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Ground-motion and Intensity: were the Basel 2006 and St. Gallen 2013 Events Fundamentally Different?

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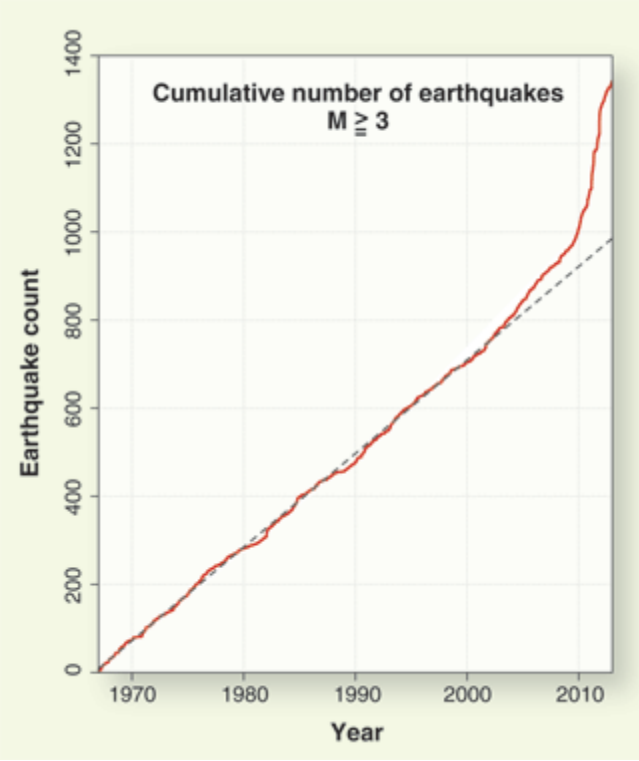
Background and Motivation

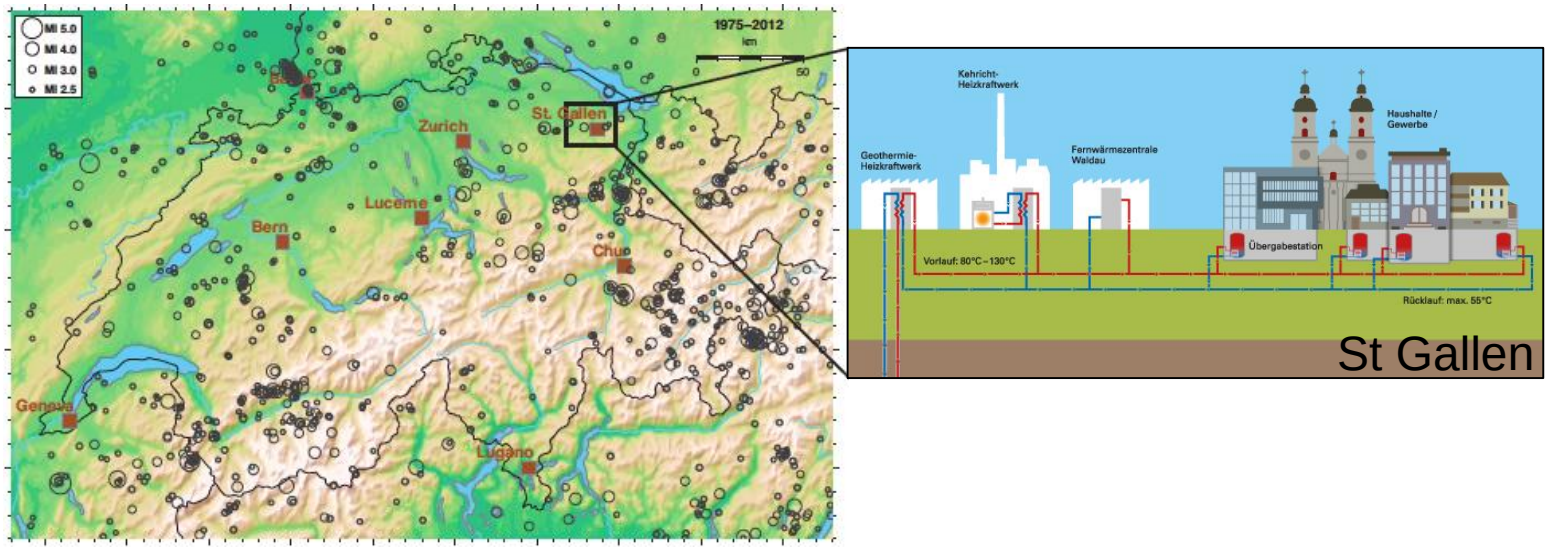
- Exploitation of the near-surface crust for energy sources. Benefits:
  - profitable (shale gas/oil);
  - green/clean (geothermal).
- Significant rise in induced seismicity.
- How to understand/quantify the hazard and risk.
  - Earthquake generation, **energy and resulting ground-motion.**



Ellsworth, W. L. (2013). Injection-Induced Earthquakes, Science 341, 142.

Two Swiss Geothermal Projects

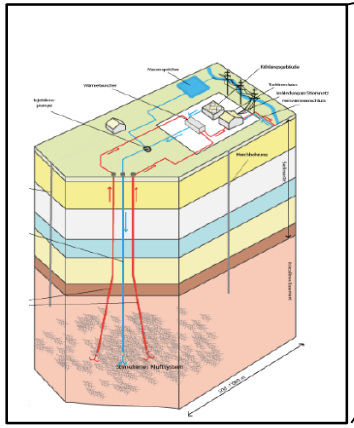
- **St Gallen**, 2013: A deep hydrothermal project.
  - Low seismicity, limited faulting: low tectonic hazard.

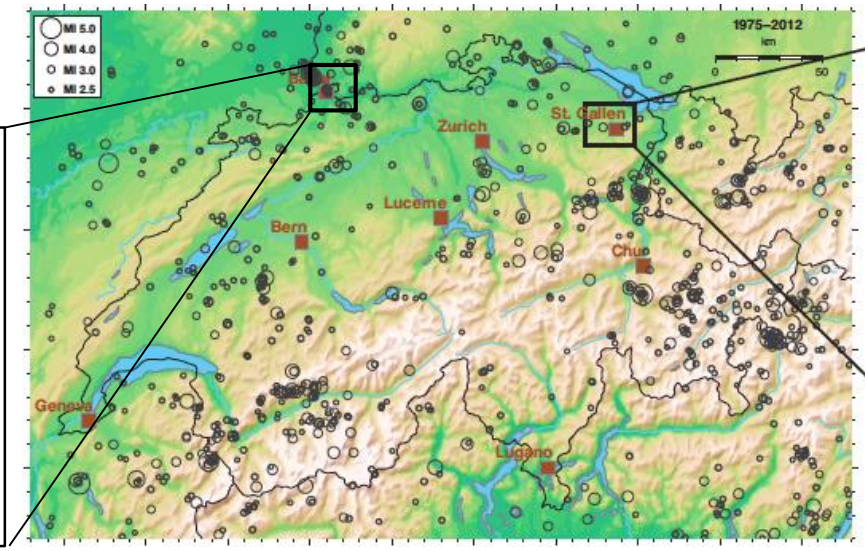


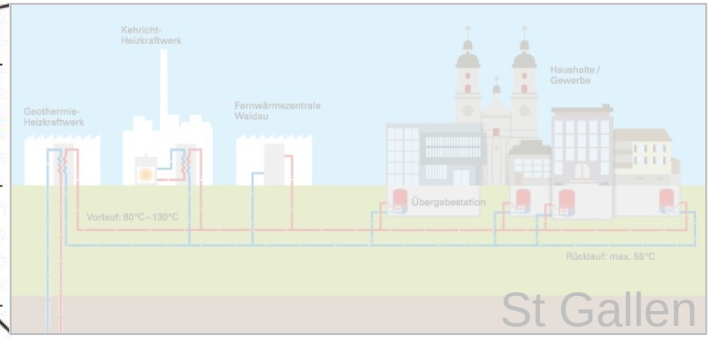
Two Swiss Geothermal Projects

- **St Gallen**, 2013: A deep hydrothermal project.
  - Low seismicity, 'limited' faulting: low tectonic hazard.
- **Basel**, 2006: A deep enhanced geothermal (EGS) project.
  - Existing high seismicity/major faulting: high tectonic hazard.

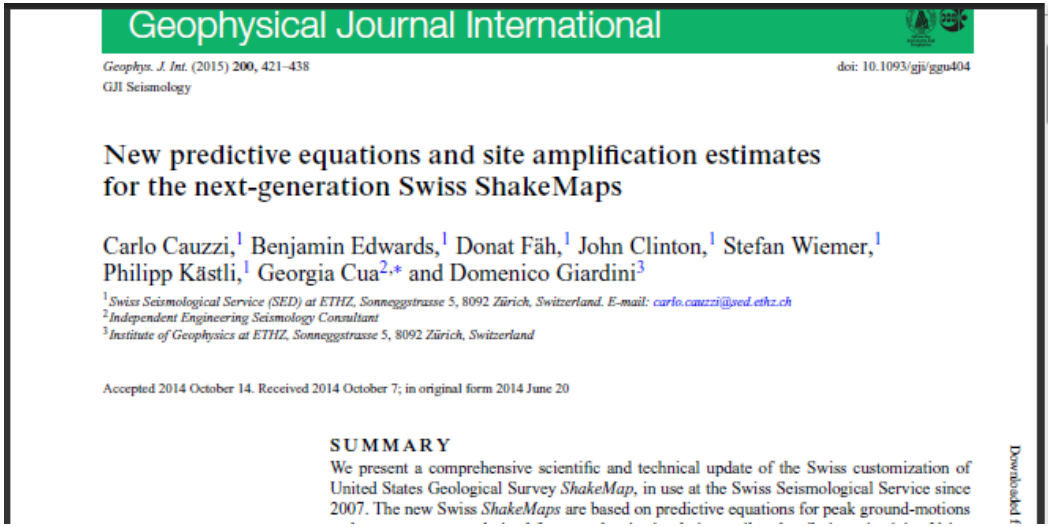
Basel







Shaking and Macroseismic Intensity



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GJI Seismology

New predictive equations and site amplification estimates for the next-generation Swiss ShakeMaps

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SUMMARY

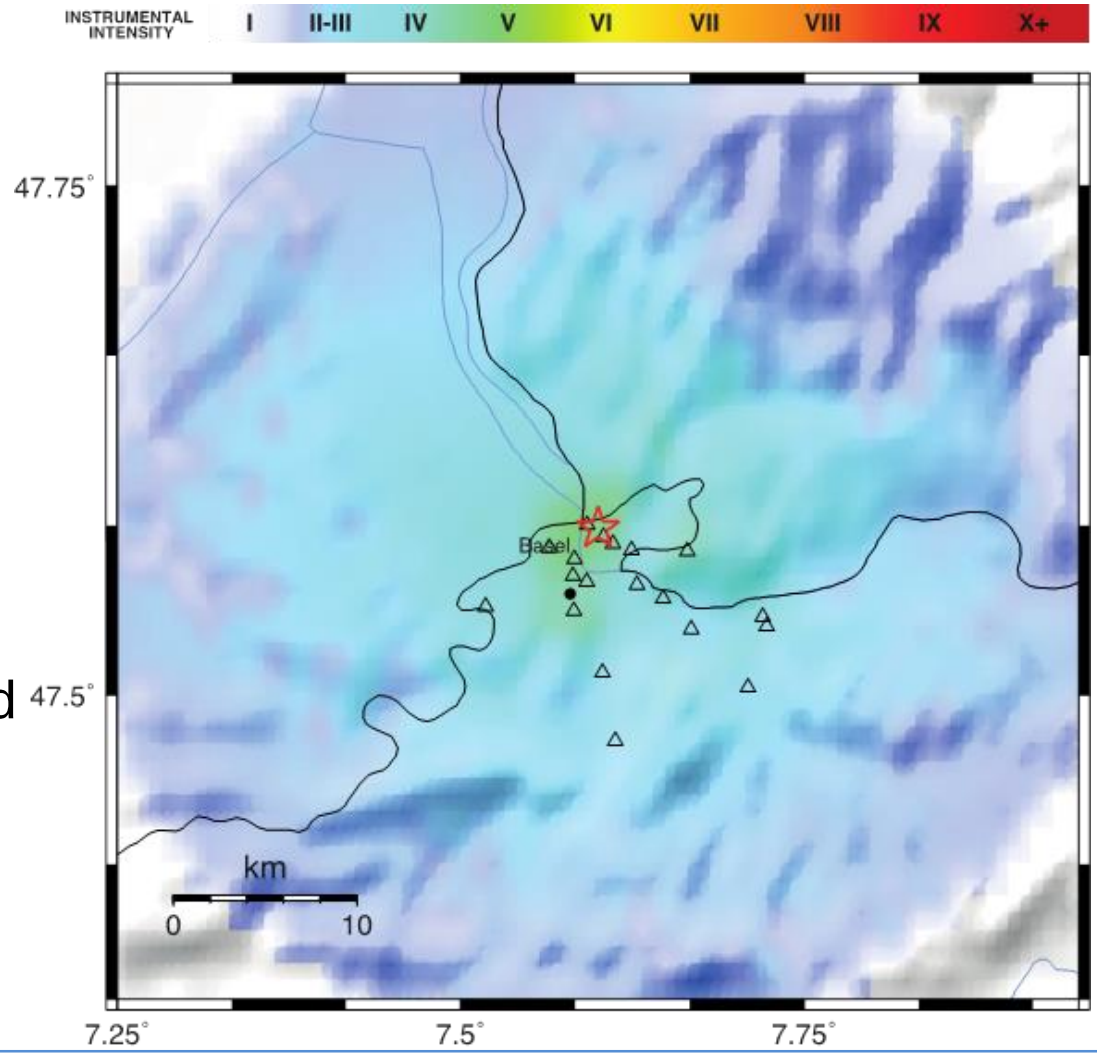
We present a comprehensive scientific and technical update of the Swiss customization of United States Geological Survey *ShakeMap*, in use at the Swiss Seismological Service since 2007. The new Swiss *ShakeMaps* are based on predictive equations for peak ground-motions

- Combines recorded data, GMPE, and site amplification with GMICE to obtain macroseismic intensies using ShakeMap (USGS).

Cauzzi, C., B. Edwards, D. Fäh, J. Clinton, S. Wiemer, P. Kästli, G. Cua and D. Giardini (2015). **New Predictive Equations and Site Amplification Estimates for the Next-Generation Swiss Shakemaps**, Geophysical Journal International 200, 421–438, doi: 10.1093/gji/ggu404.

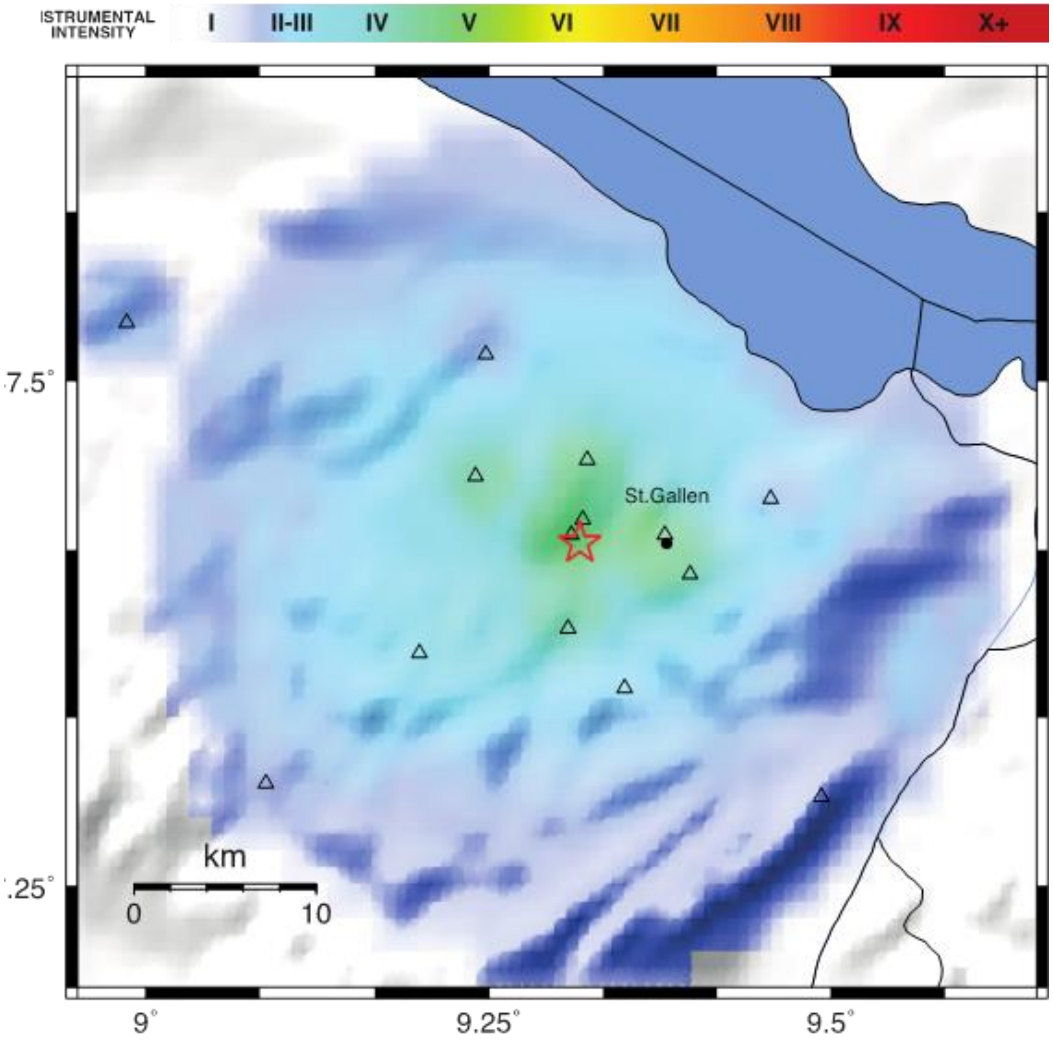
Basel EGS 'mainshock'

- Widely-felt M_L 3.6, M_w3.2.
- Significant minor (non-structural damage ($7.5M + 1.5M costs).
- Subsequent risk analysis led to shut down of project.



St Gallen 'mainshock'

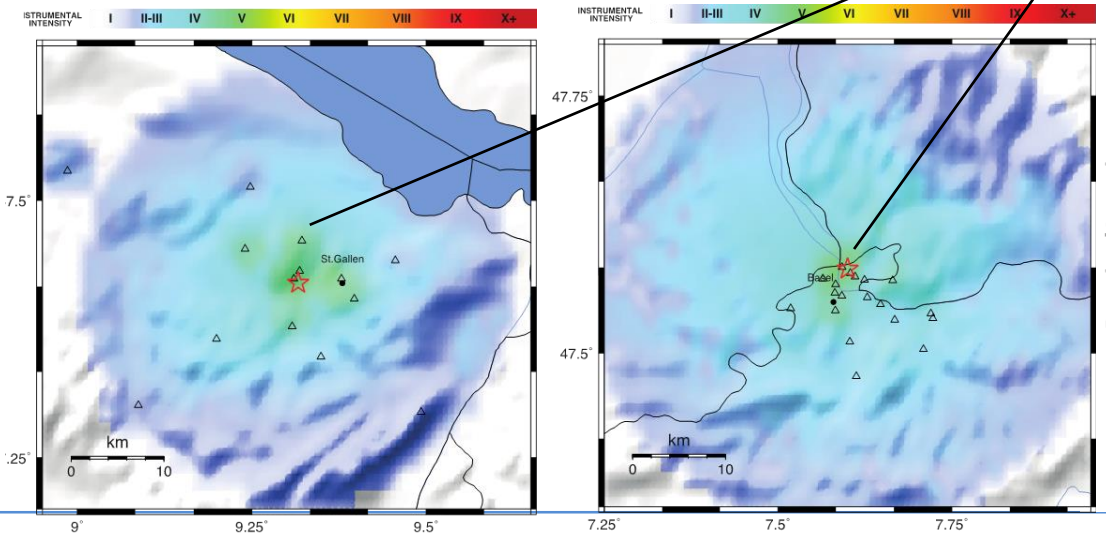
- Widely-felt M_L 3.5, M_w3.4.
- Similar epicentral shaking intensity.
- ' Smaller' extent of felt shaking area.
- No damage.

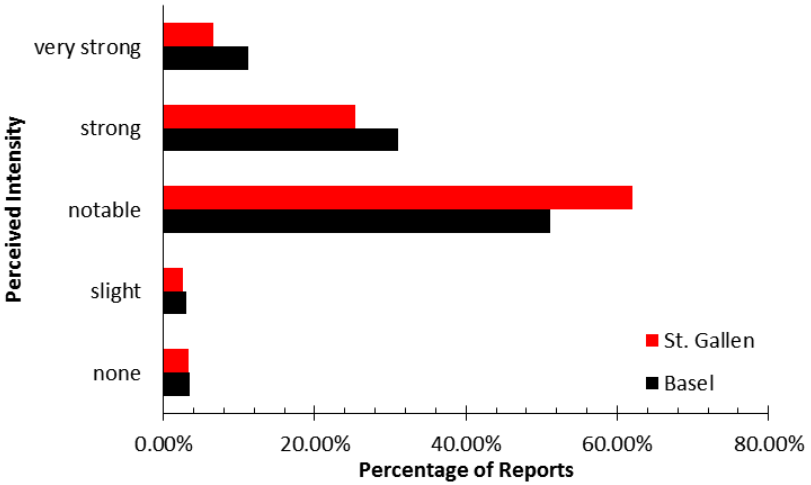


Two Events, both EMS-98 I = V

- Considering uncertainties, both macroseismic fields are comparable.
- Basel caused damage ~ $7.5M, St Gallen caused none.

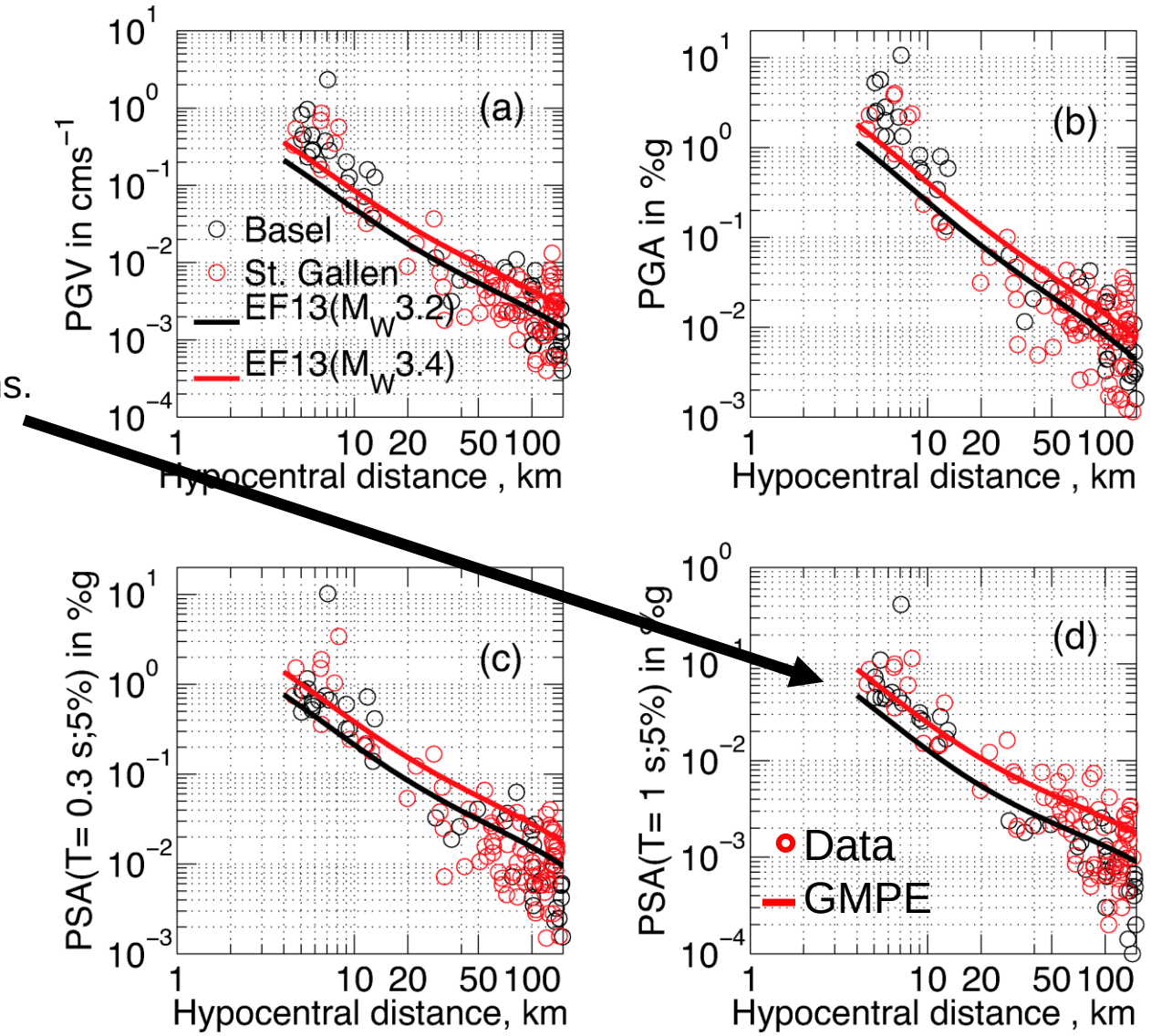
EMS-98 Intensity	Felt	Impact
V	Moderate	Felt indoors by most, outdoors by few. Many sleeping people wake up. A few are frightened. Buildings tremble throughout. Hanging objects swing considerably. Small objects are shifted. Doors and windows swing open or shut.





Recorded Ground Motion

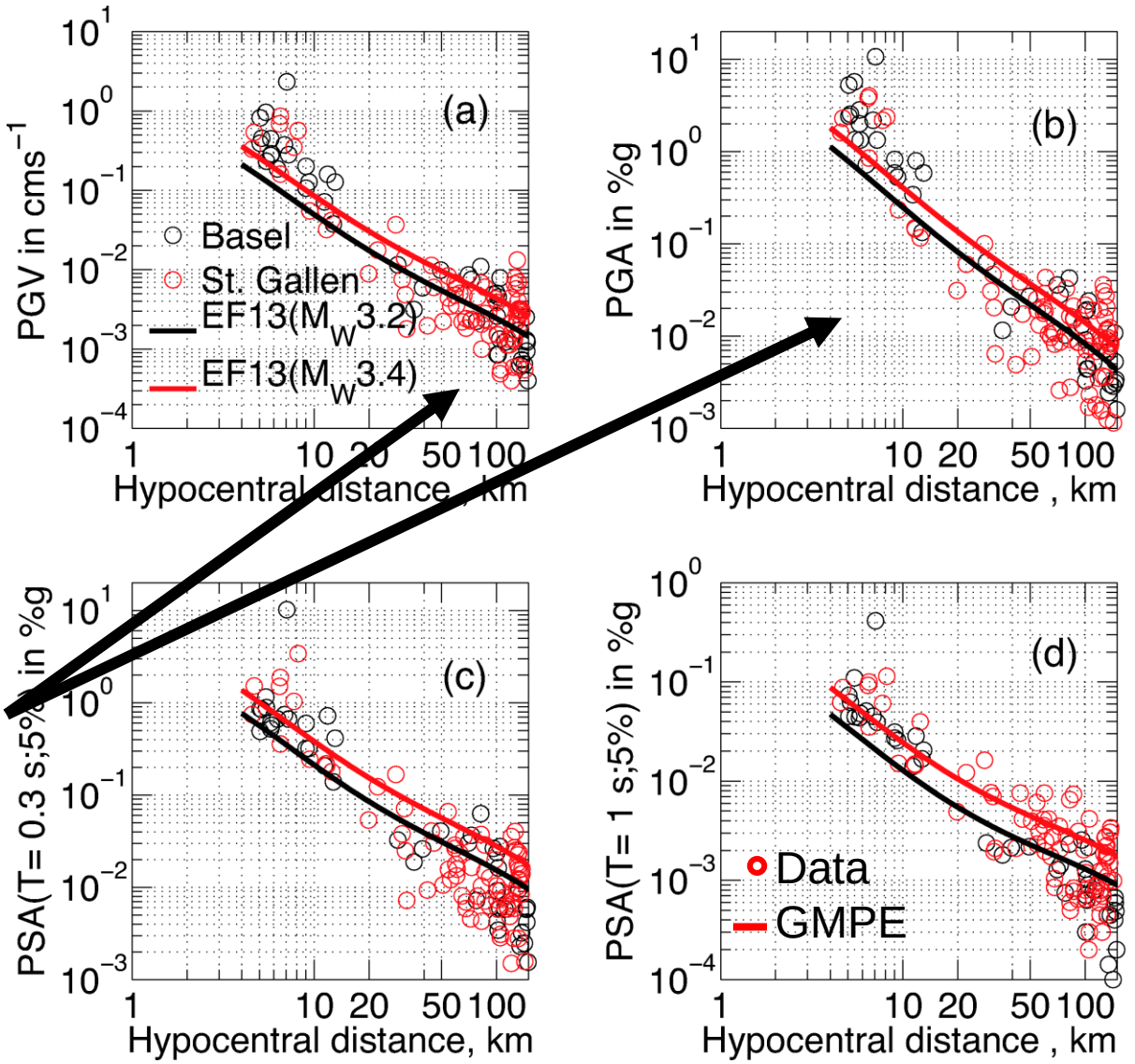
- St Gallen:
- Higher long-period motions.
- Particularly in the far field.
- Consistent with GMPE.



Recorded Ground Motion

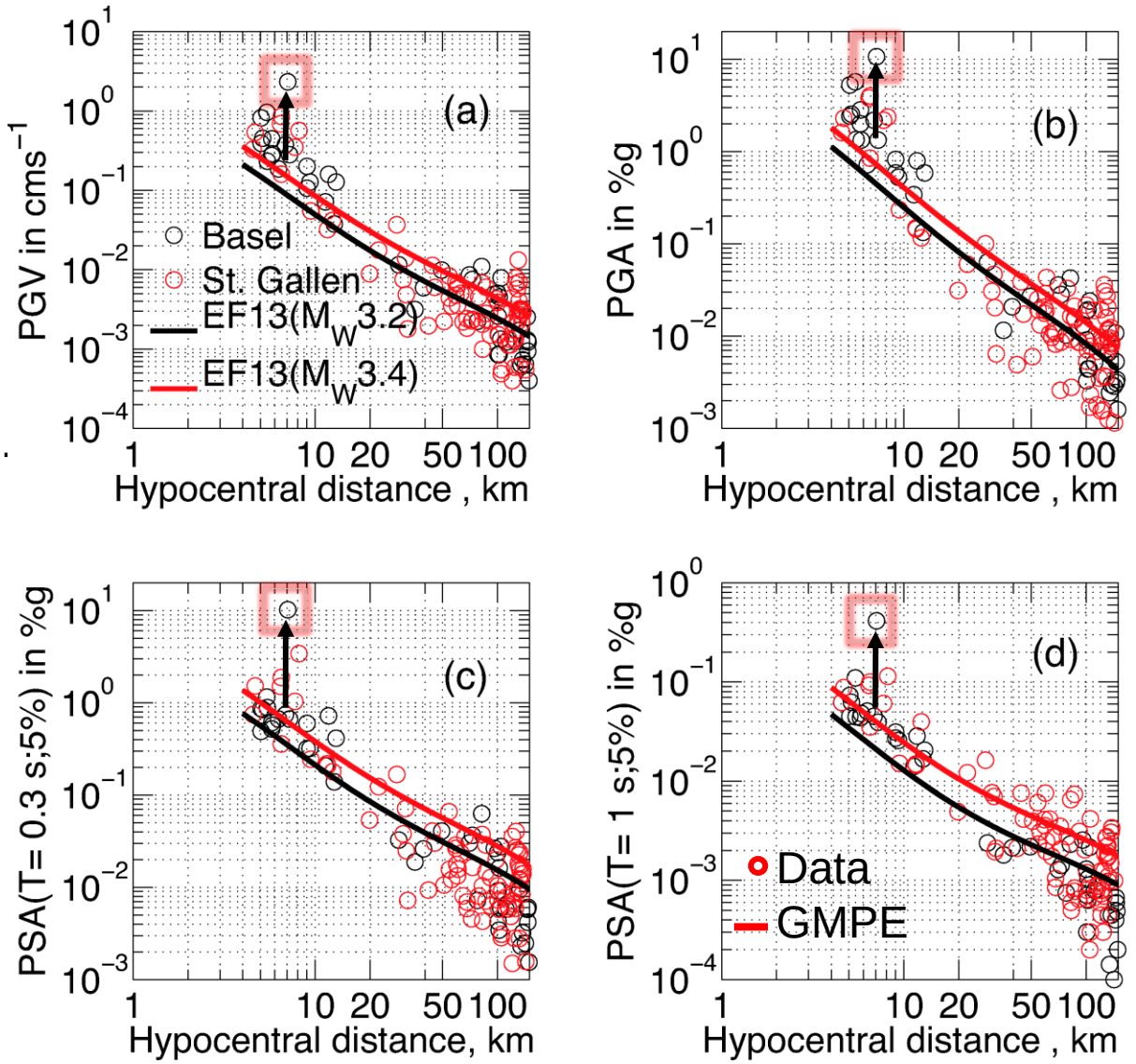
- St Gallen:
- Higher long-period motions.
- Particularly in the far field.
- Consistent with GMPE.

- Similar short period motions.
- GMPE still predicts slight differences ~ x2 – not seen.



Recorded Ground Motion

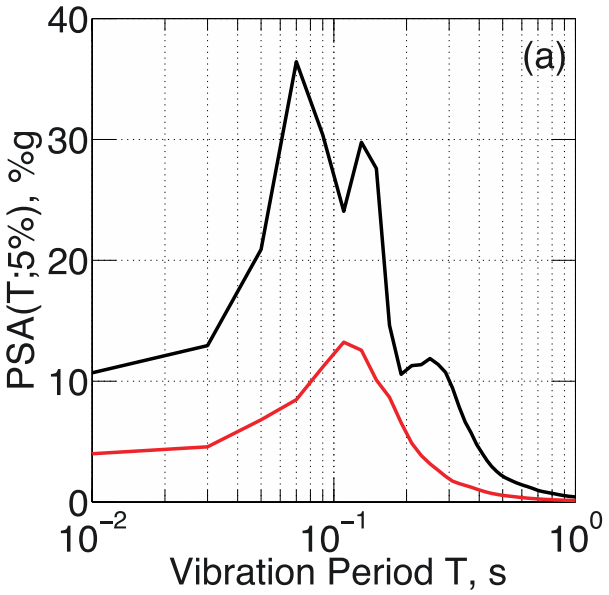
- Basel:
- Significant ground motion recorded in epicentral region.
- Up to ~ x10 (5 sigma).

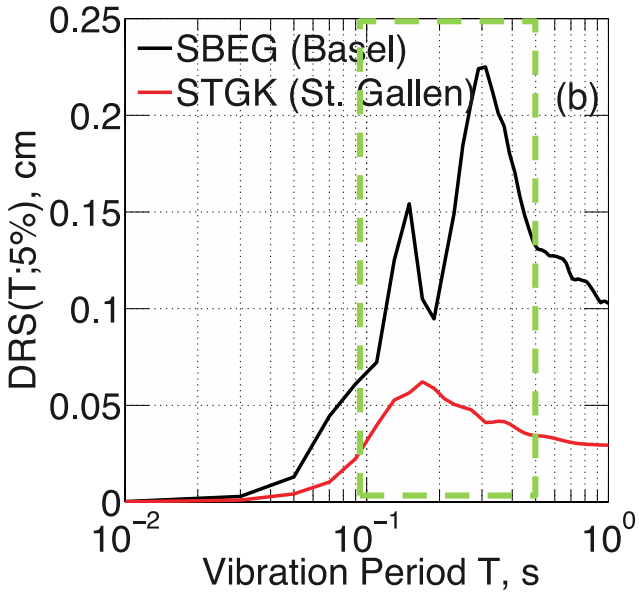


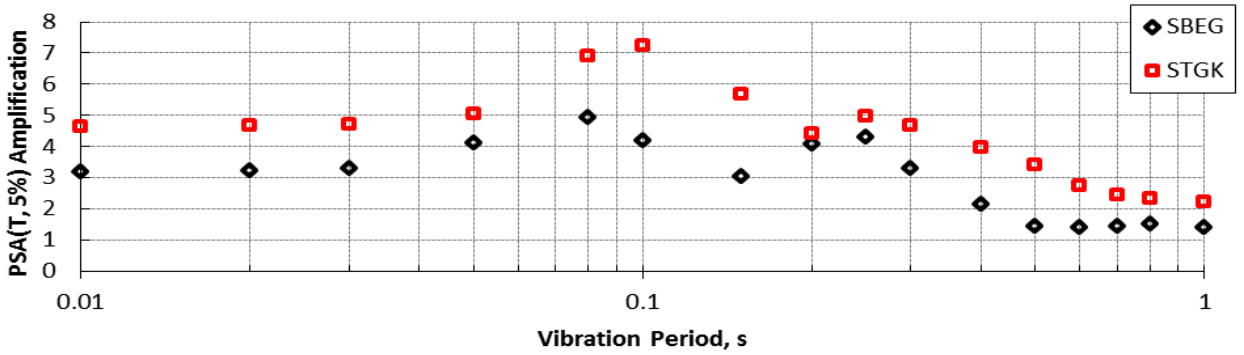
More detail … strongest recordings (~5km)

Typical natural frequencies of low-rise buildings

- Same distance.
- Same site (Vs30 ~ 450m/s).
- Similar amplification.

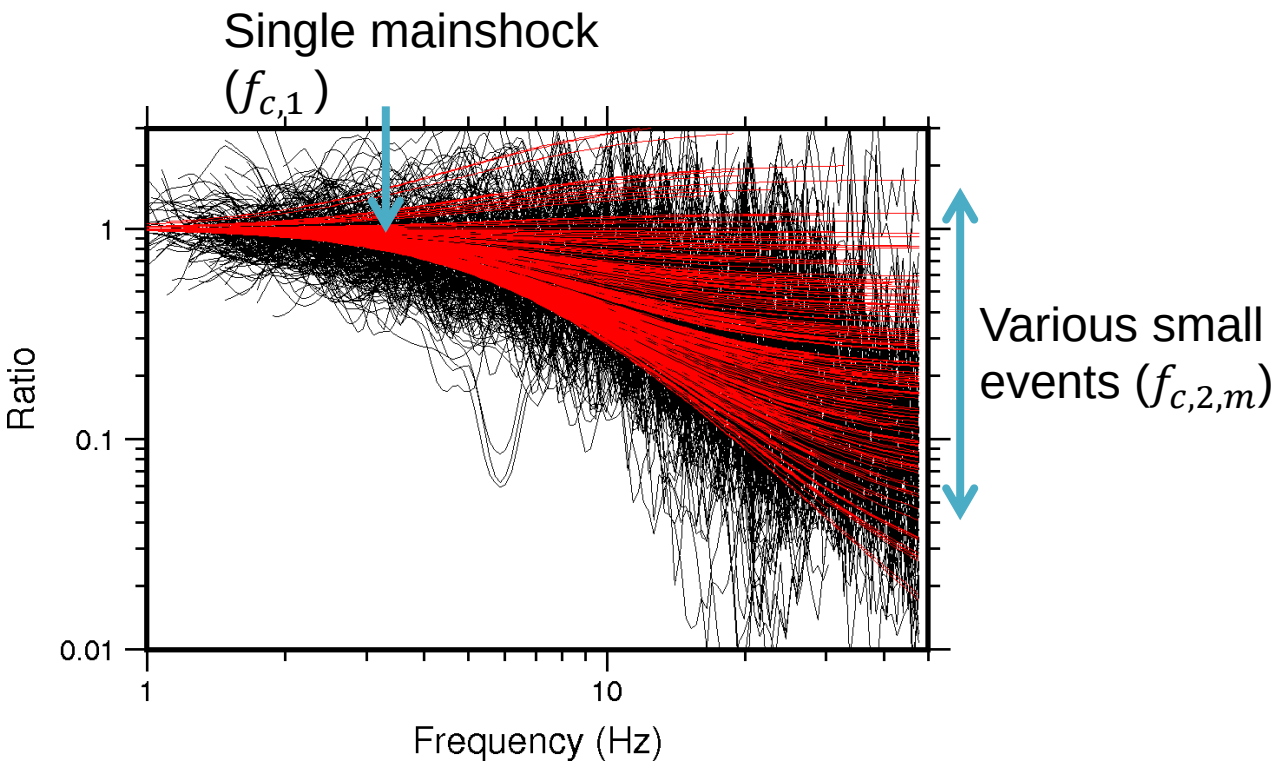






Basel Source Spectrum (M_L-M_W= 0.4)

- Source spectrum ratio: $\frac{E_1}{E_2}(f) = \frac{\Omega_{0,1}}{\Omega_{0,2}} \frac{1+\left(\frac{f}{f_{c,2}}\right)^2}{1+\left(\frac{f}{f_{c,1}}\right)^2}$

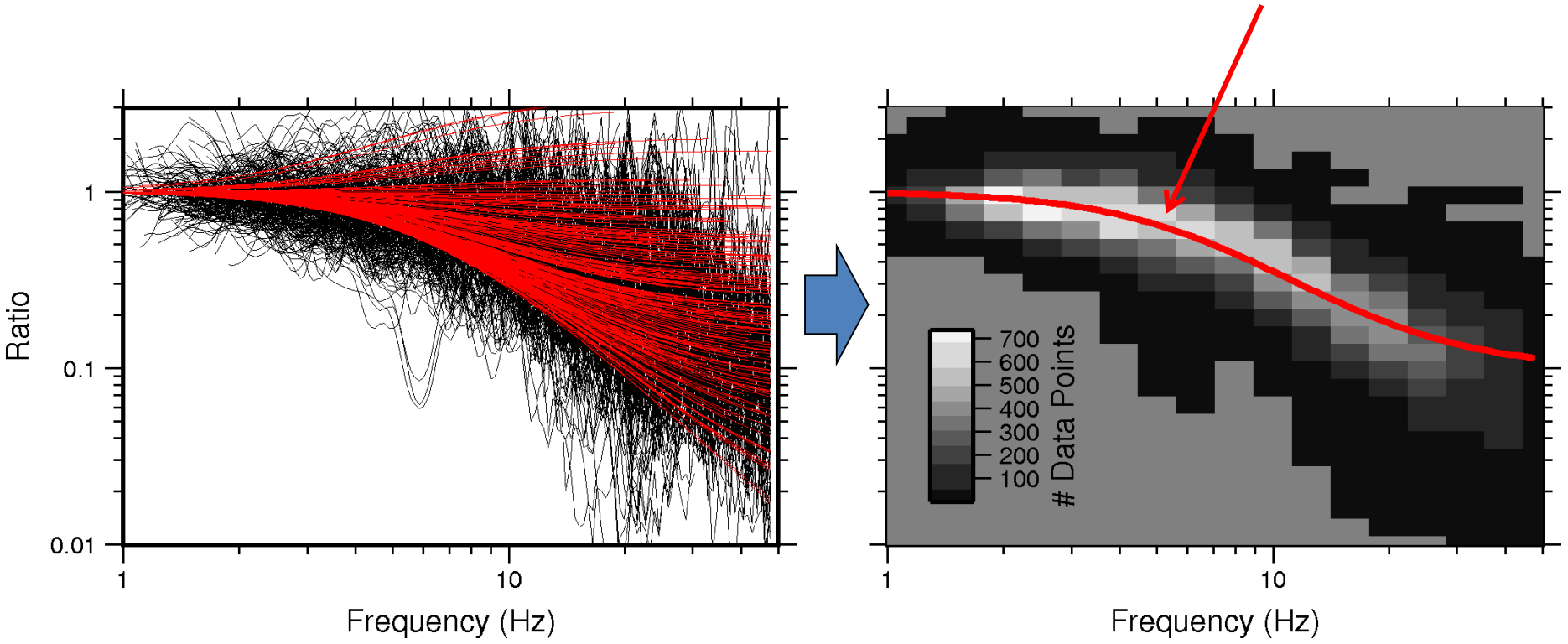


Events co-located (within ~ 100m)

Path/Site terms cancel

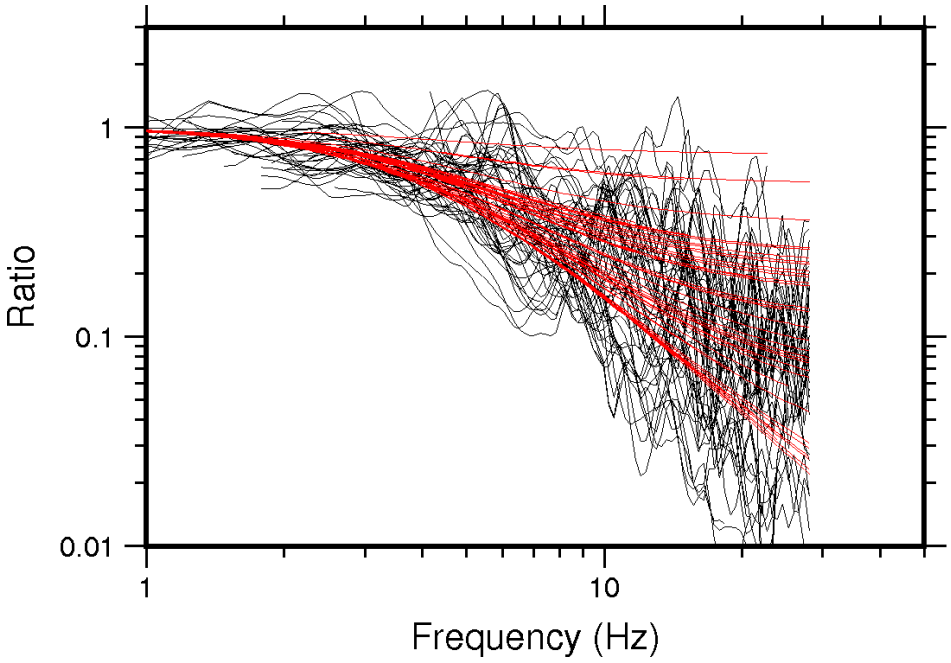
Basel Source Spectrum

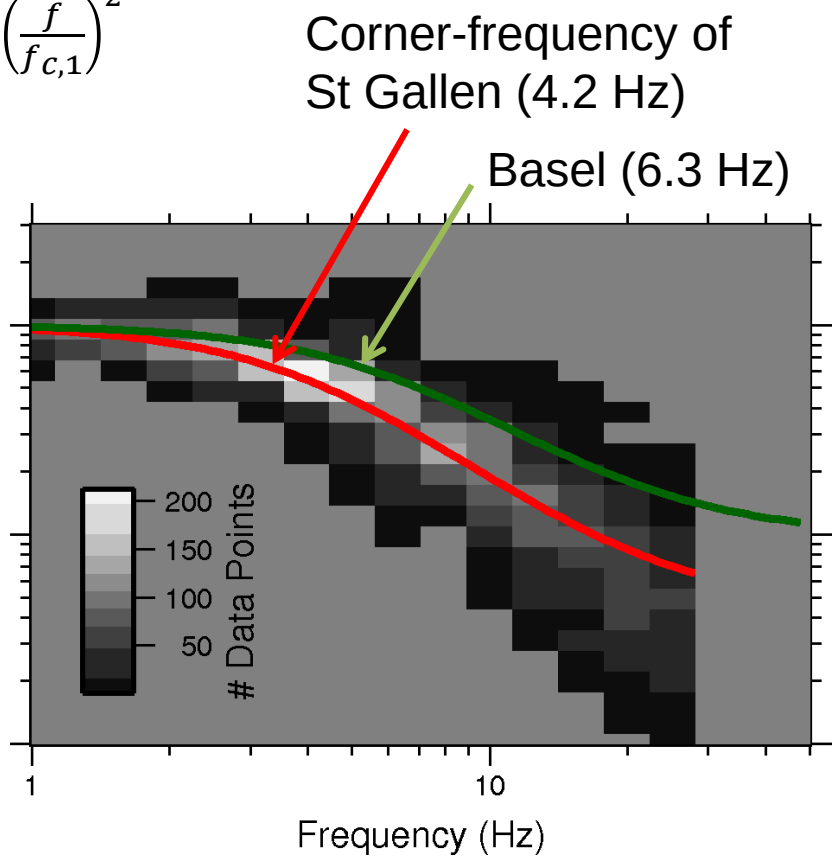
- Stacking with normalized reference (small) event.



St Gallen Source Spectrum (M_L-M_W =0.1)

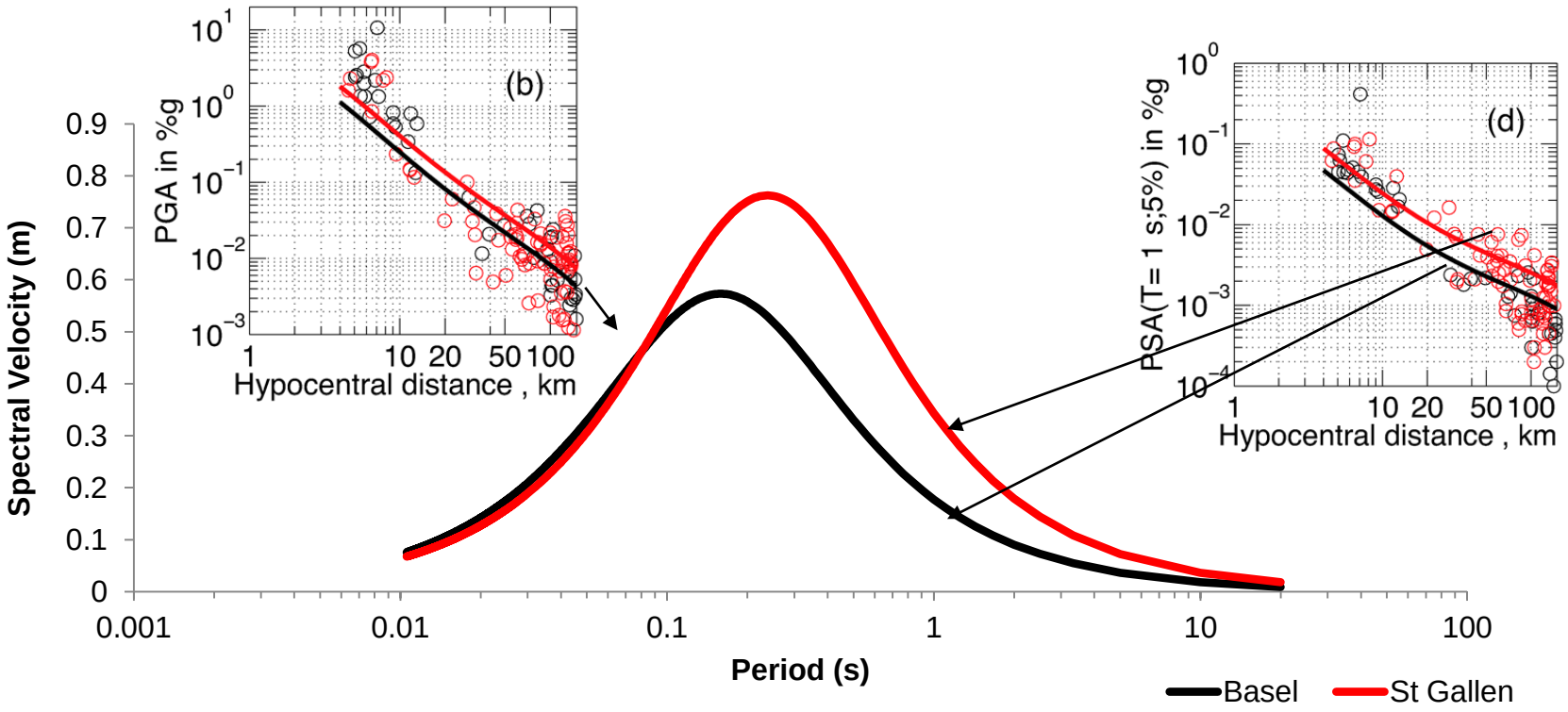
- Source spectrum ratio: $\frac{E_1}{E_2}(f) = \frac{\Omega_{0,1}}{\Omega_{0,2}} \frac{1+\left(\frac{f}{f_{c,2}}\right)^2}{1+\left(\frac{f}{f_{c,1}}\right)^2}$





Source Spectra

- Similar high-frequency motions radiated (similar M_L)
- St-Gallen had higher long-period motions (higher M_W).



Summary

- The **St Gallen event had a larger fault area** (~550m diameter c.f. 400m) and higher M_W (3.4 vs 3.2).

- **In Basel the slip duration is ~30% shorter** (due to both the smaller fault and faster rupture) leading to a larger proportion of high-frequency radiation (higher source-corner frequency).

- The combined effects lead **to larger long-period motions in St Gallen**, but **comparable short-period motions**.

- Recorded **ground motions**, felt/calculated **intensities** and **source spectra do not explain** why the Basel event led to $7.5M losses and St Gallen did not.

Conculsion

- Were the Basel 2006 and St. Gallen 2013 Events Fundamentally Different?

- **Not enough, over the average of all observations, to warrant differences in damage. With the caveat that the exceptional ground motion recording in Basel is not yet explained.**

- Edwards, B., T. Kraft, C. Cauzzi, P. Kästli and S. Wiemer (in press). **Seismic Monitoring and Analysis of Deep Geothermal Projects in St. Gallen and Basel, Switzerland**, Geophysical Journal International doi: 10.1093/gji/ggv059.