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Multiarchive paleoseismic record of late Pleistocene and Holocene strong earthquakes in Switzerland

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Abstract

A multiarchive approach has been applied to the investigation of the late Pleistocene and Holocene record of strong earthquakes in Switzerland. The geological archives used for this study include active faults, lake deposits, slope instabilities, and caves. In the Basle area, eight trenches were opened across the Basle–Reinach fault, nearby rockfall deposits were systematically investigated, sediment cores were taken from two lakes, and nine caves were studied. In Central Switzerland, five lakes were investigated by means of high-resolution seismic lines and sediment cores. Furthermore, three caves were studied in Central Switzerland. Altogether, the investigations are based on more than 350 km of high-resolution reflection seismic lines, 450 m of core samples, 260 m of trenches, and 245 radiocarbon age determinations. The measured co-seismic displacements along the Basle–Reinach fault supply independent information for the magnitude of the AD 1356 Basle earthquake exclusively based on geological evidence. Deformation features related to three well-documented strong historic earthquake shocks were identified. Deformation features of the AD 1774 Altdorf and AD 1601 Unterwalden earthquakes can be used to calibrate paleoseismic evidence in Central Switzerland. Altogether, traces of 13 earthquakes could be found in the two study areas, all of them with magnitudes M_w~6 or greater. For the first time, the earthquake catalogue for Switzerland can be extended back beyond historic records, into the late Pleistocene, spanning 15,000 years.

Keywords: Switzerland; Paleoseismicity; Historic earthquakes; Pleistocene; Holocene; Earthquake catalogue

1. Introduction

Palaeoseismic investigations have been successful in many areas of the world in complementing historic earthquake record with prehistoric events. These investigations are focussed on surface faulting (Camelbeeck and Meghraoui, 1998) and on a variety of

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geological archives that contain earthquake-related damage and deformation features such as soft-sediment deformation in lakes (Sims, 1973, 1975; Rodriguez-Pascua et al., 2000), sand injections in flood plain deposits (Obermeier, 1996), slope instabilities (Keefer, 1984), or cave collapse (Postpischl et al., 1991). The potential for identifying a complete record of major prehistoric events is restricted to areas where the geological record is complete and earthquake-induced deformation structures are preserved in a wide range of environments. Paleoseismological research is particularly important in regions where recurrence intervals for strong earthquakes are long and exceed the time span covered by the instrumental and historic earthquake catalogues.

Intraplate Europe is classified among the stable continental regions because of the low rate of deformation (Johnston, 1996; Camelbeeck and Meghraoui, 1998). However, the historic seismicity is noteworthy, and moderate to large damaging earthquakes have occurred in the past (Camelbeeck et al., 2000). In this context, the October 18, 1356 Basle (Northern Switzerland) earthquake with M_w 6.9 ± 0.5 and the September 18, 1601 Unterwalden (Central Switzerland) earthquake with M_w 6.2 ± 0.5 are among the largest historic seismic events in Western Europe (Fäh et al., 2003). At Basle and Lucerne (Fig. 1), the two strongest earthquakes in Switzerland damaged two cities, which are now major regional centres with high population density, key communication nodes, lifelines, and critical facilities. It is therefore vital for these cities to evaluate the likelihood of the occurrence of such strong earthquakes. As the Basle and Unterwalden earthquakes are unique events within their respective regions, recurrence intervals are obviously larger than the 1000 years time span covered by the historic documents. Hence, the question was raised whether Switzerland has a record of such strong earthquakes. The answer to this question can only be achieved by paleoseismological investigations on different geological archives where traces of strong seismic events are recorded. These archives include fault scarps as well as lake, slope, and cave deposits. Investigations were carried out in

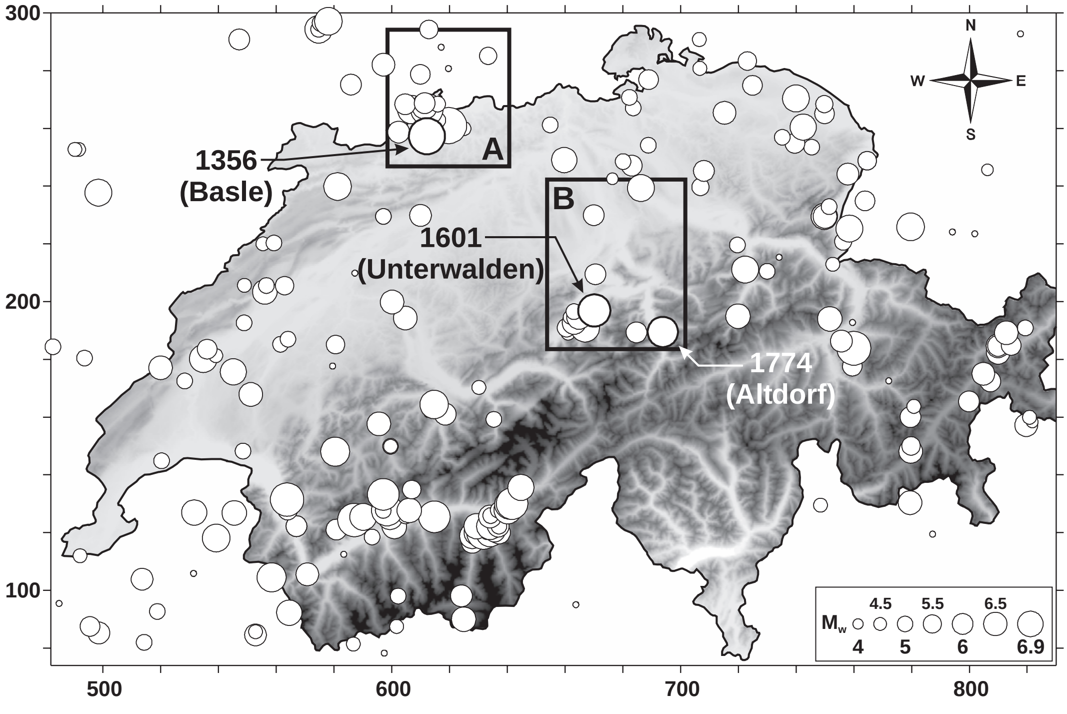

Fig. 1. Historic seismicity in Switzerland, study areas A and B, and topography.

the frame of the PALEOSEIS project at the Institute of Geophysics of ETH Zürich, with the intention to extend the earthquake catalogue for strong earthquakes back to the late Pleistocene. A summary of the results of this research project will be given in the present publication, which includes the first catalogue of strong historic and prehistoric earthquakes for Switzerland based on paleoseismological evidence in four different geological archives.

2. Geological setting

The study areas around Basle and Lucerne (Fig. 1) were selected for the investigations, mainly because of their elevated level of seismicity as indicated by the historic Earthquake Catalogue of Switzerland (Fäh et al., 2003). In the last 1000 years, the seismicity culminated in the Basle Region of northern Switzerland in the M_w 6.9 AD 1356 Basle earthquake and in the Lucerne area of Central Switzerland in the AD 1601 Unterwalden earthquake with M_w 6.2 (Schwarz-Zanetti et al., 2003). These historic earthquakes suggest that these regions experienced similar strong earthquake shocks in prehistoric times. Together with further strong historic events like the AD 1774 Altdorf earthquake with M_w 5.9, these permit the calibration of the effects of an earthquake shock of known strength in a particular geological archive and for it to be compared with potential prehistoric earthquake traces.

The study area in the north of Switzerland around the city of Basle is built up by four major tectonic units (Fig. 2). In the W and NW is the late Eocene to early Miocene rift structure of the Upper Rhine Graben. The Tertiary graben infill is not well-exposed in the Basle region. Pleistocene gravels and loess and Holocene alluvium are the most common surface deposits. In the Upper Rhine Graben south of Basle, the scarp of the active Basle–Reinach fault (Meghraoui et al., 2001) was investigated in detail. This fault is now considered as the most likely seismic source for the AD 1356 Basle earthquake. In the southern part of the study area, the late Miocene fold-and-thrust belt of the Folded Jura stretches in an E–W direction. It is mainly built up by Triassic and Jurassic shales and limestones. The same lithology can be seen in the Tabular Jura, which covers the area to the N between the Folded Jura and the Black Forest. Large areas of the Folded and Tabular Jura are characterized by steep cliffs along deeply incised valleys, built up mainly by middle and upper Jurassic limestones resting on marls. Seven cliff sites were studied (Becker and Davenport, 2003). In addition, the Jura Mountains' Mesozoic limestones are karstified and commonly host dolines and caves (Bitterli, 1996). In the frame of the research project, nine caves have been investigated in some detail. The fourth tectonic unit in the study area is the Black Forest in the N, which is the uplifted shoulder of the Upper Rhine Graben and is mainly built up by pre-Hercynian gneisses, Hercynian granites, and Permian clastics. With the exception of parts of the southern Black Forest, the study area was not covered by glaciers during the last (Würm) glaciation. Thus, over-deepened basins, carved by advancing glaciers and turned to lakes after their retreat, are missing. Thus, lakes in the Basle region are rare and the investigation of the lake archive is restricted to the glacially formed Lake Bergsee and the rockslide-dammed former Lake Seewen (Becker et al., 2000, 2002) (Fig. 2).

The main tectonic units in the Central Switzerland study area around Lake Lucerne are from S to N: the Aar Massif, the Helvetic nappes, the Subalpine, and the Plateau Molasse (Fig. 3). The youngest tectonic elements are NW–SE to NE–SW striking strike–slip faults, which are well developed in the Helvetic unit. Although the region is the location of one of the strongest historic earthquake shocks in Switzerland and although instrumental records indicate shallow earthquake foci, active fault scarps are unknown (Deichmann et al., 2000; Schwarz-Zanetti et al., 2003). In the region, Helvetic limestones are widely karstified and host the Hölloch (190 km long) and the Siebenhengste–Hogant caves (148 km long), which are the two longest cave systems of Switzerland (Wildberger and Preiswerk, 1997). Although samples for dating paleoseismic and/or neotectonic movements were taken from the Siebenhengste–Hogant system, it is beyond the scope of the PALEOSEIS project to investigate these huge cave systems in detail within its limited time period. Multiple glaciations modified the topography of the Alps and the Alpine foreland significantly by eroding deep valleys and over-deepened basins. The lakes, which presently occupy

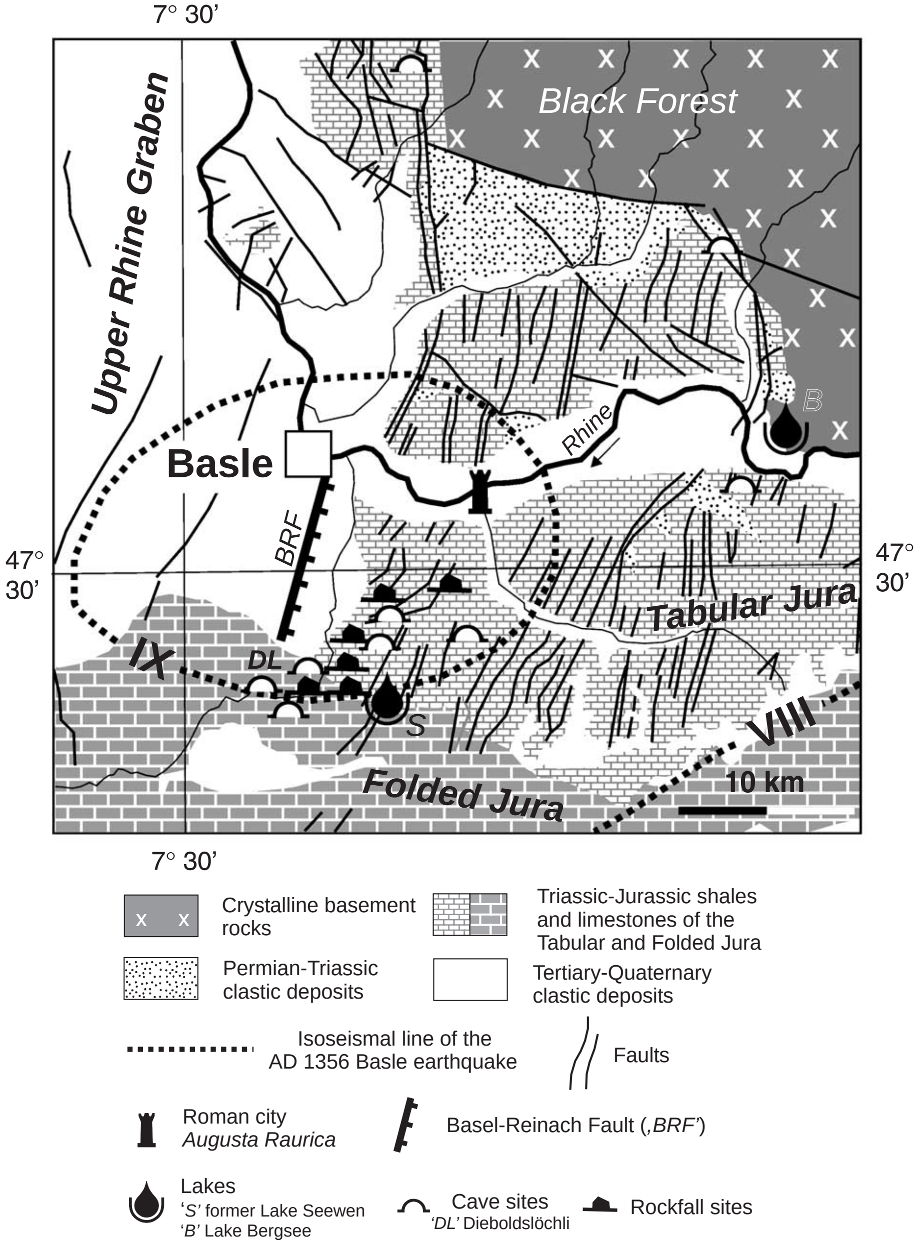

Fig. 2. Basle region: Geological sketch showing the epicentral area of the AD 1356 Basle earthquake and the geological archives used in the different sites of investigations.

these troughs, provide continuous, high-resolution archives covering more than the last 15,000 years. These archives have been investigated in detail for evidence of both historic and prehistoric seismic activity.

3. Archives and strategy

Not many features seen in the geological record can be used as a direct indicator of the occurrence of strong earthquakes. Seilacher (1969) originally intro-

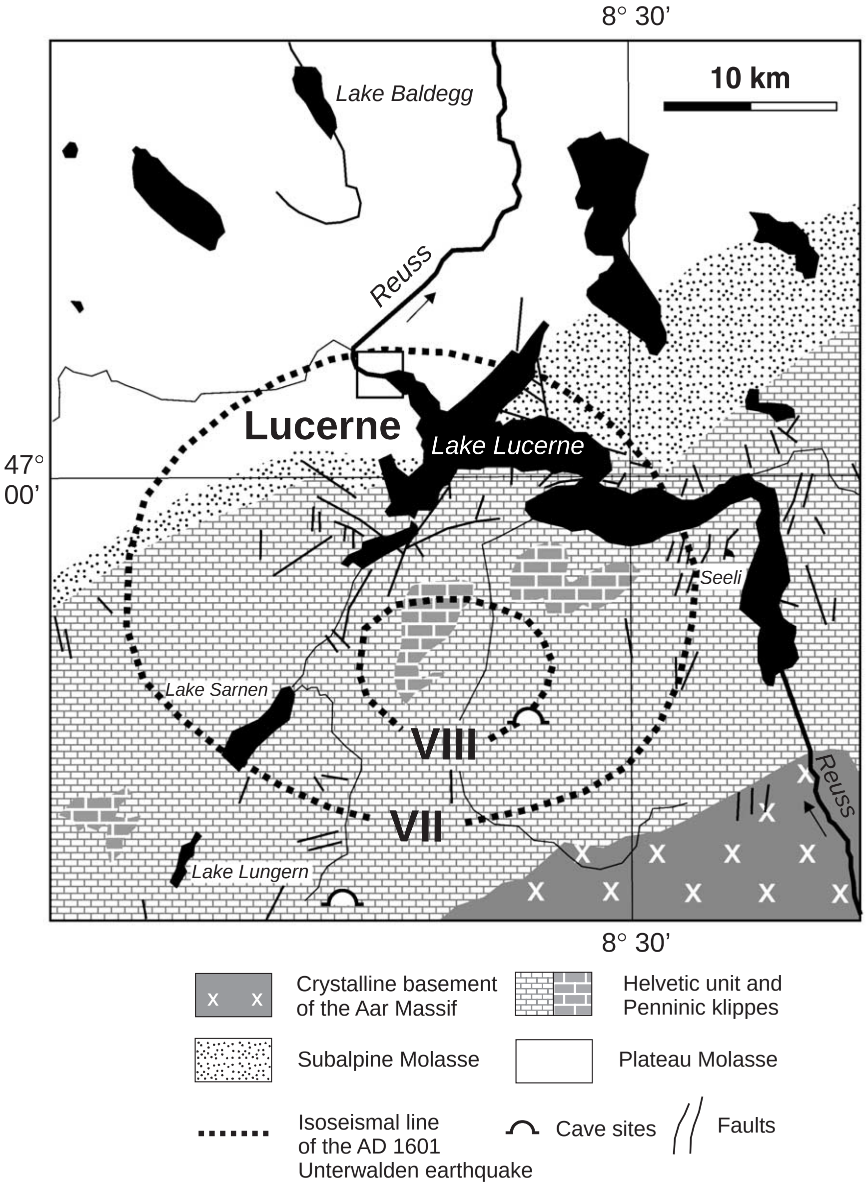

Fig. 3. Central Switzerland: Geological sketch showing the epicentral area of the AD 1601 Unterwalden earthquake. The lakes, which have been investigated in detail, are the Lakes Lucerne, Baldegg, Sarnen, Lungern, and Seeli (sberger See).

duced the term *seismite* to describe earthquake-triggered deformation features in soft sediments. Some types of deformation structures, such as *fault-graded bedding* (Seilacher, 1969), some *ball-and-pillow structures* (Davenport and Ringrose, 1987), and *mixed layers* (Marco et al., 1996), most likely fulfil the criterion to be exclusively earthquake-generated. In case of active faults, such an indicator could be the presence of a colluvial wedge against a fault scarp, as this points to a sudden rise and collapse of a scarplet. However, in most cases, geological processes unrelated to earthquake shocks may generate very similar features in the geological record. Therefore, it is important to define criteria that allow to identify seismically induced deformation features.

The geological record of an earthquake is stored in a geological archive and can be seen in the sites of investigation, for instance in a trench across an active fault, a drill core sample from a lake basin, or the debris talus at the foot of a rock cliff. Suitable archives must not only be susceptible to earthquake shaking, but also capable of storing and preserving information for several hundreds or thousands of years. In this study, four different geological archives were used, which include (1) active faults, (2) lake deposits, (3) slopes, and (4) caves, and were investigated at different sites. Such sites are single faults, lake basins, drill sites in a lake basin, single caves, or, in case of long cave systems, spatially separated cave sections, and slopes or cliffs showing different orientations or spatial separation.

3.1. Active faults

The most comprehensive geological archive for paleoseismological investigations is the active fault archive. This is mainly because it gives direct insight into the mode of rupture along a seismogenic fault and allows determining seismic parameters directly, such as rupture length and location, faulting mechanism, amount of displacement, and magnitude (Wells and Coppersmith, 1994). On the other hand, an active fault gives only information about the earthquakes that took place along this fault. Possible displacements along other co-seismic faults–even in the close vicinity–will not be recorded. In addition, it may happen that even strong earthquakes may not cause surface rupture if their focus is deeply seated in the Earth's crust. In a given region, strong seismic events frequently occur exclusively along a well-defined fault system and inevitably produce surface rupture. However, to assume that this is not the case in our study areas seems to be more realistic. Thus, one should investigate all available archives to achieve the highest completeness of the pre-historic earthquake catalogue. Furthermore, in Switzerland, it has not been possible to estimate the potential of the active fault archive. This is not only an expression of low seismic activity but also a result of geological history and human land use. Due to several glaciations that affected most parts of Switzerland and due to the pertaining fast deposition of thick glacifluvial units in over-incised valleys, evidence for recent coseismic displacements might be hidden or inaccessible. Furthermore, intense land use during the last 7000 years contributed in many places to the destruction of the most recent record. From these considerations, it appears that it is not by chance that the only known active co-seismic fault in Switzerland, the Basle–Reinach fault, is seen in a region that was probably never covered by glaciers during the Pleistocene (Hantke, 1978).

3.2. Lakes

Due to glacial erosion during the last ice age, when glaciers covered most parts of the Alps and large areas of their foreland, the lake archive is one of the richest and most complete, supplying in many cases a continuous sedimentary record for the last 15,000 years in Switzerland (Fig. 4). Climate changes, flood events, and the effects of earthquake shocks are stored in most of these lakes. However, depending on the geometry and bathymetry of the lake basin and the type of sediments, the lake archive will respond differently to strong earthquake shocks. A lake with steep basin flanks will preferentially undergo slope instabilities and display turbidity deposits in the abyssal plains. On the contrary, a shallow lake with gentle flanks will rather exhibit soft-sediment deformations or liquefaction features. Furthermore, lake deposits are easy to sample and reliable to date with the radiocarbon method. This makes lakes a unique archive for paleoseismic research, which is the most complete record of strong pre-historic earthquakes for the period of the late Pleistocene and Holocene in Switzerland (Monecke et al., 2004).

3.3. Slopes

The rugged topography of the Swiss Alps and Jura Mountains (Fig. 1) provides opportunities for the investigation of slope instabilities and mass movements, which can be studied on-shore along steep valley flanks or off-shore in glacially overdeepened lake basins. Scientifically, it is well documented that earthquakes can trigger a wide variety of slope instabilities. This includes on-shore avalanches,

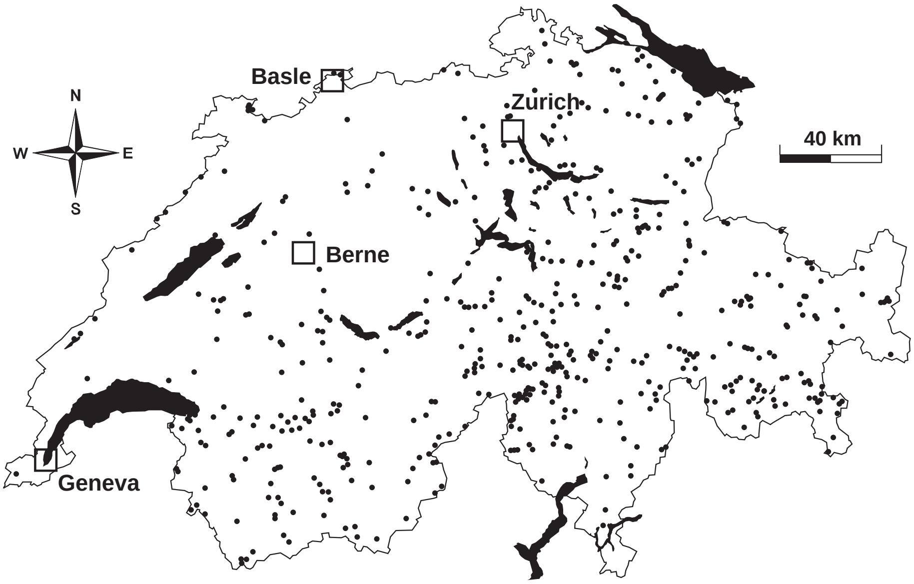

Fig. 4. Distribution and frequency of lakes in Switzerland.

slides, slumps, and falls (Cotecchia, 1987; Davenport, 1994; Jibson, 1996; Keefer, 1984; Voight, 1978) and offshore mass flows and turbidity currents (Shilts and Clague, 1992; Siegenthaler et al., 1987; Chapron et al., 1999; Syvitski and Schafer, 1996). The mode of failure strongly depends on the earthquake focal depth which influences the levels of strong ground motion, and on the slope failure susceptibility which varies with height, slope steepness, geotechnical properties, and geological structure (Harp and Noble, 1993; Harp and Wilson, 1995; Keefer, 2000; Parise and Jibson, 2000). Rockfalls are generally the most widely reported earthquake-triggered slope failures on-shore (Prestininzi and Romeo, 2000). Especially this is true for earthquakes with magnitudes ranging from 4 up to 6.5. The shortcomings of the mass-movement archive are: (1) the lack of direct evidence for earthquake-triggering of slope instabilities; (2) the frequent occurrence of non-earthquake-triggered slope instabilities; and (3) the lack of good age control for most subaerial mass movements. This shows that, for paleoseismological research on slope instabilities, the sites of investigations have to be selected very carefully with respect to the frequency of slope instabilities in a region and the possibility to date them. Areas with rare occurrences of slope instabilities will be mobilized only under specific conditions and, therefore, seem to be most interesting for paleoseismological investigations. However, it is fundamental to prove the seismic origin of the slope instabilities. This proof is often based on the correlation of individual slope failures within a region and, best, across the borders of different geological archives. In the framework of this project, both coeval subaqueous mass-movement deposits and subaerial rockfall-block deposits could be linked with known historic and prehistoric earthquakes (Becker and Davenport, 2003; Schnellmann et al., 2002).

3.4. Caves

Caves are common features in the karstified carbonatic rocks of the Jura Mountains and the Alps (Fig. 5), and supply an interesting paleoseismological archive for Switzerland. However, caves are a difficult archive which refers to the complexity of the processes affecting cave formation and evolution. Caves are, to some extent, a ‘microcosmos,’ containing all archives described above in addition to geological archives which are cave specific. Caves may follow or cut active faults; they may contain lacustrine or fluvial sediments, which can be deformed during earthquake shaking, or they may be involved in slope instabilities, which may cause the collapse of whole cave sections

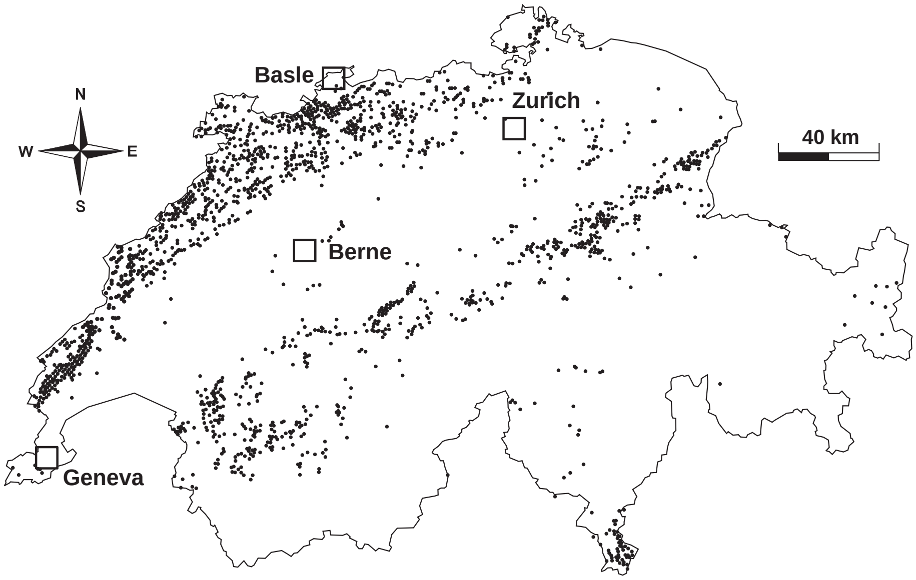

Fig. 5. Distribution and frequency of cavities in Switzerland after Wildberger and Preiswerk (1997). Most of the cavities in the Jura Mountains and northern Alps are caves, whereas the cavities in the Swiss Plateau are mostly man-made.

or trigger rockfalls in the cave (so-called "incasion"). In addition, sinter formations can be damaged, which is seen as the classical approach for paleoseismological research in caves (Postpischl et al., 1991). However, to use broken speleothems–preferentially stalagmites–to indicate past strong earthquake shocks is becoming increasingly questionable and is now generally accepted only for the most fragile speleothems, i.e. soda straws (Lacave et al., 2003; Gilli, 1999). To relate the destruction and the deformation seen in caves to the effects of strong seismic shocks is still a difficult task, mainly because dating and correlating events in caves are, in many cases, complicated by discontinuities in the sedimentary record and the lack of material suitable for dating. A variety of different dating methods can be used, of which the most common are the U/Th and the radiocarbon methods. All the dating methods have certain limitations and very often much effort is needed to accurately date speleothems and cave deposits. In some cases, different methods have to be used to spot the most suitable dating method to be used just for a specific cave. Despite all the problems, it appears that the cave archive has great potential for future paleoseismological research, mainly because in Switzerland, the age of the cave archive goes far beyond the lake archive and can cover most, if not all, of the Quaternary. At the present time, there is only one well documented example reported for cave damage caused by a historic earthquake in Switzerland (Lemeille et al., 1999).

3.5. Strategy

Using the combined strengths of the methods to overcome the (obvious) shortcomings of the archives, a strategy for Switzerland that integrates the paleoseismological evidence from different geological archives was developed. Because, as already mentioned, deformation features rarely provide direct evidence for being earthquake-generated, additional criteria have to be developed to decide about their seismic origin. An earthquake is an instantaneous event lasting for, at the longest, a few minutes during which it affects a region (Fig. 6). The intensity of the seismic shaking recorded at a site is controlled by the magnitude and focal depth of the earthquake and the distance to the epicentre. Ground motion may be amplified by local site conditions. Depending on the magnitude as well as on the geographical distribution of archives with respect to the epicentre, several sites within the same geological archive or several different archives may be affected by a given event (Fig. 6) (Vittori et al., 1991).

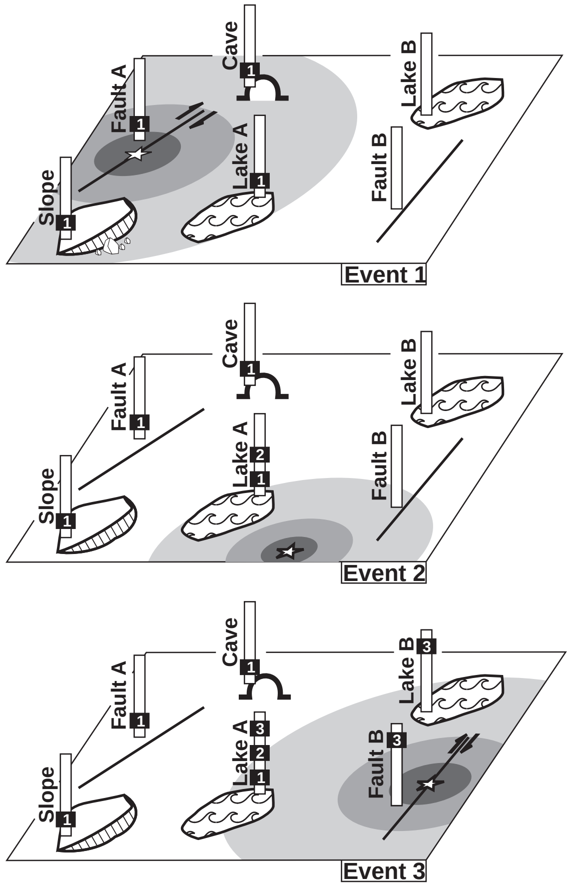

Fig. 6. Sketch illustrating the concept of 'integrated paleoseismology' using the lake, cave, slope, and active fault geological archives. The chance to achieve a complete record of pre-historic strong earthquakes in a region is highest if the evidence from different geological archives and different sites will be combined.

This supplies two further criteria for the detection of the effects of earthquake shocks in geological archives, i.e. the contemporaneity of the event within the geological archives and the restriction on a region with a general decrease of the level of damage and deformation away from the epicentral area.

Local events, such as a delta collapse under sediment overload or a single rock fall triggered by heavy rainfall, may happen spontaneously, but most likely not contemporaneously with other events. Thus, they will be observed only once, i.e. at a single drill site, in a single lake and/or at a single cliff site. Consequently, the proposed strategy helps to distinguish possible seismic events recorded in the geological archives from those local events. It also helps to avoid climatic events being interpreted as being of seismic origin, as they normally have a continental-wide or even global impact with no or minor variation of effects within a delimited region. That concept of 'integrated paleoseismology' has been applied to the two paleoseismological study areas in Northern and Central Switzerland.

4. Investigation methods

A summary of the methods used for the investigation of the different geological archives in Switzerland is given in Table 1. The most important methods are trenching and electrical resistivity measurements for the investigation of the active Basle–Reinach fault, and high-resolution seismic reflection lines and coring with the short piston, the Kullenberg, ram, and UWITEC corers in the lakes of Central Switzerland and in the Basle region. Altogether, more than 350 km of reflection seismic lines off-shore were acquired, 450 m cores were sampled, and 260 m trenches were opened. In the laboratory, the most important investigations include age determinations on 245 samples with the radiocarbon method, correlation of lake drill cores by the aid of magnetic susceptibility measurements with a Bartington Loop Sensor MS2E multiscanner, pollen analyses on 165 samples, and the analysis of sediment structures with computed X-ray tomography on more than 4000 slices.

5. Observations

Table 2 summarizes the observations in the two study areas subdivided into on-fault and off-fault observations following McCalpin (1996). All fault-related observations are shown in bold including the instantaneous, i.e. the co-seismic deformations and displacements creating the fault scarp as well as folded and faulted strata on-fault and tilted surfaces off-fault. Delayed response with respect to the co-seismically formed fault scarp is indicated by the build up of colluvial aprons and wedges as well as fissure fills and stratigraphic unconformities. Instantaneous co-seismic observations include all kind of slope instabilities, i.e. landslides on shore and

Table 1
Investigation methods used in the different geological archives in Switzerland

Investigation method	Aim	Tools
Surface geological mapping and reconnaissance	• Locate faults • Identify geological features that are deformed by the fault • Mapping of rock fall deposits • Identify earthquake damage in caves	• Aerial photography • Low angle aerial photography • Detailed topographic mapping • Surface mapping of geological units • Cave survey
Geophysical methods	• Locate faults with weak geomorphological surface expression • Identify subaqueous mass-movements in lake deposits	• Microgravimetry • Resistivity measurements • Seismic reflection
Trenching (on-fault excavation)	• Measure on-fault displacements and sample for dating	• Logging, digital photography, sedimentology, and soil analysis
Drilling	• Recovering of lake sediment drill cores • Sampling of rock fall blocks and cave speleothems	• Kullenberg, Livingstone, UWITEC, and ram coring for sampling of lake deposits • Core drilling
Laboratory methods	• Estimate the potential for liquefaction • Correlation of drill cores • In situ deformation structure analysis • Sediment analysis	• Particle size analysis • Susceptibility measurements • X-ray radiography and tomography (CT) • Smear slides
Dating methods	• Dating geological and biological materials	• Radiocarbon • Uranium-series dating • Thermoluminescence • Palynostratigraphy • Tephrostratigraphy • Varve stratigraphy

subaqueous slides, mass flows and turbidity currents in lakes, the generation of sand dykes, fissures, soft-sediment deformations, and the damage of speleothems. Delayed-responding postseismic off-fault stratigraphic expressions are, for instance, seiche deposits in lakes (Siegenthaler et al., 1987) and the deposits of dam bursts caused by overtopping of an earthquake triggered landslide-dam by a river. A short description of the observations and results from the different geological archives of the two study areas in northern and central Switzerland is given in the following sections. More detailed information are

Table 2
Paleoseismic observations

	On fault		Off fault	
Timing	Instantaneous (coseismic)	Delayed response (postseismic)	Instantaneous (coseismic)	Delayed response (postseismic)
Geomorphic expression	Fault scarps	Colluvial aprons	Tilted surfaces Landslides Fissures	
Stratigraphic expression	Faulted strata Folded strata	Colluvial wedges Fissure fills Unconformities (fault-event horizons)	Sand dykes Soft-sediment deformation Turbidites Damaged speleothems	Seiche deposits Dam burst deposits

given in Becker and Davenport (2003), Becker et al. (2002), Ferry et al. (2004), Flisch and Becker (2003), Lemeille et al. (1999), Meghraoui et al. (2001), Monecke (2004), Monecke et al. (2004), Rodriguez-Pascua et al. (2003), Schnellmann et al. (2002), and Schnellmann (2004).

5.1. Active fault in the Basle region

In northern Switzerland, where the Upper Rhine Graben, the Folded Jura, and the Tabular Jura meet (Fig. 2), the region of Basle experienced a destructive earthquake in 1356 (Mayer-Rosa and Cadiot, 1979) with a magnitude M_w 6.9 (Fäh et al., 2003). Theoretically, with a crustal thickness of 15 km (Bonjer, 1997) and a corresponding length of 15–20 km, such an event should produce more than 1 m of displacement at the surface (Wells and Coppersmith, 1994). Consequently, the mesoseismal area of the 1356 Basle earthquake was studied geomorphologically for evidence of long-term deformation south of Basle. The prominent 8-km-long Basle–Reinach fault scarp was identified (Fig. 2) that displays a clear asymmetry in its topography and drainage pattern (Meghraoui et al., 2001). Furthermore, Riss and Würm age river terraces crop out at anomalous positions that strongly suggest that the scarp recorded more than 35 m of cumulative vertical displacement during the last 240,000 years. This structure is connected at depth to a complex system of normal faults evidenced by geophysical investigations (deep seismics, high-resolution seismics, and electrical tomography) performed along the scarp (Ferry et al., 2004). The deepest visible layers are vertically displaced by ~100 m, which suggests a minimum long-term vertical deformation rate of 0.11–0.16 mm/year. The shallowest fault branches were imaged at the toe of the scarp, thus indicating that most promising sites for active fault studies are along the edge of the Birs valley.

A total of eight trenches were opened at two sites along the Basle–Reinach fault scarp, all of which display evidence for recent deformation and six display evidence for recent surface rupture. In all cases, the footwall block is composed of Oligocene *Molasse Alsacienne* made of sand to weakly cemented sandstone changing in cases to clay laterally. Against it, units composing the hanging wall systematically consist of calcareous pebbles in an organic-rich clayey matrix of Holocene age (Ferry et al., 2004). Fault structures are well expressed with a 10- to 20-cm-wide shear zone comprising highly deformed fine-grained sediments where Orellana (2002) identified secondary crystallisation of illite as well as evidence for fluid circulation. Numerous pebbles are rotated and oriented by successive shearing episodes and underline the shear zone. The most recent and least deformed units display the following typical structure (see unit b in Fig. 7a): the base is an erosion surface; the lowermost part of the unit is composed of pebbles and cobbles with fabric changes upwards from chaotically imbricated to slope-parallel; the uppermost part is composed of fine-grained slope deposits. Such a typical structure, called a colluvial wedge, is produced by a catastrophic deposition event (pebbles mark a debris facies) against a fault scarp after coseismic displacement occurred followed by a return to stable deposition processes (fine-grained unit is a wash facies) as described by McCalpin et al. (1993). The authors' model was slightly modified (Fig. 7b) to take into account the 40° slope that outlines the fault scarp. Hence, each individual colluvial wedge may be associated with an episode of displacement on the fault, i.e. to a large seismic event. The thickness of the colluvial wedge gives a minimum estimate of the amount of vertical displacement that took place during the earthquake (about half the vertical displacement for a normal fault rupturing a horizontal surface according to McCalpin, 1996). Within the different trenches, measured vertical displacements were all between 0.5 m and 1 m, thus showing consistency. Nonetheless, colluvial wedges may not be preserved due to local conditions or strong erosion. Missing events may only be recorded by secondary features and may be identified by abutting relationships. For instance, in Fig. 7a, unit e is broken and vertically displaced by ~0.5 m. However, there is no corresponding colluvial wedge overlaying it and unit d appears to be intact in its upper part. A 1356-type event probably occurred during deposition of unit d, which is significantly thicker than other comparable units observed in that trench and marks specific deposition conditions most likely related to the presence of a sag pond against the scarp. All events were dated through radiocarbon or thermoluminescence age determination. To infer a proper date, one to three samples were collected above and below the base of each colluvial wedge unit to determine the time of

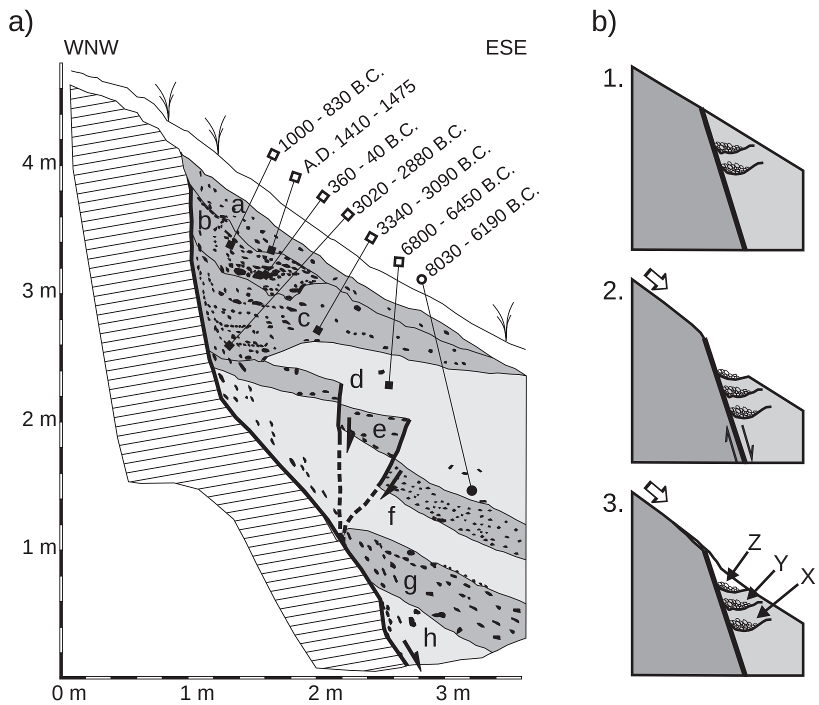

Fig. 7. Geological recording of large earthquakes on a normal fault. (a) Simplified log of trench 4 excavated across the Basle–Reinach fault. Log displays clear evidence for four events: uppermost units a, b, and c are colluvial wedges and unit e is broken and displaced by a previous event not recorded by a colluvial wedge (or recorded by a colluvial wedge that has been eroded afterwards). (b) Theoretical model displays the pre-existing slope and previous colluvial wedges (1) affected by coseismic displacement on the fault. The newly created free face on the footwall block is in a disequilibrium state and rapidly disaggregates to overlay the topmost part of the hanging wall with a debris facies (2). Transitory low-energy regime deposition produces a wash facies which topography eventually catches up with the general slope (3).

its initial deposition. Preferred radiocarbon samples were charcoal lumps, alternatively bulk soil. Although samples are relatively close to one to another, age inversions were not observed and the complete age sequences for individual trenches showed a high degree of internal consistency, thus supporting the interpretation of an episodic deposition history and the occurrence of catastrophic events. Observations in various trenches are compatible with large earthquakes on a 15–20 km long and 15 km wide rupture surface area and a moment magnitude of 6.5.

A chronological sequence of events and dated samples has been compiled and subjected to a Bayesian statistical analysis (Bronk Ramsey, 1995) to optimise probability distributions and date calibration (Ferry et al., 2004). The model shows a very good degree of internal consistency (over 100%), suggesting that events are logically inserted within the stratigraphy. Calculated events are inserted in Table 3, giving the first chronology of Holocene seismic events for an active fault in Switzerland. Indeed, five Basle-type- or larger-seismic events with clear surface rupture occurred along the Basle–Reinach fault during the last 13,000 years, with a mean recurrence interval of 2500 years (the occurrence of further events not breaking the surface cannot be excluded). Geomorphological observations revealed an 8-km-long scarp, which may not reflect the overall length of the fault (Meghraoui et al., 2001). However, strong urbanisation, man-made modifications of the landscape, and the close proximity of the Rhine river probably contribute to a less-than-ideal preservation of the scarp. Geophysical investigations performed at the southern end of the scarp (Ferry et al., 2004) and roadwork excavations opened in the southern suburbs of Basle (Barsch et al., 1971) at the northern end suggest that the fault extends for several kilometres, providing the basis for the expected length of 15 km. In addition, the Basle–Reinach fault intercepts at depth the Eastern master fault of the Upper Rhine Graben, opening the scenario that both conjugate faults may be activated during large earthquakes (as observed, for example, during the 1980 Irpinia earthquake).

5.2. In situ sediment deformations in lake deposits

Four lakes in the vicinity of Lake Lucerne (Lakes Baldegg, Seelisberg, Sarnen, and Lungern) and two lakes in the Basle region (Seewen and Bergsee) (Figs. 2 and 3) were investigated with the focus on small-scale in situ sediment deformations. As a first step towards a scheme for the recognition and calibration of such structures, traces of historic earthquakes in the sedimentary record of these lakes were sought (Monecke et al., 2004). However, this approach was only successful for Central Switzerland, whereas for the Basle region, no traces of the AD 1356 Basle earthquake could be found (Becker et al., 2002; Becker, 2003).

The investigated lakes in Central Switzerland are distributed within an area of 2000 km^2 (Fig. 3) and show different sedimentary processes. They were investigated using high-resolution reflection seismic data and sediment cores. The sediments consist of organic- and carbonate-rich clayey to sandy silts showing often fine bedding at centimeter to millimeter scale. The sediments are dated by historically reported environmental changes and climate data, ^{137}Cs activity, and radiocarbon ages. Deformation structures occur within distinct zones and include, among others, large-scale mass-movement deposits, small-scale features like disturbed, and contorted lamination and liquefaction structures. They can be attributed to three historic earthquakes: AD 1774 Altdorf, AD 1601 Unterwalden, and AD 1356 Basle. The most widespread deformation occurred during the AD 1601 Unterwalden earthquake as all investigated lakes show clear traces of this event, for instance in Lake Baldegg (Fig. 8). The sedimentary

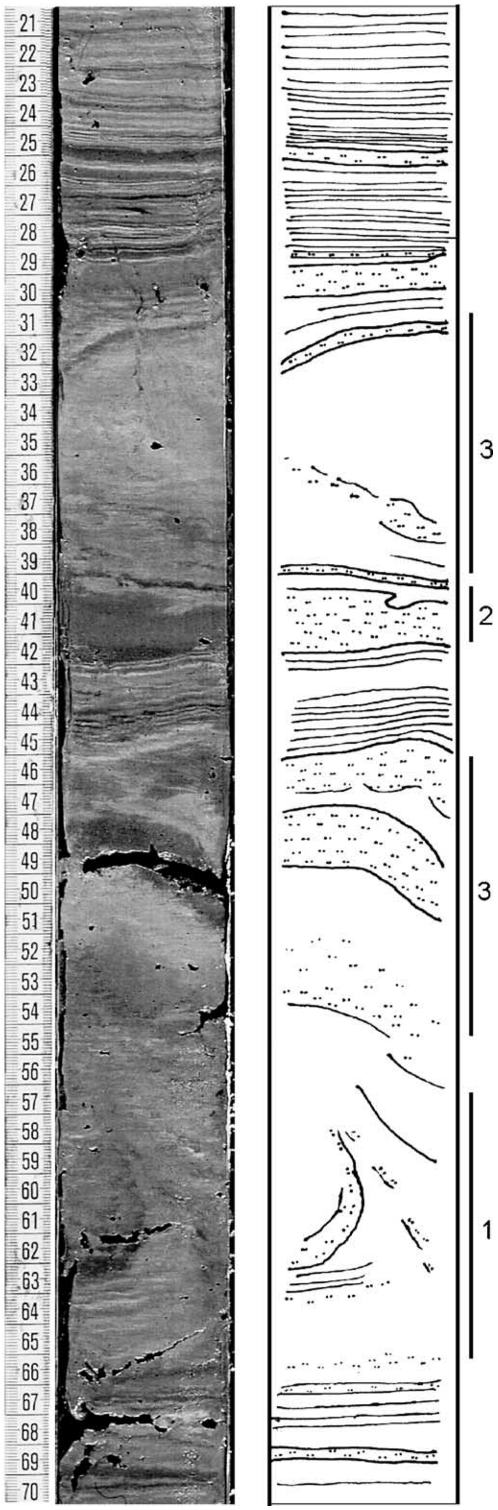

Fig. 8. Example of soft-sediment deformation structure generated during the AD 1601 Unterwalden earthquake in Lake Baldegg. The sediments consist of an alternation of well to faintly laminated carbonate mud and silty to clayey turbidites. Deformation features occur within a 40 cm thick succession: (1) folded and disrupted layers; (2) liquefaction structure: carbonate-rich mud sank into liquefied silts; (3) diffuse and disturbed layering. The lithological units can be followed throughout the lake basin indicating in situ deformation with no major mass transport.

data are compared to the historic macroseismic dataset in order to calibrate the observed structures: deformation structures in varying distances to the epicentres are related to corresponding macroseismic intensities. The spatial distribution of deformation structures in the different lakes clearly reflects the historic macroseismic dataset: lake sediments are only affected if they are within an area showing groundshaking greater than intensity VI to VII. At low intensity levels, small-scale deformation structures can be found. At higher intensities, large-scale subaqueous mass-movement deposits become more frequent and probably overprint possible small-scale structures. These observations match and complement previous studies: Galli and Ferelli (1995) and Obermeier (1996) state that liquefaction structures become common at a groundshaking of intensity VII. This is in agreement with experimental data indicating that the threshold for liquefaction lies at magnitudes 5–5.5 (Moretti et al., 1999). Paleoseismic investigations in outcrops of lake deposits reveal threshold values of intensity VI for the formation of soft sediment deformation structures (Sims, 1973, 1975; Hibsch et al., 1997). Earthquake size has been estimated by relating the epicentral distance of the farthest liquefaction structure to earthquake magnitude using the magnitude-bound method after Obermeier (1996). This relationship is in good agreement with earthquake size estimations based on the historic dataset (Fig. 9).

Using these results, earthquake-induced deformation structures can be recognized also in prehistoric lake sediments. Studies on long sediment cores from Lakes Seelisberg, Baldegg, and Lungern with ages up to 13,000 years BC show further small-scale deformation features as well as mass-movement deposits which can be tentatively correlated to prehistoric events proposed for Lake Lucerne (Monecke, 2004). In the Basle region, prehistoric earthquake events are best documented in the silty clay deposits of Lake Seewen (Becker et al., 2002), whereas the recognition of seismites in Lake Bergsee is much more difficult because of the pure

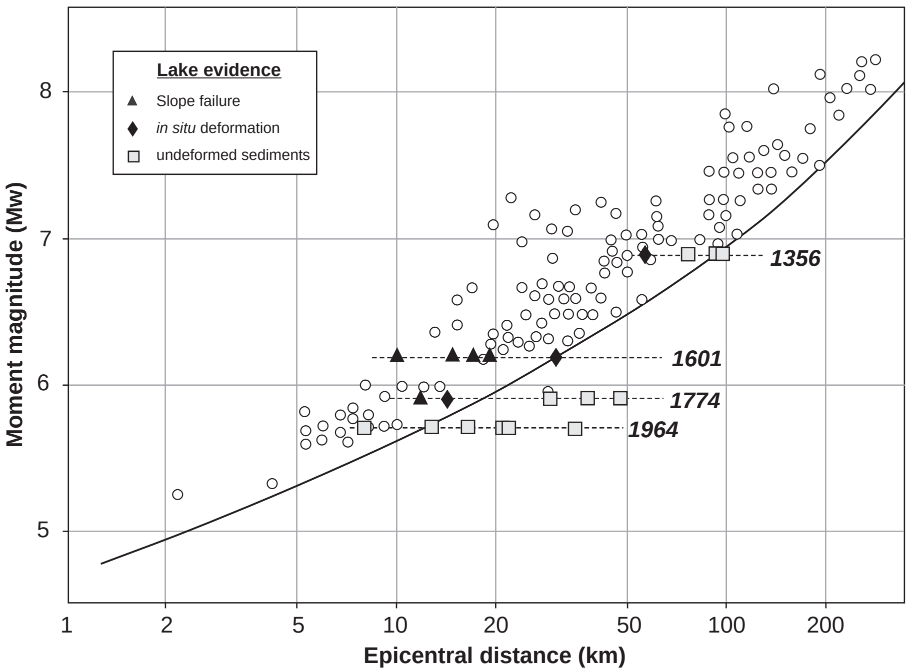

Fig. 9. Farthest reach of liquefaction for earthquakes worldwide with focal depths <50 km (circles) (after Obermeier, 1996) and a bound curve suggested by Ambraseys (1988). The results from lakes from Central Switzerland for the 1356 Basle, 1601 Unterwalden, 1774 Altdorf, and 1964 Sarnen earthquakes for comparison (after Monecke et al., 2004; Schnellmann et al., 2002; Siegenthaler and Sturm, 1991a). The magnitudes for the historic earthquakes are taken from Fäh et al. (2003). The lake evidence matches very well the data presented by Obermeier (1996) with our datapoints lying within the range of uncertainties.

organic sediments deposited during the late Pleistocene and Holocene (Becker, 2003; Becker et al., 2004). The clearest event which can be related to earthquake ground shaking is dated between 10,350 and 9750 BC and is indicated in Lake Seewen by a sand dyke, a mushroom structure, and disrupted layers. Based on radiocarbon ages, deformation features in lake deposits can be well correlated with evidence from the trench sites across the active Basle–Reinach fault (Ferry et al., 2004).

5.3. Slope instabilities

5.3.1. Subaqueous mass-movement deposits in Lake Lucerne

Historic documents describe several shore collapses and large water movements in Lake Lucerne as a consequence of the AD 1601 Unterwalden earthquake (Cysat, 1601; Schwarz-Zanetti et al., 2003). Siegenthaler et al. (1987) related two large mass-flow/megaturbidite complexes in the subsurface of the lake to this historic seismic event and thus showed that the subaqueous slopes of Lake Lucerne are sensitive to earthquake shaking. However, in the same lake, in 1674, a spontaneous delta collapse also produced a large mass-flow deposit and an associated megaturbidite (Siegenthaler and Sturm, 1991a).

A detailed study of mass-movement deposits in the subsurface of Lake Lucerne aimed to provide key criteria for separating seismically and aseismically triggered mass movements and to use these criteria for reconstructing the regional earthquake history (Schnellmann et al., 2002). To exclude large mass flows and megaturbidites caused by spontaneous delta collapses, the investigations in Lake Lucerne were focused on sub-basins that lack major deltas.

With a dense grid of high-resolution seismic lines (Fig. 10A) and seismic stratigraphic correlation, it was shown that more than 13 coeval mass-flow deposits correlate to the M_w 6.2 AD 1601 Unterwalden earthquake (Fig. 10B). These deposits occur in two separate sub-basins and are partly overlain by up to 2-m-thick megaturbidite deposits. This indicates that rather than the size of an individual mass-flow deposit, the widespread distribution of coeval deposits is the key criterion for a strong seismic trigger. A further argument for seismic triggering is the position of the slide scars. Slide scars in depths >30 m are out of the reach of surface waves and most human activities. Moreover, a slide with such a scar cannot represent the subaqueous continuation of subaerial mass movement.

Five prehistoric horizons with numerous coeval mass-flow and megaturbidite deposits have been identified deeper in the lake's subsurface and are interpreted as remnants of strong prehistoric earthquakes (e.g., Fig. 10C). AMS radiocarbon dating and tephrochronology revealed ages of 230–470, 7880–7960, 9530–10,040, 11,630–11,890, and 11,800–13,470 BC. Four of the five prehistoric multiple slide events include slide scars in water depths greater than 30 m.

5.3.2. Sub-aerial rockfalls in the Basle region

In the epicentral region of the AD 1356 event S and SE of Basle, thick-bedded Upper Jurassic coral limestones are exposed in numerous cliff sites, which are underlain by marls. Due to creep in the marls, erosion at the cliff foot, and erosion along the bedding plains, tower-like columns have been generated at different sites along the cliffs. The toppling of such rock towers will create rockfall deposits at the cliff foot consisting mainly of blocky debris. The basic assumption for the use of rockfall blocks as indicators for past strong earthquakes is that such earthquakes would trigger many rockfalls in a region of limited extent instantaneously.

Large rock fall blocks, having length along the block edges ≥ 3 m, have been selected for the investigation. Most favourable are those blocks resting on clay or marl. Such a block can produce an ideal seal which will preserve organic material that was enriched in the soil developed on top of the clay or marl layer before the block emplacement against oxidation. In addition, a big block also diminishes the danger of disturbance and contamination of organic material due to human or animal activities as well as due to the growth of roots. Mapping of rock fall deposits gave additional confidence that they have not moved since their emplacement. A light-weight drill corer was used to drill a borehole of 101 mm diameter to penetrate the block from the top centre to the base (Fig. 11a and b). With a downhole sampler (Fig. 11c) that

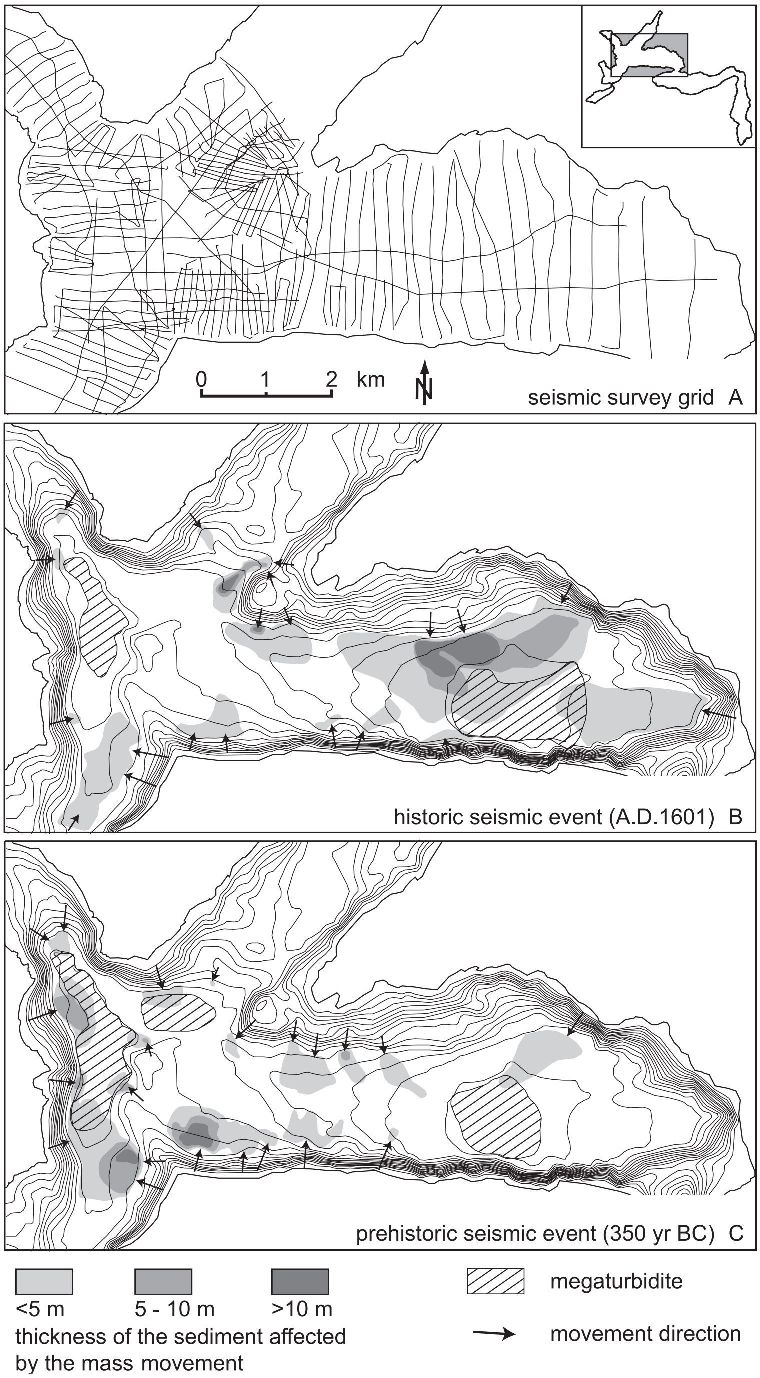

Fig. 10. Mass movement deposits in the subsurface of Lake Lucerne. (A) High-resolution seismic survey grid. (B and C) Distribution and thickness of mass-flow deposits and megaturbidite deposits related to two different events. Hatched areas mark the extent of megaturbidites directly overlying mass-flow deposits. Bathymetric contour interval is 10 m.

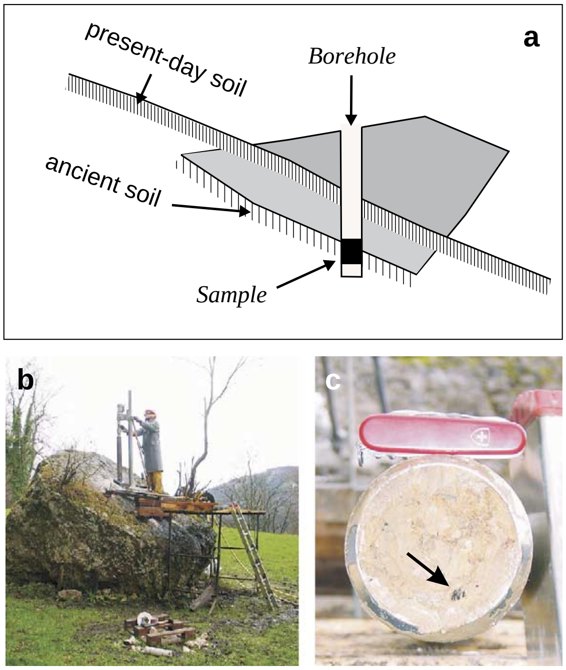

Fig. 11. (a) Scheme of sampling showing a borehole drilled just through the centre of the block and the sample site just below the block. Sampling of a rockfall block showing (b) the mounted drilling rig, and (c) the soil sampler with a soil sample containing lumps of black charcoal (arrow).

can be hammered into the ground, a soil sample from below the block is taken. From the soil recovered just below the block, organic macro-particles, mainly charcoal, wood fragments, or needles from pine trees, were picked out in the laboratory for radiocarbon dating. The preparation and pretreatment of the samples were carried out at the ^{14}C laboratory of the Department of Geography at the University of Zurich. The AMS (accelerated mass spectrometry) with the tandem accelerator of the Institute of Particle Physics at the ETH-Hönggerberg was used for dating.

Of the 20 rockfall blocks sampled at seven cliff sites in the northern Swiss Jura Mountains south of Basle (Fig. 2), 12 blocks could be dated, of which 11 blocks supplied ages which are very close together, ranging between 440 and 970 uncal. BP (Fig. 12). The 1σ and 2σ ranges of dendro-calibrated dates from cumulative probability and the probability distribution curves for the individual blocks using Bayesian statistics (Bronk Ramsey, 1995) are shown in Fig. 12. The contemporaneity of a large number of rockfall events at different cliff sites in a restricted area and the close agreement with the date of the strongest earthquake in historic times north of the Alps suggest that the rockfalls were triggered by the AD 1356 Basle earthquake (Becker and Davenport, 2003).

5.4. Cave observations

For Switzerland, only one example of a historic earthquake dated by paleoseismological evidence in caves is known. For the Dieboldslöchli cave, Lemeille et al. (1999) could demonstrate that the dating of the broken stalagmites and the following re-growths point to the AD 1356 Basle earthquake as the most likely cause of the damage. The Dieboldslöchli cave is located only 3 km SSE of the southernmost tip of the Basle–Reinach fault scarp (Fig. 2), i.e. the seismogenic fault of the AD 1356 Basle earthquake.

Caves in Central Switzerland, which were investigated in the region between the Lakes Lungern and Lucerne, are the Rundwand, Schratten, and Bettenhöhle. The dating of sinter formations which show damage gave in all cases very high ages, frequently passing the limits of the U/Th dating method. Therefore it is not yet possible to correlate any currently available evidence from the cave archive with those from the lake archive. However, work in the caves continues and the chances to discover suitable new cave sections or even new caves are high in a region where 80% of the known caves were discovered within the last 30 years.

6. Catalogue of paleo-earthquakes for northern and central Switzerland

Different geological archives reveal the occurrence of strong pre-historic earthquakes within the last 15,000 years in two regions of Switzerland. Table 3 is the first attempt to summarize these seismic events chronologically for this time period. All earthquakes included in this catalogue are based on paleoseismic observations. Because the historic Basle, Unterwalden, and Altdorf earthquakes could also be recognized in these geological archives, they are listed as well.

In the first column, the catalogue gives a code for the region (CS Central Switzerland, BR Basle Region)

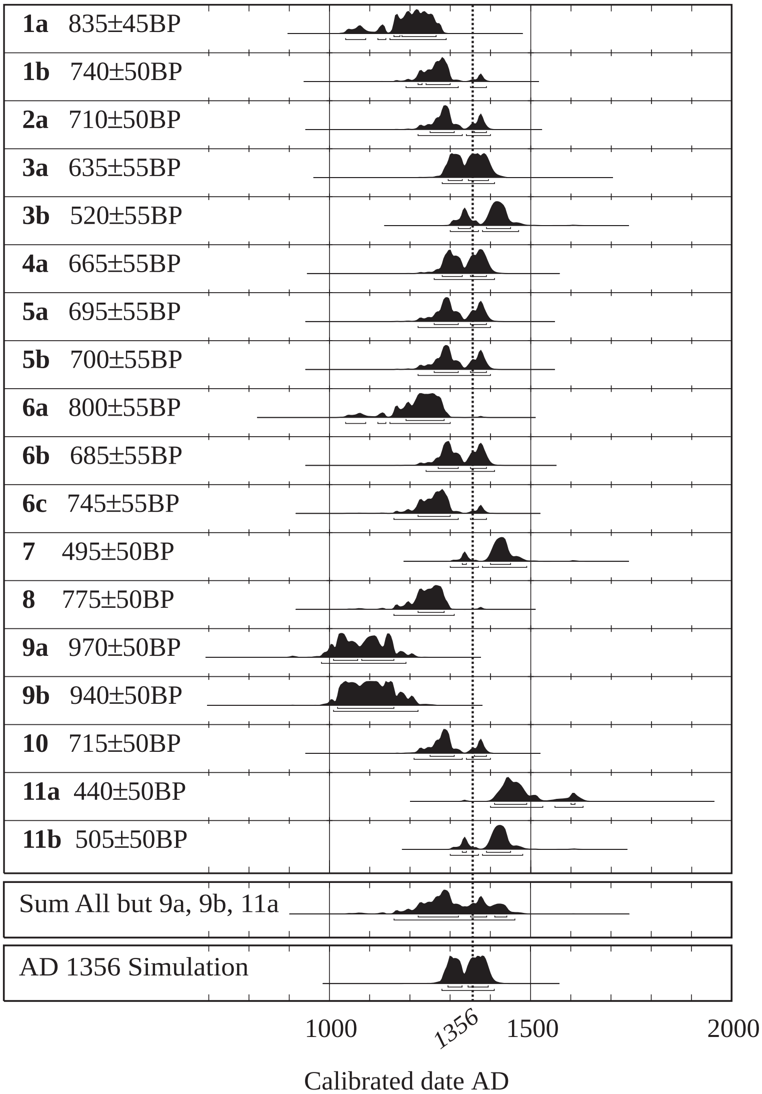

Fig. 12. Calibrated radiocarbon dates of samples from 11 rockfall blocks modified after Becker and Davenport (2003). Shown are cumulative probability distribution functions for the samples that were taken closest to the base of the blocks. A combined probability distribution by summing of the various cumulative probability distributions of individual samples beside samples 9a, 9b, and 11a is given in the lower part of the illustration. In addition, the simulated cumulative probability distribution of the calendar year AD 1356 is included. Thin lines below the probability distributions indicate their 1σ and 2σ ranges, respectively. The hatched line indicates the date for the AD 1356 Basle earthquake.

and an event number (BR-1, CS-7). The second column indicates the approximate age of the earthquake event, which is in most cases based on radiocarbon dates which immediately pre- or post-date the earthquake event horizons or on age models for individual sedimentary basins which allow to determine the ages of event horizons based on sedimentation rates. The following column contains the geological archives (fault, slope, lake, and cave) used for the interpretation. More details about the information are given in the sections of this publication which directly refer to the geological archives. In the case of historic earthquakes, the epicentral region is known and is indicated separately in the last column of the Table 3. However, in most cases, the epicentral region is unknown with the exception of the Basle–Reinach

Table 3
Catalogue of strong historical and pre-historical earthquakes in northern and central Switzerland

Event[a]	Date	Geological Archives	M_w[b]	Conf.	Comment
CS-0	10.09.1774	Slope: Lake Lucerne[1] Lake: Seelisberg	5.9[2]	Very high	AD 1774 Altdorf earthquake: 8.67°E, 46.85°N (± 20 km). [1]After Siegenthaler and Sturm (1991b). [2]Magnitude (± 0.5) from earthquake catalogue of Switzerland (Fäh et al., 2003)
CS-1	18.09.1601	Slope: Lakes Lucerne[1], Lungern[1], Seelisberg[1] Lake: Baldegg [2]	6.2[2]	Very high	AD 1601 Unterwalden earthquake: 8.36°E, 46.92°N (± 20 km). [1]Multiple mass failure. [2]In situ deformation features. [2]Magnitude (± 0.5) from earthquake catalogue of Switzerland (Fäh et al., 2003)
BR-1	18.10.1356	Fault: Basle–Reinach (Z) Slope: observations from six cliff sites Lake: Baldegg[1] Cave: broken stalagmites in Diebolds löchli	6.2–6.5	Very high	AD 1356 Basle earthquake, EMS-98 IX: 7.60°E, 47.47°N (± 20 km). [1]Very weak in situ deformation feature. Magnitude from earthquake catalogue of Switzerland (Fäh et al., 2003): M_w =6.9 ± 0.5
CS-2	180–500 AD	Slope: Lakes Lucerne, Lungern, Seelisberg Lake: Baldegg	~6.2	Average	Single mass-movement deposits in three lakes, deformed varves in one sediment core from Lake Baldegg.
CS-3	230–470 BC	Slope: Lake Lucerne[1], Lungern[2]	~6.2	Average	[1]Clear evidence in Lake Lucerne from multiple mass-movement deposits. [2]Multiple mass-movement deposits in Lake Lungern (dating uncertain).
BR-3	2210–2490 BC	Fault: Basle–Reinach[1] (Y) Lake: Baldegg[2]	6.4–6.7	Very high	[1]Seen in four trenches. [2]Deformed varves in Lake Baldegg (period of time for deformation in Lake Baldegg: 1870–2310 BC).
BR-5	3770–4480 BC	Fault: Basle–Reinach (X)[1] Slope: Baldegg[2] Lake: Seewen (S2)	6.4–6.6	High	[1]Age limits based on trench information between 3200 and 6200 BC. [2]Period of time for deformation in Lake Baldegg: 4260–4480 BC.
BR-6	7300–8600 BC	Fault: Basle–Reinach. (W) Lake: Bergsee (B4)	6.3–6.6	High	Re-evaluated date for Bergsee B4: 8000–7550 BC.
CS-7	7880–7960 BC	Slope: Lake Lucerne[1], Seelisberg[2], [Köfels, Flims][3]	≥ 6.2[3]	Average	[1]Multiple mass-movement deposits in Lake Lucerne. [2]Single small-scale mass-movement deposit in Lake Seelisberg. [3]Big rock slides from Köfels (Ivy-Ochs et al., 1998) and Flims (Poschinger and Haas, 1997) are approximately of the same age. This might point to a large paleo-earthquake in the Central Alps at this time.
CS-9	9530–10,040 BC	Slope: Lake Lucerne[1], Lake Seelisberg[2]	~6.2	Average	[1]Multiple mass-movement deposits in Lake Lucerne. [2]Single mass-movement deposit in Lake Seelisberg.
BR-8	9750–10,350 BC	Fault: Basle–Reinach (V)[1] Lake: Seewen (S5)	6.4–6.6	Very high	[1]Age limits from trench sites: 9500–11,200 BC
CS-10	11,630–11,890 BC	Slope: Lake Lucerne	~6.2	Average	Multiple mass-movement deposits in Lake Lucerne.
CS-11	11,800–13,470 BC	Slope: Lake Lucerne[1], Lake: Seelisberg[2]	~6.2	Average	[1]Multiple mass-movement deposits. [2]Liquefaction structure in one sediment core (dating uncertain)

[a] CS: Central Switzerland; BR: Basle Region. Additional events with low level of confidence are not included here.
[b] Magnitude ~6.2 indicates an earthquake with a magnitude similar to the AD 1601 Unterwalden earthquake.

fault. The estimate of the earthquake magnitudes for the active Basle–Reinach fault is based on calculations referring to the observed offset along a fault scarp following Wells and Coppersmith (1994). The confidence of the paleo-earthquake date is estimated on the basis of three different geological archives investigated in Central Switzerland and four such archives in the Basle Region. In Central Switzerland, these archives comprise the 'lake archive' summarizing all in situ deformation features in lacustrine deposits, the 'slope archive' including subaqueous mass-movement deposits as well as turbidites in the abyssal plains in the different lakes, and the cave archive. For the Basle Region, the archives are the active Basle–Reinach fault, the slope archive summarizing the rockfalls in the region, the lake archive with the in situ deformations seen in the two lakes Seewen and Bergsee, and the cave archive. The following confidence scale for paleo-earthquakes is not an absolute measure but reflects to some extent the number of geological archives showing synchronous deformation features in different sites. This is the main reason that the confidence scale used is believed to underestimate the evidence of paleoearthquake activity in Central Switzerland, where only two archives (subaqueous slopes and lakes) are available compared to the four archives available in the Basle region:

Very high: observations from four or more archives, or observations from three archives with very clear evidence from at least one archive, or clear evidence from two or more trench sites, or historically recorded earthquake.
High: observations from three archives, or observations from two archives with very clear evidence from at least one archive, or clear evidence from one trench site.
Average: observations from two archives, or observations from one archive with very clear evidence, or weak evidence for faulting from one trench site.
Low: some evidence for earthquake deformation from one archive, or evidence for warping from one trench site.
Very low: one observation with evidence for earthquake origin.

Finally, the last column gives some important information concerning the data used as indicator for the paleo-earthquake.

The earthquake events with the highest level of confidence are the three historically well documented Altdorf (CS-0), Unterwalden (CS-1), and Basle (BR-1) earthquakes and, in addition, the events BR-3 and BR-8. Based on the paleoseismic record alone, BR-1 can be already regarded as very confident because earthquake-related deformation features and damage can be seen in four archives: seven cliff sites, four trench sites, in one lake (Baldegg) and one cave. The event BR-3 is seen very clearly in four trench sites showing offsets slightly larger than those for event BR-1. This suggests an earthquake which was even stronger than the AD 1356 Basle earthquake. In addition, the trench information correlates very well with clearly deformed varves in the sediments of Lake Baldegg. BR-8 is also an event with very high confidence based on deformations seen in three trench sites and, in addition, three drill sites in Lake Seewen.

The events BR-5 and BR-6 are regarded as highly confident. BR-5 in the Basle region is seen in two trench sites, however, with poor age constraints. Clear soft-sediment deformation features in the nearby Lake Seewen (S2) and in Lake Baldegg are considered to be related to event X in the trench sites, which permit a much more precise dating of event BR-5 (i.e., between 3770 and 4020 BC). BR-6 is seen in three trench sites, and possibly correlates with event B4 in Lake Bergsee.

The event CS-2 is characterized by mass-movement deposits in Lakes Lungern, Seelisberg, and Lucerne, and deformed varves in Lake Baldegg, showing a very good coincidence in time. CS-3, CS-7, CS-9, CS-10, and CS-11 are all marked by multiple mass-movement deposits in Lake Lucerne, particularly well developed for events CS-3 and CS-10. Additionally, CS-3 in Lake Lucerne correlates with multiple mass-movement deposits in Lake Lungern, and the events CS-7, CS-9, and CS-11 coincide with small-scale mass failure or liquefaction structures in Lake Seelisberg. All these events are either seen in two archives or at least in one archive with very clear evidence, which permits these observations to be given an average level of confidence.

7. Relevance of paleoseismic data for seismic hazard assessment

The assessment of seismic hazard (the probability of occurrence of ground shaking, i.e. 10% exceedance probability in 50 years) relies on the capacity of understanding the recurrence of earthquakes. In areas of intermediate or rare seismicity, the need to obtain a long and complete record of seismic history is a condition for the correct assessment of seismic hazard. Whereas the frequency of intermediate-size events in such areas can be constrained with the historic records, large earthquakes recur only every few thousands (Table 3) or tens of thousands of years and may not be covered by the historic record. The possibility of reconstructing the pre-historic seismic record is then a key tool to evaluate the long-term earthquake history and the frequency of occurrence of large events.

The relevance of paleoseismicity constraints for the seismic hazard in northern Switzerland is clearly shown by the combined frequency–magnitude distribution of historic and prehistoric earthquakes in the Basle region. Different datasets cover different completeness periods and magnitude ranges: the instrumental record (1975–2002) covers the magnitude 2–3.2 range, while different historic periods cover the magnitude 3–5.8 range. The historic catalogue contains a single large event (the devastating AD 1356 Basle earthquake) which appears on the frequency–magnitude plot with a yearly probability of occurrence of almost 10^{-3}, as dictated by the length of the historic catalogue. It is only by including the prehistoric record constrained by the paleoseismological investigations that we are able to complete the frequency–magnitude distribution to a period of almost 8000 years. The combined distribution (Fig. 13) shows a linear Gutenberg–Richter trend, with a well defined b-value, which in turns allows to estimate the regional seismic hazard with good confidence.

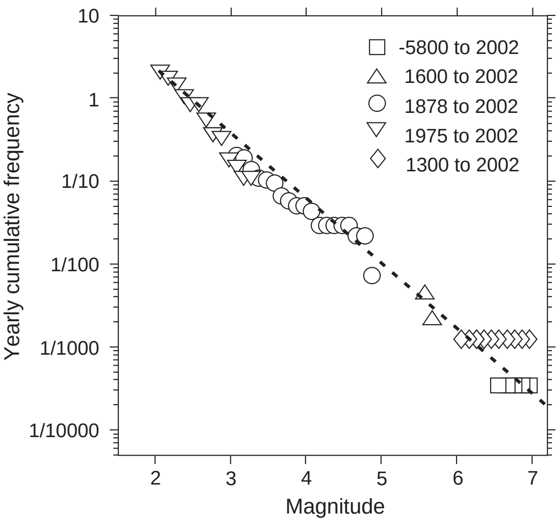

Fig. 13. Yearly cumulative magnitude–frequency distribution for earthquakes in the Basle region, northern Switzerland. The curve illustrates the relative contribution provided by different datasets to the definition of a long-term relation for the recurrence of earthquakes. Each dataset is normalized by its completeness period. Shown are the contributions from the paleoseismicity data (squares), three different historic periods (diamonds, upper triangles, circles), and recent instrumental data (lower triangles). All these data are consistent with a simple linear Gutenberg–Richter regression.

8. Discussion and outlook

The use of paleoseismological investigation methods in two study areas in Switzerland known for their elevated seismicity in historic times has led to the discovery of the finger prints in four different geological archives of the two strongest earthquakes in Switzerland within the last 1000 years, which are the AD 1601 Unterwalden and the AD 1356 Basle earthquakes. These observations, based on paleoseismological evidence of known historic earthquakes, support the interpretations of similar observations in older strata as being expressions of similar strong earthquakes which occurred in prehistoric times in these regions. Central Switzerland shows evidence for further six strong earthquake events which occurred within the prehistoric period starting 15,000 years ago when the glacier retreated from the region around Lake Lucerne, and, for northern Switzerland around Basle, for a further four strong earthquakes similar to the Basle earthquake from AD 1356 since 10,000 BC.

The recurrence interval for such strong earthquakes can be calculated for the Basle region with 2500–3000 years. However, for Central Switzerland, the calculation of such a recurrence interval seems to be less meaningful because of the uneven distribution of strong earthquakes with time. Here it appears that strong earthquakes were more frequent at the end-Pleistocene and during the last 4000 years. The higher level of seismicity in the late Pleistocene could be a rebound effect related to the rapid retreat of the glaciers after the Würm maximum and a re-establishing of isostatic equilibrium in the Earth's crust. This effect can trigger very strong earthquakes as evidenced by the elevated level of late glacial seismicity in northern and central Europe (Beck et al., 1996; Davenport et al., 1989; Muir-Wood, 2000; Ringrose, 1989; Stewart et al., 2000).

The two earthquake events CS-7 in Central Switzerland and BR-6 in the Basle region are very close together with respect to the date of their occurrences. Although it is not possible to distinguish between both

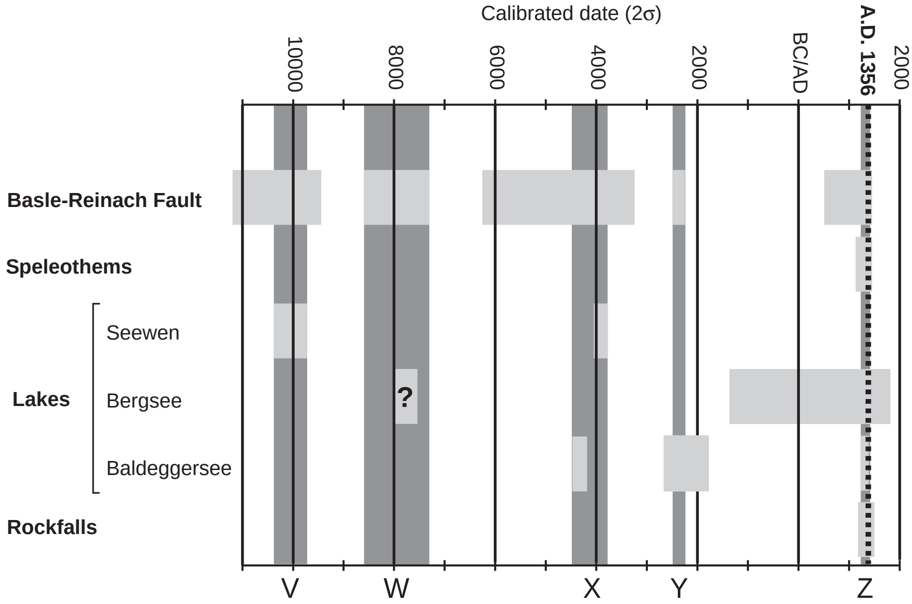

Fig. 14. Events correlation with time across different geological archives in the Basle region. The capital letters refer to the co-seismic events along the Basle–Reinach fault. The dark grey columns indicate the time window for the most likely occurrence of the events. The hatched line indicates the date for the AD 1356 Basle earthquake.

events based on their calibrated ages alone, these are thought to be two independent events. This is mainly because the Basle–Reinach fault (1) has a maximum rupture length that is not long enough to generate an earthquake which would significantly affect Central Switzerland; and (2) has a fault offset, pointing to magnitudes in the range of the other known events on this fault; moreover, (3) nothing which would point to a very strong earthquake could be seen in Lake Seewen close to the Basle–Reinach fault. Note that event CS-7 occurred about the same time as the two big rockslides at Köfels in Tyrol, western Austria, and Flims in Grison, eastern Switzerland (Ivy-Ochs et al., 1998, v. Poschinger and Haas, 1997). An earthquake of $M_w > 6.5$ has been taken into consideration as a trigger mechanism for the Köfels sturzstrom (Sørensen and Bauer, 2003). The Köfels, the Flims, and the CS-7 events could relate to a single, major earthquake event, with an epicentre somewhere in the central Alps of eastern Switzerland, western Austria, or northern Italy.

The paleoseismological investigations in the two study areas in Central Switzerland and the Basle region have shown that strong earthquake shocks hit these regions in the last 15,000 years. Although presently characterized by a moderate to intermediate level of seismicity, it is a fact that strong earthquake events like those of Basle and Unterwalden are not unique. Similar events are to be expected in the future and, thus, have to be taken into consideration for seismic hazard assessments. The concept of 'integrated paleoseismology,' comparing evidence from different geological archives, has been applied successfully in Switzerland, as demonstrated in Fig. 14 for the Basle Region. However, the catalogue of paleoseismicity is not complete and a survey of the different geological archives for signs of strong prehistoric earthquakes throughout Switzerland is needed.

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