SAMSFAULTZ: **S**tructure **A**nd **M**echanics of **S**eismogenic **Fault** **Z**ones: Insights from advanced passive and active seismic imaging

1. Summary

Information on structure and mechanics of faults and their connection with seismicity is key to the understanding of hazard related to natural and induced earthquakes. In recent years, subsurface faults (i.e. faults undetectable at the surface) have been imaged in the shallow crust by seismic reflection surveys in the Swiss Alps and its northern foreland. At the same time, improvements in seismic networks and data analysis techniques allow relative earthquake locations at resolutions up to 50 m, revealing the fine-scale structures of seismogenic zones in Switzerland. In most cases, however, the seismogenic zones cannot be directly associated with individual faults mapped by geophysical or geological surveys, which raises questions on the underlying mechanisms causing the to observed seismicity.

To improve our understanding of seismogenic zones in Switzerland, we aim to develop novel imaging methods that will provide insight into the structure and mechanical properties of faults. Images derived from active source techniques will be revisited to attempt to resolve previously unrecognized structures in seismogenic parts of the study volume. The development of passive source methods will focus on the combination of high-precision earthquake location algorithms and seismic tomography, aiming to resolve the seismic velocity structure in the source region of seismogenic zones. The source-sided velocity structure will provide information on composition and physical parameters (e.g. fluid content) of the host rock.

Testing and application of the methods will focus on two regions. We will investigate a narrow and 10 km long seismogenic lineament located in the Rawil depression north of the Rhone Valley in southwest Switzerland. In addition, we perform a detailed analysis of an earthquake sequence along a 2 km long fault segment in St. Gallen in the year 2013 that was induced during stimulation operations. Vigorous seismicity, dense instrumentation, and the wealth of available geophysical and geological data make both regions the prime fault zones in Switzerland to study processes like evolution and interaction of faults as well as earthquake triggering mechanisms on variable scales. The study regions are complementary in two ways: In the St. Gallen case, stimulation operations provide constraints on timing and location of trigger mechanisms related to fluid injections and high-resolution 3D seismic reflection data offers the rather unique opportunity to correlate earthquake locations with pre-existing faults. In the Rawil case, the long-lasting seismicity and numerous focal mechanisms allow the analysis of the temporal evolution of the locally varying stress field and seismic velocity structure along the seismogenic lineament.

The two chosen sites are also of high societal relevance. The Valais is the region with the highest natural seismic hazard in Switzerland and a large part of the present-day seismic activity is related to the seismogenic lineament in the Rawil depression. The possibility of large magnitude earthquakes critically depends on the question as to whether this activity is related to a single fault of considerable lateral extension or not. The St. Gallen site offers an excellent occasion to study local earthquake hazard in the densely populated Molasse basin, which is also the site of future geothermal plants and radioactive waste repositories.

2. Research plan

2.1. Current state of research in the field

2.1.1 Imaging faults in the uppermost crust

Information on the existence of faults, their geometry, and their mechanical properties is crucial for the assessment of hazard related to natural and induced seismicity, since lateral and vertical extents of faults as well as their orientation in respect to the present-day regional stress field are first-order indicators for estimating maximum possible magnitudes and accumulated stress on given structures. Large parts of active faults are undetectable at the surface (rupture does not reach the surface or faults are covered by scree and vegetation) and can be identified only by geophysical surveys or by earthquake activity. In most cases, observed earthquake activity cannot be associated with individual mapped faults and, in turn, mapped faults often appear seismically inactive.

The absence of geophysically mapped faults in seismogenic zones could partly reflect deficits in impedance contrast across faults, one reason why imaging of faults within the basement is rather challenging. Common near-vertical reflection methods also fail to directly resolve subvertical structures, such as vertically dipping strike-slip faults [e.g., Lynn and Deregowski 1981; Hajnal et al. 1996]. Recent advances in acquiring and processing of 3D seismic data volumes by industry campaigns allow the 2D mapping of small vertical offsets in seismic strata, from which the lateral and vertical extent of subvertical fault structures can be inferred.

Lineaments of earthquake activity imaged by high-precision earthquake location techniques are often associated with individual faults, fault systems, or fault arrays. These seismogenic lineaments can stretch over tens of kilometres and are, in many cases, seismically active over decades, dominated by the occurrence of small to moderate sized earthquakes. It is poorly understood, however, if such linear arrangements can be associated with individual continuous faults, which have the potential to rupture in a single large earthquake or rather represent fault arrays consisting of many small fault segments, which limit the rupture to small and moderate sized earthquakes. Source characterization carried out in the framework of the PEGAGOS project [Coppersmith et al. 2009, Musson et al. 2009, Schmid and Slejko 2009, Burkhard and Grünthal 2009, Wiemer et al. 2009] only found sparse indications for the existence of line sources and most areas of Switzerland and adjacent areas were treated as area sources with distributed seismicity. However, this could also partly reflect inaccuracies in epicentre location.

An important aspect in the discussion of seismicity in the uppermost crust is whether or not seismicity is confined to the sedimentary cover, the crystalline basement, or whether it affects both. Connection of faults as well as the mechanical coupling between sediments and basement is not well understood. The mechanical properties of faults and the state of stress in the uppermost crust, however, are crucial in the discussion on the current style of tectonic deformation (i.e. thick-skinned vs. thin-skinned) in the Alps and its foreland [e.g., Ustaszewski and Schmid 2007].

An improved understanding of brittle deformation and interaction of faults within the uppermost crust becomes increasingly important also for exploration of underground energy resources. For instance, fault systems in the uppermost crust become prime targets for geothermal reservoirs, since naturally increased permeability reduces the need for high-pressure stimulations [e.g., Megies and Wassermann 2014]. On the other hand, critically stressed faults can be activated during fluid injections and trigger felt or even damaging earthquakes [Häring et al. 2008]. For applications involving fluid injections, the proximity to critically stressed faults therefore increases the seismic hazard.

2.1.2 Faults in Switzerland from active source imaging and geological mapping

The majority of past seismic reflection surveys in the Alpine Region of Switzerland, such as the NFP-20 initiative [Pfiffner et al. 1997], was based on individual profiles and imaged mainly the two-dimensional structure of the subsurface. These techniques illuminate moderately dipping crustal interfaces like the Moho or the Conrad discontinuity, but can fail to image subvertical structures. In the framework of various seismic reflection campaigns, faults in the shallow crust of the Swiss Alps and its foreland have been identified and interpreted [e.g., Pfiffner et al. 1997, Sommaruga et al. 2012]. In some cases, also high-resolution industry data was included for reprocessing and geological interpretations. In addition to the geophysical mapping, compilations of geological fault data are available [e.g., Ustaszewski and Pfiffner 2008; Gasser and Mancktelow 2010]. For the majority of geologically mapped faults in the Central Alps no information on their last phase of activity exists and the low number of unambiguously active tectonic faults suggests that the current strain is either predominantly aseismic, the cumulated seismic moment is too low for surface ruptures [Ustaszewski and Pfiffner 2008], or seismicity is distributed within a wider area, unrelated to individual faults.

2.1.3 Passive source imaging of faults

Fault geometries can be inferred from precise locations of earthquake hypocentres and source mechanisms in case of a seismically active fault. In turn, the occurrence of seismicity is often used as indication whether a fault is characterized as active or inactive. In most cases, however, seismicity cannot be unambiguously associated with mapped fault structures or a certain host rock material, mainly because model and data errors limit the resolution of hypocentre determinations. Especially the depth resolution is poor in many earthquake catalogues, due to imperfect knowledge of the velocity structure and unfavourable ray-distribution. Relative earthquake relocation techniques use differential times of event pairs to improve the spatial resolution of the seismically active structure [e.g., Deichmann and Garcia-Fernadez 1992; Waldhauser and Ellsworth 2000]. Differential-time methods remove unmodeled velocity structure by directly inverting travel-time differences between events for their hypocentre separation [e.g., Waldhauser and Ellsworth 2000]. This approach permits the combined use of phase delay times measured from bulletin picks and from cross-correlation of similar seismograms. Cross-correlation methods can measure differential phase arrival times with subsample precision for events that are nearby and have similar focal mechanisms, typically resulting in more than an order of magnitude improvement over delay times formed from phase onset picks reported in earthquake bulletins [e.g., Poupinet et al. 1984]. Combined with focal mechanisms derived from first motion polarities or moment tensor inversions, high-precision relative locations of earthquake sequences can constrain the orientation and the kinematics of active rupture planes. Relative relocation techniques have been expanded to teleseismic distances recently [e.g., Waldhauser and Schaff 2007; Pesicek et al. 2010] and have been used for high-resolution seismotectonic studies on different scales worldwide [e.g., Bulut et al. 2011, Valoroso et al. 2013, Diehl et al. 2013]. Relative relocations have been routinely applied to earthquake sequences to determine the active fault planes of significant earthquakes in Switzerland [e.g., Deichmann et al. 2002; Deichmann et al. 2012; Marshall et al. 2013; Diehl et al. 2014]. Regional studies included the Valais [Maurer and Deichmann 1995] and the Fribourg fault zone [Kastrup et al. 2007]. Modern IT infrastructures allow the reprocessing of existing digital data archives using large-scale waveform cross-correlation and double-difference techniques to improve the resolution of entire earthquake catalogues on a regional scale [e.g. Waldhauser and Schaff 2008; Hauksson et al. 2012]. These regional catalogues can then be incorporated in real-time double-difference procedures, which provide rapid high-precision hypocentre locations and therefore near real-time information on e.g. rupture processes or spatio-temporal migration during on-going earthquake sequences [e.g., Waldhauser 2009; Vogfjörð et al. 2014]. Diehl et al. [2013a] made a first step towards a double-difference earthquake catalogue for Switzerland by calculating waveform cross-correlations for the entire digital waveform archive of the Swiss Seismological Service between 1984 and 2013. Catalogue picks and cross-correlation data were used for relocations of subsets of the Swiss earthquake catalogue (see Figure 1). The structures imaged by the regional scale double-difference locations agree very well with structures seen in relative locations of single sequences studied e.g. by Frechet et al. [2010] and Deichmann et al. [2012], confirming the improvement in resolution of the preliminary double-difference catalogue.

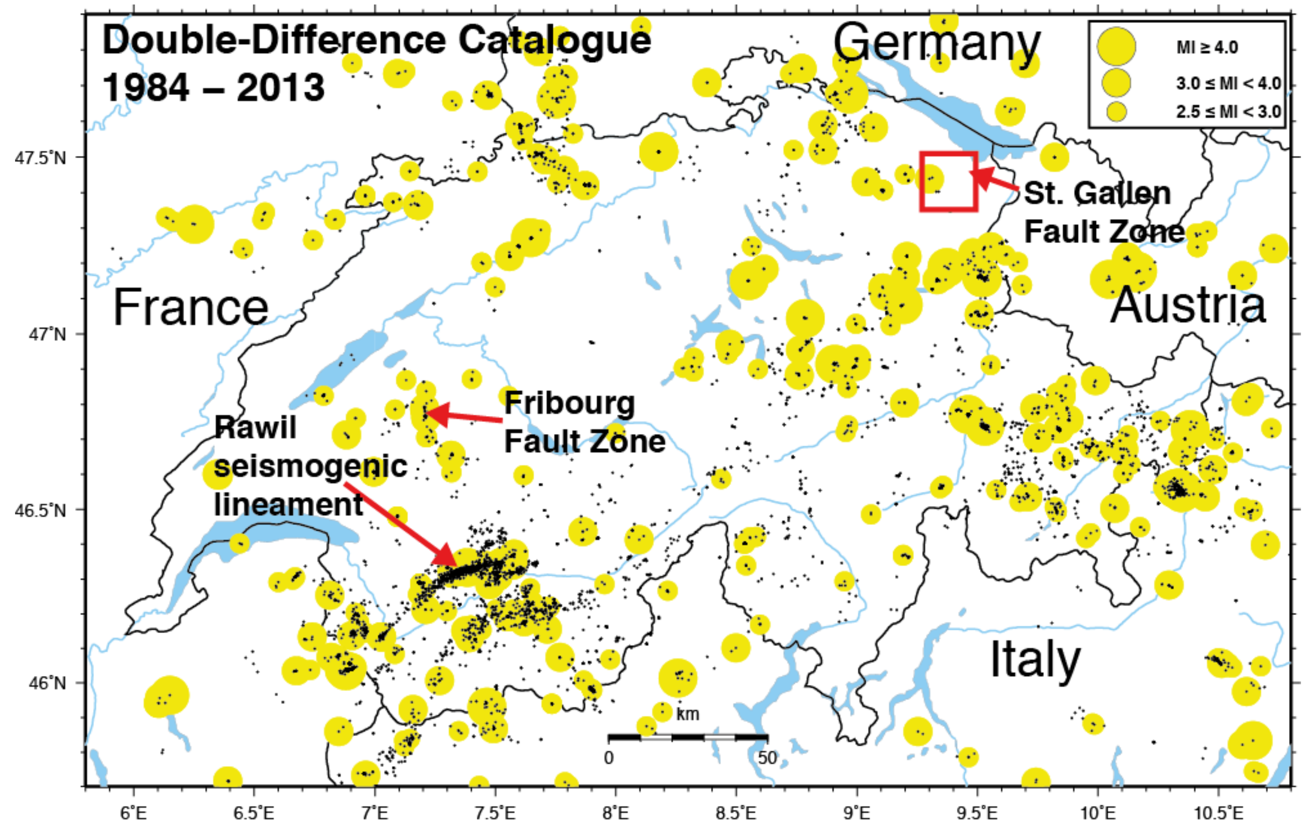

Figure 1 Preliminary regional double-difference catalogue of Switzerland using bulletin and waveform data of the Swiss Seismological Service of earthquakes between 1984 and 2013 [Diehl et al. 2013a]. The Rawil lineament north of the Rhone valley in southwest Switzerland is the most pronounced regional-scale seismogenic structure imaged by seismicity. In comparison, the spatial extent and frequency of seismicity associated to other fault zones like the Fribourg Fault Zone or the St. Gallen Fault Zone suggests that these structures are less active and play a considerably smaller role in the accommodation of tectonic strain. Black dots indicate earthquakes; yellow circles indicate earthquakes of local magnitudes ≥2.5.

Although relative location algorithms image the relative structure of seismicity at high resolution, the main drawback of this method is that the precision of absolute locations of epicentres as well as focal depth is mainly controlled by the precision of the initial locations. The precision of absolute locations, however, is crucial for interpretation of underlying mechanisms, especially if seismicity is correlated with faults mapped by geology or geophysical methods. The precision of absolute locations depends on the coupling between hypocentre determination and the seismic velocity structure (also known as the "coupled-problem") [Kissling 1988]. To reduce the bias of the un-modelled seismic velocity structure, an appropriate velocity model for hypocentre determination is commonly derived from simultaneously inverting arrival time data for velocity structure and hypocentres. The coupled-problem is usually solved by the computation of a minimum 1D model [Kissling et al. 1994], in which the seismic velocities are approximated by a 1D velocity structure and static station corrections. If the ray-coverage allows, a 3D model can be derived from local earthquake tomography [e.g., Thurber 1983]. State-of-the-art absolute earthquake location techniques combine high-resolution 1D or 3D velocity models with probabilistic, nonlinear location approaches [Lomax et al. 2000; Husen et al. 2003]. In addition to the appropriate velocity model, the precise determination of focal depths depends on observations at close-by stations. As a rule of thumb, well-constrained focal depths require the distance between epicentre and closest station not exceeding 1.5 times the focal depth [e.g., Richards et al. 2006].

In the absence of close-by observations, secondary depth-phases are used to determine the depth. Common depth-phases at regional scales are Moho-reflected P (PmP) or S (SmS) phases. Recently, the use of secondary phases like PmP was included in a multi-phase probabilistic location approach for earthquakes in the Alpine Region [Wagner et al. 2013; Singer et al. 2014]. It is shown, that the precision of absolute locations and its accuracy, especially the focal depth, can be significantly improved by the use of secondary phases. However, the absolute depth depends critically on the uncertainty of the Moho topography when PmP or Pn phases are included in the location procedure. State-of-the-art models of the Alpine crust derived from combining controlled source with earthquake data have a minimum uncertainty in Moho depth of ±3 km [Wagner et al. 2012]. This uncertainty in absolute depth, however, is too large to distinguish a source in the lowermost Mesozoic sediments from a source in the uppermost basement in most cases. In addition, secondary phases like PmP are often difficult to identify and to pick within sufficient error bounds. Husen et al. [2011] demonstrated that a velocity model calibrated by a check-shot yields location accuracies of 250 m in focal depths and that corresponding errors due to unmodeled velocity anomalies in regional 3D models can be up to 2 km.

To overcome the limitations of absolute depth resolution in earthquake locations, additional information like the velocity structure in the source region can be used to constrain the depth of seismicity. Contrasts in seismic velocities can illuminate a fault and absolute velocities within the source region are indicative for composition and mechanical properties of the host rock. The depth of seismicity relative to prominent velocity contrasts resolved by tomographic inversion provides evidences on the host rock material and can be used to calibrate the absolute locations in respect to a lithological model. The spatial resolution of the imaged velocity structure of the source region is usually limited by the resolution of the available (absolute) arrival time data. Relative travel-times derived from waveform cross-correlation provide much higher resolution. Travel-time based inversion codes commonly use relative travel-times for improving the hypocentre part of the coupled problem [Deichmann and Garcia-Fernadez 1992; Waldhauser and Ellsworth 2000]. In recent years, relative travel times have also been used to derive information on the velocity structure. Lin and Shearer [2007] derived the average Vp/Vs ratio in the source region of earthquake clusters directly from differential times of P- and S-waves computed from waveform cross-correlations and Zhang and Thurber [2003] combined relative and absolute arrival times into a double-difference tomography approach to improve the imaging of velocity structure and hypocentres on regional scales.

2.1.4 Study regions in Switzerland: The Rawil and St. Gallen Fault Zones

The two study regions proposed for developing and applying novel fault imaging methods are the Rawil depression in southwest Switzerland (Figure 1 and 2) and the St. Gallen fault zone in northeast Switzerland (Figure 1). Although located in two different tectonic realms (Helvetic nappes in the Alps, Molasse basin in the northern foreland), seismicity in both zones exhibits similar characteristics, raising similar questions on evolution and interaction of faults and the current style of deformation in the uppermost crust of the Alps and its foreland. The wealth of past geological and geophysical surveys and the density of monitoring networks in the proposed areas allow a comprehensive study of faulting processes.

The Rawil depression is situated at the northern border of the Canton Valais. We choose this area also because it is the most seismically active region with the highest natural seismic hazard in Switzerland [Giardini et al. 2004] and therefore of high societal relevance. The Valais region experiences a magnitude 6 or larger earthquake roughly every 100 years [Fäh et al. 2012]. The Rawil depression is characterized by increased earthquake activity, with the majority of seismicity occurring within a narrow ENE-WSW striking cluster (Figure 2). This cluster is part of an earthquake lineament north of the Rhone valley, which is the most prominent and largest seismogenic structure in Switzerland (Figure 1). Seismicity along this lineament is dominated by dextrally transpressive strike-slip faulting [e.g., Maurer and Deichmann 1995; Maurer et al. 1997; Kastrup et. al 2004; Fäh et al. 2012] and appears to be clustered at depths between 0 and 8 km [Maurer and Deichmann 1995; Diehl et al. 2013a]. Seismic reflection data acquired during the NFP-20 campaign identified the top of the crystalline basement between 2 and 5 km depth in this region [e.g., Pfiffner et al. 1997a] and therefore parts of the seismicity probably occurs in the autochthonous Mesozoic sediments at the base of the Helvetic nappes. It remains unclear, however, how faults in the Mesozoic sediments connect to faults in the underlain crystalline basement and how deep potential faults penetrate into the crystalline basement. The lateral boundaries of this seismogenic lineament are diffuse and it might represent a fault array rather than a single fault. Seismicity splays into other smaller dextral strike-slip segments in the northeast (Figure 2). To the southwest, seismicity appears to connect to NE-SW striking lineaments close to Martigny, consistent with a rotation of the direction of maximum compression from E-W oriented compression south of the Lake of Geneva to NW-SE oriented compression in the Helvetic domain of northern Valais [Fäh et al. 2012].

In a regional tectonic context, the seismogenic lineament imaged in Figure 1 could be associated with a dextrally transtensive shear-zone accommodating lateral displacement between southwest-directed normal-fault movement along the Simplon line and southwest-directed thrusting in the Embrunais-Ubaye and Digne nappe systems of southeastern France [e.g., Hubbard and Mancktelow 1992]. The majority of surface traces of dextral faults, however, are mapped along the axis of the Rhone valley about 10 km south of the seismogenic lineament, coinciding with the Penninic basal thrust (Figure 2). For the majority of these geologically mapped faults no information on the exact timing of their last phase of activity exists [e.g., Ustaszewski and Pfiffner 2008] and it is unclear if they are still active and related to current earthquake activity. The last destructive earthquake in the Rawil area was in 1946. The mainshock had a moment magnitude of about 5.8 [Fäh et al. 2011] and it was followed by series of strong aftershocks, whose locations are shown in Figure 2. Although the location uncertainties of historic events shown in Figure 2 are large (error in epicentre ≤20 km), the location of the 1946 Mw=5.8 mainshock as well as its approximate rupture length (estimated from empirical relationships, see Figure 2) suggest a connection between the 1946 earthquake and the seismogenic lineament in the Rawil depression. The joint interpretation of seismicity, stress-orientation and present-day deformation rates, in combination with existing geological mapping of fault patterns [e.g., Gasser and Mancktelow 2010; Cardello and Mancktelow 2014] can help to understand the amount of present-day lateral displacement accommodated by the potential fault system and its role in current large-scale tectonic processes of the Central and Western Alps.

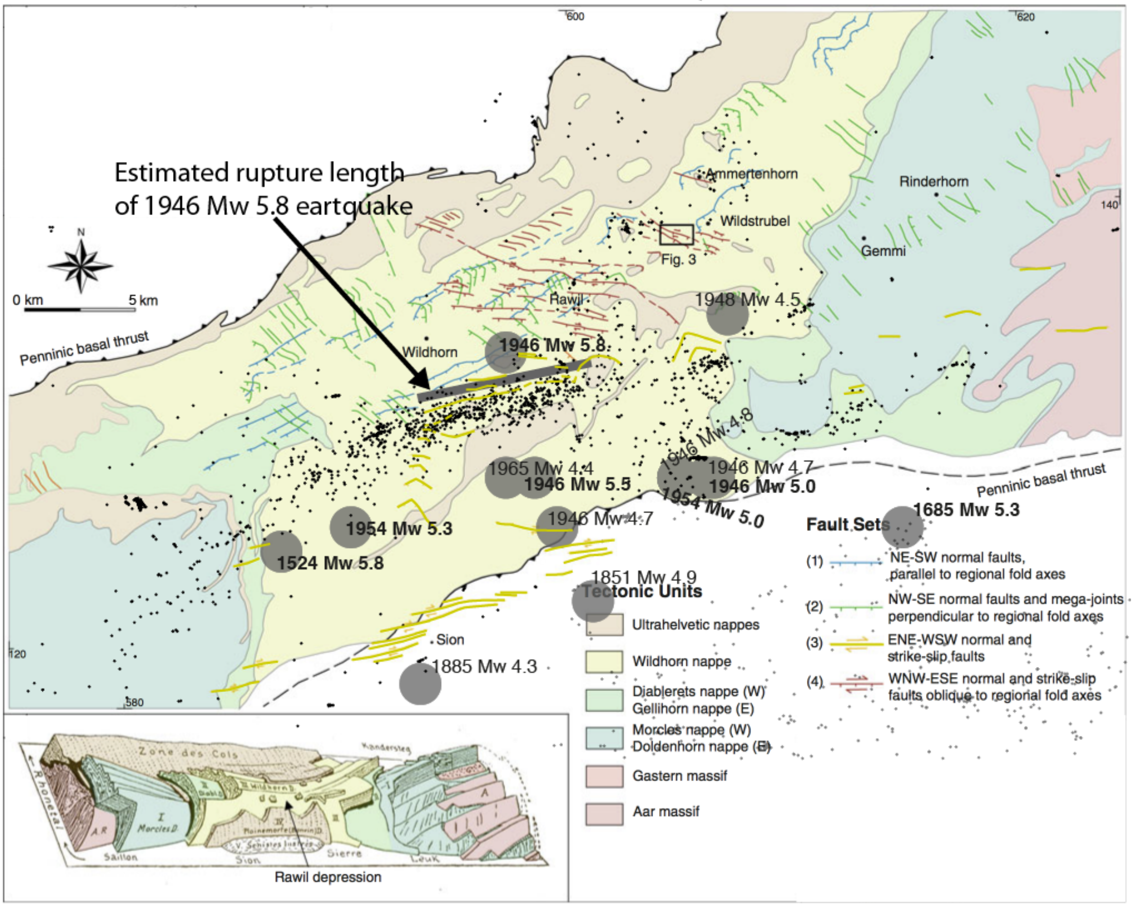

Figure 2 Tectonic units of the Rawil depression overlaid by fault data [modified from Gasser and Mancktelow 2010], historic seismicity reported in the ECOS-09 catalogue [Fäh et al. 2011] (grey circles; year and moment magnitude indicated), and high-precision relative relocations of instrumental seismicity (black dots) for earthquakes between 1984 and 2013 [Diehl et al. 2013]. The bold grey bar indicates the estimated rupture length of the January 1946 Mw 5.8 Sierre earthquake using empirical relationships of Wells and Coppersmith [1994]. The rupture length estimate is similar to the lateral extension of the seismogenic lineament, suggesting its relation to the 1946 earthquake.

The discussion on the mechanical coupling between sediments and basement and the style of present-day tectonic deformation in the uppermost crust applies likewise to fault zones in the northern foreland of the Alps. Seismic reflection data and the analysis of earthquakes focal depths suggest fault zones within the sedimentary cover of the Molasse basin and the Swiss Jura. The most prominent example is the Fribourg Fault Zone (FFZ), which is associated with a prominent concentration of earthquakes whose epicenters delineate an active 20–30 km long N–S trending tectonic feature [e.g., Kastrup et al. 2007]. In 1999 a M_L 4.3 event occurred on this structure and focal depths, constrained by modelling of travel-time differences with synthetic seismograms, are around 2 km, which places the events in the sedimentary cover. The N-S orientation of the earthquake lineament correlates with a N-S striking basement low, possibly related to a Permo-Carboniferous trough [Kastrup et al. 2007]. Since the tectonic group at the University of Fribourg currently investigates the FFZ, we do not intend to focus on the FFZ in this study, but close cooperation is planned.

A fault zone similar to the FFZ was imaged by a 3D seismic survey in the Mesozoic sediments in the Molasse Basin in the area of St. Gallen in northeast Switzerland (Figure 3a) and is the second focus of the proposed study. This fault zone was targeted as a possible reservoir for a hydrothermal plant, similar to geothermal facilities operated in the Molasse Basin in southern Germany [e.g., Megies and Wassermann 2014]. During stimulation tests, a sequence of earthquakes was triggered, which culminated in a M_L 3.5 earthquake in July 2013 [e.g., Diehl et al. 2014]. Relative relocation and focal mechanisms confirm that the sequence occurred along a sinistral NE-SW striking rupture plane, which correlates well with a fault segment in the Mesozoic sediments imaged by reflection seismics (Figure 4). Seismicity in the weeks after the M_L 3.5 earthquake, however, migrated towards NE, into a region lacking fault structures visible in the current seismic images (Figure 4). The absence of any vertical offset along a vertically dipping segment (pure strike slip) would explain the lack of features in the seismic strata and it remains unclear if the seismicity along the NE extension can be associated with a pre-existing fault that simply could not be imaged so far. It is likely that the seismicity is related to structures also affecting the basement, since the St. Gallen fault zone coincides with the margins of a local Permo-Carboniferous trough defined by a pre-existing fault. To avoid significant earthquakes triggered by fluid injection in future geothermal experiments, the relation between imaged fault structures, fault interaction, and earthquake triggering mechanisms needs to be studied at high resolution. The combination of high-precision earthquake locations and high-resolution 3D seismic reflection data makes St. Gallen an ideal location to study the structure and mechanical properties of pre-existing fault zones linked to Permo-Carboniferous troughs in the Molasse Basin of the northern Alpine Foreland. Potential reactivation of faults delimiting Permo-Carboniferous troughs is a major issue for evaluating seismic risk of nuclear power plants [e.g., Schmid and Slejko 2009] and for radioactive waste disposal [e.g., NAGRA 2008].

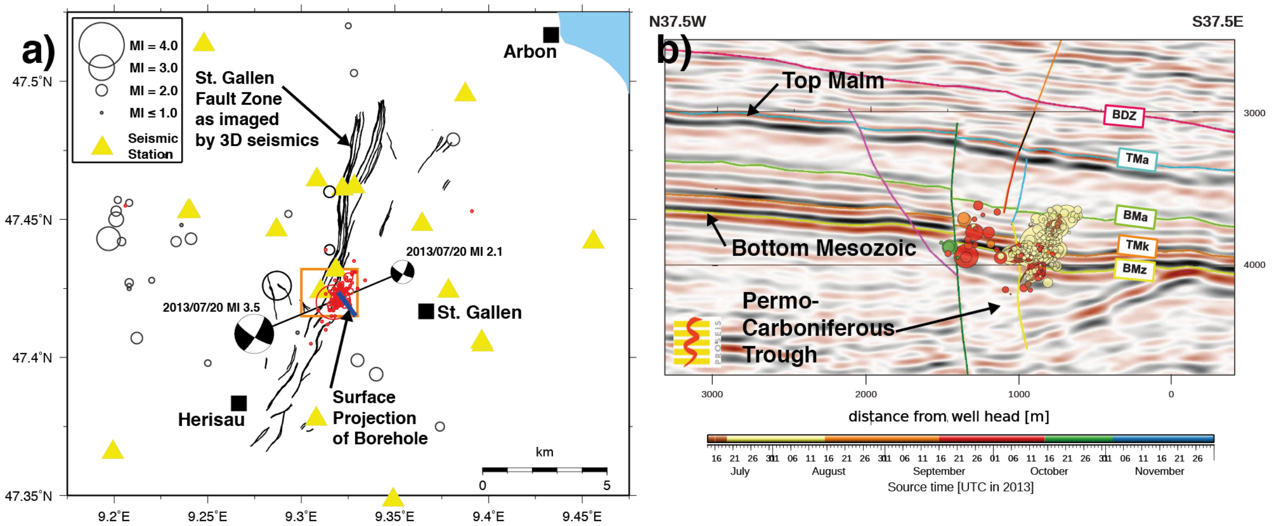

Figure 3 ***a)*** *The St. Gallen fault zone (black lines) in northeastern Switzerland (for location see Figure 1) as imaged by a 3D seismic reflection survey. Seismicity located in the region is indicated by circles (black: prior to 2013; red: induced earthquakes in 2013). Seismicity prior to 2013 is located only by regional stations of the SED, whereas seismicity in 2013 is located with a dense local network (yellow triangles) and clearly associated with the fault system. The diffuse distribution of seismicity prior to 2013 partly reflects inaccuracies in epicentre location resulting from the sparser network.* ***b)*** *Cross-section through the 3D seismic reflection data along a NW-SE striking profile. Vertical offsets in the seismic strata were used to infer and laterally map subvertical fault structures in the sediments and the basement. Relocated earthquakes (circles coulor-coded by origin time) projected to the profile can be associated with mapped faults only in some parts of the study volume (see Figure 4). To improve association between seismicity and faults, we propose to revisit seismic data, mapped offsets, and their interpretations in the seismogenic parts of the study volume.*

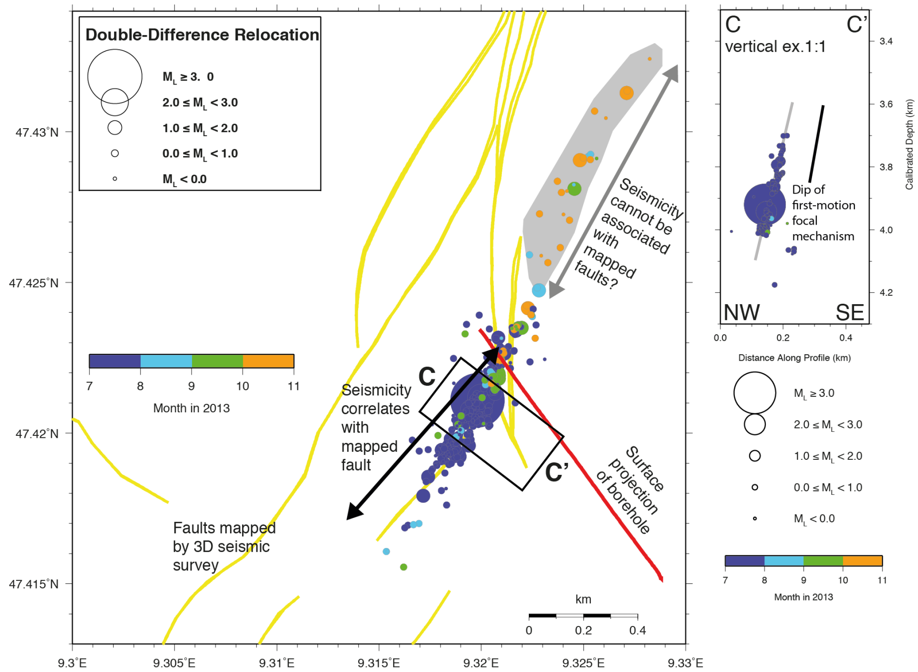

Figure 4 Left: High-precision relative relocations of the St. Gallen sequence of 2013 [Diehl et al. 2014a]. Yellow lines indicate fault strands mapped by a 3D seismic reflection survey (see Figure 3). Circles correspond to earthquakes color-coded by month of occurrence. Seismicity prior to triggered M_L 3.5 earthquake and its immediate aftershocks occur on a short fault branch of the fault zone mapped by 3D seismic reflection. Seismicity after July 2013 occurs along a linear extension of this segment, not mapped by the 3D survey (grey-shaded area). To understand the nature of this seismicity, seismic reflection data in this part needs to be revisited. Right: Vertical cross-section through seismicity in the vicinity of the M_L 3.5 earthquake (profile CC'). The fault plane is clearly resolved by the relative locations and consistent with the fault plane solutions derived from analysis of first-motion polarities.

2.1.4 Relevant projects underway

We plan close collaboration with other SNF projects addressing similar questions as our proposed project. SNF-SINERGIA project SWISS-AlpArray "assessing Alpine orogeny in 4D-space-time frame" (coordinating PI Edi Kissling) aims on the large-scale and deep structure of Alps; Installation of temporary stations in the Rawil depression will be coordinated with the project "OROG3NY: structures and processes in 3D mountain building" (PI György Hetényi); Fault maps, and tectonic and mechanical models of brittle deformation of the Aar massif developed in the framework of the SNF project "Structure and evolution of an antiformal nappe stack (Aar massif, Central Alps): Formation of mechanical anisotropies and their bearing on natural risks" (PI Marco Herwegh) will be compared to relocated seismicity of the Rawil fault zone in close collaboration with the tectonic group at the University of Bern.

2.2. Current state of your own research

Tobias Diehl: The main PI of the current proposal, Dr. Tobias Diehl, works on regional seismotectonic questions in different tectonic regimes, including orogenic belts, subduction zones, and transtensional fault systems in different parts of the world [e.g., Diehl et al. 2014b; Singer et al. 2013; Diehl et al. 2013; Waldhauser et al. 2012; Sumy et. al. 2013]. His expertise includes high-precision earthquake location techniques ranging from local to teleseismic distances and earthquake source-inversion techniques to derive focal mechanisms and moment-tensors of local and regional earthquakes. Since 2012, he is responsible for the annual earthquake report of the SED [Diehl et al. 2013b; Diehl et al. 2014]. The reports include detailed analysis of earthquakes in Switzerland and surrounding regions, which makes him one of the experts on seismicity in Switzerland. In the framework of a master thesis supervised by TD, the nature of the lower crustal seismicity in the northern Alpine Foreland of Switzerland and its relation to the deep structure of the Alps was investigated [Singer et al. 2013]. He also applied local earthquake tomography techniques to image seismic velocity structures at different scales. TD imaged large parts of the Alpine lithosphere at unprecedented resolution by combining 3D-tomography with automatically re-picked arrival times of earthquakes in the Alps [Diehl et al. 2009a, 2009b]. The relationship between the seismic velocity structure and seismicity, which is one of the fundamental components of the proposed project, was discussed in several studies of TD [e.g., Diehl et al. 2009a; Diehl et al. 2013] and is a focus in his current research [e.g., Diehl et al. 2014a]. Another area of interest is the development of automated algorithms for the processing of large datasets, including detection of earthquakes and high-resolution picking and identification of P and S phases [e.g., Diehl et al. 2009c; Küperkoch et al. 2012; Farrell et al. 2014]. He recently compiled the first high-quality local earthquake catalogue of Bhutan from seismic data recorded by a temporary network in the eastern Himalayas [Diehl et al. 2014b]. TD was co-supervisor of a Master student (J. Singer, ETHZ) and a Ph.D. student (D. Sumy, Lamont-Doherty Earth Observatory) and is currently co-supervising a Ph.D. student (J. Singer, ETHZ) aiming to image the orogenic-wedge of the Bhutanese Himalayas. In the past, TD was also in charge of installation, maintenance, and managing of several temporary broad-band deployments in the Alps, Romania, Greece, and Bhutan and is experienced in seismological fieldwork.

Edi Kissling: During the past 25 years, Prof. Kissling has been substantially involved in determing 3D lithospheric structure and tectonics of the Alps [Kissling et al. 2006; Schmid and Kissling 2000; Handy et al. 2010; Rosenberg and Kissling 2013] and other orogens [e.g., Poupinet et al. 2002] by combined controlled-source seismology and gravity modelling [e.g., Holliger and Kissling 1992], local earthquake tomography [e.g., DiStefano et al. 2009; Diehl et al. 2009a], receiver functions [Lombardi et al. 2008], surface wave [Schaefer et al. 2011a] and ambient noise tomography [Verbeke et al. 2012], and high-resolution teleseismic tomography [Lippitsch et al. 2003]. EK is a leading expert in multidisciplinary seismic tomography. He has been involved in the development of the methodologies of local earthquake tomography [Kissling 1988; Kissling et al. 1994; Kissling et al. 2001; Diehl et al. 2009b], and the methodology to combine various seismic imaging techniques for structure and physical parameters including, e.g., seismic anisotropy as an expression of the texture of crustal root beneath the Alps [Fry et al. 2010]. In a succession of 10 PhD theses tutored by EK at ETHZ, methods were further developed to derive intrinsically consistent and high-resolution 3D velocity models for the crust [e.g., Kissling et al. 1997; Waldhauser et al. 1998; Diehl et al. 2009b; Wagner et al. 2012]. The most recent development of combining the seismic imaging techniques of controlled-source seismology, local earthquake tomography and receiver functions concluded in a Moho map for Alpine-central Mediterranean region [Spada et al. 2013a] that not only precisely outlines the plate boundaries in this tectonically complex region but also reliably documents the geometries of the crustal roots beneath the orogenic belt. Furthermore, the combination of high-resolution crustal structure imaging with high-precision hypocenter analysis of the anomalous deep crustal seismicity in the northern Alpine foreland [Singer et al. 2014] yields new insight into seismotectonic processes of Alpine orogeny dominating seismicity in Switzerland.

Stefan Wiemer: Stefan Wiemer is director of the Swiss Seismological Service and full professor of seismology at ETH Zurich. His research background bridge the areas of seismic hazard and risk assessment, statistical seismology and earthquake forecasting related research as well as increasingly research related to induced seismicity. Relevant to this proposal, he and his research teams are working on an improved physical understanding of induced earthquakes [e.g., Bachman et al. 2012, Goertz-Allmann et al., 2011; Catalli et al., 2013], to model and forecast their occurrence [Goertz-

Allmann and Wiemer, 2013; Gischig and Wiemer, 2013], as well as to assess their hazard and risk [e.g., Bachmann et al., 2011; Mignan et al., 2015]. Precise re-location of hypocenters and structural information can be coupled with hydraulic knowledge and geomechanical models, and this will be the key to understand the induced seismicity in St. Gallen. Wiemer and his group also are actively researching the use of micro-earthquakes as indicative stress-meters in the Earth's crust [e.g., Tormann et al., 2015, Tormann et al., 2013; Meier et al, 2014; Spada et al, 2013b] and have proposed how these observations can be used for improved long-term and time-dependent seismic hazard assessment [e.g., Tormann et al., 2014]. In the context of this proposal, the improved knowledge on faults in Switzerland can be integrated in the next generation seismic hazard map of Switzerland, improving the current state-of-the-art that uses generic seismogenic source zones only [Wiemer et al., 2009, 2009a].

2.3. Detailed research plan

2.3.1 Goals and objectives

The project's main goals are the development of new techniques to image the structure and understand the mechanics of seismogenic fault zones. Our study can be subdivided into three major objectives:

- **Imaging of Source-Sided Velocity Structures:** We will explore and develop new passive source techniques to image the seismic velocity structure within seismogenic zones at variable scales by combining high-precision earthquake location with tomographic inversion. Synthetic travel-time data derived from realistic high-resolution fault zone models will be used to validate resolution capabilities of existing and newly developed earthquake location and seismic tomography codes.
- **Interaction of Faults and Earthquakes in the St. Gallen Fault Zone:** We will revisit subsets of the St. Gallen 3D active source data to resolve previously unrecognized structures in seismogenic parts of the study volume. High-precision earthquake locations will be correlated with (1) pre-existing faults visible in the re-interpreted 3D seismic data and (2) the source-side velocity structure. We will study the connection between seismicity, fault structures, and physical properties. We are especially interested in the high-resolution imaging of potential spatio-temporal changes of physical properties due to stimulation and injection procedures in the planned geothermal reservoir.
- **Insights into the Rawil Fault Zone:** By the use of high-precision earthquake locations, focal mechanisms, and local seismic velocity models we aim to resolve the lateral and vertical extent of the fault damaging zone, its continuation across lithological boundaries, and spatio-temporal changes of physical properties and tectonic stresses along the Rawil Fault Zone. We are especially interested in the width of the seismogenic lineament and how it relates to models of fault damage zones. A comprehensive analysis including earthquake statistics, seismic reflection profiles, geodetic, and geological data will provide new insights on the nature of this seismogenic lineament.

2.3.2 Data

The data used in the proposed study consists of active source reflection data of crustal transects in the Central and Western Alps of NFP20 [e.g., Pfiffner et al. 1997] recently recopied and made available by the Swiss Geophysical Commission (www.sgpk.ethz.ch). In addition, the Co-PI S. Wiemer has access to a subset of 3D seismic industry data gathered prior to the geothermal project in the region of St. Gallen.

The passive data used in the project consists of bulletin and waveform data of local earthquakes compiled, recorded, and archived by the Swiss Seismological Service (SED). Digital data is available since 1984. Starting in 1999, the network has been constantly upgraded to a digital network (SDSNet) with the majority of instruments consisting of broadband instruments. By the end of 2013, the SDSNet consisted of 54 weak-motion stations [Diehl et al. 2014c]. Starting in 2009, existing dial-up stations of the national strong motion network of the SED (SMSNet) have been replaced by state-of-the-art broad-band strong-motion instruments [e.g., Clinton et al. 2011]. By the end of 2013, the SMSNet consisted of 61 continuously streaming stations. The dense SMSNet complements the real-time monitoring of the SDSNet and is also included in the analysis of microseismicity in Switzerland. To improve locations for events at the periphery of or outside of Switzerland, the SED exchanges data of 40 stations in real-time with agencies in Austria, Italy Germany, and France. Local earthquake data is manually picked and routinely located by experienced seismologists. In addition, focal mechanisms and moment tensor solutions are routinely computed for earthquakes of sufficient magnitude. These data are openly available at the SED.

The density of seismic networks in the two study regions was improved by installation of local networks. The St. Gallen area was monitored by a dense array before, during, and after the stimulation tests in 2013 [Diehl et al. 2014] (see Figure 3a). Starting in 2009, also the density of the SDSNet in the Valais region was improved by the installation of permanent stations in the framework of the COGEAR project [Fäh et al. 2012] and several temporary networks have been installed in the region in the past [e.g., Maurer et al. 1997; Roten et al. 2008]. All data of local networks in these regions are readily available from the digital waveform archives of the SED. Figure 5 shows open and closed weak- and strong-motion stations in the proposed study area in southwest Switzerland. To better constrain the absolute focal depths of the shallow part of seismicity within the lineament north of the Rhone valley and to improve event detection and the spatial resolution of local tomographic images, we propose to install three to four additional stations in the vicinity of the seismic lineament for about 2 years. Potential sites are indicated by red triangles in Figure 5. Installation of the stations would be planned in close collaboration with SED.

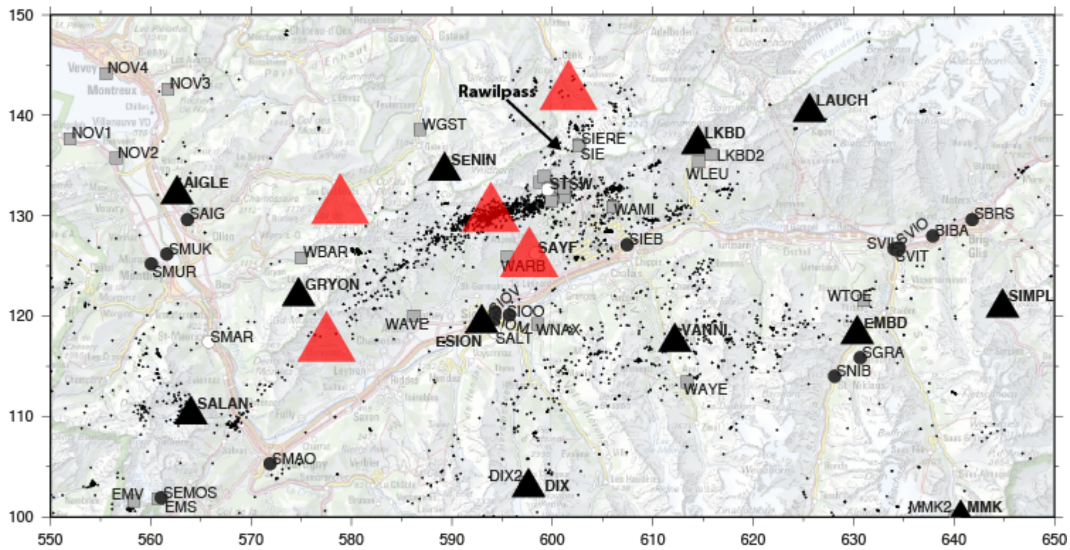

Figure 5. Red triangles indicate possible sites for 3-4 temporary stations installed and maintained during the project to improve event detection, absolute focal depth estimates, and spatial resolution of local tomographic images of the Rawil seismogenic lineament (black dots: earthquakes) in the Valais. Black triangles indicate open online weak-motion stations operated by the Swiss Seismological Service. Grey circles indicate open online strong-motion stations; white circles correspond to triggered strong motion stations. Grey squares indicate closed permanent or temporary stations.

2.3.3 Methods of Investigation

2.3.3.1 High-precision Regional Earthquake Catalogues

In order to connect seismicity with fault structures mapped by geological or geophysical surveys, clusters of seismicity have to be identified and absolute and relative locations of earthquake hypocentres have to be improved. The processing of state-of-the-art high-precision regional earthquake catalogues involve the following steps:

- Homogeneous single-event relocation of the entire earthquake catalogue using an appropriate regional velocity model. Besides a homogenisation of absolute locations, a consistent description of the location uncertainties is obtained. Probabilistic, non-linear approaches provide realistic absolute location uncertainties [e.g., Lomax et al. 2000; Husen et al. 2003].
- Large-scale waveform cross-correlation of neighbouring earthquakes of the entire digital archive. The cross-correlation data provides high-resolution measurements of differential times as well as information on earthquake clusters with similar waveforms. The latter can be used to identify multiplets, which are indicative for active faults repeatedly rupturing with similar slip orientations. Identified multiplets can also be used to study source properties like stress-drop and scaling relations [e.g., Allmann and Shearer 2007; Bethmann et al. 2010]
- The improved absolute hypocentres in combination with differential times from bulletin picks and cross-correlation measurements are used for regional-scale double-difference relocations [e.g., Waldhauser and Schaff 2008; Hauksson et al. 2012].

Within the framework of this project we propose to extend the work of Diehl et al. [2013a] considering all three steps mentioned above. First, the entire SED earthquake catalogue starting from 1984 will be homogeneously relocated using non-linear location algorithms in combination with a regional velocity model. Several suitable models have been computed in the last years [e.g.; Husen et al. 2003; Diehl et al. 2009a; Wagner et al. 2012] and will be systematically evaluated. Subsequently, large-scale waveform cross-correlation will be performed using algorithms, which have been developed for SED data and optimized through testing on smaller sequences. The PI of the project will mainly focus on the regional double-difference catalogue and it will used in a regional effort to identify clusters of earthquakes, potential geometries, and association of earthquakes with faults in Switzerland. The regional catalogue will also be used as the reference catalogue for a planned real-time double-difference implementation at the SED, similar to the procedure proposed by Waldhauser [2009].

2.3.3.2 High-Resolution Imaging of Earthquake Source Regions

Imaging fault zones geometries and physical properties at high resolution in space and time requires solving the coupled hypocentre-velocity problem by combining local earthquake tomography with differential times measured from waveform cross-correlation and double-difference relocation techniques. In the framework of this project, we will explore possibilities to image the P- and S-wave velocity structure in the vicinity of source regions of earthquake clusters. To test and validate the potential methods we will first generate synthetic travel-time data by applying finite-difference forward solvers [Podvin and Lecomte 1991] to realistic high-resolution fault-zone models. The synthetic models will be based on geological and geophysical information available for the two study regions. Uncertainties mimicking errors in catalogue picks and cross-correlation data will be added and the synthetic data will be used to explore the following questions:

- Can we derive information on the host rock material and possible spatial and temporal velocity changes within the earthquake source region directly from cross-correlation data similar to the approach of Lin and Shearer

[2007]? What are the conditions under which it is possible to image such changes (distribution of earthquakes, distribution of cross-correlation pairs, network configuration etc.)? How do data errors affect the relative location uncertainties?

- Can existing 1D (VELEST [Kissling et al. 1994]) or 3D (SIMULPS [Thurber 1983], TOMO-DD [Zhang and Thurber 2003]) tomographic codes image the lateral and vertical velocity structure in the vicinity of the earthquake source region? How do data, inversion, and forward grids affect the resolution? What is the impact of regional velocity heterogeneities on the source-side velocity structure in these approaches?
- Can we use residuals of differential-times from the double-difference relocation approach to directly invert for the source side-velocity structure (see sketch in Figure 6)? What is the appropriate damping of hypocentre and velocity adjustments in this inversion?

In the framework of this project we will first evaluate the resolution capabilities and caveats of cross-correlation (Lin and Shearer method) and 1D velocity models (VELEST) by applying them to synthetic and real data of the two study regions. The advantages of these methods are that they require little a priori information, little processing and therefore provide prompt constraints on velocities in the source region. A first test to constrain the average absolute velocities in the source region was performed for the St. Gallen sequence of 2013 [Diehl et al. 2014a]. A minimum 1D P- and S-wave velocity model was derived from travel-time data of about 100 earthquakes. From the joint interpretation of the 3D active seismic model, the increase in P- and S-wave velocities at 3.5 km depth is interpreted as the Top-Malm interface (Figure 6a). The depth of seismicity relative this interface suggests that the majority of earthquakes occurred in the Mesozoic sediments (Figure 6b). In the framework of this project, we will apply similar approaches to other earthquake sequences to determine the average seismic velocities of source-regions. In addition to the Rawil earthquake cluster, the induced seismicity in Basel between 2006 and 2007 represents a prime data set to test this concept. In contrast to the induced St. Gallen sequence, seismicity associated with stimulations in Basel appears to be restricted to the crystalline basement [Deichmann and Giardini 2009]. High-quality arrival time picks of the sequence are available at the SED and can be used for the 1D velocity inversion. The derived velocity structure will then be compared to available structural models of the Basel region [e.g., Ripperger et al. 2009].

In the second step, we will test the resolution capabilities of existing 3D inversion codes (SIMULPS, TOMO-DD) by applying them to synthetic and real data of the two study regions. Beyond testing the existing algorithms, we aim to develop a framework for a scalable 3D double-difference tomography inversion scheme targeting the source-side velocity structure (see Figure 6c). However, achieving a source-side resolution of few hundreds meters, necessary to resolve fine-scale variations within source zones, requires significant modifications of existing inversion codes including multi-grid model parameterizations and high-precision forward solvers [e.g., Kissling et al. 2001]. The proposed algorithm would overcome numerical limitations of existing earthquake tomography algorithms designed for regional models and therefore be applicable for imaging small-scale velocity structures within micro-networks deployed, for example, during geothermal projects, CO_2 sequestration, or monitoring of volcanic areas.

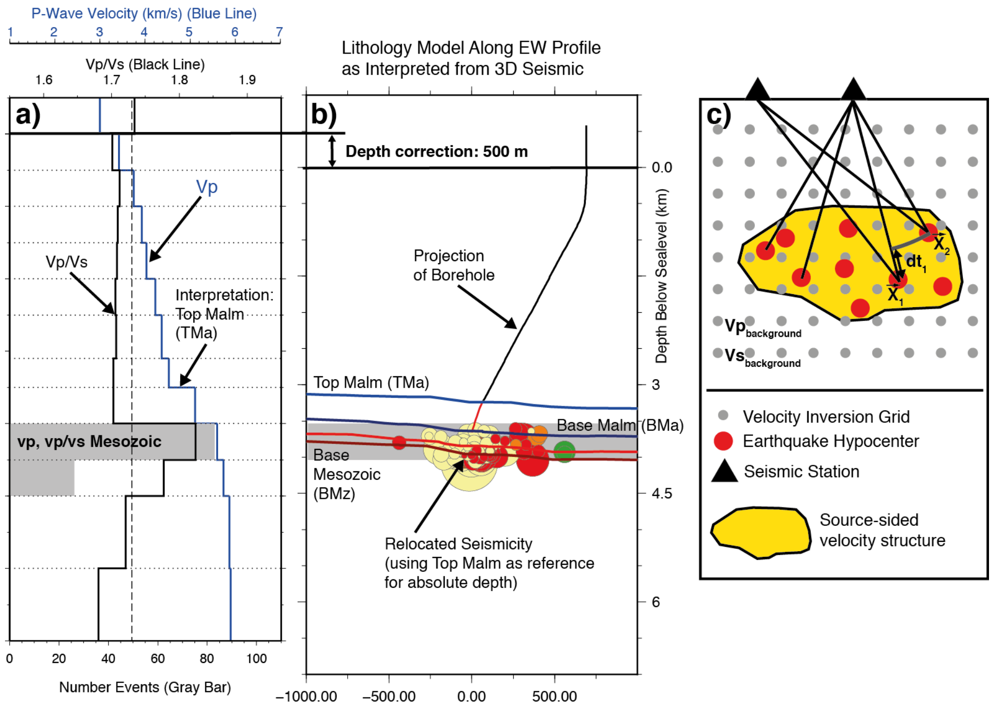

Figure 6. Examples for imaging source-sided velocities of seismogenic zones and how derived velocities can be used for interpretation of host rock material and absolute focal depths. ***a)*** *One dimensional P- and S-wave velocity structure in the source region of the St. Gallen sequence of 2013 derived from the inversion of manually picked arrival times of local earthquakes. The jump in P- and S-wave velocity at 3.5 km depth is interpreted as the Top Malm interface and the Vp and Vp/Vs ratio in the source region are indicative for Mesozoic sediments. Velocities are well constrained in (and around) layers containing earthquakes [e.g., Kissling 1988].* ***b)*** *Comparison with a lithology model derived from borehole and 3D seismic data in the St. Gallen region. The relative location of seismicity with respect to the assumed Top Malm interface suggests that the majority of earthquakes occurred in the Mesozoic sediments.* ***c)*** *Sketch illustrating the proposed source-side double-difference tomography to resolve fine-scale variations of seismic velocities in 2D or 3D. Networks of differential time residuals of event pairs, such as dt_1, measured by waveform cross-correlation at different stations are used to invert for relative locations of hypocentres (e.g. $\vec{x_1}$, $\vec{x_2}$) and local deviations of seismic velocities from the background velocities in the source region of seismicity.*

2.3.3.3 Evaluating Processing Techniques in Active Source Data

To better understand the mechanisms and the evolution of faults, seismicity needs to be associated with fault models derived from seismic reflection data. In many cases, information on seismicity within the study volume was missing at the time the seismic data was processed and interpreted. By revisiting seismic images with the focus on seismogenic zones we might identify previously unrecognized features in the seismic data, which add to a deeper understanding of the mechanics of fault zones. In case of the induced seismicity in St. Gallen, we are particularly interested in the occurrence of seismicity on an apparent NE continuation of the imaged fault branch (see Figure 4) and its relation to stimulation activities. We propose to carefully re-evaluate the seismic images in this part of the data volume. The initial interpretation of the 3D seismic data was based on NS-EW oriented grid (Figure 7a). To enhance possible features along the apparent NE striking continuation of the fault, we propose to reprocess the data on a grid parallel and normal to the strike of the earthquake lineament (Figure 7b). Another focus will be on the lateral mapping of structures associated with the Permo-Carboniferous Trough and its potential connection to the overlain fault system in the Mesozoic sediments.

The evaluation and processing of the 3D seismic data will be done in close collaboration with the exploration company Proseis AG in Zurich. Proseis was contracted by the operator of the St. Gallen geothermal project for the initial 3D seismic survey of the area. Data are readily available at their offices in Zurich.

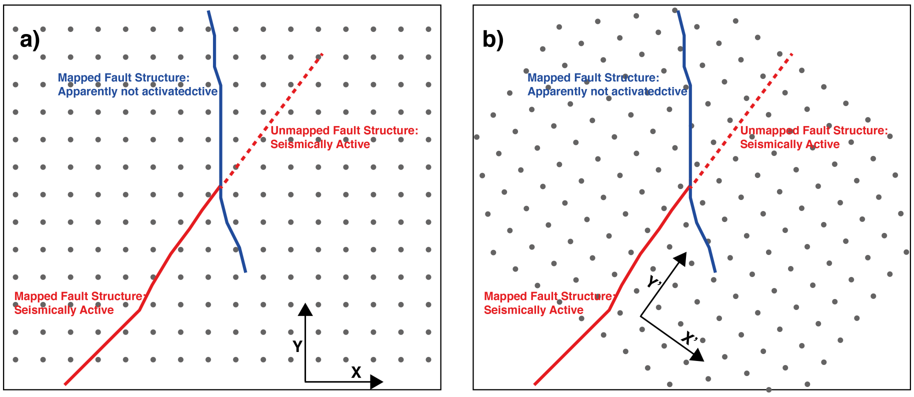

*Figure 7. **a)** Sketch illustrating the initial processing grid used to identify vertical offsets in the strata of the 3D seismic data in the St. Gallen area (see Figure 3b). **b)** To further enhance features indicating potential fault structures along the NE branch of induced seismicity (grey shaded area in Figure 4), we propose to process the 3D seismic data on a grid parallel and normal to the strike of the earthquake lineament.*

2.3.4 Application and Interpretation

The passive seismic methods described in 2.3.3.1 and 2.3.3.2 will be applied to real data, with the focus on the Rawil and St. Gallen fault zones. The spatial distribution and density of seismic stations and earthquake sources will allow us to compute a 3D seismic velocity model of the upper crust of the entire Valais region using well-established local earthquake tomography. This model will then be used as a reference model for imaging the source-side velocity structures in the Rawil area. Information on velocity structure, high-precision earthquake locations, focal mechanisms, seismic reflection, and geological data will be used for a comprehensive interpretation of the Rawil seismogenic lineament. In addition to a spatio-temporal and statistical analysis of seismicity, we will compare the width of the seismogenic lineament to fracture distributions of fault damage zone models published by Savage and Brodsky [2011].

Results from passive source imaging of the St. Gallen fault zone will be interpreted in combination with the reprocessed 3D seismic data. The interpretation will focus on possible connection and interaction of faults and their relation to stimulation and fluid injections in the planned reservoir. In close collaboration with Stefan Schmid (ETH) and Marco Herwegh (University of Bern), the joint interpretation with geological field data and tectonic models will lead to a comprehensive understanding of seismicity in the Rawil and St. Gallen fault zones.

2.4. Schedule and milestones

The project proposed here encompasses one Ph.D. scholarship of three years. In parallel to the Ph.D. work, the PI will establish a regional double-difference catalogue for Switzerland, which will be used by the Ph.D. student. The Ph.D. theses is planned to be carried out under the supervision and close collaboration of the three PIs and will be divided in the following main phases:

Year 1:

Ph.D.: Establish synthetic models of the two fault zones (St. Gallen, Rawil) and implement test-bench for high-precision forward solvers used for testing and evaluation of existing and novel passive source imaging techniques. Test resolution capabilities of existing tomography codes for imaging source-side velocities in the two study regions. **ST. GALLEN:** Evaluation and reprocessing of the 3D seismic data of the St. Gallen region in collaboration with Proseis.

PIs, Collaborators: Waveform cross-correlation of the entire digital data archive of the SED. Systematic analysis of multiplets and identification of earthquake clusters based on waveform similarity. Iterative relocation of earthquakes in Switzerland including: a) non-linear single-event approach. b) double-difference relative relocation. Systematic analysis of DD-catalogue to identify presently unrecognized seismogenic lineaments.

Year 2:

Ph.D., PIs, Collaborators: **RAWIL:** Establish 1D and 3D velocity models of the Valais region using existing 3D local earthquake tomography codes and data available from the SED. Validate model resolution with synthetic data set. Model will be used as reference model for high-resolution imaging of source-side velocities. **ST. GALLEN:** Test if source-side velocity anomalies can be imaged by cross-correlation data of the St. Gallen sequence. Joint interpretation of synthetic tests, velocity structure, high-precision locations and reprocessed seismic data.

Paper 1: Paper on imaging of source-sided velocity structures (resolution capabilities and limitations of existing algorithms validated by synthetic data, use of cross-correlation and pick data for precise hypocentre location and imaging of source-side velocity structures).

Year 3:

Ph.D., ***PIs, Collaborators*****:** Develop framework for double-difference tomography. Implement high-precision finite-difference forward solver in inversion algorithm. **RAWIL:** Analysis of CC data, 1D models, to image source-side velocities. spatio-temporal analysis of seismicity, statistical aspects, focal mechanisms.

Paper 2: Paper on St. Gallen (4D velocity structure, interpretation of reprocessed 3D seismic data, earthquake triggering mechanisms, interaction of faults and seismicity)

Paper 3: Paper on Rawil seismogenic lineament (regional and local velocity structures, high-precision hypocentre locations, spatio-temporal analysis of seismicity, statistical aspects, regional tectonics, comparison with geological field data and tectonic models in collaboration with Stefan Schmid and Marco Herwegh.

2.5 Importance and impact

The key question our project aims to address is how are earthquakes related to pre-existing individual faults and how do faults mechanically interact within fault zones. There are two major reasons these important questions have hitherto not been sufficiently answered (1) the lack of accuracy and precision in earthquake location, concerning epicentre location and focal depth, and (2) the limited resolution capabilities of seismic imaging to detect potential seismogenic faults or fault segments. In regard to question (1) it is of great importance to know if seismicity is indeed distributed within a wider area or whether diffuse seismogenic lineaments just reflect inaccuracies in the location. Should seismicity be diffuse indeed there is also a possibility that such seismic lineaments reflect a finite fault damage zone or fault arrays rather than singular faults. In regard to question (2) our project will potentially lead to the detection of hitherto undetected pre-existing faults that are prone for reactivation. The outcome of the proposed evaluation of the St. Gallen 3D seismic data will have particular impact on the assessment of seismic hazard, since it has the potential to demonstrate incompleteness and uncertainties of fault models derived from seismic imaging.

The expected impact of our study is twofold. Firstly we expect an improvement of geophysical imaging methods that allow insights into the interaction of pre-existing faults with seismic activity leading to a better understanding of seismogenic structures in general. Secondly, we chose two particular sites for our study, which are of high societal relevance. The Valais is the most active seismogenic zone of Switzerland and a large part of this seismic activity is related to the seismogenic lineament in the Rawil depression. The question about the possibility of large magnitude earthquakes critically depends on the question as to whether this activity is related to a single fault of considerable lateral extension or not. The St. Gallen site offers an excellent occasion to study local earthquake hazard in the densely populated Molasse basin, which is also the site of future geothermal plants and radioactive waste repositories.

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