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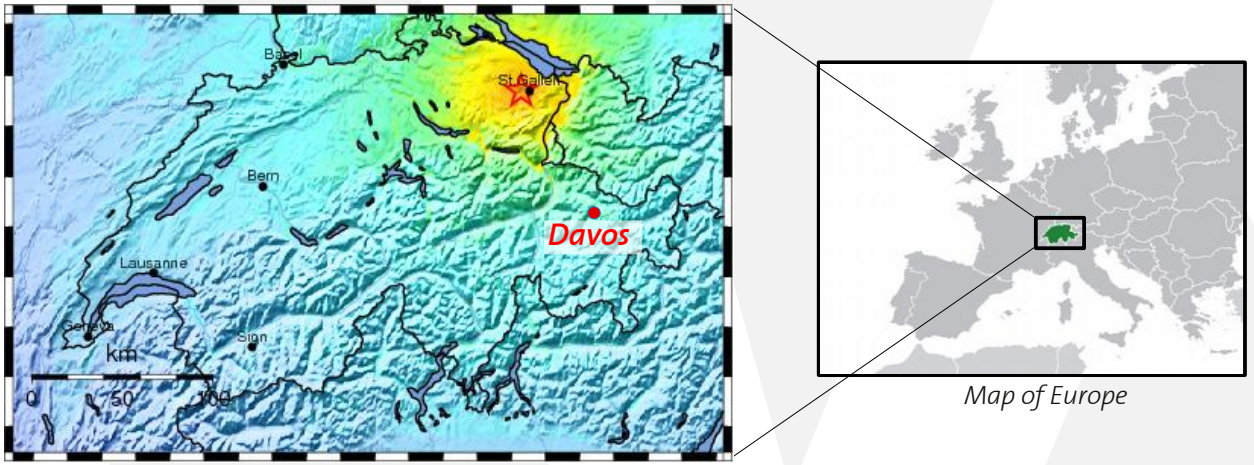
Lessons learned from the 2013 ML3.5 induced earthquake sequence at the St. Gallen geothermal site

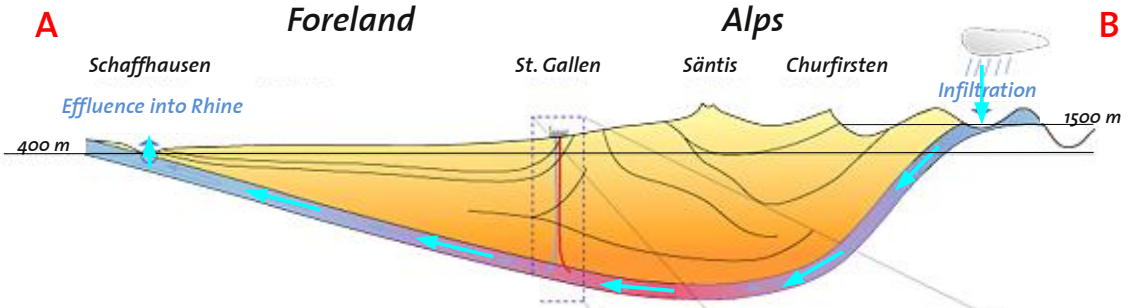
Toni Kraft, Stefan Wiemer, Tobias Diehl, Benjamin Edwards, Anne Obermann, Eszter Kiraly, Thessa Torman, Eduard Kissling, Nicholas Deichmann

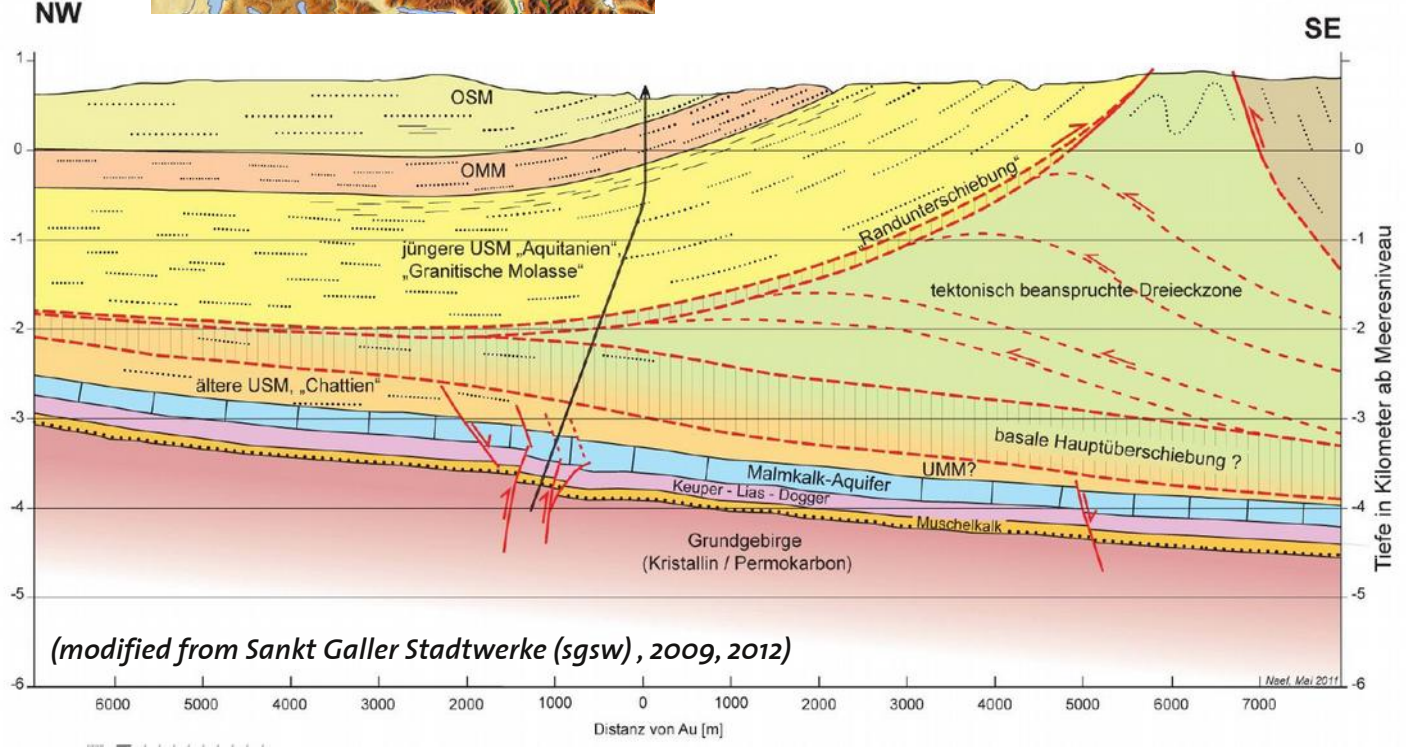


Shakemap: ML5.5 Scenario EQ in St. Gallen, CH

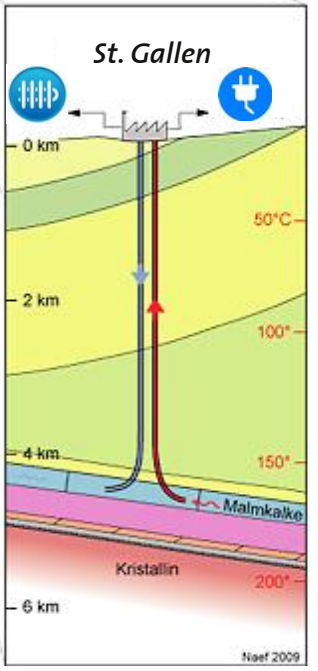
Map of Europe

St. Gallen geothermal project – background





(modified from Sankt Galler Stadtwerke (sgsw) , 2009, 2012)



St. Gallen geothermal project – timeline

2007 – *City of St. Gallen proclaims Energy Strategy 2020*

2009 – *Feasibility study for geothermal project*

2010 – *3D Seismic Campaign (270 km²)*

– *Citizens of St. Gallen vote on 150 M$ credit*

→ accepted with 82% yes

2012 – *SED starts seismic monitoring (GeoBest Project)*

2013 – Mar.: *Start of drilling operation*

– Jul.: *Stimulation of Malm aquifer (4.1 kmTVD)*

→ ML3.5 earthquake

– Aug.: *City parliament decides to go on.*

Population generally supportive.

– Oct.: *Production test*

→ seismicity turned off (SG = Rangely II)

– Nov.: *Well conservation and rig release*

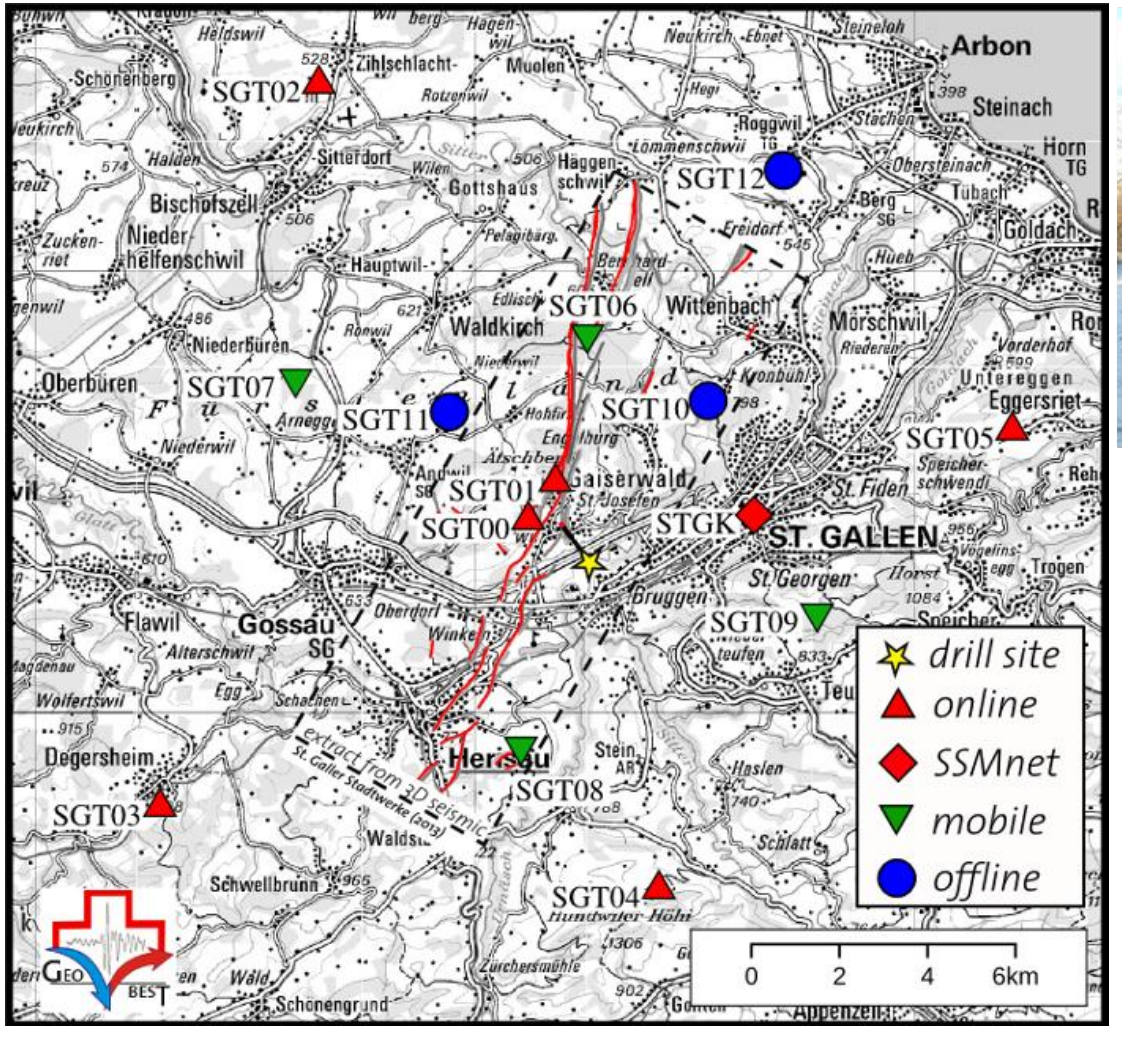
2014 – May.: geothermal project terminated (5 l/s)

2015/16 – *LT-production test (gas) &decision on project future*

(Sankt Galler Stadtwerke (sgsw) , 2009)


(Sankt Galler Stadtwerke (sgsw) , 2013)

The seismic network



[Feb. 2012](#)

- 1 Borehole (205m, 4.5Hz)
- 5 BB (Trillium compact)
- 2 SM (Episensor)

[July 1, 2013](#)

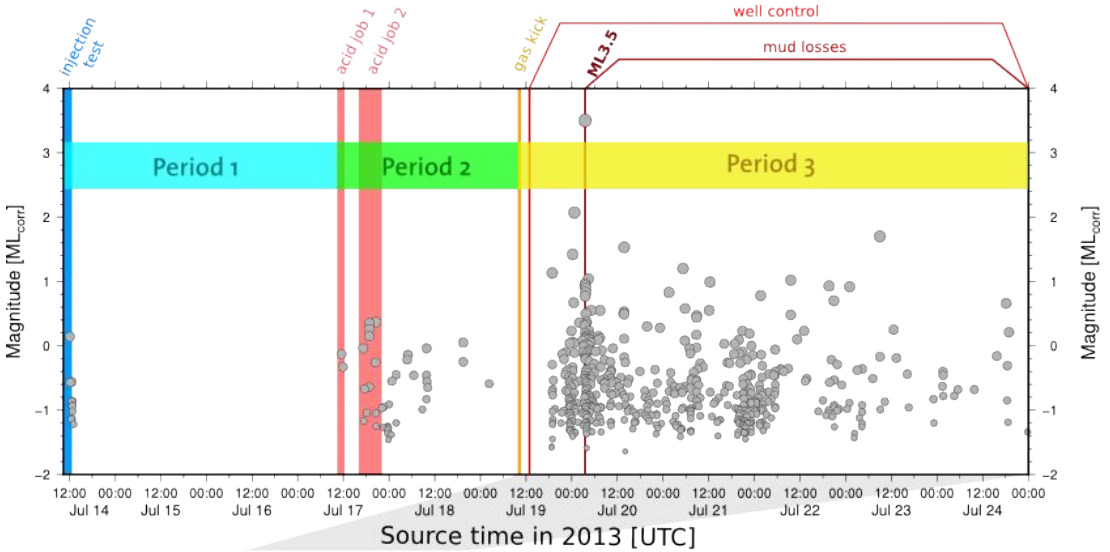
- 4 SP (LE3D-1s)

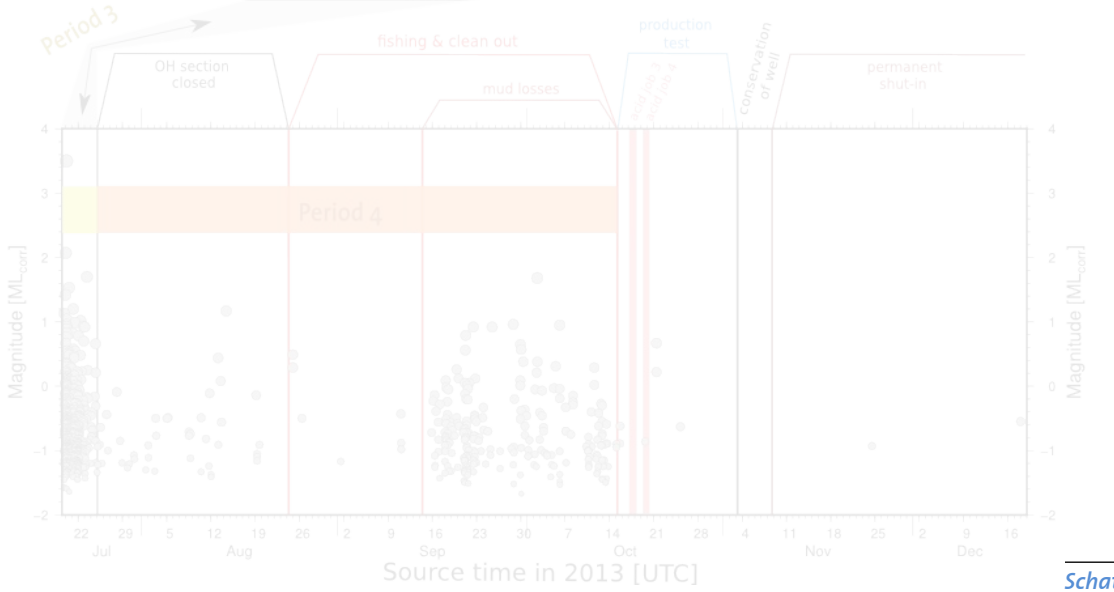
[July 22, 2013](#)

- 3 SP (LE3D-1s)

Funded by Sankt Galler Stadtwerke (sgsw) and Federal Office of Energy

The induced earthquake sequence – 1st part





July 14, 2013
injection test (120m³)

July 17, 2013
1st & 2nd acid job (170m³)

July 19, 2013
10:00 *gas kick*

12:00 *standard killing procedure*

18:51 *ML 1.6 EQ triggers yellow TLS level .*

Yet, pumps can not be stopped to ensure well safety.
→ Seismic TLS ineffective !!!

July 20, 2013

00:40 *ML 2.1 EQ*

03:30 *ML3.5 EQ*

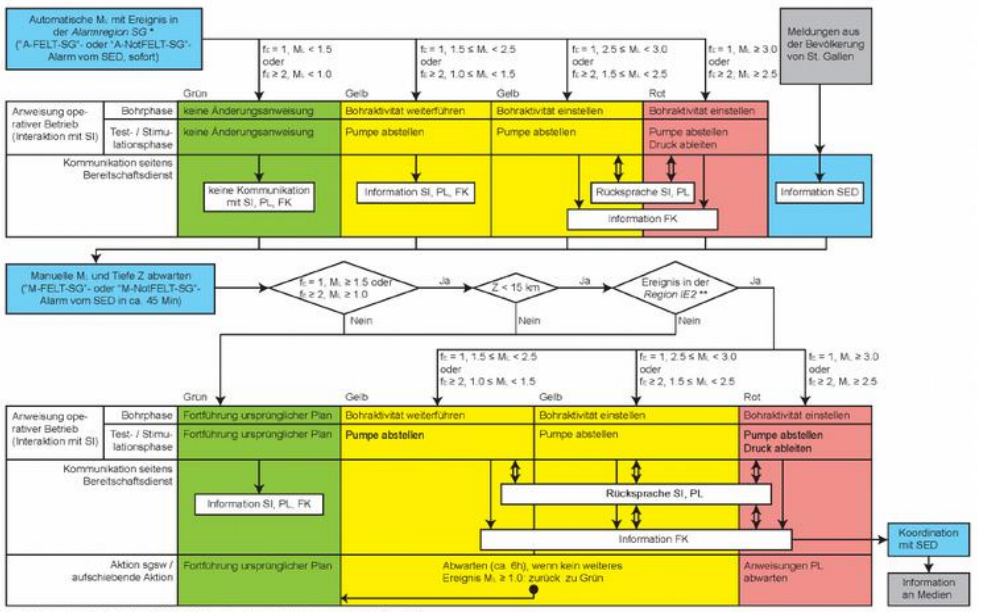
rapid decrease in P_{wh}
steady mud loss & gas entry

July 24, 2013

backfill & sealing of open hole

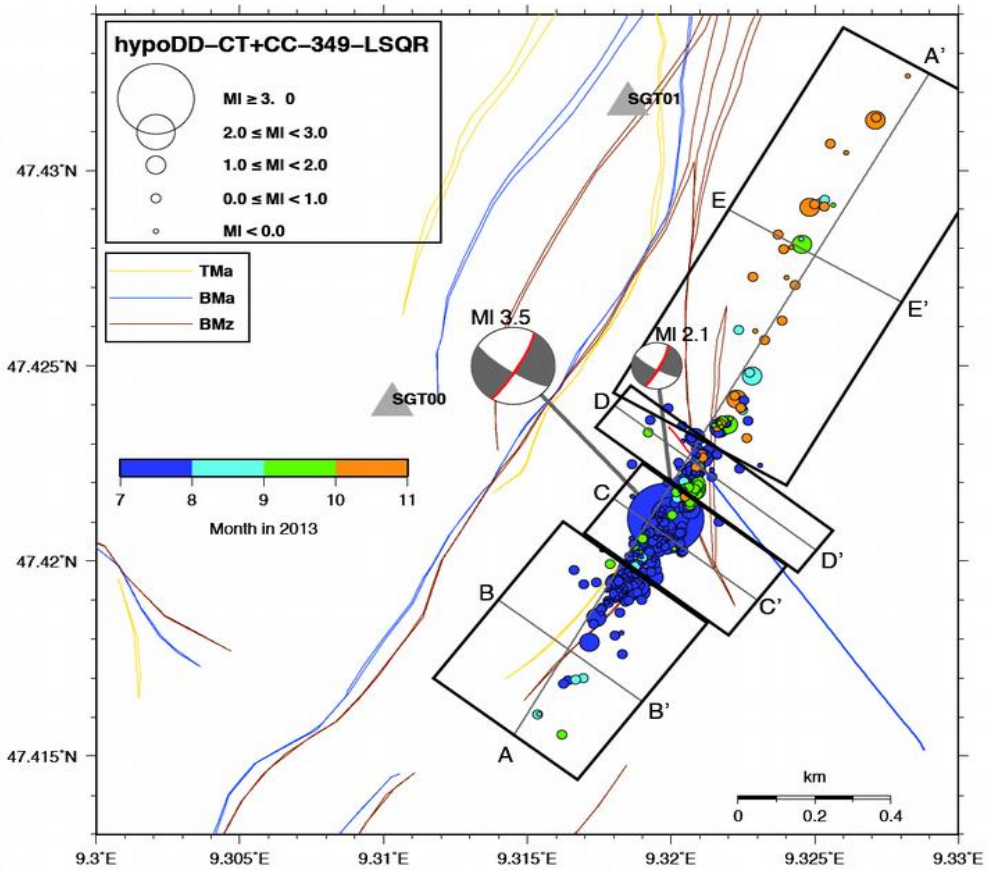
The induced earthquake sequence – 1st part

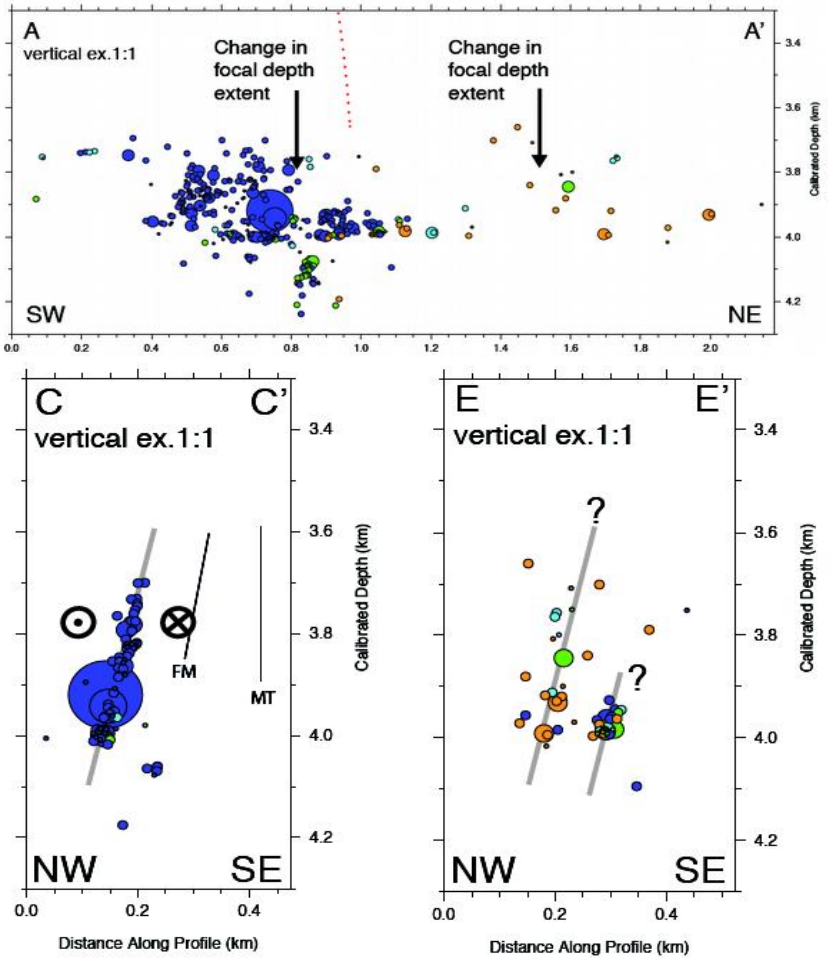
A state of the art Traffic Light System (TLS) was implemented by the project operator:



Yet, neither do current TLS consider standard drilling safety procedures, nor do current drilling safety procedures consider the risk of induced seismicity.

High precision relative EQ-location

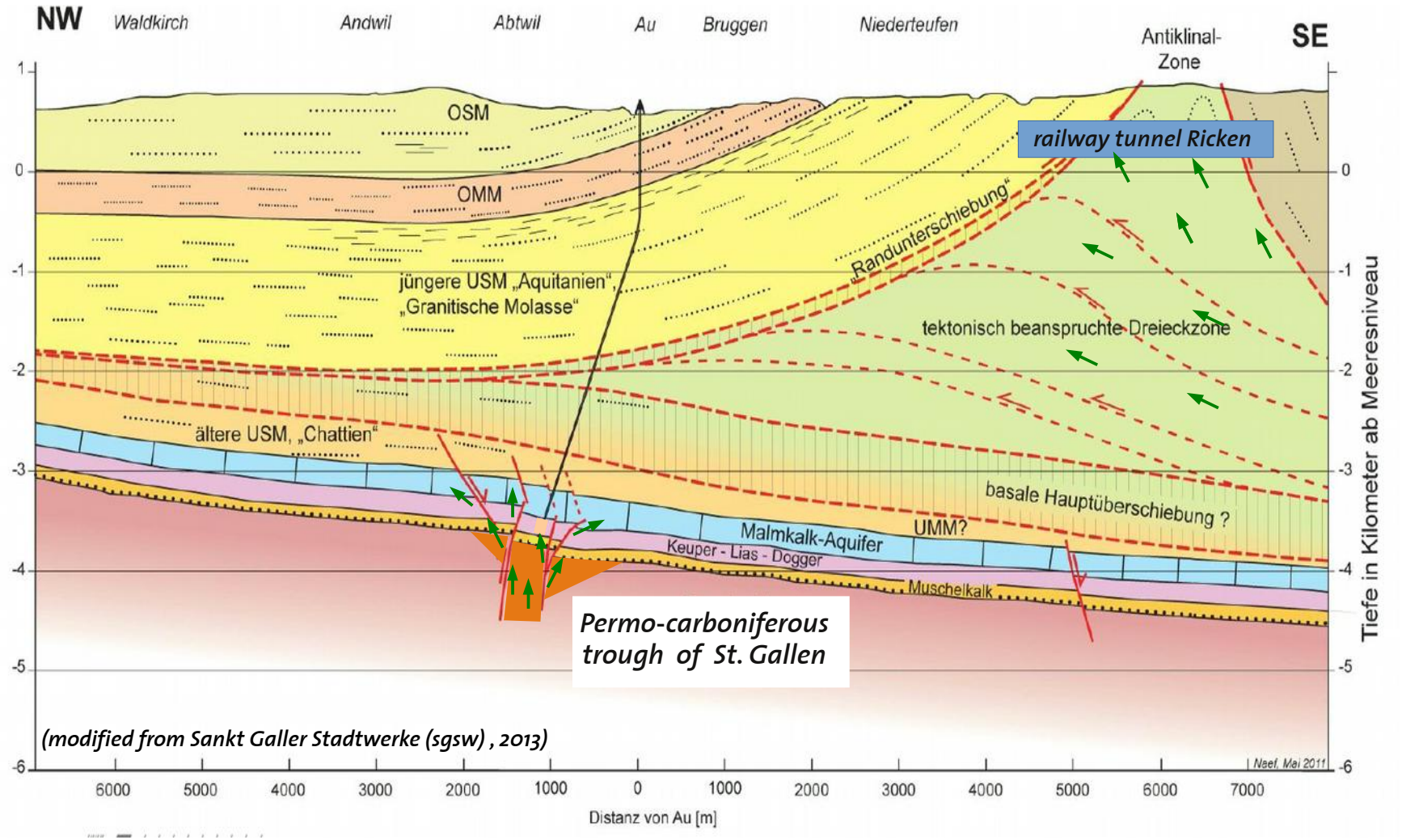




- *Location uncertainties of < 40m*
- *High correlation with faults from 3D-seismics*
- ***Late sequence in area with no mapped faults***

*(visit **poster S6P06** by Diehl et al. for details)*

Where did the gas come from?



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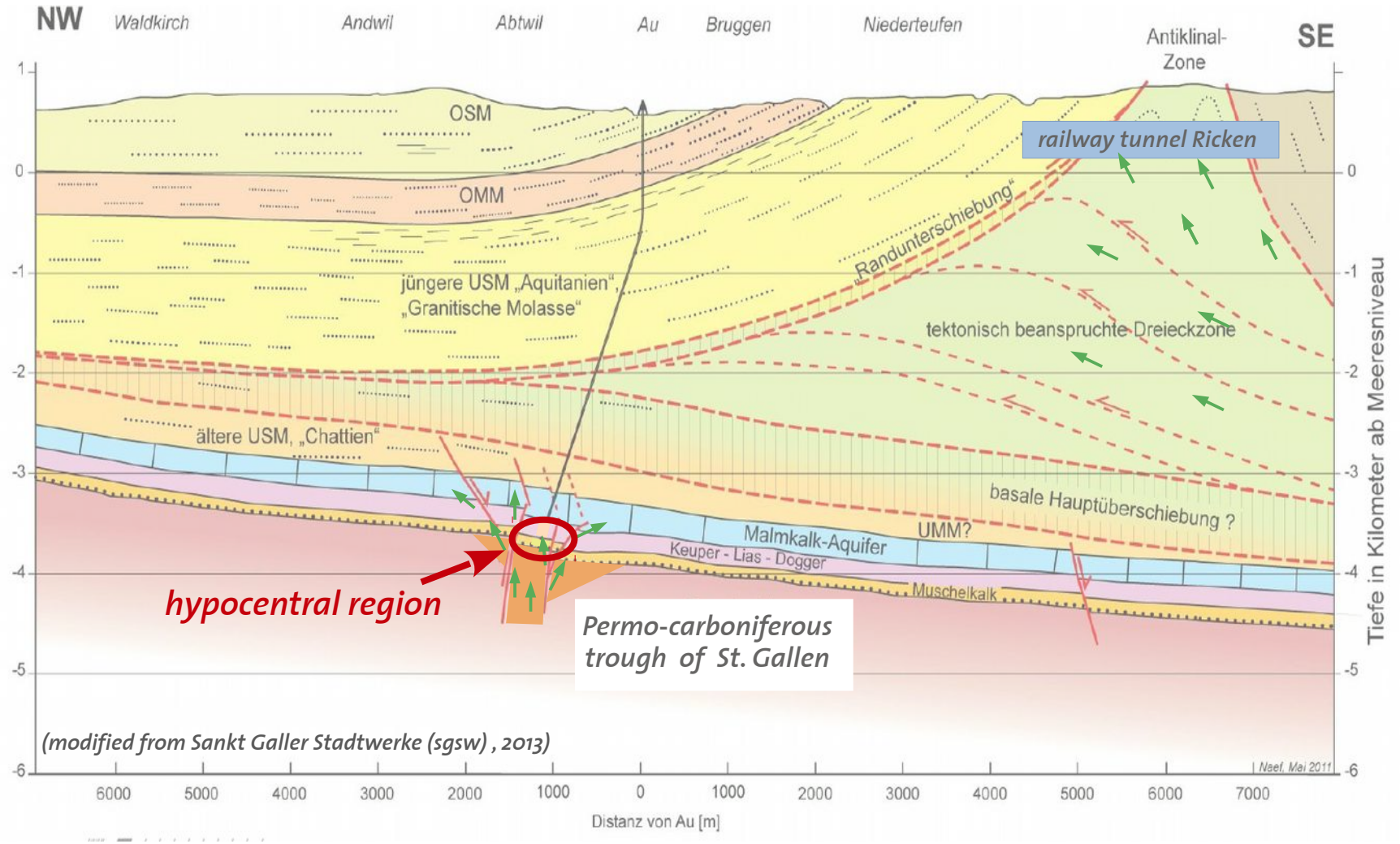


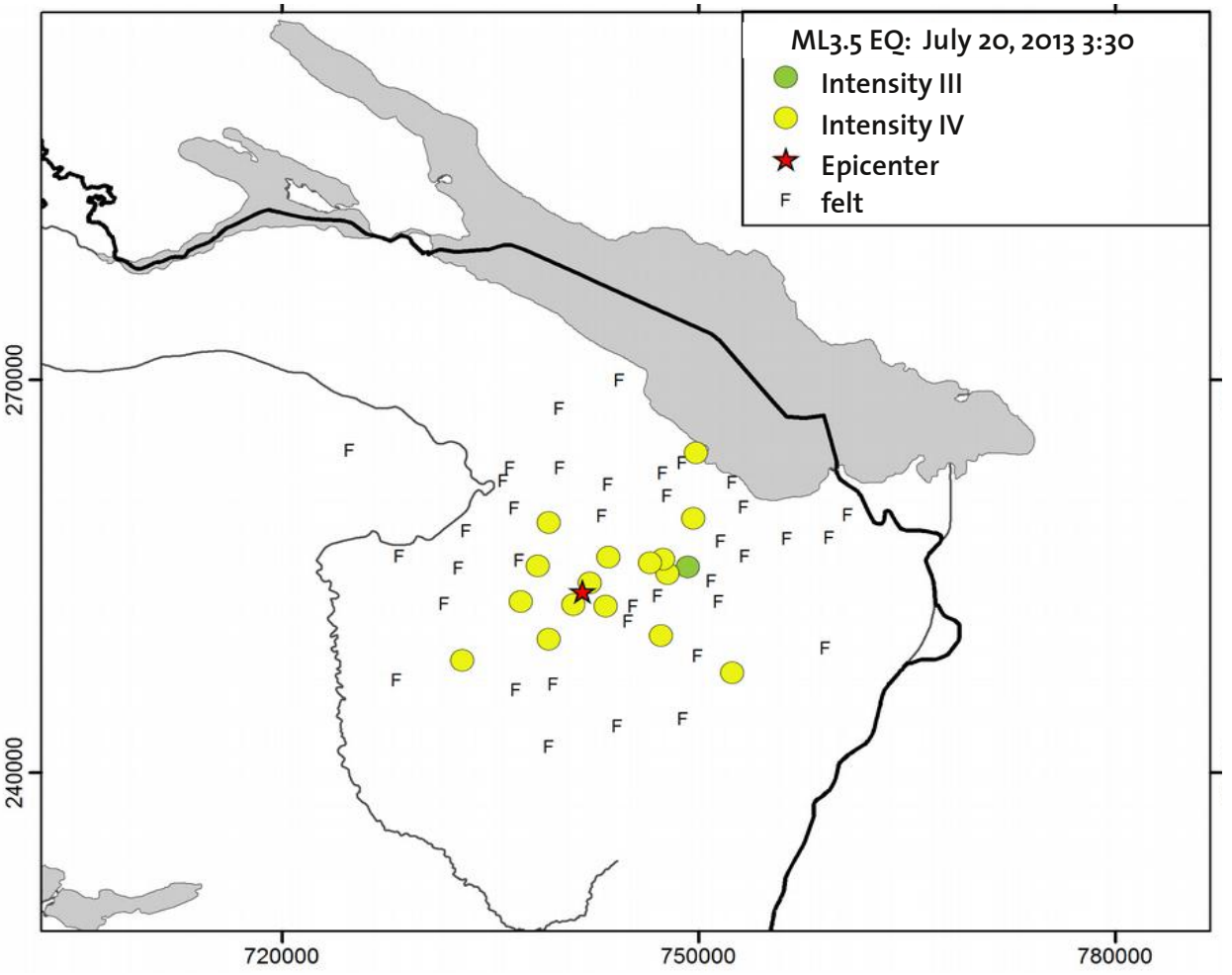
Macroseismics: St. Gallen (ML3.5) ↔ Basel (ML3.4)

ML3.5 St. Gallen EQ:

- More then 400 felt reports submitted online
- Max. macroseismic intensity **Io = IV**
- Only few reports of minor damage

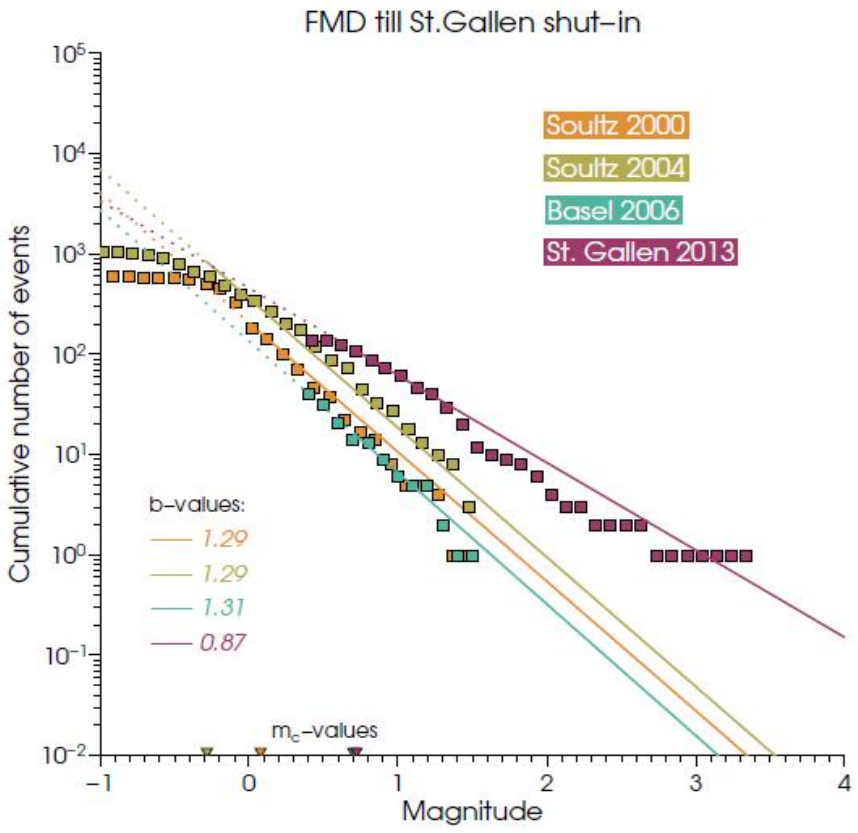
Contrast to Basel ML3.4

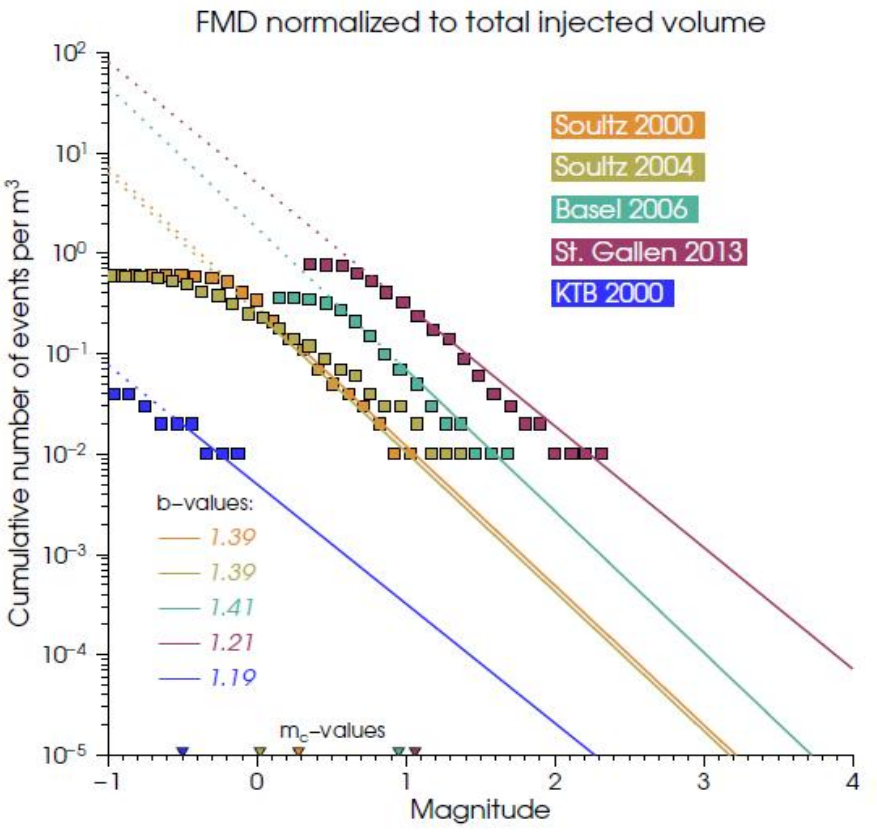
- Max. Intensity **Io=V**
- Many reports of minor damage
- Heard by many as loud bang



(next talk & Edwards et al., GJI (in print) for details)

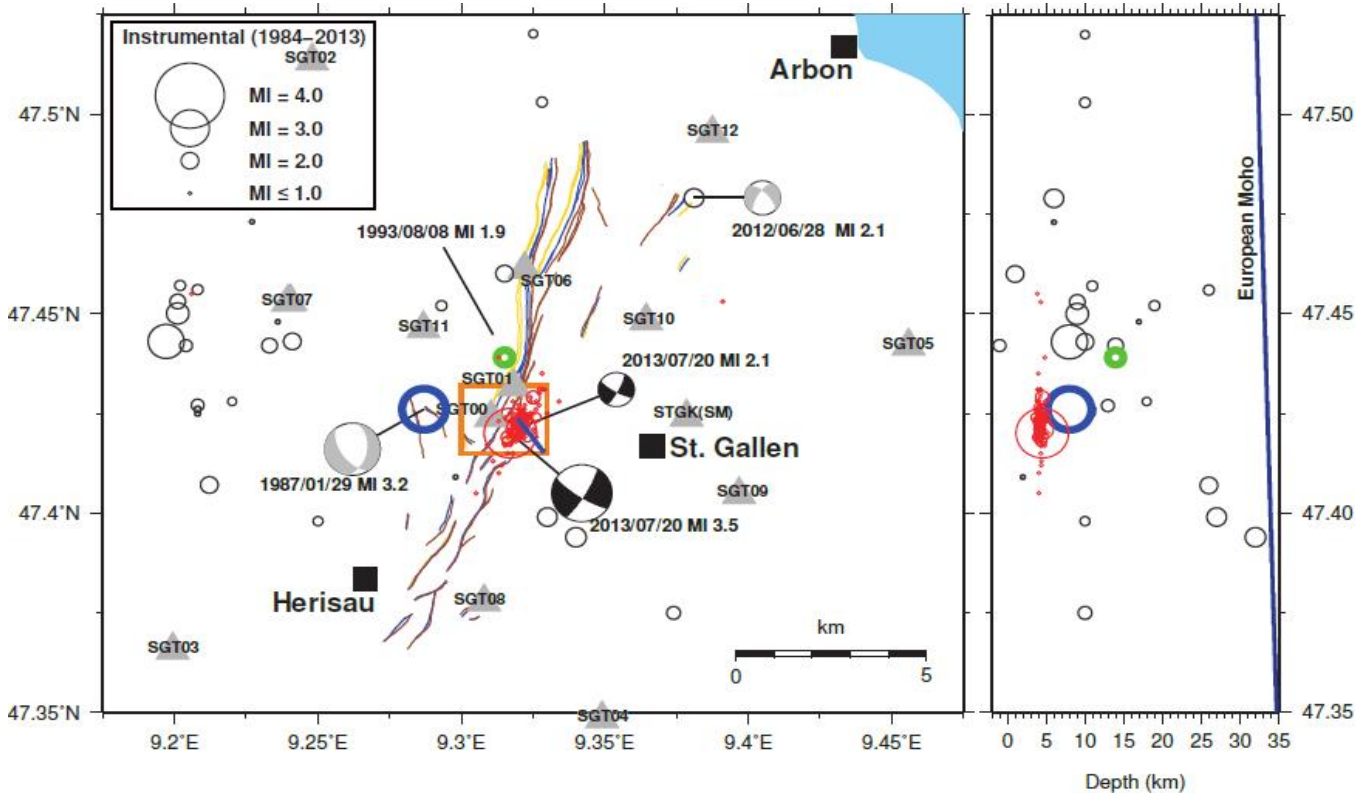
Comparison to other IIS sequences

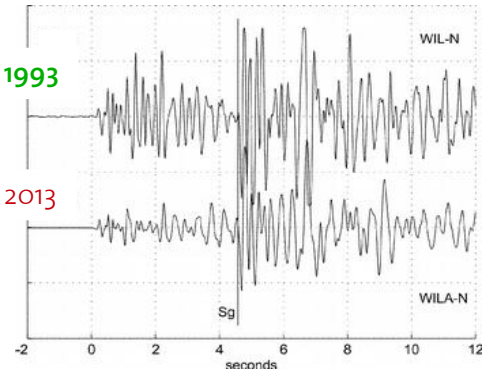


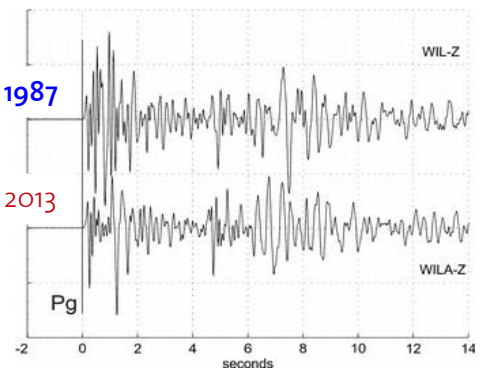


- *Not distinguishable from natural aftershock sequences*
- *SG seismic response per volume injected unusually intense*
  → ***Due to injection into per-stressed optimally oriented fault?***

Natural earthquakes of the past

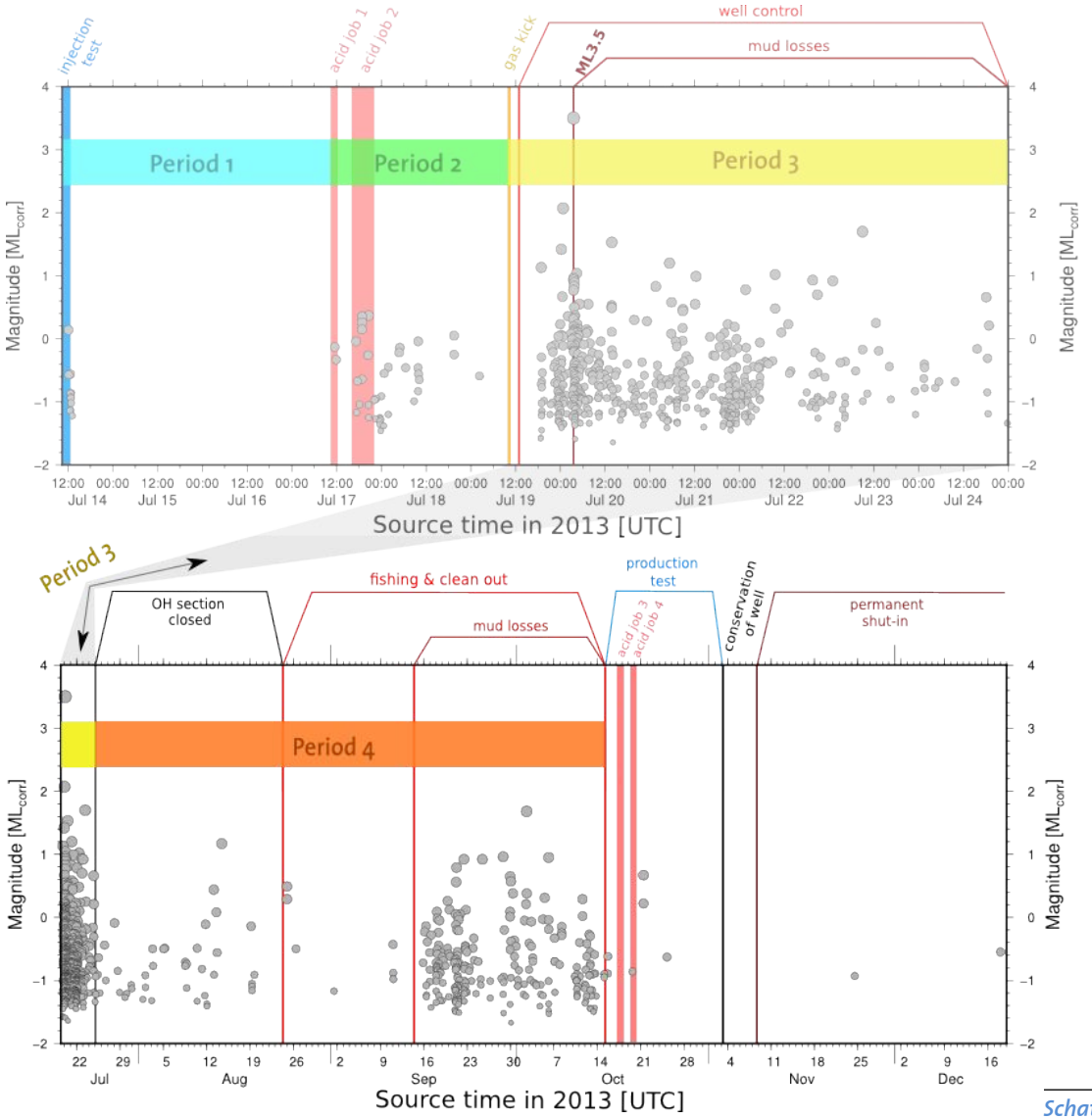






- *Source depth of past events strongly overestimated!*
- *Hypocenter separation between events < 2-3 km*

The induced earthquake sequence – 2nd part



July 24, 2013

backfill of open hole

July 24 – Aug. 8, 2003

open hole sealed

Aug. 8 – Oct. 15 , 2013

fishing for lost equipment & clean out of open hole

→ ***seismicity slowly decreases***

Sep. 15 – Oct. 15, 2013

weak steady mud losses

→ ***seismicity increases significantly***

Oct. 15 – Nov. 3, 2013

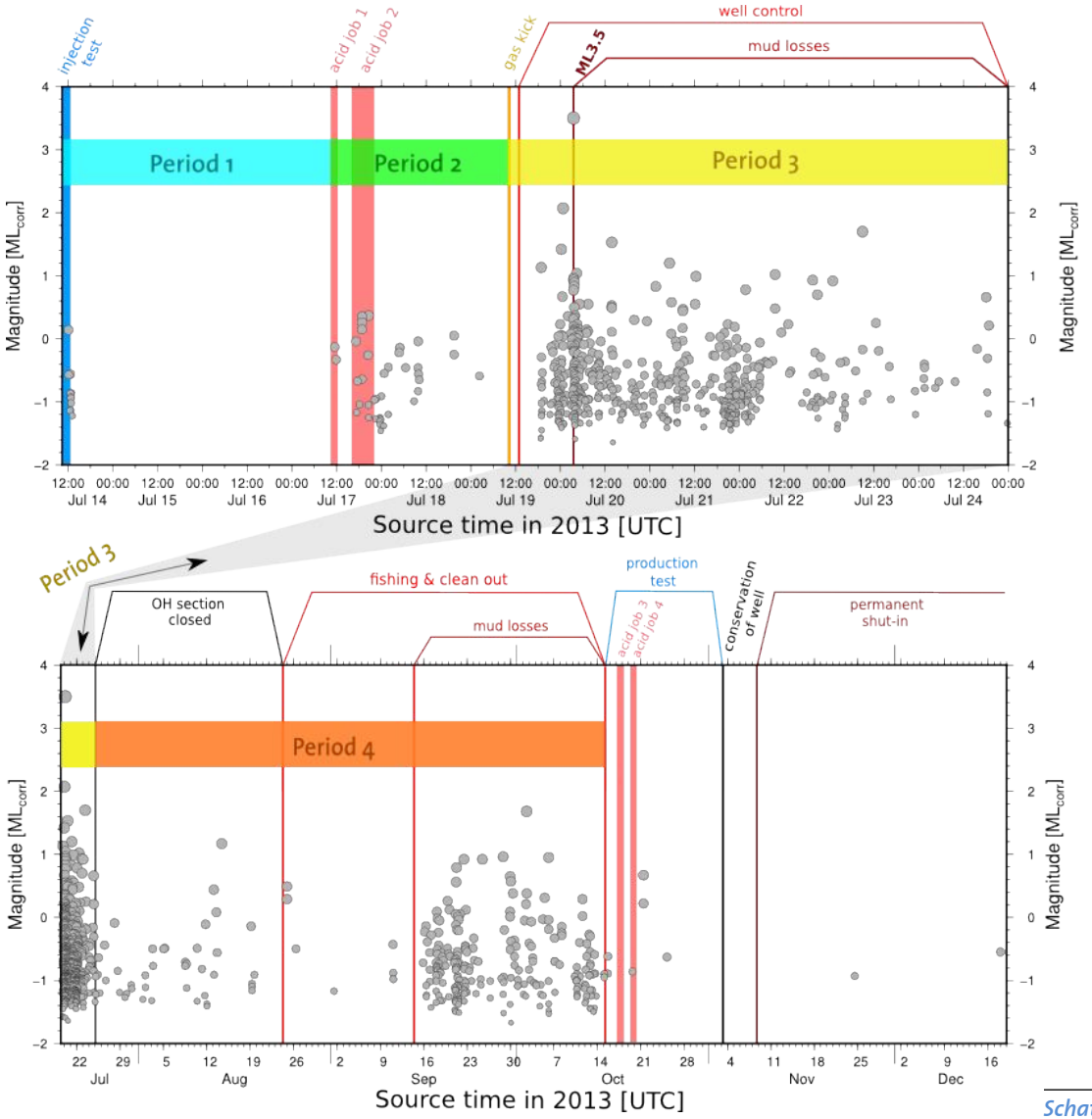
production test

→ ***seismicity rapidly decreases & is completely turned off (Dec. 18)***

since Nov. 9, 2013

permanent shut-in of well

The induced EQ sequence – microseismic response



Micro seismic response closely follows fluid injection activity.

The gas kick causes no detected earthquakes. Seismicity starts with killing operation 6h later.

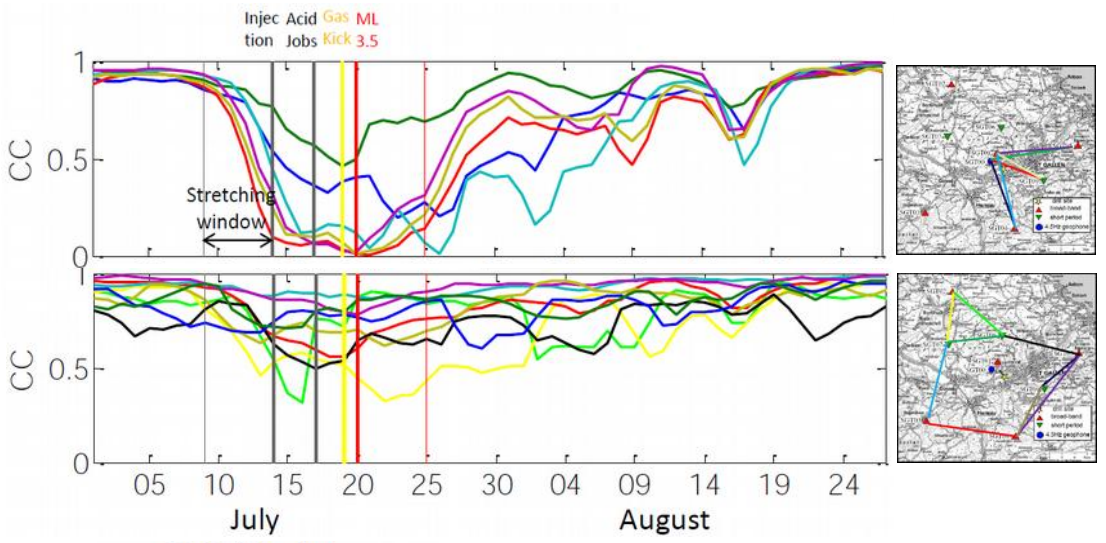
- completeness Mc ~ -0.4$_{ML}$
- daytime detection ~ -1.1$_{ML}$

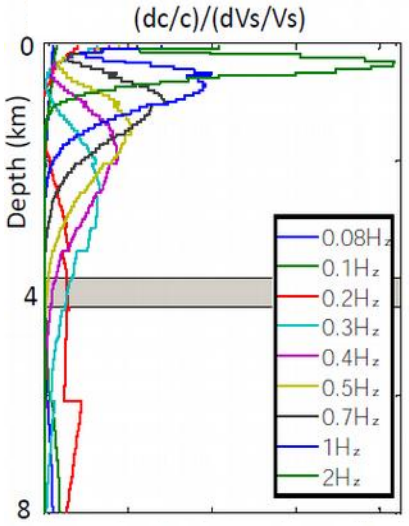
High seismic activity only:

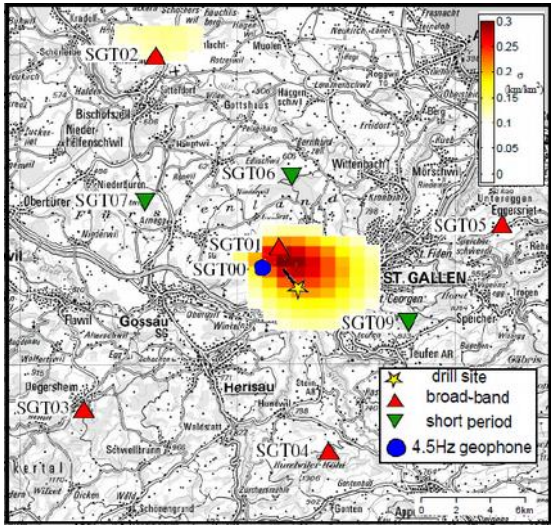
- during injection activity
- when mud losses occur
- following larger EQs

Gas migration plays a minor role for the microseismic response at St. Gallen

Ambient seismic noise analysis – aseismic response







We compute noise-correlograms (NC) to construct the Greens fct. between SGTnet station pairs.

We use the stretching technique to find changes in the coda of the 5-day stack NC, representing tiny changes in the medium.

Decorrelaion in NC is strongest

- around gas kick and ML3.5
- For frequencies w. Rayleigh wave sensitivity at aquifer depth (0.2-0.4 Hz).

A tomographic inversion locates the source of the change at the injection site.

(Obermann et al., JGR, in review)

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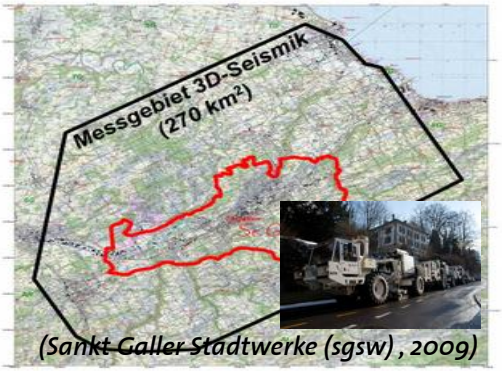
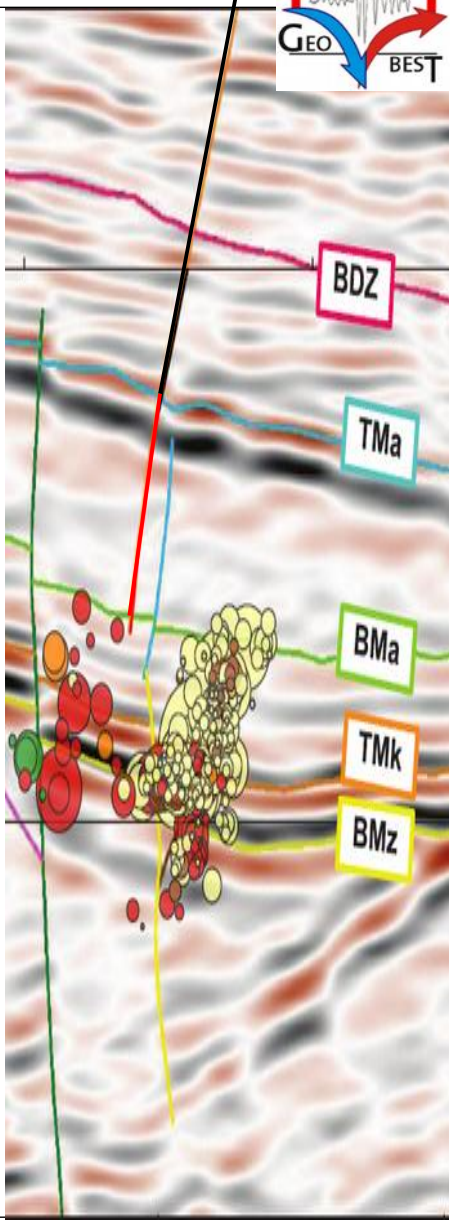


(Sankt Galler Stadtwerke (sgsw), 2009)


(Sankt Galler Stadtwerke (sgsw), 2013)

Conclusions

- *Standard well control procedure following a gas kick induced a ML3.5 EQ at the St. Gallen geothermal project.*
- *The need to kill the gas kick overruled seismic TLS. Future projects need to **carefully investigate potential conflicts** in the involved safety procedures.*
- *Targeted fault zone most likely critically stressed, and active in recent and historic past.*
- *Microseismic response closely follows fluid injection activity. Ambient seismic noise identifies possible **aseismic response** due to gas migration.*
- *St.Gallen EQ shallower and stronger, yet intensity lower than in Basel EQ*
- *Seismic response per volume injected unusually intense (**~700 m³ → ML3.5**).*
- *Production test turned off seismicity completely.*




Thank you for
listening!
ITAG
(Sankt Galler Stadtwerke (sgsw) , 2013)