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Compilation of data relevant to assess the geothermal potential of the Rhône Valley

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Executive summary

The Rhône Valley represents the geothermally most active domain in Switzerland and is characterized by a highly mountainous domain, the occurrence of numerous thermal springs, regional-scale faults, enhanced seismic activity as well as high surface uplift rates. This combination suggests a close link between active tectonic processes creating permeability as well as the recharge of cold meteoric water, followed by heating and subsequent ascend/discharge of the hot waters. Based on this natural hydrothermal activity the study area is prone for the exploitation of renewable geothermal energy requiring innovative and reliable exploration strategies. In this light, we suggest to apply a Play Fairway Analysis (PFA), a concept adapted from the oil industry for the exploration of hydrocarbons. PFAs for geothermal systems require fundamental knowledge on three major data categories: (i) **background information**, (ii) **heat distribution**, and (iii) **permeability**. This report provides information on the relevance of different parameters of each category, compiles the data available but also discusses which additional data are necessary for a PFA but are currently missing, since simply not yet collected or not publicly available. The study is framed into three major compartments: (i) The report which addresses the three categories and associated parameters/data, (ii) an extensive appendix discussing availability of the respective data, and (iii) an ArcGIS database visualizing the data layers providing the base for a future PFA.

As a general conclusion, many individual data being highly relevant for a PFA already exist but the data are very heterogeneous with insufficient spatial coverage. Besides lacking data, a particular problem is that a substantial amount of information is neither publicly available nor yet processed to be applied for a PFA. Hence, major advances in terms of manpower and funding are mandatory to obtain a complete and harmonized database which fulfills the requirements of a sufficient spatial coverage and resolution for a proper evaluation of the regional geothermal potential. In terms of **background** information, we recommend to exploit data automatically gathered from existing ground source heat pumps (temperature, power rating, etc.) as well as the generation of a complete area wide groundwater hydrogeological data set. For the **heat distribution,** a regional heat flow map is mandatory. Aforementioned data from ground source heat pumps, combined with measurements of temperature gradients (boreholes, underground facilities) and temperatures of discharge waters would provide an excellent base for the modelling of such a regional scale heat flow map. For **permeability**, large-scale 3D information on the hydraulically active fault pattern as well as fault-related porosities/permeabilities are fundamental. Here, combinations of quantitative remote sensing approaches, digital structural mapping, petrophysical data (e.g. porosity/permeability) from drill holes, as well as hand specimen and 3D numerical fault modelling deliver the missing information. Depth information of the hydraulic cells can be obtained from approaches relying on fluid geochemistry.

Interdisciplinary collaborative projects are most promising to obtain the missing information. This requires close interactions between scientists, cantonal and federal authorities, as well as industry (hydropower, consultancy companies). Based on such collaborations the data gaps of the presented data framework (ArcGIS database, PFA structure) can be completed. Once accomplished, this database provides in future a useful and dynamic planning tool for geothermal exploration projects, not only in the Rhône Valley but also for other promising areas in Switzerland.

Contents

1 Introduction and Background

The Rhône Valley is the most active geothermal domain in Switzerland, which is characterized by mountainous terrain, high seismic activity and high uplift rates, regional-scale strike-slip faults and numerous thermal springs, including the 110 °C, 22 L/s system at Lavey-les-Bains. The thermal waters in the Rhône Valley are derived from the infiltration and deep (up to 10 km) circulation of meteoric waters, which are heated by the background geothermal gradient (geothermal play). Sufficient heat exchange as well as fluid circulation is controlled by a complex interplay between fluid pathways and their permeability (controlled by the structural framework), circulation time, hydraulic gradients (mainly controlled by the topography and the infiltration elevation/quantity) as well as the thermal conductivity of the country rocks. Moreover, fluid pathways can change in space and time owing to clogging by mineral precipitation and to renewed opening by further fracturing.

For years, people have studied orogenic systems in Switzerland by looking at the same known sites without exploring the area for additional, unknown thermal water occurrences. Due to the prevailing geothermal play in an orogenic system, it is likely that there are many more, so far unknown systems. They are obscured by the thick and water-saturated unconsolidated sedimentary filling of the Rhône Valley which results in mixing between cold, shallow groundwater and the deeper thermal component. At high mixing ratios, the thermal signature can be diluted so it is no longer easily recognized. Such a system therefore has no surface manifestation and is called “blind system”. However, these blind systems are of great interest for geothermal exploration and need to be identified and the energy available within quantified, in order to quantitatively assess the geothermal potential of the study area.

Originally, this compilation was supposed to represent the starting point for the project *Evolution and potential of an orogenic geothermal system: Coupling of fluid flow, heat flow, faults and seismicity*. The proposal was submitted to SNSF in 2018 as part of the Sinergia call and wanted to gain new understanding of

- The evolution and present-day thermal-mechanical–hydraulic-chemical–seismic state of the Rhône Valley geothermal domain as a proxy for orogenic geothermal systems
- The processes and associated feedback mechanisms necessary to create and sustain such orogenic geothermal systems;
- The current 3D distribution of subsurface heat in the domain and its potential for future exploitation.

Unfortunately, the project was rejected in the second half of 2018. Some of the proposed studies will be/have been submitted to SNFS within the project funding scheme while other parts of the Sinergia proposal will now not be realized. Therefore the aim of this data compilation changed from focusing on the fundamental science of evolution of orogenic geothermal systems to supporting the geothermal exploration of the Rhône Valley and its surroundings. Basically, the present data compilation represents the first step of a **Play Fairway Analysis (PFA)** (see Section 2), an exploration tool from the hydrocarbon industry which works by spatially correlating known geological data and drawing a favorability map to increase the likelihood of success for future exploration aiming at the discovery of additional, blind systems.

1.1 Known thermal occurrences

Thermal springs in the Rhône Valley and the surrounding areas have been known and exploited since Roman times (e.g. Leukerbad and Brigerbad). Currently, one or several (sub)thermal springs are known from at least 9 sites across the study area (Table 1). Their temperatures range from 16.8 to 51 °C with flow rates of up to 22 L/s. Several of these thermal springs became the sites of thermal baths (Brigerbad, Lavey-les-Bains, Leukerbad and Val d'Illiez). Often additional wells were drilled to reach deeper and hotter as well as more productive thermal water occurrences. In addition, thermal SPAs were built after successful drilling for hot water in the subsurface of Saillon and Saxon, where the nearby springs of Leytron suggested thermal water occurrences at depth. Other wells such as Combioula or Epinassey did not yield enough thermal water and remain unused.

In addition to springs and thermal groundwaters, warm tunnel waters are used at several locations within the Rhône Valley and surrounding areas. These waters represent groundwaters circulating through the mountains through which the tunnel was drilled. Depending on the thickness of the overlying formations, these waters can reach temperatures of over 40 °C and can thus be used for spatial heating (Furka W-portal) or industrial purposes such as greenhouses or fish farming (Lötschberg Base Tunnel N- and S-portal). The water emerging from the Simplon rail tunnel is currently only used on the Italian side.

Table 1: Thermal water occurrences in the Rhône Valley and surrounding areas. Data are from the 2007 Swiss-wide thermal water database BDFGeotherm (Sonney and Vuataz, 2008 and references therein) and from Buser et al. (2013) for the more recent wells drilled at Brigerbad.

Name	Type	Number of springs, wells, etc.	Max. Temperature [°C]	Max. Flow rate [L/s]	Usage
Bovernier	Spring	1	21.5	3.3	None
Brigerbad	Spring	3	20.5	5.0	Thermal bath
Brigerbad	Gallery	1	52.0	12.0	
Brigerbad	Well	7	60.0	17.0	
Combioula	Spring	2	28.0	13.3	None
Combioula	Gallery	1	29.4	13.3	
Combioula	Well	3	31.0	20.0	
Epinassey	Well	1	22.0	3.9	None
Furka W-portal	Tunnel	1	21.7	0.3	Building heating
Gletsch	Spring	1	18.6	3.3	
Grimsel	Tunnel	1	28.0	0.03	None
Lavey-les-Bains	Spring	1	16.8	No data	Thermal bath and building heating
Lavey-les-Bains	Well	12	72.0	20.0	
Leukerbad	Spring	7	51.0	15.2	Thermal bath
Leytron	Spring	1	25.1	2.1	None
Lötschberg S-portal	Tunnel	1	25.8	0.13	Fish farming
Rawyl	Gallery	1	29.7	20.0	None
Saillon	Well	4	32.0	20.0	Thermal bath
Saxon	Well	2	27.0	29.0	Drinking water
Simplon S-portal (I)	Tunnel	1	45.5	8.5	None
Val de Bagnes	Spring	1	18.0	1.7	None
Val d'Illiez	Spring	2	30.1	22.0	Thermal bath
Val d'Illiez	Well	1	30.0	11.7	

In addition, two more projects are being planned at the moment. The consortium Alpine Geothermal Power Production (AGEPP) is planning a deep well (2000 to 3000 m) into the highly permeable naturally fractured gneisses at Lavey-les-Bains. They expect to encounter water at 110°C (at the drill head) and at a rate of 40 l/s. These conditions would enable the production of 4.2 GWh of electricity and 15.5 GWh of thermal energy. In the long run, the residual energy could be used for district heating, greenhouses or fish farming. The last report detailing the current state of the project (Phase B1: Feasibility study and preparation of a deep well) was published by Bianchetti et al. (2007). According to a press release published by AGEPP in later October 2019, all permits are in place and drilling is expected to start in 2021.The second project currently under planning is a new deep well at Brigerbad. Originally, a 3000 m deep well was planned with the aim to produce electricity in addition to thermal energy. However, after the failure of the St. Gallen project in 2013, these plans were put on hold. Instead, a 1000 m well is currently being discussed. Depending on the encountered permeability, either direct production of thermal water for district heating or the installation of a deep ground source heat pump would be possible (presentation by W. Leu as part of the festivities “10 Jahre Alpenstadt Brig-Glis”, 2018).

1.2 Geological setting

The Rhône Valley is situated in the Western Central Alps (Steck et al., 1999) in south western Switzerland, i.e. the cantons of Valais and Vaud. In the NW, basement rocks of the External Crystalline Massifs (Aar-, Aiguilles rouges and Mont Blanc massifs) with their sedimentary cover are found together with the overlying sedimentary Helvetic nappes (Escher et al., 1993; Pfiffner, 2011 and references therein; Steck et al., 1999). They are separated from the metamorphosed sediments and basement of the Penninic nappes in the SE by the Rhône-Simplon fault system (e.g. Campani et al., 2010; Mancktelow, 1985) the latter largely controlling the E-W-orientation of the Rhône Valley.

The Helvetic and Penninic nappes were sheared off their respective basement units in the earlier stages of the Alpine collision and both stacks were transported to the North where the Penninic nappes ended up on top of the Helvetic formations. Towards the end of the collision between the Adriatic and European plates, the continent-continent collision resulted in a complex dome-shaped structure with complex internal tectonic architecture, which stalled plate convergence and ultimately uplifted and exhumed mid-crustal portions (e.g. Froitzheim et al., 2008; Rosenbaum and Lister, 2005; Stampfli et al., 1998) involving slab rollback (Herwegh et al., 2017; Schlunegger and Kissling, 2015; Singer et al., 2014). Increased glacial denudation and relief development in the Pleistocene intensified the tectonically induced uplift and brought further warm basement rocks near to the surface (Valla et al., 2012). The temperature field and accordingly the heat flow resulting from conductive heat transport is strongly influenced by topography and therefore the near-surface geothermal gradient can vary significantly on a local scale (Mancktelow and Grasemann, 1997) but average values are around 25 °C (e.g. Glotzbach et al., 2010; Vernon et al., 2008). The local thermal structure can also be strongly affected by the recharge of meteoric water. The water infiltrates at high-altitude, cools the rock mass during its descent (→ negative temperature anomaly) and then, following topographically induced hydraulic gradients, transports the acquired heat towards lower-altitude discharge sites (→ positive temperature anomaly), emerging as warm/hot springs (e.g. Diamond et al., 2018 and references therein).

In order to understand the distribution of these thermal anomalies, the distribution of structures with sufficient permeability to act as fluid pathways needs to be understood. In case of the Helvetic nappe stacks, three mechanical anisotropies are known to act as potential fluid pathways: (1) former ductile thrust planes that are reactivated in a brittle manner during retrograde shearing (Burkhard and Kerrich, 1988; Crespo-Blanc et al., 1995; Ebert et al., 2007; Herwegh et al., 2008; Herwegh and Pfiffner, 2005; Kirschner et al., 1999), (2) NW-SE trending vertical strike-slip faults, which evolved out of A-C joints perpendicular to massif-parallel, large-scale folds (Ustaszewski et al., 2007), and (3) porous stratigraphic layers (e.g. Triassic evaporites; Bianchetti et al., 1992). In the underlying basement, numerous studies document the occurrence of steeply oriented shear zones (Baumberger, 2015; Belgrano et al., 2016; Egli and Mancktelow, 2013; Krayenbuhl and Steck, 2009; Rolland et al., 2009; Steck, 1968; Steck and Vocat, 1973; Wehrens et al., 2016, 2017) that facilitated the exhumation of the Aar massif (Herwegh et al., 2017). If such shear zones are reactivated in the brittle regime, they too represent prime pathways for fluid circulation (Baietto et al., 2009; Belgrano et al., 2016; Egli et al., 2018; Wehrens et al., 2016).

The Rhône Valley was carved out by the Rhône glacier during the Pleistocene ice ages along the trace of the Rhône-Simplon-fault line. The glacier carved out the bedrock to great depth and, upon retreating, left a thick stack of sediments (up to 1 km) behind. These sediments are characterized by highly permeable and loose gravel at the bottom, representing the subglacial drainage system. These gravels are followed by a succession of unconsolidated sediments representing ground and end moraine as well as lacustrine and fluviatile deposits (Finckh and Klingelé, 1991).

Currently, the area of the Rhône Valley is one of the most tectonically active regions of Switzerland. Enhanced uplift rates (up to 1.6 mm/a; Kahle et al., 1997), indications of tectonically active faults (Ustaszewski et al., 2007; Ustaszewski and Pfiffner, 2008), and enhanced seismic activity (Diehl et al., 2018; Maurer et al., 1997) all point to intensive recent deformation in the study area. In addition, the large number of thermal occurrences (Table 1) indicates that several hydrothermal systems are currently active across the study area as the deformation structures inherited from the Alpine orogeny and their brittle reactivation during exhumation have formed many fluid pathways through the upper crust.

1.3 Overview of geothermal studies in the Rhone Valley

The geothermal potential of the Rhône Valley and its surrounding areas has been of great interest for several decades. In the late 1980s, the GEOTHERMOVAL I study carried out by CREALP, former CRSFA, was started. As part of the preliminary and first phase, the authors gathered a large dataset consisting of geological, geo- and petrophysical as well as hydrological and –chemical data for locations with known and partly used (sub)thermal springs (Val d'Illiez, St. Maurice-Lavey-les-Bains, Bovernier, Val de Bagnes, Saillon, Leukerbad, Brigerbad-Visp), thermal water emerging from tunnels (Rawyl, Simplon, Oberwald) and towns situated in geological settings similar to known thermal sites (Martigny, Sion). Most of the data were summarized in CRSFA Internal Reports or Diploma theses at the University of Neuchâtel, which unfortunately have never been published. However, a summary was published in Vuataz et al. (1993) and the studies at Val d'Illiez, Rawyl, Saillon, and Leukerbad were published in Bianchetti et al. (1992), Bianchetti (1993), Dubois et al. (1993), and Muralt and Vuataz (1993), respectively. These studies allowed drawing some first, very general conclusions on the nature of hydrothermal activity in the Rhône Valley: The hydrothermal activity is due to penetration and deep circulation of meteoric waters which are heated by the background geothermal gradient. The reservoirs for these fluids are situated in the Triassic dolomites, the crystalline basement and the base of the deep Quaternary valley infill. It is thus assumed that the individual systems largely function independently and are controlled primarily by the local structural setting.

In a second part of GEOTHERMOVAL I, a 929 m long exploration well was drilled at Saillon (JAFE well). The well produced 32 °C warm water at a flow rate of 6 L/s (after acidification). However, major problems due to scaling of iron phases and subsequent pump failures were encountered and the project had to be terminated. From 2013 to 2015, the follow-up project GEOTHERMOVAL II was conducted with the aim of exploring the potential of low- to medium-enthalpy reservoirs at the base of the Quaternary valley infill of the Rhone Valley and its main side valleys. So far only a preliminary internal report exists as well as a brief summary in the 2014 and 2015 annual activity reports of CREALP. While giving a detailed overview over the existing thermal occurrences as well as substantially enhancing our understanding of their characteristics, neither GEOTHERMOVAL studies can be described as a potential study sensu stricto.

An actual potential study was published in 2003 for the canton of Vaud. It features some information about Lavey-les-Bains where a new well will be drilled in the near future (likely 2019) as part of the AGEPP (Alpine Geothermal Power Production) commercial project. It is hoped to reach waters at a temperature of 110 °C at a depth of 2000 - 3000 m. With flow rates of around 40 l/s, the system could produce 4.2 GWh of electricity and 15.5 GWh of thermal energy.

The Grimsel hydrothermal field, as north-eastern extend of the Rhône Valley system, was studied recently within the NFP70 framework. Owing to the long-lasting exhumation history of a former ductile fault system, which has been hydrothermally active since at least 3.4 Ma (Hofmann et al., 2004), the spatial and temporal evolution of recent hydrothermal activity can be investigated in great detail. Building on pioneering studies of Pfeifer et al. (1992); research groups of the Universities of Bern, Lausanne and the ETHZ investigated this natural geothermal system by means of discharge (Grimsel Breccia Fault) and recharge (Nagra Grimsel Test Site; project LASMO) areas. Here information from field investigations (surface and underground mapping, sampling, 3D structural analyses), geochemical sampling and analysis of thermal water and a research-drilling project (NFP70; SNF-153889) were combined to receive a comprehensive system analysis. Major outcomes of these projects were:

(i) Recharge of cold meteoric water

- Recharge is driven by hydraulic head and occurs along brittley overprinted former ductile shear zones and metabasic dikes (case study nagra Grimsel Test Site; Schneeberger et al., 2017, 2018).
- Water percolation preferentially occurs either along fault planes with enhanced slip tendency or fault intersections (case study nagra Grimsel Test Site; Schneeberger et al., 2017, 2018).
- Meteoric water can infiltrate as deep as 9-10 km (Grimsel Breccia Fault; Diamond et al., 2018).

(ii) Discharge of warm hydrothermal water (Grimsel Breccia Fault)

- Strike-slip with domains prone for dilatancy (e.g. fault linkages) provide spatially very restricted 3D tube-like domains, along which hydrothermal waters can efficiently ascent towards the surface (Belgrano et al., 2016).
- Domains of increased fracture density as well as the matrix of fault breccias generate porosities of 10-25 vol%, which are significantly enhanced compared to wall rock porosities (Egli et al., 2018).
- Hydraulic conductivities can be as high as 10^{-7} and 10^{-5}-10^{-4} m/s, respectively, in the case of fracture and matrix porosity being 5-8 orders of magnitude higher than those of the wall rocks (Egli et al., 2018).
- Circulation from time of infiltration as meteoric water till discharge as hydrothermal water can take between 8'000 to 30'000 years (Waber et al., 2017).
- The time-integrated average flux is locally episodic owing the clogging by mineral precipitates (Berger and Herwegh, 2019; Hofmann et al., 2004).
- Clogging is counteracted by re-fracturing of the fault rocks, which occurs in parts at seismic rates (Berger and Herwegh, 2019).

As analogue for other hydrothermally active domains of the Rhône Valley, these new findings are of great importance for the further exploration of the geothermal potential in this hydrothermally so active domain. Note that this type of geothermal system is not only common in the Central Alps but similar systems have been observed in many orogenic systems around the world (Chamberlain et al., 2002; Jenkin et al., 1994; McCaig et al., 1990; Menzies et al., 2014).

In addition to these regional studies, Vuataz (1983) and Sonney and Vuataz (2008) have published a database of (sub)thermal waters of Switzerland. This valuable database includes information on the geology of the site, temperatures (measured at the surface as well as extrapolated to reservoir depth) and flow rates, concentrations of major cations and anions, as well as stable and radiogenic isotope analyses (δ^2H, $\delta^{18}O$, ^3H, ^{14}C) of 82 geothermal occurrences in Switzerland, 17 of which are situated in our study area. Another compilation of Swiss-wide geothermal data was performed within the framework of GEOTHERM, the public federal information system for deep geothermal energy financed by SFOE and put together by swisstopo. The aim of the project is to make all non-confidential data relevant to deep geothermal projects publicly available and create a database of confidential data. So far, 3 layers are online: operational/under construction/in planning/abandoned deep geothermal projects, wells > 500 m and cantonal geothermal potential studies. In 2019, different layers on underground temperatures will be added for the project area of GeoMol (i.e. the Swiss Molasse Basin; Landesgeologie, 2017).

2 Play Fairway Analysis (PFA) for geothermal exploration

Based on the compilations/studies described above it becomes clear that geothermal studies in and around the Rhône Valley have largely focused on known occurrences, i.e. areas where (sub)thermal springs were discovered decades to centuries ago. However, based on the type of geological setting (i.e. deep penetration of meteoric water along brittely reactivated structures, which is then heated by the background geothermal gradient), it is likely that there exist more locations where thermal waters emerge from the bedrock. Given the high topographic elevations, significant hydraulic heads can be considered as one of the driving forces of hydrothermal circulation. In most cases, discharge will occur along permeable structures outcropping at the lowermost bedrock exposures. Situations like the Grimsel breccia with its discharge at high altitudes are probably very rare. The difficulty in the Rhône Valley is that repeated glaciations have eroded the bedrock and filled the valley with up to 1000 m of unconsolidated sediments. Hence, many of these thermal water systems are likely blind, meaning that they show no surface manifestations as the thermal water does not reach the surface or is mixed with enough cold groundwaters on its way up to lose its thermal and chemical signature. This is a critical parameter when exploring for new hydrothermal sites. By sinking more deep wells in and around the Rhône Valley such blind systems might be discovered. However, the likelihood of success using this approach would be minimal. Therefore, we suggest conducting a so-called Play Fairway Analysis (PFA) for the canton of Valais and parts of the canton of Vaud.

The concept of a PFA is borrowed from the hydrocarbon industry where the approach is commonly used to assess exploration risks at a basin scale (e.g. Miller, 1982). It is based on spatially correlating relevant geological data to yield a favorability map, i.e. a map, giving information on the probable presence or absence of a source rock, reservoir rock and seal in the area studied. This allows channeling of the exploration effort into the most prospective parts of a basin. Similarly, a PFA can be conducted for geothermal exploration (e.g. Siler et al., 2017). Instead of looking for source rock, reservoir rock and seal, the geothermal PFA compiles and correlates data on the presence of a heat source, presence of a fluid and/or fluid flow paths. The resulting map identifies areas where blind geothermal systems, i.e. hydrothermal systems without any surface manifestations, are most likely to be present. Using known thermal occurrences such as hot springs or fumaroles, the PFA approach can be calibrated as they should show up as an area with a high likelihood of success.

2.1 PFA for the Rhône Valley and surrounding areas

In a first step, the type of play expected in the study area needs to be defined. Due to regional geology, which is characterized by extensive tectonic deformation and medium- to high-grade metamorphism and the absence of recent magmatic or volcanic activity, the play can be defined as a conduction dominant (i.e. fairly low permeability as flow paths are limited to faults and fractures) system situated within an orogenic belt (Moeck, 2014). More specifically, it can be specified as an intra-orogen system where the topography drives water circulation from the peaks to the valleys: Precipitation infiltrating at high-altitude is driven downwards by the hydraulic head to depths of ~ 10 km (where it is heated up) before emerging as warm/hot water in the valleys (e.g. Diamond et al., 2018).

In a second step, the types of data relevant for a geothermal PFA have to be decided. In recent years, geothermal PFA were started/conducted for 11 regions in the USA (Garchar et al., 2016 and references therein) and the whole of Ireland (Pasquali et al., 2015). Based on these results, we concluded that information on general geology, heat source and permeability are crucial to include in any geothermal PFA. For our study we have combined data from the previous compilations (GEOTHERMOVAL I and II, BDF GEOTHERM etc.) with additional data found on the national and cantonal geoportals and in the scientific literature. While we have added a substantial amount of data compared to the previous compilations for the study area, the information summarized in this report does by no means represent a complete review of available literature. A much more work consuming effort would be necessary to reach a satisfactory level of data completeness (see below). All datasets were discussed briefly (see Appendix) but the quality of the available data was not assessed as part of this study. In a next step all the data was integrated into a GIS database, which is delivered to the Federal Office of Topography swisstopo together with this report for internal use and possible publication on swisstopo's online map server www.maps.admin.ch.

Further steps like interpolating of the data to obtain probability maps (also called common risk segment (CRS) maps) for each geological condition as well as combining these probability maps to an overall favorability map (also called composite common risk segment (CCRS) map) were outside the scope of the present study. However, they are the crucial steps in obtaining a complete PFA to guide further exploration of the study area.

3 Brief description of the data compiled

To organize the present compilation, we sorted the relevant data according to the following three categories: (i) background, (ii) heat distribution and (iii) permeability (Figure 1). Each of these categories is subdivided into several sections which in turn are made up of individual datasets. Below, each category will be described briefly. A more in-depth discussion of the individual datasets can be found in the appendix.

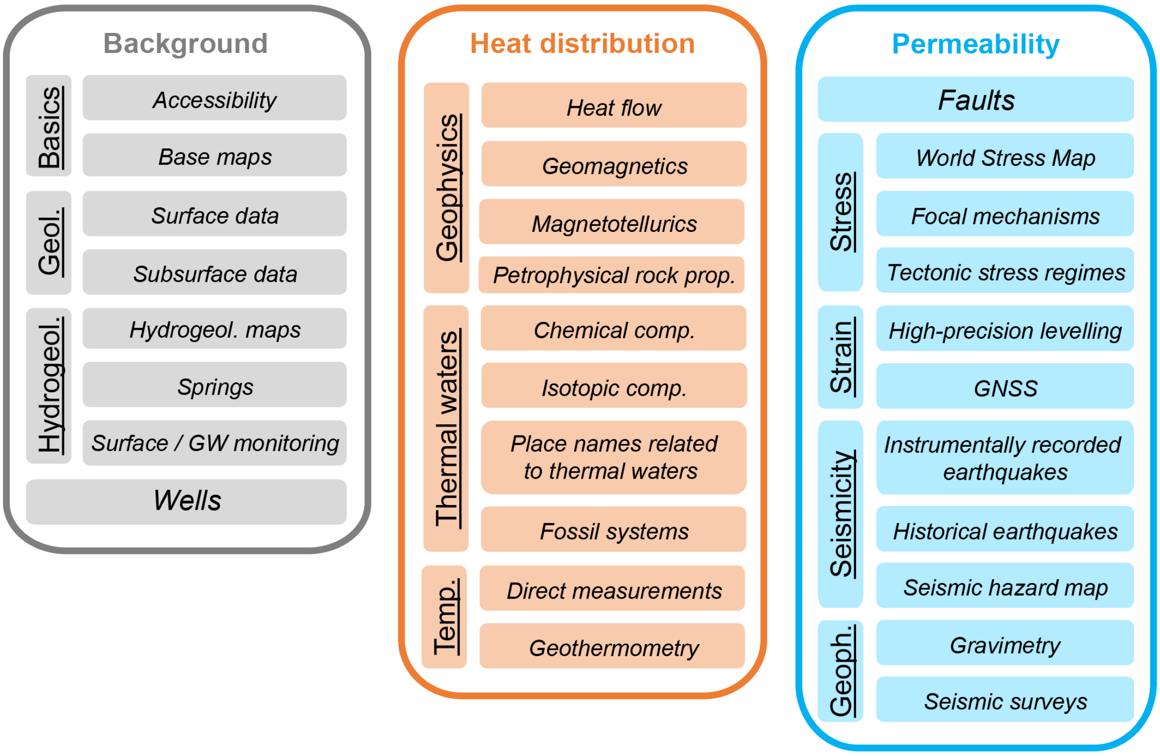

Figure 1: Structure of data compilation forming the base of both, this report (detailed description of individual datasets in appendix) and the accompanying GIS database.

3.1 Background

This category contains general information on the study area such as topographic and geological base-maps, accessibility (e.g. infrastructure and location of protected areas), well locations, and hydrogeology. While this information does not directly relate to the geothermal potential of the study area, it provides the basic data framework. Many of the corresponding datasets are not crucial during exploration for geothermal energy, they however become very important for site selection as they can exclude sites with a high potential, e.g. due to missing infrastructure or because drilling is prohibited in (groundwater) protected areas.

3.2 Heat distribution[1]

The distribution of subsurface heat can be determined in several ways: (1) regional geophysical surveys trying to identify thermal anomalies directly (e.g. by geomagnetics or magnetotellurics), (2) mapping of subsurface temperatures and (3) investigating known thermal anomalies (i.e. thermal water occurrences) and using that knowledge to search for similar settings where no thermal anomaly is known yet. Unfortunately, regional geophysical surveys are of limited use in the study area. Most of these methods aim at finding thermal anomalies related to magmatic activity such as recent volcanics or deep intrusions. However, in the study area, the heat source is the background geothermal gradient and thus no thermal anomaly can be detected. In addition, the signal quality in geomagnetics and magnetotellurics is strongly affected by anthropogenic noise (e.g. power lines, railways). Therefore, they are of limited use in the study area where population density is highest in the areas most promising for geothermal occurrences (i.e. the valley bottoms). The only geophysical approach of use for geothermal

[1] The occurrence and distribution of heat in the subsurface is closely related to the geology.

exploration in orogenic settings is the measurement of regional and local heat flow. If the resolution of the heat flow map is high enough, thermal water conducting features can potentially be identified and guide exploration to interesting areas. Unfortunately, no heat flow data is currently available for the study area. In addition to the regional geophysical surveys, a number of geophysical rock properties (e.g. porosity, radioactive heat production, thermal conductivity) have been collected for samples from the study area. While they are not necessarily useful to guide geothermal exploration, they are important to link regional geophysical data with different lithological units.

The second approach to obtain data on the heat distribution is the direct measurement of subsurface temperatures. This is the simplest approach with least amount of data processing and interpretation required. However, it requires temperature data from boreholes or underground facilities. While the number of boreholes in the study area is high (several hundreds of shallow wells related to drinking water and the installation of ground source heat pumps and 20 boreholes > 500 m), there is very little temperature data available. Based on previous studies it seems that at least for the groundwater wells, temperature data are collected but not made available to the public. In addition, a considerable amount of underground facilities exist. Few of them have been explored in terms of the real rock temperatures, and where done, these data are hidden in internal reports and not publically available (e.g. NEAT railway tunnels).

A third approach to understand the subsurface temperature distribution is the study of known geothermal and/or paleo geothermal systems. If we understand the origin of the fluid, its flow path, including the properties of the water conducting features (see "Permeability") and the maximum depth to which it penetrated, we can look for areas where similar features occur and might expect a blind system to be present. In addition, a detailed understanding of the geometry of an orogenic geothermal system allows calculating the amount of excess energy present in the thermal anomaly, which in turn allows a better estimation of the potential of the study area. Unfortunately, most of the available water compositions (chemical and isotopic) are relatively old, of uncertain quality (as the reports presenting the data are not published) and represent single points in time, not taking into account the variations in fluid composition as a function of time. Therefore, they are of little use for detailed evaluations of the known geothermal systems. When looking at thermal water occurrences, we also investigate exhumed paleo-geothermal systems (e.g. hydrothermal veins, breccias and mineral deposits) as they give us information on the geometry of the subsurface part of the circulation cells as well as their longevity and evolution as a function of time.

3.3 Permeability

Under "Permeability", we collect data which allows us to characterize and localize possible permeable features. This encompasses mainly fault, earthquake, stress, and strain data. Strain may be the result of tectonic stresses released by movement along a critically stressed fault which may trigger earthquakes. This interplay between cause and effect makes these datasets crucial for the assessment of crustal permeability. We also added gravimetric and reflection seismic data since both these methods allow the localization of permeable structures which can act as fluid flow paths for rising thermal fluids and thus represent ideal exploration targets in light of gaining energy directly out of the circulating natural thermal water or exploiting heat indirectly from the resulting thermal anomaly.

Permeability is primarily bound to faults and fault zones. Especially at fault interaction areas and fault intersections a much higher likelihood of elevated porosity and permeability is expected (Curewitz and Karson, 1997). This has in fact recently been demonstrated in the case of the Grimsel Breccia fault (Egli et al, 2018, Belgrano et al. 2016). Hence, knowledge about the occurrence and distribution of faults is of great importance when searching for hot water conduits. Furthermore, faults which are critically stressed are more likely to provide a pathway for fluids to circulate than faults which are not optimally oriented in the given stress regime (e.g. Barton et al., 1995, see also Schneeberger et al., 2018). In order to assess the state of stress of a given fault it is therefore crucial to know the acting stress regime.

As mentioned above, a more detailed description of the data is given in the appendix A4.

4 Gaps in data available

Overall, the data available is largely limited to point data collected from individual locations. Exceptions are certain geophysical studies (e.g. gravimetry) as they cover the whole study area. The distribution of the point data across the study site is not even but generally clustered around certain areas, mostly known thermal occurrences. As these known sites are primarily located in the Rhône Valley, interpolation of data necessary for a PFA is rather challenging. One option to alleviate this is to include data from the surrounding areas of France and Italy in the future to increase the number of peripheral data points for interpolation.

Apart from spatial coverage, the data generally lack any information on time. Very few datasets compiled contain a temporal dimension, i.e. no variability as a function of time or no information on the parameter's evolution over time is reported. This is especially crucial with respect to fluid and underground temperatures, fluid flow measurements and chemical as well as isotopic analyses, which all can change on short timescales (days to years). In addition, there is evolution on a geological timescale such as the development of an extensive network of fluid flow paths by brittle reactivating of Alpine ductile shear zones during late stage exhumation. This long-term evolution is extremely interesting from a scientific point of view (and plenty of publications exploring different aspects of it exist) and needed to fully understand orogenic geothermal systems. However, it was deemed to be (largely) outside the scope of this study which focuses more on geothermal exploration (i.e. plus minus present day conditions).

While the above points represent general comments on data availability, the gaps in the data of the individual sections of the report are discussed below.

4.1 Background

With respect to background data, there are two things missing (and hence aren't on Figure 1): (1) Information on the location, extent and operating parameters of existing and planned district heating networks and (2) enough groundwater data (composition and temperature) to resolve small-scale anomalies both laterally and with depth and thus identify the presence of potential blind subsurface thermal systems.

- The information on existing and planned district heating networks is of importance as most medium to deep geothermal projects produce a substantial amount of thermal energy which cannot necessarily be used where it is produced. Therefore access to a district heating network can become an important location factor when planning a geothermal project. It is not only important to know where district heating networks are present but also what their operating parameters are as these need to be matched (e.g. by using a heat pump to raise temperature) by the energy input from the geothermal project.
- Most of the thermal waters emerging from the crystalline basements or the overlying sediments will mix with cold groundwaters during the ascent. For some systems, where the source of the thermal water is shallow or the flux is very high, surface manifestations (e.g. thermal springs) can be observed. This is how most of the thermal water occurrences currently known and used in the study area were discovered. In order to characterize the thermal system at depth in detail, the mixing can be reversed by numerical modelling, if the cold groundwater end member is well

characterized. This was recently done for the subthermal springs at Grimsel (Diamond et al., 2018; Wanner et al., submitted) and showed the enormous potential of the thermal plume at depth. In addition, it is likely that in between the known thermal occurrences there are several blind systems, i.e. systems without surface manifestations as the mixing with shallow groundwaters has obscured any obvious thermal signatures. Such blind systems could be identified most easily by detailed mapping of groundwater chemistry and temperatures across the Rhône Valley, both laterally but also with depth. It is known that both, chemical and thermal data are routinely collected by communal authorities to monitor drinking water quality but they are not publicly available.

4.2 Heat distribution

4.2.1 Geophysics

The only really relevant type of geophysical data for geothermal exploration in the study area is high resolution heat flow measurements. However, such heat flow maps exist only for the Alpine foreland and the northern part of Switzerland (Bodmer and Rybach, 1985; Medici and Rybach, 1995) and any interpolation in Alpine internal regions is subject of substantial uncertainty given the scarce and spatially very heterogeneous data base. Reliable heat flow or temperature distribution maps for the Swiss Alpine parts and the Rhône Valley in particular are missing. Data on the numerous thermal springs, short- to medium-length wells and associated temperature measurements all apply to the immediate vicinity of the Rhône Valley, i.e. there is a lack of data on the adjacent mountainous areas.

In addition, a large and spatially well distributed dataset of petrophysical properties is useful when trying to conduct more detailed site investigations. The available data is fairly well distributed, with clusters in certain areas such as Grimsel or the Mont Blanc Massif. As the publication of the SAPHYR database (Swiss Geophysical Commission) is imminent and it is not known how much additional data will be included for the study area, it cannot currently be judged if there is a gap in data available.

4.2.2 Subsurface temperatures

The problem with subsurface temperatures is that the currently available measured or calculated (by geothermometry) values are few and far in between. In addition, they are generally related to known thermal occurrences, i.e. the data are of no use in the search for blind geothermal systems. To identify unknown thermal anomalies, we need closely spaced temperature data from the subsurface, ideally at different depth intervals.

4.2.3 Thermal water occurrences

There is evidence for innumerable active and fossil thermal water occurrences in the study area. For most of the active sites, chemical and isotopic analyses are available. However, the original reports detailing the sampling and the analytical procedure are mostly non-published because they were written as internal CRÉALP reports or as undergraduate theses at the CHYN (Centre d'Hydrogéologie et de Géothermie de l'Université de Neuchâtel). This means that the data available cannot be examined critically or the calculations (e.g. the geothermometry) cannot be verified and all that is available is what is listed in the BDF database (Sonney and Vuataz, 2008). In addition, many of the analyses were done years to decades ago. As thermal systems can change over time, both regularly (e.g. due to seasonal changes in mixing ratio with groundwater), suddenly (e.g. because of seismic activity) or gradually (e.g. because a fluid pathway slowly becomes clogged due to mineral precipitation), these values might no longer represent the systems properties.

For thermal waters which are utilized, e.g. for thermal SPAs, the parameters (e.g. temperature, flow rate, chemistry) are measured regularly to ensure high enough quality and quantity for continued operation. However, this data is not publicly available and we never got a reply by the SPA operators when asked for data on their thermal waters.

Besides the active thermal systems there is a number of place names which suggest relatively recent (in geological terms) thermal activity. However, there are no observations of (sub)thermal waters at any of these sites so far.

The number of fossil thermal water occurrences, i.e. hydrothermal veins, breccias and mineral deposits in the study area is very high. However, for most of these sites, very little is known. In order to establish a link of these fossil occurrences to present day ones (known or blind ones), we would need information on their age, duration of activity, fluid chemistry and temperatures, which would require substantial field and laboratory work.

4.3 Permeability

4.3.1 Geophysics

There are primarily two geophysical methods which yield information on permeable subsurface structures: seismics and gravimetry. There are 8 seismic lines through the Rhône Valley which were shot in the 1990s and provide some information on the top bedrock as well as the internal structure of the Quaternary sediments. Since then, the collection and processing of seismic data has improved substantially. New seismic surveys should therefore not only be able to identify top bedrock and some stratigraphic elements within the unconsolidated sediments but also major faults and fault zones within the crystalline basement and/or the overlying sediment stack. These fault zones are of great interest for geothermal exploration as they provide pathways for the hot water to emerge.

The density and resolution of gravimetric data for Switzerland is excellent (gravimetric data base of the Swiss Geophysical Commission). However, so far nobody has used this data for geothermal exploration despite previous studies showing that gravimetry can be used to identify water-conducting structures in the subsurface (Guglielmetti et al., 2013).

4.3.2 Faults

With respect to fault data, the major problem is the inconsistency and incompleteness of the datasets which are currently available. With the Tectonic Map of Switzerland (Spicher, 1980), swisstopo manages a fault database, which comprises faults mapped mainly by classical field work. In terms of age of faulting, and kinematics (i.e. sense of faulting) the fault classification is oversimplified and important attributes in terms of permeability assessment are missing altogether (e.g. fault length, width, and displacement). The dataset reflects the surface structures and has thus a high degree of completeness in high-relief areas, whereas in areas with low relief and low bedrock exposure, the dataset is underdetermined. The same is true for fault data of the GeoCover dataset (version 1). For the latter, further inconsistency stems from the fact that the individual sheets are based on mappings from different field geologists each having a different focus and professional background (e.g. structural geologist vs. petrologist). Furthermore, the sheets are not yet harmonized. However, a harmonized version 2 will be released by swisstopo by summer 2019.

In the future, geological data will be acquired and stored increasingly in 3-D datasets. With projects like GeoMol and GeoQuat, swisstopo moves fast in this direction and even heads towards a nationwide geological 3-D model. For a geothermal potential assessment, 3-D fault information is of great value, since it improves the possibility of the detection of permeable underground structures which may hold blind hydrothermal systems.

4.3.3 Stress

Stress data is usually shown in the form of stress maps. They integrate all stress measurements across the crust and are currently not accounting for the fact that the stress pattern in the lithosphere varies with depth (see Singer et al., 2014).

5 Next steps and suggestions for future studies

5.1 Next steps

For several datasets, a substantial amount of information can be added by expanding, reprocessing or re-evaluating the datasets as presented here without the need to collect new data. The following data analysis tasks should be quite feasible in terms of time consumption and resources.

(i) Background:

- District heating networks: Contact cantonal authorities and energy providers to obtain information on operating and planned district heating networks and their operational parameters (e.g. temperature) and include in database as well as the cantonal and federal geoportals if possible. In this way, a comprehensive overview on the subsurface thermal structures can be obtained, at least in the valleys and their adjacent mountain slopes.
- Groundwater hydrogeological dataset: In the current compilation, there are springs and groundwater wells from several sources, some of which will be included in several sources while other will only be present in a single source. This dataset should be harmonized and eventually linked to measurements of temperature and chemical composition.
- Groundwater hydrogeological dataset: A large number of groundwater data related to drinking water wells has been measured. However, these analyses are not easily accessible to the public or the research community. We recommend that the cantonal and/or federal authorities encourage private operators to share their analyses with researchers upon request and potentially even establish a metadata repository. If the data can be obtained, it will be compiled and thermal and compositional anomalies throughout the Rhône Valley identified by geostatistics (see below).
  - For compositional data: Is there an indicator element/compound (e.g. SiO_2 or SO_4) which strongly suggests the presence of a thermal component in the groundwater analyses? If yes, could this become a requirement to include for future ground- and drinking water analyses?

(ii) Heat distribution:

- Geophysics: Add the relevant information which will be published as part of the SAPHYR database (expected publication in 2019) to the compilation.
- Subsurface temperatures: The CREALP annual report 2015 suggests that there are extensive sets of groundwater temperature data collected and managed by cantonal authorities. We will try to obtain the data for further processing with the aim of

developing a map showing the temperature distribution and chemical composition of groundwaters across the study area. Ideally, this map will highlight one or several areas with thermal and compositional anomalies which can then be considered for future studies. In addition, the high density of GSHP in many parts of the study area could potentially be used to derive additional temperature data. Their exergetic efficiency (= actual energy produced by a GSHP) depends on heat pump-specific parameters such as $T_{vaporiser}$ and $T_{condenser}$ but also on underground temperatures. Thus, if a way can be found to collect and convert the specifications and efficiencies for a number of heat pumps, the density of data on subsurface temperatures could be drastically increased. The two datasets (one derived from groundwater temperatures and one derived from GSHP) would be complementary as generally drilling for GSHPs is not allowed in areas with useable groundwaters. Thus, it would allow us to derive information on subsurface temperatures for large parts of the study area.

- Thermal waters: Thermal water data related to operating thermal SPAs have been and is being measured regularly as part of their monitoring of springs and wells. However, these analyses are not accessible to the public or the research community. We recommend that the cantonal and/or federal authorities encourage private operators to share their analyses with researchers upon request and potentially even establish a metadata repository. If the data can be obtained, they could be used for studies similar to what recently has been done at Grimsel pass (e.g. Diamond et al., 2018), allowing for a detailed characterization of the thermal water and the deep seated thermal anomaly related to the upflow.

(iii) Large-scale permeability:

- Geophysics (gravimetry): The Reservoir Geology and Basin Analysis group at University of Geneva will re-process the gravimetric data for several cantons (GE, SG, VD and VS) over the next months and try to obtain as much data on potentially water-conducting features as possible.
- Collection of information from in-situ drill hole pumping tests to obtain reliable data on the permeability of recently explored hydrothermally active systems in SPAs of the Rhône Valley region. Since this information is hidden within non-public reports, cantonal and federal authorities should encourage private companies to provide access to such information upon request.

5.2 Further studies

Many datasets would benefit from more extensive additions, i.e. studies including the collection of substantial amounts of new data. Ideas for such studies are given below.

(i) Background:

- Groundwater hydrogeological dataset: Compilation of a 1:100’000 hydrological map of the study area.

(ii) Heat distribution:

- Geophysics (Heat flow): A high resolution heat flow map for the study area would be of great interest for future geothermal exploration. In a first step, recent bedrock temperatures from accessible (i.e. boreholes are present) and well-known thermal sites should be collected. Once the data is corrected, it can be used to estimate the local heat flow. For the second phase, ambient bedrock temperatures and vertical temperature gradients at locations that are more difficult to access (e.g. numerous underground tunnels associated, for example, with hydroelectric or military installations) are measured by drilling shallow sub-horizontal boreholes into the walls of the tunnels.

- Thermal waters (composition and isotopy): Many chemical and isotopic data on available thermal water occurrences is years to decades old and contains no information on temporal variability of temperature, composition or flow. Therefore we suggest a monitoring study of all thermal occurrences listed in the BDF database during which the springs/wells are regularly sampled over 6 – 12 months (with 1 week of intense sampling to see short term variations). The extent of the sampling campaign depends on the amount of data which can potentially be obtained from SPA operators (see above). With this new dataset, the thermal anomalies could be analyzed in a similar way to Grimsel (Diamond et al., 2018), deriving much more data about the thermal endmember and the thermal anomaly at depth. This in turn would allow a much more accurate characterization of the geothermal play "orogenic geothermal system" as well as allow a better prediction of the geothermal potential of the study area.
- Place names related to thermal waters: Several field and place names related to warm water occurrences were identified. However, none of these locations are known for warm/hot springs. A short field trip to each site to try and find thermal water discharge is planned for summer 2019. One option to increase the likelihood of success would be to bring along an infrared camera to identify thermal anomalies more easily.
- Fossil systems: Detailed chemical and structural analyses of other known fossil systems (e.g. Kleines Furkahorn and Gemmi, pers. observations Marco Herwegh) would strongly increase our knowledge of the architecture and evolution of orogenic hydrothermal systems. This in turn would enhance the understanding of active systems and allow better predictions on their longevity. This in turn enhances the predictions of the geothermal potential for the entire study area. The knowledge gained from these big systems could be expanded across the study site by investigating smaller fossil occurrences such as hydrothermal veins and deposits.

(ii) Small-scale permeability

- Paleo fault systems: 3D information of pre-existing large-scale fault structures can be obtained by a rigorous combination of remote sensing techniques and field work which can then be used for the generation of 3D structural models as recently successfully demonstrated (Baumberger 2015; Schneeberger et al. 2017; 2018). In this way a consistent fault data base with a nearly 'complete' spatial coverage can be achieved. Knowledge of such inherited fault geometries is crucial since these structural discontinuities provide the sites to be reactivated by recent seismic activity as well as geothermal fluid circulation.
- More detailed data on faults would be very beneficial in order to detect possible fluid pathways but also to better assess the relationship between stress variations (artificial and natural), fault reactivation, and seismicity. Key fault attributes are for example length, width, displacement, and age. To this end, a data mining campaign would be needed to compile fault data from published and unpublished maps, articles, reports, and theses.
- Define local scale structural setting by searching for structures which may favorably act as fluid conduits (e.g. fault intersections, fault step-overs, accommodation zones). Knowledge on the spatial extent, the 3D geometry, and kinematics of these faults is

mandatory but is only partly available and without full spatial coverage. Using existing 2D fault traces on maps can be extrapolated to 3D fault planes by using topographic information and 3D structural modelling. This step can be done without additional field work.

- Critically stressed faults are more likely to provide fluid flow pathways than none-critically stressed faults. To assess the stress state of faults, we can perform a slip and dilation tendency analysis for fault segments (e.g. Morris et al., 1996; Schneeberger et al., 2018). Parameters needed are the (1) fault geometry and the (2) stress field. (1) Can be gained by the previous task but large uncertainty exists with respect to (2). Here a first order approach has to rely on stress values estimates from the World Stress Map (Heidbach et al., 2016) and from focal mechanisms (Kastrup et al., 2004).
- Active faults: Recent advancements in earthquake monitoring and processing (e.g. improved data quality, improved seismic velocity models, and advanced relative relocation techniques) made it possible to locate earthquake hypocenters much more accurately, so that location uncertainties can be narrowed down to the sub-kilometer scale (e.g. Diehl et al., 2017). Currently, the Seismotectonics Group at the Swiss Seismological Service at ETH Zurich are relocating earthquake sequences in the Valais. This data should be incorporated into database of a PFA. The Valais has also been chosen as a potential case study area for the SeismoTeCH project of the Swiss Geophysical Commission. By establishing the link to known structures, 3D information on active faults can be gained, providing valuable information on permeable structures and the current state of crustal stress.

(ii) Large-scale permeability:

- Performing a rigorous pumping test program to obtain as good permeability and fluid flux information as possible from all planned hydrothermal wells. The availability of such data for the research community is mandatory to reach a more profound system understanding.
- Evaluation of permeability and its evolution in paleo systems. This can be achieved by experimental in-situ permeability investigations on field samples as well as 3D computer tomography in combination with numerical modelling. Given the clogging of the system by mineral precipitates, the study of natural samples provides information about the timing/availability of open interconnected pore space at depth.
- Re-fracturing of fault-bound hydrothermal systems represents a crucial process to provide a long-term permeability (e.g. Grimsel Breccia fault; Belgrano et al., 2016; Egli et al., 2018). Detection of evidence of paleoseismicity, i.e. the reoccurrence of seismic events and the spatial extend/geometry of associated fracture pattern, would allow estimating the dimensions and amounts of fluids being involved (Berger and Herwegh, 2019).

5.3 Completion of the Play Fairway Analysis for the Rhône Valley

As described in Section 2, this compilation represents the first step towards a PFA of the study area. Before continuing with the next steps of the PFA, it would be advisable to complete the work listed in Section 5.1 as a substantial amount of additional information can be gathered without the need for extensive and costly sampling campaigns. The suggestions listed in Section 5.2 would strongly enhance the size and quality of the dataset at hand for the PFA. However, most of these studies are very time-consuming and expensive and thus need to be conducted within a federally funded project (SNSF or

BFE) or paid for by cantonal authorities. Once additional work has been completed, the data can be spatially correlated and favorability maps derived. A final product of the evaluation of the geothermal potential in the study area could look very similar to the CO_2 sequestration potential study done by Chevalier et al. (2010).

6 Conclusion

The Rhône Valley (canton of Valais) and its surrounding areas are expected to have a high overall geothermal potential. The region is tectonically very active, which is evidenced by elevated crustal deformation rates and a high seismic activity. Associated brittle deformation and reactivation of older structures generates pathways for water, infiltrated at high altitude areas, to descend to depth, heat up and eventually emerge at the valley floor. Numerous thermal springs known and also exploited in the Valais are a manifestation of these hydrothermal systems. Recent studies in the Grimsel area confirm the occurrence and interplay of these processes and show that the Valais is a highly active orogenic geothermal system (Belgrano et al., 2016; Diamond et al., 2018; Egli et al., 2018).

In order to assess the geothermal potential of the Valais and to detect promising regions for hydrothermal exploration, many data need to reviewed, linked and interpreted. To this end, we propose to follow the framework of a Play Fairway Analysis (PFA), by collecting and processing the data in three thematic containers: (1) background, (2) heat distribution, and (3) permeability. Many data already exists but a complete and homogeneous coverage of data, which would be necessary for a proper spatial analysis, is missing. Several important gaps were identified in the course of this study. By re-evaluating and re-processing available data some of these gaps can be closed. However, the database would substantially benefit from the collection of new data.

At this point it is important to mention that there are many crucial data which are currently not available to us, due to copyright and property right restrictions and administrative barriers. We therefore urge the responsible authorities (i.e. cantonal, federal) and industry partners to work on a solution to make this data publicly available.

Finally, we think that the geostatistical approach of a PFA is very promising in order to assess the geothermal potential of the Rhône Valley. This approach is however also applicable in other areas of interest in Switzerland and we recommend the use of the database structure presented here for such projects in the future.

PFA data categories	Gaps in available data	Next steps	Further studies
Background	• Information about existing and planned district heating networks • Publicly available chemical and thermal groundwater measurement data	• Compile information on operating and planned district heating networks (incl. temperature data) →Contact cantonal authorities and power companies • Harmonize groundwater hydrogeological data • Get access to drinking water analyses (temperature and composition)	
Heat distribution	• Heat flow data • Petrophysical properties • Closely spaced subsurface temperature data • More recent chemical and isotopic analysis measurements of thermal waters	• Add petrophysical properties of the soon to be released SAPHYR database • Get access to cantonal groundwater temperature data and temperature data from installed ground source heat pumps • Get access to thermal water analyses from SPAs	• Generation of a high-resolution heat flow map • 6-12 month monitoring study of thermal waters listed in the BDF database • Small field campaign to ground truth place names related to thermal waters • Study on more known fossil hydrothermal systems
Permeability	• Gravimetric data tailored for geothermal exploration • Consistent attributed fault data	• Reprocessing of gravimetric data to target potential water-conducting features • Get access to confidential information from in-situ droll hole pumping tests from SPAs	• Data mining campaign targeting on attributed fault data • Define local scale structural setting (e.g. fault intersection, fault interaction areas) • Slip and dilation tendency analysis on well characterized fault segments • Studies on active faults using high-resolution earthquake data • Pumping tests on planned hydrothermal wells • Experimental in-situ permeability studies on field samples • Paleoseismic studies on fault-bound hydrothermal systems

Appendix – Contents of the GIS database

A 1 General remarks

The GIS database (*GIS_db*) and the "Table Of Contents" view in ArcMap are organized similarly to the structure presented in this study. The data is managed in 3 thematic folders (*01_Background, 02_Heat_Source, and 03_Permeability*). A fourth folder (*04_Literature*) contains literature relevant to the project. Each data-specific folder then contains 2 to 3 subfolders containing (i) the data itself, (ii) metadata and accompanying documents, and (iii) the layer file which defines the symbology. The data source can be retrieved from the metadata and accompanying documents in the corresponding subfolder of the GIS database. Empty layers in the ArcMap "Table of Contents" serve as placeholders for data which is either not readily available or which we think would be beneficial to include in a geothermal database but does not exist at this point. The following sections describe the most important data in more detail.

A 2 Background

A 2.1 Basics

A 2.1.1 Accessibility: Infrastructure

The Rhône Valley is surrounded by high mountains with steep slopes. Therefore both, population and infrastructure are largely concentrated along the valley floor. Some of the side valleys (e.g. Vispertäler or Val de Bagnes) also represent relatively built-up areas, especially due to famous tourist resorts. Most of the other valleys are relatively sparsely populated and thus with limited infrastructure. At the end of most valleys, especially in the Penninic Alps, dams have been built to ensure year-round water flow for the hydropower plants further down in the valleys.

Infrastructure is an important aspect when assessing a site for a potential geothermal project. There are several points that need to be considered:

- Buildings: For geothermal projects primarily producing thermal energy it is crucial to be close to potential customers as heat cannot be transported over long distances economically. On the other hand, for deeper geothermal projects where hydraulic stimulation is potentially considered and where seismicity can be induced, a more isolated location can be preferential. This information can easily be extracted from the GIS base map.
- Roads: Easy access to the site by road is crucial. Initially, it is so the heavy machinery for drilling can be brought on site. Later, maintenance is easier and less costly if the site is easily accessible. Also this information can be extracted from the GIS base map.
- Energy infrastructure: Shallow to medium depth geothermal systems produce only thermal energy. This energy can be used directly where it is generated as is the case for ground source heat pumps or many of the thermal SPAs, or it can be transported to nearby users. For systems with a bigger power output, integration into an existing district heating network is key for economic viability. Even deep systems producing electricity will always produce a substantial amount of thermal energy and are ideally connected to a district heating network. Unfortunately,

there is no Swiss-wide database of district heating networks. This would be a useful addition to the online map server.

A 2.1.2 Accessibility: Protected areas

There are many different types of protected areas in Switzerland. The most important areas for this compilation are the groundwater protection zones. Areas with potentially useable shallow groundwaters are designated by the water protection zone A_u. Around springs and wells additional groundwater protection zones are designated (S1 – S3). In all these zones, building activities are prohibited or limited to activities without risk to groundwater quality. Drilling for geothermal energy (including ground source heat pumps) is prohibited in groundwater protection zones S1 – S3 and only allowed in certain areas of A_u. Due to the growing number of ground source heat pumps in recent years, most cantons have developed specific maps showing the areas where ground source heat pumps are allowed in addition to the maps showing water protection areas.

Large portions of the study area fall within the water protection zone A_u. This includes the valley bottoms of the Rhône Valley and many of the tributaries. In addition, most of the limestone-rich Helvetic nappes to the north of the Rhône Valley are designated as A_u due to the presence of karst groundwaters. But even large areas of the crystalline massifs and the Penninic Alps are designated as A_u due to the presence of fracture groundwater. The groundwater protection zones (S1 – S3) are limited to the immediate surroundings of a spring/well in the unconsolidated sediments. However, for karst and fracture groundwaters the outer zones can be much larger as they also include the infiltration zone.

The areas where ground source heat pumps are banned largely overlap with the groundwater protection zones and include large parts of the valley bottom of both, the Rhône Valley and its main tributaries. This is an important limitation for geothermal exploration and the development of future geothermal systems. However, it is possible for the cantons to issue special drilling permits in the groundwater protection zone A_u

In addition to groundwater areas, protected sites are included in the GIS database as drilling is also prohibited in these areas or will at least require special permits.

A 2.1.3 Other data

Other data collected in the *Basics* consists of political boundaries, topographic and relief maps, digital elevation models, and orthophotos.

A 2.2 Geology and tectonics

The geology of the study area was briefly summarized in section 1.2 of the main part of the report and will not be repeated here. For a more in depth discussion on the regional geology see Pfiffner (2015) and references therein.

The data available for the study area are largely based on three datasets and are grouped under *Surface Data*: The Geological and the Tectonic Map of Switzerland both at the scale of 1:500’000 (Spicher, 1980), and the much more detailed GeoCover vector dataset at the scale of 1:25’000. The latter is primarily based on the available map sheets of the Geological Atlas of Switzerland (1:25’000) or in some cases on special maps and map originals of different scales and sources. The GeoCover dataset used in our compilation is of version 1. Version 2, which will be fully harmonized, will be available from swisstopo by summer 2019.

For the subsurface geology (grouped under *Subsurface Data)* the only regional information available are the thicknesses of the sediments in the Rhône Valley derived from subtracting the bedrock surface from the terrain surface the digital height model (DHM25). The values increase from 80 to 300 m in the

Visp area to nearly 1000 m between Conthey and Martigny as well as the Vouvry area. For the side valleys information on the sediment thickness could be obtained from the large number of drill profiles obtained from wells drilled for ground source heat pumps. A compilation of the information contained in these profiles allows a detailed characterization of the different formations within the Quaternary sediments. This has been done for the area around Visp (Brig to Blatten) as part of the GeoQuat project by swisstopo. For this project the profiles of nearly 800 wells were compiled and combined with available geological profiles, surface geology information, and geophysical data (where available). The project was terminated at the end of 2018 and the final report will be published at some point in 2019. Compatible data will be included in the GIS project as soon as it becomes available.

A 2.3 Hydrogeology

The hydrogeology of the Rhône Valley is dominated by the Rhône river. It is fed by the Rhône glacier at the upper end of the Oberwallis and the many tributary rivers and streams entering the Rhône Valley from both north and south. Below the surface, three types of groundwaters can be found in the study area. The first and most important are the pore aquifers in the unconsolidated Quaternary deposits of the Rhône Valley. These permeable gravel layers generally represent glacial deposits reworked by the Rhône river before its correction and are surrounded by much less permeable original glacial and lacustrine deposits. These aquifers are generally at depths of a few meters to a few tens of meters and provide drinking water to the majority of the Rhône Valley's population. In the side valleys the drinking water is primarily obtained from different springs. In the Peninnic Alps and the External Crystalline Massifs in the northeast, the springs are fed by groundwater percolating along fractures and faults within the low-permeability lithologies. In the Helvetic nappes to the northwest the groundwaters are primarily contained in karstified limestones. General information about groundwater (i.e. hydrogeological overview map and groundwater protection zones) is grouped under *Hydrogeological Maps.*

Surface and groundwater data are included in this compilation (grouped under *Surface and Groundwater monitoring*) in order to have a well-defined (near) surface water endmember for geothermal exploration. Thermal fluids rising from depth often mix with these (near) surface waters when rising from depth so that the emerging water contains a hot and cold component. If the cold endmember is characterized well, this, together with the measured temperature, composition and/or isotopy of the spring, can be used to unmix the two endmembers and obtain information on the thermal water. This was done in a recent study for the warm springs at Grimsel Pass (Diamond et al., 2018) and the same approach could be applied to all thermal springs in the study area. In addition, a thorough understanding of the groundwater conditions in the Rhône Valley could help to find blind hydrothermal systems (i.e. systems with no surface manifestation) from the surface by carefully evaluating variations in temperature and chemical as well as isotopic compositions of an area's groundwater. If identifiable, such thermal or compositional anomalies indicate the presence of thermal waters at depth (see sections A 3.2.1 and A 3.3 in the appendix for more detail) and thus highlight areas of interest for further exploration.

Within the study area of the Rhône Valley and its surroundings a considerable number of stations are regularly recording river, spring, and groundwater water-level, discharge, composition, and/or isotopy. The Federal Office for the Environment (FOEN) operates a monitoring network for surfaces waters as well as the national groundwater monitoring program NAQUA: A total of 27 stations are constantly measuring the water level and discharge of several rivers (n = 18), aquifers (n = 6) and springs (n = 3). In addition, some stations also measure temperature (n = 12) and some stations are routinely sampled for chemical (n = 3) or isotopic (n = 1) analyses. These datasets can be obtained from the Federal Office for the Environment (FOEN). In addition, there is a large number of springs used to provide drinking water to different communities as well as many springs which are currently not used. The spring locations included in the GIS project (grouped under *Springs)* were included from several sources: the GeoCover dataset, the 1:500'000 Hydrogeological Map of Switzerland, and the cantonal groundwater database of the canton of Valais.. Many springs will probably be included in all three datasets and thus appear multiple times. In addition, the exact locations of drinking water springs are often not available to the public due to health and safety concerns. Rather, the coordinates given are those of the closest kilometric perimeter. It is unclear if this applies to all three datasets. Thus, there might be several springs which appear on the compiled map several times in slightly different locations but represent a single spring in reality. Harmonizing the datasets to avoid multiple data was not part of the present project. Given the aforementioned uncertainty in the exact coordinates, rather time consuming research would be necessary for each data pair being geographically closely located to each other, which was out of the capabilities within the current project frame.

The composition of these shallow groundwaters is monitored regularly by the drinking water providers. They have to regularly check for and inform the public (at least once a year) about the quality of the drinking water. Thus, a large number of compositional data should be available. While most providers inform their consumers directly via newsletters, some communities (Aletsch region, Lax, Visp, Eyholz, Sierre, Sion, Fully, Val d'Illiez, Bex, Collombey-Muraz, Villeneuve) have decided to make their analyses public via the online platform of the Swiss Society for Gas and Water (SVGW, www.trinkwasser.svgw.ch). To obtain more compositional data (and possibly temperature data), the remaining providers would have to be contacted individually. This was considered to be outside the scope of this study but might become necessary to obtain the required density of data points to evaluate the spatial variations in groundwater temperature or composition and identify blind systems.

A 2.4 Wells

Information on wells is grouped under *Wells*. We included two datasets from the geological cadaster of the canton of Valais (wells > 200 m and geothermal probes) and two datasets from swisstopo (deep wells > 500m and sites of geothermal projects).

A 3 Heat distribution

A 3.1 Geophysics

A 3.1.1 Heat flow

Heat flow is the movement of heat (energy) from the interior of Earth to the surface. Heat flow anomalies, i.e. areas with higher than average crustal heat flow are due to thin and/or young crust, a high concentration of radioactive elements or the presence of plate boundaries or mantle plumes. In addition, strong lateral and vertical heat flow anomalies without a clearly identified tectonic or radioactive explanation can develop locally related to enhanced fluid flow. From a geothermal point of view, areas of high heat flow density are preferred as higher temperatures are encountered at shallower depths. Of even greater interest are heat flow anomalies caused by upwelling of deep fluids as these suggest not only a heat source but also the presence of fluids as well as sufficient permeability at depth.

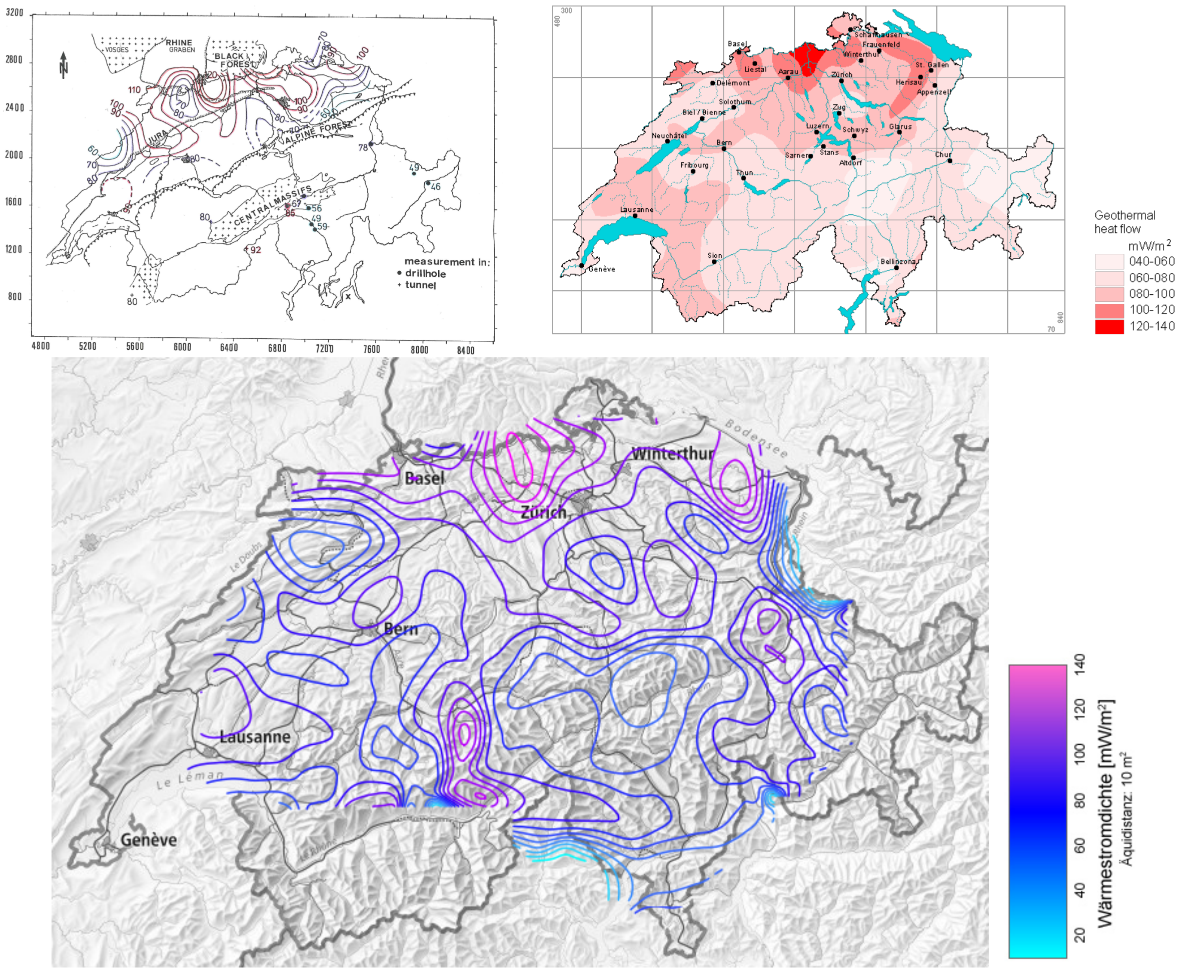

Figure A1: Evolution of the heat flow map of Switzerland from Bodmer and Rybach (1985) (top left) to Medici and Rybach (1995) (top right) to the currently available map on swisstopo's map.geo.admin.ch (bottom).

Heat flow densities are calculated from a range of temperature measurements (temperature profiles, individual temperature analyses and bottom-hole temperatures in wells, shafts and tunnels) combined with measurements of thermal conductivities and corrected for topography. Bodmer and Rybach (1985) determined the average heat flow density of Switzerland (= 85 mW/m^2). The authors showed that the values generally decreased towards the Alps and the Jura Mountains. This trend was overlain by a couple of distinctive positive and negative anomalies (Figure A1), which were interpreted to be associated with convection of hot fluids as they coincide with thermal water occurrences at the surface, e.g. in the area of St. Gallen and Baden/Schinznach. Unfortunately, no temperature measurements were available for our study area and no heat flow density could be extrapolated. Over a decade later, an updated version of the heat flow density map of Switzerland, now containing nearly twice the amount of temperature data, was published by Medici and Rybach (1995). However, still no temperature measurements were available for the Valais and lower Rhône Valley. As the number of data points in the surrounding areas had increased, the authors cautiously extrapolated the heat flow density values across the Rhône Valley. The extrapolation suggests that the Rhône Valais down to Riddes/Leytron is characterized by values below the Swiss average (60 – 80 mW/m^2) while the region further down the valley shows slightly higher values of 80 – 100 mW/m^2 (Figure A1). A third heat flow density map is available on the mapping platform maps.admin.ch. Similarly to the other maps, it shows no data for most of the Rhône Valley. The exception is the Goms where isolines show a positive heat flow anomaly of over 120 mW/m^2 in the Blatten-Belalp-Riederalp area. The isolines presented for the areas surrounding the Valais indicate that there are potentially two more anomalies within the Rhône Valley: A positive anomaly (100+ mW/m^2) in the area of Crans-Montana-Sierre and a negative anomaly (max. 20 mW/m2) in the area of Gampel-Raron. According to the information provided on the mapping platform, the data presented is based on the thesis of Bodmer (1982). However, the map contains much more detail than the younger maps from Bodmer and Rybach (1985) and Medici and Rybach (1995). Currently, the source of the additional data is unclear. However, the better resolution of the heat flow data, especially in the SE Bernese Alps north of Brig, suggests that additional, non-credited heat flow measurements were obtained during the planning and building of the Lötschberg Base Tunnel, which were incorporated into the heat flow map digitized in 2001 but remain confidential.

Hence, it is very likely that the apparent heat flow anomalies are related to a data concentration along the trace of the NEAT railway project rather than representing a local concentration. However, here the measured high heat flow values are real, raising the question about a generally increased background heat flow along the northern rim of the Rhône Valley. Answers to these fundamental questions could be addressed by a network of in-situ heat flow measurements. Particularly the dense network of underground facilities (galleries from hydropower plants, military, and transport systems) would be prone for such analyses. Within a pilot study of the Swiss Geophysical Commission, the Applied and Environmental Geophysics research group at the University of Lausanne made a first attempt, where a combination of in-situ temperature measurements and numerical heat flow modelling was suggested. Currently, the project is on hold since access permits to underground facilities seems to be difficult to obtain (pers. comm. K. Holliger).

As described above, convection of fluids can strongly alter the heat flow measured. Bodri and Rybach (1998) evaluated the effect of topography-driven convection of fluids on the measured heat flow at two sites in SE Switzerland (Biaschina, TI and St. Moritz, GR). While these findings cannot be transferred directly to our area of interest, some findings can likely be applied to the Rhône Valley nevertheless:

- The hydrothermal systems are characterized by recharge areas in the summit region and narrow and concentrated discharge areas in the intermontane valleys at the foot of the mountains.
- Flow system is depicted in the heat flow isolines. Especially the discharge zones are easily identified as regions of heating (nearly twice the background heat flow value). The recharge areas in turn might show reduced heat flow densities. In the deeper part of the system, the flow rates are too low to substantially affect the heat flow. The heat flow anomalies derived from fluid convection are thus likely restricted to the uppermost 1 to 1.5 km. In order to change the thermal regime in an advection-dominated system, changes in conductivity in the range of orders of magnitude are needed. This indicates that thermal anomalies derived from convections are relatively long lived.
- Flow rates are enhanced compared to flat terrain and reach up to several cm/a in the recharge and discharge areas but drop to a few mm/a at depth.

These assumptions were recently confirmed by Diamond et al. (2018) for the Grimsel pass thermal anomaly on the northern end of the Rhône Valley. There, meteoric water is driven to depths 9–10 km depth where the background geothermal gradient brings the fluid to temperatures of 230–250 °C. The model shows that the thermal anomaly is relatively localized. Thus, a regional heat flow map for the whole study area might not capture such small-scale (laterally) anomalies but a survey with a high enough resolution to investigate such local anomalies would be required. No such survey is currently available or planned.

A 3.1.2 Geomagnetics

Geomagnetics is the study of the magnetization of crustal rocks, a signal they obtain as soon as they cool below the so-called Curie point temperature, where they become ferromagnetic rather than paramagnetic. The Curie temperature for titanomagnetite, the most common magnetic mineral in igneous rocks, is below 570 °C. With higher Ti-content in more mafic rocks the Curie temperature is decreased to around 200 °C (Byerly and Stolt, 1977). Consequently, determining the depth where the magnetic signal disappears will yield a Curie point isotherm. A region containing substantial geothermal resources (e.g. granitic intrusion at shallow depth) shows an anomalously high geothermal gradient and thus shows a suspiciously shallow Curie point isotherm compared to the surrounding areas (Bhattacharyya and Leu, 1977).

Airborne magnetic studies represent an excellent tool for rapid data collection at a regional scale. Recently, aeromagnetic surveys from across Central Europe, including the Alps, were combined to a single total magnetic field anomalies map (Chiozzi et al., 2005). The map shows a broad negative anomaly (hatched) in the northern part of the Alps with localized strong positive (grey) and more negative anomalies (Figure A2). The positive anomalies follow the crescent-shape of the Alps down to the Mediterranean Sea in the area of Genoa. They can be correlated with the ophiolitic sequences of the subducted Penninic ocean. For example in the Penninic Alps, the presence of the Zermatt-Saas Zone can be clearly seen in the Aereomagnetic Map of Switzerland (Figure A2; Klingelé, 1982). In addition, declination, inclination, and total intensity maps were also produced (Fischer and Schnegg, 1979a, 1979b, 1979c).

The presence of such strong magnetic anomalies due to mafic lithologies limits the use of magnetics for exploration in the Rhône Valley. In addition, the heat source in the Rhône Valley is not an intrusion or related to young volcanic activity but the background geothermal gradient and deep circulating fluids. Thus the resulting thermal anomalies are less than even the lowest Curie point temperature and will not produce a magnetic anomaly. Geomagnetics can therefore not be used for geothermal exploration in and around the Rhône Valley and similar orogenic systems.

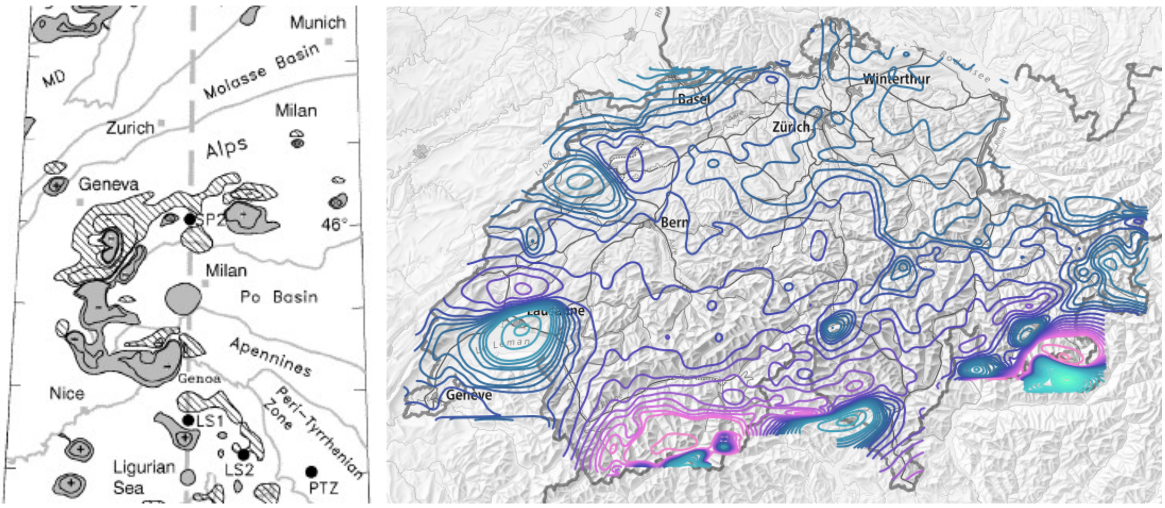

Figure A2: Aeromagnetic survey of Central Europe (left) showing the strong anomalies associated with the Alps (Chiozzi et al., 2005), especially the ophiolitic sequences, which can also be recognized in the Swiss total intensity map (right; Fischer and Schnegg, 1979c).

A 3.1.3 Magnetotellurics

Short term variations within the Earth's magnetic field cause electromagnetic eddy currents which are in proportion to the electrical conductivity of different lithologies. By measuring these currents, zones with abnormal conductivities can be identified. This approach is called magnetotellurics (MT). Abnormal MT signals are caused by (1) layers containing interconnected, highly conductive minerals such as graphite/antracite or pyrite (Jödicke, 1992; Losito et al., 2001), (2) rock textures related to strong deformation (mylonites and cataclasites; Schnegg, 1998), (3) partial melting zones (Schmeling, 1986; Shankland and Waff, 1977) or (4) the presence of aqueous fluids (Jödicke, 1992). The measured bulk electrical resistivity depends not only on the presence of a fluid phase but also on the temperature of the rock, its water content, the type of fluid as well as its salinity (Unsworth, 2010). However, MT alone cannot determine the nature of the fluid (Li et al., 2003). Nevertheless, the ability of MT to identify such deep reservoirs of fluids makes the technique a highly important asset in geothermal exploration. For an overview of studies on the use of MT in geothermal exploration see the recent review by Muñoz (2014).

For the area of interest, MT data were collected as part of "The Magnetotelluric Survey of the Penninic Alps of Valais" and have been published in Schnegg (1998). The survey was conducted between 1988 and 1996 and was based on measurements obtained from 34 stations covering the area between the Rhône Valley and the Swiss-Italian border. The aim was to use this novel technique (in Switzerland) to support the findings from the seismic lines of the NRP 20 (Pfiffner et al., 1997) and better understand the 3D geometry of the Swiss Alps. It became obvious that a major regional low resistivity anomaly, extending laterally over several of kilometers and following the Penninic thrust front to depths of 10+ km is present. The source of this MT anomaly is the Zone Houillère (ZH), a unit comprised of dense, black, fine-grained, slightly silty slates (metasediments) of Carboniferous age. The main minerals are quartz and sheet silicates such as illite, muscovite and chlorite but the schists also contain abundant graphite. They were deposited into a so-called Permo-Carboniferous trough (part of the Briançonnais microcontinent), which was tectonically inverted during the Alpine orogeny and ended up incorporated into the Penninic nappe stack. In the Penninic Alps of the Valais the ZH outcrops N-S from the Swiss-Italian border (close to Col du Gd St Bernard) between the Val Ferret and the Val d'Entremont to Verbier. In this area, its orientation gradually changes to E-W and it runs more or less parallel to the Rhône Valley up to Sion (Figure A3). The ZH crops out again at Chalais and in the area between Visp and the Simplon Pass. The ZH is not present north of the Rhône-Simplon-Fault in the Helvetic domain of the Swiss Alps.

Drill core samples of the ZH black shales were studied in detail by Schnegg (1998) and Losito et al. (2001). They found that the electrical conductivity of some samples was indeed very high. Other samples from the ZH, however, showed average conductivity values, suggesting that there is a degree of variability within the black shales of the ZH. The differences in C-content between the samples was not substantial (1.3 to 3.3 wt%) but the texture and grain size of the more conductive samples was different, suggesting that the interconnectivity of the graphite flakes (= carbon film along grain boundaries) is more important than the amount of graphite present. Overall these laboratory measurements make it likely that the ZH is indeed responsible for the regional resistivity anomaly observed in the Penninic Alps of Valais.

Unfortunately, the presence of an extensive natural resistivity anomaly south of the Rhône Valley limits the use of MT for geothermal exploration in Valais. In addition, ever increasing electromagnetic noise levels from electric railways, more power lines and hydroelectric power stations (Schnegg, 1998; Unsworth, 2010) will result in poorer data quality in the future. Schnegg (1998) suggested for that reason that all MT analyses in Valais should be completed within 15 – 20 yrs of his study. Therefore, careful evaluation of potential interference by the Zone Houillère as well as man-made interference needs to take place before any more MT studies are planned within the Rhône Valley.

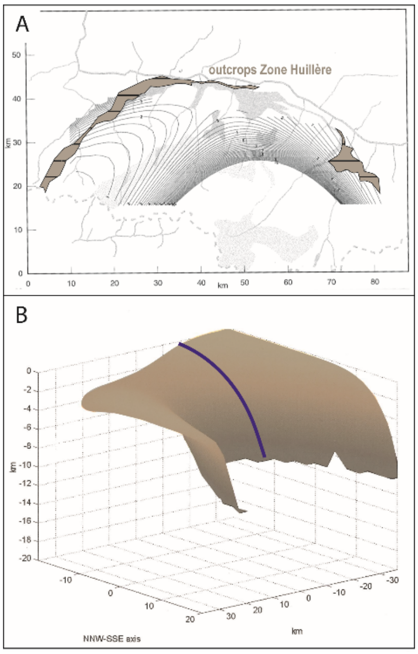

Figure A3: Location of Zone Houillère outcrops (top) and the structure of the unit at depth (modified after Schnegg, 1998).

A 3.1.4 Petrophysical data collection of rocks

In order to link regional geophysical data with different lithological units, petrophysical data of individual rock samples are needed. For example, by evaluating the relationship between the radioactive heat production *A* and seismic velocity v_P, thermal properties of deep-seated rocks can be assessed from the surface without the need for drilling (Rybach, 1973 and later publications by the same author). The author found that *A* and v_P (and density ρ) correlate negatively, i.e. as v_P (and density ρ) increase, *A* decreases. Other authors (e.g. Fountain, 1986; Kern and Siegesmund, 1989) found no such correlation. They attribute this to the fact that the petrophysical rock properties are mainly related to the properties of the main minerals, whereas heat production results from radiogenic components, which are largely concentrated in accessory minerals. In his original study, Rybach (1973) also reported that he did not observe a correlation between *A* and the thermal conductivity *K* for magmatic and metamorphic rocks. In clastic sedimentary rocks the two parameters correlate negatively as an increasing clay mineral content, characterized by increasing *A*, causes the decrease of *K*.

In the last decades, the properties of over 2000 rock samples from across Switzerland were measured by the research group of radiometry and geothermics at the Institute of Geophysics (ETH Zürich) and the Institute of Mineralogy (University of Geneva). More recently, Schärli and Kohl (2002) compiled the geothermally relevant rock parameters such as heat conductivity, radioactive element content (U, Th and K), radioactive heat production as well as porosity and density from all original publications. The compilation did not include the discussion of methods, uncertainties and meaning of the measured rock parameters. For more details, please refer to the original publications. In addition to the data published in the appendices to Schärli and Kohl (2002) there should be a CD-ROM with additional data, especially porosity and density of the samples included in this data compilation, which was not included in the paper copy of the report nor could we find it via library services or online.

For this report, we extracted all the data measured on samples from the Valais and surrounding areas (dataset *GPK compilation*). In total, there are data for 32 granites, 41 metamorphic rocks and 21 sedimentary rocks (primarily limestones and sandstones) for our study area obtained from surface samples as well as samples from tunnels. We obtained all the data from Schärli and Kohl (2002) as we found no electronic or paper copy of Rybach (1973), Schärli and Rybach (1984) and Wagner et al. (1999). This also means that we have no additional data on the rock samples such as porosity, density or potentially seismic velocity. In addition, only for the samples collected from the Aar Massif (more precisely the Grimsel Test Site; n=22) values for both, thermal conductivity *K* and heat production A are available. For the other samples, only one of the two is available. Thus, the available dataset on thermal properties of rocks from Valais are rather limited.

In the near future (likely 2019), the SAPHIR database compiled by the Swiss Geophysical Commission will become available. This database contains a large number of petrophysical properties of rocks from across Switzerland. As soon as it becomes available, relevant data will be included in our database.

A 3.2 Subsurface temperatures

A 3.2.1 Geothermometry on fluids

When thermal fluids circulate through a formation, rock-water interactions cause the fluid to obtain a chemical signature typical of the reservoir rocks. The maximum concentration obtained for all dissolved ions or compounds is controlled by residence time, mineral availability as well as mineral solubility under reservoir conditions. As the residence time of fluids is generally high due to the relatively low permeability of the rocks and the rock-water-ratio is very high, the concentration of dissolved species is generally only controlled by mineral solubility (primarily a function of temperature). As the solubility as a function of temperature are known for most minerals, the concentrations of dissolved species can be used to derive the minimum temperature at which equilibrium between the solid and fluid phase was obtained, i.e. the reservoir temperature. This approach is called geothermometry. A variety of dissolved species can be used as geothermometers. The oldest and still commonly used one is the SiO_2-geothermometer. It is based on the solubility of quartz under reservoir conditions (or chalcedony or amorphous silica for shallower and/or cooler reservoirs) and works by simply analyzing the concentration of dissolved silica and calculating the corresponding reservoir temperature (Sonney and Vuataz, 2010 and references therein). While this geothermometer has been used extensively, especially in high-enthalpy fields, it is not very robust to mixing of the hydrothermal fluid with other fluids or potential mineral precipitation during ascent as it is based on silica concentration of the thermal fluid. This is why multicomponent geothermometers have been developed. They are based on the ratios between different dissolved species such as Na, K, Ca, Mg and/or Li (Sonney and Vuataz, 2010 and references therein). These geothermometers are not based on a single mineral but the whole assemblage of reservoir minerals such as feldspars, carbonates and sheet silicates (e.g. micas, chlorites and clays). Depending on the amount of dissolved species considered, the calculations are relatively simple or they require the computation of the (theoretical) equilibration temperature of the whole mineral assemblage to infer reservoir temperature. While this is a more complex approach, multicomponent geothermometers are much more robust to effects of dilution by shallow and dilute groundwaters as the calculations are based on cation ratios rather than absolute concentrations. However, they can only be applied if the mineral assemblage has reached equilibrium, which has to be evaluated in detail for low- to medium-enthalpy systems (Sonney and Vuataz, 2010). In addition to solute geothermometers, isotope and gas geothermometers can be applied.

Geothermometry has been applied to most of the known thermal occurrences in the study area of the Rhône Valley. As these known systems represent low-enthalpy systems with substantial mixing with colder groundwaters, many geothermometers described above cannot be applied as they strongly under- (quartz geothermometer due to mixing) or overestimate (several multicomponent geothermometers as mineral equilibria are not established) the reservoir temperature. According to Sonney (2010), the most reliable geothermometers for the fluids of the Rhône Valley are chalcedony, Na-K-Ca with Mg correction, K/Mg, ^{18}O isotopes as well as the computation of the equilibration of the whole mineral assemblage. Extrapolated reservoir temperatures are listed in the BDF Database for all locations except Gletsch. Most sites show reservoir temperatures of 30 to 60 °C with the exception of Brigerbad, Grimsel and Lavey-les-Bains where reservoir temperatures of around 100 °C were determined. A new study for the Grimsel site shows that temperatures of 230-250 °C are reached at a depth of 9 – 10 kilometers, drastically increasing the maximum temperature derived from geothermometry for any orogenic hydrothermal system (Diamond et al., 2018). Unfortunately, for most other sites it is unclear how these reservoir temperatures were calculated as there is no description of the geothermometry available in the documentation accompanying the BDF Database. Only for the sites of Combioula (Ladner, 2005; Suski et al., 2008), Lavey-les-Bains (Sonney, 2010) and Grimsel (Diamond et al., 2018) the geothermometric approach is described in detail. All of these studies determined reservoir temperatures by numerically unmixing the thermal component from a cold groundwater component and subsequently computing the equilibration temperature of the entire mineral assemblage. We suggest to follow the same approach for several of the other sites (especially Brigerbad, Saillon, Saxon and Val d'Illiez) in order to obtain comparable results. This would then help to understand if Brigerbad, Grimsel and Lavey-les-Bains actually represent systems with higher reservoir temperatures or if the reservoir temperatures at the other sites were underestimated, e.g. due to extensive mixing with colder groundwaters. This in turn would allow a much more accurate characterization of the geothermal play in the study area as well as better prediction of the geothermal potential of Valais and the VD-part of the Rhône Valley.

A 3.2.2 Direct measurements

The easiest way to determine the presence of a potential heat source is to directly measure underground temperatures. This is usually done by inserting a temperature sensor inside a well. By combining temperature data from various wells and at different depths, thermal isosurfaces of an area can be drawn. However, in order to obtain meaningful temperature measurements, a number of points need to be considered. In the uppermost ~20 m below surface, the underground temperatures are dependent on daily as well as seasonal variations of air temperature. When considering such shallow temperature measurements, the weather conditions before and during the measurement need to be taken into account. At depths greater than 20 m the temperature is no longer dependent on surface conditions. However, the thermal properties of the surrounding formation become very important, especially if the lithologies are water saturated. In the case of fast groundwater flow rates, the temperature is also affected by this. During drilling, the in-situ temperature field around the well is disturbed due to the high flux of cool drilling mud or water used. In addition, the installation of a ground source heat pump or casing inside the well can also affect the in-situ temperature field as the setting of the cement is an exothermal process, releasing energy. Over time the temperature field returns to its pre-drilling state. It has been shown that in case of a shallow well (i.e. 100 to 400 m for the installation of a ground source heat pump) the return to in-situ conditions takes about 8 to 10 days (Badoux et al., 2016).

In our study area, an enormous number of wells has been drilled for drinking water, to install ground source heat pumps (GSHP) as well as thermal or mineral water exploitation. Most of these wells are shallow (less than 150 m) and many do not reach the bedrock where the thermal waters are emerging. Thus, we cannot identify such outflow points at depth precisely using the wells available. However, the thermal waters mix with groundwaters during ascent, creating weak thermal anomalies which can potentially be picked up by the shallow wells. Thus, by compiling the temperature data from all shallow wells, we should be able to obtain a detailed map of underground temperatures, potentially allowing us to identify positive thermal anomalies caused by blind geothermal systems. Groundwater temperatures from 183 groundwater stations for the period of 1990 to 2013 were compiled as part of the GEOTHERMOVAL II program by CREALP. By determining the average groundwater temperature, they identified areas where the temperatures deviated more than $\pm 1\sigma$. Positive temperature anomalies were identified in areas with well-known thermal anomalies (Brigerbad and Saillon) as well as areas with no known thermal springs (Gampel, Sierre, Sion, Fully, Follatères and Monthey). In the CREALP annual report 2015 it is stated that CREALP will be applying for federal funding to realize two exploration wells (up to 1.5 km) to further investigate these potential thermal water reservoirs. However, to date no information could be found on any such follow up project. In addition, it is unclear where CREALP obtained the groundwater temperature data from and it could therefore not be included in our GIS database.

There is a second potential source of information on subsurface temperatures at shallow depths: the exergetic efficiency (= actual energy produced) of GSHPs. This efficiency depends on heat pump-specific parameters such as $T_{vaporiser}$ and $T_{condenser}$ but also on the subsurface temperatures. Unfortunately, a dataset containing the operating parameters of installed heat pumps is not available centrally but would require access to a huge number of GSHP, most of which are installed in private homes. In addition, it is, as of now, unclear how accurately the operating parameters of GSHPs can be converted to underground temperatures. Therefore, a detailed study on deriving the exergetic efficiencies of installed GSHPs and their conversion to underground temperatures would be required first.

A 3.3 Thermal water occurrences

Thermal waters emerging from the subsurface are commonly analyzed in order to obtain information on their origin and fluid flow path. Several aspects can be determined: the overall chemical composition (major and trace elements), the content of dissolved gases, certain element ratios as well as the stable water ($\delta^{18}O$ and δH) and radiogenic isotopes present in the fluid. Together, these data give information on the origin of the fluid, the type of lithologies the fluid has interacted with along the flow path, the temperatures and depth of the reservoir as well as the age (or mean residence time) of the fluid. Often, the physicochemical properties of the fluid emerging from hot springs or encountered in wells represents a mix of different fluid sources such as old fluids incorporated into a lithology during its formation, deep magmatic or metamorphic fluids, fluids migrating from the surrounding lithologies, shallow and cold groundwaters or meteoric waters percolating through the subsurface. By analyzing several independent parameters (e.g. conservative anion ratios and stable water isotopes) of the thermal water and one or several of the endmembers, the fluid can be unmixed giving information on the other endmember(s).

For the study area, a range of geochemical and isotopic data is available for all known thermal occurrences (17 sites; Table 1). Most data was collected during the GEOTHERMOVAL I project and has been summarized by Bianchetti (1993) and Vuataz et al. (1993). The data was later included in the BDF database (Sonney and Vuataz, 2008). While these compilations are very valuable to understand known thermal occurrences, there are several drawbacks:

- Most of the data was collected by diploma students or hydrogeology companies and described in non-published theses and internal, non-published reports. There is thus no information on how the data was collected, measured and processed which makes it very difficult to assess the quality of the data and use it for further studies. The exceptions are the studies conducted by Bianchetti et al. (1992; Val d'Illiez), Bianchetti (1993; Rawyl), Dubois et al. (1993; Saillon), Muralt and Vuataz (1993; springs in the Dala gorge, Leukerbad), Bianchetti (2002; P201 and P600 wells at Lavey-les-Bains), and Bianchetti (2003; JAFE well, Saillon), where the data collection is described and the data discussed in more detail.
- It is unclear what exactly the data given in the BDF database represents: Are these individual analyses or do they represent average values of a number of analyses? If the later, how many analyses were done and over what kind of time period where the samples collected? The only hint given is the criteria "variability TDS" which is described as n.d., zero, weak or large,

suggesting that at least some sites show substantial changes over time. However, without any additional information it cannot be concluded if this is due to seasonal changes, seismic activity, pump rate of the thermal waters, or any other reason.

- Some parameters were analyzed for (nearly) all sampling locations (e.g. major element chemistry) while other parameters were analyzed for only few sites (e.g. ^{14}C). In most cases it is unclear if the absence of data means that the value was zero or if the water was simply not analyzed for said parameter.
- Many of the data listed are measurements done during or even before GEOTHERMOVAL I, i.e. during the late 70s to early 90s. For some sites (Brigerbad, Combioula and Lavey-les-Bains) data from the early 2000s are available. This is partly problematic because measurement technologies have substantially improved in the meantime but even more so as it is unknown if the fluid composition has remained similar or if changes have occurred over the last decades.

Overall, this makes the content of the BDF database of limited use for future studies aiming at a better understanding of the circulation of thermal water in the Rhône Valley.

There is also a substantial amount of data on the thermal waters of the Rhône Valley and surrounding areas which was not included in the BDF database. Firstly, these are data collected after the compilation of the BDF database such as results from the new wells at Brigerbad which were drilled in 2008 – 2010 (Buser et al., 2013) or the recent results from the Grimsel area (Diamond et al., 2018; Schneeberger et al., 2018). Both studies investigated the hydrochemistry of (sub)thermal waters as well as cold springs/groundwaters, which allowed to assess mixing and thus yielded a better characterization of the deep thermal water component and, in the case of the Grimsel system, the deep thermal anomaly.

A second type of data not included in the BDF database is data collected by private companies. Firstly, there is a wealth of data from the different thermal SPAs situated in the study area. The operators are required to continuously monitor their water composition to ensure the quality of the bathing water. It is unclear if only health-relevant parameters such as the presence of bacteria are analyzed or if complete chemical analyses of the bathing water are performed as well. It is assumed that the operators regularly measure the fluid emerging from their springs, wells and or galleries to ensure that the composition and/or flow rates remain constant as small changes over time could indicate for example changing productivity of the fluid reservoir or build-up of scale and/or corrosion materials in a well. We tried to obtain this data by contacting several thermal SPA operators. However, not a single operator replied despite several follow-up attempts from our side. In addition to the routine analyses with respect to water quality, large datasets were collected to monitor the effect of the construction of the Lötschberg Base Tunnel (LBT) on the thermal springs of Leukerbad and Brigerbad. The monitoring was done by G. Bianchetti (associated with CRÉALP) in collaboration with OSPAG from 1991 until the end of 1999. Ever since, the monitoring has been continued as a routine job by a private company, presumably OSPAG, but the data is not published. There is also a substantial amount of data collected in the LBT and the associated galleries and boreholes. Unfortunately, none of this data could be accessed. Making these datasets available to researchers would allow detailed studies (like the one at Grimsel) to be performed for other sites of know thermal occurrences without any need for additional sampling. This would allow evaluating similarities and differences between the individual hydrothermal systems in the study area which in turn would strongly enhance the success of future exploration for blind hydrothermal systems.

A 3.3.1 Chemical composition

The determination of the chemical composition of a water is the most common type of analyses done for fluids. For most samples the conductivity, pH and TDS as well as the concentration of major (Na, Ca, Mg, K, HCO_3, SO_4) and minor to trace groundwater components (SiO_2, Sr, Cl, F plus any other element of interest to a certain study) is performed. This data can be used as input for reactive-transport modelling, which can provide important information on the origin of the waters, the circulation depth and residence times (e.g. Diamond et al., 2018).

Instead of reporting the complete composition for each thermal water (for example on a map), usually the chemical type of the water is given. In order to do this, analyses in mol/L or mg/L are converted to meq/L and subsequently to meq% (for cations and anions individually). The water types are then constructed as follows (Jäckli, 1970):

- Component > 50 % → underlined
- Component 20 – 50 % → listed
- Component < 20 % → in brackets

By determining these water types from the chemical analysis of a fluid allows to directly obtain some information on the source of the water as different lithologies result in different types of water. For example crystalline rocks (granite and gneisses) in Switzerland generally have waters of Ca-(Na)-HCO_3-SO_4 or Ca-(Na)-(Mg)- HCO_3-SO_4 type, respectively. Sedimentary reservoirs such as limestones or evaporites on the other hand have *C*a-(Mg)-$\underline{HCO_3}$ and Ca-(Mg)-$\underline{SO_4}$-(HCO_3) type waters, respectively.

Most of the waters analyzed for the study area have calcium as the dominant cation and sulphate as the dominant anion. These elements are primarily derived from the dissolution of evaporites (e.g. anhydrite) and the oxidation of pyrite, which occurs as an accessory in many of the lithologies present. Generally, waters derived from an evaporitic reservoir are expected to have high TDS values (e.g. springs at Leukerbad) while waters derived from a crystalline reservoir, likely picking up their sulphate concentration from dissolution of sulphides, have a much lower TDS (e.g. Lavey-les-Bains). In order to better separate these two sources for the sulphate, sulphur isotope analyses would have to be performed.

There are some waters which are not dominated by calcium. In the deep wells at Brigerbad and Lavey sodium becomes the dominant ion, while the shallow wells are dominated by Ca. This suggests that the water composition is not constant with increasing depth. Similar observations have been made in the gneissic rocks of Olkiluoto Island (Finland) where studies found that with increasing depth different types of groundwater can be found and that there is a transition from Ca- to Na-dominated waters at a depth of less than 100 m. Similarly, they observed the transition from a brackish HCO_3-type to a SO_4-type to a Cl-type and eventually to a saline groundwater of Na-Ca-Cl type (Pitkänen et al., 2004). This stratification is due to different waters (e.g. sea water, glacial meltwater) infiltrating at different times. The results from Brigerbad and Lavey indicate that similar processes can be observed in the Rhône Valley. However, we do not have enough data to understand these variations with depth. The other waters, which are Na-dominated instead of Ca-dominated, are all high elevation sources (Grimsel, Gletsch, Rawyl) which are far away from any lithologies containing evaporate minerals.

A 3.3.2 Isotopic composition

To determine the origin of ground- and thermal waters, stable water isotopes ($\delta^{18}O$ and δH) are often measured. The results are plotted in relation to the global or local meteoric water line (MWL; Figure A4). If the data points plot on or close to the MWL, they are derived from meteoric waters, i.e. recent or old precipitation. Precipitation under colder conditions, higher altitude or at higher latitude plots at more negative values of $\delta^{18}O$ and δH; while warm, low altitude and low latitude precipitation plots at less negative values. A trend away from the MWL to less negative $\delta^{18}O$ values at constant δH values is indicative of hydrothermal rock-water interactions.

In addition to stable isotopes, radioactive isotopes are used to determine the average mean residence time of ground- and thermal waters. The most common isotopes used are: ^{3}H (up to 50 yrs), ^{14}C (up to 30'000 yrs) and ^{81}Kr (up to 1 Ma). By determining the concentration of the isotopes and correcting for factors such as mixing, hydrodynamic dispersion and interaction with ^{14}C free carbonates, the age range of the waters can be determined.

Isotopic analyses for thermal waters from our study site are given in the BDF Database for all locations except the springs at Gletsch and Val de Bagnes. When plotted, they fall close to the local meteoric water line (LMWL). This suggests that all these waters are of meteoric in origin, which is in line with the geothermal play of orogenic geothermal systems including the deep circulation of meteoric waters. Two samples (Brigerbad and Grimsel) plot to the right of the MWL, potentially suggesting rock-water interactions which lead to heavier oxygen isotope signals.

The mean residence times of the thermal waters in the study area could not be determined. All waters where ^{3}H was measured contained some concentration of the isotope. This could suggest that the waters are (a) very young which is unlikely due to the long flow path and thus substantial residence time or (b) that all the tritium originates from mixing with young, shallow groundwaters. Thus, the tritium concentration is one option to determine the degree of mixing between cold groundwaters and the thermal water component. At Leukerbad and in the deepest well at Lavey-les-Bains ^{14}C values were measured. Again, this could mean that the waters are less than 30'000 yrs old or that the ^{14}C is derived from mixing with young groundwater.

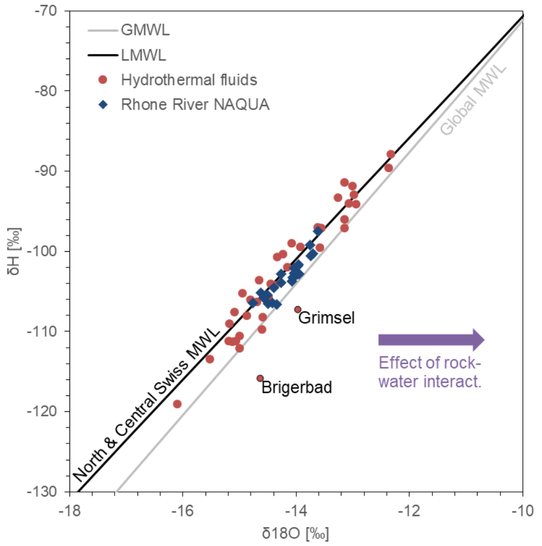

Figure A4: Stable isotope values of all known thermal occurrences in the study area. GMWL and LMWL from Schürch and Vuataz (2000).

A 3.3.3 Place names related to thermal waters

Another approach to obtain information on the occurrence of thermal water within the Rhône Valley is to look at place and field names. A plethora of place and field names in the Rhône Valley are derived from the natural occurrence of water (e.g. lakes, pools, rivers, streams, springs, marshes etc.) as well as man-made water sources (reservoirs, channels, bisses/suonen etc.). For the early inhabitants of the Rhône Valley, water courses and sources were primarily of interest if they could be used (drinking water or irrigation) or if they posed a threat (i.e. flooding). In addition, there were two well-known thermal water occurrences (Leukerbad and Brigerbad) which had been used for balneotherapy since Roman times.

To potentially find additional references to thermal waters, we turned to the project ortsnamen.ch. For several decades the project has aimed at putting together a more comprehensive place and field name registry for Switzerland. Unfortunately, the Orts- und Flurnamenbuch (place and field name registry) for the German-speaking Upper Valais has not yet been completed and as of now no data are available online. In order to obtain some information nevertheless, we contacted Iwar Werlen, professor emeritus of linguistics and project leader of the Oberwalliser Orts- und Flurnamenbuch (place and field name registry Upper Valais) and asked him for place names with indications of hot or warm fluids, and/or other characteristics that might be associated with thermal activity such as sulphuric odours (Table A1).

Several of the field and place names are historic and are no longer used. The reasons for the discontinuation of a place or field name are manifold, for example change in ownership (renaming a location after a new owner rather than a landscape feature) or forgetting of a place and later rediscovery together with renaming. It is also possible that some of the warm springs mentioned in historic sources were destroyed due to natural disasters (landslides, rockfall, flooding, avalenches etc.). For example the thermal springs at what is now Brigerbad, known since Roman times, were destroyed by a rockslide in the 15th century and were only rediscovered in the early 16th century. It is also possible that some of the known warm springs were destroyed during the extensive changes to the course of the Rhône river during the river corrections in 1863 and 1864 (Summermatter, 2004).

While Table A1 represents a comprehensive list of field and place names relating to potential thermal water occurrences in the Upper Valais, no data is available for the French-speaking Lower Valais and the parts of the Rhône Valley part of the canton of Vaud as no place and field name registry or plans to compile such exist for these areas. A field trip to visit the sites in Table A1 to check for thermal water occurrences is planned for summer 2019.

A 3.3.4 Evidence of old thermal systems

Information on past hydrothermal activity can be extracted from the relict mineralogical and structural features at fossil sites. The mineralogy of hydrothermal veins and alteration zones places constraints (via thermodynamic and kinetic modelling) on the temperature and chemistry of the parent fluid (e.g. Alt-Epping et al., 2013). Analysis of the stable and radiogenic isotopes of H, C, O, S, Sr, Pb, U and Th in hydrothermal minerals can be used to reconstruct the temperature of mineralization and the origin of the solvent and solutes (Hofmann et al., 2004; Janots et al., 2012; Pettke et al., 2000). Fluid inclusions in the hydrothermal minerals can be analyzed to determine the composition, phase-state and P–T conditions of the paleo-fluid (Hofmann et al., 2004). Structural analyses yield the orientations and style of water-conducting features (e.g. Belgrano et al., 2016) and radiometric dating yields the age of the hydrothermal activity (Hofmann et al., 2004; Janots et al., 2012). While some of these fossil systems are linked to currently active systems (e.g. Grimsel), others are completely unrelated. Nevertheless, their study allows us to investigate the structure and evolution of thermal systems which in turn helps to better predict the geothermal potential of the whole region.

Table A1: Field and place names in the Upper Valais related to “warm” and “water” as well as “sulphur”. The words “Wÿer” (Visp) and “Gilla” (Raron West) both relate to a pond while the expression “Lischen” describes sedge growing along the River Rhône. The three fieldnames in the Leuk district are all derived from the francoprovençale word of “chaudanne” meaning “warm water” or “warm spring”. Similarly, “ts Galdi” and “di Gaaldinu” (in the 13th and 15th century listed as Caldaria and Caldana, respectively) is likely derived from lat. “calidus” meaning warm.

Name	**Location (District)**	**Period**	**Coordinates**
bim Warmen Brunnen	Obergesteln (Goms)	Uncertain but likely before 1798	Location unknown

sub dem Schwebell Brunnen	Geschinen (Goms)[2]	1520	2'665'675.750 / 1'149'851.125
beÿ dem Vndren Schwebelbrúnen	Ritzingen (Goms)	1742	Location unknown
die Schwäbel Lischen	Ulrichen (Goms)	1619, 1789	Location unknown
bim warme Wasser	Blitzingen (Goms)	Still in use	2'657652.000 / 1'144'350.000
Warme Wasser	Niederwald (Goms)	Still in use	2'658'105.500 / 1'143'179.500
im Warm Brunne	Binn (Goms)	Still in use	2'659'957.500 / 1'135'414.750
zum Waren Brunnen	Grengiols (Raron East)	1758	Location unknown
ze Warme Brunnu	Bitsch (Raron East)	Still in use	2'644'655.750 / 1'131'957.500
von dem Warmun Brunnen	Mörel (Raron East)	1638 and earlier	Location unknown
zuo Warmen Brúnnen	Mörel (Raron East)	1645 and later	Location unknown
beim Warmen Brunnen	Brig (Brig)	1649, 1744	Location unknown
zún Warmen Brúnnen	Simplon (Brig)	1758	Location unknown
zum Warmu Brunnji	Visperterminen (Visp)	Still in use	2'634'954.000 / 1'122'366.000
zum Warmun Wÿer	Visperterminen (Visp)	1554	Location unknown
Ts Galdi („Bietschi")[3]	Raron – Hohtenn-Steg – Gampel (Raron West)	Still in use	2'627'726.700 / 1'128'550.000 2'623'490.000 / 1'128.408.000
t Waarem Gilla	Ferden (Raron West)	Still in use	2'623104.000 / 1'139'324.000
di Galdinu (around 1/3 of the village of Leuk)	Leuk (Leuk)	Still in use	2'614'915.000 / 1'129'618.750
Tschüdanu	Leuk (Leuk)	Still in use	2'611'735.000 / 1'128'596.000
Tschüdangnä	Salgesch (Leuk)	Still in use	2'610'964.000 / 1'128'656.000
Tschüdangna	Varen (Leuk)	Still in use	2'611'331.000 / 1'128'527.000

Several sites of fossil hydrothermal activity with or without present-day discharge of warm water are known in the External Crystalline Massifs (ECM) and the overlying Helvetic and Penninic nappes. Some sites are marked by hydrothermally mineralized fault rocks, e.g. Grimsel Pass (Belgrano et al., 2016; Hofmann et al., 2004), Kleines Furkahorn (own observations) and Gemmi (Ustaszewski et al., 2007), while others simply show an abundance of hydrothermal quartz veins (Heijboer, 2006; Sharp et al., 2005). In all these cases, hydrothermal fluid flow occurred along brittle strike-slip faults, fracture systems or tectonic breccias that are coplanar with and overprint precursor ductile shear zones (Belgrano et al., 2016; Egli et al., 2018; Ustaszewski et al., 2007; Wehrens et al., 2016). Only the Grimsel Pass system has been investigated in detail, showing that the system has been active for at least 3.3 Ma and that the circulating fluid was meteoric water (Belgrano et al., 2016; Diamond et al., 2018; Hofmann et al., 2004; Schneeberger et al., 2018). Meteoric water circulation was also shown by isotopic analyses of hydrothermal quartz veins (Heijboer, 2006; Sharp et al., 2005). However, only during late stage precipitation was the fluid of meteoric origin. During initial stages of precipitation, the fluid was of late metamorphic origin. At several locations, mixing of these late fluids with meteoric water has led to the formation of orogenic gold deposits (Kündig, 1997). In addition, there are some hydrothermal copper and uranium deposits of Alpine age which formed in tensile joints (e.g. La Creusaz in the Vallée du Trient). Other Cu- and U-deposits found in Switzerland are older, often of Variscan age. All deposits are included in the Swiss Resource Information System RIS (https://map.georessourcen.ethz.ch/). However, for most of the copper and uranium deposits there is very little information on the formation

[2] According to Prof. Werlen, the sulphur-related place names in the Goms district potentially relate to a single location. However, it is unsure where exactly this location could be. One hypothesis is that the potential sulphur source was located in what is now the boggy terrain of the Honeije (2'665'675.750 / 1'149'851.125) on the left side of the River Rhône close to Geschinen as the sources from the 16th century commonly mention together with "sub dem Schwebell Brunnen".

[3] Small canal; coordinates of easternmost and westernmost point given

conditions available. They were thus not included in the GIS database as their formation by recent hydrothermal fluids is uncertain and they may not be linked to the Alpine orogeny.

A 4 Permeability

In the following sections, we give a detailed overview on the data grouped under “Permeability”. This includes fault, stress, and strain data, as well as gravimetric and reflection seismic data. We like to note that the paragraphs on faults, stress, and strain are largely based on an unpublished report for a pilot study of the SeismoTeCH project of the Swiss Geophysical Commission. In the pilot study called “Towards a new seismotectonic characterization of Switzerland – data, visualizations, and models” Samuel Mock and co-authors assess the requirements and approach for the development of a new seismotectonic characterization of Switzerland.

A 4.1 Faults

The faults extracted from swisstopo’s Tectonic Map of Switzerland (1:500’000) and the GeoCover (1:25’000) dataset, represent structures, which are mapped by classical field work. In terms of age of faulting and kinematics (i.e. sense of faulting) the fault classification is oversimplified. Since the fault data reflect only surface structures, it has a certain degree of completeness in high-relief areas. In areas with low relief and low bedrock exposure, the dataset is underdetermined. The GeoCover dataset (version 1, 2016) is largely based on the published map sheets of the Geological Atlas of Switzerland at the scale of 1:25’000 and in cases on special maps and map originals of different scales and sources. A fully harmonized version 2 will be available from swisstopo by summer 2019.

A third fault dataset has been extracted from the Seismotectonic Atlas of Switzerland, a project which aimed to map recent and sub-recent faults across the central Alps (Persaud, 2002; Ustaszewski, 2007). The regions for mapping, including the Valais, were chosen due to their high present-day rock uplift rates (Brockmann, 2018; Schlatter, 2014) and high seismic activity. Following lineament mapping and field verification, the faults were classified as either being of tectonic, gravitational or composite nature, with the latter resulting from a combination of gravitational, tectonic, post-glacial rebound processes (Ustaszewski, 2007). In the end only a handful of faults could be unequivocally determined as active faults. However, the dataset is in itself consistent and further complements the aforementioned datasets extracted from GeoCover and the Tectonic Map of Switzerland.

A 4.2 Stress

There is a variety of methods to measure stress in rocks (e.g. Ljunggren et al., 2003). The host rock is either intentionally disturbed (e.g. hydraulic fracturing and overcoring) or the rock’s behavior is observed without a disturbance through the applied method (e.g. borehole breakouts and focal mechanisms). Stress data for the study area is mainly given by earthquake focal mechanisms and is provided by the World Stress Map (Heidbach et al., 2010, 2016), a compilation of Kastrup et al. (2004), and a dataset which we compiled for this study from several sources (Deichmann, 2014; Diehl et al., 2014, 2018; Kastrup et al., 2004). Except for the northeast (Oberwallis), data coverage for the canton of Valais is fairly well. Maximum horizontal stresses distinctly differ when comparing the northern Valais to the southern Valais. North of the Rhône Valley, axes of maximum horizontal stress are NW-SE oriented and fault plane solutions show mainly strike-slip to normal faulting with occasional thrust faulting, while south of the Rhône Valley, the axes of the maximum horizontal stresses are E-W oriented and almost exclusively indicate normal faulting. Although focal mechanisms are a first-order tool to analyze the recent stress field of a region, single fault plane solutions may not necessarily describe the actual stress regime, since the orientation of the activated fault may be significantly altered by crustal heterogeneities, such as tectonic preconditioning and structural inheritance. In order to overcome this effect, Kastrup et al. (2004) analyzed the stress variations across Switzerland (Figure A5) by applying stress inversion methods to regionally distinct subsets of focal mechanisms. They distinguished two different main stress regimes acting in the canton of Valais: (i) a strike-slip to normal faulting regime in the north and (ii) a purely normal faulting regime in the south. The stress regimes are divided by the Rhône Line, a major tectonic line, which forms a segment of the Rhône-Simplon Fault System (Mancktelow, 1985).

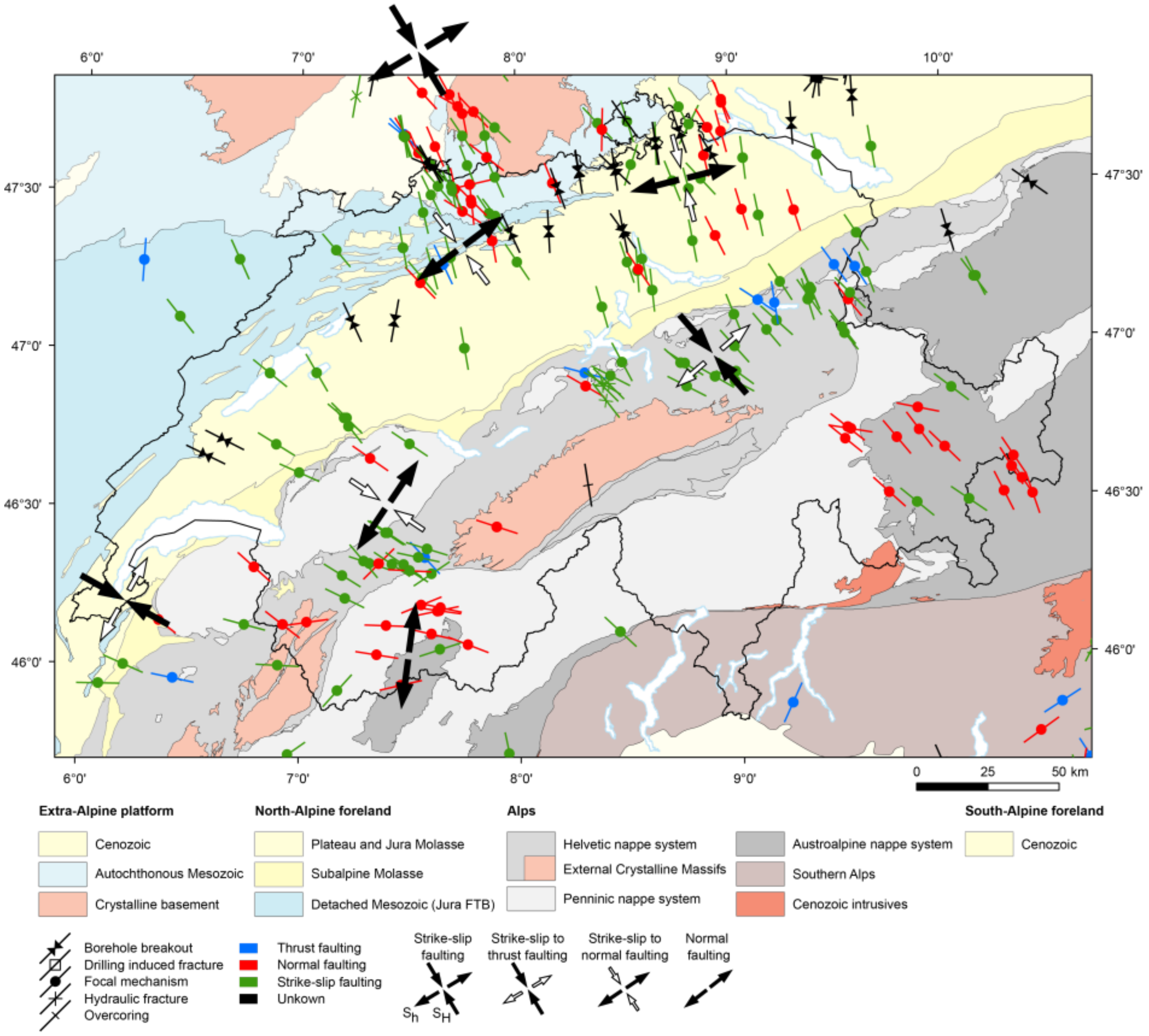

Figure A5: Present-day stress field of Switzerland. Single stress measurements are taken from the World Stress Map (Heidbach et al., 2016) and are shown here according to the measurement method and the stress regime. Regional stress determinations from stress inversions of focal mechanisms are shown as large arrows (Kastrup et al., 2004). The tectonic map is modified from (Spicher, 1980).

A 4.3 Strain

With the Automated GNSS (global navigation satellite system) Network for Switzerland (AGNES), swisstopo operates a network of 30 permanent GNSS (Global Navigation Satellite System) stations (Brockmann et al., 2012; Villiger, 2014). The stations are in operation since at least 10 yrs, with some stations being in operation as long as 20 yrs. This provides information on the long-term (decadal) evolution of crustal movements. By analyzing these data station positions can be estimated on a daily basis. Measurement uncertainties at the individual stations are in the range of 1-2 mm and 3-4 mm in horizontal and vertical directions, respectively. However, caution must be taken when interpreting data from stations which are mounted on buildings, since their signal may be artificial (e.g. expansion or shrinking of metal construction). All AGNES measurements are measured relative to the **Zimmerwald** (canton of Bern) permanent station, which itself is calibrated to stable Europe.

The temporal resolution of the AGNES data is very high (daily to hourly basis) and thus sensitive to short-lived events such as faulting. However, since the stations are currently too widely spaced and their setup is not targeted to resolve movements along a specific fault, it is hardly possible to relate events of rapid crustal movements to a particular fault or fault zone yet. A better approach would be to try to discriminate areas with similar rates and directions of crustal movement and relate them to tectonic regimes.

A first order reference network LV95 of about 200 passive points exists, which was setup between 1988 and 1995 on geologically stable locations. This network is re-measured with GNSS every 6 yrs (last measurements 2016, CHTRF2016; Brockmann, 2018). Tectonic movement can be determined on a much more densified scale. In total, tectonic movements in Switzerland seem to be very small. Maximum velocities are found in the Ticino and the Valais (Figure A6). The assumption of a static reference frame holds true for the horizontal component on a level (standard deviation) of 0.2 – 0.3 mm/a. A recent study has shown that the current GPS station network is able to record earthquake events with $M_W > 5.8$ (Michel et al., 2017). The sensitivity to the magnitude is primarily governed by the station density, hence the distance from the hypocenter to the nearest GPS receiver, and the sampling rate of the latter.

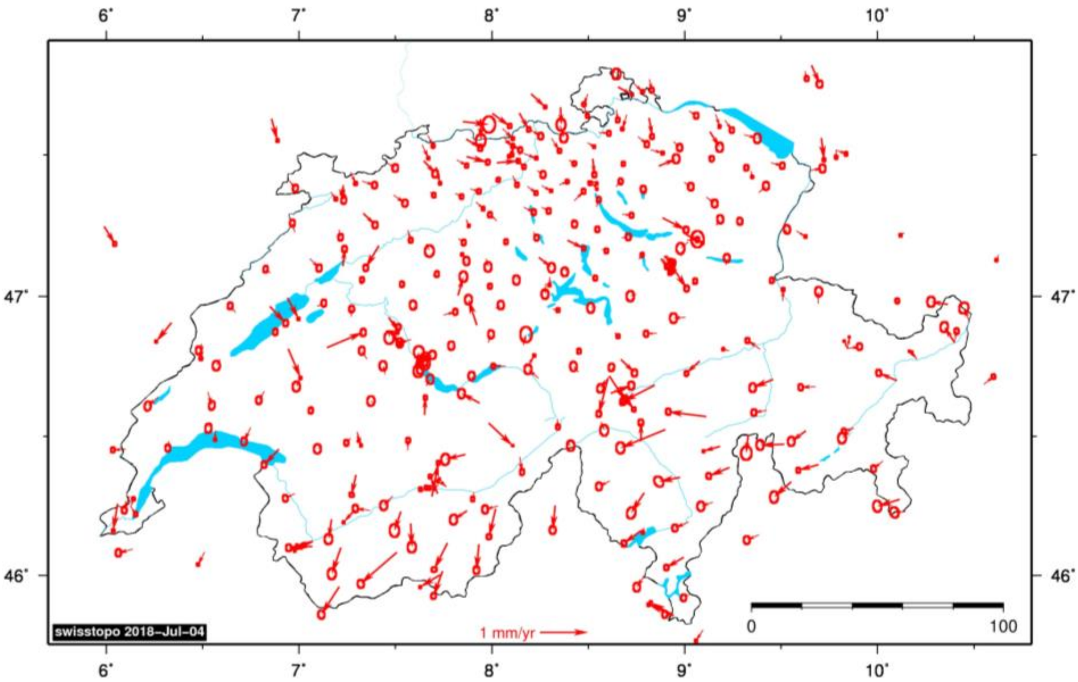

Figure A6: Current velocity field based on the CHTRF2016 campaign (Brockmann, 2018).

High-precision levelling data exists and is being re-measured every 50 yrs by swisstopo. The values are only accurate along the actual measured lines, which are mainly along the main roads; hence the interpretation of interpolated data is prone to large uncertainties and should be taken with great caution. Highest uplift rates recorded from levelling data in the Valais are up to 1.4 mm/a with respect to a fixed point in **Laufenburg** in northern Switzerland (Schlatter, 2007, 2014). When comparing high-precision levelling uplift rates with GNSS vertical velocities, please keep in mind that a different reference point is used for GNSS data (**Zimmerwald**).

A 4.4 Seismicity

A 4.4.1 Earthquakes

Two different earthquake catalogues are currently maintained by the Swiss Seismological Service (SED):

1. Macroseismic historical earthquakes since 250 AD and instrumentally recorded earthquakes between 1975 and 2009 are stored in the ECOS-09 catalogue. At the moment, this publicly available catalogue is static. It contains events which are heterogeneous with respect to locations and location uncertainties, but it is uniform in how the magnitudes are reported (moment magnitudes Mw).
2. The continuously updated SED-Bulletin contains earthquakes with digital waveforms, which have been instrumentally recorded since 1984. For events between 1984 and 2009, it is largely identical with ECOS-09. Due to changes in the configuration of the seismic network and location procedures over time, the catalogue is heterogeneous with respect to locations and location uncertainties. Relevant events have been carefully reviewed and documented in the (bi-)annual reports of the SED since 1996 and an empirical uncertainty estimation has been introduced as a quality index for the individual events (Deichmann et al., 2000; Table A2).

In the next few years, the SED will gradually relocate the entire SED instrumental catalogue. Improved seismic velocity models and nonlinear relocation methods will lead to significantly improved absolute and relative event localizations. In the course of this, multiple earthquake catalogues will be established:

- A single-event, absolute relocated Swiss Earthquake Catalogue (SECOS) with improved absolute location uncertainty and
- a relative-relocated Swiss Earthquake Catalog (RECOS), delivering the highest precision for event localization (in cases able to resolve fault plane geometries).

Table A2: Location uncertainty as introduced by *Deichmann et al.* [2000].

Rating	**Criteria**		**Uncertainty**	
Q	GAP (degrees)	DM (km)	H (km)	Z (km)
A	≤ 180	≤ 1.5 x Z	≤ 2	≤ 3
B	≤ 200	≤ 25	≤ 5	≤ 10
C	≤ 270	≤ 60	≤ 10	> 10
D	> 270	> 60	> 10	> 10

GAP, largest angle between epicenter and two adjacent stations; *DM,* minimum epicentral distance; *H,* horizontal location; *Z,* focal depth

A 4.4.2 Seismic Hazard

For the sake of completeness, the official seismic hazard map of Switzerland (Wiemer et al., 2016) has been added to the GIS database. It shows the enhanced seismic hazard in the Valais.

A 4.5 Geophysical methods

A 4.5.1 Gravimetry

The basics of gravimetry are variations in the earth's gravitational field generated by density differences between subsurface rocks, so called gravity anomalies. Gravimetric modelling has one of two aims: (1) Determine the densities starting from known shapes and structures or (2) determine the geometric parameters of one or several structures starting from a density hypothesis. In both cases the nature of the gravity data makes its interpretation ambiguous, as several different bodies can induce the same anomaly. Therefore, gravity is often used in combination with other geophysical methods (e.g. seismics) to avoid or decrease the ambiguity.

In geology, gravity is used to identify dense subsurface anomalies such as magmatic intrusives but also structures less dense than the host rock such as fault zones. Gravity has also been used for porosity determination in off-shore petroleum exploration (e.g. Johnson et al., 2000). More recently, gravimetry has been used to investigate geothermal reservoirs such as the Geysers geothermal field (N-California; Denlinger and Bufe, 1982), Soultz-sous-Forêts (Schill et al., 2010) and geothermal reservoirs in Hungary (Tulinius et al., 2010). Another study was performed in the Argenterra massif where negative gravity anomalies could be linked to faulting along which geothermal fluids rise naturally (Guglielmetti et al., 2013). This idea was further developed in a recent PhD study where gravimetry was used to estimate the porosity of fault zones at depth which might be used as geothermal reservoir (Altwegg, 2015). The author suggests a multi-step process, involving a 3D geological model which is used to compute the effects of the different geological structures on gravity before subtracting this from the measured gravimetric data, leaving only the gravity effects of the targeted structures. This approach was successfully applied to the geothermal projects at St. Gallen and Éclepens. In addition, the fractured granitic basement of Switzerland was studied by gravimetry (Baillieux et al., 2013).

Extensive gravity surveys were conducted throughout Switzerland which culminated in the publication of the Gravimetric Atlas of Switzerland. Our study area is part of four sheets: 41 – Col du Pillon, 42 – Oberwallis, 46 – Val de Bagnes and 47 – Monte Rosa. So far the gravimetric data has only been used to investigate the thickness of the quaternary sediments within the Rhône Valley (Gonet, 1965; Rosselli et al., 1999; Wagner, 1970) as well as the internal structure of these deposits where possible (Finckh and Klingelé, 1991).The Reservoir Geology and Basin Analysis group at University of Geneva , has recently started to reprocess the data published in the Gravimetric Atlas for the cantons of Geneva, Vaud, Valais and St. Gallen to be used in geothermal exploration. If successful, the reprocessed data will show major structural features which potentially channel thermal fluids. The first results for Valais are expected in early 2019 and will be included in the GIS project as soon as they become available.

A 4.5.2 Seismic surveys

Seismic surveying represents the most widely used geophysical method and the method with the best resolution of the subsurface. Seismic waves are created by an artificial source (e.g. a controlled blast, an air gun or a seismic vibrator) and their two-way travel times, are measured. These travel times are then converted into depth values and thus the subsurface structure can be determined as a function of depth.

Two types of seismic surveys have been conducted in and around the Rhône Valley: (1) investigations of the nappe structures and the deep (tens of kilometers) crust beneath the Alps and (2) shallow investigations, assessing top bedrock and the Quaternary fill of the Rhône Valley. The data on the structure of the Alps was obtained as part of the NRP-20 West transect (Fribourg – Jaun – Lenk – Sierre – Vissoie – Zermatt – Cimes Blanches – Biella) in the 1980s/1990s (Pfiffner et al., 1997). The interpretation of the NRP-20 results reveals a lot about the structure of the Alps at the kilometer scale.

However, the profile contains very little information relevant at the scale of the Rhône Valley. These results are therefore of limited use to the exploration for geothermal resources in the Rhône Valley.

In contrast, the short profiles across the Rhône Valley cover a much smaller area but at much higher resolution. These surveys allowed determining the geometry of the reflective hard bedrock underlying the softer and unconsolidated Quaternary sediments. In total, 8 profiles were collected across the valley: Roche-Vouvry (Finckh and Frei, 1991), St. Maurice (unpublished), Martigny East, Saillon-Saxon, Sion West, Sion East (all Besson et al., 1991), Agarn and Trutmann (Finckh and Frei, 1991). The focus of the earlier profiles (Roche-Vouvry, Agarn and Trutmann) was to evaluate the thickness of the sediments within the Rhône Valley, characterize top bedrock and to assess the internal structures of the Quaternary sediments by combining seismic data with gravimetric and petrophysical considerations (Finckh and Klingelé, 1991). The younger transects (St. Maurice, Martigny East, Saillon-Saxon, Sion West and Sion East) focused less on the Quaternary filling but more on the contact bedrock/unconsolidated sediments as well as the structures within the bedrock. To better evaluate the seismic data, it was combined with data from nearby boreholes (Besson et al., 1991). The authors argue that the contact bedrock/sediments is of hydrogeological importance as it is where thermal waters emerging along faults and fractures within the bedrock accumulate and percolate along until they encounter a permeable layer extend to the surface. Where they do not encounter such a permeable layer, they cannot reach the surface and thus represent a blind geothermal system.

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