Quaternary Science Reviews 168 (2017) 1–18

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Invited review

Lake-sediment based paleoseismology: Limitations and perspectives from the Swiss Alps

Katrina Kremer [a, b, *], Stefanie B. Wirth [c], Anna Reusch [a, d], Donat Fäh [b], Benjamin Bellwald [e], Flavio S. Anselmetti [f], Stéphanie Girardclos [g], Michael Strasser [a, h]

[a] Geological Institute, ETH Zurich, Sonneggstrasse 5, 8092, Switzerland
[b] Swiss Seismological Service, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland
[c] Centre for Hydrogeology and Geothermics, University of Neuchâtel, Emile-Argand 11, 2000 Neuchâtel, Switzerland
[d] Department of Geosciences, University of Bremen, Gebäude GEO, Klagenfurter Strasse 2, 28359 Bremen, Germany
[e] Department of Earth Sciences, University of Bergen, Postboks 7803, 5020 Bergen, Norway
[f] Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland
[g] Department of Earth Sciences and Institute for Environmental Sciences, University of Geneva, Rue des Maraîchers 13, 1205 Geneva, Switzerland
[h] Institute of Geology, University of Innsbruck, Innrain 52, 6020 Innsbruck, Austria

ARTICLE INFO

Article history:
Received 7 July 2016
Received in revised form
4 April 2017
Accepted 27 April 2017

Keywords:
Mass-movement deposits
Sediment deformation
Lake sediments
Paleoseismology
Alps
Paleoepicentre
Holocene

ABSTRACT

In regions with moderate seismicity and large intervals between strong earthquakes, paleoseismological archives that exceed the historical and instrumental timescale are needed to establish reliable estimates of earthquake recurrence for long return periods. In several regions, lake sediments have shown to be suitable for paleoseismological studies by causally linking characteristic sedimentological features to historic earthquakes. Studies on single lakes, however, do neither allow determining the paleoepicentre nor the paleomagnitude for the potential paleoearthquakes. Here we compile, using shaking-induced mass movements and micro deformations (summarized as Sedimentary Event Deposits SEDs), the sedimentary paleoseismic record of 11 lakes from Switzerland over the last 10,000 years. The large dating uncertainty attributed to such deposits (up to 250 years) does not allow us to conclusively test for one large earthquake hypothesis when comparing the different lake records and therefore represents one of the major limitations of this approach. Instead, using a new approach of exploring the normalized frequency of occurrence averaged over a larger area, the compiled dataset reveals striking periods of enhanced occurrence of SEDs in the studied lakes during several phases of the past 10,000 years, centered at 9700, 6500 and during the last 4000 cal yr BP. Moreover, we use a calibrated intensity attenuation relation in order to model scenarios of possible epicentral areas and ranges of magnitudes of paleoearthquakes. We differentiate two cases: (i) a 'single-earthquake' scenario if SEDs occur simultaneously in various studied lakes, or (ii) a 'multi-earthquake' scenario if SEDs in the studied lakes cluster within a time interval. The modelled scenarios allow us to propose maximally possible magnitudes of large paleoearthquakes, constituting an important input for seismic hazard assessment in the Swiss Alps.

1. Introduction

Regions characterised by low deformation rates usually have long recurrence intervals of strong earthquakes that often exceed the time span covered by instrumental and historic records (Gangopadhyay and Talwani, 2003; Lafuente et al., 2014; Michetti et al., 2005). Moreover, instrumental records do not allow the identification of active faults of strong damaging events due to the low recurrence rates. Therefore, there is a need in extending the knowledge on the spatial and temporal distribution of prehistoric earthquakes to be able to identify potential seismically active fault zones.

Prehistoric earthquake investigations rely on paleoseismic archives registering the earthquake-induced effects. Lake sediments are sensitive to seismic shaking and, moreover, provide very high temporal resolution with continuous sedimentation. Thus, they can be used to extend the regional earthquake catalogue if mass-transport deposits (MTDs: turbidites, slumps, slide and mass-flow

* Corresponding author.
E-mail address: katrinakremer@sed.ethz.ch (K. Kremer).

http://dx.doi.org/10.1016/j.quascirev.2017.04.026
0277-3791/

deposits) or deformation structures (DSs: liquefaction structures, in situ soft sediment deformations) recorded in the lake sediments can be linked to earthquakes (e.g., Arnaud et al., 2002; Avsar et al., 2015; Chapron et al., 1999; Garrett et al., 2016; Howarth et al., 2014; Moernaut et al., 2007, 2014; Monecke et al., 2004; Petersen et al., 2013; Schnellmann et al., 2002; Schwab et al., 2009; Strasser et al., 2013). However, earthquakes are not the sole trigger mechanism for MTDs (Hampton et al., 1996). Subaquatic MTDs have also been attributed to historical events such as floods (e.g. Gilli et al., 2003; Siegenthaler et al., 1987; Wilhelm et al., 2013), rock falls (e.g. Bussmann and Anselmetti, 2010; Hilbe et al., 2011; Schnellmann et al., 2006) or spontaneous failures of delta slopes (e.g. Girardclos et al., 2007). Thus, it is of major importance to unambiguously identify earthquake-triggered MTDs. In this study, we group MTDs and DSs into the term 'Sedimentary Event Deposits' (SEDs), and discuss the likelihood of them being seismically triggered.

We compile a large dataset of SEDs recorded in Swiss lakes available from peer-reviewed publications and unpublished research (PhD and master theses). A previous review of Strasser et al. (2013) compiled a smaller number of lakes from Central Switzerland. Here we expand the number of lakes and the regional frame by adding six critical lake records: Lake Geneva (Kremer et al., 2015), Lake Neuchâtel (Reusch, 2016; Reusch et al., 2016), Lake Thun (Wirth, 2008; Wirth et al., 2011), Lake Silvaplana (Bellwald, 2012), Lake Walen (Zimmermann, 2008) and Lake Aegeri (Hofmann, 2015; Müller, 2007). The age-depth models of all sediment cores retrieved from the studied lakes were recalculated for this study by using the most recent calibration curve for radiocarbon dating (Intcal13; Reimer et al., 2013) in order to reach consistent event dating for the entire dataset. We examine the dataset for sedimentary evidence indicating (i) the occurrence of single large prehistoric earthquakes (single-earthquake scenario) and/or (ii) time periods of 'enhanced' regional seismicity (multi-earthquake scenario). Negative evidence, i.e. the absence of MTDs or DSs for a given time period, is also considered. Finally, we use empirical intensity attenuation equations (Fäh et al., 2003, 2011) to discuss ranges of magnitudes and areas of epicentres of possible earthquake scenarios based on the observations in the lake sediments.

2. Regional setting

2.1. Seismotectonic setting and seismic activity

In Switzerland, four main tectonic units can be defined from north to south: the Rhine Graben, the Jura Mountains, the Molasse basin and the Alpine belt (e.g. Deichmann et al., 2000). Northwestern Switzerland is primarily affected by the extensional regime of the Rhine Graben. The transition between the Molasse basin and the Alpine belt is defined as the Northern Alpine Front (NAF, Fig. 1) that strikes WSW-ENE between the Alpine nappes and the tilted Sub-Alpine Molasse. The latter is thrusted over the flat-lying Molasse at the Sub-Alpine Molasse Front (SAMF). Overall, seismicity is

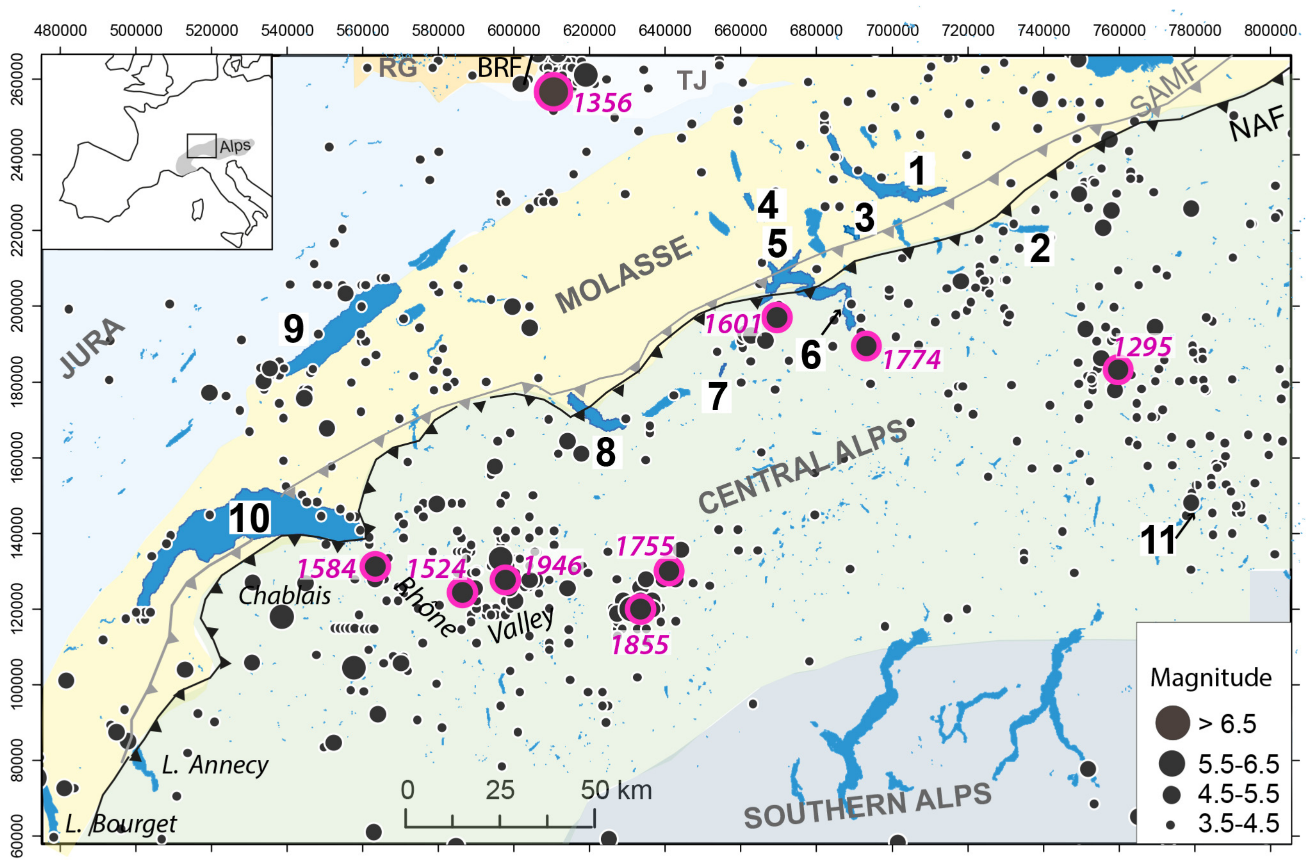

Fig. 1. Map locating the main tectonic units (Rhine Graben (RG), Tabular Jura (TJ), Jura Mountains, Molasse Basin and the Alps), fronts (Northern Alpine Front (NAF) and Sub-Alpine Molasse Front (SAMF)), and epicentres of instrumentally and historically documented earthquakes with magnitudes Mw > 3.5 (dots) extracted from the ECOS09 database (Fäh et al., 2011). The large historical earthquakes (with magnitudes > 5.7 that are mentioned in the text), are highlighted with a pink outer circle and a pink number referring to the year. The studied lakes are marked with black numbers: 1 = Lake Zurich, 2 = Lake Walen, 3 = Lake Aegeri, 4 = Lake Baldegg, 5 = Lake Lucerne, 6 = Lake Seelisberg, 7 = Lake Lungern, 8 = Lake Thun, 9 = Lake Neuchâtel, 10 = Lake Geneva, 11 = Lake Silvaplana. BFR: Basel Reinach Fault. L. Bourget: Lake Bourget. L. Annecy: Lake Annecy.