COUPLED SEISMOGENIC GEOHAZARDS IN ALPINE REGIONS (COGEAR)

D. Fäh[1] and the COGEAR Working Group[2]

[1] *Swiss Seismological Service, ETH Hönggerberg, Zurich, Switzerland*
[2] *http://www.cogear.ethz.ch*
Email: cogear@sed.ethz.ch

ABSTRACT :

COGEAR is an interdisciplinary natural hazard project to investigate short and long-term earthquake preparation processes as well as complex surface effects induced by seismic strong ground motion. It addresses tectonic processes and related variability of seismicity in space and time, earthquake forecasting and observation of possible short-term precursors, and modelling and observation of weak and strong ground motion as a result of complex source and path effects. In soils and rock, we study non-linear wave propagation phenomena and liquefaction, the long-term impacts of repeated earthquakes on slope stability through rock mass strength degradation, and the triggering of landslides; the potential of earthquake-induced snow avalanches is also be estimated. Our focus is on the physics of non-linear processes in relation to topography, geological disposition, water saturation and slope stability. The consequences of earthquakes will be evaluated through scenarios of direct seismic hazard and assessment of susceptibility to induced (secondary) effects.
The Valais region in Switzerland, and specifically the area of Visp, as well as the Visper and Matter valleys, have been selected. In the past, the Valais has experienced every 100 years a magnitude 6 or larger event, with the last magnitude 6.1 earthquake in 1946. The region of Visp is hit by damaging earthquakes every 40 years (Intensity VI-VIII), with the last nearby event in 1960 reaching a macroseismic intensity of VIII. During all such events significant damage occurred from ground motion and different kinds of secondary phenomena such as liquefaction in the Rhone plain, slope instabilities and extended rock fall.
Our integrated approach includes detailed field investigations, the development of new investigatory techniques, the development and application of numerical modelling techniques, and the installation of prototype multi-sensor monitoring systems. Such systems are planned for long-term operation and will include a continuous GPS and seismic network, a test installation for observing any earthquake precursors, and two test areas (Visp, St. Niklaus-Randa) for studying site-effects and non-linear surface phenomena as well as their interaction.

KEYWORDS: seismic ground motion, non-linear phenomena, liquefaction, landslides, seismic precursors, earthquake forecasting, monitoring, Valais, Switzerland

1. EARTHQUAKES IN THE VALAIS (SWITZERLAND)

Although damaging earthquakes are rare in Switzerland when compared to more seismically active regions, such events have occurred in the past and will continue to do so. Over the past 700 years, a total of 28 events of a moment magnitude Mw≥5.5 are known to have occurred, twelve of which caused severe damage (Intensity of VIII or higher).
Moderate to high seismic risk in Switzerland results from high population density and high degrees of industrialization, as well as from little preparedness due to the relatively long return periods of strong ground shaking. Earthquakes strike generally without warning, and the best preparation modern society can achieve is to upgrade the building stock, infrastructure and critical facilities so that damage is minimized. The input for all measures of risk mitigation is the assessment of the different kinds of hazards associated with earthquakes through advanced technology.
The Valais is the area of largest seismic hazard in Switzerland (Fäh et al., 2003) and has experienced a magnitude 6 or larger event every 100 years (1524, 1584, 1685, 1755, 1855, 1946), with the last magnitude 6.1 earthquake in 1946 close to Sion and Sierre (Figure 1). This area and in particular the region of Visp hold special interest: on average the Visp region was hit by damaging earthquakes every 40 years (Intensity VI-VIII), with the last in 1960 reaching a macroseismic intensity of VIII. The Visp event of 1855 was the largest in Switzerland for the last 300 years. Besides its seismic activity the test area in the Valais is characterized by several factors adding to the total hazard level: rough topography, unstable and steep slopes, deep sediment-filled valleys, wide glacier- and snow-covered areas. On the one hand, during the Brig event (Mw=6.1) in 1755, the Visp event in 1855 (Mw=6.4) and Sion/Sierre event in 1946 (Mw=6.1) the area experienced great damage from earthquake ground motion and different secondary phenomena such as liquefaction in the Rhone plain, landslide reactivation and extended rock fall. On the other hand, we expect that smaller and more frequent earthquakes induce large ground motions locally, as well as small-scale movements and failures in critically stressed slopes. Earthquakes also reduce rock mass strength and thus add to landslide preparation.

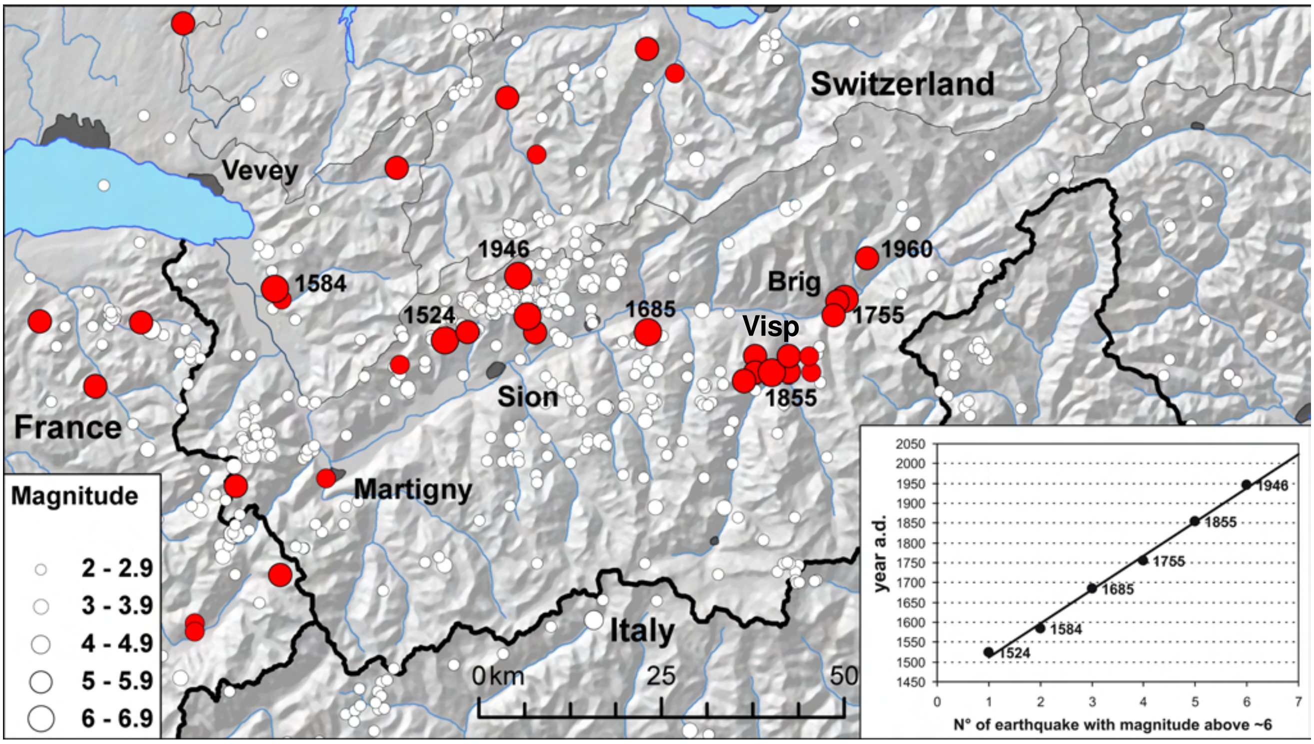

Figure 1 Large earthquakes in the Valais and the timing of magnitude 6 or larger historical events.

1. GOALS OF PROJECT COGEAR

Due to river regulations and engineering progress in the last two centuries, seismically unfavourable sites have become attractive for expanded settlement and industries. During the last century, many villages grew into the Rhone plain and expanded near hazardous slopes in the valleys. They are still growing. Future earthquakes will therefore cause more damage than was observed in the past. For this reason it is important to recognize and map potential areas, estimate ground motion and non-linear behavior for engineers and planners, and provide adequate estimates for the building code.

While predicting damaging earthquakes remains currently impossible, it is important to lay a solid foundation for improving our ability to forecast earthquakes. Although the Visp area shows only moderate seismicity on a worldwide scale, the region offers an excellent opportunity to observe and study the preparation processes for a moderate to large event in the Alpine collision zone. The probability of observing a major earthquake in the next 40 years is high and project COGEAR is a first step in studying the preparation phase of a coming event. Moreover, it will allow us to set-up a scientific base for detailed monitoring and analysis. Due to the limited size of the area where the next large earthquake in the Valais might be expected, this region is one of the best for a natural observatory in Europe. The project therefore adds to ongoing surveillance and seismic hazard assessment two new elements: interdisciplinary investigation and monitoring of short and long-term earthquake preparation processes at regional scale, and study of complex non-linear surface effects induced by seismic strong ground motion at local scale.

Earthquakes are inherently complex phenomena, beginning with the physics of rupture nucleation, propagation and arrest and the excitation of seismic waves propagating through geologically heterogeneous structures. Earthquakes result from long-term deformation processes in the Earth's crust and induce several coupled primary, secondary and tertiary hazardous processes. Strong ground motion acts on buildings and infrastructure and may considerably change the environment. In the Alps, quakes are known to have caused widespread liquefaction, subsidence and lateral spreading in fluvial and lacustrine deposits as well as landslide (re)activation and slope failure in soils and rocks. While most landslides in the Alps are triggered by climatic events (heavy precipitation and snow melt), the preparation of larger geological mass movements through progressive failure – taking typically thousands of years – is also driven by other cyclic loads like temperature effects or earthquake induced stresses and strains.

Considerable effort and resources have been devoted to understanding single processes, which were studied more or less independently. Coupled geohazards have been studied with simplified models resulting in large uncertainties over the respective hazard and risk. In contrast, the project will underwrite an interdisciplinary network of scientists addressing the physical interaction between individual processes in order to develop and verify quantitative models that describe both the preparation and propagation of strong earthquakes (Figure 2) and the interactions of earthquake waves with near surface geological units in a complex alpine environment (Figure 3). Within COGEAR, three interdisciplinary modules exist. The objective and sub-modules are briefly described in the following paragraphs.

1.1. Module 1: Coordination and Data Integration

The purpose of this module is to manage all modules, serve as an interface between them, and provide a common geo-referenced GIS-platform and remote sensing data. A task of this module is a database of observed earthquake effects in the Valais as well as quantification of secondary hazards from possible earthquakes. A new type of database is developed with distributed data repositories. This database type is highly flexible and extensible (not only for new sensors and sensor data, but also for new project partners). This scalable structure is provided by a de-centralised approach in the database schema. Each project partner can maintain his own data (and database) and provide them via well-defined web service interfaces to the database. The sub-tasks are:

a) Overview of earthquakes effects (past and possible future)
b) Database and GIS platform
c) Vulnerability of buildings and risk assessment
d) Hazard scenarios summarizing the results of the entire project

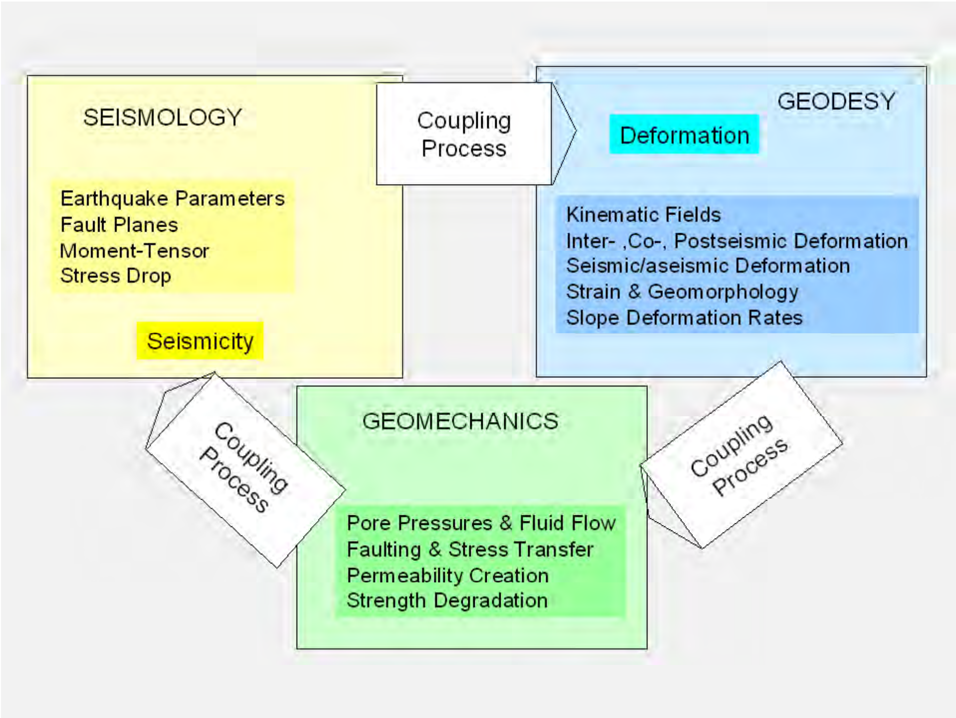

Figure 2 Scheme of coupled systems and interdisciplinary integration of Module 2 of COGEAR: Seismology - Deformation – Geomechanics. Coupling can also work in opposite directions.

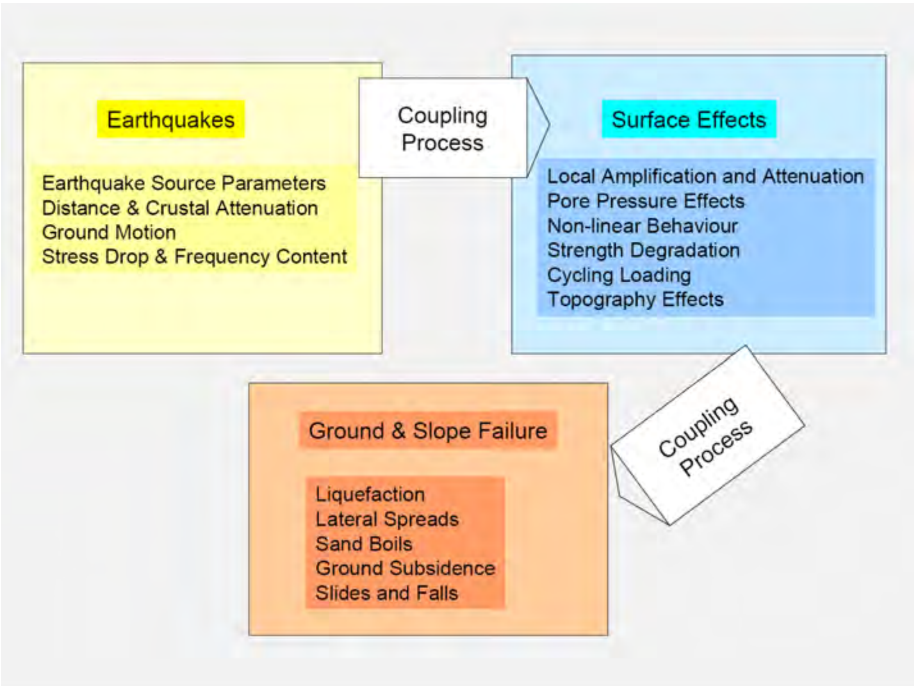

Figure 3 Scheme of coupled systems and interdisciplinary integration of Module 3 of COGEAR: Earthquake – Surface Effects - Ground and Slope Failure (rock, soil and snow).

1.2. Module 2: Earthquake preparation (Figure 2)

Within Module 2 we establish local geodetic and seismic monitoring networks. Such monitoring will detect and quantify inter-seismic strain-rates in the Valais, connect this information with observed faulting styles to understand temporal changes in earthquake activity for forecasting, and observe possible short-term precursors as well as post-seismic motion. A revision of the seismo-tectonic framework of the Valais will be carried out and scaling relations developed to allow for ground motion simulations of potential earthquakes. In module 2, ground motion modeling will focus on the influence of complex source properties and wave propagation in the crust. The sub-tasks are:

a) Seismicity, deformations and active faults
b) Geodetic measurements and kinematic modelling
c) Long-term earthquake hazard assessment and forecasting
d) Short-term earthquake precursors

1.3. Module 3: Complex surface phenomena (Figure 3)

By contrast, Module 3 studies wave propagation phenomena in complex surface structures. Local strong-motion networks and novel geotechnical monitoring systems will be installed. These systems will monitor near-field and complex site effects, related pore pressure effects and non-linear phenomena in liquefiable soils and fractured rocks (Visp and the Matter Valley). Through monitoring, modeling and susceptibility analysis, we will compare how long and short-term seismic loading and cyclic climatic effects (such as snow melt and heavy precipitation) affect slope stability. The monitoring systems will provide data to verify the results of the numerical modeling. The sub-task are:

a) Non-linear soil behavior and liquefaction in alluvial sand deposits
b) Topographic effects and non-linear behavior of rock and soil slopes
c) Earthquakes and snow avalanches

1.4. Monitoring system

COGEAR targets research work with a long-term prospective. The planned monitoring system is the key element (Figure 4). It is focused on the epicentral areas of the 1755 and 1855 earthquakes, including the Rhone river plain at Visp and the Visper and Matter valleys. The following networks and sites are planned:

1) A dense regional network for monitoring crustal deformation, seismicity and possible active faults (entire Valais), including seismic stations in boreholes.
2) Local strong-motion networks for monitoring earthquake ground motion and 3D site-effects at Visp and St. Niklaus;
3) Test sites for studying site effects, non-linear phenomena in liquefiable soils and related pore pressure effects (Visp);
4) Test sites on landslides to study site effects and dynamic loading of landslides in relation to topography, geological disposition, kinematics and (static/dynamic) slope stability (Matter valley);
5) Installations, including electromagnetic and geo-chemical sensors, to monitor possible short-term precursors of earthquakes.
6) Seismic monitoring of buildings in the Visp area.

Such a monitoring system will be innovative for the Swiss scientific community, and will provide data of unique value and quality. We expect that these systems will be operational for many decades, with a high probability that they will monitor the next damaging earthquake in the Valais.

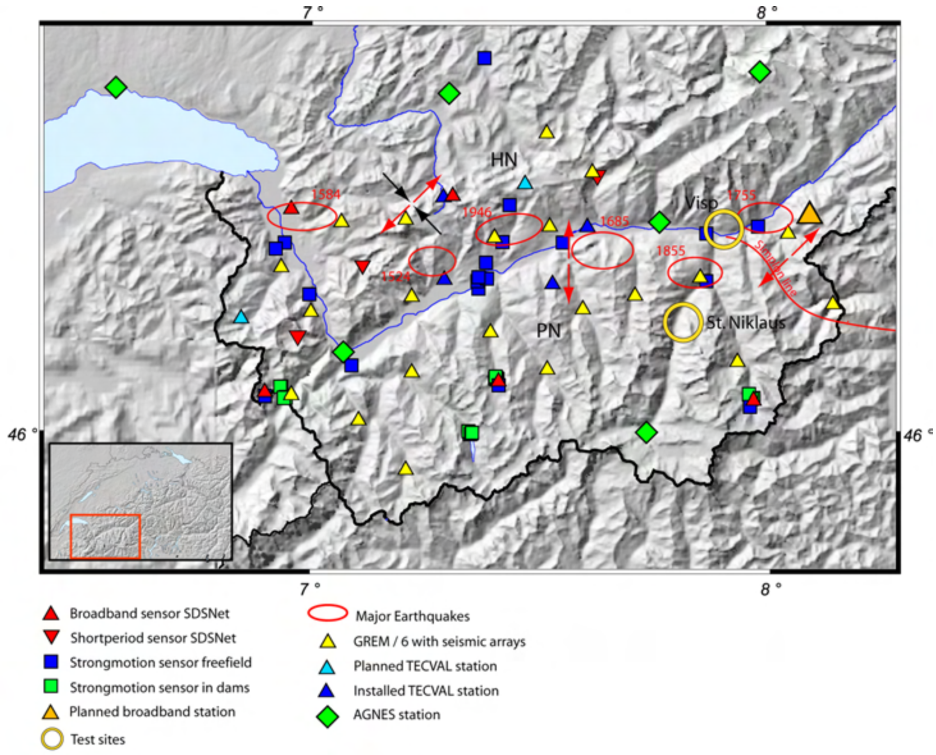

Figure 4 Main stress field, existing and proposed continuous GPS stations and seismic stations in the project area; Test sites of Modules 3a and 3b; proposed network of continuous GPS (GREM) and seismic stations ensuring a high spatial resolution; AGNES: GPS stations operated by the Swiss Federal Office of Topography (Swisstopo); TECVAL: Ongoing project funded by the SNF. HN = Helvetic nappes; PN = Penninic nappes. The positions of the electro-magnetic and geochemical sensors are not yet decided and are not shown.

1.4.1. A dense regional seismic and GPS network

To provide the observational data needed for geodetic and seismological investigations, the density of existing networks in the Valais is improved. A denser network of continuous GPS stations is planned, consisting of 21 stations. Together with the 11 existing ones, the improved network will allow for constraining crustal movement in the project area with a good spatial and temporal resolution (Figure 4). The continuous operation is important to link geodetic strain accumulation with seismic moment release and to enable detection of the low inter-seismic strain-rates expected.

Historically, we have observed strong temporal clustering of seismicity in the Valais; however, we do not know the underlying physical processes nor do we have adequate statistical descriptions for the clustering. To improve our grasp on clustering in an area of moderate seismicity requires observational capacities to monitor real time seismicity well below magnitude 1. Within COGEAR, the location capacity and detection threshold of the seismic network in the Valais will be significantly enhanced.

1.4.2.Local strong-motion networks

Earthquake observations and numerical simulations show that the seismic response of the Rhone valley is dominated by 2D resonance at low frequencies, while edge-generated surface waves and vertically propagating body waves are responsible for significant amplification at higher frequencies (Roten et al., 2008). Locally ground motion can be characterized by large amplitudes and long duration, and within certain frequency bands. In order to quantify the ground motion and its variability, numerical modeling and semi-permanent installations are used to optimize the position of permanent strong motion instruments. The recorded signals are used at the long-term to test numerical models for predicting ground motions of possible future event, and to optimize building-code response spectra for the area.

1.4.3. Test sites for studying site effects, non-linear phenomena in liquefiable soils
A configuration of alternating silty, sandy and gravelly layers can be found in many places in the river plain of the Rhone. In many areas of the Rhone plane, the silty-sandy layer is known to have liquefied during past earthquakes (e.g. Fritsche et al., 2006) (Figure 5). However these areas were not populated in the centuries of the large Valais events. Realistic wave propagation models are needed that include non-linear soil models which can account for both non-linear soil behaviour and accompanying pore pressure changes, and liquefaction. In order to test the models, boreholes instruments are installed including seismic monitoring stations in boreholes, at bedrock and at a depth of about 30 meters where non-linear behavior is anticipated to start, as well as geotechnical equipment to monitor deformations and pressures.

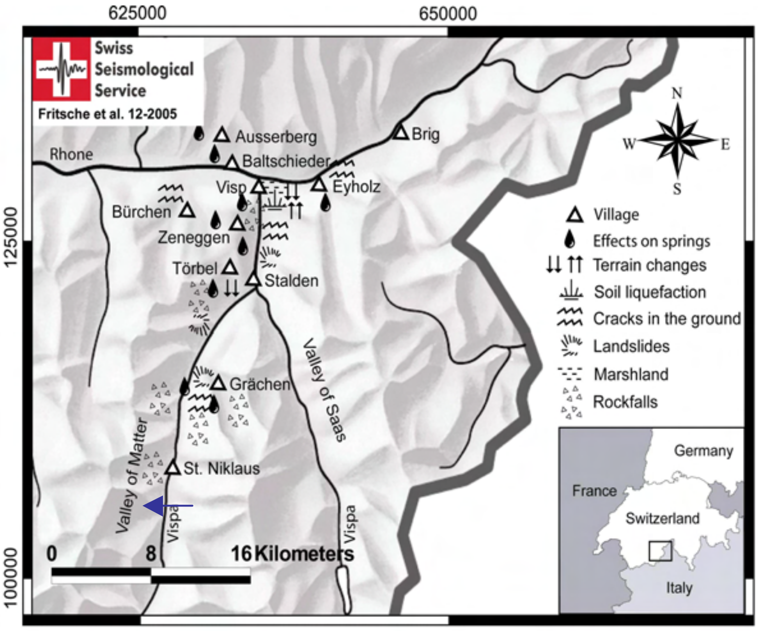

Figure 5 Secondary effects observed in the Valais during the 1855 earthquake (Fritsche et al., 2006).

1.4.4. Seismic monitoring of buildings in the Visp area
As the probability of a damaging event is quite high in the investigated area in the next ten years, long-term instrumentation of a well-selected building provides the opportunity to gain data on its real seismic behaviour under significant deformations. These measures will yield extremely valuable data for calibrating the developed fragility functions. Moreover, soil-structure interaction may also be calibrated on the basis of such data.

2. FIRST RESULTS AND OUTLOOK

The project started in January 2008. During the first months a series of field measurements have been performed in the region of Visp and in the Matter valley (Figure 6). Together with the collected geological information, these measurements will help to develop a local three-dimensional structural model for earthquake scenario modeling. A series of tests with ambient vibration array methods have been performed on the instable rock slope at Randa, and combined active and passive seismic methods have been applied on different geological formations. The main goal is to provide estimates of S-wave velocities and layer thickness of the instable and soft materials, and the bedrock, in order to estimate amplification of the seismic waves together with the ground displacements, the induced stresses and strains, and non-linear behavior. A semi-permanent local seismometer network has been operated during six months. A series of small events have been recorded that will be used to better define the local system of active faults as well as to optimize the selection of sites of the planned future network.

The multi-sensor network is in the planning phase. A major challenge is to find optimum sites for the geo-chemical and the magneto-telluric sensors for studying possible earthquakes precursors due to the high requirements for such installations. The project will progressively open towards other interested partners and there is a strong interest to cooperate with similar initiatives in other areas of the world.

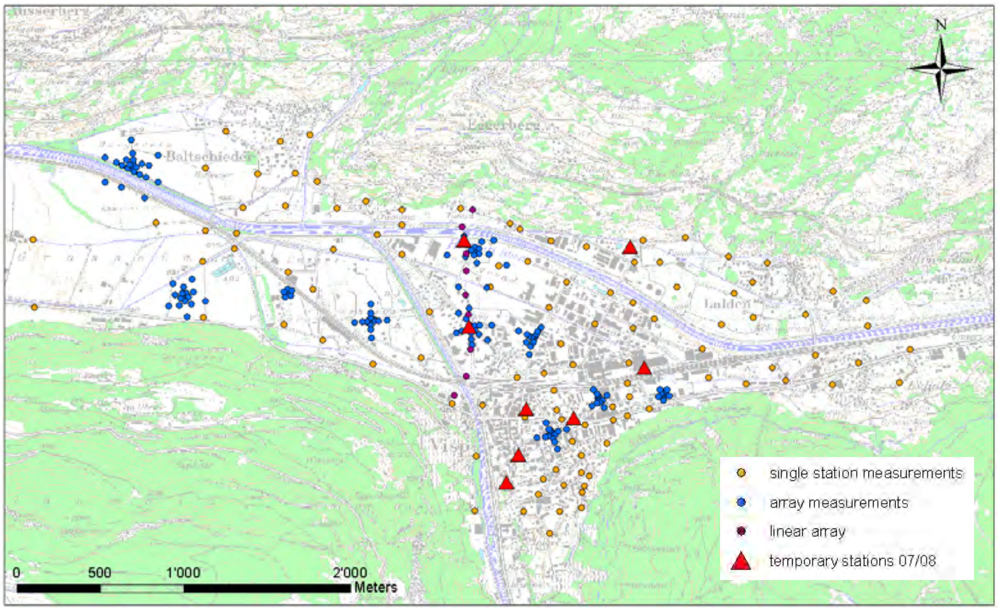

Figure 6 Geophysical measurements in the area of Visp.

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