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Combining amphibious geomorphology with subsurface geophysical and geological data: A neotectonic study at the front of the Alps (Bernese Alps, Switzerland)

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ABSTRACT

In the vicinity of Lake Thun at the front of the Bernese Alps (Switzerland), we performed a multidisciplinary neotectonic study combining onshore and offshore geological data and geophysical measurements in order to identify potentially active fault structures. Paleoseismic reconstructions on the northern margin of the Alps have documented several strong earthquakes with moment magnitudes ≥6 during the Late Quaternary, which have long recurrence intervals of 1,000 to 2,000 years. Such earthquakes are expected to produce surface ruptures. In this light, we investigated the study area located near Lake Thun primarily for on-fault evidence, to date still a shortcoming in Switzerland. We detected several features indicating potential fault activity, such as aligned subaquatic morphological depressions, offset horizons observed in reflection seismic profiles of lake sediments and in ground-penetrating radar images, all delineating a fault trace. Observations of fluvial deposits in a nearby gravel pit in the prolongation of the inferred structure supports these findings. A narrow zone with rotated long axes of pebbles (inclining at ~60°) is clearly distinguishable and crosscuts the original bedding with predominantly horizontal orientation of pebble axes. This zone further shows an apparent 1.1 m offset of oxidized horizons and is therefore considered as a potential fault plane in a normal faulting regime. A dated radiocarbon age of ~11,000 years BP of the gravel deposits hence suggests a younger fault activity during the Holocene. The Einigen Fault Zone (EFZ), proposed on the basis of these observations, is considered as a complex fault system with a combination of dextral strike-slip and normal faulting, as suggested by GPR images. Observations in the gravel pit and radar data independently show that it includes at least two fault strands. However, while five earthquakes with epicentral intensities $I_0 \geq$ VI and numerous smaller seismic events are known within less than 30 km epicentral distance to Lake Thun over the past 400 years, none of these seem to coincide with the location of the EFZ.

1. Introduction

Current probabilistic seismic hazard assessments in Switzerland are mainly based on historically documented and instrumentally recorded earthquakes (Wiemer et al., 2009). The earthquake catalogue of Switzerland (e.g. ECOS-09, Fäh et al., 2011) builds such a basis for the hazard assessment, covering a time span of roughly 1,000 years with ~20,000 events (including eight historic earthquakes with moment magnitudes of 5.7–6.2 along the Swiss Alps). However, a compilation of paleoseismic data based mainly on earthquake-triggered mass movements in several lakes along the northern margin of the Central Swiss Alps shows that strong earthquakes, with local intensities I > VI - VII, occur on fairly regular recurrence periods of ~1,000–2,000 years (Strasser et al., 2013). The strongest of these seismic events have reached reconstructed moment magnitudes of 6.2–6.7 (Strasser et al., 2006, 2013). These recurrence intervals are beyond the

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time span of the earthquake catalogue of Switzerland (ECOS). To quantify the hazard of future earthquakes and their associated damage, in particular that of rare and strong events, a thorough analysis of geological evidence for past events is essential. This study aims to find such evidence related to recently active tectonic fault structures in a terrestrial and lacustrine setting in the vicinity of Lake Thun (Switzerland). Apart from its tectonic setting with strong contrasts from the north to the south of Lake Thun and several geological and morphological indications suggesting neotectonic activity, the area was exposed to five moderate earthquakes in the last three centuries (moment magnitudes 4.7–5.2). These characteristics make the area likely to have experienced even stronger earthquakes in the past, so that it is ideal to investigate recent deformation caused by neotectonics.

Earthquake-triggered subaquatic mass movements, turbidites and small-scale in situ deformation features (e.g. liquefaction structures, microfaults, mushroom-like intrusions, etc.) in lake sediments are considered as significant off-fault paleoseismic evidence and have been used to document prehistoric earthquakes throughout the Holocene and Late Pleistocene period, reflecting recent tectonic activity in the Alpine region (Monecke et al., 2004; Schnellmann et al., 2006; Strasser et al., 2011). The strongest of these events (moment magnitude $M_W > 6$) are expected to produce surface ruptures due to the size and displacement of the slipping surface (Wells and Coppersmith, 1994; Stirling et al., 2002). Considering the present off-fault paleoseismic evidence in the Alpine region, primary on-fault evidence should be present as well. However, seismogenic fault structures with clear surface ruptures are scarcely found in Switzerland (Madritsch et al., 2010). To date, only few on-fault studies identified active fault structures and neotectonic features in Switzerland in order to improve our understanding of the hazard imposed by strong earthquakes.

Maurer and Deichmann (1995) showed in their investigation of two earthquake clusters in the western Swiss Alps that presently active fault planes in the Helvetic nappes belong to the reactivation of Riedel shears of a large-scale dextral strike-slip structure (Pavoni, 1980). Ustaszewski and Pfiffner (2008) investigated neotectonic faulting in the western and central Swiss Alps. They identified two tectonic faults based on mapping lineaments on aerial photographs and subsequent field studies characterizing the structures using displaced post-glacial landforms or sedimentary infills. We also follow their definition of the time frame concerning 'neotectonics' that includes all fault activity since the Last Glacial Maximum (LGM) 23 ka ago (Wirsig et al., 2016, and references therein). A similar approach was chosen in the eastern Swiss Alps by Persaud and Pfiffner (2004), revealing the difficulty of assigning observed lineaments and active faults to its physical source, which can be of tectonic nature, surface uplift due to post-glacial rebound or a combination of the two. Meghraoui et al. (2001) identified an active normal fault near the eastern edge of the Upper Rheingraben based on geomorphological and geophysical analysis, supplemented by six trenches at two different sites, and they attribute two prehistoric events as well as the 1356 Basel earthquake (Mw = 6.7, ECOS) to this fault. Ustaszewski et al. (2007) documented an active fault located in the western Swiss Alps. The fault was formed during Alpine nappe emplacement and cataclasite formation as well as numerous periods of fluid flow dated between 0.5 Ma and 2.5 Ma derived from combined $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ ratios. They observed several stages of reactivation with its most recent activity in Late Holocene times indicated by displaced and OSL dated late-glacial loess and slope-wash deposits. For a hydrothermally active strike-slip fault at Grimsel pass, Belgrano et al. (2016) suggest a close interplay between recent faulting, seismic activity and fluid flux of meteoric waters down to depths of at least 4–5 km. Here a complex geometric system consisting of major fault zones and associated fault linkages in Riedel orientations accommodates young strike-slip movements. In an instrumentally based approach for the identification of an active fault structure, Kastrup et al. (2007) related the temporal clustering of a series of seismic events in the vicinity of Fribourg, in the Molasse Basin of western Switzerland, to a large-scale, N-S striking fault. They concluded that the N-S striking epicenter alignment, similarity in deformational style and orientation of faults mapped from seismic reflection data around Fribourg fit well with the fault characteristics of the crystalline basement and its overlying Molasse sediments in the larger region. Using cross-correlation based relocation of epicenters, seismic reflection data and magnetic data, they consider the Fribourg fault as being active. In France, de La Taille et al. (2015) recognized Riedel-like fault structures in Lake Le Bourget affecting Holocene sediments and lake-floor morphology. They interpreted the structures as imprints of two known strike-slip faults crossing the lake basin.

Irrespective of these examples, the prevalent lack of on-fault evidence is attributed primarily to high erosion rates in the Alpine region and to pervasive anthropogenic landscape modification, as suggested by Ustaszewski et al. (2007). They note that the scarceness of precisely dateable Quaternary deposits imposes an additional challenge when it comes to the exact timing of fault movements. Furthermore, temporal and spatial clustering of seismic events leads to variable recurrence intervals, sometimes accompanied by long periods of quiescence, which complicates the recognition of mid- to long-term occurrence patterns (Michetti et al., 2005).

This study presents a potentially active fault structure near Einigen on the southern shore of Lake Thun at the front of the Bernese Alps. Our multidisciplinary approach combines amphibious geomorphology including terrestrial and subaquatic topography data with subsurface geological and geophysical data. An existing digital elevation model derived from airborne laser scanning (swissALTI3D, swisstopo) and a newly acquired high-resolution bathymetric data set of Lake Thun are combined in an effort to identify topographic features potentially associated with fault traces. Including the lake floor has the advantage that the diffusive impact of erosive processes on the landscape is much smaller, as underwater processes occur at rates that are much slower than on land (Sturm and Matter, 1972, 1978). In a second step, we complement the geomorphologic data with subsurface data using ground-penetrating radar (GPR) on land and seismic reflection data in the lake. In addition, 'trench-style' outcrops in a gravel pit are used to further refine and quantify a potential fault zone through mapping displaced layers and rotated clasts. The combination of these various data sets provides a series of evidence pointing towards a recently active fault and thus supplements the thin catalog of known Quaternary fault structures supported by on-fault evidence. These findings increase the awareness for seismic hazards in the Bernese Alps and the approach builds a possible recipe to discover other potentially active fault traces at the forefront of the Swiss Alps.

2. Geologic and seismotectonic setting

Perialpine Lake Thun (Fig. 1) is situated in the upper Aare valley between Interlaken and Bern, and is located at the northern front of the Alpine nappes. The overdeepened basin of Lake Thun is surrounded by the Penninic and Helvetic thrust nappes and the Subalpine Molasse. The basin is elongated orthogonal to the general strike direction of the Alpine front