Appendix 2

Seismicity, state of stress and induced seismicity in the Molasse Basin and Jura (N-Switzerland)

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Zuammenfassung

Seit etwa 1983 führt der Schweizerische Erdbebendienst in Zusammenarbeit mit der Nagra detaillierte Studien zur Seismotektonik der Nordschweiz durch. Weitere Untersuchungen sind zur Zeit auch im Zusammenhang mit der durch ein Geothermie Projekt in Basel induzierten Seismizität im Gange. Die Resultate dieser Arbeiten können wie folgt zusammengefasst werden:

- Die Erdbebenherde in der Nordschweiz sind über die gesamte Kruste verteilt.
- Beben können auch in geringen Tiefen auftreten (1-2 km).
- Die Herdmechanismen der induzierten Beben in Basel stehen im Einklang mit den Mechanismen der natürlichen Seismizität und mit den in situ gemessenen Spannungen im Grundgebirge.
- Die Herdmechanismen in der Nordschweiz entsprechen praktisch ausschliesslich Blattverschiebungen und Abschiebungen.
- Herausragendes Merkmal ist die horizontale und stabile ENE-WSW Ausrichtung der T-Achsen und entsprechender NNW-SSE ausgerichteter Kompression.
- Die Spannungen im Deckgebirge scheinen gegenüber dem Grundgebirge leicht im Uhrzeigersinn gedreht zu sein.

1. Seismicity in Switzerland and surroundings

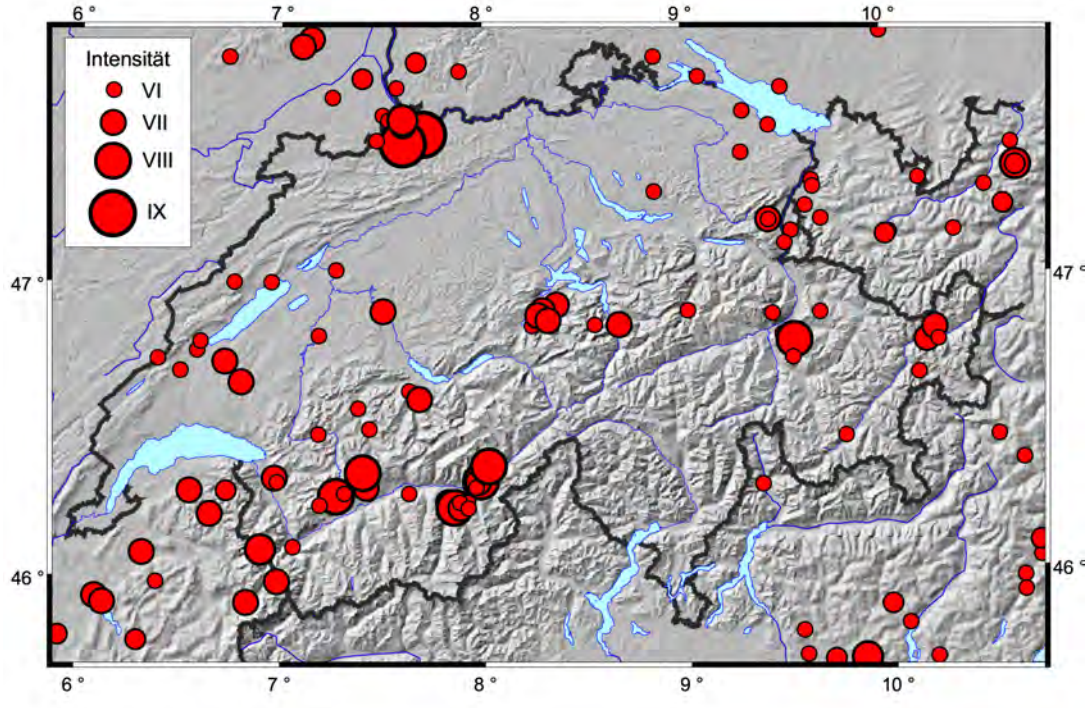


Fig. 1.Historical earthquakes in Switzerland and surroundings since the year 250.

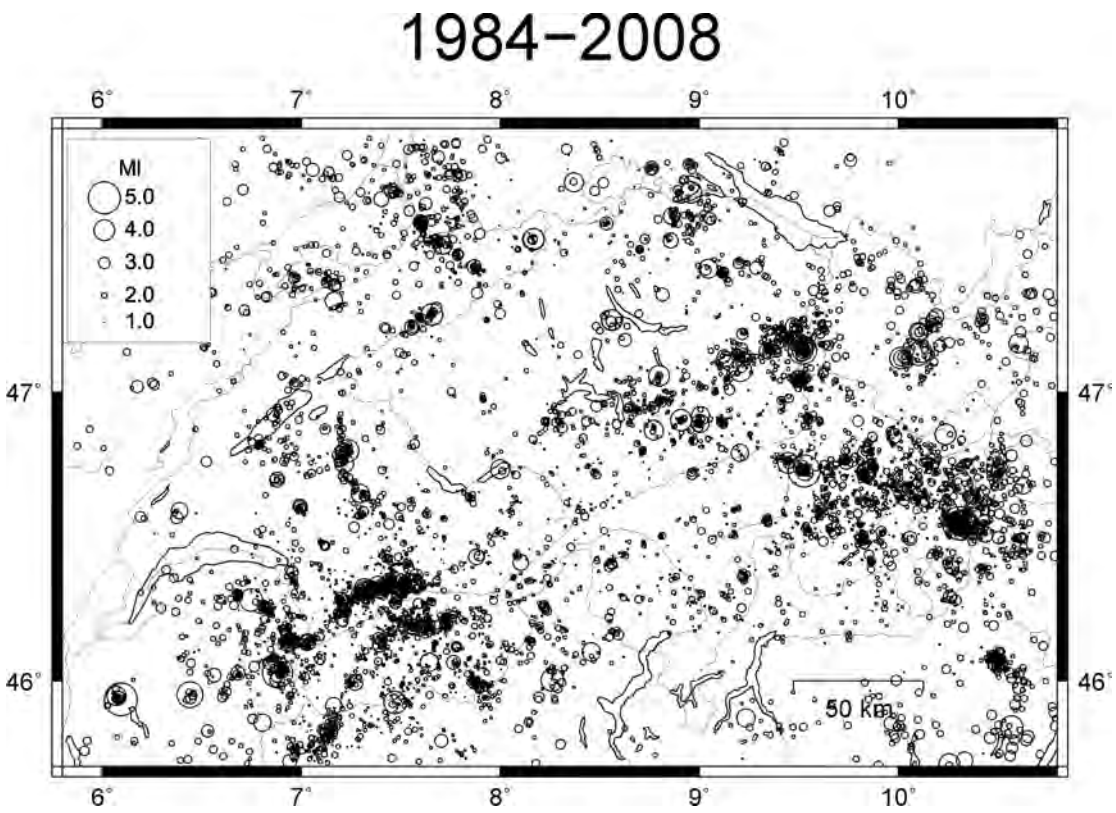


Fig. 2. Recent earthquakes in Switzerland and surroundings.
The map in Figure 1 shows the location of the epicenters of all earthquakes in Switzerland known to have caused damage to buildings over the course of history. Most prominent on this map is the earthquake of 1356, which destroyed large parts of the city of Basel and which is the strongest historically known earthquake to have occurred in Europe north of the Alps. Other significant events are the earthquakes of 1601 in central Switzerland, of 1755 near Brig, of 1855 south of Visp and of 1946 north of Sierre, as well as the earthquake sequence of Sarnen in 1964.

The higher seismic activity in the Alps compared to the Alpine foreland seen in the historical seismicity is confirmed by the distribution of instrumentally determined epicenters over the past 25 years (Figure 2). Seismic activity seems to be particularly low in the central parts of the Molasse Basin. One can however recognize two diffuse bands of increased activity extending south-south-westward from the Lake of Constance and southward from the southern end of the Rhine Graben near Basel across the Jura Mountains towards Lac Léman (Deichmann et al. 2000b). Particular noteworthy in this last region is the N-S alignment of epicenters just east of the city of Fribourg. As shown in Figure 3, this constitutes, in fact, one of the few instances in which the otherwise rather diffuse distribution of seismicity delineates and active fault below the northern Alpine foreland (Kastrup et al, 2007).

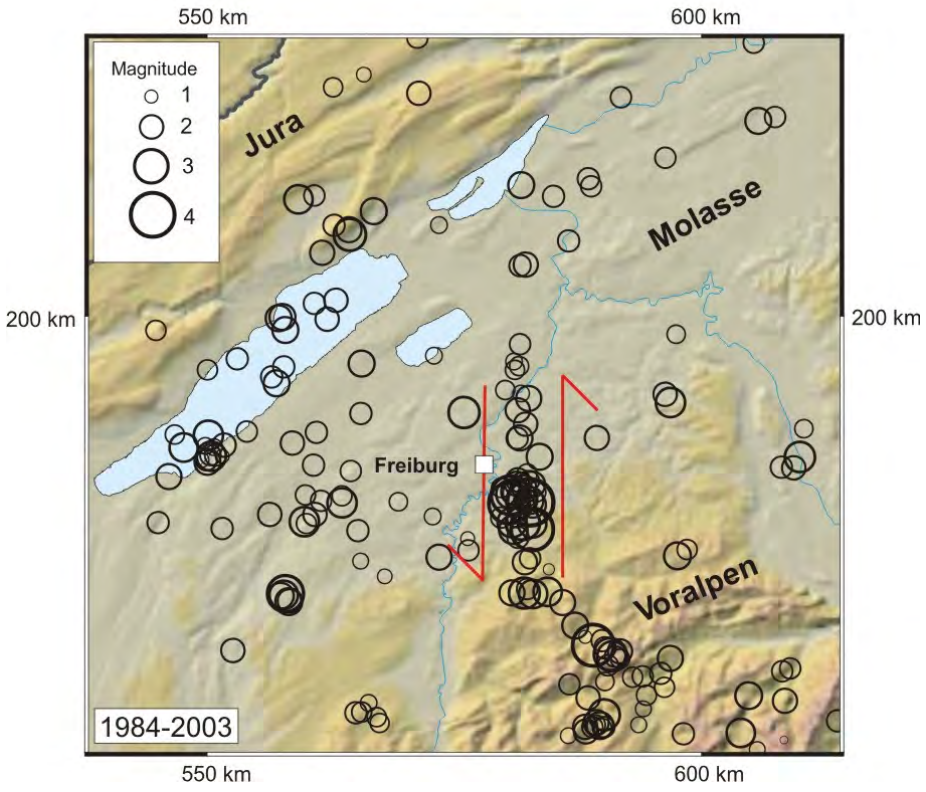


Fig. 3. The three earthquake sequences of 1987, 1995 and 1999 in the vicinity of Fribourg, with a maximum magnitude (ML) of 4.3, delineate a NS striking fault within the sedimentary cover. The corresponding focal mechanisms represent left-lateral transcurrent motion along this NS striking fault (Kastrup et al. 2007).

2. Focal depths

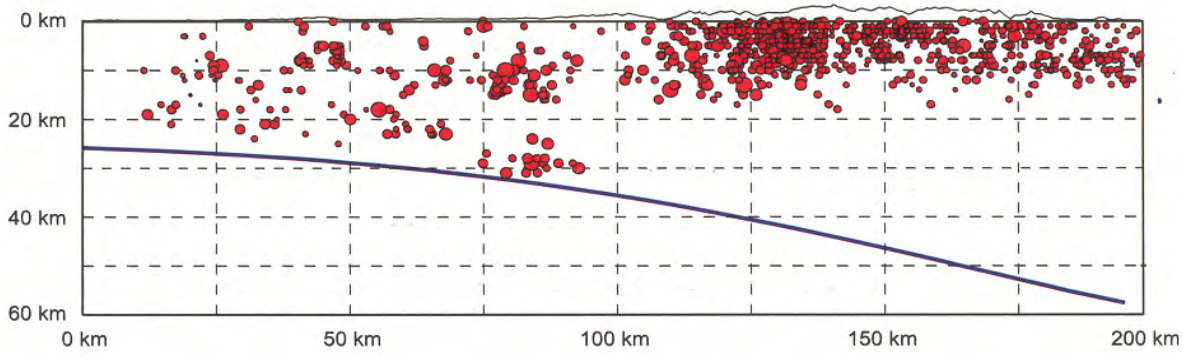


Fig. 4. Focal depth of selected recent earthquakes below Switzerland projected onto a NNW-SSE striking cross-section from Basel (left) to Locarno (right). The blue curve delineates the apprximate depth of the crust-mantle boundary (Moho). Only those events are included for which hypocenter locations are sufficiently reliable (see Deichmann et al. 2000a).

It is well-known that focal depths of locally recorded earthquakes are more difficult to determine with confidence than epicentral coordinates. Thus, in general, the large majority of routinely determined focal depths are not reliable, and tectonically relevant interpretations should be based only on data sets that meet suitable quality criteria.

In Figure 4 are shown the hypocenters of selected earthquakes projected onto a NNW-SSE striking cross-section from Basel to Locarno. The direction of the profile is such that it is perpendicular to the predominant trend of the Alps and of the major tectonic units and to the isolines of the Moho depth. The dataset was selected from all earthquakes recorded between 1975 and 2007 according to the criteria documented in Deichmann et al (2000a). Figure 4 shows that earthquake hypocenters below the northern Alpine foreland of Switzerland are distributed throughout the entire crust from close to the surface down to the Moho at a depth of about 30 km, whereas below the central Alps, where the Moho lies at depths of 40-60 km, earthquakes are restricted to the upper 15-20 km of the crust. With the adopted selection criteria, the hypocenters that are shallower than about 20 km are generally still poorly constrained, unless they happen to have been recorded by at least one station at an epicentral distance that is less than about 1.5 times their focal depth. However, the reliability of the computed hypocentral parameters increases with depth and consequently both the existence of the lower crustal earthquakes below the foreland and their absence beneath the Alpine mountain range are significant. In addition, there is no evidence of any seismicity in the upper mantle beneath Switzerland. The transition from the deeper to the shallower seismicity cut-off consists of an abrupt vertical jump of more than 10 km, that seems to coincide with the Helvetic front at the northern margin of the Alps.

The difference in focal depth distribution between Alps and Alpine foreland is also illustrated in the histograms in Figure 5. Note that the energy release as a function of depth is determined to a very large degree by just a few stronger events and should not be over-interpreted.

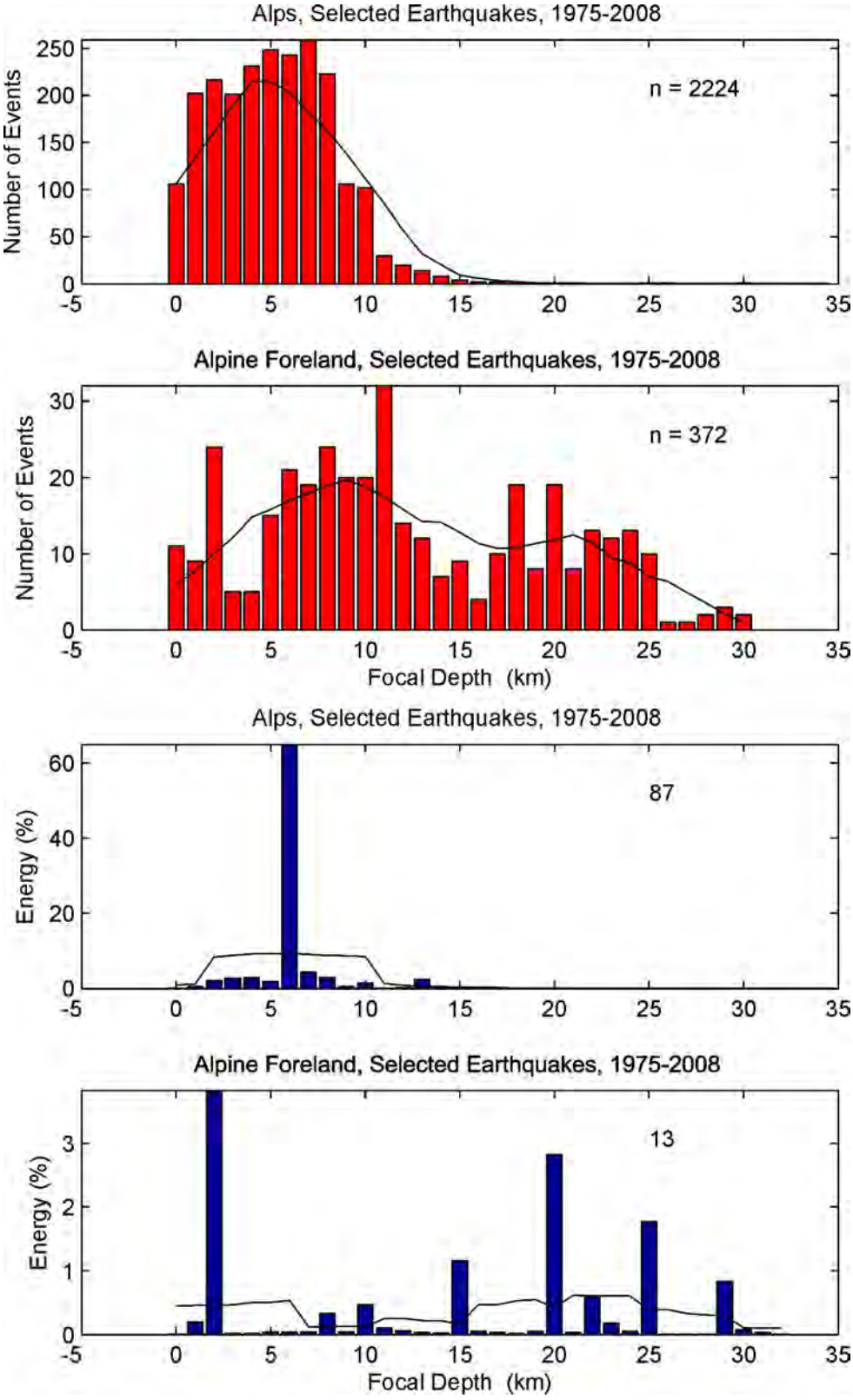


Fig. 5.Histograms of number of events (top) and released energy (bottom) of selected earthquakes below the Alps and the northern Alpine foreland of Switzerland. Selection criteria: maximum gap 180 degrees, maximum epicentral distance to the nearest station 20 km, minimum number of arrival times 9 and maximum rms of the travel-time residuals 0.4 seconds. The continuous curves represent a moving average over a 9 km depth interval. Note that the histogram of the released energy is dominated by only a few stronger events (Deichmann, unpublished).

In the context of planned projects for the storage of CO_2, it is important to note that earthquakes are not restricted to larger depths in the crystalline basement. In fact with the increased density of the available seismic networks and improved analysis tools, evidence has increased over the recent past that earthquakes can also occur at depths of only a few km within the sedimentary cover. A representative sample is listed in the table below.

Date	Depth (km)	Mag	Location
1996/07/15	2	5.1	Annecy
1997/11/22	1	3.8	Walensee
1999/02/14	2	4.3	Fribourg
1999/09/12	2	3.2	Eglisau
2000/04/06	1	3.2	Saint Ursanne
2003/02/03	2	2.9	Neuchatel
2006/03/29	2	3.2	Cortaillod

With magnitudes reaching 5 (Annecy), these shallow earthquakes can be quite damaging (for more details concerning these events, see the corresponding annual reports of the SED).

3. State of stress

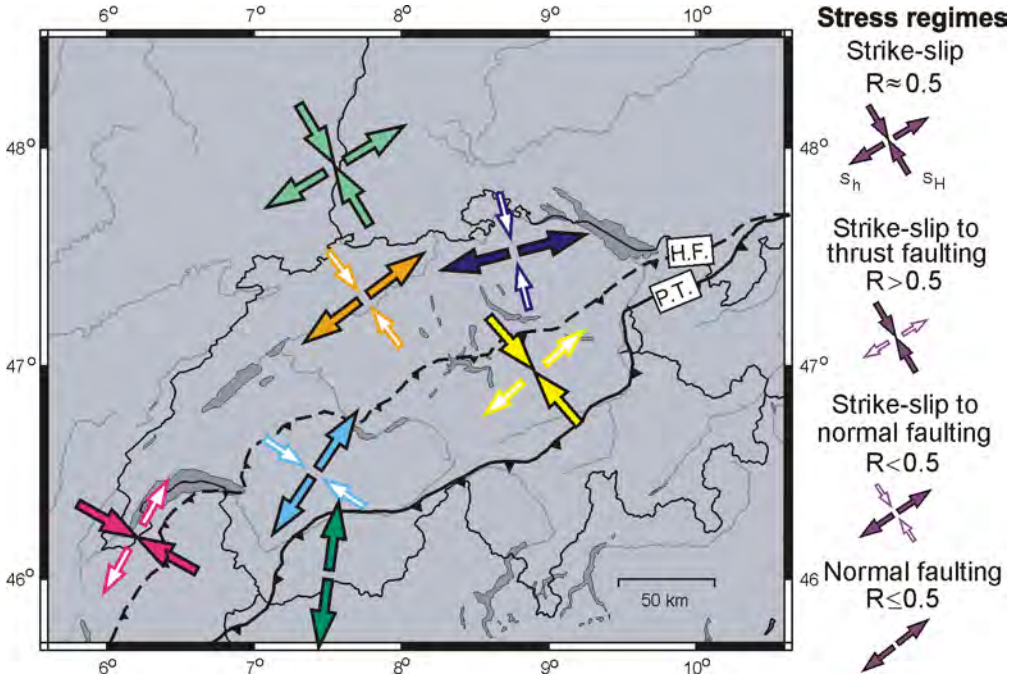


Fig. 6. Stress regime in the Alps and northern Alpine Foreland (Kastrup et al. 2004). P.T. denotes the northern margin of the Penninic thrust and H.F. the Helvetic front.

Figure 6 is taken from a study devoted to a systematic analysis of the state of stress of the central European Alps and northern Alpine foreland in Switzerland, based on focal mechanisms of 138 earthquakes with magnitudes between 1 and 5. The most robust feature of the results is that the azimuth of the minimum compressive stress, S3, is generally well constrained for all data subsets and always lies in the NE quadrant (Figure 7). However within this quadrant, the orientation of S3 changes systematically both along the structural strike of the Alpine chain and across it. The variation in stress along the mountain belt from NE to SW involves a progressive, counter-clockwise rotation of S3, and is most clear in the foreland, where it amounts to 45 – 50 degrees. This pattern of rotation is compatible with the disturbance to the stress field expected from the indentation of the Adriatic Block into the Central European Plate, possibly together with buoyancy forces arising from the strongly arcuate structure of the Moho to the immediate west of our study area. Across the Alps, the variation in azimuth of S3 is defined by a progressive, counter clockwise rotation of about 45 degrees from the foreland in the north across the Helvetic domain to the Penninic nappes in the south and is accompanied by a change from a slight predominance of strike-slip mechanisms in the foreland to a strong predominance of normal faulting in the high parts of the Alps. The observed rotation can be explained by the perturbation of the large-scale regional stress by a local uniaxial deviatoric tension with a magnitude similar to that of the regional differential stress and with an orientation perpendicular to the strike of the Alpine belt (Figure 8). The tensile nature and orientation of this stress is consistent with the 'spreading' stress expected from lateral density changes due to a crustal root beneath the Alps (Kastrup et al. 2004).

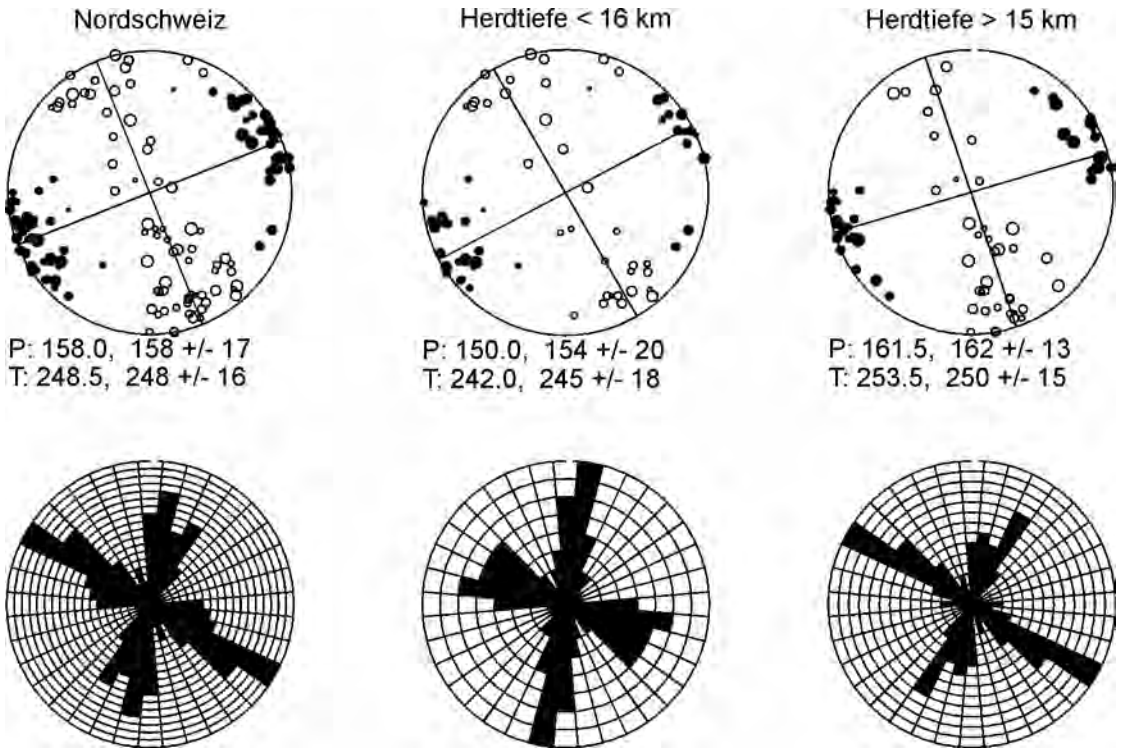


Fig. 7. Top: stereographs of P- (empty dots) and T-axes (black dots). Bottom: polar histograms of the orientation of focal mechanism nodal planes. Left: for all focal mechanisms in northern Switzerland; middle: upper-crustal events; right: lower-crustal events (Deichmann, unpublished).

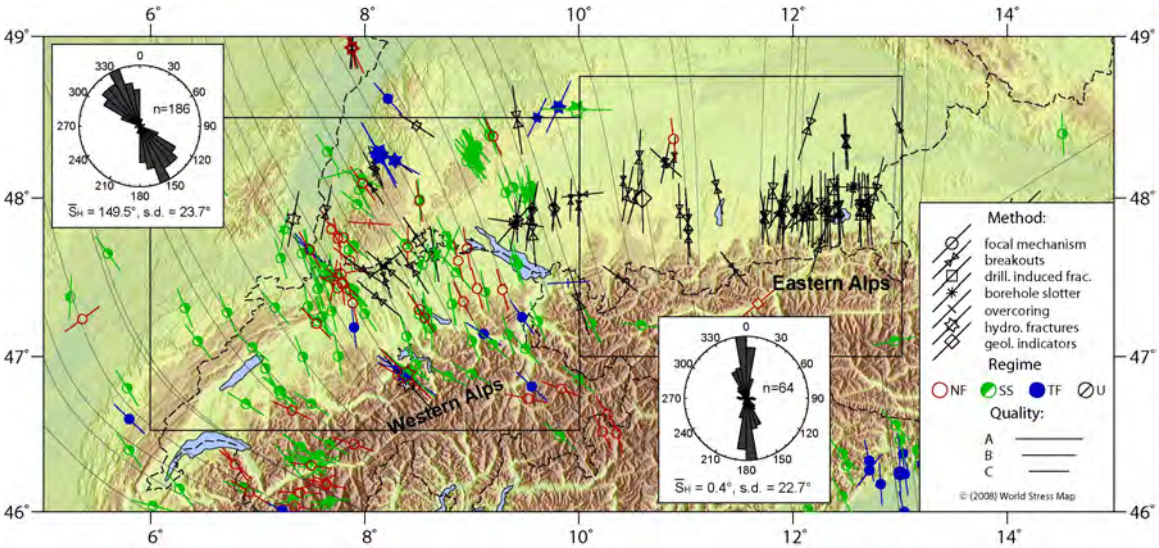


Fig. 8. Stress field indicators in the Alpine foreland of northern Switzerland and southern Germany (Reinecker et al. 2009).

4. Cases of induced seismicity in Switzerland.

The first documented case of induced seismicity in Switzerland dates back to the year 1953: the impoundment of the hydropower reservoir of Lac de Salanfe in the Wallis was followed by a sequence of earthquakes, of which several were strongly felt by the local population. At the same time new thermal springs appeared in the neighboring Val d'Illiez, which were linked to severe water leakage from the lake. In 1995/96 efforts were made to seal the water leakages. The following rise in the water level was again followed by a revival of seismic activity in the region between Lac de Salanfe and Val d'Illiez.

Two other recent cases of induced seismicity are related a quarry near Quinten on the northern shore of the Walensee in 1997 and 1998 and to the construction of the new railway tunnel below the Gotthard between 2004 and 2006 (see the corresponding annual reports of the SED).

In the following, we document the two most spectacular cases of induced seismicity in Switzerland that occurred in the recent past.

4.1 Seismicity induced by rainfall in central Switzerland, August 2008.

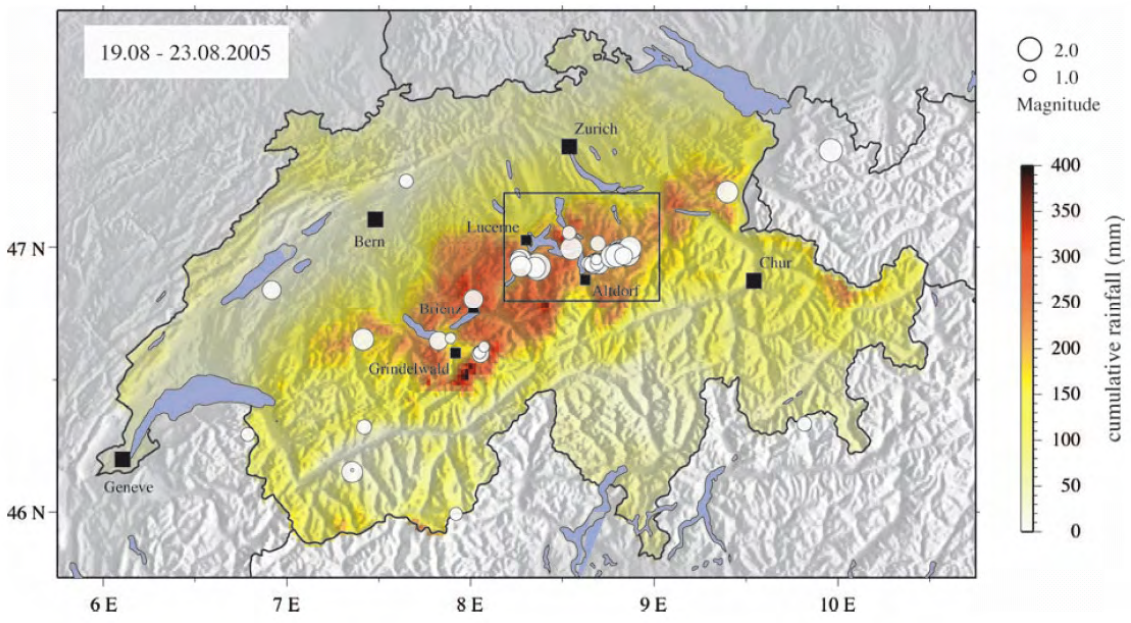


Fig. 9. Rain-induced seismicity in Central Switzerland in August 2005 (Husen et al. 2007).

The summer of 2005 saw an anomalous burst of activity that includes 51 events over a period of less than 48 hours that started on the afternoon of August 22nd. Of these events, 39 occurred within 12 hours between 9 PM and 9 AM of the following day. Magnitudes of these events range between 1.0 and 2.4. Single earthquake swarms that produce a large number of small earthquakes over a period of a few days are quite common. What is however unusual about this concentration of seismic activity is that it occurred simultaneously over a very large region that extends from Canton Schwyz in the northeast across the region around Stans and Alpnach, south of Lake Lucerne, all the way to Grindelwald in the Bernese Oberland. The main centers of activity were two separate

clusters around Bisistal and south of Riemenstalden in Canton Schwyz (Figure 9). Together these two clusters contributed more than half the total number of earthquakes observed in those two days. Although focal depths of most of these events are poorly constrained by routine location procedures, the shallow sources are confirmed at least qualitatively by both the signal character of the events (conspicuous surface waves even at short epicentral distances) and the fact that numerous events with magnitudes less than 2 were perceived by the population as loud bangs.

During this time, the region in which all of these earthquakes occurred, suffered very intense rainfalls, which caused massive floods and numerous landslides. Given this spatial and temporal coincidence and the shallow focal depths, it is thus likely that this unusual seismic activity was induced by a sudden increase in pore pressure due to the intense precipitation. This hypothesis is furthermore supported by the fact that the two main centers of activity around Bisistal and Riemenstalden are highly permeable carsic regions, where surface waters and thus fluid pressure perturbations
can propagate rapidly to greater depths.

4.2 Seismicity induced by geothermal reservoir stimulation below Basel

To stimulate the reservoir for a ”hot dry rock” geothermal project, that was initiated by a private/public consortium in the city of Basel, Switzerland, approximately 11500 m3 of water were injected between December 2nd and 8th, 2006, at high pressures into a 5 km deep well. More than 10500 seismic events were recorded during the injection phase (Figure 10) and more than three years later, seismic activity still had not returned to pre-stimulation levels. The 195 strongest events, with ML between 0.7 and 3.4, that occurred between December 2nd, 2006, and November 30th, 2007 have also been recorded by the Swiss Seismological Service (SED). The analyzed data were recorded by a six-station borehole network, operated by the project developers, as well as by several permanent and temporary surface networks. The overall hypocenter distribution, based on a relative master location technique, defines a near-vertical lens-shaped cloud that strikes NNW-SSE with a diameter of about 1.2 km at a depth between 4 and 5 km (Figure 11). With continuing injection, the seismicity migrated away from the borehole, as would be expected from a diffusion process, and after shut-in and bleed-off, seismic activity took place mainly at the periphery of the stimulated volume. Focal mechanisms have been constructed for the 28 strongest events (Figure 12). Based on high-precision relative hypocenter locations, the ML 3.4 mainshock occurred as dextral strike-slip motion on a steeply dipping WNW-ESE striking fault, that is oriented favorably with respect to the ambient stress field. Overall, the observed focal mechanisms agree with what would be expected from both the in-situ stress observations and the stress field derived from the previously known natural seismicity (Figure 13). This, together with the fact that most of the induced seismicity occurred at water pressures in the formation that were well below the level of the least compressive stress, supports the conclusion that the earthquakes induced by the reservoir stimulation below Basel, rather than representing a case of hydro-fracking, correspond to shear dislocations on pre-existing faults driven by the ambient tectonic stress. For further details see Häring et al. (2008), Deichmann and Ernst (2009), Deichmann and Giardini (2009), Valley and Evans (2009).

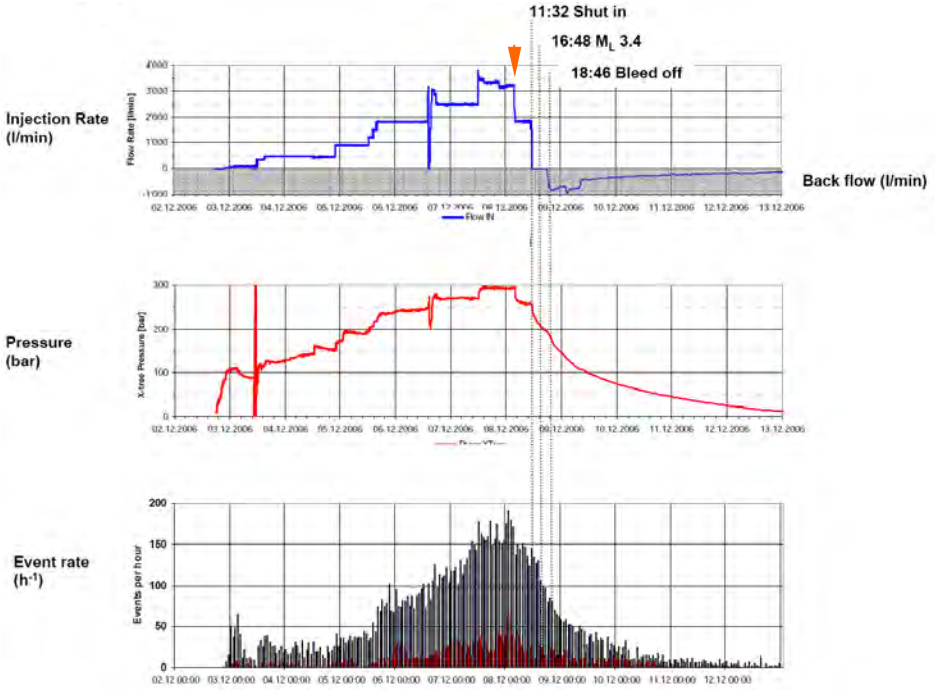


Fig. 10. Injection rate, well-head pressure and induced seismicity in Basel in December 2006 (Häring et al. 2008).

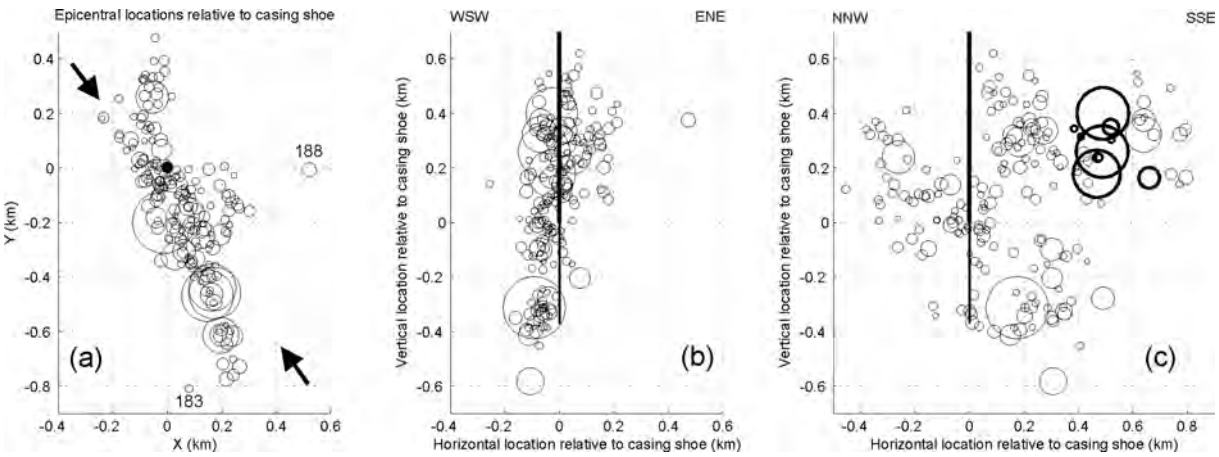


Fig.11. Relative epicenter locations (a) and focal depths along strike (b) and perpendicular to the strike of the hypocenter distribution of the 195 strongest induced events (Dec. 2006 – Nov. 2007). Symbol size is proportional to seismic moment. The location of the injection borehole is marked by a black dot in (a) and by the vertical lines in (b) and (c). The heavy

circles in (c) correspond to the nine events that occurred between Jan. 1st and Feb 2nd, 2007 (Deichmann and Giardini, 2009).

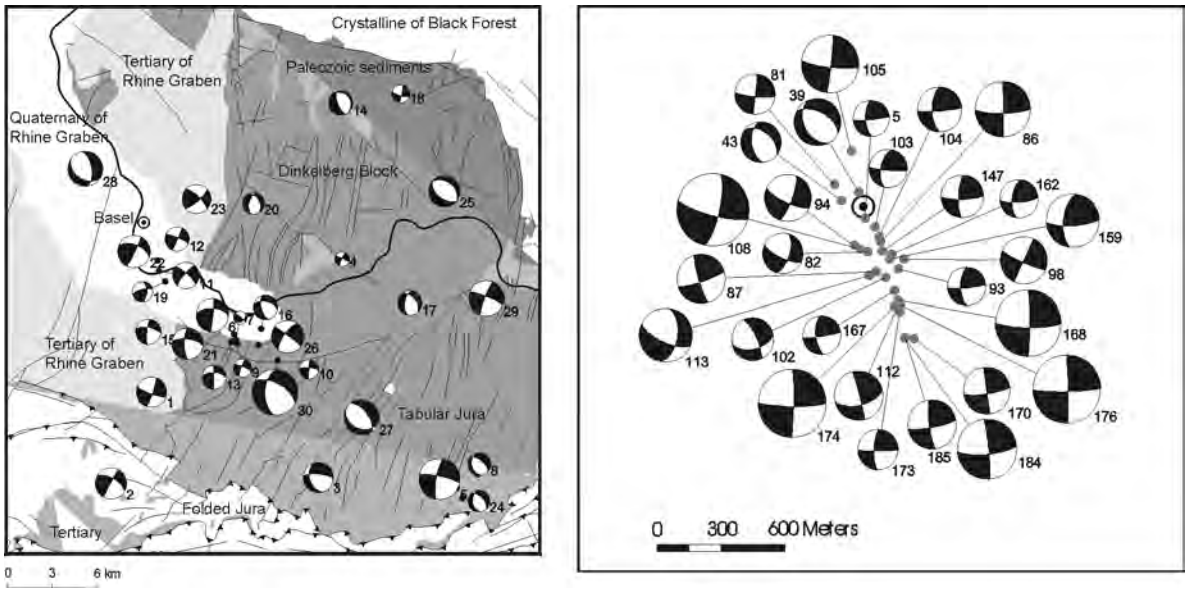


Fig. 12. Focal mechanisms of the natural seismicity in the Basel region recorded between 1982 and 2004 (left) and focal mechanisms of the 28 largest events induced in 2006 and 2007 by the geothermal reservoir stimulation (Deichmann and Giardini, 2009).

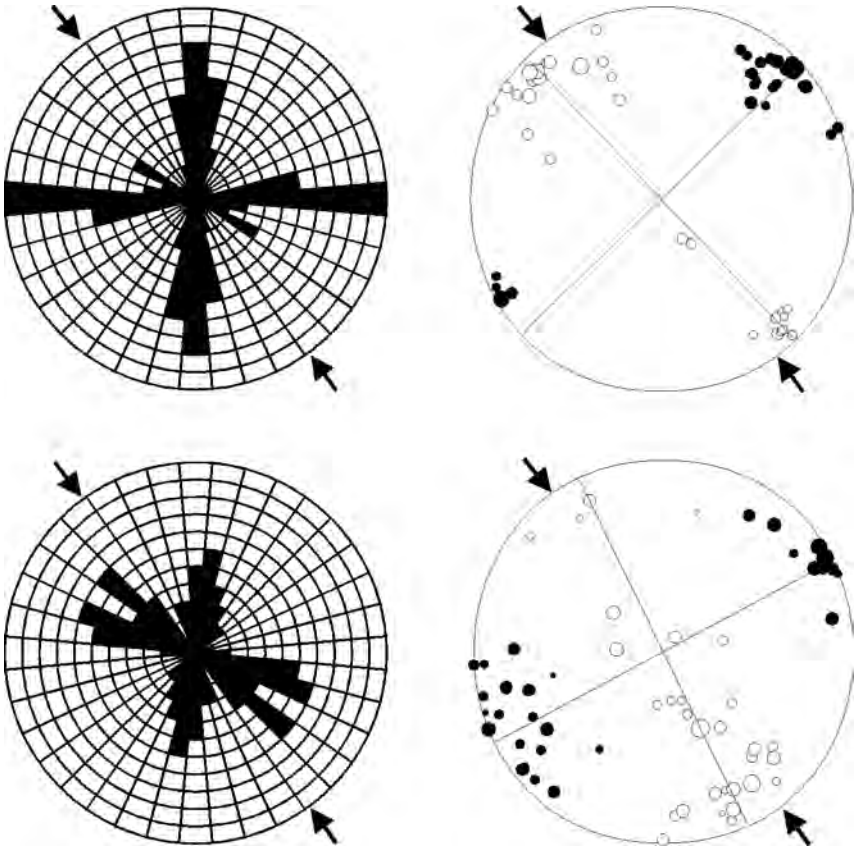


Fig. 13. Polar histograms of the nodal planes and stereographic plots of the P- (empty dots) and T-axes (black dots) of the induced (top row) and natural seismicity (bottom row), corresponding to the focal mechanisms shown in Figure 12 (Deichmann and Giardini, 2009). The arrows point in the direction of the maximum horizontal compressive stress derived from wellbore failure measurements in the crystalline basement down to 5 km depth below Basel from Valley and Evans (2009).

5. Conclusions

The results from numerous seismotectonic studies based on earthquake monitoring performed by the Swiss Seismological Service as well as on analyses of induced seismicity can be summarized as follows:

- Hypocenters below northern Switzerland are distributed throughout the Earth's crust;
- Earthquakes can occur also at shallow depths (1-2 km), and at least in one instances they have also caused significant damage (Annecy);
- Earthquake focal mechanisms in northern Switzerland correspond to a strike-slip to normal faulting regime;
- The salient feature is the nearly horizontal and stable ENE-WSW orientation of the T-axes (extension) and a corresponding NNW-SSE oriented compression;
- Stress in the sedimentary cover seems to be rotated slightly in a clockwise direction with respect to the dominant orientation in the basement;
- The focal mechanisms associated with the seismicity induced by the geothermal project in Basel are in good agreement with the natural seismicity and with the stress orientation deduced from in-situ stress measurement in the crystalline basement.

6. References

Annual seismicity reports have been published by the Swiss Seismological Service since 1996 in the second or third issue of the following year of the Swiss Journal of Geoscience (former Eclogae Geologicae Helvetiae) under the title Earthquakes in Switzerland and surrounding regions. (Also available, in a slightly modified and in some cases updated form, on http://histserver.ethz.ch/seismotectonics/reports.php).

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