Assessing fault criticality using seismic monitoring and fluid pressure analysis

Léa Perrochet, Giona Preisig, Benoît Valley

Center for Hydrogeology and Geothermics, University of Neuchâtel, Switzerland

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Motivation & Objectives

The aim of the *JuraHydroTectonics* project is to combine the natural microseismicity and groundwater level fluctuations to estimate the fault criticality.

To this end, the objectives are to :

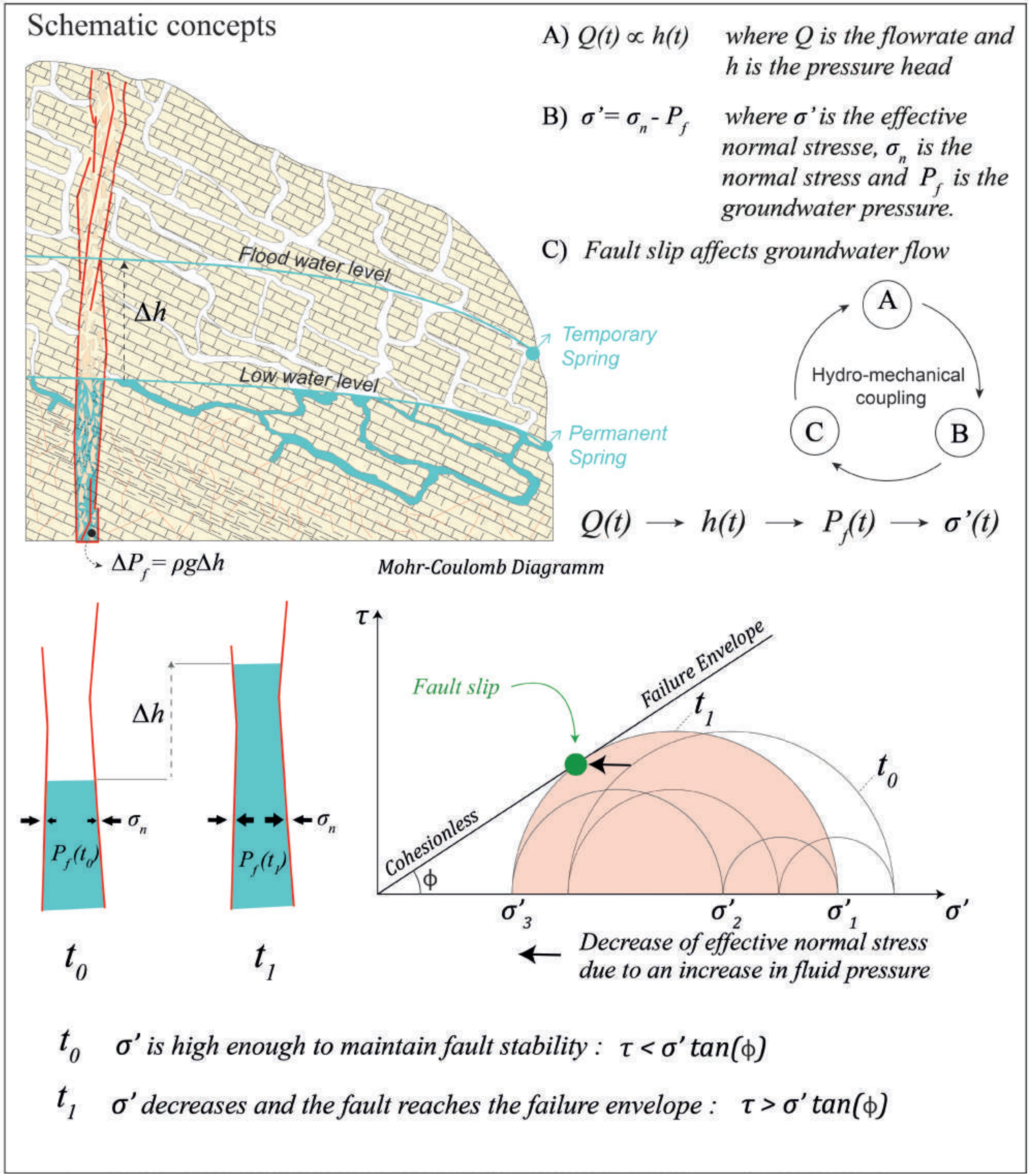
- **Monitor microseismicity** of several strike-slip faults in the Jura Mountains;
- Have continuous **spring discharge rates** and groundwater table **measurements** of the major karstic springs and aquifers in the vicinity of the faults;
- Determine **relations** between increasing **spring discharge** rates, groundwater levels and **low magnitude earthquakes**;
- Develop a straightforward methodology to assess fault criticality;
- Generate stress models of the shallow earth's crust based on field data.

Theoretical Background

A) In a mature karst aquifer, channeling effects allows large and rapid water table fluctuation, resulting in a rapid and important increase in fluid pressure. This has a direct effect on discharge rates of karstic springs.

B) An increasing fluid pressure in the deep aquifers and in the fault zone change the stress-regime by reducing the effective normal stress, leading to the shifting of the Mohr circle towards the Coulomb failure envelope.

C) Fault slip affects the fault's transmisivity leading to fluid flow changes.



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Rain-induced seismicity in karstic regions

Existing Cases

Mount Hochstaufen, Germany

Located in the Northern Calcareous Alps (NCA), Mount Hochstaufen (SE Germany) is part of the Staufen Massif. The geology mainly consists of limestones and dolomites. The higher part of Mount Hochstaufen is constitued of Wetterstein limestone, which is one of the most important karst host rock in the NCA.

In 2002, the region experienced two important rainfall events, in March and August. According to the Figure 1 (Kraft et al., 2006), an average of approx. 300 mm precipitation felt over the Mount Hochstaufen region in August during one week, following this intense rainfall period a seismic swarm was recorded in the Staufen Massif.

Earthquakes have epicentres distributed around the Mount Hochstaufen and their depth mostly lie between 0 and 3 km depth.

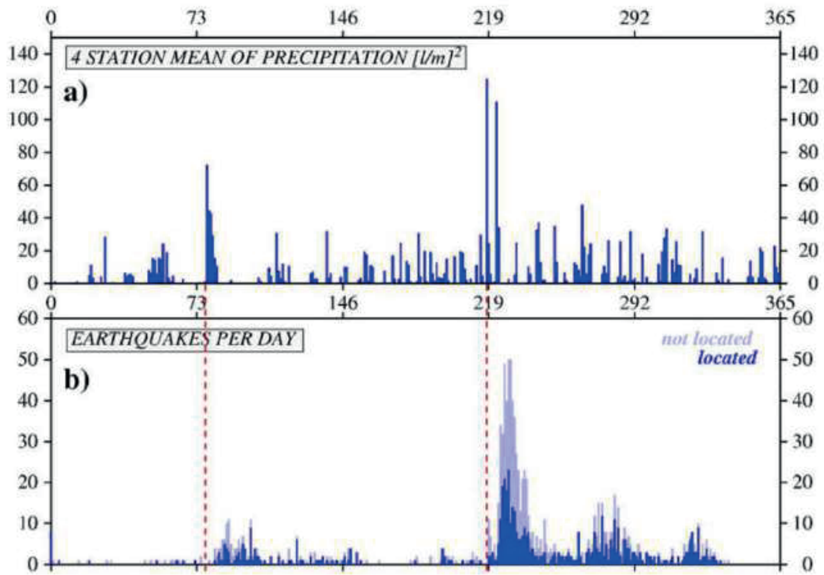


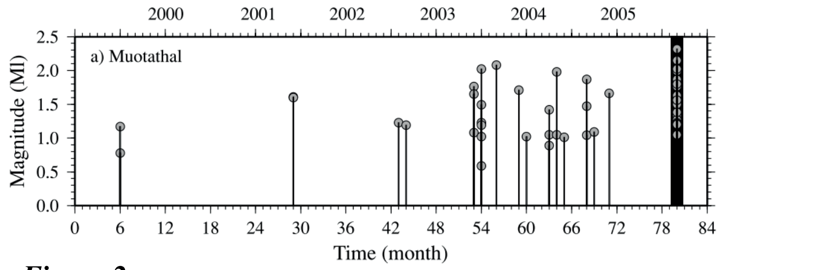
***Figure 1 :** (a) Daily cumulated precipitation in 2002 obtained by averaging 4 rain gauge stations, (b) Earthquake per day during 2002. Red dashed lines show the onset of intense rainfall. (Kraft et al., 2006)*

Muotathal, Switzerland

The geology in the region of Muotathal, central Switzerland, is dominated by limestone. The region is known for its karstic galleries reaching a total length of 250 km.

In 2005, the region experienced a succession of seismic events over a 12-hour period after a 3-day period of heavy rainfall (up to 300 mm). Such intense rainfalls have a return period of approx. 10 years [1].

Focal depths lie between 0 and 5 km.



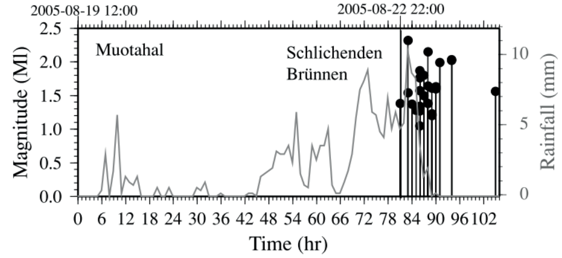


***Figure 2:** Earthquakes magnitude versus time for time period 1999-2006 (top) and 19.08.2005-24.08.2005 (bottom). (Husen et al., 2007)*

[1] https://hydromaps.ch

Nîmes Fault, Gard, France

The regional geology of the Gard department mainly consist in the Cenozoic and Mesozoic sedimentary cover, varying in thickness between 2 and 7 km. The area is known for its important karstic springs, such as La Fontaine de Nîmes and La Fontaine de Vaucluse.

In Septembre 2002, a catastrophic storm hit the region. Between the 8 and 9 septembre cumulated precipitation reached the value of 400 mm.

Seismicity increased during the two weeks following the storm. Focal depths mostly lie between 0 and 10 km.

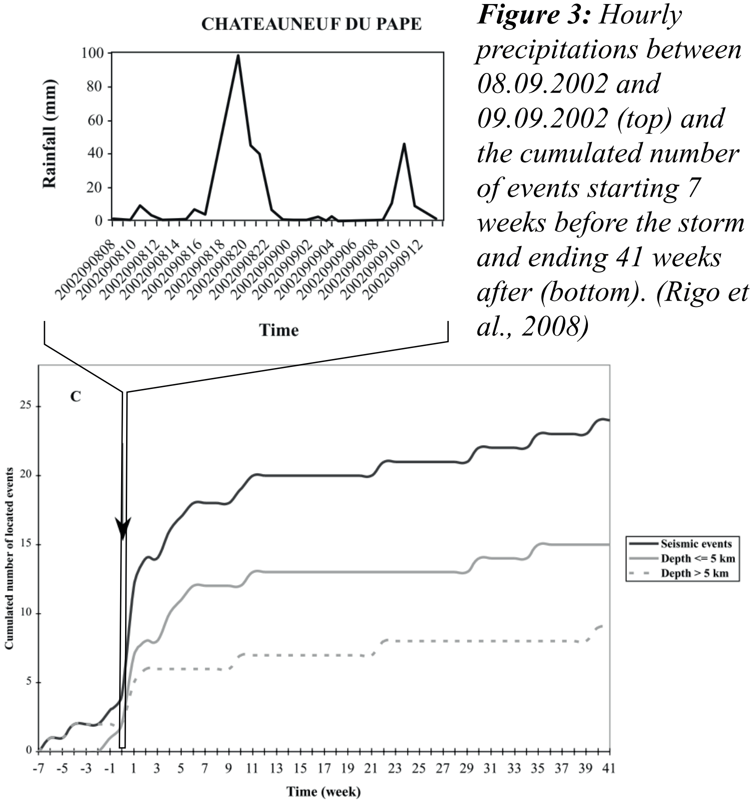


***Figure 3:** Hourly precipitations between 08.09.2002 and 09.09.2002 (top) and the cumulated number of events starting 7 weeks before the storm and ending 41 weeks after (bottom). (Rigo et al., 2008)*

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Area of Interest
&
Study site

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Area of Interest I

Internal Jura, Neuchâtel, Switzerland

The study site is located in the Internal Jura, on the northern shore of lake Neuchâtel (NW Switzerland). The Internal Jura consists in a succession of well developed folds, as well as thrusts and strike-slip faults. Strike-slip faults have a NNE-SSW orientation with associated ENE-WSW oriented faults forming a conjugate fault system. Thrust faults strike SW-NE resulting from the SE-NW Alpine compression.

The strike-slip faults are favourably oriented for failure assuming a strike-slip stress regime with NW-SE oriented maximum horizontal stress.

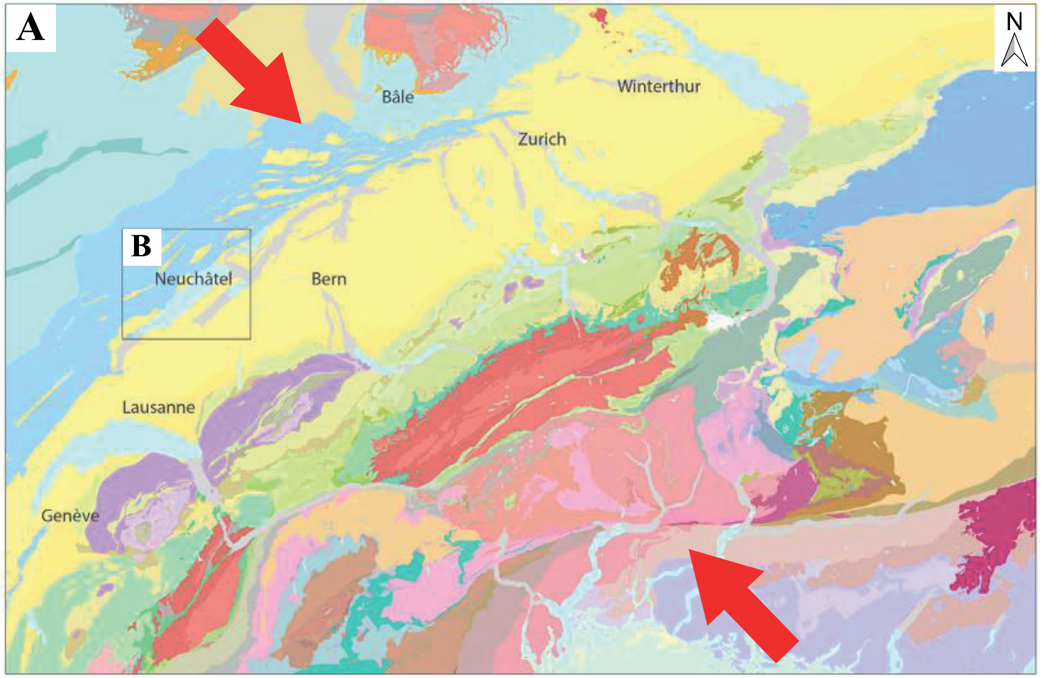

Figure 4: *(A) Tectonic map of Switzerland (Swiss Geological Survey at swisstopo), with the area of interest (Figure 5). Red arrows represent the maximum horizontal stress orientation. Colours represent the tectonic units. In the area of interest, these units consist of the Molasse (yellow) and the Internal Jura (blue).*

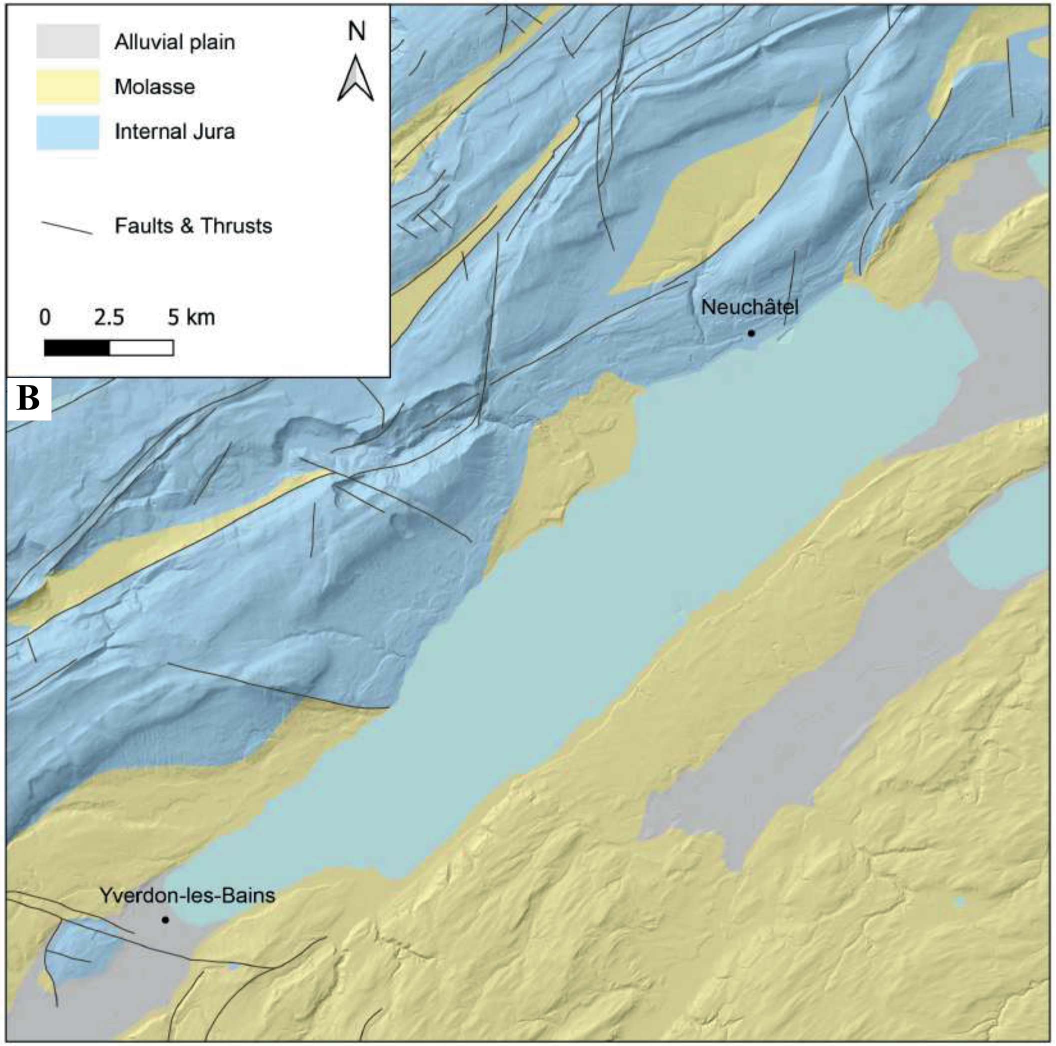

Figure 5: *(B) Tectonic map and shaded relief (Swiss Geological Survey at swisstopo), of the area of interest highlighting the fold-and-thrust belt, with the succession of anticlines and synclines, as well as the major faults and thrusts.*

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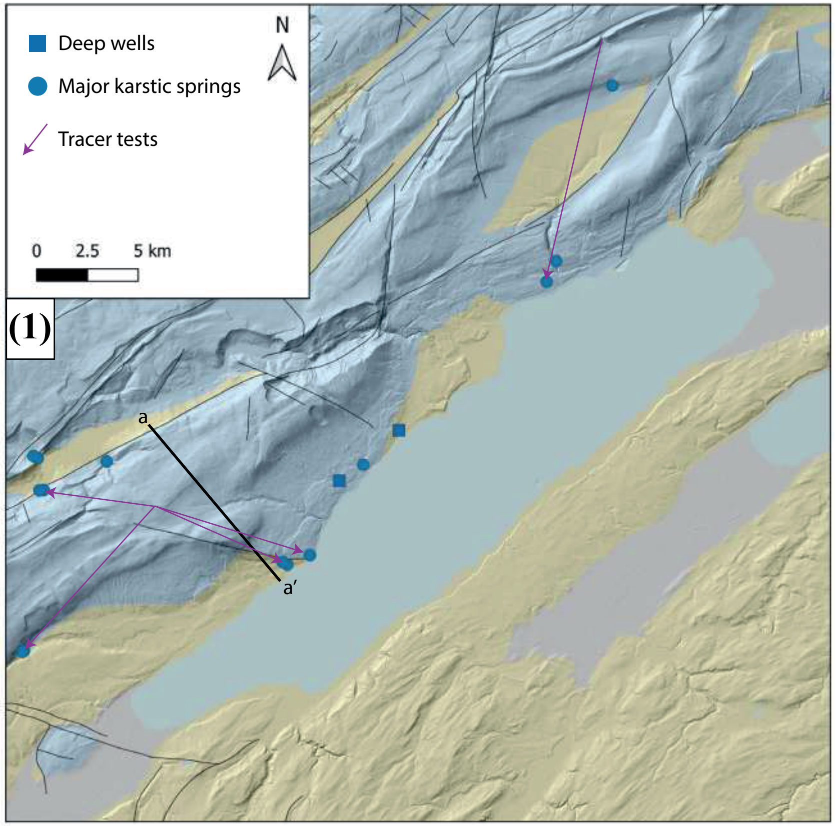
Area of Interest II

Geological & Hydrogeological setting

The geology of the Internal Jura consists in an alterning succession of marls and limestones layers from the Cenozoic and Mesozoic. The sedimentary cover is 2-3 km thick in this area, and the strike-slip faults are thought to affect the entire Cenozoic and Mesozoic cover (Sommaruga 1997).

The cross section a-a' illustrates the different lithologies and the fold-and-thrust geometry, typical for the Internal Jura, as well as hydrogeological properties of the different layers.

These formations show distinct signs of karst and several karstic spring are documented in the area of interest.

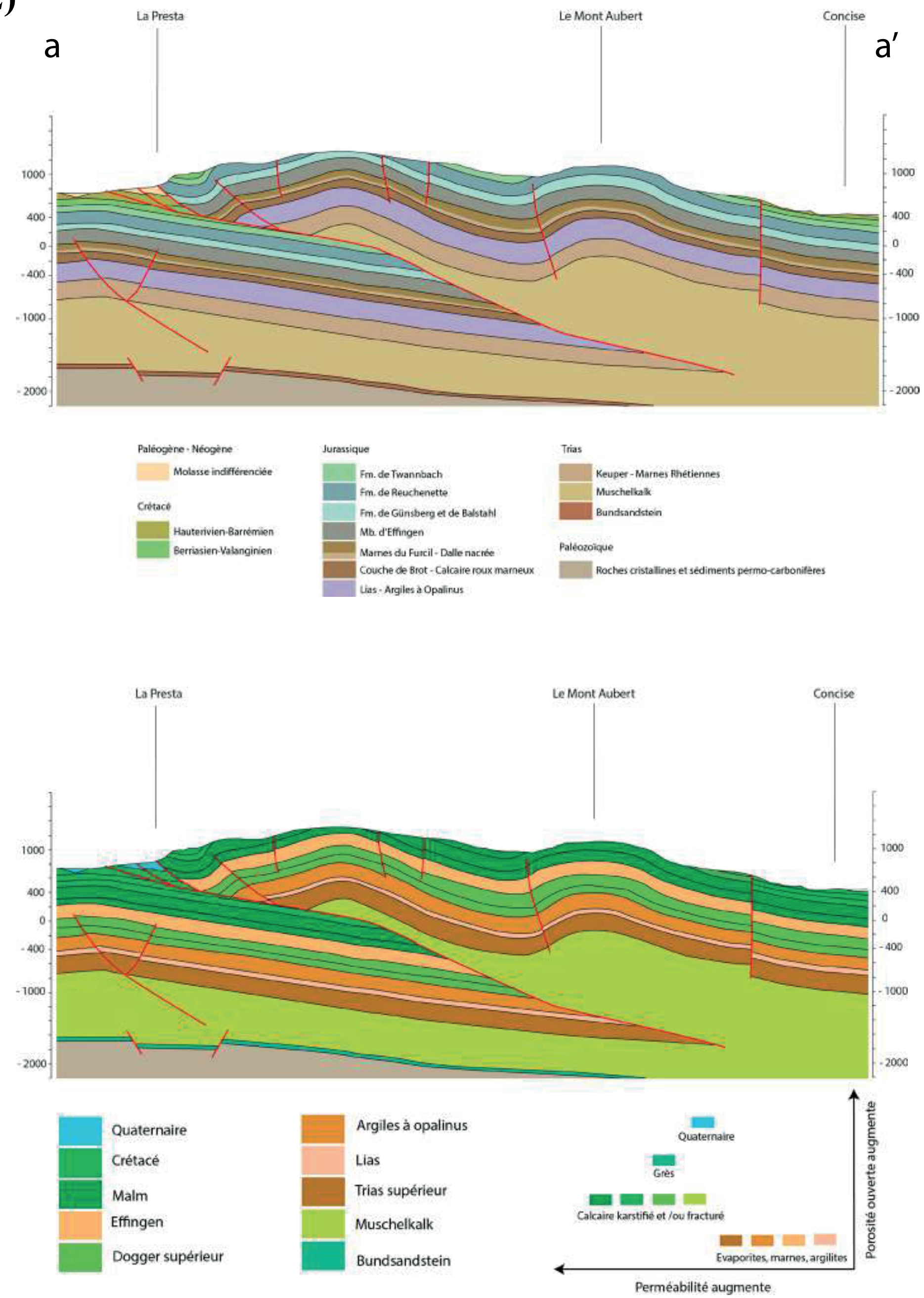


(1)

Figure 6: *(1) Area of interest with major strike-slip and thrust faults, major karstic springs (blue circle), as well as two deep wells (~300m, blue square)*

Figure 7: *(2) Cross section a-a', showing the lithologies (top) and their hydraulic properties (bottom). The cross section illustrates the typical geometry of a fold-and-thrust belt.*

(2)



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Area of Interest III

Seismicity - 2000-2019

In the area of interest, the seismicity is moderate to low, but nonetheless present, as expressed by the map showing seismicity between the years 2000 and 2019, that was recorded by the Swiss Seismological Service (SED). The station coverage of the SED is less dense in NW Switzerland compared to the rest of the country. Combined with rather small earthquakes (ML < 2), the error in the location and the focal depth is quite important, which makes it difficult to assign an earthquake to a specific structure.

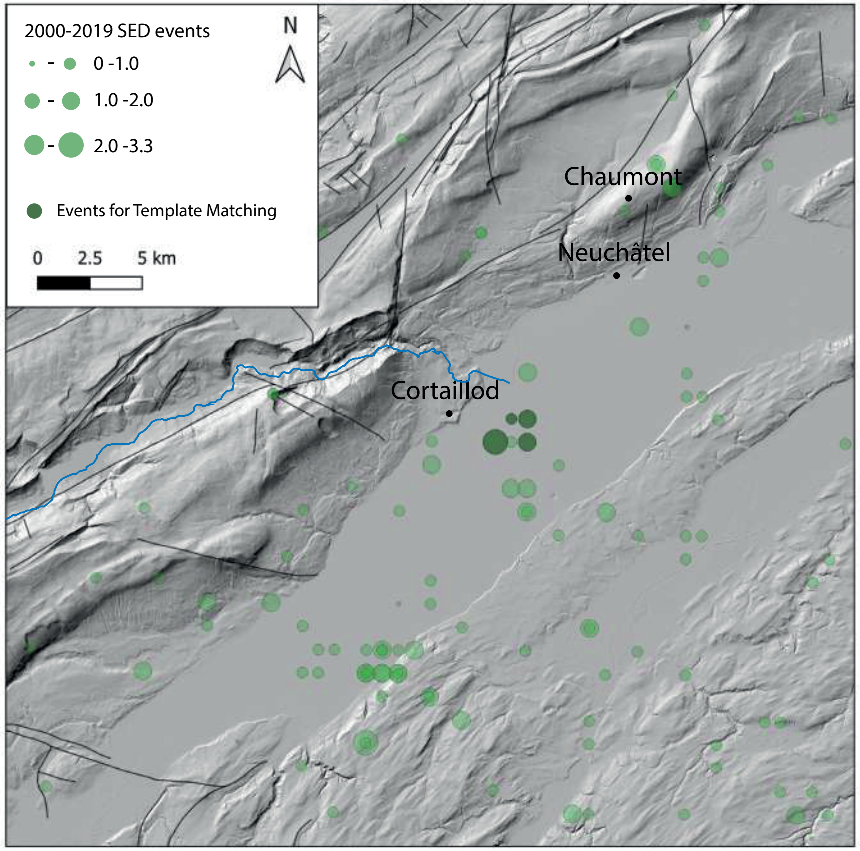

__Figure 8:__ Seismicity recorded between the years 2000 and 2019, in the area of interest. The size of the circles correspond to the ML. Also shown, the 4 events used for template matching (dark green), and the Areuse River (blue).

Among these earthquakes, some of them have been located with higher accuracy due to larger magnitudes (ML > 2.5) and better signal quality. This is the case for the ML=3.2 event of the 29.03.2006, SE of the village of Cortaillod.

Following this main event, three others events were recorded between the 01.04 and 01.08.2006. These four events were used as templates to screen continuous data from a broadband station for the entire year 2006, using the *Template Matching* tool (Hermann et al., 2019) and 14 additional events were found (Toni Kraft, SED). Although these events might be aftershocks of the ML = 3.2 event, it is observed that they occure after an important snow-melt and rainfall period in spring. This observation gives a first insight in how seismicity might be influenced by groundwater level fluctuations.

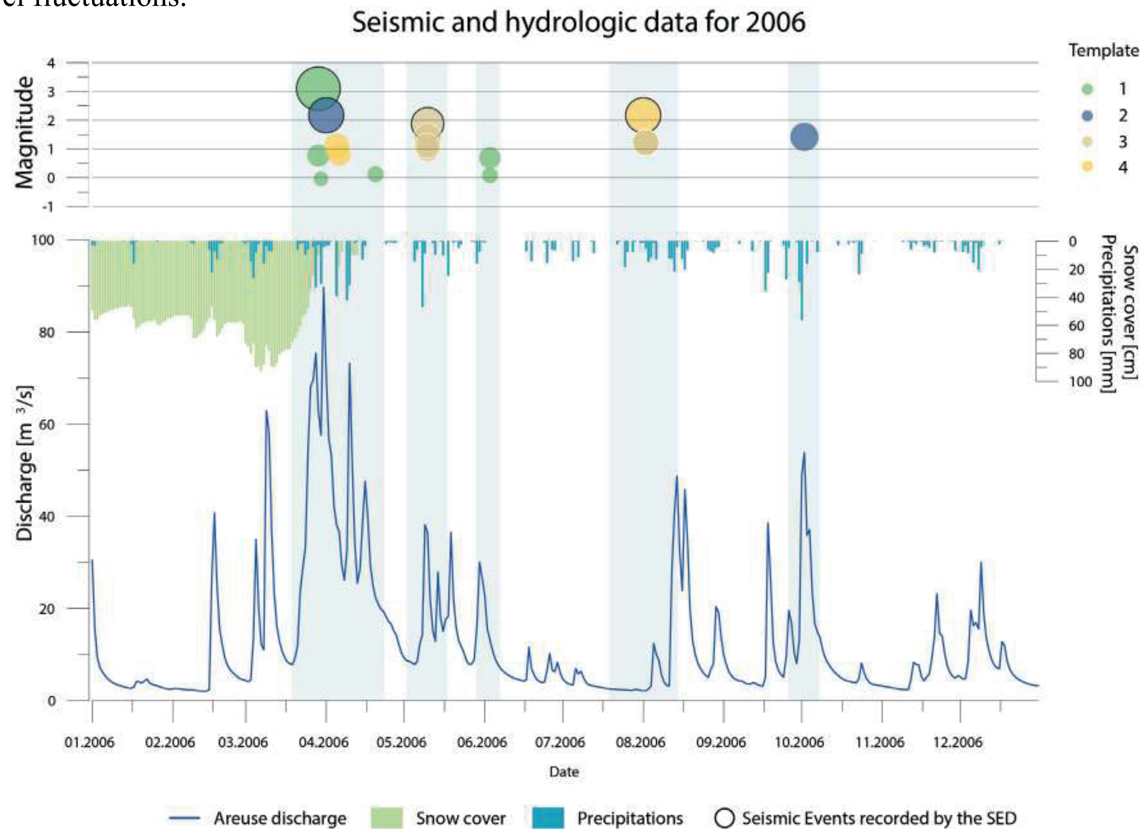

__Figure 9:__ Graphic representing 1-year discharge rate of the Areuse river, daily snow cover and daily precipitations at MétéoSuisse gauging stations, in Chaumont and Neuchâtel, respectively, during the year 2006. Also shown, earthquakes recorded by the SED with additional events found through template matching.

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Study Site

Hydrogeologic and Seismic monitoring

In order to combine microseismicity and groundwater level fluctuations to estimate fault criticality, several zones are under continuous hydrogeologic and seismic monitoring. These zones have been chosen according to the size of the regional faults, the historical seismicity as well as the presence and the importance of karstic springs.

Seismic monitoring

At this point in the project, three faults are currently under continuous seismic monitoring - La Lance, Montagne de Boudry and La Ferrière faults. Continuous seismic data is aquired using cableless 3-Channel geophones. Theses nodes are retrieved once a month for downloading data and charging batteries.

Hydrogeologic monitoring

Hydrogeologic data is aquired using automatic level loggers installed at karstic springs. Punctual flow rates measurements are realized to establish the mathematical function between water height and flow rate at the monitoring station in order to have continuous discharge rates at these springs. Moreover, 2 deep wells reaching the Malm karstic aquifer (~400m depth), showing artesian water levels, are also under monitoring. This allows us to know the groundwater pressure at depth.

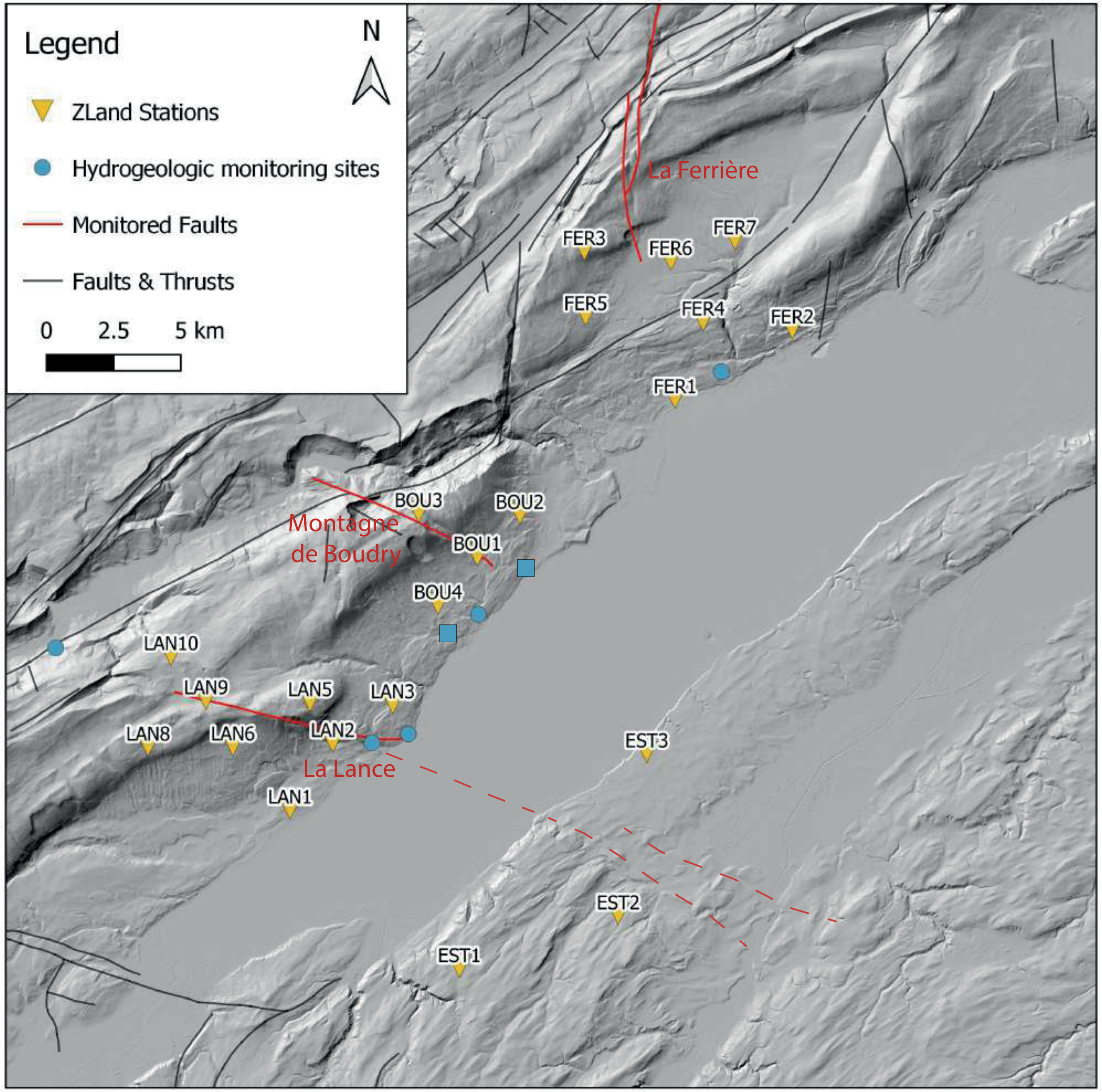

Figure 10: *Map showing the monitored faults (red), with 3-Channel geophones (yellow triangles) as well as the monitored karstic springs (blue circles) and the 2 wells (blue square). Also shown, southern probable continuation of the La Lance fault.*

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Workflow
&
Preliminary results

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Workflow

Hydrogeologic and Seismic data

Hydrogeologic and seismic monitoring started at the begining of January 2019 and middle of July 2019, respectively.

Seismic data

Conversion from raw continuous seismic data to *miniseed*, as well as *STA/LTA* trigger algorithm, is done using the *Obspy* toolbox. After this first processing, the triggered events are checked visually in *SEISAN* (Havskov and Ottemoller, 1999, Ottemoller et al. 2017), where P and S phases are eventually picked. For the location *SEISAN* uses a modified version of *HYPOCENTER* (Linert et al., 1986). The velocity model used is from Husen et al. (2003).

Hydrogeologic data

Automatic level logger are installed at karstic springs and measure a pressure (water column + atmospheric pressure). Atmospheric pressure measurements are then substracted to get the water column height. Punctual discharge rates at karstic springs at different hydrological periods (i.e. at different water height) allows to establish a rating curve (mathematical experimental function), which is then used to transform the water height measurements into flow rates.

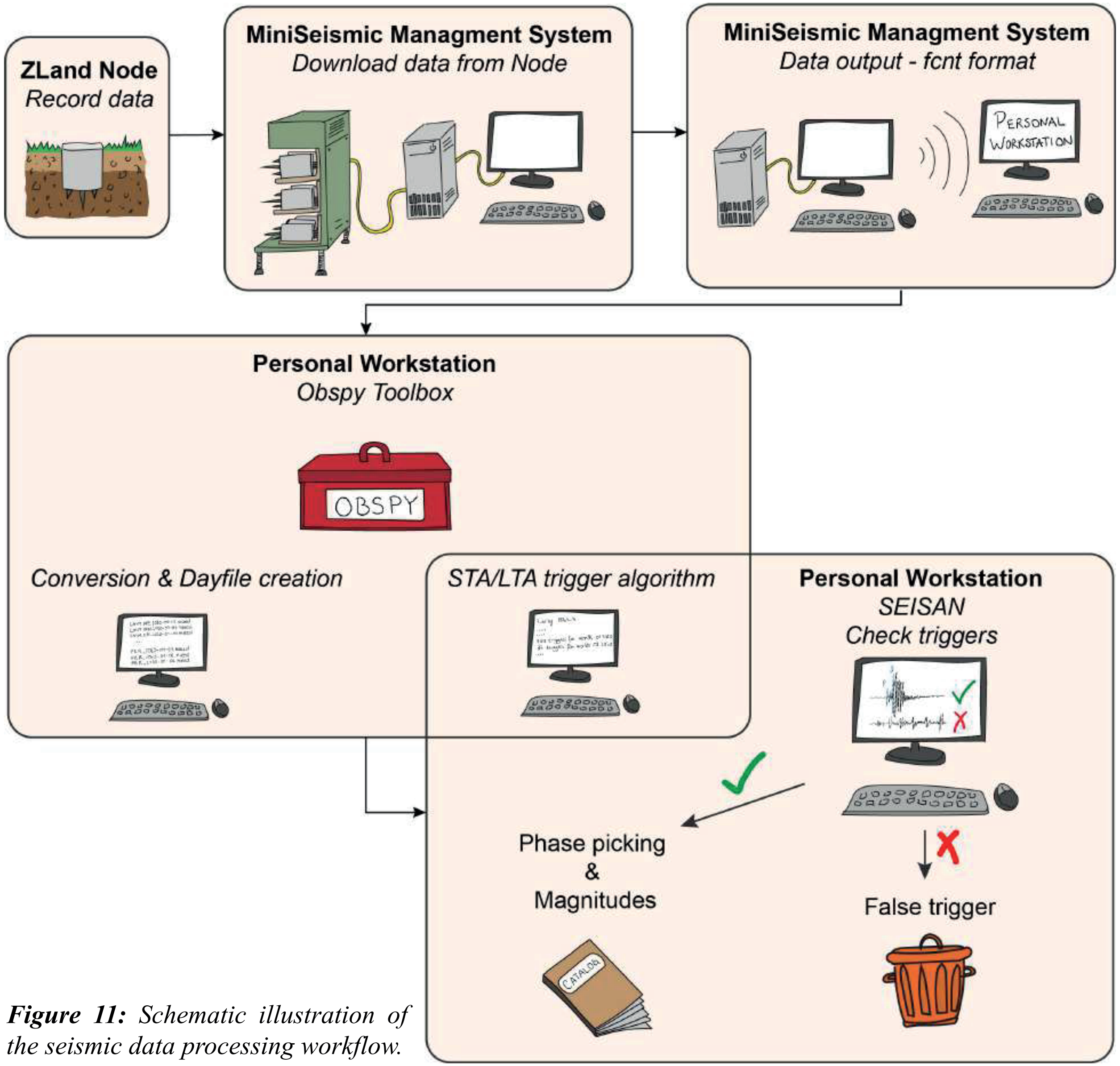

Figure 11: *Schematic illustration of the seismic data processing workflow.*

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Preliminary results

Hydrogeologic and Seismic data

Seismic data aquisition since July 2019 has allowed to identify small magnitudes earthquakes as illustrated on the map (Figure 13). The majority of the events occur in the southern zone of the area of interest.

The hydrogeologic monitoring of the different springs allows to observe the discharge variation over the year 2019 (time period 02.2019 - 03.2020), here illustrated for the Raisse Spring (Figure 12).

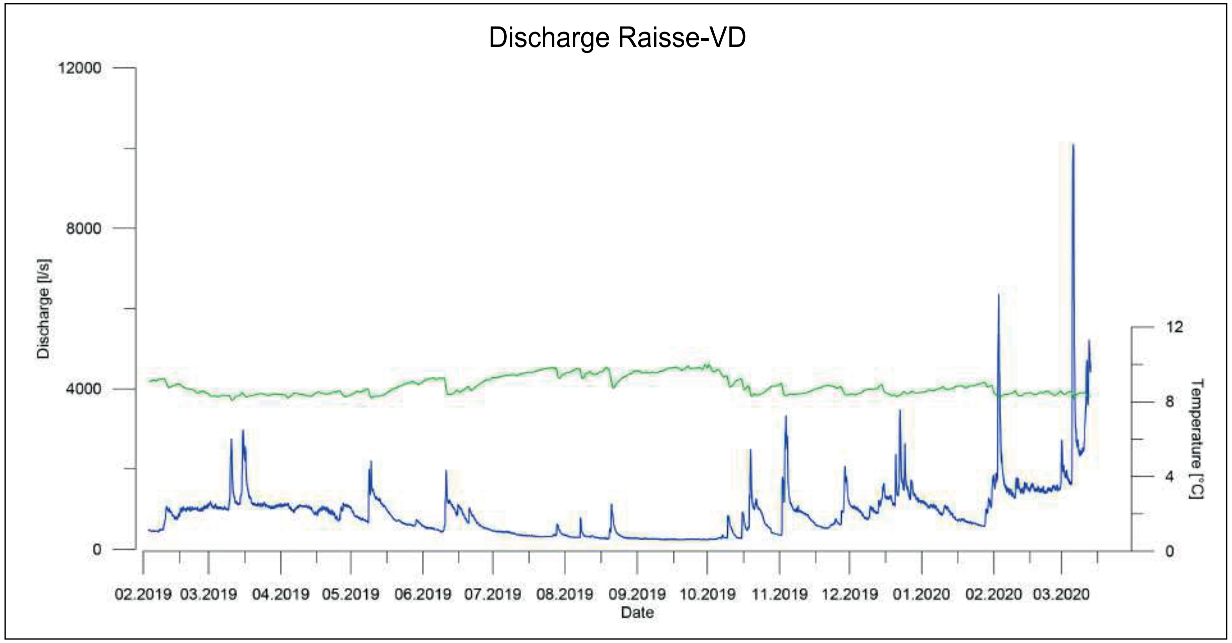

Figure 12: Data from the hydrogeological monitoring. Here, data is from the La Raisse spring (see map for location). Also measured at the spring, the water temperature (green line).

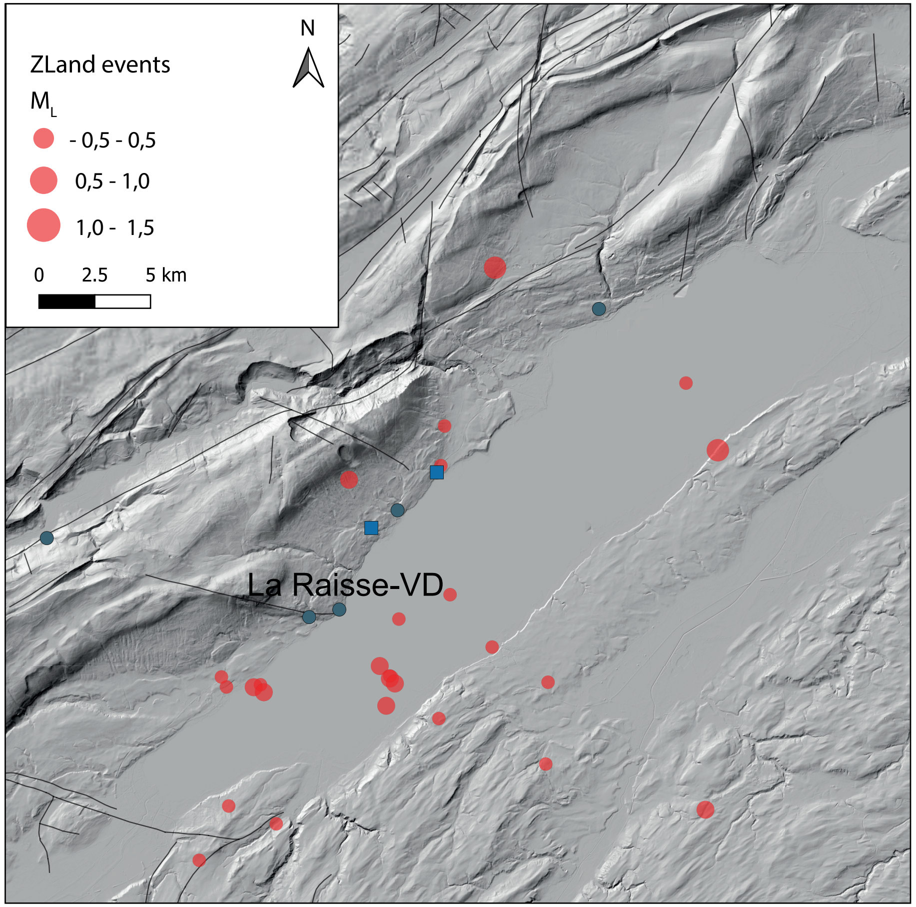

Figure 13: Map with the identified events (red circles) from the continuous seismic data record since July 2019. Also shown the different monitored springs and wells (blue circle and squares, respectively). The size of the circle depends on the M_L.

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Conclusion

&

References

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Conclusion

Plotting the hydrogeologic data along with the seismic data illustrates the possible relation between the hydrogeological conditions and seismicity. However, more data is necessary to develop a conceptual model of groundwater flow, pressure changes and its relation with microseismic events. This will allow to develop a modelling framework for simulating stresses in the Jura Mountains, and evaluate fault criticality.

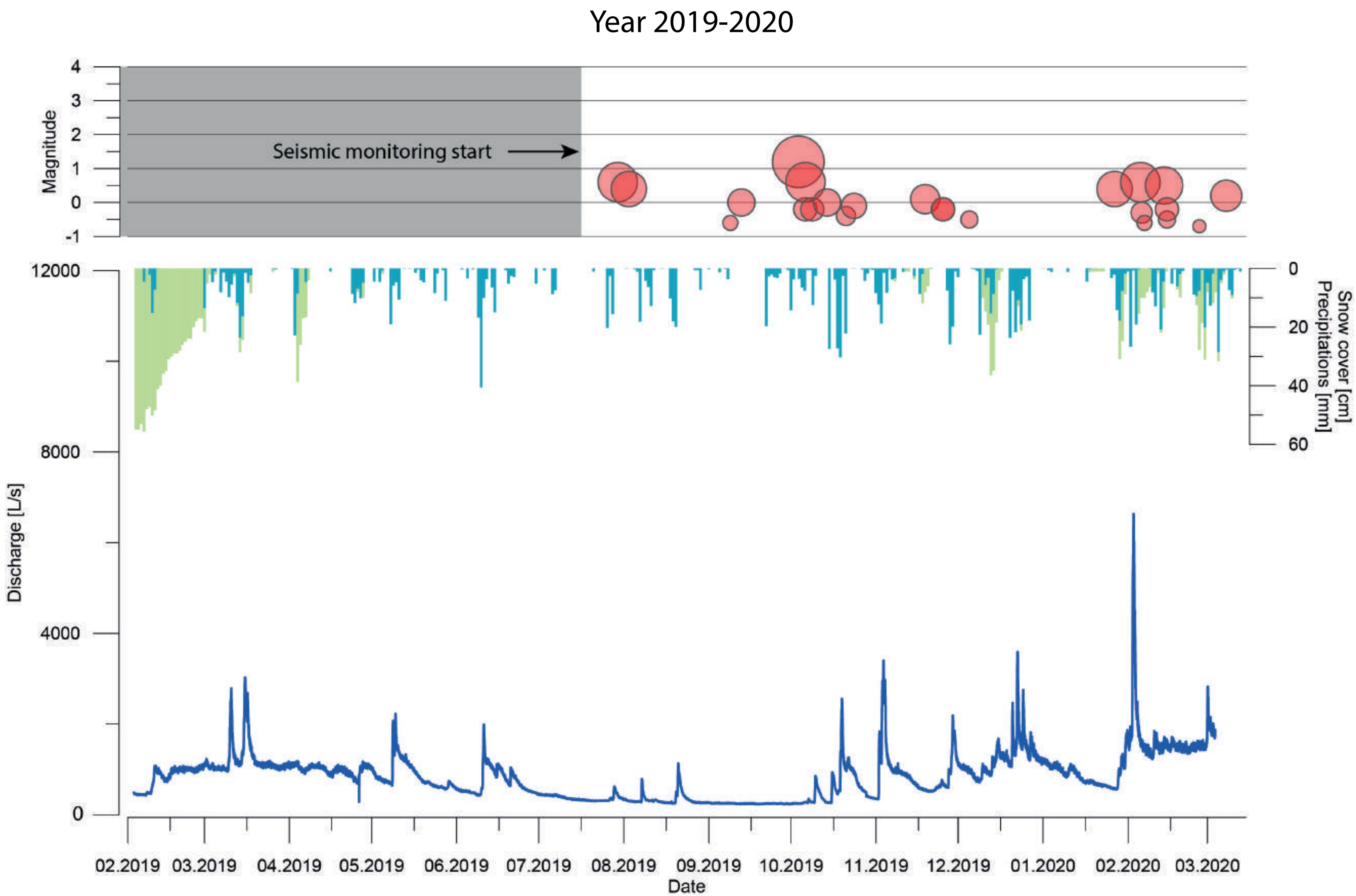

Figure 14: *Discharge of the La Raisse-VD (blue line), snowcover on the Jura mountains (green), precipitations (blue) as well as the recorded events and their magnitudes (red circle). Also shown, beginning of seismic data acquisition.*

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References

Herrmann, M., Kraft, T., Tormann, T., Scarabello, L. & Wiemer, S. A Consistent High-Resolution Catalog of Induced Seismicity in Basel Based on Matched Filter Detection and Tailored Post-Processing. *J. Geophys. Res. Solid Earth* **124**, 8449–8477 (2019).

Husen, S. *et al.* Probabilistic earthquake location in complex three-dimensional velocity models: Application to Switzerland. *J. Geophys. Res.* **108**, (2003).

Husen, S., Bachmann, C. & Giardini, D. Locally triggered seismicity in the central Swiss Alps following the large rainfall event of August 2005. *Geophys. J. Int.* **171**, 1126–1134 (2007).

Kraft, T., Wassermann, J., Schmedes, E. & Igel, H. Meteorological triggering of earthquake swarms at Mt. Hochstaufen, SE-Germany. *Tectonophysics* **424**, 245–258 (2006).

Lienert, B. R., Berg, E. & Frazer, L. N. HYPOCENTER: An earthquake location method using centered, scaled, and adaptively damped least squares. *Bull. Seismol. Soc. Am.* **76**, 771–783 (1986).

Rigo, A., Béthoux, N., Masson, F. & Ritz, J. F. Seismicity rate and wave-velocity variations as consequences of rainfall: The case of the catastrophic storm of September 2002 in the Nîmes Fault region (Gard, France). *Geophys. J. Int.* **173**, 473–482 (2008).

Sommaruga, A. *Geology of the Central Jura and the Molasse Basin*. *Memoire de la Société neuchateloise des sciences naturelles* **12**, (1997).

Swiss Federal Office for Topography (swisstopo): *map.geo.admin.ch,* last accessed on 24.04.2020

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