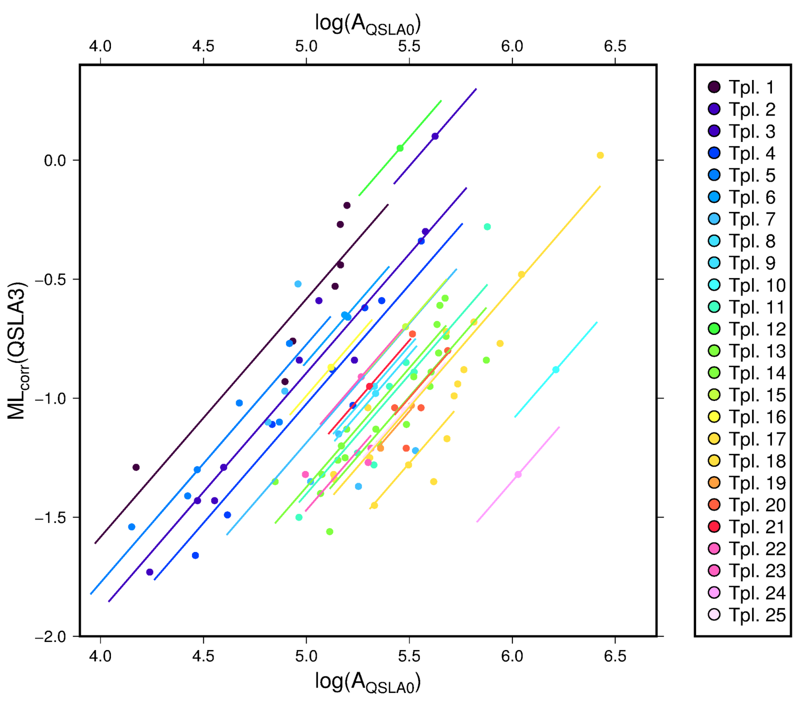




Geological cross-section & well layout of Schlattingen geothermal project. The Schlattingen borehole SLA1 penetrates the typical stratigraphy of the Swiss Molasse Basin (Molasse, Mesozoic Sediments, Permo-Carboniferous sediments (less thick (right) than predicted (left)), and crystalline basement. The left profile indicates typical scenarios for deep geothermal projects at the Schlattingen example (from Wyss, 2010). Right cross-section shows the geology reached by drilling. Vertical (SLA1) and deviated wells (SLA2a/b) are indicated (SLA2a back-cemented). The borehole sensor (QSLA0) is indicated as red diamond in well SLA1.

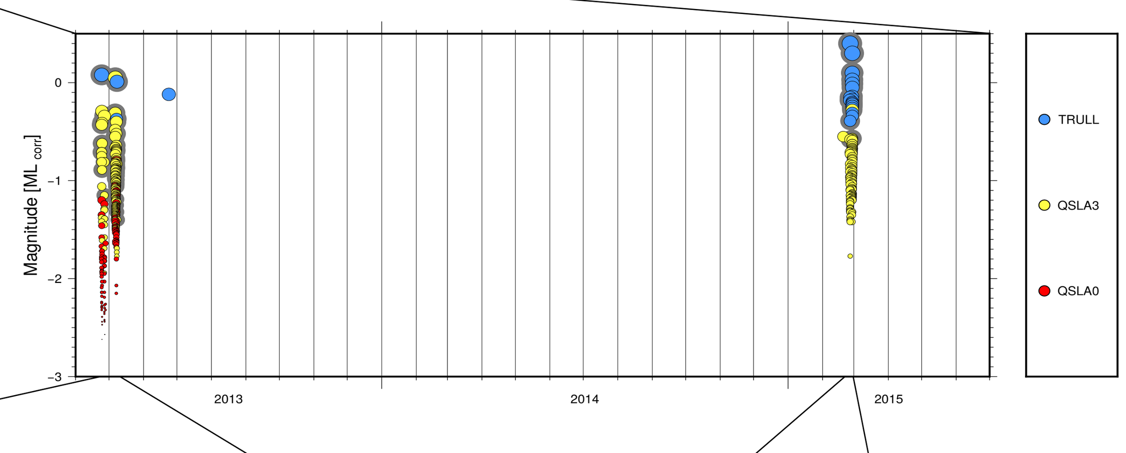
Analysis of induced seismicity

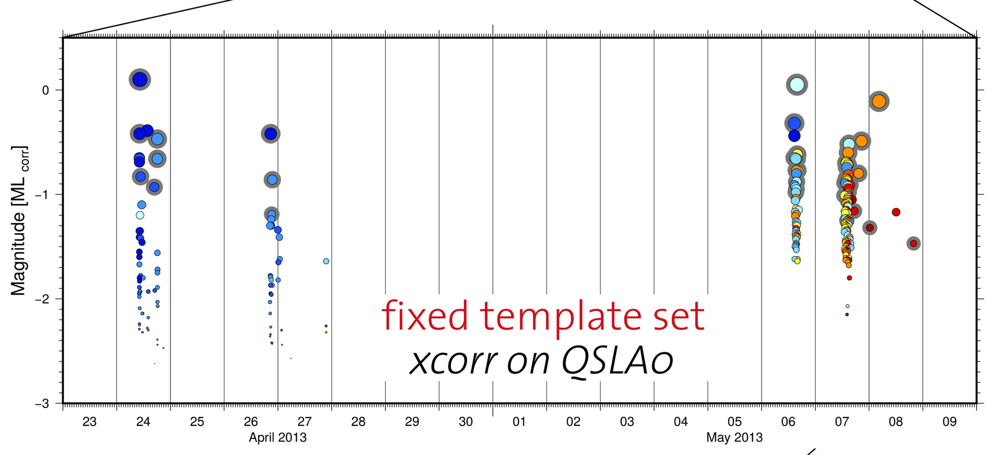




Magnitudes ML_{corr} were estimated following Edwards et al. (2015) We use ML_{SED} of the strongest event (ML0.4) as reference to calibrate ML_{corr}(QSLA3). The latter magnitude is used to find ML_{corr}-relations for each of the 25 template families of QSLA0 (see above; slope for fit fixed to 1). Offsets of the 25 relations may be explained by differences in radiation patterns and hypocentral distance .

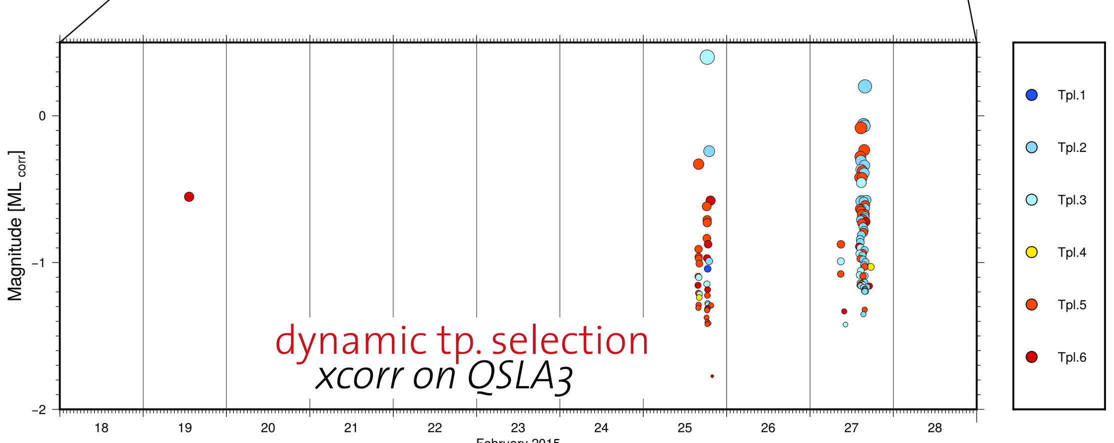
The **combined detection** list contains 399 induced microearthquakes. Even though we scanned TRULL between 2010 and 2016, activity is only detected in Apr/May 2013 and Feb 2015. This indicates no induced earthquake larger then ML0.0 was induced in stimulation of SLA1, between May 2013 and Feb 2015 and after Jul 2015.





In **Apr and May 2013** highest sensitivity due to borehole station QSLA0. Events down to ML_{corr}-2.5 detected, and down to ML_{corr}-1.5 located.
Seismicity in Apr due to **heavy mud losses** when drilling into **fracture zone at end of sub-horizontal well branch**.
Seismicity in May due to two **acid jobs** in "open-hole" section of well (horizontal branch in Muschelkalk). **Probably mainly fracture zone at end of well stimulated.**

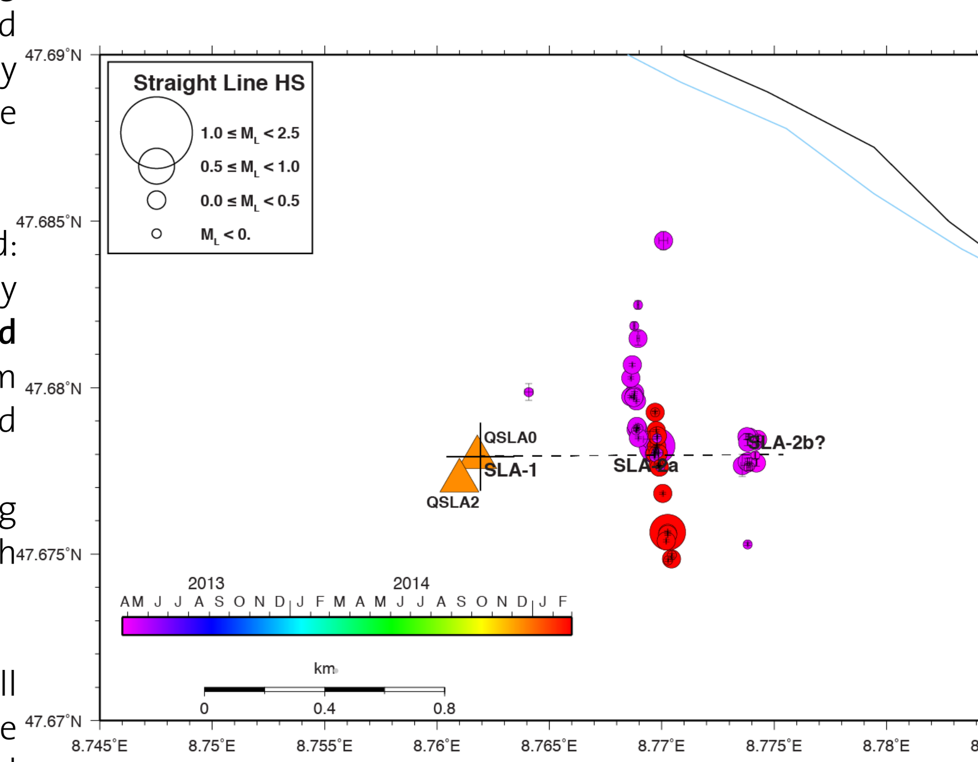
In **Feb 2015** lower sensitivity as only surface network. Events down to ML_{corr}-1.5 detected, and down to ML_{corr}-0.6 located. **Seismicity** mainly due to **two acid jobs**. The **two stages can be clearly separated in both cases.**
The **largest event** (ML_{corr}0.4) occurred in the second stage of the first acid job.
An **early event** was detected when the well was **shot-perforated** between 17-19 Feb.

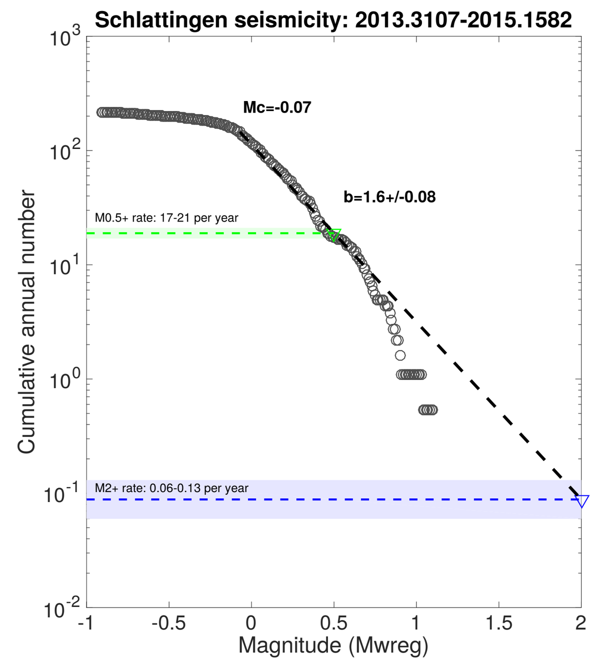


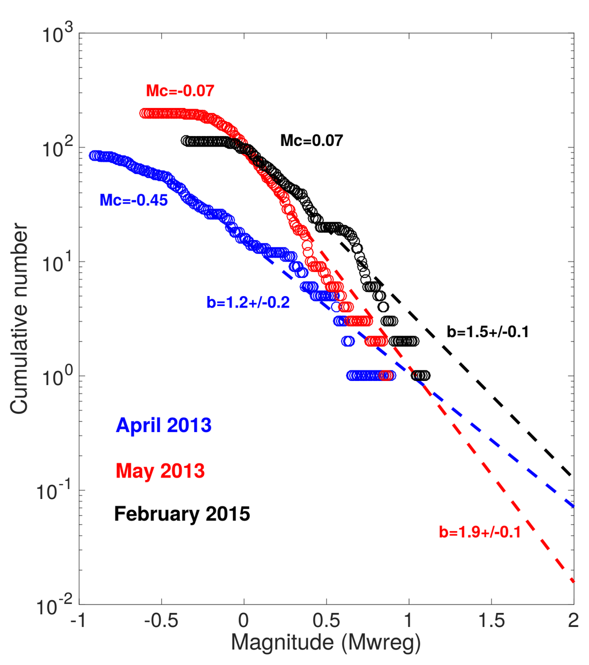
High-precision relative locations were obtained using the double difference technique and X-correlated differential arrival times and a half-space velocity model. Uncertainties estimated by SVD are in the order of 10s of meters.

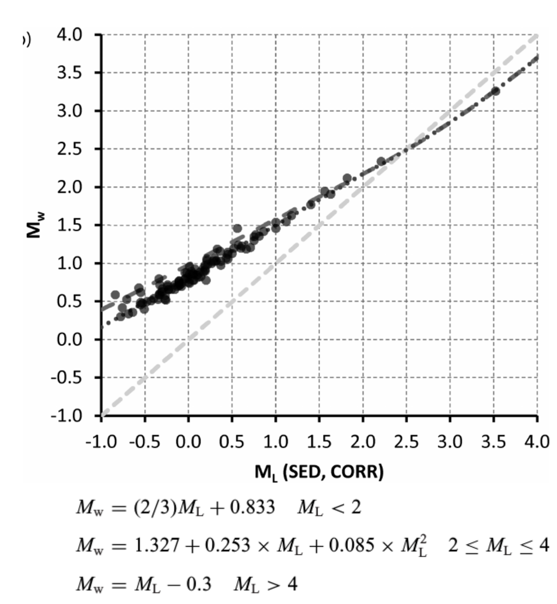
Two distinct clusters of seismicity can be observed: (Magenta) Seismicity starts in a cluster of tightly spaced events in the east at the time of the **mud losses**. During the **2013 acid jobs** a cluster some 200m further west is active, illuminating a NS oriented lineament. Seismicity propagates to the north.
(Red) During the **2015 acid jobs** the same NS striking lineament is active, yet events migrate to the south this time.

The absolute location of the seismicity is not well constrained yet. Well operations suggest that the eastern cluster locates at the end of the horizontal well section.









Scaling ML - Mw after Edwards et al. (2015)

For the **statistical analysis of the sequence** we converted ML_{corr} to Mw using the relationship of Edwards et al. (2015).

The **sequence as a whole** has a completeness of **Mc(Mw)-0.07** and follows the GR-law in good approximation with a high **b-value of 1.**. The probability of a Mw2.0 (~felt) earthquake was very small (1.6 - 3.6) 10^{-4} per day.

Looking at the **mud losses**, the **2013 acid jobs** and the **2015 acid jobs** separately reveals significant differences in b-values. Lower **b=1.2** and **b=1.5** were observed for the **mud losses**, the **2015 acid jobs**, respectively. A very high **b=1.9** was observed for the **2013 acid jobs**.

The **lower b-values** during mud losses and the 2015 acid jobs could indicate that seismicity reactivated **preexisting structures** (*fracture zone and previously acid simulated lineament*). Whereas the **higher b-value** during the 2013 acid stimulation could indicate that a **new fracture** was propagated into the medium. Similar differences have been observed in hydraulic fracturing (Davies et al., 2013).

Davis et al. (2013) Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. Marine and Petroleum Geology, 45, pp. 171-185.

Edwards et al. (2015). Seismic monitoring and analysis of deep geothermal projects in St Gallen and Basel, Switzerland. Geophysical Journal International, 201(2), 1020–1037. http://doi.org/10.1093/gji/ggv059.

References

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Our commitment: our future.

Acknowledgement