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ORIGINAL ARTICLE

A database of potential paleoseismic evidence in Switzerland

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Abstract Paleoseismological evidence is indispensable for the identification of large prehistoric earthquakes and the extension of the temporal coverage of historical and instrumental earthquake catalogues. In the geological record, diverse traces of past earthquakes are found. This study presents a database of potential primary and secondary evidence for seismic activity in the past 20,000 years in Switzerland. The database includes data from sedimentological, archaeological, speleological and geomorphological research. This unique dataset allows identifying periods during which the geologic record reveals enhanced occurrence of evidence that are further discussed as potentially earthquake-triggered. For the most recent 700 years, an increased occurrence of evidence features was found. This clustering is an effect of the historical earthquakes. Furthermore, periods with enhanced occurrence are identified at six phases during the past 20,000 years. Even though dating uncertainties for the geological record are large (e.g. ^{14}C calibration range) and an unequivocal attribution of earthquakes as trigger

Highlights
- This study presents a database of potential paleoseismic evidence for Switzerland
- Enhanced occurrence of evidence during 6 phases over the past 20,000 years
- Coeval evidence might present an indicator for paleo-earthquakes

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mechanism for secondary evidence is not possible, the database reflects the natural-hazard potential of a region and represents valuable information for seismic hazard assessment. Furthermore, despite the uncertainty regarding the definition of the trigger mechanism, we propose that the database can be used to validate and improve earthquake-hazard models.

Keywords Paleoseismology · Paleoseismological database · Earthquakes · Sublacustrine mass movements · Rockfalls · Soft sediment deformation structures · Tsunami · Liquefaction

1 Introduction

Paleoseismology is the study of magnitude, location and size of prehistoric earthquakes and their secondary effects (McCalpin 2009). Such information are required to validate seismic hazard models and to potentially reduce their uncertainties for long return periods. These data are especially valuable in regions with low deformation rates (such as the Alps) where the return periods of large earthquakes may exceed the period covered by historical and instrumental datasets, and where the knowledge of active faults is limited. Therefore, for prehistoric periods, where written and instrumental records are inexistent, paleoseismological and archeoseismic studies are needed. Earthquakes produce primary and secondary environmental on- and off-fault effects. Primary evidence is created by tectonic deformation and is characterised by the surface expression of the seismogenic tectonic source (surface faulting, uplift and subsidence). Seismogenic fault structures may provide information on magnitude, location, recurrence and size of past prehistoric earthquakes. However in regions, where these structures are rare (either because of glacial overprinting, human activity or due to earthquake size), secondary seismic evidence as response to ground motion can be used to trace past earthquakes (McCalpin 2009). Secondary evidence can be located on- or off-fault, such as the following: mass movements (e.g. Becker and Davenport 2003; Becker et al. 2002; Fritsche et al. 2012; Goldfinger 2009; Monecke et al. 2004; Schnellmann et al. 2002; Van Daele et al. 2015), tsunami deposits (e.g. Kempf et al. 2017), sediment liquefaction and soft sediment deformation (e.g. Monecke et al. 2004; Rodríguez-Pascua et al. 2000) and broken speleothems in caves (e.g. Becker et al. 2012; Gilli et al. 1999). A characteristic of these evidences is that they form suddenly relative to geological timescales, during or just after an earthquake (McCalpin 2009). These evidences are sometimes preserved in the geological record (e.g. lake sediments, caves, geomorphological features (e.g. displacement at the surface, slide scars)) and can often be dated (e.g. radiocarbon dating, exposure dating, stratigraphy). Thus, the geological record may represent an archive for prehistoric earthquakes (pre 1000 AD), especially in areas where fault information is missing.

However, earthquakes are not the only possible cause of geological features that might be interpreted as secondary effects, and the unequivocal identification of a seismic trigger remains a challenge. Potential secondary earthquake effects such as mass movements can also have a non-seismic cause such as climatic effects (heavy rainfalls, storms and temperature changes), human activity or spontaneous slipping due to overloading. Thus, extensive studies are needed to exclude any non-seismic effects for a potential seismically induced geomorphological or sedimentological feature observed in the geological record. In this regard, a way forward to identify potential paleoearthquakes is to use analogy studies from lakes. It is assumed that a strong indicator for a seismic trigger is the occurrence of coeval traces of evidence (deformation, mass movements) in one or several basins or in several lakes demonstrating a trigger that affects a larger spatial extent (Kremer et al. 2017; Monecke et al. 2006). The probability for a seismic trigger is in such cases much higher as, for instance, in the case of a single slide related to a collapsing delta that could also be caused by a non-seismic trigger (Corella et al. 2016; Girardclos et al. 2007; Kremer et al. 2012).

The secondary seismic evidence can give local information on earthquake intensity (Michetti et al. 2007 or, e.g. for soft sediment deformation structures (SSDS) in Rodríguez-Pascua et al. 2000). Having coeval seismic evidence on a larger regional extent, scenarios of past earthquakes can be reconstructed (Obermeier 1996) as it has been also shown using sublacustrine landslides in Swiss lakes (Kremer et al. 2017; Strasser et al. 2006) and in Chilean fjords (Vanneste et al. 2018).

In Switzerland, during the last years, many studies from different research fields have investigated prehistorical and historical earthquakes revealed by earthquake-related traces in sediments and different geological environments in Switzerland. Most of the data that were gathered during these investigations was published in research papers, as well as in BSc, MSc or PhD theses, and has already been interpreted regarding their potential as evidence of prehistoric earthquakes. In many other cases, however, findings with a potential implication for paleoseismological research are presented as a side product of investigations with other primary study objectives. The studies also vary with respect to the interpretations of the dating methods and age models. Therefore, a merging of the results into a consistent overall image is a required first step for a common systematic interpretation. Therefore, a database documenting dated potential environmental effects of potential earthquakes on a larger scale in a homogeneous way is mandatory. A similar database has been established for Germany and adjacent regions (Hürtgen 2017). However, since information on active faults is rare in Switzerland, the majority of data represents potential secondary environmental effects of earthquakes. We use the term ‘potential’, as each of this effect considered individually could be also triggered by another cause, as already mentioned above. Therefore, we first create a database with all potential traces of past earthquakes and discuss the paleoseismological framework in a second phase. With such a database, we are searching in a second phase clusters of evidence on a temporal and regional scale. This leaves also space for re-interpretation of the evidence. In addition to the potential paleoseismic framework, such a database will also highlight the overall natural hazard potential of the studied areas.

The experience from evaluating historical data (Fäh et al. 2011) during the compilation of the earthquake catalogue of Switzerland (ECOS-09) shows that a well-organised and homogeneous data archive is an essential base for the systematic interpretation of earthquakes as well as for further research (Gisler and Fäh 2011; Schwarz-Zanetti and Fäh 2011). The goal of our compiled information on natural hazard is therefore to get an overview of all existing data that could represent traces of past earthquakes coming from limnogeology, geomorphology, archaeology and speleology and to collect these data in a single common database. In this contribution, we present (1) the approach used to build the database, (2) the current status and (3) first results and interpretations.

2 Geological and seismic setting

The seismicity in Switzerland is considered as moderate, with 10–15 events per year of magnitude Mw > 2.5 (Wiemer et al. 2016) during the past decades. Small to moderate earthquakes are mainly located within the upper 15 km of the crust (Deichmann et al. 2012; Diehl et al. 2015). In contrast to the instrumental dataset, a number of stronger earthquakes is reported from historical records, with 10 earthquakes of magnitude Mw > 5.5 (Fig. 2; Fäh et al. 2011; Gisler and Fäh 2011; Schwarz-Zanetti and Fäh 2011) since the thirteenth century AD. Both instrumental and historical datasets show that the regions with the highest seismicity are the Rhone Valley in the Valais and the Rhine Graben (Basel region). Although numerous faults are identified (Fig.1), the observed seismicity does not correlate significantly with the fault density and the knowledge about presently active faults is limited. This might be caused by the location uncertainty of the historical events. Moreover, the knowledge of deformation rates on these faults is limited (Wiemer et al. 2009). This might suggest either that the current strain is mainly aseismic or that the cumulated seismic moment is too low to produce surface rupture (Ustaszewski and Pfiffner 2008).

3 Database

3.1 Definitions

In this study, we use the term ‘prehistoric’ as the time before 1000 AD that marks in Switzerland the beginning of the available documentation of natural phenomena (Gisler et al. 2007). Before, only a few documents exist that are mentioning earthquakes back to 250 AD (Fäh et al. 2011; Gisler et al. 2007).

The term ‘evidence’ refers to any trace/feature in the geological and geomorphologic record that can be associated to a sudden formation that could potentially have been triggered by an earthquake. The ‘hint’ represents raw observation/data that leads to the interpretation of the evidence. In some cases, several evidences are interpreted to have occurred simultaneously or coevally through the same trigger. Figure 2 shows examples on how the nomenclature is used.

3.2 Database structure

The database considers all tectonic, geomorphological, sedimentological or archaeological features, showing instantaneous deformation of the surface or sediments and that can potentially be interpreted as a trace of an

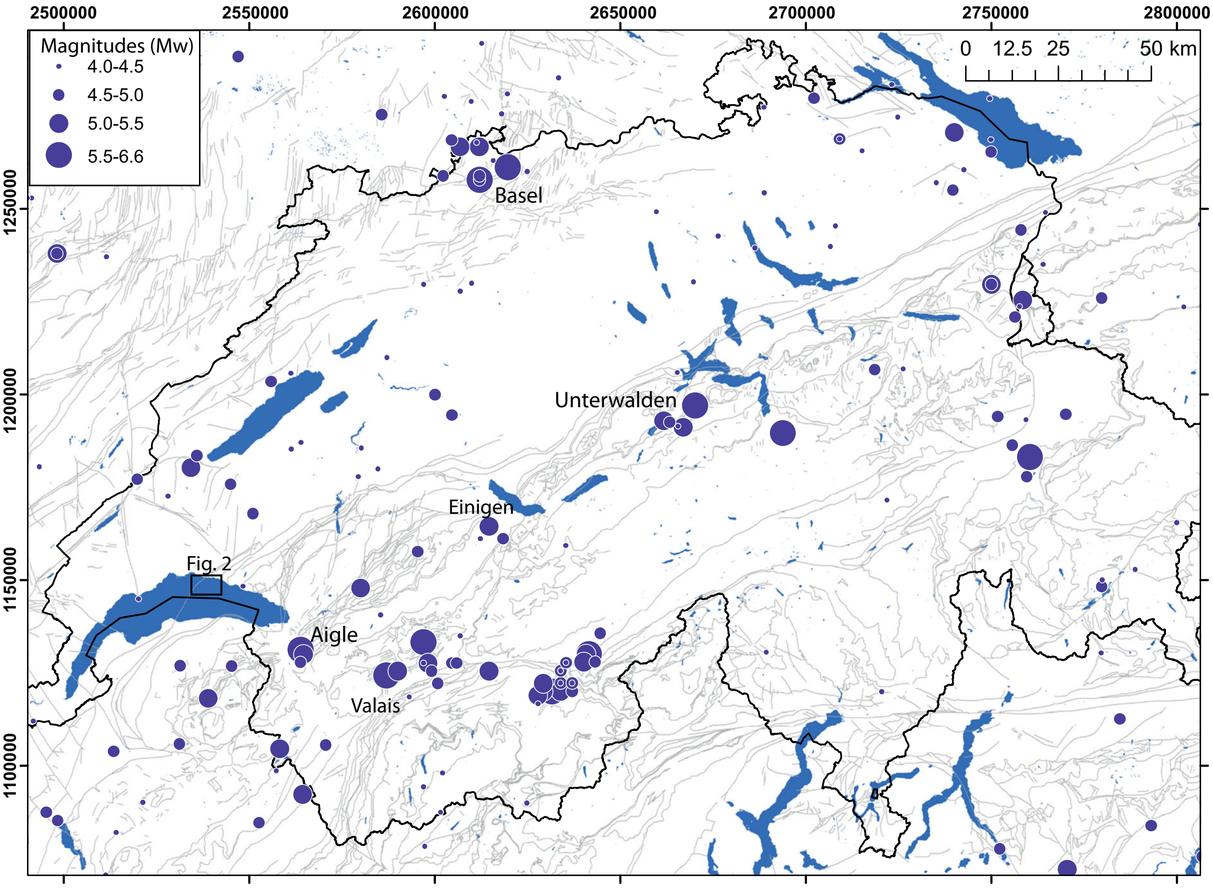


Fig. 1 Fault dataset from the tectonic map of Switzerland (1:500,000 from Swiss Federal Office of Topography, Wabern, Switzerland) and the instrumental and historical seismicity showing the location of earthquakes with Magnitude Mw > 4.0 (ECOS-09; Fäh et al. 2011). The names written on the map are referring to locations mentioned in this work

earthquake. In this database, primary and secondary evidence that has been published in the literature or unpublished reports, and bachelor, master and PhD theses, is listed. It is regionally limited to the area of Switzerland and neighbouring regions. Most of the data result from reflection seismic surveys and sediment coring in lakes, others were obtained through geomorphological studies, trenching, archaeological excavations and speleology.

The primary on-fault evidence features available in the database are features due to fault ruptures such as colluvial wedges, strata offsets, flexure and warping. The secondary evidence features are: sublacustrine mass movements (recognised based on chaotic to transparent facies in reflection seismic profiles and as mass flow, slump and turbidite deposits, or duplexing and foldings in the sediment cores; Fig. 2), sublacustrine soft-sediment deformation structures in sediment cores (microfaults, disturbed varve lamination), terrestrial mass movements (rockfalls, rock avalanches, rock slides), destruction in caves (broken speleothems, rockfall blocks), as well as wave deposits considered as a consequence of sublacustrine mass movements (Table 1). Evidence features that have been interpreted through archaeological discovery of damaged buildings/constructions are also considered (Table 1). The list of hints leading to the interpretation of the evidence is documented in the original studies and has been reported in the database (hint table, Fig. 3). In this database, we do not re-interpret the evidence, but only collect the data necessary to characterise, date and locate them. The list of evidence features constitutes the main table of this database.

The evidence is characterised by a number (unique identification), the local description (referring to the locality used in the original publication), a location

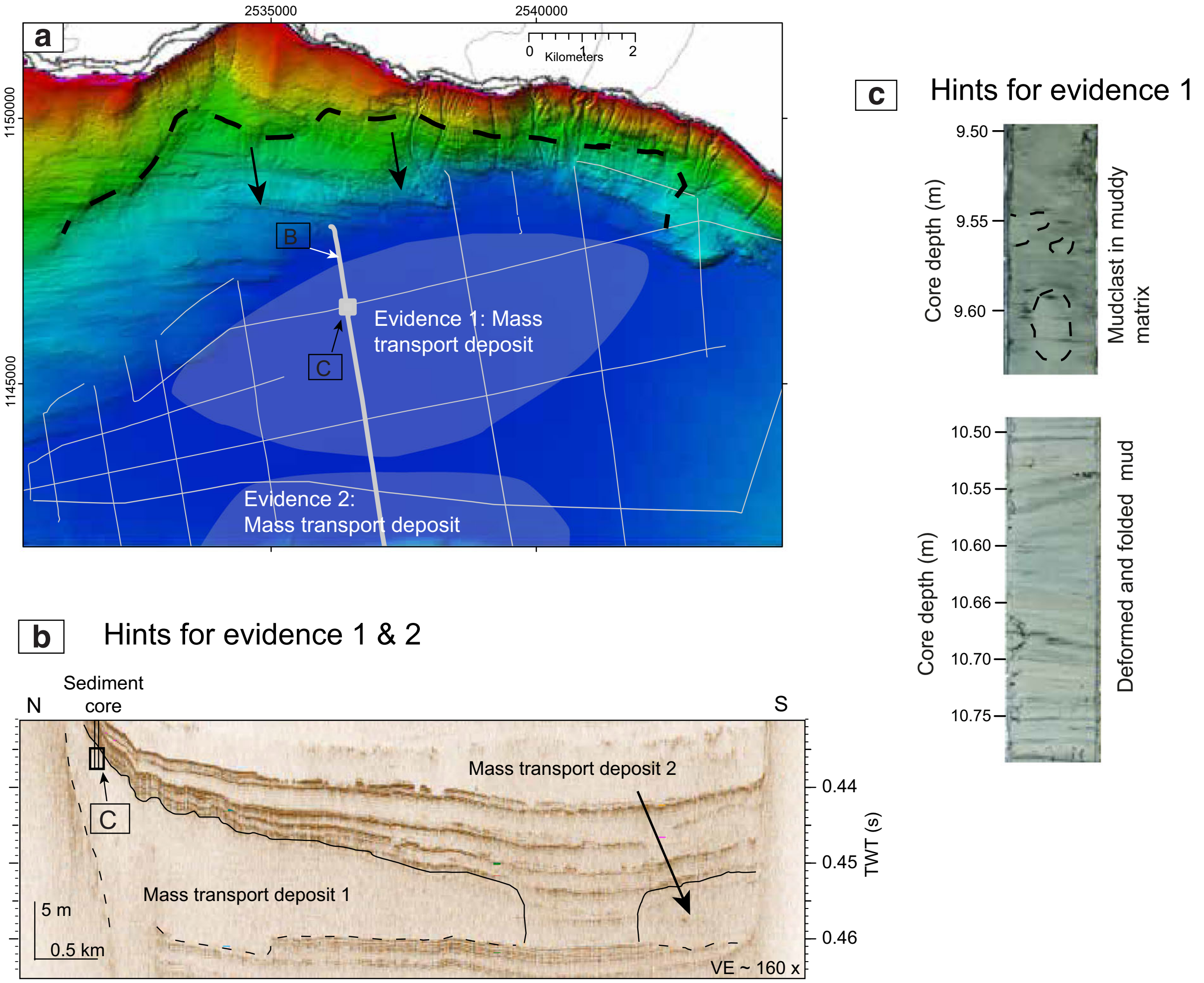


Fig. 2 This figure visualises the nomenclature used in this study. As an example, two mass movement deposits (evidence 1 and 2) originating from the northern and southern slope of Lake Geneva are shown on the map (**a**) (for the location, see Fig. 1). The hints are mass transport deposit facies in reflection seismic profiles (**b**) and the sedimentological features in the sediment core such as mudclast in muddy matrix and deformed and folded mud (**c**). The location of profile (b) is shown with a white bold line and the location of the sediment core is marked with a white square on the map (**a**)

identification number, the original name of the evidence (from the publication), the new name for this study (to have a homogeneous nomenclature), the feature type, investigation type, timing (minimum and maximum age in calibrated years before present; cal year BP), quality and method of age determination, the source (publication or reference) and the location (*x* and *y* coordinates in the Swiss grid LV95). In the case of trenches, geometrical attributes are added to the table, such as the length of the trench and the vertical displacement if available. In the case of evidence features where the surface extent is known (mostly mass movements), the affected area (mainly deposit) interpreted in the publications is represented by an ellipse (major and minor axis and azimuth) for a simplified approximation of the size (Fig. 3), as for most cases, the extents are not available in a georeferenced digital form.

In addition to the main table, several supplementary tables exist that specify the feature type, investigation methods, the dating methods and quality, hints and references or source. The hint table groups all published observations (such as sedimentary features of mass movements in sediment cores, information from trenching, etc.) that led to the interpretation of the evidence features. The structure of the database is summarised in Fig. 4.

In the database, all dated and undated evidence are considered. However, a good age determination is crucial

Table 1 List of references. Some of these publications already represent compilations of evidence

Type of evidence	References
Primary evidence	
Fault rupture	Ferry et al. 2005, Meghroui et al. 2001, Fabbri et al. 2017
Secondary evidence	
Sublacustrine mass movements	Bellwald 2012; Blass et al. 2005; Brönnimann 2006; Bussmann and Anselmetti 2010; Fanetti et al. 2008; Glur et al. 2015; Grischott 2010; Hilbe and Anselmetti 2014; Hofmann 2015; Knapp et al. 2018; Kremer et al. 2015; Kremer et al. 2014; Kremer et al. 2012; Kremer et al. 2017; Landtwing 2009; Lauterbach et al. 2012; Monecke et al. 2006; Müller 2007; Reusch et al. 2016; Schnellmann et al. 2006; Schönbächler 2012; Simonneau et al. 2013; Stalder 2011; Strasser et al. 2006; Strasser et al. 2013; Wirth 2013; Wirth et al. 2011; Wohlwend 2010; Zimmermann 2008
Sublacustrine soft sediment deformation structures	Becker et al. 2002; Deplazes et al. 2007; Glur et al. 2015; Monecke et al. 2006; Wirth 2013
Subaerial mass movements	Becker and Davenport 2003; Deplazes et al. 2007; Grämiger et al. 2016; Knapp et al. 2018; Köpfli et al. 2018; Schnellmann et al. 2006; Poschinger 2005; Poschinger 2011; Tinner et al. 2005
Destruction in stalactite caves	Becker et al. 2012
Damages in archeology	Schatzmann 2013
Waves	Garcia and Petit 2009 ; Curdy et al. 1992; Curdy et al. 1995; Schwab 1992
Subsurface sediment mobilization	Reusch et al. 2016

for the identification of potential paleoearthquakes. For a dated evidence, a dating quality has been defined. The quality of the age is considered either as high, medium low, not reliable or nonexisting/unknown. The quality of the age is considered as high if based on dated samples (e.g. ^{14}C, exposure dating). However, if the age is determined through extrapolation, e.g. as it is the case for the base section of some lake-sediment cores, then the age quality is considered as low. If dated samples exist but the sedimentological sequences show disturbances (as it can be the case in lakes, such as Lake Engstlen; Brönnimann 2006; Wirth 2013), the quality is considered as medium. The age model is considered as not reliable if based on random assumptions, such as sedimentation rates without having supporting dating data. ^{14}C ages were re-calibrated with the most recent Intcal13 calibration curve of Reimer et al. (2013) and added to the database (Kremer et al. 2017). The raw data are also provided in a separate table and allows re-interpretation and re-calibration of the ages (Fig. 4).

In sublacustrine environments, rockfall deposits and their consequences (evolved mass flows for example) are identified (e.g. Lake Lucerne, Bürgenstock Rockfall in Schnellmann et al. 2006; Lake Walen, 1946 Quinten Rockfall). These deposits can be interpreted as rockfall deposits based on seismic reflection and sediment core data in combination with geomorphological features of the digital elevation maps. In the database, we decided to consider these evidence features as rockfall, when it is explicitly mentioned in the source. Another point that needs to be mentioned is that a megaturbidite that is mapped out in the published dataset and interpreted as the distal deposit of another already mentioned evidence is not considered in the database, as it would double the evidence. However, we are mentioning the occurrence of associated megaturbidites in the comment field.

If an evidence is analysed in different studies by different methods (e.g. different dating methods such as radiocarbon dating or exposure dating), both studies are mentioned in the database with a reference to each other (e.g. for the Oeschinen rockslide; Knapp et al. 2018; Köpfli et al. 2018).

Historical reports on geological evidence (rockfalls, tsunamis, etc.) are not yet included but will be added in the future to the database. A considerable set of historical information on geological evidence is recorded in the database underlying the earthquake catalogue of Switzerland (ECOS-09; e.g. Fritsche et al. 2012; Gisler and Fäh 2011; Schwarz-Zanetti and Fäh 2011). However, they are presently not stored in a readily available homogenised form. It is planned to revise the data structure of this repository to allow the extraction of a homogenised dataset. Then, the historical information will be added as a supplementary table to the paleoseismic database. Hence, the two databases can be coupled for future studies to combine all available information documented in historical as well as in prehistorical times.

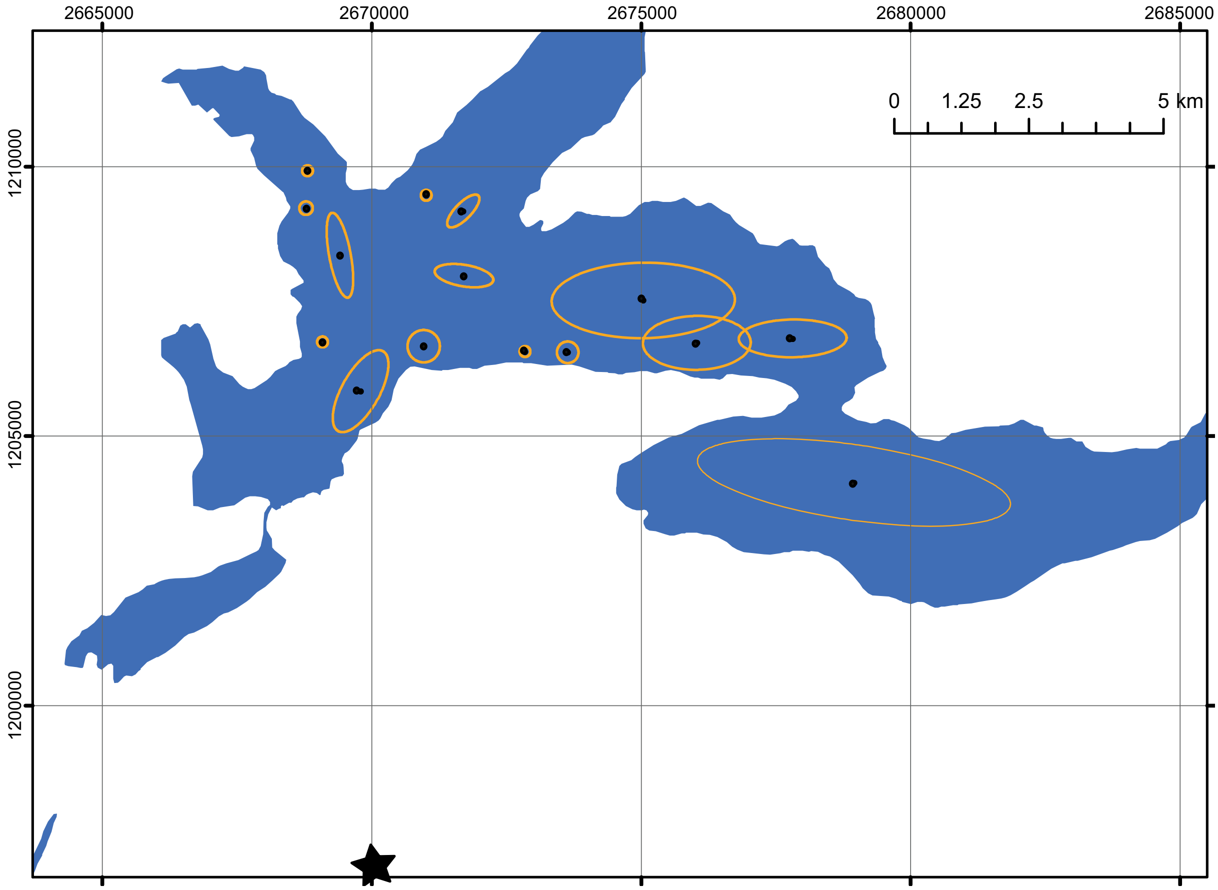


Fig. 3 Sublacustrine mass movement deposits related to the 1601 AD Unterwalden earthquake (epicentre is shown by a star). Ellipses approximate the extent of each individual deposit mapped out with reflection seismic grids (Schnellmann et al. 2002; Hilbe and Anselmetti 2014). The black points represent the centre of the deposit (taken as coordinates of the geo-event in the database)

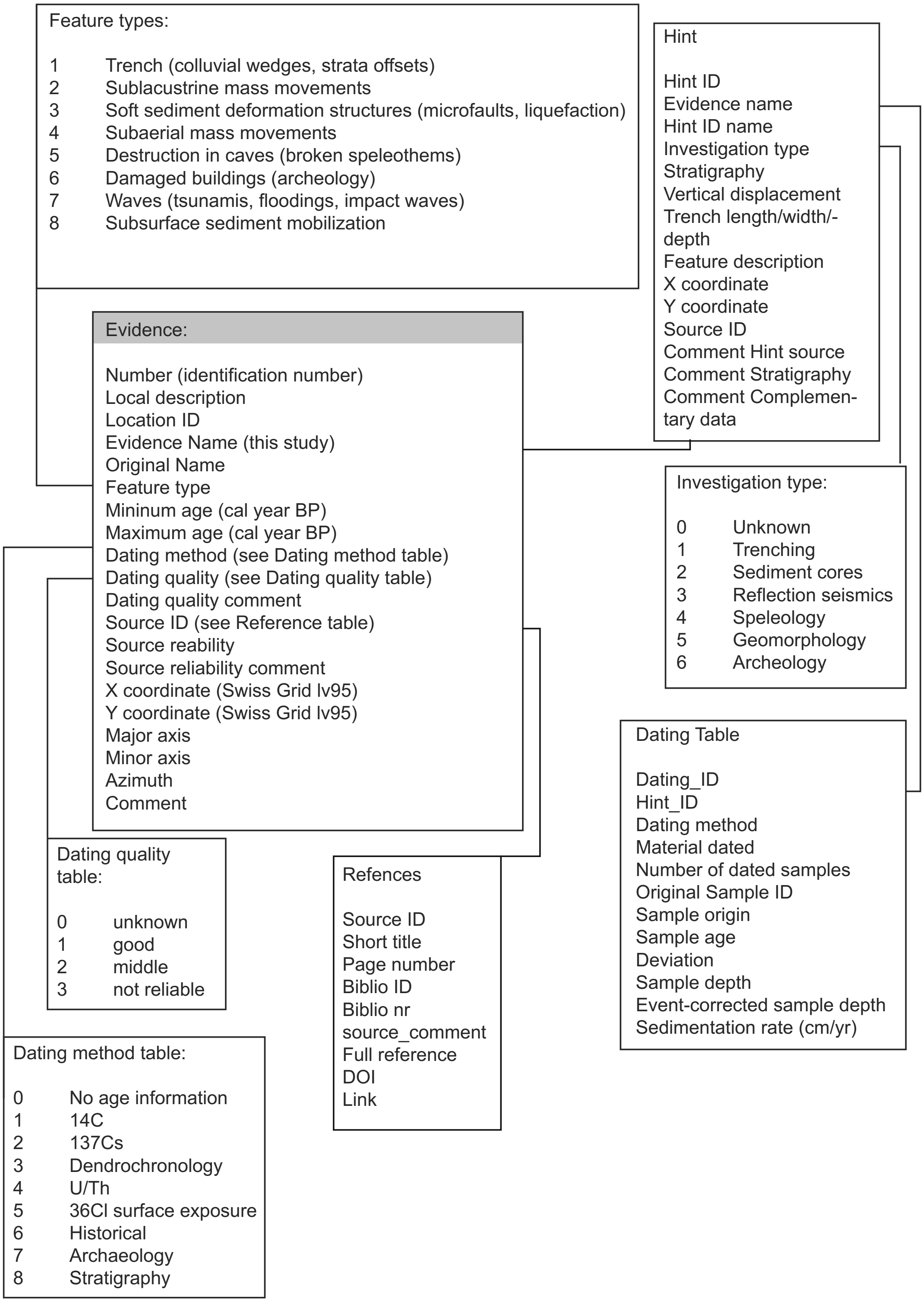
It is anticipated that the status of the database will be updated with new studies and results becoming available. In a similar way, if the evidence is re-interpreted, a comment will be added and the old version will also be kept in a separate table. The database will be available on request at paleoseismology@sed.ethz.ch. The intention is to make the database available after a feedback phase of the community, and once the historical information is included.

4 Results

In the current compiled database, around 680 evidence features are available at 65 locations covering the time window of the past 500,000 years. Since a large part of the dataset consists of evidence younger than 20,000 years and since very old evidence features (destructions in cave) have a large dating uncertainty, we only consider the time span < 20,000 years in the following. The spatial distribution of evidence is shown in Fig. 5 while the temporal distribution of evidence is represented in Fig. 6. The database reflects the current data status available from literature.

4.1 Primary evidence: trenches

Evidence features from trenches are primary on-fault evidence and represent the most reliable indicator for the occurrence of paleoearthquakes. Colluvial wedges on the Basel-Reinach fault have been analysed on several trenches (Meghraoui et al. 2001; Ferry et al. 2005). Five events over the past 15,000 years have been related to the activity of the Basel-Reinach fault in the Upper Rheingraben (Ferry et al. 2005).



Feature types:

1	Trench (colluvial wedges, strata offsets)
2	Sublacustrine mass movements
3	Soft sediment deformation structures (microfaults, liquefaction)
4	Subaerial mass movements
5	Destruction in caves (broken speleothems)
6	Damaged buildings (archeology)
7	Waves (tsunamis, floodings, impact waves)
8	Subsurface sediment mobilization

Hint

Hint ID
Evidence name
Hint ID name
Investigation type
Stratigraphy
Vertical displacement
Trench length/width/-depth
Feature description
X coordinate
Y coordinate
Source ID
Comment Hint source
Comment Stratigraphy
Comment Complementary data

Evidence:

Number (identification number)
Local description
Location ID
Evidence Name (this study)
Original Name
Feature type
Mininum age (cal year BP)
Maximum age (cal year BP)
Dating method (see Dating method table)
Dating quality (see Dating quality table)
Dating quality comment
Source ID (see Reference table)
Source reability
Source reliability comment
X coordinate (Swiss Grid lv95)
Y coordinate (Swiss Grid lv95)
Major axis
Minor axis
Azimuth
Comment

Investigation type:

0	Unknown
1	Trenching
2	Sediment cores
3	Reflection seismics
4	Speleology
5	Geomorphology
6	Archeology

Dating Table

Dating_ID
Hint_ID
Dating method
Material dated
Number of dated samples
Original Sample ID
Sample origin
Sample age
Deviation
Sample depth
Event-corrected sample depth
Sedimentation rate (cm/yr)

Dating quality table:

0	unknown
1	good
2	middle
3	not reliable

Refences

Source ID
Short title
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Full reference
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Dating method table:

0	No age information
1	14C
2	137Cs
3	Dendrochronology
4	U/Th
5	36Cl surface exposure
6	Historical
7	Archaeology
8	Stratigraphy

Fig. 4 Database structure with the main table 'Evidence' and the associated supplementary tables

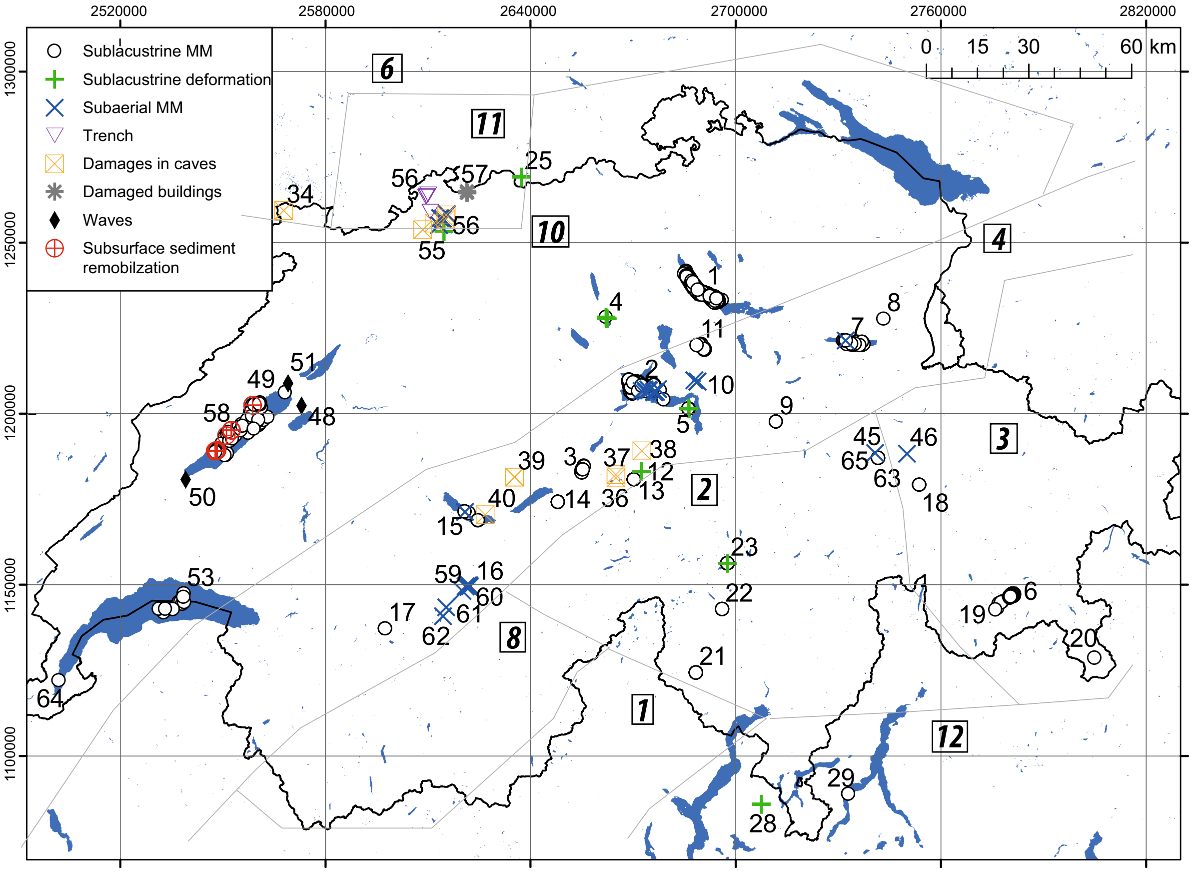
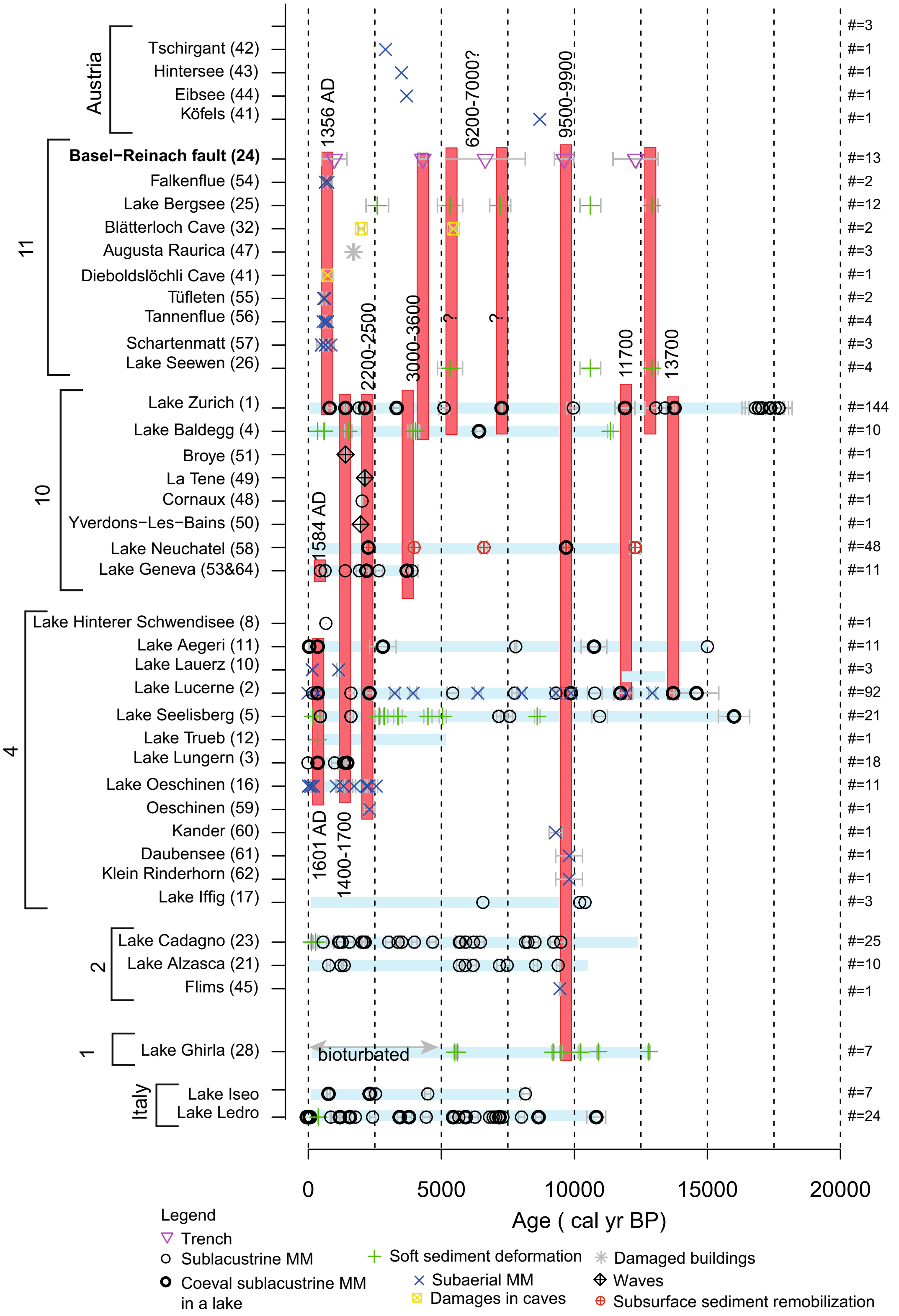


Fig. 5 The spatial distribution of evidence that has been compiled in the database. The numbers refer to the location identification numbers that are also used in Fig. 6. The map is divided in zones that refer to the tectonic zones presented in Fig. 6 (Wiemer et al. 2009) (numbers in bold italic surrounded by squares)

Fabbri et al. (2017) found evidence features for the activity of the Einigen fault zone in the vicinity of Lake Thun such as gas-releasing pockmarks between 15 and 50 m water depth in Lake Thun, south of Einigen (Fig. 1) and close to the western shoreline, offsets in horizons in reflection seismic profiles from Lake Thun and in ground penetration radar profiles in the area of a gravel pit around 2 km SW of Einigen, as well as observations in a fluvial deposits in a gravel pit ('gravel pit of Gesige'). A radiocarbon age of 11,000 years BP (before present) suggests a fault activity during the early Holocene (Fabbri et al. 2017).

4.2 Mass movements and soft sediment deformation structures

Ninety percent of the evidence of the current database originates from limnogeological studies; thus, the dataset is highly dominated by the availability of sublacustrine data (Fig. 5). The number of deposits found in a lake record is linked to diverse sedimentological and geomorphological processes (size of the lake, sedimentation rates) but is also related to the coverage and to the resolution of data acquisition at which the study was carried out. Thus, it is important to consider that the sublacustrine catalogue is not complete, and we might also miss evidence (especially those features that are smaller than the spatial sampling grid of the original study). In other words, whether a mass movement or soft sediment deformation structure is mapped out is highly depending on the position of the sediment cores as well as on the density of the reflection seismic grids that image mass movements and soft sediment deformation structures. A large number of the sublacustrine evidence (320 of 700) are registered in lakes Zurich, Lucerne and Neuchatel, as these studies


Austria
Tschirgant (42)
Hintersee (43)
Eibsee (44)
Köfels (41)
11
Basel−Reinach fault (24)
Falkenflue (54)
Lake Bergsee (25)
Blätterloch Cave (32)
Augusta Raurica (47)
Dieboldslöchli Cave (41)
Tüfleten (55)
Tannenflue (56)
Schartenmatt (57)
Lake Seewen (26)
10
Lake Zurich (1)
Lake Baldegg (4)
Broye (51)
La Tene (49)
Cornaux (48)
Yverdons−Les−Bains (50)
Lake Neuchatel (58)
Lake Geneva (53&64)
4
Lake Hinterer Schwendisee (8)
Lake Aegeri (11)
Lake Lauerz (10)
Lake Lucerne (2)
Lake Seelisberg (5)
Lake Trueb (12)
Lake Lungern (3)
Lake Oeschinen (16)
Oeschinen (59)
Kander (60)
Daubensee (61)
Klein Rinderhorn (62)
Lake Iffig (17)
2
Lake Cadagno (23)
Lake Alzasca (21)
Flims (45)
1
Lake Ghirla (28)
Italy
Lake Iseo
Lake Ledro
1356 AD
6200-7000?
9500-9900
2200-2500
3000-3600
?
?
11700
13700
1584 AD
1601 AD
1400-1700
bioturbated
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#=18
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#=1
#=1
#=1
#=1
#=3
#=25
#=10
#=1
#=7
#=7
#=24
0
5000
10000
15000
20000
Age (cal yr BP)
Legend
Trench
Sublacustrine MM
Coeval sublacustrine MM in a lake
Soft sediment deformation
Subaerial MM
Damages in caves
Damaged buildings
Waves
Subsurface sediment remobilization

◀ **Fig. 6** Temporal distribution of the evidence features at each location. The locations are shown on the map in Fig. 5 and are here grouped according to the tectonic zones of Switzerland following Wiemer et al. (2009) (Fig. 5). Only evidence features with a good age quality are considered. Thus, not the entire dataset is not visualised here. The length of the blue bar represents the time window covered by the studied record. The vertical red bars show coeval evidence and might represent potential past earthquakes, especially if coinciding with primary evidence and/or secondary evidence with strong indicator for seismic trigger such as coeval sublacustrine mass movements (bold and filled symbols indicate coeval deposits in a lake basin). The numbers related to the red bars mark their timing. The evidence features related to historic earthquakes (1356 AD Basel; 1584 AD Aigle; 1601 AD Unterwalden) are labelled with the corresponding date. The number of evidence is counted for each location and is given on the right side of the graph. MM, mass movement

were performed with the densest reflection seismic grid. For example, 92 evidence features are recorded in the sediments of Lake Lucerne, from which, 7 are interpreted as deposits of subaerial mass movements (mostly rockfalls), while the others are interpreted as sublacustrine mass movements (Schnellmann et al. 2006). These 92 evidence features cluster around 19 points in time during the past 15,000 cal years BP. For instance, 15 mass movement deposits were imaged in Lake Lucerne using reflection seismic surveys and recorded in sediment cores (Hilbe and Anselmetti 2014; Schnellmann et al. 2002) and have been related to the 1601 AD Unterwalden earthquake. This example of the 1601 Unterwalden earthquake (Monecke et al. 2004; Schnellmann et al. 2002), as well as other studies worldwide (e.g. Arnaud et al. 2002; Howarth et al. 2012; Moernaut et al. 2014; Moernaut et al. 2007; Van Daele et al. 2015), have shown that coeval mass movement deposits can be used as an indicator for an earthquake trigger. However, a careful study of the potential trigger mechanism is essential in each study.

Following this approach, apart from trench data as primary paleoseismic evidence and most reliable indicator for paleoseismology, coeval sublacustrine mass movements can be used as an indicator for past earthquakes. In Fig. 6, these coeval mass movement deposits are highlighted by bold symbols.

Single mass movements are also implemented in the database. However, these data need to be considered with caution when placed within a paleoseismological framework. Single mass movements can also be triggered by climatic causes (heavy rainfall, temperature changes, etc.) or also spontaneously due to overload. In the case of some small alpine lakes, with no seismic reflection data, some small turbidites that appear in the sediment cores have been interpreted as potential seismically induced (Wirth 2013). However, as also stated in Wirth et al. (2013), these data need to be considered with caution and cannot be considered individually as an indicator for paleoearthquakes. They are only used as supporting information.

The second largest group of evidence within our database is subaerial mass movements. Some of these mass movements are rockfalls associated to the historical earthquakes such as the 1356 AD Basel and the 1601 AD Unterwalden events. For the prehistorical subaerial mass movements, a seismic cause is discussed.

4.3 Destruction in stalactitic caves

Broken speleothems and blocks from a rock fall discovered in a stalactitic cave were related to the 1356 AD Basel earthquake (Lemeille et al. 1999). In contrast, the 1601 AD earthquake did not cause any noticeable destruction in nearby caves (Becker et al. 2012). These examples show that earthquakes can trigger destruction in caves. Some caves have been studied and compiled in Becker et al. (2012). These evidence features are also accompanied with huge dating uncertainties.

4.4 Waves and archaeological features

Sedimentological and archaeological features suggest three wave events in Lake Neuchatel (Garcia and Petit 2009; Schwab 1992; Curdy et al. 1995) at around 2100, 1965 and 1400 cal years BP.

Archaeological excavation and findings suggest that the Roman city Augusta Raurica might have been hit by an earthquake in 250 AD. However, not all damages were dated to the same point in time. Thus, the debate is going on (these uncertainties are marked in the database). Geotechnical, geological and seismological investigations have shown that an earthquake Mw 6 would at least explain partly the damage of the city (Fäh et al. 2006).

5 Discussion

As the knowledge on active faults is limited, the few primary evidence features and mainly the secondary evidence features, presented here, are used to discuss potential paleoearthquakes.

For further discussion, we are looking for regional and temporal clusters of evidence. Assuming that if evidence features are clustering within a certain timing and region, especially if primary evidence and multiple coeval sublacustrine mass movements are also present, the paleoearthquake hypothesis might be applied.

In order to better visualise the data, the evidence is plotted per location as a function of time and is organised following the tectonic zones of the SEIS-14 model of Switzerland after Wiemer et al. (2009) (Figs. 5 and 6). The temporal distribution of evidence shows an increase of features during several distinct phases: 300–600, 1400–1700, 2200–2500, 3000–3600, 6200–7000 and at around 9500–9900 years cal BP (Fig. 6).

The historical phase of 300–600 years cal BP includes evidence that can be attributed to the 1601 AD Unterwalden in Central Switzerland as well as to the 1356 AD Basel in the Basel region. This already shows that the intervals of an increased occurrence of evidence features as highlighted by the database cannot necessarily be explained by a single large earthquake, but more likely for a period or phase of increased seismic activity with several possibly smaller events. Regarding the geographical distribution, the 1400–1700 and 2200–2500 cal years BP evidence features are mainly recorded in northern, western and Central Switzerland. The phase between 3000 and 3600 and 6200–7000 cal BP are mainly produced by the evidence documented in the Basel region. Only for the phase at around 9500–9900 cal years BP, a general increase in evidence features is observed over the entire study area. The older phases at around 11,700 cal BP and 13,700 cal years BP are generated by coeval deposits in Lake Lucerne and Lake Zurich, previously discussed as possible large paleoearthquakes in central Switzerland (Strasser et al. 2006; Strasser et al. 2013). The 2200–2500 cal years BP phase was also previously discussed as paleoearthquake (Strasser et al. 2006). However, new studies show that coeval sublacustrine mass movements are also present in Lake Neuchatel and Lake Geneva at this time (Kremer et al. 2017; Reusch et al. 2016). In addition, the timing of the Oeschienen rockfall coincides with this time window (Knapp et al. 2018; Köpfli et al. 2018). Therefore, this phase has been discussed as either a phase of increased earthquake-triggered events recorded in northern, western and Central Switzerland (similar to the historical phase at 300–600 cal years BP) or potentially as a single strong earthquake (> Mw 6) (Kremer et al. 2017).

The phase of 9500–9900 cal years BP is characterised by an increase in evidence features spread all over the study area. Also, in studies in France, subaerial and sublacustrine mass movements are recorded at 9800 years cal BP (Chapron et al. 2015). As primary evidence (trench) and coeval sublacustrine mass movements in several lakes in Switzerland are recorded within this phase, the likelihood of a seismic trigger is higher. However, whether it is related to a single earthquake or to several cannot be concluded from the dataset. In addition, this increased occurrence of evidence features around the Alps might also suggest a climatic effect as a preconditioning factor. In fact, for this phase around 9500–9900 cal years BP, glacial rebound conditions during post-glacial times have also been previously discussed (Strasser et al. 2013; Kremer et al. 2017).

The question may also be raised if a climate signal is hidden in this dataset. A first comparison of a part of the lacustrine dataset and climate indicators (such as glacier retreat and flood occurrence) was made in Kremer et al. (2017). An increase in sedimentation rate is observed during the past 2000 years, accompanied by an increase in flood activity in the northern Alps (Kremer et al. 2017; Wirth et al. 2013). More rainfall might lead to more intense sediment mobilisation and transport into lake basins. These phenomena would increase the susceptibility of sublacustrine slopes to fail when affected by increased sediment input and could thus explain an increased occurrence of sublacustrine mass movement deposits. Thus, a climatic influence on the evidence record cannot be excluded, but further studies are needed to discuss this issue.

If we assume that the coeval evidence features are indicative for paleoearthquakes, our observation allows us to start the discussion on the recurrence rates of past earthquakes. For instance, this approach shows that in the Basel region (zone 11; Figs. 5 and 6), strong earthquakes (Mw 6.5 and larger) occurred 5 times within the past 15,000 years cal BP (also discussed in Becker et al. 2005). This corresponds to the mean recurrence rates of about 3000 years for such earthquakes, an information used in the seismic hazard model for Switzerland (Wiemer et al. 2016). In contrast, in the Valais region (Fig. 1), no studies of prehistoric evidence features are known up to now. Only three locations (Lake Oeschienen (16), Lake Iffig (17) and the rockfalls of

Daubensee, Klein Rinderhorn and Kander; Figs. 4 and 5) may be potential effects of prehistoric earthquakes in the Valais. In the Valais, during the past 500 years, Mw 6 earthquakes have occurred every century (Fritsche et al. 2012). This means that even if we assume that the evidences are all earthquake-triggered, the number of studied evidence (contained in the database) is largely insufficient to make a reliable comparison with the earthquake-hazard model. Thus, this database also allows to set priorities for future paleoseismological studies.

6 Conclusions

We compiled a database of evidence features that occurred in Switzerland and neighbouring regions covering mainly the last 20,000 years. This database allows highlighting the natural hazard potential of different regions. While updating this database in the future, some of the interpretational steps might change. Nevertheless, the database allows to visualise the existing primary and potential secondary effects on a temporal and geographical scale. An increased occurrence of coeval evidence features (especially when coinciding with primary evidence and/or coeval sublacustrine mass movements) might be an indicator for an earthquake as trigger. The periods of increased occurrence of evidence features (300–600, 1400–1700, 2200–2500, 3000–3600, 6200–7000 and at around 9500–9900 years cal BP) that have been suggested in previous studies are confirmed. The distinction between single large and several smaller earthquakes cannot be made due to large dating uncertainties. The potential recurrence rate earthquakes in the Basel area based on paleorecords was used in the recent seismic hazard model of Switzerland. However, in other highly seismically active regions such as the Valais, the coverage of the database is not good enough to allow any discussion on the occurrence of paleoearthquakes. This database thus not only allows us to work on scenarios but also highlights where priorities for future studies should be set.

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