Historical Earthquakes, Paleoseismology, Neotectonics, and Seismic Hazard: New Insights and Suggested Procedures

Deutsche Gesellschaft für Erdbeben-ingenieurwesen und Baudynamik

DGEB

DGEB-Publikation Nr. 18

Historical Earthquakes, Paleoseismology, Neotectonics, and Seismic Hazard: New Insights and Suggested Procedures

Deutsche Gesellschaft für Erdbebeningenieurwesen und Baudynamik

Editor
Diethelm Kaiser

Publisher
Deutsche Gesellschaft für
Erdbebeningenieurwesen
und Baudynamik (DGEB) e.V.

DGEB-Publikation Nr. 18

Editor
Dr. rer. nat. Diethelm Kaiser
Bundesanstalt für Geowissenschaften und Rohstoffe,
Hannover, Germany

Publisher
Deutsche Gesellschaft für Erdbebeningenieurwesen
und Baudynamik (DGEB) e.V.
Prof. Dr.-Ing. habil. Frank Wuttke
c/o Christian-Albrechts-Universität zu Kiel
Lehrstuhl für Geomechanik und Geotechnik
Ludewig-Meyn-Strasse 10
24118 Kiel

Umschlaggestaltung: Lena Haubner
Lektorat, Korrektorat: Diethelm Kaiser

Cover image: Historical representation of earthquake
impacts in Bielefeld 1612 (Alzenbach, 1612), Source:
City Archive Bielefeld. Electronic Edition: Frankfurt
a. M. : Stadt- und Universitätsbibliothek, 2002.
urn:nbn:de:hebis:30:2-40162

ISBN 3-930108-14-3
DOI: 10.23689/fidgeo-3860

Contents

DOI: 10.23689/fidgeo-3868

Introduction: Historical Earthquakes, Paleoseismology, Neotectonics and Seismic Hazard: New Insights and Suggested Procedures

Diethelm Kaiser

Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany, diethelm.kaiser@bgr.de

This publication developed from the 5th International Colloquium on "Historical Earthquakes, Paleoseismology, Neotectonics and Seismic Hazard" which was held from 11 to 13 October 2017 at the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover, Germany. In this colloquium, 75 experts from 17 countries presented and discussed recent results, ongoing studies and planned projects on the topics historical earthquakes, macroseismology, archeoseismology, paleoseismology, earthquake catalogues and databases, active faults, seismotectonics, neotectonics, and seismic hazard assessment.

This Colloquium was the continuation of a surprisingly successful series that began in 2013 in Paris, France with the Colloquium "Macroseismicity: sharing and use of historical data". The need for an intensive collaboration and exchange was expressed and in 2014 the Colloquium on "Historical earthquakes and macroseismology - historical sources, methods and case studies" was organized in Freiburg, Germany. It was followed by the "International Colloquium on Major Historical Earthquakes of the Rhine Graben, Interplate - Intraplate Continental Deformation, From archives to comparative seismotectonics" 2015 in Strasbourg, France and the "4th International Colloquium on Historical Earthquakes and Macroseismology" 2016 in Vienna, Austria. Subsequent meetings have so far been the "Sixth International Colloquium on Historical earthquakes & paleoseismology studies, their contribution to the knowledge of the long-term seismic activity and to seismic hazard assessment" 2018 in Han-sur-Lesse, Belgium, and the "7th International Colloquium on Historical Earthquakes & Paleoseismology Studies - Past seismicity knowledge for today's earthquake science" 2019 in Barcelona, Spain.

The 5th Colloquium in this series was organized by the "Seismic Hazard Assessment" Unit at BGR, the Institute of Geology of the Leibniz Universität Hannover, and the Neotectonics and Natural Hazards Group of RWTH Aachen University. Abstracts and presentations are available from the Colloquiums webpage: https://www.bgr.bund.de/DE/Themen/Erdbeben-Gefaehrdungsanalysen/Veranstaltungen/HistEarth_Paleoseis_Okt2017/histEarth_paleoseis_2017_node.html.

The present publication comprises four contributions:

The paper by Brüstle et al. (2020) is the result of several years of comprehensive work on the determination of macroseismic intensities as part of the compilation of a new earthquake catalogue for southwest Germany. For this purpose, the authors developed comprehensible methods for intensity assessment using EMS-98, which are presented here in full detail.

Damaging earthquakes are very rare events in Northern Germany and one of them, the so-called Alfhausen earthquake of 1770, has been under debate for three decades. Leydecker & Lehmann (2020) examine the observations for this event in detail in order to find out if it actually is an earthquake and which cause and strength may be determined.

Growing evidence shows, that earthquake occurrence in the plate interiors is episodic. Starting with a detailed description of the current state of knowledge on seismicity in Western Europe between the Lower Rhine Graben and the North Sea and its connection with fault zones and their deformation rates in the Quaternary, Camelbeeck et al. (2020) derives fundamentally different seismicity models between the Lower Rhine Graben on the one hand and the region west of it on the other.

Paleoseismology is an indispensable discipline to identify and date prehistoric large earthquakes by investigating their geologic evidence. Hürtgen et al. (2020) developed and present the first database of paleoseismic evidences in the area of Germany.

I would like to thank the Deutsche Gesellschaft für Erdbebeningenieurwesen und Baudynamik (DGEB) for the financial support that made this publication possible and Thomas Spies, Frank Wuttke and Volkmar Zabel for their basic support. The manuscripts were reviewed by the following colleagues: Anke Bebiolka, Klaus-Peter Bonjer, Uwe Braumann, Christa Hammerl, Diethelm Kaiser. The papers have been considerably improved as a result, and for this, I thank all of them sincerely.

References

Brüstle, W., Braumann, U., Hock, S. & Rodler, F.-A. (2020). Best practice of macroseismic intensity assessment applied to the earthquake catalogue of southwestern Germany. *In: Kaiser, D. (Ed.). Historical Earthquakes, Paleoseismology, Neotectonics, and Seismic Hazard: New Insights and Suggested Procedures*, *DGEB-Publikation 18,* Deutsche Gesellschaft für Erdbebeningenieurwesen und Baudynamik, 7-35. doi: 10.23689/fidgeo-3864

Camelbeeck, T., Vanneste, K., Verbeeck, K., Garcia-Moreno, D., Van Noten, K. & Lecocq, T. (2020). How well does known seismicity between the Lower Rhine Graben and southern North Sea reflect future earthquake activity? *In: Kaiser, D. (Ed.). Historical Earthquakes, Paleoseismology, Neotectonics, and Seismic Hazard: New Insights and Suggested Procedures*, *DGEB-Publikation 18,* Deutsche Gesellschaft für Erdbebeningenieurwesen und Baudynamik, 53-72. doi: 10.23689/fidgeo-3866

Hürtgen, J., Reicherter, K., Spies, T., Geisler, C. & Schlittenhardt, J. (2020). The Paleoseismic Database of Germany and Adjacent Regions PalSeisDB v1.0. *In: Kaiser, D. (Ed.). Historical Earthquakes, Paleoseismology, Neotectonics, and Seismic Hazard: New Insights and Suggested Procedures*, *DGEB-Publikation 18,* Deutsche Gesellschaft für Erdbebeningenieurwesen und Baudynamik, 73-136. doi: 10.23689/fidgeo-3867

Leydecker, G. & Lehmann, K. (2020). The earthquake of September 3, 1770 near Alfhausen (Lower Saxony, Germany): a real, doubtful, or a fake event? *In: Kaiser, D. (Ed.). Historical Earthquakes, Paleoseismology, Neotectonics, and Seismic Hazard: New Insights and Suggested Procedures*, *DGEB-Publikation 18,* Deutsche Gesellschaft für Erdbebeningenieurwesen und Baudynamik, 36-52. doi: 10.23689/fidgeo-3865

DOI: 10.23689/fidgeo-3864

Best practice of macroseismic intensity assessment applied to the earthquake catalogue of southwestern Germany

Wolfgang Brüstle[1], Uwe Braumann[1], Silke Hock[1] & Fee-Alexandra Rodler[1]

[1] formerly at Regierungspräsidium Freiburg, Landesamt für Geologie, Rohstoffe und Bergbau, Landeserdbebendienst Baden-Württemberg, Freiburg, Germany, email address of corresponding author is wolfgang.bruestle@online.de

Abstract

The earthquake catalogue of southwestern Germany for the last millennium now contains about 30,000 digital macroseismic intensity data points (IDPs). Intensity assessments are based mainly on primary sources using the European Macroseismic Scale 1998 (EMS). The article describes a guideline for best practice of conventional macroseismic evaluation in application to historical and modern-time earthquakes in SW-Germany. Suitability of various diagnostics for intensity assessment is discussed. Assumptions to estimate damage grades and vulnerability classes of buildings are presented. Data restrictions and treatment of special cases are outlined. Further topics are quantification of uncertainties and IDP quality as well as substitutes for intensity. An essential task is to bridge the gap between information from historical sources and seismological needs for use in the earthquake catalogue, thus all issues have a focus on historical earthquakes. Questions of completeness, subjectivity, transparency, and interdisciplinary work are addressed also. Special emphasis is given to a well balanced use of the EMS scale throughout all time periods leading to consistent assessments in the catalogue.

1. Introduction

1.1. Earthquake catalogue

The parametric *earthquake catalogue* of southwestern Germany (SW-Germany) was compiled by the Seismological Service Baden-Württemberg (the “Landeserdbebendienst”, abbreviated: LED) in a five-years project from 2013 until 2017 at Freiburg, Germany (Brüstle et al., 2021). The name of the project was “Seismological and historical compilation of the earthquake catalogue for Baden-Württemberg, SW-Germany, from 1000 AD until today and acquisition of earthquake information in a database” (referred to as “the/this project”). The “LED catalogue” (or simply “the catalogue”, if not specified otherwise) covers the region that is today the German Federal State of Baden-Württemberg including surroundings, as far as seismicity there is seen relevant for the catalogue, hence particularly including the border regions in France and Switzerland alongside the river Rhine.

In this article, the term “historical” is used generally for the time period of the last millennium before the turn of the 19th to the 20th century. All year dates mentioned are years AD. The period of the 20th century and thereafter is called “modern time” or “instrumental time” with reference to the seismographical records. The project was oriented towards a conventional assessment of macroseismic "intensity data points" (abbreviated: IDPs in plural, and IDP in singular form, see section 2.1.1. below) from the most relevant sources. "Conventional" stands for a non-formalized manual evaluation of the sources by expert judgement. The term "sources" is used denoting any kind of information on that the evaluation can be based on. Macroseismic intensities (or "intensities" for short) were assessed using the *European Macroseismic Scale 1998* (published by Grünthal, 1998; hereafter abbreviated and shortly quoted as "EMS" or "EMS scale") and a special guideline (see section 1.2.). Intensity is notated in Arabic numerals. The terms "damage" and "vulnerability" refer to buildings in the sense of the EMS, if not specified otherwise. Internet macroseismic data acquisition and automated determination of intensities are not considered in this article.

The present article focuses on methodological issues of macroseismic evaluations. Examples from the catalogue serve for illustrative purposes only. – In the remainder of this section just a short overview over the catalogue is given. Detailed information about the catalogue and the project, including sources and IDP data, will be published elsewhere (Brüstle et al., 2021).

For the first time in SW-Germany, a systematic and comprehensive search for information about *historical earthquakes* was carried out in the project using *primary sources* as far as possible. "Primary sources" are understood as contemporary witness testimonies, on-site records, field survey reports, first-hand information accounts of various kinds, etc. (occasionally also referred to as "direct sources" or "original sources"). The search for primary sources was considered an essential prerequisite for the compilation of a reliable earthquake catalogue (see also IDP quality in section 2.8.4.). More than 30 archives and libraries were visited on-site and many others online. Altogether about 1,100 relevant documentary sources from the 15th to the 19th century could be found, of which 700 had been unknown to seismology before. For earthquakes in the Middle Ages, on the other hand, almost no new primary sources were found. – Earthquake information was retrieved from various source types, comprising both official and private documents, either handwritten, printed or pictured, for example from annals, chronicles, protocols, repair bills, church registers, sermons, diaries, memoirs, letters, leaflets, notices, gazettes, newspapers, questionnaires, bulletins, catalogues, journals, and visual material. – The historical sources were evaluated in a *historical-critical* way by properly taking into account their context with regard to geographical, political, social, cultural, and mental, as well as to linguistic, historiographical, and archival aspects (see EMS, pages 50-53; Gutdeutsch et al., 1987; Guidoboni, 2000; Gisler, 2003; Grünthal, 2004; Albini et al., 2004; Mayer-Rosa & Schwarz-Zanetti, 2004; Hammerl, 2017; and many others). Great care was taken to ascertain historical detail and to document the sources as well as the evaluation process. Special emphasis was given to a well-balanced use of the EMS scale throughout historical and modern times.

The project work was strongly focussed on historical IDP assessment. For the *historical time period* only few IDPs had been available before. Now, for the first time, historical seismicity of SW-Germany is fully present in IDP format. About 3,000 digital IDPs, with intensities based on the EMS scale, from more than 400 historical earthquakes were determined in the project, in majority of the 15th to the 19th century. This constitutes a completely new data set.

In the *modern time period*, instrumental seismology started in SW-Germany at the beginning of the 20th century. Routine seismographic epicentre localisation and calculation of local magnitudes on the Richter-Scale, however, were established just in the 1960ies. *Traditional macroseismic questionnaire surveys* have been continuously carried out already since the end of the 19th century. At first, the questionnaires had been replied primarily by selected correspondents ("makroseismische Beobachter", i.e. macroseismic observers) with focus on their individual observations. Later on, the system has been changed towards responses from the municipality or town administration offices using a collective form (with questions to the burgomaster office in the style of, "what happened in your commune?"). Hence, in general, an IDP has been based on one collective questionnaire. To a minor part, spontaneous responses, usually in the form of letters and postcards, came in as well. Questionnaires have been distributed and returned by postal mail, lately also by fax and email; the originals are kept in the LED archive. – The bulk of these questionnaires was completely re-evaluated in the project on the basis of the EMS scale. Dealing with various questionnaire styles and handwritings, appropriate working procedures had to be established. Thereby, a high level of consistency of intensity assessments from questionnaires could be achieved, which had not been given before due to changing questions, forms, practices, scales, and evaluators in the course of the 20th century.

For the *modern time*, about 140 of the strongest 20th-century earthquakes in SW-Germany (from about intensity 5 EMS upwards), plus a few after 2000, were re-assessed in the project yielding an amount of about 26,000 digital IDPs. About 80% of these IDPs were derived from the questionnaires, about 20% from direct surveys, letters, postcards, newspaper reports, as well as from secondary transcriptions. This data set is also novel inasmuch as the IDPs are now all digital and consistently based on the EMS scale.

The most recent macroseismic data come from questionnaires using forms made available via the internet (hereinafter termed *internet macroseismic questionnaires*, abbreviated: IMQ); this kind of data is processed automatically, usually within postal code areas (e.g. Wald et al., 1999 and 2011). IMQ data have been collected by the LED since 2012 but are not dealt with in this article.

In a few cases, some IDP data were adopted from other seismological agencies, catalogues, or compilations keeping the original choice of the intensity scale; hence, no transformation of intensities from other scales into the EMS scale (e.g. by using a formula) was carried out. To some part, these "imported IDPs" complement own ones. If own IDPs had been present from earlier work and were replaced by re-assessed ones in the project, the "replaced IDPs" were kept in the database as well, for comparison, with original intensities and scales. A review of intensity scales has been published by Musson et al. (2010).

A *relational database* hosts the entire catalogue, including earthquake and IDP data, all relevant source information, and links relating with the respective text documents. The database structure, with its tables and attributes, is particularly adapted to the needs of historical IDPs and sources. – *Information regarding IDP data* is stored in a table with the following IDP attributes: responsible agency, geographical coordinates, administrative region, seismo-geographical region, location (place name) and additional location information, lower and upper bound intensity, most probable intensity, intensity scale, quality, felt-flag, damage-flag, sound-flag, lights-flag, ground-flag, earliest reporting date, earthquake evidence, and comments. Each IDP is linked to the related earthquake, including date and time, and to the related source(s) using author/reference key(s) and associated importance weight(s). – *Information regarding source documents* is stored in a table with the following source attributes: author(s) or reference, year of publication/origin, place of publication/origin, original archive, complete quotation, comments, type, duration period (time span covered by the source), appraisal, local archive for the source, and local archive for the transliteration (explanations further below). Bibliographical data can thus be queried for IDPs or earthquakes alike. One IDP may be based on many sources (and one source may be related to many IDPs). Within the project, the number of sources supporting an IDP ranged from one to about a dozen.

For the first time, *seismic histories* (chronological sequences of IDP intensities) for places in SW-Germany can be plotted, even though partly incomplete. For the time being, no attempts have been made to draw *isoseismal lines* onto the IDP maps as scatter is generally quite large. Also, earthquake *magnitude and depth* estimates from IDP data have not yet been determined.

At the end of the project, the catalogue contained a total number of about 10,000 *earthquakes with epicentres in SW-Germany* and surroundings, the majority of which were not-felt earthquakes, i.e. instrumentally recorded only, within the last decades. The number of IDPs per earthquake in the catalogue ranged from zero to well over a thousand, some extending to far outside of SW-Germany. For a historical earthquake, the number of IDPs can be considered "a sort of measure of the quality and quantity of information a preinstrumental earthquake relies upon" (quoted from Rovida et al., 2020). *Maximum intensities* of the earthquakes in the catalogue covered the range from 1 to 9 EMS, located mainly in the regions of the Upper Rhine Graben, the Swabian Jura, and northern Switzerland. Earthquake epicentres derived from IDP data (*macroseismic epicentres*) and intensities at the epicentres (*epicentral intensities*) were determined in general on an empirical basis. For completeness, additional earthquake event data was implemented into the catalogue also, adopted from existing regional and national catalogues of Germany, Switzerland, and France, from seismological bulletins and data collections as well as from unpublished documents.

1.2. Guideline

One of the major tasks in the earthquake catalogue project was the evaluation of sources and the IDP intensity assessment. For reasons of standardisation and guidance within a multidisciplinary team working in the fields of historical science, seismology, as well as information technology, a *guideline* has been required to serve as a methodological and coordinative reference and a link of common understanding within the project (see also e.g. Moroni et al., 1996; Guidoboni & Ebel, 2009). Among other topics, the guideline documents best practice procedures of intensity assessment based on EMS principles under historical, seismological, and engineering aspects. It is in general conformity with the EMS scale and has insofar also supported the proper implementation of EMS rules and the consistency of EMS intensity assessments in the project. In part, however, it had to go beyond the EMS. Particularly for assessment of intensity from historical accounts, the guideline also served as a detailing supplement and extension. It has been specially designed for use in the evaluation of earthquakes in SW-Germany, but may be helpful for macroseismic work in other regions as well.

The present article draws from the guideline (see Brüstle et al., 2021) and deals mainly with intensity and IDP assessment related issues in the following sections:

(2.1.) basic concepts (intensity data points, quantities, distribution of effects);
(2.2.) diagnostics (suitable, weak, and unsuitable diagnostics, frightening earthquakes);
(2.3.) damage grades;
(2.4.) vulnerability classes (vulnerability in different time periods, assumptions);
(2.5.) data restrictions (poor data, missing and extrapolating information, negative reports, fake and lost earthquakes);
(2.6.) special cases (earthquake series, earthquakes at night, during mass, ringing of church bells, falling of roof tiles, damage to chimneys, freestanding walls, tall buildings, secondary damage);
(2.7.) substitutes for intensity;
(2.8.) uncertainties (probabilities, uncertainty notation, intermediate intensity, IDP quality, quality and precision); and
(2.9.) other issues (completeness, consistency, subjectivity, transparency, interdisciplinarity).

References are made to the EMS scale (Grünthal, 1998) throughout this article.

2. Intensity assessment

2.1. Basic concepts

2.1.1. Intensity data points

Macroseismic intensity is considered a classification of the severity of ground shaking of an earthquake on the basis of observed effects in a limited area; intensity is derived from “sensors”, which can be people, objects, buildings, and nature (EMS, page 21). The core of the intensity assessment procedure is tied to the conception of the *intensity data point* (abbreviated: IDP). The IDP concept aims at just one single intensity value (“IDP intensity”) that best characterizes the severity of shaking during a particular earthquake expressed by all its macroseismic effects in a village or town as a whole. This locality is called “IDP place”. An IDP is identified as a data triplet of intensity, place, and date (plus time). Our *IDP intensities* were conventionally assessed by expert judgement using the EMS scale. Some authors prefer to use the term *macroseismic data point* (abbreviated: MDP), including also cases where macroseismic information is available but insufficient to assign an intensity value. In this article we use the term IDP only, with IDP being equivalent to MDP without this distinction. The information to assess IDP intensity may come from a variety of sources. In this project, we mainly dealt with paper sources ranging from classical historical documents to postal questionnaires (see e.g. Cecić & Musson, 2004); internet based sources (IMQ, etc.) were not considered.

We assigned *IDP places* to rural municipalities (or sub-municipalities) and urban towns (or town districts in cases of large towns) and evaluated macroseismic effects for assessment of IDP intensity within respective areas (i.e. within respective administrative boundaries). We did not use postal code areas (as it is common for IMQ) because our data were related to towns, villages, and parishes. Our IDPs are thus more related to localities than to population. The place list contained about 3,600 IDP places inside of Baden-Württemberg. This corresponded to an average area of about 10 square kilometres and an average number of about 3,000 people per IDP (in historical time much less people, of course). Only rarely we had to "split an IDP" because of a too large area of the IDP place, for example in case of a large rural municipality, or in order to separate parts of the IDP place area with grossly different underground settings, to obtain suitably smaller areas for intensity assessment in accordance with EMS rules (EMS, pages 26-27). As geo-referencing and geographical coordinates (latitude and longitude in the WGS84 system) of IDPs inside of Baden-Württemberg were concerned, mainly central points of the IDP place areas were used, as derived from data of the land surveying office of Baden-Württemberg.

We based *IDP place names* on a modern gazetteer derived from official lists of commune and town names and took care to use identical place names for historical and modern times. In principal, the most recent name was chosen. We also were attentive to discriminate between different places of the same or a similar name in order to avoid "name confusions". To take an example, 19 different places named "Hausen", some with name extensions, had to be distinguished inside of Baden-Württemberg. Differing names, as for example former names, name extensions, name suffixes and affixes, different language versions, different styles of writing, of the same place were noted in a comment to the IDPs. We also took note of extinctions or movements of places in the course of history as well as of changes in administrative structures. Additional database information was added to the place names, with regard to community, district, region, country, etc., for clarification and to ensure unambiguity. Both place names and coordinates ensured the identity of IDP places.

For historical documents, it was also important to be sure that an IDP place of macroseismic observation was not confused with the locality where the respective source document had been written or published (to avoid "place confusions"; see also Musson, 1998b). Information about earthquake observations that could not be associated with a place in IDP format was entered as a comment to the corresponding event in the database, if possible, or had to be laid aside. Examples for that were occasional fragments of information that had been mentioned in passing, as for instance, "An earthquake was felt in the duchy of Württemberg in the year ….".

We made a particular effort to provide a *common time base* for all periods in the catalogue. We determined the date (day, month, year) and the day of the week associated with historical IDP observations to the best of historical knowledge (see Grotefend, 2007). As for the type of calendar, we transformed Julian calendar dates into that of the *Gregorian calendar*, where applicable (10 days had to be added in the first period of calendar transformation starting 1582). Attention was paid to avoiding the frequent "calendar date errors" and subsequent duplications of earthquakes. Ambiguities of date also arose from an occasional uncertainty in some historical sources whether an earthquake at night time had occurred before or after midnight ("midnight error").

If the hour of the day, or even the minute, had been mentioned in historical reports, we transformed the time into today's *Universal Time* system (Coordinated Universal Time, abbreviated: UTC) to the best of our knowledge. UTC time was generally set as 1 hour earlier than the corresponding local time, if not required otherwise. Different measuring scales of time and hour styles had to be minded. Substitutes for time of day in the historical past had been, for example, "at cock-crow", "at sunrise", "at vespers time", "at dawn", "at midnight", etc. Some of these expressions of time we could translate into an approximate hour of the day, some others remained unspecified. From about mid of the 19th century reported times have become more precise but have also become subject to further corrections (e.g. different local time zones in Germany according to geographical longitude, later also differences due to the alternation of wintertime and summertime, and even double summertime, etc.).

Calendar date and time of day of historical earthquakes were derived from that of related IDPs; reversely, date and time, as well as respective uncertainties, were crucial information for correctly associating IDPs to respective earthquakes. Correct dating/timing helped therefore to untangle IDPs and earthquakes within clusters. This frequently meant to separate erroneously merged or to combine erroneously separated IDPs and earthquakes, respectively, thereby avoiding lost, duplicated, or time-shifted earthquakes in the catalogue due to errors of date and/or time.

In strict accordance with the EMS scale rules, we deliberately did not take the amplifying or attenuating effect of geological underground and soil conditions on seismic waves and ground shaking into account for intensity assessment (EMS, pages 29-30). Any *geological effect* on intensity, whether known or conjectured, was not corrected for but has been kept implicit in the intensity value. Hence, earthquake hazard can be derived directly from IDP data, if so desired. Should a "geological correction" of intensities, nonetheless, be required for some specific application, this will have to be done in the course of a separate processing at a later stage. – The same applies to *topographical effects* on intensity.

Our IDP intensities are *observed values* as they were derived from reported observations. We did not calculate IDP intensities for places with no observations, neither by inter- or extrapolation from other IDP data nor by conversion from instrumental data. We also did not derive any IDP intensities from existing macroseismic maps but we rather re-evaluated the sources. An atlas of traditional macroseismic maps of the 19th- and 20th-century earthquakes in the region has been published by Brüstle et al. (2015), though, for historical documentation.

Maximum intensity for a particular earthquake was, by definition, set to equal the highest IDP intensity observed anywhere in the macroseismic field, if it had a reasonably good IDP quality, and provided that it appeared likely that the maximum could be captured thereby. – By contrast, if *epicentral intensity* could not be based on an IDP observation at the epicentre, simply if there was none, it was generally derived from IDPs nearby in an empirical way (no fractional intensity was calculated, though; epicentral intensities followed the same format as IDP intensities). Epicentres and epicentral intensities outside of SW-Germany were mainly taken over from earthquake catalogues of neighbouring regions.

2.1.2. Quantities

The core concept of the EMS scale is based on the *quantifiers* "few", "many", and "most" (EMS, pages 25-26). In principle, any macroseismic effect should be used for IDP intensity assessment together with its quantity, i.e. together with the frequency of occurrence at the respective IDP place. The definitions of contiguous ranges of respective percentages, as read from the graph in EMS on page 17, are: "few" from 0% to about 15%, "many" from about 15% to about 55%, "most" from about 55% to 100%, with an overlapping range of about 10% in both transitions. In practice, though, we interpreted "few" starting from about 1%. We assumed that "a few", as used in the EMS scale text, can be understood synonymously with "few". "Only very few", however, we interpreted in the sense of less than few, similar to "only at isolated instances …" (which should be less than 1%, according to EMS, page 17). If a source text had used the term "all", we, in general, did not take this literally but translated it into "most" of the EMS-quantification. We were aware of the frequent comprehension of "many" in an absolute sense (meaning "a large number"), which is not the relative sense of the EMS-quantifier percentages. For historical earthquakes, determination of quantities was particularly difficult. In practice, we often had to guess EMS-quantities just from the context. Absolute numbers of buildings and people living at the IDP places could, to some extent, approximately be estimated from town pictures and population statistics.

2.1.3. Distribution of effects

Macroseismic effects are not expected to be uniform within the IDP place. Conventional IDP-intensity assessment is, in general, based on the strongest effects observed at the respective IDP place for the particular earthquake, i.e. on so-called *maximal effects*, and not on effects of average strength. Maximal effects of an IDP usually occur just in few cases ("few" in the sense of EMS-quantifiers) within the IDP place, whereas *average effects* usually occur more frequently, except e.g. for "pile-up" or saturation effects near the upper end of the scale or scale segment (compare EMS, Figure 4-1 on page 60). Finding maximal effects was facilitated by the circumstance that major effects were quite likely much better reported than minor ones. In particular, also spontaneously communicated singular observations tended to be rather on the side of the stronger effects, as this might have been the reason for writing in the first place. Therefore, a sample of known effects was not random but probably skewed towards the stronger ones. We were aware, however, that IMQ data are being evaluated differently (see e.g. Tosi et al., 2015).

Maximal effects should be coherent with other effects at the same IDP place. This is why effects of smaller strength or size should be examined as well, if it is possible. On the other hand, one has to be aware of *singular extreme effects* that may have been caused by constructional defects of buildings ("an earthquake finds out deficiencies"), geotechnical problems or locally-limited anomalous soil conditions at the respective building sites; or may have affected tall (except for 2 EMS; see section 2.6.8.), monumental, or exceptional buildings only (see section 2.2.2.); or may have been extraordinary for some other reason. Singular extremes could also have been due to exaggeration or incorrectness in reporting. The right way for us was to look for maximal effects that were not isolated extremes standing far out from all other effects at the same place. We disregarded any singular large building-damage for intensity assessment at a place where shaking obviously was moderate (see also EMS, pages 27-28). A scenario where, for example, "no other damage occurred except that the church spire broke", even though the shaking was moderate, was reason to assign a lower intensity, if applicable, accompanied by a comment describing the singularity. Notably for historical earthquakes, however, it often remained a discretionary decision whether the report of an individual case of large damage could be included or should be downgraded or disregarded for intensity assessment (see also e.g. Hough, 2013).

It has been postulated that, in an ideal case, the *occurrence-probability distribution of building damage* is, for a given IDP place, intensity, and vulnerability class, an almost normally (Gaussian like) shaped curve about the mean damage grade, except for the "pile-up" effect near the lower and upper bound of damage (with reference to EMS, Figure 4-1 on page 60, and pages 58-60). Intensity is derived from the highest, as well as possibly from the second-highest, damage grade observed for a particular vulnerability class with regard to EMS-quantities (EMS, pages 17-20), and excluding singular extremes (as above).

Similarly, it can be conjectured that, to some extent and for limited parts of the intensity scale, also the strength of macroseismic effects on ordinary objects and on people may follow a quasi-normal occurrence-probability distribution, ranging from minimal to median to maximal effects that are observed for a particular IDP (except near both ends of the scale or scale segment because of "pile-up" or saturation, accordingly); an idealized example distribution of the expected *occurrence frequency of the strength of macroseismic effects* for an IDP, with regard to EMS-quantities, is schematically sketched in Figure 1.

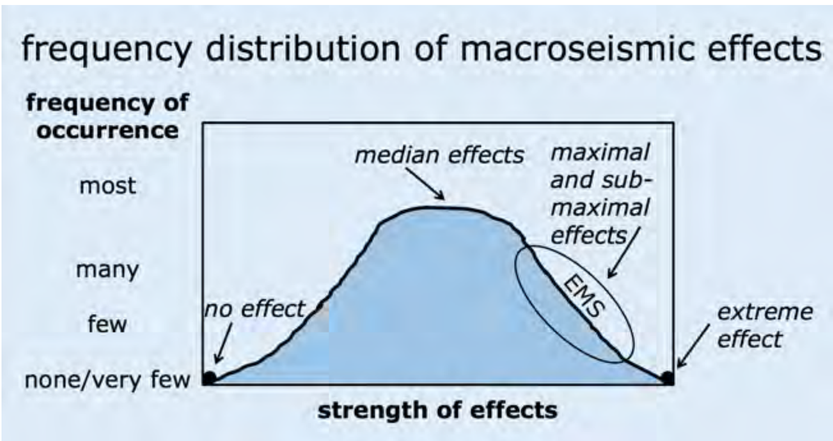


Figure 1. Sketched example of expected occurrence-frequency distribution of the strength of macroseismic effects for an IDP (within the IDP place for the particular earthquake). IDP intensity (EMS) is assessed from effects at the upper tail of the distribution curve. Further explanation is given in the text.

Again, IDP intensity is assessed from the maximal, as well as possibly from the sub-maximal, effects at the upper tail of the distribution curve, taking respective quantities into account. Obviously, given this distribution, an IDP intensity assessment based on the effects that occur with the highest frequency (sometimes referred to as being the "representative" ones) would quite likely be too low, and an assessment based on effects at a randomly selected single site within the area of the IDP place would hardly be relevant. In practice, a detailed distribution can be obtained in cases of high-quality IDP data sets only.

2.2. Diagnostics

2.2.1. Suitable diagnostics

What are suitable *sensors* and *diagnostics* for assessment of intensity (EMS, pages 21-22)? All features that by and large linearly scale with intensity are suitable to be used as indicators ("diagnostics"), at least in parts of the scale. Up to intensity 6 EMS, one of the best type of diagnostics simply is the percentage of people (the "sensors") that have felt the earthquake. Situations where observers are indoors, outdoors, or sleeping are differentiated by the EMS scale (see, however, Sbarra et al., 2014). For intensities of 6 EMS and higher, buildings are generally the best sensors, and building damage is the best diagnostic if taken as the quantities of buildings of a particular vulnerability class that suffered particular damage grades at the respective IDP place. Observations and diagnostics are never complete, though. Hence, the best way of intensity assessment is that of a *pattern matching* between the observations (i.e. "the data") and the scale (i.e. "the model") and thus determine the best fit in each case (EMS, pages 27-28; Musson, 1998a; and others).

2.2.2. Weak diagnostics

Any building damage that is not directly caused by seismic ground shaking should according to the EMS scale not be considered for intensity assessment (EMS, page 24). Nevertheless, in cases of sparse information we did consider some other earthquake-related effects, described in the following, offering *weak diagnostics*.

Weak diagnostics, in the aforementioned sense, may have been derived from building damage that was not due to ground shaking but due to dislocation of building foundation because of non-reversible, i.e. permanent, *earthquake related ground movement* (e.g. ground dislocation, subsidence, spreading, tilting, sliding, etc.). We noted earthquake-induced permanent changes on the ground surface in any case, at least in form of a "ground-flag" to the IDP. Likewise, weak diagnostics could have come from *geotechnical damage* resulting from such permanent ground movement (e.g. base failure, breaking of subsurface pipes, cracks in embankments and pavements, etc.).

Furthermore, we regarded some *effects in the natural environment* related to the earthquake as potentially representing weak diagnostics. Such effects in nature were, for example, hydrological anomalies (changes of springs, wells, ground water, etc.), anomalous waves in lakes or basins (seiches, etc.), cracks and fissures in the ground, liquefaction, slope instabilities (landslides, rock falls, etc.), shaking of trees and bushes, etc. (see EMS, pages 95-98; Vogt et al., 1994; and others). Effects in the natural environment, however, are more favourably measured on the *Environmental Seismic Intensity Scale* (abbreviated: ESI; e.g. Michetti et al., 2007) and were, for the intensity range below 9 EMS and in presence of "ordinary diagnostics", not regarded essential for assessment of intensity in this project.

With care and restrictions, we did also use some reports of *damage to exceptional buildings* (towers, freestanding walls, fortifications, bridges, dams, etc.) and to *monumental buildings* (palaces, castles, large churches such as cathedrals, halls, etc.) as constituting weak diagnostics, even though these are not buildings listed for standard EMS intensity assessment (EMS, pages 29 and 53, etc.). We were particularly aware of the danger to overestimate intensity from this sort of damage (see e.g. Graziani et al., 2015). Damage to monumental buildings, on the other hand, was the sort of damage preferably reported in historical times. In view of the generally sparse information from historical earthquakes, we could not completely exclude it from the assessments; we made exceptions if it was accompanied by comparatively coherent other observations. If it was the only information for an IDP, however, a favourite choice was to merely assign a "damage-flag". A particular feature that had to be paid attention to is that damage to monumental buildings to a greater extent results from a lower frequency band of ground motion (see e.g. Camelbeeck et al., 2014). If churches and halls were just of small size, we generally did not classify them as monumental buildings. Caution was demanded, though, if damage at several places in the region had exclusively been reported from church towers, for example.

The *twisting and rotation of objects* (for example gravestones, monuments, etc.) was considered typical for earthquake damage scenarios on the one hand, but proved less suitable for intensity assessment on the other (e.g. Lombardi et al., 2016). The same held for *falling of roof tiles*. – *Falling of elements of parapets, claddings, architectural decorations* (pillars, statues, figures, etc.) from the façade or from the top of buildings was even more difficult to evaluate than that of roof tiles, as the building settings were more divers. A civil engineering study on this topic has been published e.g. by Rudisch et al. (2016). A notable example in the catalogue is the incident in the November 16, 1911, earthquake with epicentre at Albstadt, SW-Germany, where the large stone monument of the imperial eagle was thrown down from the top of the main post office at Konstanz, SW-Germany, in about 60 km epicentral distance (IDP intensity at Konstanz was assessed as 7 EMS from the total of observations there).

Some of the aforementioned diagnostics are discussed as "special cases" in section 2.6. We tried, with caution, to make use of weak diagnostics in complementing other observations or, at least, for assigning a lower limit of intensity. A last resort to parameterize weak information was just using a "flag" substituting intensity (see section 2.7.).

2.2.3. Frightening earthquakes

The personal judgement of a witness or author whether an earthquake had been experienced as *slight, moderate, or strong shaking* turned out to be a weak diagnostic as well, even though it directly points to the meaning of intensity. The reason was that, in our opinion, such rating was per se rather subjective and, in general, inconsistently used. It sometimes also seemed to have been intrinsically linked to the individual sensation of fright.

In the same way, we found the extent to which earthquakes had *frightened people* in historical times to be rather subjective, and hence rather unreliable for assessing intensity (accompanying reports of how many people had been running outdoors were seen to be more objective, though).

When earthquakes in SW-Germany were mentioned in older historical sources, the incidents often seemed to have been termed "frightening" out of habit. A common way of speaking about earthquakes was that of "ein schröckliches Erdbeben", meaning "a terrible earthquake". Earthquakes apparently scared people in general, not necessarily because shaking was strong but merely because even a moderate one was a rare and disquieting experience in SW-Germany. Various historical theories "from Aristotele to Kant" (Oeser, 1992) about the origin of earthquakes, searching for natural causes inside the earth instead of a religious explanation as an "act of God", could not relieve the general fear. Particularly before the Age of Enlightenment, an earthquake was frequently seen as a supernatural event, a *miraculous sign* (prodigium, "Wunderzeichen"), as God's warning ("Menetekel"), anger, or punishment, and eventually as a forerunner of something worse (see e.g. Gisler, 2003; Schwarz-Zanetti & Fäh, 2011; Hammerl, 2017; and many others). The contemporaneous writer himself may have had a mindset, belief, or even intention that favoured the report of "fear and fright". The frightening effect actually related to intensity was hard to assess for us, as frightening, historically, seemed to have been more dependent on mental, cultural, social, and religious factors than on earthquake intensity; hence, we used it, if at all, as a weak diagnostic only.

Similarly, we could hardly interpret the reported *duration of earthquake shaking* in terms of earthquake parameters, since shaking durations in historical times often seemed to have been exaggerated. Reports ranged from the "duration of a Lord's prayer" to "several minutes". Eventually, an earthquake was even said to have "lasted for hours", hence probably was confused with the following aftershocks.

We also found that the *behaviour of animals* during earthquake shaking could not easily be related to intensity. Frequently, domestic animals were reported to have shown frightened reactions at lower intensities than is suggested by the EMS scale. Hence, we disregarded the EMS-rating of animal reactions.

2.2.4. Unsuitable diagnostics

A vast number of *meteorological and astronomical observations* during earthquakes have been reported in historical documents, such as wind, precipitation, air pressure, temperature, phases of the moon, fall of meteorites, and several other. We disregarded all these for intensity assessment as there were no proven physical relations to earthquakes and intensity. Yet, we usually noted the observations in a comment, as well as concurrent events of other kind.

Observations of *earthquake sounds* and *earthquake lights* we did not use for intensity assessment either (the latter are poorly understood anyway) but rather described these acoustical and visual effects in a comment to the respective IDP and attributed a "sound-flag" and a "lights-flag", if applicable.

In historical sources we found reports of observations of *visibly swinging walls or towers*; observations of this kind could, for the earthquakes evaluated in this project, not justify high intensities on its own. We rather suspected that such observations could have been caused by an effect of motion of the observers eyes, if they were not just pure imaginations triggered by excitement. In a similar way, we decided in cases of reports of e.g. "waves seen on firm ground".

The number of *human fatalities* and *injured people* in an earthquake was, albeit correlated in general, regarded not to be related to intensity in a way to allow assessment of intensity without further constraints (see e.g. Coburn et al., 1992). An example taken from the region is the 1356 Basel, Switzerland, earthquake (e.g. Fäh et al., 2009).

Finally, we excluded all "secondary damage" effects (subsequent damage following the primary one, see section 2.6.9.) from intensity assessment.

2.3. Damage grades

For intensity assessment in the damage part of the EMS scale (i.e. from 5 EMS upwards) earthquake damage to buildings is considered according to *damage grades* (see EMS, pages 24-25). The EMS-classification of damage grades ranges from grade 1 (lowest damage grade) to 5 (highest damage grade). In simplified terms, damage grade 1 is for negligible to slight damage, grade 2 for moderate damage, grade 3 for substantial to heavy damage, grade 4 for very heavy damage, and grade 5 for destruction; a distinction is made between structural and non-structural damage (EMS, pages 15-16). For the relevant provisions of damage grades we refer to EMS.

In principal, the damage grade may change from one house to the next at the same IDP place, even with unchanged vulnerability class; thus, damage to one randomly selected house is not decisive for IDP intensity (see section 2.1.3.).

We were aware of the problem of *pre-damaged or weakened buildings*. Damage from previous earthquakes had to be excluded as far as possible (see section 2.6.1. about earthquake series). We also attempted to distinguish between shaking as the relevant cause for building damage on the one hand and shaking that constitutes a kind of "triggering effect" for building damage, whereby deficits in construction, material, or maintenance were likely to actually be the relevant causes, on the other hand. These problems are addressed also in the context of building vulnerability.

Determination of *damage grades from historical sources* was particularly difficult, as damage descriptions were rarely detailed to the needs of the EMS scale and almost no pictures were available. Therefore, the assessment of damage depended on text and wording. The vocabulary had been different, though; hence, the meaning of terms as "damaged", "destroyed", "ruined", "collapsed", etc., as well as "much", "large", "great", "terrible", etc., or even respective superlatives, in historical documents was not necessarily the same as in modern times or in the EMS scale text. For assessment of damage grades from historical accounts, historical criticism had to be applied and inferences had to be made from the general context (see e.g. Musson, 1998b). We took care to avoid any overestimation of intensity due to reports of singular damage, suspected exaggerations or generalisations. A reliable intensity value could be assigned only if historical sources included sufficiently detailed information about the damage.

In general, an error in building damage being wrong by one grade may result in an error of intensity of one degree of the EMS scale. We nonetheless felt that, in comparison of sources, IDPs, and earthquakes over several centuries, our assessed intensities were not grossly over- or underestimated due to systematic errors in damage grades.

2.4. Vulnerability classes

2.4.1. General remarks

For intensity assessment in the damage part of the EMS scale (i.e. from 5 EMS upwards) earthquake vulnerability of buildings is considered according to *vulnerability classes* (see EMS, pages 31-49). The EMS-classification of building vulnerability comprises four main groups: masonry, reinforced concrete (abbreviated: RC; possibly with some level of earthquake-resistant design, abbreviated: ERD), steel, and wood; the structures (buildings) are differentiated into six vulnerability classes ranging alphabetically from class A (highest vulnerability) to class F (lowest vulnerability). According to EMS, in simplified terms, class A is the most likely vulnerability class for adobe (earth brick), rubble stone, and fieldstone masonry; class B for simple stone masonry and unreinforced masonry with manufactured stone units; class C for massive stone masonry, unreinforced masonry with RC floors, and RC frame / RC walls without ERD; class D for reinforced or confined masonry, RC frame / RC walls with moderate level of ERD, and timber structures; and class E for RC frame / RC walls with high level of ERD and steel structures (with reference to EMS, page 14). Strengths and weaknesses of a building may change its vulnerability class within specific ranges (EMS, pages 14 and 47-48). The lower the vulnerability the higher is the *earthquake resistance* of the buildings (EMS, pages 33-34). Class F is for structures of the highest earthquake resistance due to the incorporated design principles (EMS, page 32). For the relevant provisions of vulnerability classes we refer to EMS.

Because of lack of information we mostly could accomplish the determination of vulnerability classes, particularly for historical earthquakes, in a general and presumptive way only. We distinguished different time periods.

2.4.2. Vulnerability in different time periods

Tyagunov et al. (2006) have given an overview over vulnerability classes of the recent residential building stock in Germany. Based on this publication, we estimated *for the second half of the 20th century* that vulnerabilities of residential buildings in SW-Germany were essentially represented by the vulnerability classes A to D and were, generalized, predominantly of class B and C, with a smaller fraction in class D, and a very small one in class A. Notably, in communities up to 3,000 inhabitants most buildings were classed as B, whereas in towns starting from 30,000 inhabitants most were classed as C (Tyagunov et al., 2006). As these findings provide just a general vulnerability composition, they could only be applied in a generalised way. Beginning with this most recent time period, we developed a tentative picture of building vulnerabilities in earlier times.

For the first half of the 20th century, we estimated that the general distribution of vulnerability classes from the second half of the century, as described above, was shifted a little bit towards higher vulnerabilities, such as that there were fewer C- and D-class buildings and in turn more of class B. The reason for this was seen, among others, in fewer RC buildings on the whole and, particularly also, fewer RC floors in masonry buildings and more wooden floors accordingly.

For the period from the end of the 19th century backwards in time to about the 16th century, we found very little information about historical building techniques and architectural history in SW-Germany from that earthquake resistance could be derived. Moreover, the EMS vulnerability classification is not specially adapted for historical buildings (see, however, EMS, page 51). On the whole, we regarded the main part of the residential building stock in SW-Germany for this time period to have been of masonry type and half-timbered structures, respectively, to a smaller part also timber structures; we tentatively estimated that the general distribution of vulnerability classes was again shifted to higher vulnerabilities as compared to the first half of the 20th century, but again not very much so. If going back in history, we assumed that the portion of A-class buildings was, on the whole, increasingly larger, partly because of lower structural engineering standards and poorer economic conditions. At times, high vulnerability could also have been related to wars and crises, for example. In general, however, the *sustainable material* that had commonly been used for buildings in SW-Germany and the *good workmanship* at large still spoke in favour of a majority being of vulnerability lower than class A. Houses had been built to resist wind and snow, particularly also in the countryside and in the low mountain ranges, which implied a basic resistance against earthquakes as well. A robust design, high-quality building materials available nearby (mainly brick, stone, and wood), and a good state of maintenance and repair had been sought, as the quality of the houses reflected the reputation of the people and the houses ought to be used by subsequent generations as well. The number of storeys had generally been low, the openings small, and the ground plans and structures fairly regular. – Compound constructions using wooden framework (*half-timbered structures*, "Fachwerk"), with infill panels of stone, brick, wattle and daub, or other, had widely been in use. A collection of almost 700 painted "town views" in the duchy of Württemberg was prepared by Kieser in the years 1681 to 1686 (Kieser, 1681-1686). The "Kieser atlas" pictures showed that half-timbered masonry constructions had at that time dominated for residential houses in towns and villages of the region. The atlas also showed the size of each settlement. We assumed a favourable performance of half-timbered buildings in earthquakes, which, however, extended primarily to the bearing wooden structure and therefore rather applied to high damage grades (heavy structural damage or collapse) but not to low damage grades (related to cracks in masonry infill, cladding, plaster, etc.). See also EMS, pages 48-49, as well as pages 40-42.

The considerations above led us to assume that, for the purpose of this project, the majority of residential buildings in SW-Germany in the time period from about the 16th to the end of the 19th century can be estimated to be of vulnerability class B, with minor parts in class A and class C, and some minor portion even in class D. A differentiation between urban and rural areas was considered in individual cases if possible. In conclusion, we were aware that our picture of historical building vulnerability is generalized and hypothetical. Much more research is necessary to better determine building vulnerability in the historical time period.

For the medieval time period (the Middle Ages), building vulnerabilities have, in a general way, not been evaluated in this project.

2.4.3. Vulnerability assumptions

In practice, building damage should be linked to the actual vulnerability of the buildings in question. If the vulnerability of the damaged buildings was known, we could properly take it into account. If it was not known, as usually was the case in the historical time period, and if no better estimate could be made, we assumed a *notional vulnerability* class B for intensity assessment of residential buildings in SW-Germany for all time periods after the Middle Ages (see also EMS, pages 48-51). If there were some indications to one or the other side, we rather considered notional "intermediate classes" B-C in the 20th century and A-B in the historical time range on a case-by-case basis. For the medieval time, in particular, we decided on vulnerability classes individually. Non-residential buildings had to be treated separately and also case-by-case.

If buildings are pre-damaged or weakened, for instance due to preceding strong earthquakes, or due to acts of war, bad state of maintenance and repair, or simply age and dilapidation, it can be seen as a *conditional increase of building vulnerability* with regard to the original vulnerability. We tried to handle these cases individually (see also sections 2.3. and 2.6.1.).

We were aware that damaging earthquakes affect the higher-vulnerability buildings in a stronger way than the lower ones (see also EMS, pages 47-48 and 51). Thus, for IDP cases of a small number of damaged houses at a particular place and without knowledge of their actual vulnerabilities, it could be suspected that the damaged houses were just those with the *highest vulnerability locally* (hence e.g. rather class A than B or better). As, on the other hand, a few ordinary houses of vulnerability class A, respectively also houses in poor condition, had quite likely not been in the focus of historical reports, we did not take this consideration as a reason to a priori change the general rule. For the modern time period, on the other hand, vulnerabilities of damaged buildings were much better known, though.

In general, an error in building vulnerability being wrong by one class may result in an error of intensity of one degree of the EMS scale. The dependence of intensity on vulnerability class is of the same order as on damage grade. Since, in general, it was easier to determine damage grades and quantities than vulnerability classes, vulnerability was seen as the least known and hence most delicate parameter in the assessments. We nonetheless felt that, applying the assumptions above, our assessed intensities were best estimates, for the time being, also in regard to uncertainties of vulnerability class.

2.5. Data restrictions

2.5.1. Poor data

Documentary sources reporting about historical earthquakes tended to be brief and fragmentary, and, with respect to the seismological information contained, frequently even sparse, vague, ambiguous, and contradictory. Obviously, reports about earthquakes were in historical times rarely written for seismological purposes but rather for social ones; hence, the seismologically useful information content may have been small even in a lengthy treatise. The choice of what was important to be written down in case of earthquakes changed during the centuries. A different mentality was reason for a different kind of awareness and also a different *style of writing* (e.g. Guidoboni, 2000). The purpose of writing may even have been anything else but reporting facts. The "Zeitgeist" has changed then in the 19^{th} century when many reports began to consider seismological aspects out of their own interest.

Particularly for historical accounts, quantities, damage grades, and vulnerability classes, as specified in the EMS, had mostly to be inferred from the context or conjectured by way of comparison. We were very cautious in dealing with IDP intensity assessments based on *singular observations*, for example, if we only knew a single person's perception or a single building's damage description (see also EMS, page 28). For historical earthquakes, we could, nevertheless, not completely omit all *poor-data* IDP cases. We made exceptions if circumstances suggested that a singular observation reported can be understood as an example standing for similar perceptions or comparable damage at the same place as well. Particularly, the damage to the village church could have been mentioned exemplifying damage in the village as a whole. Whether this had probably been the case or not, we had to judge from the context. Ultimately, we tried to assess IDP intensities from poor information also, but rated them as being uncertain (see section 2.8.4. about IDP quality).

Such exceptions were justified, however, just to a certain limit. In cases of *very poor information*, we generally did not assign an intensity value but a "felt-flag" or a "damage-flag", if possible (see section 2.7. about substitutes for intensity). We avoided any inappropriate parameterisation of vague historical information but stored such information in textual form.

If, moreover, an earthquake was documented by one single and poor-data IDP only, the situation was even more precarious for the question of certainty of event type ("has it actually been an earthquake?"), let alone for the question of epicentral location and intensity. All such "one-IDP-events" in historical times are encumbered with uncertainty (e.g. Musson, 1998b).

2.5.2. Missing information

For the lower part of the scale (below 6 EMS), intensity is assessed mainly from the severity of earthquake shaking as perceived by people; for the upper part, intensity is to be based on damage. We generally assigned IDP intensity 6 EMS or higher only if building damage had occurred; this applied for modern-time earthquakes in any case. A small exception to this rule were some historical IDPs assessed as 6 EMS where shaking believably had been very strong but *damage was not mentioned* ("no evidence"). In historical context it seemed possible, though, that strong shaking as such and its various effects on people and objects were seen to be more relevant for reporting than a few detached roof tiles or cracks in ordinary houses, for example. The latter may have been unknown to the writer also.

We generally tried to avoid concluding from any *missing information* that something, we would like to know but was not mentioned in the sources, actually had not happened (see also EMS, pages 28 and 52; Musson, 1998b; and others). Especially in the historical past, there may have been many reasons for omitted information, missing reports, or just gaps in knowledge. In some cases, however, no mention of damage from authoritative sources could be used to, at least, disprove a high IDP intensity.

2.5.3. Negative reports

Negative earthquake reports ("Fehlanzeigen", "état néant", "nil returns", etc.) usually stood for the message "nothing to be reported". Negative reports were frequent in 20th-century questionnaires collectively reporting for an entire village or town, since the return of the questionnaire form was asked for even at the edge of perceptibility. We interpreted such negative reports in collective community-questionnaires cautiously in the sense of "the local authority / the reporter is not aware of the earthquake being felt at this place". We generally did not translate negative reports of this kind into intensity 1 EMS (which is for "Not felt, even under the most favourable circumstances"; EMS on page 17) without careful review, even if the report literately read "the earthquake has not been felt here" (which often more likely meant "has not been felt here to our knowledge"). In many such cases, particularly near the presumed edge of the area of perceptibility, an IDP that came with a negative report in the first place turned out later to be probably of intensity 2 or 3 EMS, occasionally it could have even been 4 EMS.

Estimating the outer *edge of perceptibility* was difficult as intensities 1 and 2 EMS can hardly be discriminated by conventional questionnaire surveys, let alone by historical research. Intensity 2 EMS is, by definition, scarcely felt, i.e. felt by less than 1% of the people under special circumstances (EMS, page 17), and many of them will have ignored or quickly forgotten about the tiny sensation. Even news media today are unlikely to report about an intensity as low as 2 EMS. The situation might change with IMQ (see e.g. Boatwright & Phillips, 2017), though, or with reports focussed on high rise buildings, for instance. For good reasons, the traditionally determined "perceptibility radius" is better defined referring to 3 EMS rather than to 2 EMS.

Overall, we were very careful in evaluating any "negative evidence" for the perception of shaking. Negative reports in the sense that the earthquake has been felt but building damage did not occur we regarded to be more credible and significant, though.

2.5.4. Extrapolating information

In general, we also avoided to "extrapolate" a diagnostic that is specified in the EMS scale for one intensity degree only to a higher or lower degree, if this was not supported by empirical evidence. For example, "In a few cases window panes break" is a diagnostic for 5 EMS (EMS, page 18). "Many window panes break" is not explicitly mentioned in the EMS scale text but could point to an intensity higher than 5 EMS. Which intensity was appropriate therefor, had to be decided case-by-case. – Some diagnostics, moreover, show a *saturation effect*. If, for example, a report read "felt indoors by all", we did not take it, on its own, as an evidence that the intensity was higher than 5 EMS.

2.5.5. Fake earthquakes

Particularly in historical sources, we encountered a number of reports describing "earthquakes" that finally had to be classified as events that are not tectonic earthquakes in the seismological sense. This, first of all, resulted from the habit of some historical authors to use the term "earthquake" for any sudden shock or vibration. In many such cases, we had to deal with observations during a storm, particularly a *thunderstorm*, that had been associated with an earthquake or even named as such. IDPs of this kind ranged from virtually 3 to 5 EMS. Only careful interpretation of the sources led us to recognise such an event as a *fake earthquake*. Decision about the type of event came from the kind of effects reported (e.g. "rattle", "tremble", "bang", etc. in case of a storm) and, more convincing, from evaluation of several IDPs of the same event. In particular, a "flag" for "earthquake evidence" was routinely assigned to IDPs indicating whether the reported effects for themselves, at this place, suggested that the event was a tectonic earthquake or not. – Similarly, also several occurrences of *landslides*, and even *meteorite falls*, had erroneously been classified as earthquakes in some earlier publications, which we could correct in this project. Most prominently, we found the event in 1588 at Singen (Hohentwiel), SW-Germany, to be definitely not a damaging earthquake, as it had been claimed before, but a large landslide.

Many fakes simply arose from dating errors, erroneous locations, transcription errors, confusions, misinterpretations, and hoaxes. We documented fake earthquakes, and included them into the database (flagged as "false/fake"), to prevent their reappearance in future earthquake catalogues as "zombies" (e.g. Musson, 2005).

2.5.6. Lost earthquakes

We have to assume that in the historical past many earthquakes had been documented of which the information is no longer available today or, at least, has not been found yet. These “forgotten earthquakes” are missing in the catalogue, unless they are recovered by future research. The research done in this project yielded 134 “new” earthquakes, i.e. earthquakes that had been unknown to modern catalogues before. These earthquakes, almost entirely, occurred from the 16th to the 19th century; none of them had an intensity of more than 6 EMS.

Earthquake historiography is strongly affected by other contemporaneous events. If earthquakes occurred during natural disasters of larger size, during times of war (e.g. The Thirty Years’ War 1618 to 1648), famine, epidemic plagues, etc., nothing at all may have been written down about them. In historical times, smaller earthquakes were probably often not recognized by chroniclers or, if so, were regarded not to be relevant for any writing. A particular consequence of *lost earthquake information* is the increasing incompleteness of IDPs and earthquakes as we go back in historical time (see section 2.9.1. about completeness).

2.6. Special cases

2.6.1. Observations during earthquake series

Assessing intensity, special caution is warranted in cases of *earthquake series* (seismological terminology distinguishes foreshocks, mainshocks, aftershocks, multiple shocks, etc., and sequence, cluster, swarm, etc.), when earthquakes follow each other rather closely in time and space. This regards to both building damage as well as perception of shaking.

If the time interval between successive strong earthquakes had been short and damage could not be assigned to a particular earthquake in the series (see e.g. Camassi et al., 2008), an individual assessment of intensity was not possible. Building vulnerability, moreover, may have been increased for buildings affected by preceding damaging earthquakes even though structural damage may not have been obvious (see also EMS, pages 25 and 41, etc.); in such cases of *pre-damaged or weakened structures*, intensities in subsequent earthquakes could have been overestimated. Even if *damage progression* had been surveyed, the problem of *vulnerability increase* in subsequent events remained. Often only a kind of “cumulative assessment” of damage and intensity was possible, but not an individual one (compare e.g. Graziani et al., 2019). The sequence pattern of damaging earthquakes in a series can also be very complex (e.g. Guidoboni & Valensise, 2015; Rossi et al., 2019; Azzaro et al., 2020; and others). – An example taken from the SW-Germany catalogue is a series of damaging earthquakes in 1943 with epicentres in Albstadt, SW-Germany; a strong foreshock and the mainshock occurred within one month, on the 2nd and on the 28th of May 1943, respectively, reaching IDP intensities up to 7 and 8 EMS. In this case, we tried to assess intensities of the two earthquakes individually.

On the other hand, also people’s perceptions and corresponding reports are strongly influenced during a series of felt earthquakes; *individual and public awareness* is generally intensified. Within long lasting series in SW-Germany we encountered amplified perception by *sensitisation*, depending on the sequence of events and intensities, earlier seismic history, perceived seismic risk, opinion-forming, individual attitudes, etc. (see also e.g. Cucci & Tertulliani, 2007). – In rare cases, there was also a tendency towards diminished perception because of *habituation*. An example for the latter is the earthquake series 1822/23 with epicentres near Freudenstadt, SW-Germany, comprising almost 100 felt events within about one year and maximum intensities of up to 6 EMS. A report from the Freudenstadt series read, “We had an earthquake as usual”, without many details. Newspaper reporting had ceased to some extent as there had been “no news” about “the earthquakes” any more.

There inevitably are historical earthquakes in the catalogue that are *intrinsically cumulative* consisting of closely successive events that could not be distinguished on the basis of the available reports. Any suspicion, coming from the sources, that an earthquake had in fact been a double, triple, or multiple event was noted in a comment.

We did not apply a rule of thumb to solve the problems of assessing intensity within earthquake series. We took, however, all constraints into account, mostly case-by-case. If in doubt, we just assigned a "felt-flag" or a "damage-flag", respectively. We tried, in any case, to acquire earthquake series data as completely as possible.

2.6.2. Earthquakes at night

On a long term average, about half of all earthquakes should occur at night. We nonetheless regarded an earthquake during night time as a case that demanded attention. Being *woken up by an earthquake* is a simple and objective characteristic for intensity. Hence, the information on how many sleeping people were woken up by the shaking is a particularly good type of diagnostics in the lower intensity range. In this respect, we consistently evaluated the 20^{th}-century macroseismic questionnaires of earthquakes at night. Unfortunately, the quantity of people that had been woken up was rarely specified. With some assumptions, however, this quantity could be derived from the overall quantity of people that were reported to have felt the earthquake (indoors). As a result of this study, we assumed that if the earthquake had been "felt by many" (in the sense of EMS-quantifiers) during main sleeping-hours (i.e. between about 1 and 5 o'clock at night), this pointed to 5 EMS, instead of 4 EMS outside this time window.

2.6.3. Earthquakes during mass

Historical earthquakes that had occurred *during church service* were seen as being special cases in that the perception of shaking seemed to have been intensified. Occasionally, also panic reactions had occurred due to the special circumstances. We interpreted these scenarios in a historical context.

2.6.4. Ringing of church bells

Also special cases in the historical past were those when bells in church towers started to ring caused by earthquake shaking. *Ringing of church bells* was included in some earlier intensity scales, but had, to our knowledge, just occasionally been reported in the sources. Historically, it surely was a remarkable effect and should hardly have failed to be heard and noticed. We regarded church bells to be bad sensors for assessing intensity inasmuch as spontaneous church-bell ringing in case of earthquakes depended heavily on several other factors, as for example on dominating frequencies of seismic waves and resonance of the church tower, design of the bell system, and unknown technical details of ringing mechanism and practices (locked, hammered, or "pre-set" bells, etc.). An engineering study about the topic has been published by Blakeborough (2001). We assumed that ringing of church bells, if it had occurred, could be seen as an indication for a lower limit IDP intensity 5-6 EMS (see e.g. Hough et al., 2000, for a few observations). Notably, there were several cases in history when strong distant earthquakes caused church bells ringing over a large area in SW-Germany.

2.6.5. Falling of roof tiles

Detachment of roof tiles is an earthquake effect listed for damage grade 3 in the EMS scale (EMS, page 15). We did not follow this classification as we thought that, for SW-Germany earthquakes, roof tiles started to slip and fall in situations that were closer to damage grade 2 or even grade 1 of masonry buildings (let alone that tiles used to fall during storms also). Falling tiles have, on the other hand, little to do with building vulnerability as a whole or damage to the main part of the building, as was confirmed by pictures of heavily damaged buildings with almost unaffected roof tiles on top (for example from several European earthquakes of the last decade). We estimated roof tiles not to be particularly good sensors of intensity anyway, since *detachment and fall of roof tiles* in case of earthquakes strongly depended also on several other factors, as for instance the dynamic response of the building top, the steepness of the roof, the type of tiles, how firm the tiles lay on the roof battens and were attached to each other, the state of repair in general, whether there was a snow grid, etc. According to Brendler et al. (2006) horizontal acceleration alone will hardly lead to detachment and fall of roof tiles, vertical acceleration was seen to be relevant. We usually considered roof-tile damage as an indication for an IDP intensity of at least 5-6 EMS if some tiles had detached respectively fallen from the roofs of several houses at the place.

2.6.6. Damage to chimneys

Earthquake damage to chimneys in SW-Germany has widely been reported, particularly as it has been (and still is) enquired by questionnaires. Chimneys had even been used as special sensors of intensity in older studies (e.g. von Schmidt & Mack, 1912), and chimney damage has since been regarded to be a favourite diagnostic. We found empirically that IDP intensities 6 and 7 EMS could be derived, or at least consistently been supported, from surveys that had focussed on quantities and grades of chimney damage. We disregarded damage to factory chimneys, however, for assessing intensity. – In the following, only residential masonry chimneys are considered. Fragility of these chimneys depended, for example, on design, height (i.e. height above the roof), material, age, state of repair, and further on the way the chimneys were integrated into the structure of the buildings (see e.g. Maison & McDonald, 2018). We, nevertheless, took damage to 20th-century un-reinforced brick-built rooftop-chimneys of ordinary height to be an indication for damage grade 2 or 3 of masonry buildings (EMS, page 15), depending on how badly chimneys were damaged. We attributed a damage grade 2 for reports of "cracked", "partly collapsed", "partly broken", "damaged", etc. chimneys and a (minimum) damage grade 3 to cases where chimneys had been reported to have "fractured at the roof-line", "fallen off the roof", "collapsed", "been broken", "been destroyed", etc. As there was little dependence of chimney damage on the overall building vulnerability, damage to chimneys could be considered separately. If assessing intensity solely from chimney damage, we generally assumed a fictitious building vulnerability of class B (with results proven empirically).

2.6.7. Damage to freestanding walls

In case of historical earthquakes, there were a number of reports of *damage to freestanding walls*, as for example town walls, graveyard walls, garden walls, etc. *Non-freestanding walls*, as retaining walls, embankment walls, fortification walls, etc., were occasionally also mentioned in the sources. All these kind of walls are not buildings, or parts of buildings, in the sense of the EMS vulnerability classification. In looking to archeo-seismological studies, however, we nevertheless could come to some cautious estimates regarding lower limits of intensity (generally about 6-7 EMS).

2.6.8. Perceptions in and damage to tall buildings

Intensity assessments from *observations in tall buildings or on higher floors*, respectively, have been discussed by many authors, some also with regard to earthquake magnitude and distance (e.g. Sbarra et al., 2012 and 2015). In SW-Germany, this discussion goes back to Lais (1914). We followed the EMS recommendation to discount all perception reports "from observers higher than the fifth floor" for assessing intensity (which we interpreted as the fifth floor above the ground floor at street level; EMS, page 29). As an exception to this "floor rule", we may have assigned 2 EMS from perceptions on higher floors at IDP places where no other observations were available because shaking was very weak (see EMS, page 29). As far as observations from watch or church towers were concerned, we treated these on a case-by-case basis according to the height of the tower. – As for *damage to tall buildings*, we took such damage into consideration only as a weak diagnostic, if at all. In many such cases, just a lower limit of intensity could be derived thereof.

2.6.9. Secondary damage effects

Intensity assessment should be made from building damage that is caused by the reaction of buildings to earthquake ground-shaking motion. If damage had resulted from ground movement that was not shaking but was of permanent-displacing type, we considered this in form of weak diagnostics only (see section 2.2.2.).

We excluded building damage from intensity assessment, however, that had not been caused by the aforementioned seismic actions in a direct way ("primary damage") but constituted an indirect or *secondary damage effect* ("secondary damage") mostly being caused by the primary one (for example, damage caused by building parts falling off the building, by fire or inundation after the earthquake, etc.; see e.g. EMS, page 72). Only primary damage was considered relevant for intensity. Albeit, falling building parts, parapets, chimneys, roof tiles, etc., causing damage on other parts of the building or in its neighbourhood, have been frequent earthquake scenarios in SW-Germany also (and a danger of life for people). In case of the June 27, 1935, earthquake with epicentre at Bad Saulgau, SW-Germany, a prominent secondary damage occurred as parts of the church tower at nearby Buchau fell onto the roof of the nave and thus destroyed the main part of the church.

2.7. Substitutes for intensity

In cases of very poor, contradictory, or insufficient information, serious doubts in credibility, or large uncertainties out of any reason we generally did not assign an IDP intensity but assigned an annotation, called a "flag". Well known are the *felt-flags* and the *damage-flags* (see e.g. EMS, page 58). An IDP with a flag, instead of an intensity value, may be called a macroseismic data point (MDP), if one wants to make this distinction (in this article we do not).

On the whole, we used the following felt-flags and damage-flags for macroseismic information of IDPs:

- "felt unknown" (even after enquiry, it is not known whether the earthquake has been felt at that place),
- "not felt" (should be intensity 1 EMS),
- "felt" (means higher than 1 EMS),
- "strongly felt" (probably higher than 4 EMS),
- "damage unknown" (even after enquiry),
- "no damage" (probably lower than 6 EMS, a few buildings of damage grade 1 may have gone unnoticed),
- "damage" (probably higher than 5 EMS), and
- "heavy damage" (probably higher than 7 EMS).

The flags "felt unknown" and "damage unknown" underline that respective enquiries about "felt?" or "damage?" remained unknown, even after searching for information. For historical earthquakes this is an important detail to be noted. A negative report (section 2.5.3.) was coded as "felt unknown" if there were doubts as to whether really nobody felt the earthquake at the place concerned. The damage-flags refer to damage to buildings; the felt-flags do not a priori exclude damage; the flag "felt" includes "heard only"-cases also.

In general, the flags were not assigned in parallel to intensity but as a substitute. Exceptions to this rule were flags not replacing intensity but giving additional information, for example an IDP intensity assignment of 6 EMS together with a flag "damage unknown" (could be unreported damage), or of 5 EMS with a flag "damage" (damage reported not qualifying for a higher intensity), or of 4 EMS with a flag "damage" (damage reported but disregarded for intensity), etc. If neither intensity nor flag were assigned, the case is pending.

2.8. Uncertainties

2.8.1. Probabilities

Dealing with uncertainties of macroseismic evaluations, particularly for historical earthquakes, implicit or explicit assumptions of probability play an important role. Historical earthquake evaluations are subject to many uncertainties; hardly anything is proven beyond doubt; occasionally even the existence of the earthquake itself is not certain. Hence, dealing with uncertainties of various types and sizes makes it necessary to introduce probability. Within this project, it was essential to have a common understanding of the verbal representations of probability, as several terms had been understood quite differently by the project team members.

For communicating probability in questions regarding macroseismic evaluations, we established the following simplified *scale of probabilities* for use within the project:

- "certain" for more than about 95% probability,
- "probable" for considerably more than 50% probability,
- "questionable" for roughly about 50% probability ("fifty-fifty case"), and

- "improbable" for considerably less than 50% probability with a lower cut off at about 10%, below which probability was assumed to be "negligibly small" for the macroseismic issue at hand (see also e.g. Renooij & Witteman, 1999).

The advantage over earlier procedures dealing with uncertainties was that, in this way, uncertainties were consistently quantified and included in the assessments.

2.8.2. A notation of uncertainty

In the process of assessing IDP intensity (see section 2.2.1.), we used two intensity values to denote the *range of uncertainty*: A lowermost (1) and an uppermost estimate (2) of intensity that are, on the basis of the available data, still assumed to be reasonably possible (even if "questionable" or "improbable", according to the "scale of probabilities" above). Thereby, a reasonable range of uncertainty of IDP intensity was specified (see also Fäh et al., 2011); statistical error measures (e.g. standard deviations) were not regarded to be appropriate. The uncertainty of intensity assessment was to a large part related to *epistemic uncertainties* due to imperfect knowledge of what really happened. If data allowed, a "least conservative" and a "most conservative" scenario could be constructed, for example from combinations of the triplet "vulnerability class, damage grade, quantity" that were considered reasonably possible (see e.g. Monachesi & Moroni, 1995). These two scenarios, in turn, could have yielded the aforementioned range of uncertainty from estimate (1) to (2). – Having done this, we assigned a best-estimate intensity (3), which we supposed to be the most probable value within the range of uncertainty and was the final intensity assignment for entry into the catalogue as the IDP intensity.

We assigned historical IDP intensities jointly together within the project team. At times, the range of individual judgements of the team members also reflected part of the uncertainty. The reasons why a given uncertainty range may have been small or large are discussed below. A full evaluation of IDP uncertainties led to the overall IDP quality code (see section 2.8.4.).

2.8.3. Intermediate intensity

If the aforementioned best-estimate intensity remained undecidable between two consecutive intensity degrees on the scale, i.e. if the data fitted equally well with the lower and the higher value hence there was about the same probability for both of them, we expressed this ambivalence by assigning a so-called "*intermediate intensity*". If, for example, the best estimate was 6 EMS or 7 EMS with approximately equal probability, the final assignment was denoted as 6-7 EMS, which means the intensity was "either 6 or 7 EMS". This was not expression of an "intermediary degree" of 6½ between 6 and 7 in the scale (see also EMS, page 62), but was just saying that the question whether intensity was 6 or 7 EMS could not be decided. Nevertheless, in this case, we entered the number 6.5 as an *intermediate value for the IDP intensity* into the catalogue database; this number may be processed for numerical calculation purposes in later applications. – If in another case, for example, data somehow "exceeded" the description for 6 EMS, but were much less compatible with the description for 7 EMS than with that for 6 EMS, we assigned 6 EMS as best estimate being most probable. – If, in still another case, uncertainty was even higher, and intensity assignment could, for example, have been 6-8 EMS, meaning "6 or 7 or 8 EMS" with about equal probability, we mostly preferred to assign a "damage-flag" instead of an intensity value (of e.g. 7 EMS, in this example). – The examples in this section were taken from EMS (compare EMS, page 57; Musson, 1998a).

During the 20th century in SW-Germany, there even had been the habit of assigning "quarter-degree" intensities, for example "6+" standing for about 6¼, or "7-" standing for about 6¾, etc., referring to some older scale. Whenever possible, we re-evaluated the sources and assigned intensities according to the EMS scale, instead.

2.8.4. IDP quality

IDP quality, on the whole, has to be estimated starting with the sources. We rated the sources according to their *reliability* in general and to their *credibility* and *independence* for the individual case. The evaluation of sources implied various kinds of uncertainties, particularly if sources were sparse in information, "filtered" due to intention or format, or doubtful out of any other reason.

If the historical sources at hand were not *primary sources* but contained information that had been copied, cited, retold, paraphrased, or reworked from (several) earlier ones, the likelihood for alteration, distortion, or loss of original information in these *secondary sources* (occasionally also termed "indirect sources") tended to be quite large. Frequently, the distorting effect had stepwise increased in the course of time. Eventually, the original facts may, to some extent, have got lost during the passing on of information through the centuries. The larger the delay between the date of writing and the date of the earthquake had been, the more unreliable the source had possibly become (with some exceptions, though, for publications that had reviewed the event with the benefit of hindsight after a reasonably short delay, for example). We used a database attribute (the "earliest reporting date") to denote this time delay for historical IDPs, notably to serve as an indication for potential unreliability. – Similar held for the distance of the place of writing from the earthquake.

The further going back in historical time, the more the *absence or loss of primary sources* was something we had to live with. For earthquakes in the time before about the 15th century primary sources were rare, and secondary sources had to be used. When using secondary sources, we did this with a special focus on veracity.

An important bias that we encountered for IDPs from historical sources about medieval earthquakes was that reporting had been concentrated towards cultural centres and large towns. This implied that in ancient documents, urban areas had, according to circumstances of the time, been given a greater reporting attention than sparsely populated rural areas, where earthquake information had possibly even been disregarded by the chroniclers. The further back in time, the more pronounced this *attraction of earthquake information towards urban centres* had been.

We also were attentive to a possible *reporting bias* that may have come with selection and emphasis of information. Well known examples were the dramatizing presentations in historical news-pamphlets. When, for example, a rather small earthquake was reported on the front page of newspapers, this implied a special importance factor. Sometimes, the significance was further enlarged just by reworking and reprinting of local news by papers in greater distance. A possible "media bias" was described by Hough & Pande (2007) and Hough (2013) for 19th-century newspapers. – Possibly generalized singular effects and overemphasized or exaggerated reports had to be paid attention to in any case. We were particularly aware of possible biases in historical sources and, despite the critical approach we used, we had to assume that there still remained a considerable amount of uncertainty due to reporting biases inherent in the sources. We did, however, not see reasons to apply a general "correction factor" to the historical intensities assessed in this project (compare e.g. Hough, 2014). A favourite situation was, particularly for an historical case, if there were two or more independent sources for an IDP thus giving a "second opinion".

Apart from the rating of the sources, IDP quality mainly depends on the *quality of data* in the sense of the available amount of reliable and useful information for assessing IDP intensity (as outlined in this article). Additionally, we also considered uncertainties regarding IDP place and time (see also Musson, 1998a) as being part of (and potentially reducing) IDP quality. We finally condensed all appraisals regarding source(s) and information into a rating scale called the *quality code of the IDP*. This code ranged alphabetically from A (very good) down to E (very bad). It can be viewed as an overall measure of quality of the IDP. We were attentive to ensure that the IDP quality code was consistent over time, in particular over the transition from prevailing classical historical documents before about the 19th century to those thereafter, which were, to a large part, newspapers and questionnaires. IDP quality codes can be used also for weighting the IDPs in algorithms to determine earthquake epicentre and magnitude or to estimate seismic hazard from IDP data.

To illustrate the *assignment of IDP quality codes*, a few examples are given. IDP quality code A was rarely assigned, since for code A we required quantitative information about perception of shaking or building damage, including building vulnerabilities, on a sufficiently dense grid of individual sites within the area of the respective IDP place. In this way, the IDP could be "fully covered" in its areal "distribution of effects" (see section 2.1.3.) and the intensity-relevant EMS-quantities could be calculated. A rating with code A could be achieved by a detailed macroseismic field survey (see e.g. Cecić & Musson, 2004), for example. Intensity assessment from a number of individual reports or from a respective summarizing report may have lead up to IDP quality code B depending how well relevant quantities and parameters could be estimated. The 20th-century collective community-questionnaires, filled in by one person as a report for the entire IDP place, in average yielded IDP quality code C. An IDP from one individually-answered questionnaire or letter, reporting one person's perception or reporting damage to one building, could be rated with code D if the singular observation sounded reasonable and could be seen exemplary. Historical IDP quality codes generally ranged from rare B's to frequent D's. There were even IDPs with quality code E in cases of very poor data, serious doubts, or large uncertainties inherent in the source(s), which may have also included uncertainties about the respective IDP place and time. In cases of code-E intensities, however, we may have substituted intensity by a "flag" instead (see also section 2.5.1.).

Quality rating of IDPs was regarded highly important, particularly for historical data. IDP quality needed to be quantified; a simple "flag for uncertainty" (e.g. a question mark) was seen to be inadequate. It also turned out to be very advantageous for the entire catalogue, as low-quality IDP data that otherwise would probably have been disqualified could hence be kept in the catalogue with appropriate distinction. If, however, historical information could not be parameterized at all, we had room for keeping it in form of notes and comments.

2.8.5. Quality and precision

Occasionally, we noticed a kind of trade-off between *quality of data* available for IDP intensity assessment (in the sense stated above) on the one hand and *precision of IDP intensity* (in the sense of certainty of assignment of a particular intensity degree) on the other hand (see also EMS, page 58; Musson, 1998a). Unfortunately, and to our surprise, increasing quality of data did in some cases not lead to a smaller range of uncertainty of intensity, in particular did not necessarily allow us to resolve an "intermediate intensity" (see section 2.8.3.) to be finalized to a single integer value. An example is the September 3, 1978 Albstadt, SW-Germany, earthquake at the maximum-intensity IDP Albstadt-NE, where we assigned 7-8 EMS; i.e. we could not decide whether intensity was 7 or 8 EMS even though unprecedentedly dense and high-quality data (IDP quality code A) were available for this IDP (see e.g. Schwarz et al., 2005). – Sparse data, on the other hand, could have been such that, from the information available, only one single intensity degree could possibly be considered. This formally constituted a precise assignment on one hand, but a doubtful value on the other because of poor or very poor data quality (IDP quality code being D or E, for example). – Finally, if an IDP was both of low-quality data and uncertain intensity, the case may also have been solved with a "flag".

Occasionally, earthquake effects appeared to be more complex and irregular than is suggested by the EMS scale (and by the usual scheme of "distribution of effects", see section 2.1.3.). Reasons for that could be sought, for example, in anomalies of seismic waves, subsoil effects, building factors, demographic structures, etc. Precision of intensity was not improvable in some IDP cases, data quality was considered to be highly essential in any case.

2.9. Other issues

2.9.1. Completeness

Low seismicity in certain time periods may be due to lack of earthquakes or lack of sources. Hence, there is the fundamental question of *completeness*, particularly for the historical part of the earthquake catalogue. Completeness of archives is essential for completeness of IDP acquisition and, in turn, also for completeness of the earthquakes in the catalogue with respect to particular intensity thresholds. There were a number of limiting factors, among them were the completeness of documentation in writing as such, the continuity of archiving the sources, the likelihood that respective documents still exist in repositories (despite loss of sources due to destruction, disposal, disorder, dislocation, etc.), and the chances to actually identify and find the relevant sources today (see e.g. Guidoboni, 2000; Castelli, 2003; Stucchi et al., 2004; Bragato, 2018; and others). Even if number and quality of historical sources available for a particular time period were excellent, the question remained as to what extent the sources "speak of earthquakes" or "are silent".

For a regularly appearing 19th-century SW-Germany newspaper, for example, completeness of reporting earthquakes that were felt in the geographical distribution area of the newspaper could be assumed for intensities down to 5 EMS. This was not as favourably the case for many other historical source types that, for some reason or other, reported earthquakes irregularly, or only in cases of heavy damage, or refrained from mentioning earthquakes altogether. Damage to private residential buildings was often assumed to just be a private matter and was therefore not registered in official documents, in contrast to damage to public, administrative, or clerical buildings. Official sources first and foremost recorded what was relevant for official matters and frequently were silent with respect to other issues.

Overall, we felt that, through historical research done in this project, a fairly high level of potential completeness for IDPs in SW-Germany could be achieved. For a discussion of completeness of IDPs and earthquakes in the catalogue see Brüstle et al. (2021).

2.9.2. Consistency

A major achievement of this project is that IDP intensities of historical and modern-time earthquakes in the catalogue are now based on primary sources as far as possible, and are based on one and the same scale (EMS). A particular EMS intensity value, moreover, should have the same meaning regardless of the date and the place of the IDP. To some extent, systematically evaluating an extensive amount of IDP data within a tight project has been a favourable basis for the achievement of temporal and spatial homogeneity of results. As we knew that there is a possibility that intensities derived for historical earthquakes might be biased towards higher values (for reasons some of which are discussed in this article), we particularly have focussed on *consistency* in this respect. We made an effort to achieve consistency of IDP intensities and quality rating, as well as consistency of IDP coordinates, name places, calendar dates, and times of day, during all centuries to thus produce a homogeneous earthquake catalogue. A major guarantor of consistency was the consequent implementation of the guideline. In a way, the guideline also helped to minimize any personal bias or subjectivity in the team assessment process (see below).

The transition from historical to modern time, around the turn from the 19th to the 20th century, can be seen as a turning point with respect to macroseismic investigations in SW-Germany. Hence, it was of special concern for us to secure consistency of assessments for IDPs before with those after this transition. Extensive macroseismic surveys started at that time and yielded very dense IDP data sets, which never had existed before. Particularly the earthquake on November 16, 1911, with epicentre at Albstadt, SW-Germany (maximum intensity 7-8 EMS and perceptibility radius about 500 km), served as a benchmark and calibration event, as it was the first earthquake with an extensive macroseismic questionnaire survey in all of SW-Germany and beyond. The 20th-century data constitute the *main reference* on that intensity is calibrated; therefore, historical IDP intensities had to be measured in comparison with that of modern time. The EMS scale as well, through its precursor scales, is mainly based on macroseismic evaluations of 20th-century earthquakes. Apart from the enormous amount of macroseismic data, there were in modern time also many ways of cross-checking with instrumental data.

From the experience that we gathered with the re-evaluation of the 20th-century IDP data in SW-Germany we were able to approach historical-earthquake evaluations in the centuries before with best possible consistency. A helpful exam was to imagine how a modern-time earthquake scenario would look like if it had occurred in historical time considering the sources available, and vice versa (see e.g. Hough, 2013).

2.9.3. Subjectivity

Apart from any subjectivity in observation and reporting (as discussed in this article), there is also *subjectivity in evaluation*. Frequently, in particular for intensity assessments from historical accounts, macroseismic evaluations are not straightforward and not unequivocal, and, even on the basis of the same data, the same scale, the same scientific background, etc., differing intensity assignments by experienced evaluators may have to be regarded as valid results because of an ambiguity factor. Moreover, any IDP intensity assessment is dependent on a certain amount of personal subjectivity inherent in an evaluator’s comprehension, opinion, preferences, or even mood in interpreting the data.

There is, generally speaking, quite often some arbitrariness in evaluation because of a lack of standards in procedure. In cases of sparse data, even nuances of wording and details of context may have an influence on the judgement. The intrinsic subjectivity in macroseismic evaluations is widely known and has been accepted to some extent as being inevitable. Automated algorithms have been proposed to reduce subjectivity in historical assessments by a formalized decision process (e.g. Ferrari et al., 1995), but have not yet become established to our knowledge. According to the results of an intensity assessment exercise, Moroni et al. (1996) concluded that "the lack of procedures" is even more important than the incompleteness of the data. With regard to this conclusion, we attached great importance to project management, implementation, and process (e.g. workflow, team work, decision making, quality control, documentation, reproducibility, etc., see also section 2.9.4.).

In this project, we tried to minimize the subjective component of expert decisions by consistently applying the rules of the guideline, but subjectivity could never be zero, though. In practice, differing judgements by the project team members resulted in differences in IDP intensity assessments, which, at times, were as large as one full degree of the EMS scale, however not often so. Yet, such cases of disagreement usually went in parallel with a low IDP quality. Discrepancies had then to be reconciled in the project team after re-examinations and re-assessments. Overall, we felt that the *team results* were more significant and robust than those of a single evaluator.

2.9.4. Transparency

In particular for assessment of historical IDPs, we followed a predetermined workflow from (a) acquisition, transcription, translation and interpretation of sources; to (b) individual intensity assessments by up to four members of the project team; to (c) reconcilement to achieve a common final result, if necessary; to (d) documentation of sources and arguments on that the final IDP assessment was based on; to (e) protocol denoting evaluators and date of the assessment; to, finally, (f) database entry and quality control. All sources that were seen relevant for IDP assessment were archived (originals or copies of relevant pages, and/or bibliographical links) and connected to the IDP(s) by a link in the database, comprising also "silent sources" in some cases. A ranking of sources for individual IDPs was denoted also. Additional descriptive information, characteristics, and peculiarities of the IDPs were recorded in accompanying comments, where appropriate, including e.g. a short abstract of the most relevant macroseismic information, effects in the natural environment, remarkable details that could not be parameterized, etc.; further including e.g. a reference to preceding, simultaneous, or subsequent earthquakes and other events, hints to the historical context, reasoning for the assessment, problems in evaluation, inconsistencies, lack of knowledge, stage of review, relevant scientific studies and cross-references, where applicable. A revision history is kept in the database as well. In this way, a high level of *transparency of work process and results* could be achieved, which may serve as a basis for any continuation or revision of this project.

2.9.5. Interdisciplinarity

Since the establishment of historical seismology as a science field some decades ago, it has been recognized by the scientific community that historical seismology is by definition an *interdisciplinary field* where historians and seismologists, and possibly also civil engineers and architects, should work closely together (see e.g. Eisinger et al., 1992, among many others). Historical seismology has proven to be an independent branch of science in connection with paleo-, archeo-, and instrumental seismological records (e.g. Valensise et al., 2020).

For this project, it turned out that professional historical work was indispensable for the evaluation of sources before about mid of the 19th century. This insight was one of the most important "lessons learned". *For the historical work*, this meant investigative historical research tracing back information to the primary sources whenever possible (a complete "genealogical tree" was followed, however, just if necessary); searching for the relevant documents; deciphering (handwriting, script), transcribing, and translating the significant text passages with respect to language (Latin, Old-German, partly also French), style of writing, and wording. It further meant critically interpreting the text in its historical and social context regarding author, addressee, purpose, locality and time of writing; determining date and time of the earthquake; applying historical thinking to investigate circumstances, clarify ambiguities, separate facts from fiction, and to appraise sources and texts from an historian's point of view. Finally, results had to be secured and source information had to be edited for use in the following assessments within the seismological framework.

On the side of seismology, the task was first and foremost to understand the historical information within its context and limitations as far as possible in order to be able to assess intensity. Due to the aim of this project, historical work had to follow seismological needs. Seismological requirement was to search for primary information and to aim at completeness of the earthquake catalogue, both in space and time. Future seismological utilisation of the catalogue data had to be kept in mind; catalogue work, however, was done irrespective of any particular application. Special questions had to be asked from the seismological side that helped to parameterise historical information in a proper way, as far as the sources allowed parameterisation. Evaluating the historical information, seismological constraints were applied in respect of geophysical plausibility (identifying unlikely effects and relations, probable outlier IDPs, for example) and consistency (as above). Historical earthquake scenarios were mirrored in recent ones; thereby, consistency could be established in comparison with sources and earthquake scenarios of the modern time period. Particularly advantageous was an iterative working scheme that "fed back" preliminary seismological results into the historical work to improve the research.

Overall, the main task was to make best use of historical sources for the earthquake catalogue. The guideline helped to bridge the gap between historical information and seismological needs.

3. Conclusions

The earthquake catalogue of SW-Germany contains about 30,000 newly determined digital IDPs of historical and modern times. To date, this data set is unique in Germany. The usage of primary sources and the quantification of uncertainties have been considered essential. Macroseismic intensities were assessed conventionally using the EMS scale. The EMS has proven to be a suitable instrument, where data came from all kinds of sources ranging from historical documents to 20th-century macroseismic questionnaires. For project work within a multidisciplinary team, a guideline has been required. The guideline had to go beyond the EMS defining best practice of macroseismic evaluations in greater detail, in particular for historical earthquakes. This has allowed earthquake information to be best used for the purpose of a consistent catalogue. The guideline may be helpful for other projects as well.

Acknowledgements

The "LED catalogue project" was funded by the government of Baden-Württemberg and was carried out by the Regierungspräsidium Freiburg, Abteilung Landesamt für Geologie, Rohstoffe und Bergbau, Referat Landeserdbebendienst (LED) at Freiburg, Germany, from 2013 to 2017. The guideline has been written in the frame of the project. Discussions within the LED and with a large number of colleagues from scientific institutions throughout Europe during meetings and workshops helped to develop the ideas for the guideline. Particularly fruitful in this respect were the "International Colloquiums on Historical Earthquakes", 2013 in Paris, 2014 in Freiburg, 2015 in Strasbourg, 2016 in Vienna, and 2017 in Hannover. All this is gratefully acknowledged. We, moreover, thank Christa Hammerl and Diethelm Kaiser for their reviews, which have helped to improve this article.

References

Albini, P., García Acosta, V., Musson, R. M. W. & Stucchi, M., eds. (2004). Investigating the records of past earthquakes. *Proceedings of the 21st Course of the International School of Geophysics, Erice Sicily, July 2002, special issue of Annals of Geophysics*, 47, 2-3, 911pp. Online version accessed on July 17, 2019: https://www.annalsofgeophysics.eu/index.php/annals/issue/view/244

Azzaro, R., Barbano, M. S., Tertulliani, A. & Pirrotta, C. (2020). A reappraisal of the 1968 Valle del Belice seismic sequence (western Sicily): a case study of intensity assessment with cumulated damage effects. *Annals of Geophysics*, 63, 1, SE105. https://doi.org/10.4401/ag-8308

Blakeborough, A. (2001). An analytical response of church bells to earthquake excitation. *Journal of Earthquake Engineering*, 5, 1, 69-92. https://doi.org/10.1080/13632460109350386

Boatwright, J. & Phillips, E. (2017). Exploiting the demographics of "Did You Feel It?" responses to estimate the felt area of moderate earthquakes in California. *Seismological Research Letters*, 88, 2A, 335–341. https://doi.org/10.1785/0220160041

Bragato, P. L. (2018). Past economic conditions affect the reconstruction of the seismic history of Italy. *Seismological Research Letters*, 89, 6, 2404-2410. https://doi.org/10.1785/0220180129

Brendler, S., Gerlinger, T. & Haufe, A. (2006). Wenn die Erde bebt: Detailuntersuchungen vor dem Hintergrund der neuen Erdbebennorm mit LS-DYNA. *5. LS-DYNA Anwenderforum*, Ulm, 2006. Online version accessed on July 17, 2019: https://www.dynamore.de/de/download/papers/forum06/implicit/wenn-die-erde-bebt-detailuntersuchungen-vor-dem

Brüstle, W., Hock, S. & Benn, N. (2015). *Makroseismischer Atlas Baden-Württemberg – 19. und 20. Jahrhundert*. 1. Auflage, Regierungspräsidium Freiburg, Abt. 9 – Landesamt für Geologie, Rohstoffe und Bergbau (Hrsg.), Freiburg, Germany. ISBN 978-3-00-047525-2

Brüstle, W., Hock, S., Braumann, U., Rodler, F.-A., Greve, A. & Stange, S. (2021). Erdbebenkatalog Baden-Württemberg – Seismologische und geschichtswissenschaftliche Bearbeitung des Erdbebenkatalogs Baden-Württemberg von 1000 n. Chr. bis heute und datenbankkompatible Erfassung der Erdbebendaten. *Informationen des Landesamts für Geologie, Rohstoffe und Bergbau im Regierungspräsidium Freiburg,* Freiburg im Breisgau, Germany (in preparation).

Camassi, R., Azzaro, R. & Tertulliani, A. (2008). Macroseismology: the lessons learnt from the 1997/1998 Colfiorito seismic sequence. *Annals of Geophysics*, 51, 2/3, 331-342. https://doi.org/10.4401/ag-4453

Camelbeeck, T., Alexandre, P., Sabbe, A., Knuts, E., Moreno, D. G. & Lecocq, T. (2014). The impact of the earthquake activity in Western Europe from the historical and architectural heritage records. In *Intraplate Earthquakes*, ed. by P. Talwani, Cambridge University Press, Cambridge, 198-230. https://doi.org/10.1017/CBO9781139628921.009

Castelli, V. (2003). Strong earthquakes included «by chance» in Italian catalogues: single cases or a hint of more? *Annals of Geophysics*, 46, 6, 1247-1263. https://doi.org/10.4401/ag-3470

Cecić, I. & Musson, R. W. M. (2004). Macroseismic surveys in theory and practice. *Natural Hazards*, 31, 1, 39-61. https://doi.org/10.1023/B:NHAZ.0000020255.00986.37

Coburn, A. W., Spence R. J. S. & Pomonis, A. (1992). Factors determining human casualty levels in earthquakes: Mortality prediction in building collapse. *Proceedings of the 10th World Conference on Earthquake Engineering in Madrid*, Balkema, Rotterdam, 5989-5994. ISBN 9054100605

Cucci, L. & Tertulliani, A. (2007). Variation of human perceptiveness of earthquakes during seismic sequences. *Journal of Seismology*, 11, 2, 205-219. https://doi.org/10.1007/s10950-007-9048-0

Eisinger, U., Gutdeutsch, R. & Hammerl, C. (1992). Historical earthquake research – an example of interdisciplinary cooperation between geophysicists and historians. In *Historical Earthquakes in Central Europe*, Vol. I, ed. R. Gutdeutsch, G. Grünthal and R. Musson, Abhandlungen der Geologischen Bundesanstalt, Wien, 48, 33-50. ISBN 3-900312-83-4, online version accessed on July 17, 2019: https://www.zobodat.at/pdf/AbhGeolBA_48_0033-0050.pdf

Fäh, D., Gisler, M., Jaggi, B., Kästli, P., Lutz, T., Masciadri, V., Matt, C., Mayer-Rosa, D., Rippmann, D., Schwarz-Zanetti, G., Tauber, J. & Wenk, T. (2009). The 1356 Basel earthquake: an interdisciplinary revision. *Geophysical Journal International*, 178, 1, 351-374. https://doi.org/10.1111/j.1365-246X.2009.04130.x

Fäh, D., Giardini, D., Kästli, P., Deichmann, N., Gisler, M., Schwarz-Zanetti, G., Alvarez-Rubio, S., Sellami, S., Edwards, B., Allmann, B., Bethmann, F., Wössner, J., Gassner-Stamm, G., Fritsche, S. & Eberhard, D. (2011). *ECOS-09 Earthquake Catalogue of Switzerland Release 2011. Report and Database*. Public catalogue, 17. 4. 2011, Swiss Seismological Service ETH Zurich, Report SED/RISK/R/001/20110417. Online version accessed on July 17, 2019: http://ecos09.seismo.ethz.ch/ecos09/

Ferrari, G., Gasperini, P. & Guidoboni, E. (1995). Macroseismic intensity evaluation with the «fuzzy sets logic». *Annali di Geofisica*, 38, 5-6, 811-826. https://doi.org/10.4401/ag-4087

Gisler, M. (2003). Historical seismology in Switzerland: Reflections on issues and insights. *Environment and History*, 9, 2, 215-237. https://doi.org/10.3197/096734003129342836

Graziani, L., Bernardini, F., Castellano, C., Del Mese, S., Ercolani, E., Rossi, A., Tertulliani, A. & Vecchi, M. (2015). The 2012 Emilia (Northern Italy) earthquake sequence: an attempt of historical reading. *Journal of Seismology*, 19, 2, 371-387. https://doi.org/10.1007/s10950-014-9471-y

Graziani, L., Del Mese, S., Tertulliani, A., Arcoraci, L., Maramai, A. & Rossi, A. (2019). Investigation on damage progression during the 2016-2017 seismic sequence in Central Italy using the European Macroseismic Scale (EMS-98). *Bulletin of Earthquake Engineering*, 17, 10, 5535-5558. https://doi.org/10.1007/s10518-019-00645-w

Grotefend, H. (2007). *Taschenbuch der Zeitrechnung des deutschen Mittelalters und der Neuzeit*, 14. Auflage, unveränderter Nachdruck der Originalausgabe von 1898, Hahn'sche Buchhandlung, Hannover. ISBN 978-3-74338-975-5, online version accessed on July 17, 2019: http://www.manuscripta-mediaevalia.de/gaeste/grotefend/grotefend.htm

Grünthal, G., ed. (1998). European Macroseismic Scale 1998. *Cahiers du Centre Européen de Géodynamique et de Séismologie*, volume 15, Centre Européen de Géodynamique et de Séismologie, Luxembourg. ISBN 2-87977-008-4, https://doi.org/10.2312/EMS-98.full.en, online version accessed on July 17, 2019: http://media.gfz-potsdam.de/gfz/sec26/resources/documents/PDF/EMS-98_Original_englisch.pdf

Grünthal, G. (2004). The history of historical earthquake research in Germany. *Annals of Geophysics*, 47, 2-3, 631-643. https://doi.org/10.4401/ag-3328

Guidoboni, E. (2000). Method of investigation, typology and taxonomy of the basic data: navigating between seismic effects and historical contexts. *Annali di Geofisica*, 43, 4, 621-666. https://doi.org/10.4401/ag-3661

Guidoboni, E. & Ebel, J. E. (2009). *Earthquakes and tsunamis in the past – A guide to techniques in historical seismology*. 1st edition, Cambridge University Press, New York. ISBN 978-0-521-83795-8

Guidoboni, E. & Valensise, G. (2015). On the complexity of earthquake sequences: a historical seismology perspective based on the L'Aquila seismicity (Abruzzo, Central Italy), 1315-1915. *Earthquakes and Structures*, 8, 1, 153-184. https://doi.org/10.12989/eas.2015.8.1.153

Gutdeutsch, R., Hammerl, C., Mayer, I. & Vocelka, K. (1987). *Erdbeben als historisches Ereignis – Die Rekonstruktion des Bebens von 1590 in Niederösterreich*. 1. Auflage, Springer Verlag, Berlin. ISBN 978-3-540-18048-7

Hammerl, C. (2017). Historical earthquake research in Austria. *Geoscience Letters*, 4, 7. https://doi.org/10.1186/s40562-017-0073-8

Hough, S. E., Armbruster, J. G., Seeber, L. & Hough, J. F. (2000). On the Modified Mercalli intensities and magnitudes of the 1811-1812 New Madrid earthquakes. *Journal of Geophysical Research*, 105, B10, 23839-23864. https://doi.org/10.1029/2000JB900110

Hough, S. E. & Pande, P. (2007). Quantifying the media bias in intensity surveys: Lessons from the 2001 Bhuj, India, earthquake. *Bulletin of the Seismological Society of America*, 97, 2, 638-645. https://doi.org/10.1785/0120060072

Hough, S. E. (2013). Spatial variability of "Did You Feel It?" intensity data: Insights into sampling biases in historical earthquake intensity distributions. *Bulletin of the Seismological Society of America*, 103, 5, 2767-2781. https://doi.org/10.1785/0120120285

Hough, S. E. (2014). Earthquake intensity distributions: a new view. *Bulletin of Earthquake Engineering*, 12, 1, 135-155. https://doi.org/10.1007/s10518-013-9573-x

Kieser, A. (1681-1686). *Die württembergischen Ortsansichten des Andreas Kieser (1681-1686)*. Landesarchiv Baden-Württemberg, Abteilung Hauptstaatsarchiv Stuttgart, Bestandssignatur H 107. Online documents accessed on July 17, 2019: https://www2.landesarchiv-bw.de/ofs21/olf/startbild.php?bestand=21067

Lais, R. (1914). Die Wirkungen des Erdbebens vom 20. Juli 1913 in der Stadt Freiburg i. Br. *Mitteilungen der Großherzoglich Badischen Geologischen Landesanstalt*, 7, 2, 673-699, Verlag Carl Winter, Heidelberg, Germany.

Lombardi, A. M., Cucci, L. & Tertulliani, A. (2016). The first world catalog of earthquake-rotated objects (EROs), Part II: Statistical analyses and related interpretations. *Bulletin of the Seismological Society of America*, 106, 2, 386–397. https://doi.org/10.1785/0120150256

Maison, B. & McDonald, B. (2018). Fragility curves for residential masonry chimneys. *Earthquake Spectra*, 34, 3, 1001-1023. https://doi.org/10.1193/021217EQS028EP

Mayer-Rosa, D. & Schwarz-Zanetti, G. (2004). On historical earthquakes in Switzerland: summary of compilations and investigations. *Annals of Geophysics*, 47, 2-3, 621-630. https://doi.org/10.4401/ag-3327

Michetti, A., Esposito, E., Guerrieri, L., Porfido, S., Serva, L., Tatevossian, R., Vittori, E., Audemard, F., Azuma, T., Clague, J., Comerci, V., Gürpinar, A., McCalpin, J., Mohammadioun, B., Mörner, N.-A., Ota, Y. & Roghozin, E. (2007). Environmental Seismic Intensity Scale – ESI 2007. *Memorie descrittive della carta geologica d'ITALIA*, Servizio Geologico d'Italia, Dipartimento Difesa del Suolo, APAT, 74, Rome, Italy. Online version accessed on July 17, 2019: https://www.researchgate.net/publication/233759642_Environmental_Seismic_Intensity_Scale_-_ESI_2007-

Monachesi, G. & Moroni, A. (1995). From historical earthquake records to intensity value: some results of a study. *Annali di Geofisica*, 38, 5-6, 827-836. https://doi.org/10.4401/ag-4091

Moroni, A., Monachesi, G. & Albarello, D. (1996). Intensity assessment from documentary data – Criteria and procedures in the daily practice of seismologists. *Annali di Geofisica*, 39, 5, 969-979. https://doi.org/10.4401/ag-4027

Musson, R. M. W. (1998a). Intensity assignments from historical earthquake data: Issues of certainty and quality. *Annali di Geofisica*, 41, 1, 79-91. https://doi.org/10.4401/ag-3795

Musson, R. M. W. (1998b). Inference and assumption in historical seismology. *Surveys in Geophysics*, 19, 2, 189-203. https://doi.org/10.1023/A:1006502118523

Musson, R. M. W. (2005). Undead earthquakes. *Journal of Seismology*, 9, 1, 111-114. https://doi.org/10.1007/s10950-005-2733-y

Musson, R. M. W., Grünthal, G. & Stucchi, M. (2010). The comparison of macroseismic intensity scales. *Journal of Seismology*, 14, 2, 413-428. https://doi.org/10.1007/s10950-009-9172-0

Oeser, E. (1992). Historical earthquake theories from Aristotele to Kant. In *Historical Earthquakes in Central Europe*, Vol. I, eds. R. Gutdeutsch, G. Grünthal, R. Musson, Abhandlungen der Geologischen Bundesanstalt, Wien, 48, 11-31. ISBN 3-900312-83-4, online version accessed on July 17, 2019: https://www.zobodat.at/pdf/AbhGeolBA_48_0011-0031.pdf

Renooij, S. & Witteman, C. (1999). Talking probabilities: communicating probabilistic information with words and numbers. *International Journal of Approximate Reasoning*, 22, 3, 169-194. https://doi.org/10.1016/S0888-613X(99)00027-4

Rossi, A., Tertulliani, A., Azzaro, R., Graziani, L., Rovida, A., Maramai, A., Pessina, V., Hailemikael, S., Buffarini, G., Bernardini, F., Camassi, R., Del Mese, S., Ercolani, E., Fodarella, A., Locati, M., Martini, G., Paciello, A., Paolini, S., Arcoraci, L., Castellano, C., Verrubbi, V. & Stucchi, M. (2019). The 2016-2017 earthquake sequence in Central Italy: macroseismic survey and damage scenario through the EMS-98 intensity assessment. *Bulletin of Earthquake Engineering*, 17, 2407-2431. https://doi.org/10.1007/s10518-019-00556-w

Rovida, A. N., Albini, P., Locati, M. & Antonucci, A. (2020). Insights into preinstrumental earthquake data and catalogs in Europe. *Seismological Research Letters*, 91, 5, 2546–2553. https://doi.org/10.1785/0220200058

Rudisch, A., Dunjic, V. & Kolbitsch, A. (2016). Historische Zierelemente unter Erdbeben-beanspruchung – State of the art. In D-A-CH-Mitteilungsblatt, *Bauingenieur*, 91, 10, 14-22. ISSN 0005-6650 and ISSN 1434-6591, online version accessed on July 17, 2019: https://sgeb.ch/userdata/uploads/pdf/mitteilungsblatt/dach-mitteilungsblatt-16-10.pdf

Sbarra, P., Tosi, P., De Rubeis, V. & Rovelli, A. (2012). Influence of observation floor and building height on macroseismic intensity. *Seismological Research Letters*, 83, 2, 261-266. https://doi.org/10.1785/gssrl.83.2.261

Sbarra, P., Tosi, P. & De Rubeis, V. (2014). How observer conditions impact earthquake perception. *Seismological Research Letters*, 85, 2, 306-313. https://doi.org/10.1785/0220130080

Sbarra, P., Fodarella, A., Tosi, P., De Rubeis, V. & Rovelli, A. (2015). Difference in shaking intensity between short and tall buildings: Known and new findings. *Bulletin of the Seismological Society of America*, 105, 3, 1803-1809. https://doi.org/10.1785/0120140341

von Schmidt, A. & Mack, K. F. (1912). Das süddeutsche Erdbeben vom 16. November 1911. *Württembergische Jahrbücher für Statistik und Landeskunde*, Jahrgang 1912, Heft 1, Stuttgart, Germany.

Schwarz, J., Langhammer, T. & Kaufmann, C. (2005). Quantifizierung der Schadenspotentiale infolge Erdbeben – Teil 1: Rekonstruktion des Bebens in der Schwäbischen Alb vom 03. September 1978. *Bautechnik*, 82, 8, 520-532. https://doi.org/10.1002/bate.200590170

Schwarz-Zanetti, G. & Fäh, D. (2011). *Grundlagen des Makroseismischen Erdbebenkatalogs der Schweiz – Band 1: 1000-1680*. Schweizerischer Erdbebendienst (Hrsg.), 1. Auflage, 280pp, vdf-Hochschulverlag AG an der ETH Zürich, Zürich. ISBN 978-3-7281-3236-9, https://doi.org/10.3218/3406-6

Stucchi, M., Albini, P., Mirto, C. & Rebez, A. (2004). Assessing the completeness of Italian historical earthquake data. *Annals of Geophysics*, 47, 2-3, 659-673. https://doi.org/10.4401/ag-3330

Tosi, P., Sbarra, P., De Rubeis, V. & Ferrari, C. (2015). Macroseismic intensity assessment method for web questionnaires. *Seismological Research Letters*, 86, 3, 985-990. https://doi.org/10.1785/0220140229

Tyagunov, S., Grünthal, G., Wahlström, R., Stempniewski, L. & Zschau, J. (2006). Seismic risk mapping for Germany. *Natural Hazards and Earth System Sciences*, 6, 573-586. https://doi.org/10.5194/nhess-6-573-2006

Valensise, G., Vannoli, P., Burrato, P. & Fracassi, U. (2020). From historical seismology to seismogenic source models, 20 years on: Excerpts from the Italian experience. *Tectonophysics*, 774, 228189. https://doi.org/10.1016/j.tecto.2019.228189

Vogt, J., Musson, R. M. W. & Stucchi, M. (1994). Seismogeological and hydrological criteria for the new European Macroseismic Scale (MSK-92). *Natural Hazards*, 10, 1-2, 1-6. https://doi.org/10.1007/BF00643437

Wald, D. J., Quitoriano, V., Dengler, L. A. & Dewey, J. W. (1999). Utilization of the internet for rapid Community Intensity Maps. *Seismological Research Letters*, 70, 6, 680-697. https://doi.org/10.1785/gssrl.70.6.680

Wald, D. J., Quitoriano, V., Worden, C. B., Hopper, M. & Dewey, J. W. (2011). USGS "Did You Feel It?" Internet-based macroseismic intensity maps. *Annals of Geophysics*, 54, 6, 688-707. https://doi.org/10.4401/ag-5354

Historical Earthquakes, Paleoseismology,
Neotectonics and Seismic Hazard:
New Insights and Suggested Procedures

DOI: 10.23689/fidgeo-3865

The earthquake of September 3, 1770 near Alfhausen (Lower Saxony, Germany): a real, doubtful, or fake event?

Günter Leydecker[1] *& Klaus Lehmann*[2]

[1] Isernhagen/Germany, guenter.leydecker@gmx.de
[2] Geological Survey of North Rhine-Westphalia, State Seismological Service, Krefeld/Germany, klaus.lehmann@gd.nrw.de

Abstract

In the weekly newspaper of Osnabrück (Germany) of November 3, 1770, a report about a local earthquake was published. Pastor Buck described ground motion effects in the manor 'Haus Horst', 1.5 km away from the village of Alfhausen: 'roof tiles rattled, a chimney fell down, inside the house the top of a stove was overturned, abraded chalk trickled down in all rooms; in the nearby villages, people felt the shaking, and especially the churches suffered noticeably'. The epicentral intensity was estimated to VII (MSK) by Ahorner et al. (1970), but later modified to VI (EMS) by Meier & Grünthal (1992) considering Buck's report in detail. Since this event is the only documented earthquake in this region, a reliable characterization of its parameters is important. Our re-examination reveals that some reported effects are quite inconsistent. Contrary to Buck's statement, no documents of damages on churches or costs of repairs could be found in the parish registers. As a result, the event appears to be a tectonic earthquake with an epicenter at Alfhausen / Haus Horst. Applying intensity-attenuation relationships, a revised value of the epicentral intensity of $I_0 \leq$ V (EMS-98) with a focal depth of $z \geq 2$ km was derived. A cavity collapse due to leaching processes as a cause of the effects can be ruled out here. However, several details given in the primary source turned out to be unrealistic or at least exaggerated. The tectonic earthquake on September 3, 1770 near Alfhausen should be classified therefore as uncertain or even doubtful.

1. Introduction

Strong earthquakes with major damage to buildings are rare events in Germany. In order to estimate the seismic hazard at a certain location, the occurrence of earthquakes in space and time as well as their strengths must be determined. The time period of denser and systematic instrumental observations began in the sixties of the 20th century and is far too short for this purpose. Therefore, it is essential to collect and to evaluate any written evidence available from historical reports on earthquake effects to determine characteristic parameters such as e.g. epicenter location, epicentral intensity, and area of perceptibility. However, historical sources must be reviewed very critically for an identification of potential exaggerations, false reports, pomposity, or even misinterpretation of other natural phenomena.

These considerations caused the re-examination of the seismic event of September 3, 1770 near Alfhausen (district of Osnabrück, Lower Saxony, Germany). According to the current state of knowledge, no noticeable earthquake has occurred in this region since historical times (Fig. 1). Therefore, a reliable characterization of this event is very important. The result of this study has the potential to significantly refine the assessment of seismic hazard in the region of western Lower Saxony and northern North Rhine-Westphalia (north-western Germany).

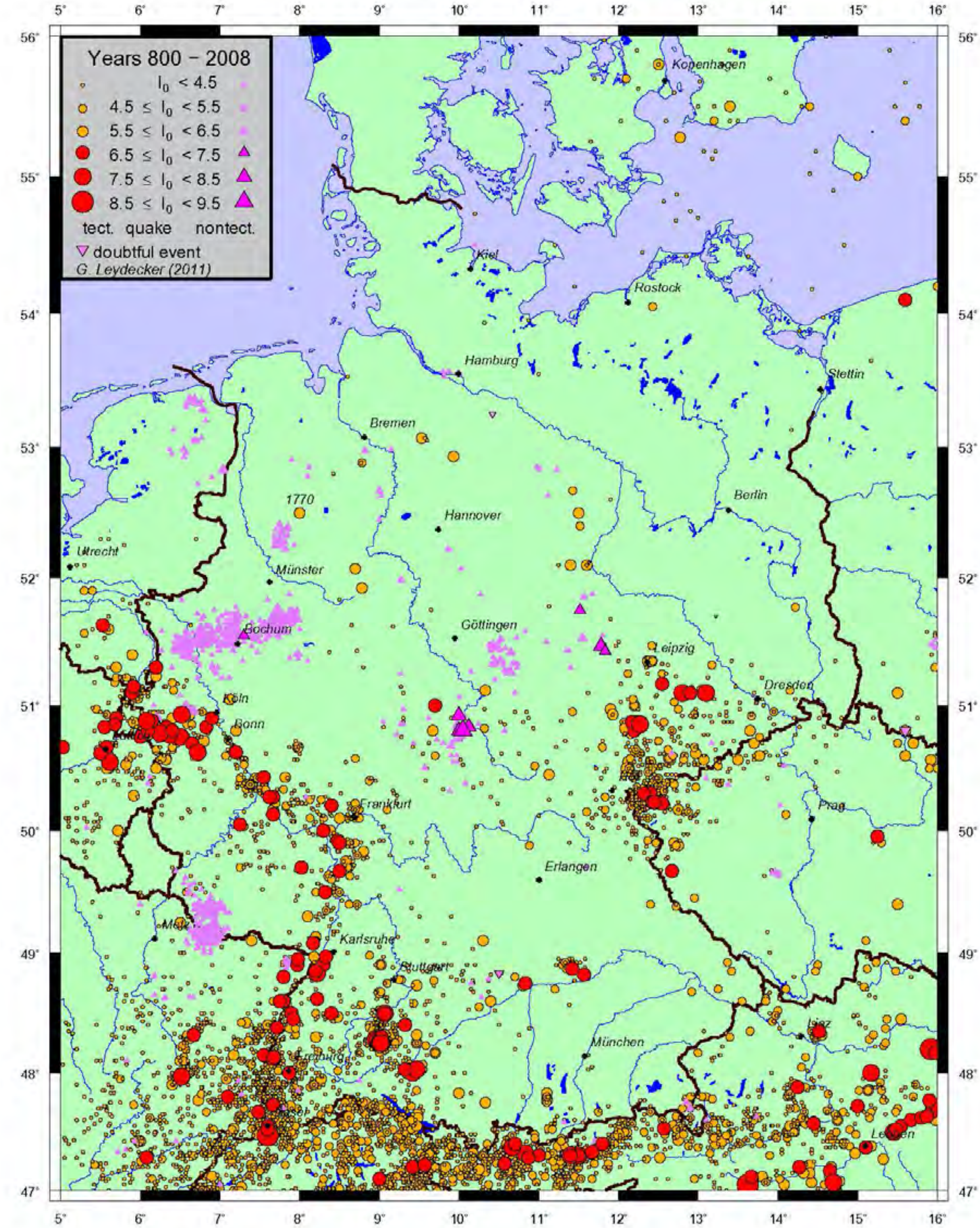


Figure 1. Map of earthquake epicenters in Germany and adjacent areas for the period AD 800 to 2008 (after Leydecker, 2011). The size of symbols is according to the epicentral intensity I_0. The earthquake of Alfhausen (52° 30′ N, 7° 57′ E) is situated north of Münster and is marked with the year “1770”.

2. Previous studies

The most common report available for the earthquake of Alfhausen on September 3, 1770 was the ‘earthquake chronicle’ of August Sieberg (1940). Here, the event is described as follows (p. 95, translation from the original in German):

> “*1770, September (or November?) 3, at 11¾ h. Earthquake in the Weser Hills* [Weserbergland]*, in the small district of the Bishopric of Osnabrück: In Alfhausen, from Haus Horst a chimney, numerous roof tiles, and plaster from the walls and ceilings of all rooms fell down. In Merzen, Gerde, Neunkirchen, Bramsche, and Vörden, in particular the large and massive buildings, especially the church buildings, had suffered noticeably.*”

The original source for this description could not be revealed from Sieberg’s report, since he cites only his own manuscript, the ‘Erdbebenkatalog der Preußischen Rheinlande, umfassend die Jahre 600-1895’ (earthquake catalogue of the Prussian Rhine Province, covering the years 600-1895), which has not been preserved. Sponheuer (1962) classified the strength of the 1770 event on the basis of Sieberg’s description (p. 34, translation from the original in German):

> “*In the North German lowlands,* [...] *epicenters can be found: that of the earthquake of Alfhausen in 1770 with the 6th degree of strength,* [...].“

Sponheuer used the macroseismic ‘Mercalli-Cancani-Sieberg-Scale’ (MCS; e.g. Sieberg, 1923, pp. 102–ff.), in which the ‘6th degree’ is characterized by the short description ‘strong’. Ahorner et al. (1970) re-evaluated the epicentral intensity I_0 with a value of VII (‘damage to buildings’) according to the updated macroseismic scale ‘Medvedev-Sponheuer-Kárník’ (MSK 1964; Sponheuer, 1965). This value was also included in the German earthquake catalogue of Leydecker (1986).

In the course of extensive research by Meier & Grünthal (1992), a new source for the 1770 Alfhausen seismic event was revealed. The information given here was obviously used in the description by Sieberg. In the weekly newspaper ‘Osnabrückisches Intelligenz-Blate’ (Osnabrück Intelligence Newspaper), published in Osnabrück, the supplement ‘Nützlicher Beylagen zum Osnabrückischen Intelligenz-Blate’ (Useful Supplements to the ...) appeared on November 3, 1770 (Fig. 2) with an article, which was written by Pastor J.H. Buck (1770) from Neuenkirchen (approx. 6 km away from Alfhausen):

> “*Notice of the remarkable earthquake in the northern region of the Bishopric of Osnabrück on Sept. 3rd, 1770*”.


345 346
Nützlicher Beylagen
zum
Osnabrückischen Intelligenz-Blate
Sonnabends den 3 November 1770
Vierundvierzigstes Stück.

Figure 2. Title page of the newspaper supplement ‘Nützlicher Beylagen zum Osnabrückischen Intelligenz-Blate’ (Useful Supplements to the Osnabrück Intelligence Newspaper), issue of November 3, 1770.

The full name of the author was identified with Pastor Johann Heinrich Buck (U. Braumann, Freiburg i.Br., pers. comm.). This text is reproduced, transliterated, and translated in the appendix.

Based on this report, Meier & Grünthal (1992) re-evaluated the seismic effects of this events with the epicentral intensity of VI (‘light building damage’) according to the scale EMS-92, a previous version of the actual ‘European Macroseismic Scale 1998’ (EMS-98, 1998). This intensity value was consecutively adopted in the updated earthquake catalogues of Leydecker (1997, 2011).

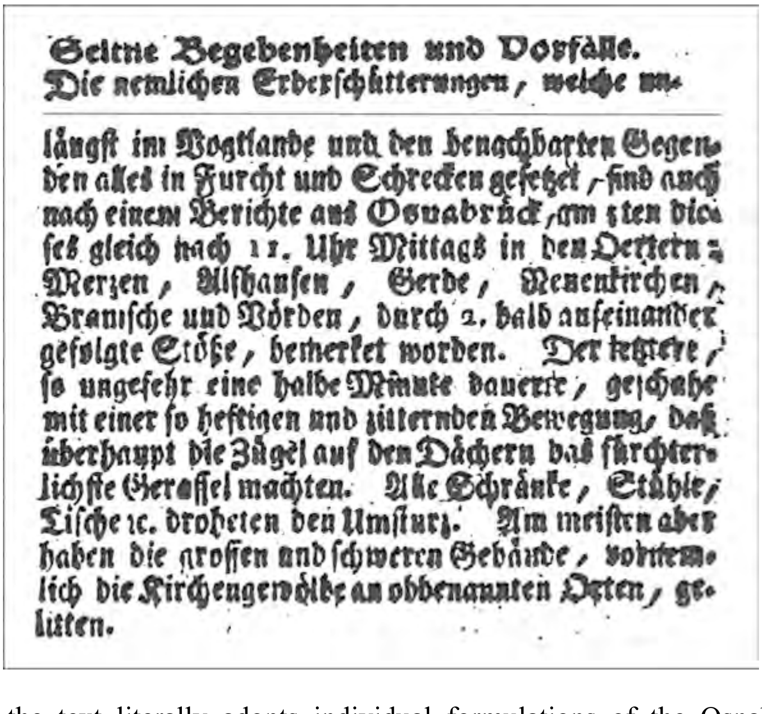
However, a detailed re-examination of all information available on the 1770 Alfhausen event raised fundamental questions. The aim of this study was therefore to check whether the earthquake – as it is currently interpreted – can be reliably verified, or whether the event has to be classified as doubtful or uncertain. Principally, a cause other than a tectonic earthquake must also be considered: the effects of a sinkhole in this region cannot be excluded *a priori*. All available information were used for a source-critical re-evaluation of the 1770 Alfhausen event.

3. Further research on available sources

New research showed that the report in the ‘Osnabrückisches Intelligenz-Blate’ was also taken over by the newspaper ‘Staats-Relation derer neuesten Europäischen Nachrichten und Begebenheiten’ (State Relation (newspaper) of the newest European news and occurrences) from the city of Regensburg (Bavaria, Germany) in its issue of November 30, 1770 (Fig. 3, translated):

> “*The earth tremors, which have recently frightened everyone in the Vogtland region and the surroundings, have also been noticed, according to a report from Osnabrück, on the 3rd of this* [month, i.e. November] *soon after 11 o’clock at noon in the villages of Merzen, Alfhausen, Gerde, Neuenkirchen, Bramsche, and Vörden, by 2 immediately successive shocks. The latter, which lasted about half a minute, happened with such a violent and trembling movement that the tiles on the roofs made a very terrible rattling. All cupboards, chairs, tables, etc. threatened to overthrow. But most of the large and massive buildings, especially the church vaults in the above-mentioned places, had suffered.*”

Figure 3. Article on the 1770 Alfhausen earthquake in the Regensburg newspaper ‘Staats-Relation’, issue of November 30, 1770.



Seltne Begebenheiten und Vorfälle.
Die nemlichen Erderschütterungen, welche unlängst im Vogtlande und den benachbarten Gegenden alles in Furcht und Schrecken gesetzet, sind auch nach einem Berichte aus Osnabrück, am 3ten dieses gleich nach 11. Uhr Mittags in den Oertern: Merzen, Alfhausen, Gerde, Neuenkirchen, Bramsche und Vörden, durch 2. bald aufeinander gefolgte Stöße, bemerket worden. Der letztere, so ungefehr eine halbe Minute dauerte, geschahe mit einer so heftigen und zitternden Bewegung, daß überhaupt die Ziegel auf den Dächern das fürchterlichste Geraffel machten. Alle Schränke, Stühle, Tische ꝛc. droheten den Umsturz. Am meisten aber haben die grossen und schweren Gebäude, sonderlich die Kirchengewölbe an obbenannten Orten, gelitten.

It is obvious that the text literally adopts individual formulations of the Osnabrück article. The descriptions of the Alfhausen event, however, are interpreted here as an effect of the earthquake series in the Vogtland region (Saxony, Germany) which lasted from September to November 1770 (cf. Rabe, 1771, p. 61; Sieberg, 1940, p. 95). Because of these formulations, Sieberg's doubt about the month in which the event occurred ("*September (or November?)*") appears to be understandable.

The 'Augspurgische Extra-Zeitung' (Extra Newspaper Augsburg) contains a further report in its issue of December 11, 1770 and copies entire passages from the Osnabrück article (a facsimile of this article is printed in Leydecker & Lehmann, 2019a). Here again the 3rd of September is mentioned as the day of the event. However, the late publication date and the mistake with the spelling of the village names ("[...] *Mergen, Ahlhausen,* [...]" instead of Merzen, Alfhausen) clearly identify the article as an adaptation.

The message was also taken up in the 'Meteorologische Beobachtungen' (Meteorological Observations) for November 1770 by Johann Georg Rabe (1771), but instead of the third day of the month the fifth is mentioned here, probably due to a transcription mistake. Here, the earthquake is described as a local event (p. 61, translation from the original in German):

> "*In the Osnabrück region, on the 5th of this* [month, i.e. November] *noon, 1 quarter past 11 o'clock, in Merzen, Alfhäusen, Gerde, etc., two successive earth tremors were felt; the last of them was so violent that cupboards, tables, and chairs in the homes threatened to be overturned, and even the church vaults in the named villages had suffered noticeably.*"

In the latter publication – as well as in Bucks's report and in the compilation of the Augsburg newspaper – the event time is formulated with the term "*ein Viertel auf Zwölfe in der Mittagsstunde*" (translated literally: "a quarter 'on' twelve at noon"). Uwe Braumann explained, that people at that time understood with this description: "a quarter past eleven at noon", or 11:15 (pers. comm.). Therefore, the time "*soon after 11 o'clock at noon*" in the newspaper 'Staats-Relation' of Regensburg is consistent with the original description. In contrast, since Sieberg (1940), the event time has been fixed with 11:45 in German earthquake catalogues.

From the early 20th century, an additional brief mention of the event was found in the 1911 report of the 'Naturwissenschaftlicher Verein zu Osnabrück' (Osnabrück Society for Natural Sciences). Again, the earthquake of 1770 is regarded as an effect of a distant earthquake (translation from the original in German):

> "*Mr. Freund, railway secretary, reports on earthquakes observed according to the Osnabrückische Anzeigen* [Osnabrück Newspaper] *in earlier times in our region, so* [...] *on a heavy one on September 3, 1770 in the area of Merzen, Alfhausen, Gehrde, Neuenkirchen, Bramsche.* [...] *In all cases it is probably a matter of effects from catastrophes that had their epicenter elsewhere. There have been no serious accidents in our area.*"

Although the date and time has been confused several times, all these sources are probably directly or indirectly based on Buck's article. However, additional details of the seismic effects cannot be derived. The report in the newspaper 'Osnabrückisches Intelligenz-Blate' is thus the only known primary source for the 1770 Alfhausen event.

An evaluation of the principal reliability of articles published in the supplement 'Nützlicher Beylagen zum Osnabrückischen Intelligenz-Blate' could not be carried out within this study. But it is clear, that the article on the 1770 event has the character of a letter to the editor. There is no indication that the contribution was revised or even proven by the editorial office of the newspaper 'Osnabrückisches Intelligenz-Blate'.

Further research showed that there is no report about earthquakes to be found in the available church registers of the villages in the vicinity of Alfhausen. There is also no mention of an earthquake in a list of important events which was included in the parish register of the nearby village of Gehrde (U. Braumann, Freiburg i.Br., pers. comm.). As a result, our knowledge of the 1770 Alfhausen event is based exclusively on the individual report of Pastor Buck.

4. Earthquake effects and geological conditions

The details of the damage and the perceptibility are analyzed intensely and discussed critically. The geological conditions are also considered in order to identify potential site effects. This information forms the basis for our re-evaluation of the earthquake report.

Pastor Buck mentions in his article "*Merzen, Alfhausen, Gerde, Neuenkirchen, Bramsche, and Vörden*" as places where the earthquake was felt. In addition, he describes the seismic effects at the "*noble Haus Horst near Alfhausen*" in detail. 'Haus Horst' is a detached manor, about 1.9 km northeast of the village of Alfhausen (Fig. 4). All other places mentioned are located within a radius of approx. 10 km around Haus Horst (Fig. 5) in the district of Osnabrück (Lower Saxony, Germany).

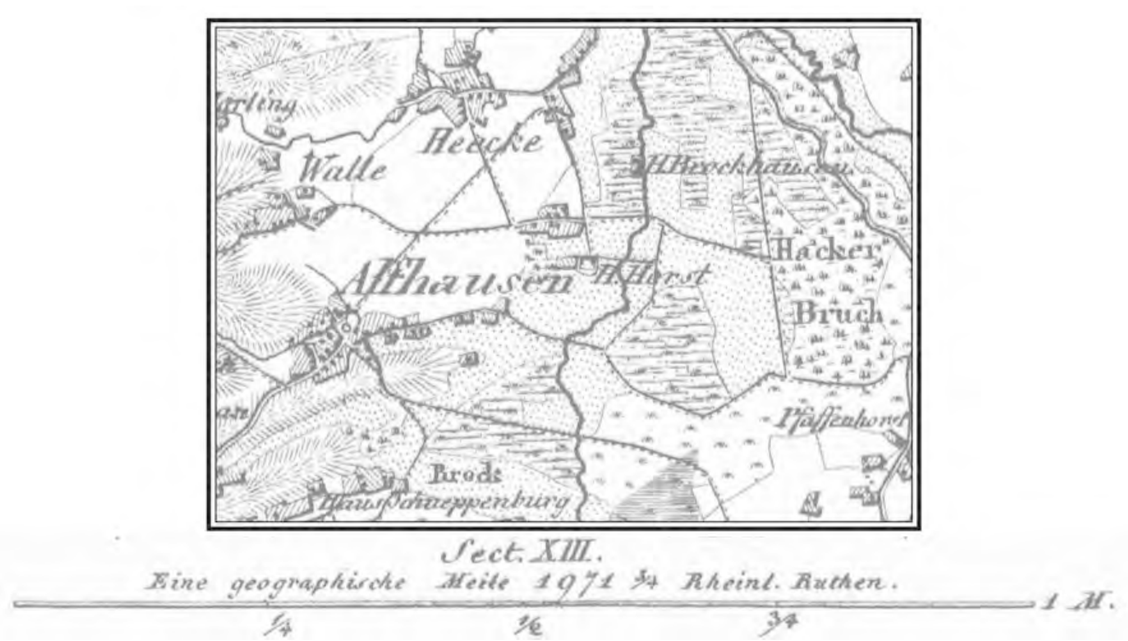


Figure 4. Topographic map (detail) of the surroundings of 'Haus Horst' (*H. Horst*) (von LeCoq, 1805).

4.1. Earthquake damage and effects at Haus Horst

For the manor Haus Horst, the following observations and damage are mentioned as being caused by an earthquake:

- A chimney fell from the roof.
- Inside the house, in a large hall, the top of the oven was overturned.
- At the cross-beams of all rooms, lime is rubbed off the ceiling.

Reports on the management and administration of Haus Horst for the years 1754–1917 are preserved in the so-called 'Lager Buch' (stock-book). They describe the relevant events concerning the manor in detail, also for the period around 1770. At that time the property was managed by an estate administrator, who was obliged – in his own interest – to inform the owner about all incidents. However, the 'Lager Buch' does not contain any references to the earthquake nor to damage or possible repair costs (Meier & Grünthal, 1992, pp. 72 f.). Therefore, it can be deduced that, either damage could be repaired at low cost and was not worth mentioning, or the extent of damage was strongly exaggerated by Buck.

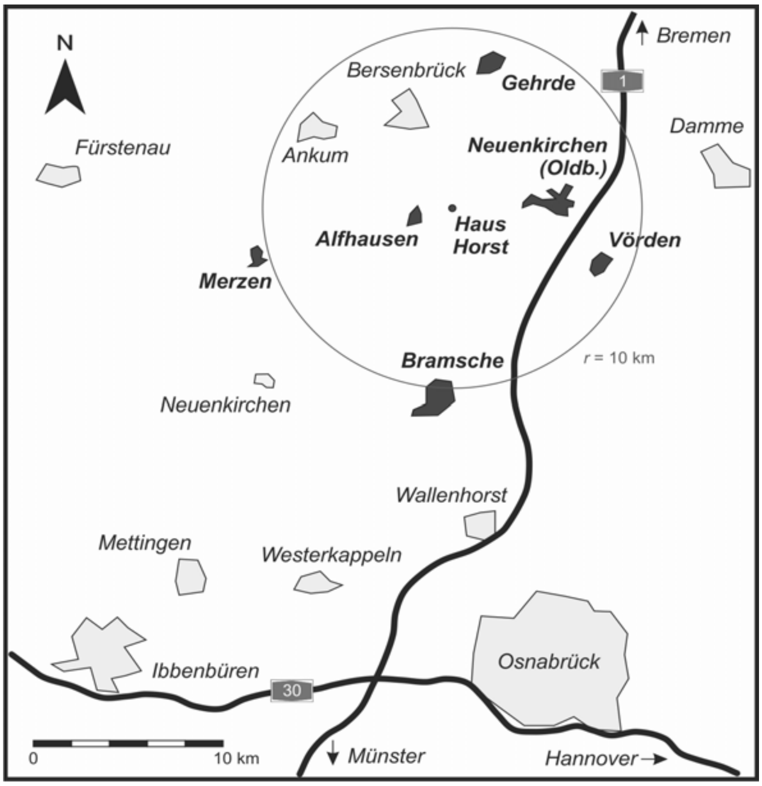


Figure 5. Locations where the earthquake of 1770 was perceived (names of villages in bold letters) according to the report of Pastor J.H. Buck.

Pastor Buck summarizes the damage in the surrounding villages with the description that "[...] *especially large and heavy buildings, in particular the vaults of the churches at most of the abovementioned villages, had suffered noticeably*". It remains unclear, which effects are specifically meant by the term "*suffered noticeably*": it would generally appear to designate clearly visible damage. In this case, it is surprising that Pastor Buck describes meticulously the damage in Haus Horst but does not mention at all any damage at his own church in Neuenkirchen (about 6 km east of Haus Horst). Additionally, there is no further evidence of serious damage to the church buildings mentioned in other sources.

The extensive investigations by Meier & Grünthal (1992) have also shown that neither the holdings of the Regional Archive of the Protestant Church nor those of the Diocesan Archive of Osnabrück contain any evidence of the earthquake, of damage, or of the respective repair. Mr. zu Hoene, who has worked up the history of Alfhausen (zu Hoene, 1977), carried out further investigations, but did not discover any indication of damage in the church registers. Also, the preserved bills of the catholic parish church St. Johannis in Alfhausen show no expenses for repair works in the respective time period (Meier & Grünthal, 1992, p. 74).

Despite intensive research in the surroundings of Haus Horst, further damage caused by the earthquake could not be substantiated. According to the available information, the description of the overturned chimney and of the lime abrasion on the cross-beams in all rooms of Haus Horst remains singular. According to the macroseismic scale EMS-98, this condition does not really permit an intensity assessment.

In addition, it should be noted that the structural condition of the farm house at that time may have favored the extent of the reported damage. Since the contemporary building had been pulled down and was subsequently replaced in 1885 (Steinwachs et al., 1996), further evidence of the damage does not exist anymore.

4.2. Perceptibility of the event and effects in the environment

The area affected by the earthquake of 1770 is described as "[...] *the area from west to east, doubtless 3 miles in length and 2 in width, namely the villages of Merzen, Alfhausen, Gerde, Neuenkirchen, Bramsche and Vörden* [...]". Applying the 'Prussian mile' or a related measure with a value of 7.5 km, this description corresponds to an area of about 20 km by 15 km. According to the statement of Pastor Buck, the earthquake was explicitly not noticeable in the 'Artland' ("*Orth- or Arthland*"), i.e. in the area of the landscape about north of the villages of Ankum and Bersenbrück (see Fig. 5).

The following facts support this assumption:

(1) The earthquake happened on September 3, 1770. The report was written by Pastor Buck on October 9 and published in a supplement to the weekly newspaper 'Osnabrückisches Intelligenz-Blate' on November 3. This is not in accordance with a far-reaching and heavily perceptible event that had to be immediately reported.

(2) In the introduction to the article, the author mentions that some persons were surprised that the earthquake had not been reported in the public newspaper so far. Even if the event was felt only weakly (intensity III) in Osnabrück (in a distance of some 25 km), this remark would certainly not have been necessary. In this case, at least a supplementary description of Buck's report or a hint about what happened in Osnabrück could have been expected.

It is reported in Buck's description that the church vaults in most of the above-mentioned villages "*suffered noticeably*".

Additionally, it is stated that the roof tiles rattled "throughout" and furniture in the houses were heavily shaken. All the inhabitants ("everyone") were frightened and flew from their houses. It is not clear, whether the author relates these effects and the people's reaction to the entire area which he describes to be affected.

4.3. Geological conditions

In the Alfhausen region, the geological unit 'Münder marl' (Upper Jurassic) gets in contact with the groundwater. Leaching processes of these ground layers have already led to subrosion and the occurrence of sinkholes in the northern foreland of the Wiehen mountains ('Wiehengebirge', cf. Tüxen, 1986). Such events were documented since the 16th century (e.g. Grahle & Schneekloth, 1963). However, there is no evidence that these events were accompanied by any noticeable shaking.

In the area of Alfhausen, the documented sinkholes have only a very small extent. In the section '3514 Vörden' of the Geological Map 1 : 25 000 (GK 25, Mengeling 1986), 21 small-scale sinkholes were documented. The most recent one has been recorded in 1985 (status of 1995, pers. comm. K.-H. Büchner, Hannover). However, there is no (geological) evidence for local sinkholes at Haus Horst, nor in the reports of the above-mentioned 'stock-book'. The Geological Map (GK 25, Landesamt für Bergbau, Energie und Geologie, 2018) describes the near-surface ground of Haus Horst as fluviatile deposited middle sand (Weichsel glacial). The soil conditions immediately to the west and east of Haus Horst were investigated with two sounding boreholes. According to Steinwachs et al. (1996, p. 3) "[…] *relatively stable meltwater sands lie here at a depth of about 8 m and deeper*". Additionally, the foundations of Haus Horst support the existence of a weak ground: "*According to the owner, the current building was founded on oak piles* [...]" (Steinwachs et al., 1996), built in the second half of the 19th century.

A Holocene peat area ('Ueffelner Aue') extending in north-south direction is situated directly east of Haus Horst. This area is about 250 m wide and ends about 200 m northeast of the manor. A peat thickness of up to 2 m is known in this area, and a postglacial subsidence area due to leaching processes can be supposed there.

The underlying layer of the Saliniferous Formation is assumed to be found at a depth of about 2 km. Tectonic earthquakes can therefore principally only occur below this depth. There is no indication of seismically active faults in this area.

5. Macroseismic evaluation

In all previous investigations, the epicentral intensity was derived solely from the seismic effects mentioned for Haus Horst. Form and extent of isoseismals or assumptions about the focal depth had not been considered. In contrast to the studies published so far, we think that the descriptions for Haus Horst are not reliable and thus not suitable for the determination of the epicentral intensity. Therefore, we try to combine all reported aspects for a plausible intensity assessment.

The intensity distribution of an earthquake principally depends on the epicentral intensity I_0 and on the focal depth z. Figure 6 shows the intensity-attenuation relationship for different values of z using two common models, derived for the area of Germany (Sponheuer, 1958) and for northwest Europe (Ambraseys, 1985), respectively. These relations are based on intensity values according to the macroseismic scale MSK 1964, but can also be applied in a first approximation to the actual scale EMS-98.

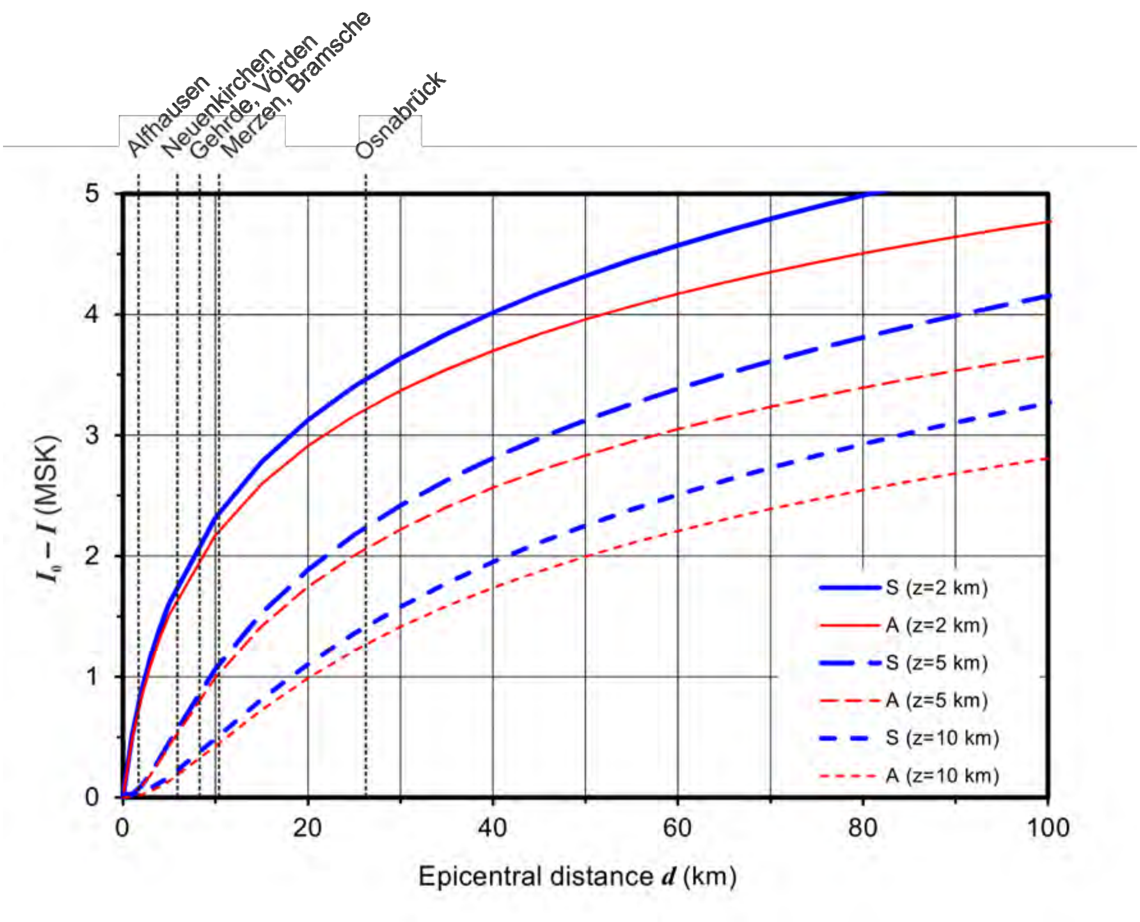


Figure 6. Intensity-attenuation relationship for different focal depths z after Sponheuer (1958, 'S', $\alpha = 0.002\ \mathrm{km}^{-1}$) and Ambraseys (1985, 'A'). I_0 is the epicentral intensity and I the intensity at a certain place in the distance d from the epicenter. Several distances are marked, for the villages, which were mentioned in the report by Pastor Buck, and for the city of Osnabrück.

Because Alfhausen, respectively Haus Horst, is located in the center of the affected area, it can be plausibly associated with the epicentral area. However, it is noticeable that neither for the village of Bersenbrück nor for Ankum, situated inside the assumed affected area, perceptibility is reported (cf. Fig. 5).

The intensity-attenuation relationships do not permit any combination of epicentral intensity and focal depth which meet the following conditions: (1) damage to the vaults of the churches in the surroundings of Alfhausen (i.e. $I \approx$ V–VI), a large number of inhabitants escaping from their houses (i.e. $I =$ VI) at an epicentral distance of 10 km and – at the same time – (2) no perceptibility in only slightly larger distances (Artland: more than 10 km, Osnabrück: about 25 km). This leads to the conclusion that the description of the church vaults having "*suffered noticeably*" cannot be synonymous with the occurrence of damage and has to be classified to be by far exaggerated. Nor the description of the inhabitants' reaction can be reliable, neither for the epicentral area nor for the entire affected region.

If we assume instead that the earthquake was at least clearly felt in the villages at an epicentral distance of 10 km ($I_{10} \geq$ III), the difference between the intensities at a distance of 10 km and 25 km (Osnabrück: $I_{25} <$ II), amounts to $I_{10} - I_{25} > 1$. Figure 6 shows that these conditions can only be met for focal depths of less than about 5 km. For focal depths of 2 and 5 km, the epicentral intensity I_0 reaches maximum values of V or IV, respectively. An epicentral intensity of VI, as derived by Meier & Grünthal (1992) (and also later confirmed by L. Ahorner, pers. comm., 1995) cannot be reproduced within this model. The earthquake would still have been felt with intensity III in Osnabrück assuming a very shallow focal depth (2 km), or even with an intensity IV assuming a depth of 5 km. It was already shown that this case is not plausible.

Seismic effects caused by relatively small sinkholes are in principle possible, but would only be felt in the immediate vicinity. An affected area comprising the seven villages mentioned by Buck cannot be explained by such an event. Theoretically, larger sinkholes due to subrosion processes may explain the described ground motions. However, since there is no documented sinkhole in this area that had been associated with noticeable seismic effects, this explanation seems to be very unlikely.

As a working hypothesis, an earthquake near Alfhausen seems to be the only possible explanation as the cause of the reported effects. In this case, the epicentral intensity must be estimated with $I_0 \leq$ V at an assumed focal depth of $z \geq 2$ km. Only under these conditions an affected area with a radius of about 10 km and simultaneously rattling of the glasses and a trembling of the furniture ($I =$ IV) in at least the nearby village of Alfhausen can be assumed to be plausible. The fallen chimney at Haus Horst cannot be used for intensity evaluation because the structural condition of the estate is unknown.

With the solution described here, Pastor Buck's report can possibly be explained in its basic elements. In contrast, the effects mentioned for the surroundings of Haus Horst and the description of the effects in the affected area appear to be grossly exaggerated. Thus, the remark of the local historian Mr. zu Hoene is probably pretty close to the truth: "*Pastor J.H. Buck's (Neuenkirchen) report seems to be somewhat sensational after all.*" (Meier & Grünthal, 1992, p. 74). Additional sources which enables us to decide whether Pastor Buck's report can be rated to be basically trustworthy, are not known so far.

It must be noted, that the source material is quite sparse, and the solution presented here is based on many assumptions. Therefore, we recommend the earthquake of 1770 near Alfhausen to be classified as 'uncertain', or even as 'doubtful'.

6. Conclusions

In this study, the information available on the earthquake of Alfhausen (Lower Saxony, Germany) of September 3, 1770 was examined in detail, and the literary source was critically discussed. The intensity of this event could be re-evaluated with regard to the documented seismic effects. The local ground conditions were also included in the interpretation. With the use of intensity-attenuation relationships, the extent of the affected area could only be explained if a shallow focal depth is assumed and the epicentral intensity has a lower value than in previous studies. Essential elements of the primary report by Pastor Buck can be confirmed in principle, but only on condition that all descriptions are rated to be grossly exaggerated.

A tectonic earthquake can be assumed on September 3, 1770 at 11:15 local time with an epicenter in the vicinity of Alfhausen. The parameters of this event are listed in Table 1 (see Leydecker & Lehmann, 2019b).

The possibility of the effects being caused by a collapse of a ground cavity seems to be extremely unlikely. Since all evaluations carried out are based on only one primary source, which does not seem to be reliable in significant points, we recommend the occurrence of a tectonic earthquake on September 3, 1770 near Alfhausen to be regarded as uncertain, or even doubtful.

Table 1. Parameters of the earthquake of September 3, 1770.

Date	September 3, 1770
Time	11:15 (local time)
Epicenter	Alfhausen / Haus Horst
Coordinates	52° 30′ N, 7° 57′ E
Focal depth	$z \geq 2$ km
Maximum intensity	$I_0 \leq$ V (EMS-98)
Radius of perceptibility	$R_S \approx 10$ km
Remark	Uncertain or doubtful event

Acknowledgements

We thank Florian Leydecker for taking the photographs from the 1770 newspaper, Holger Busche for his help with compiling the epicenter map, and Sebastian Busch for his valuable comments on the manuscript. Furthermore, we thank Klaus-Peter Bonjer for his critical review and his detailed and helpful comments. Uwe Braumann, historian, contributed with a careful historical review. We are very grateful for his expertise which enabled a more comprehensive discussion of the Alfhausen event.

References

Ahorner, L., Murawski, H. & Schneider, G. (1970): Die Verbreitung von schadenverursachenden Erdbeben auf dem Gebiet der Bundesrepublik Deutschland. *Zeitschrift für Geophysik*, 36, 313-343.

Ambraseys, N. (1985): Intensity attenuation and magnitude-intensity relationship for Northwest European earthquakes. *Earthquake Engineering and Structural Dynamics*, 13, 733-778.

Augspurgische Extra-Zeitung von Staats-politischen und anderen Neuigkeiten (1770). Anno 1770 (Num. 296, 11. Dec.). Augspurg (Augsburg).

Buck, J.H. (1770): Nachricht von dem merkwürdigen Erdbeben im Nordlande im Fürstentum Osnabrück den 3. Sept. 1770. *Nützlicher Beylagen zum Osnabrückischen Intelligenz-Blate*, 1770 (Vierundvierzigstes Stück, 3 November), c. 349-352. Osnabrück.

Grahle, H.-O. & Schneekloth, H. (1963): Der Darnsee bei Bramsche (geologische Untersuchungen an niedersächsischen Binnengewässern II). *Geologisches Jahrbuch*, 82, 43-64. Hannover.

EMS-98 (1998): European Macroseismic Scale 1998. Grünthal, G. (ed.), Musson, R.M.W., Schwarz, J. & Stucchi, M. (assoc. eds.). *European Seismological Commission. Cahiers du Centre Européen de Géodynamique et de Séismologie*, 15, 99 p. Luxembourg, Conseil de l'Europe.

zu Hoene, O. (1977): Denkwürdigkeiten. In: zu Hoene, O. & Meyer, R. (eds.). *1000 Jahre Alfhausen 977–1977. Beiträge zur geschichtlichen Entwicklung des Kirchspiels*. 69-71. Alfhausen.

Landesamt für Bergbau, Energie und Geologie (2018): *NIBIS-Kartenserver: Geologische Karte 1 : 25 000*. www.lbeg.niedersachsen.de/kartenserver. Hannover.

von LeCoq, K.L. (ed., 1805): *Karte Gegend von Osnabrück und von Dümmer-See, so wie eines Theils von Oldenburg und Hannover*. Section IX. Hannover, Niedersächsisches Landesverwaltungsamt – Landesvermessung.

Leydecker, G. (1986): Erdbebenkatalog für die Bundesrepublik Deutschland mit Randgebieten für die Jahre 1000–1981. *Geologisches Jahrbuch*, E 36, 3-83. Hannover.

Leydecker, G. (1997): *Erdbebenkatalog für die Bundesrepublik Deutschland mit Randgebieten für die Jahre 800–1993 (Schadenbeben bis 1996)*. Extended data file. Hannover, Bundesanstalt für Geowissenschaften und Rohstoffe.

Leydecker, G. (2011): Erdbebenkatalog für Deutschland mit Randgebieten für die Jahre 800 bis 2008 (Earthquake catalogue for Germany and adjacent areas for the years 800 to 2008). *Geologisches Jahrbuch*, E 59, 1-198. Hannover. cf. www.bgr.de/quakecat_en.

Leydecker, G. & Lehmann, K. (2019a): Das Erdbeben vom 3. September 1770 bei Alfhausen (Niedersachsen): real, zweifelhaft oder erfunden? *Mitteilungen der Deutschen Geophysikalischen Gesellschaft*, 1/2019, 10-17.

Leydecker, G. & Lehmann, K. (2019b): Erratum zu Leydecker & Lehmann, DGG-Mitteilungen, Heft 1/2019. *Mitteilungen der Deutschen Geophysikalischen Gesellschaft*, 2/2019, 26.

Meier, R. & Grünthal, G. (1992): Eine Neubewertung des Erdbebens vom 3. September 1770 bei Alfhausen (Niedersachsen). *Osnabrücker Naturwissenschaftliche Mitteilungen*, 18, 67-80. Osnabrück.

Mengeling, H. (1986): *Geologische Karte von Niedersachsen 1 : 25 000*. Section 3514 Vörden. 7 maps, explanation, 125 p. Hannover, Niedersächsisches Landesamt für Bodenforschung.

Naturwissenschaftlicher Verein zu Osnabrück (ed., 1911): Tätigkeit des Vereins. 1907. *Siebzehnter Jahresbericht. Für die Jahre 1907, 1908, 1909, 1910*, I-XVIII. Osnabrück, Meinderssche Buchhandlung.

Rabe, J.G. (1771): *Meteorologische Beobachtungen vor das Jahr 1770. Worinnen sowohl die Barometer- als Thermometerhöhen, ingleichen die Wind- und Wetterveränderungen, nebst der Höhe des gefallenen Regenwassers, täglich zu drey verschiedenen mahlen aufgezeichnet worden*. 64 p. Anspach, Poschische Hofbuchhandlung.

Sieberg, A. (1923): *Geologische, physikalische und angewandte Erdbebenkunde*. 572 p. Jena, Gustav Fischer.

Sieberg, A. (1940): Beiträge zum Erdbebenkatalog Deutschlands und angrenzender Gebiete für die Jahre 58 bis 1799. *Mitteilungen des Deutschen Reichserdbebendienstes*, 2, 1-111. Berlin.

Sponheuer, W. (1958): Die Tiefen der Erdbebenherde in Deutschland aufgrund makroseismischer Berechnungen. *Annali di Geofisica*, XI (3-4), 157-167. Roma.

Sponheuer, W. (1962): Untersuchung zur Seismizität von Deutschland. In: Sponheuer, W. (ed.). Zum Gedenken Emil Wiecherts anläßlich der 100. Wiederkehr seines Geburtstages. *Veröffentlichungen des Instituts für Bodendynamik und Erdbebenforschung in Jena*, 72, 23-52. Berlin.

Sponheuer, W. (1965): Bericht über die Weiterentwicklung der seismischen Skala. *Veröffentlichungen des Instituts für Geodynamik Jena*, 8, 1-21. Berlin.

Staats-Relation derer neuesten Europäischen Nachrichten und Begebenheiten (1770). 1770 (CXLIII. Stück, 30. November). Regensburg, Joh. Christoph Reindl.

Steinwachs, M., Hinze, C. & Mengeling, H. (1996): *Erkundung des Untergrundes im Bereich des Erdbebens von Alfhausen bei Osnabrück im Jahre 1770*. – Report 114846, 11 p. (Aug. 5, 1996). Hannover, Niedersächsisches Landesamt für Bodenforschung.

Tüxen, J. (1986): Erdfälle und Subrosionssenken. In: Mengeling, H. (1986). *Geologische Karte von Niedersachsen 1 : 25000, Erläuterungen zu Blatt Nr. 3514 Vörden*. 93-99. Hannover, Niedersächsisches Landesamt für Bodenforschung.

Appendix

A. Facsimile of the article of Pastor J.H. Buck (1770)

All issues of the weekly newspaper 'Osnabrückisches Intelligenz-Blate' (Osnabrück Intelligence Newspaper) with the respective supplements 'Nützlicher Beylagen zum Osnabrückischen Intelligenz-Blate' (Useful Supplements of the ...) of the year 1770 are collected in the central municipal library (Stadtbibliothek-Zentralbibliothek) of Hannover/Germany, bound in the volume 'ZsH 301 1770'. The pages of the newspaper have a size of ca. 20.5 cm in height and 16.5 cm in width, printed on both sides, and organized in two columns, serially numbered beginning with the first issue of January. The described earthquake report can be found in the columns 349 to 352 (Figs. A1, A2).

dorbenem Getreide, aus welchem schlechtes Brod gebacken ward, dessen Gebrauch einen andern Menschen in eben die Krankheit, die aber weit gelinder war, versetzte. Die Ursache der Krankheit war also im Korn zu suchen, welches, wie Hr. Wollaston bemerkt, schwarz und verdorben war. Müller hat, zwar unrichtig, aber doch vielleicht nicht ohne einige Wahrnehmung geglaubt, daß das Mutterkorn nicht geschadet habe, ohne daß der Brand (ustilago) mit dabey gewesen sey.

Warum hat aber diese Familie vor andern diese Krankheit gelitten?

1) In Schlesien sind zwo ganze Familien gestorben, die also eine gewisse vorläufige schädliche Beschaffenheit des Leibes gehabt haben.

In Solagne lagen vor andern besonders zween Brüder daran krank. Zu Blois scheint nur ein einziger Mensch krank gewesen zu seyn. Andere Beobachtungen zeigen, daß einige Personen am leichtesten vom heissen Brande angegriffen werden i).

i) Quesnay de gangraena. 413.

2) In Schlesien hat die Krankheit die Kinder besonders angegriffen. In Bretagne waren es junge Leute und eine Mutter, die vom Säugen schwach war.

3) Alle waren mager, und schwächlich, welches von einem verdorbenen Geblüte zeugt.

4) Man hat angemerkt, daß anderswo eine feuchte und eingeschlossene Luft, Schweinefleisch, Milchspeisen die Gewalt der Krankheit vermehrt haben, und alles dieses war in der downingischen Familie vorhanden.

5) Diese unglückliche Familie hat nicht allein schlechtes Brod, sondern auch schlechtes Hammelfleisch, schlechten Speck, schlechte Erbsen, wovon einige Dinge an sich gleich schädlich sind, genossen; alles das hat zu der Krankheit beygetragen.

6) Die Krankheit ist nicht ansteckend gewesen.

Leben Sie wohl. H. H. und nehmen Sie diese geringen Blätter gütig auf.

Lausanne d. 28 Jun. 1764.

Nachricht von dem merkwürdigen Erdbeben im Nordlande * im Hochstift Osnabrück den 3 Sept. 1770.

Verschiedene selbst einsichtsvolle Patrioten, haben gelegentlich keine geringe Befremdung darüber geäußert, daß man von dem gewiß sehr fürchterlichen und schreckenvollen Erdbeben, welches das Nordland im Hochstift Osnabrück den 3 September d. J. betroffen, in öffentlichen Blättern, die öffentliche Anzeige vermisset hat. Um desto geringer

* Von einem hohen verehrungswürdigen Gönner bin belehret, daß der Norderwinkel des Hochstifts Osnabrück in alten Documenten in das Nordland und Orth- oder Arthland, wie es auch oft ausgedruckt wird, eingetheilet sey. Zu den letztern zählet man die äußersten Gegenden dieses Hochstifts an dieser Seite, und zu dem ersten die nächst angrenzende Seite und Oerter gegen Südosten; in jenem Striche hat man auch von dem jetzt beschriebenen Erdbeben keine Empfindung gehabt. B.

Figure A.1. First part of the article about the 1770 earthquake by J.H. Buck in the newspaper supplement 'Nützlicher Beylagen zum Osnabrückischen Intelligenz-Blate', issue of November 3, 1770, c. 349-350.

ringer ist der Zweifel, daß man der Nachricht hievon, in den gegenwärtigen Anzeigen, ihren Platz mißgönnen werde. Ohngefehr ein Viertel auf Zwölfe in der Mittagsstunde, der schon berührten Zeit, wurde der Strich von Westen gegen Osten, ohngefehr 3 Meile in die Länge und 2 in der Breite, und zwar namentlich die Oerter Merzen, Alfhausen, Gerde, Neuenkirchen, Bramsche und Vörden, durch zwo bald auf einander folgende Erderschütterungen, in das äußerste Schrecken versetzet. Mit der letztern, welche die heftigste war, und die, wie man will angemerket haben, eine halbe Minute gedauret, und ohngefehr eine Minute auf die erste erfolget sey, war eine so merkliche Bewegung und zugleich eine so zitternde Erschütterung verbunden, daß überhaupt die Ziegeln auf den Dächern, das fürchterlichste Gerassel machten, und alle sonst sogenannte Mobilia, Schränke, Tische und Stühle ihren Umfall, wie ein jeder in seiner Wohnung angemerket, gedrohet haben. Mit wie vieler mit Angst und Furcht untermischter Bestürzung und Erwartung eines neuen schreckenvollen Besuchs dieses unterirdischen Orcans, ein jeder die Flucht aus seiner Wohnung ergriffen, läßt sich in der Kürze nicht leicht deutlich genug beschreiben. Ob nnn gleich (dem HErrn, dem allerhöchsten Gebieter der Natur, sey herzlich Dank) diese zagenvolle Erwartung eines schleunigen allgemeinen Jammers nicht erfolget ist; so haben doch besonders große und schwere Gebäude, vornemlich die Kirchengewölbe an deu mehresten oben benanten Oertern, hiebey merklich gelitten. Nebst diesen verdienet hier unter andern das hochadeliche Haus Horst zu Alfhausen bemerket zu werden. Nicht allein ein auf allen Zimmern besonders an den Querbalken abgeriebener Kalk, sondern auch ein umgestürzter Aufsatz eines, auf einem geraumigen Saale dieses Hauses, befindlichen Ofens, und vornemlich ein vom Dache herunter gestürzter Schornstein, wobey dern hohe Besitzer dieses Hauses, leicht ein Unfall zustossen können; eins so wohl wie das andere ist das deutlichste Zeugniß, von diesem gewiß sehr heftigen und merkwürdigem Erdbeben. Ans einer vom Erdbeben besonders entworfenen Geschichte erhellet, daß Westphalen, vor ohngefehr anderthalb hundert Jahren, diese höchst unangenehme Begebenheit merklich empfunden habe; der HErr gebe, daß der Erneurung einer so schreckenvollen Erscheinung, künftighin in keinen Jahrbüchern der Welt dürfe gedacht werden.

N. den 9 Oct. 1770. J. H. B. P.

Figure A.2. Second part of the article about the 1770 earthquake by J.H. Buck in the newspaper supplement 'Nützlicher Beylagen zum Osnabrückischen Intelligenz-Blate', issue of November 3, 1770, c. 351-352.

B. Transliteration of the article of Pastor J.H. Buck (1770)

Nachricht von dem merkwürdigen Erdbeben im Nordlande* im Hochstift Osnabrück den 3 Sept. 1770.

Verschiedene selbst einsichtsvolle Patrioten, haben gelegentlich keine geringe Befremdung darüber geäußert, daß man von dem gewiß sehr fürchterlichen und schreckenvollen Erdbeben, welches das Nordland im Hochstift Osnabrück den 3 September d. J. betroffen, in öffentlichen Blättern, die öffentliche Anzeige vermisset hat. Um desto geringer ist der Zweifel, daß man der Nachricht hievon, in den gegenwärtigen Anzeigen, ihren Platz mißgönnen werde. Ohngefehr ein Viertel auf Zwölfe in der Mittagsstunde, der schon berührten Zeit, wurde der Strich von Westen gegen Osten, ohngefehr 3 Meile in die Länge und 2 in der Breite, und zwar namentlich die Oerter Merzen, Alfhausen, Gerde, Neuenkirchen, Bramsche und Vörden, durch zwo bald auf einander folgende Erderschütterungen, in das äußerste Schrecken versetzet. Mit der letztern, welche die heftigste war, und die, wie man will angemerket haben, eine halbe Minute gedauret, und ohngefehr eine Minute auf die erste erfolget sey, war eine so merkliche Bewegung und zugleich eine so zitternde Erschütterung verbunden, daß überhaupt die Ziegeln auf den Dächern, das fürchterlichste Gerassel machten, und alle sonst sogenannte Mobilia, Schränke, Tische und Stühle ihren Umfall, wie ein jeder in seiner Wohnung angemerket, gedrohet haben. Mit wie vieler mit Angst und Furcht untermischter Bestürzung und Erwartung eines neuen schreckenvollen Besuchs dieses unterirdischen Orcans, ein jeder die Flucht aus seiner Wohnung ergriffen, läßt sich in der Kürze nicht leicht deutlich genug beschreiben. Ob nun gleich (dem HErrn, dem allerhöchsten Gebieter der Natur, sey herzlich Dank) diese zagenvolle Erwartung eines schleunigen allgemeinen Jammers nicht erfolget ist; so haben doch besonders große und schwere Gebäude, vornemlich die Kirchengewölbe an den mehresten oben benanten Oertern, hiebey merklich gelitten. Nebst diesen verdienet hier unter andern das hochadeliche Haus Horst zu Alfhausen bemerket zu werden. Nicht allein ein auf allen Zimmern besonders an den Querbalken abgeriebener Kalk, sondern auch ein umgestürzter Aufsatz eines, auf einem geraumigen Saale dieses Hauses, befindlichen Ofens, und vornemlich ein vom Dache herunter gestürzter Schornstein, wobey dern hohe Besitzer dieses Hauses, leicht ein Unfall zustossen können; eins so wohl wie das andere ist das deutlichste Zeugniß, von diesem gewiß sehr heftigen und merkwürdigem Erdbeben. Aus einer vom Erdbeben besonders entworfenen Geschichte erhellet, daß Westphalen, vor ohngefehr anderthalb hundert Jahren, diese höchst unangenehme Begebenheit merklich empfunden habe; der HErr gebe, daß der Erneurung einer so schreckenvollen Erscheinung, künftighin in keinen Jahrbüchern der Welt dürfe gedacht werden.

N. den 9 Oct. 1770. *J.H.B. P.*

** Von einem hohen verehrungswürdigen Gönner bin belehret, daß der Norderwinkel des Hochstifts Osnabrück in alten Documenten in das Nordland und Orth- oder Arthland, wie es auch so oft ausgedruckt wird, eingetheilet sey. Zu den letztern zählet man die äußersten Gegenden dieses Hochstifts an dieser Seite, und zu dem ersten die nächst angrenzende Seite und Oerter gegen Südosten; in jenem Striche hat man auch von dem jetzt beschriebenen Erdbeben keine Empfindung gehabt. B.*

C. Translation (attempt) of the article of Pastor J.H. Buck (1770)

Notice of the remarkable earthquake in the Nordland* of the Bishopric of Osnabrück on Sept. 3, 1770

Various reasonable patriots have occasionally expressed their utter astonishment at the fact that any public report has been missed in public newspapers of the really very terrible and frightening earthquake which affected the Nordland of the Bishopric of Osnabrück on September 3, this year. The less is the doubt that one will grudge the news a place in the actual newspapers. A quarter past eleven at noon, on the already mentioned date, the area from west to east, roughly 3 miles in length and 2 in width, namely the villages of Merzen, Alfhausen, Gerde, Neuenkirchen, Bramsche and Vörden, was heavily frightened by two earth tremors soon following each other. The latter, which was the most violent, and, as one believed to have noted, lasted half a minute, and which happened approximately a minute after the first, was accompanied by such a noticeable movement and, at the same time, such a trembling shock that the tiles on the roofs rattled in the most terrible way, and in addition all the so-called Mobilia, cupboards, tables, and chairs threatened to fall down, as everyone noted in his home. With how much fear and anxiety, mixed with dismay and expectation, of a new frightful visit to this underground storm everyone was fleeing from his home, cannot easily be described clearly enough in the brevity. Whether this timid expectation of a sudden general misery has not been met (to the Lord, the supreme lord of nature, be cordially thanked); yet especially large and massive buildings, in particular the vaults of the churches at most the above-mentioned villages, had suffered noticeably. Additionally, among others the noble Haus Horst near Alfhausen deserves to be noticed. Not only a lime rubbed off in all the rooms, especially on the cross-beams, but also an overturned top of a stove in a spacious hall of this house, and especially a chimney fallen down from the roof, which could have easily caused an accident to the noble owner of this house; the one as well as the other is the clearest testimony of this certainly very violent and remarkable earthquake. From a story especially dealing with the earthquake it becomes clear that Westphalia, one and a half hundred years ago, had noticeably felt this most unpleasant incident; the Lord may give that in the future, no renewal of such a frightful phenomenon may occur which has to be remembered in any yearbooks of the world.

N., Oct. 9, 1770. *J.H.B. P.*

** I was informed by a noble venerated patron that in old documents the Norderwinkel of the Bishopric of Osnabrück is divided into the Nordland and the Orth- or Arthland, as it is often called. The outermost regions of this bishopric on this side belong to the latter one, and the next adjoining side and villages towards southeast belong to the first; in that area one had no perception of the earthquake described here. B.*

Historical Earthquakes, Paleoseismology,
Neotectonics and Seismic Hazard:
New Insights and Suggested Procedures

DOI: 10.23689/fidgeo-3866

How well does known seismicity between the Lower Rhine Graben and southern North Sea reflect future earthquake activity?

Thierry Camelbeeck[1], Kris Vanneste[1], Koen Verbeek[1], David Garcia-Moreno[1,2], Koen van Noten[1] & Thomas Lecocq[1]

[1] Royal Observatory of Belgium: thierry.camelbeeck@oma.be, kris.vanneste@oma.be, koen.verbeeck@oma.be, koen.vannoten@oma.be, thomas.lecocq@oma.be

[2] University of Ghent: David.garciaMoreno@Ugent.be

Abstract

Since the 14th century, moderate seismic activity with 14 earthquakes of magnitude $M_W \geq 5.0$ occurred in Western Europe in a region extending from the Lower Rhine Graben (LRG) to the southern North Sea. In this paper, we investigate how well this seismic activity could reflect that of the future.

The observed earthquake activity in the LRG is continuous and concentrates on the Quaternary normal faults delimiting the LRG, which are also the source of large surface rupturing Holocene and Late Pleistocene earthquakes. The estimated magnitude of these past earthquakes ranges from 6.3±0.3 to 7.0±0.3 while their average recurrence on individual faults varies from ten thousand to a few ten thousand years, which makes foreseeing future activity over the long-term possible.

Three of the largest historical earthquakes with $M_W \geq 5.5$ occurred outside the LRG. Late Quaternary activity along the fault zones suspected to be the source of two of these earthquakes, i.e. the 1580 Strait of Dover and 1692 northern Belgian Ardennes earthquakes, is very elusive if it exists. Hence, similar earthquakes would be very infrequent at these locations suggesting that the seismicity outside of the LRG would be episodic and clustered on some faults during periods of a few hundreds of years interrupted by long periods of inactivity typically lasting for some tens to hundreds of thousand years. Seismic moment release estimation and its comparison between recent geological and historical seismicity periods lead us to suggest that the high seismicity level observed between AD 1350 and AD 1700 west of the LRG would be uncommon.

1. Introduction

Moderate and rare large historical earthquakes in Western Europe in the region north of the Pyrenees and the Alpine arc are sparsely located (Figure 1). Nevertheless, they occurred clustered in patches of activity separated from regions where seismicity is absent. At first sight, this observation could indicate that some regions would be more susceptible than other ones to generate moderate to large earthquakes. Moreover, the observation that most of these earthquakes occurred at different locations inside the active patches suggests an apparent random spatial distribution of seismicity at different spatial scales.

However, recent studies of plate interior seismic activity suggest that such apparent concentrations and gaps in seismicity likely reflect the short earthquake record compared to the long and variable recurrence interval of large earthquakes (Swafford and Stein, 2007). Therefore, to evaluate whether persistent or absent seismicity in current active or inactive regions, respectively, is simply a consequence of the short duration of the observation period or is more permanent in the current tectonic context are important issues for seismic hazard evaluation (Stein et al., 2015). Answering these questions needs an identification and collection of information on large earthquakes that occurred before the period when written earthquake eyewitnesses began. Retrieving traces of past large earthquakes in the geomorphology and the recent geologic record is the subject of the disciplines active tectonics and paleoseismology.

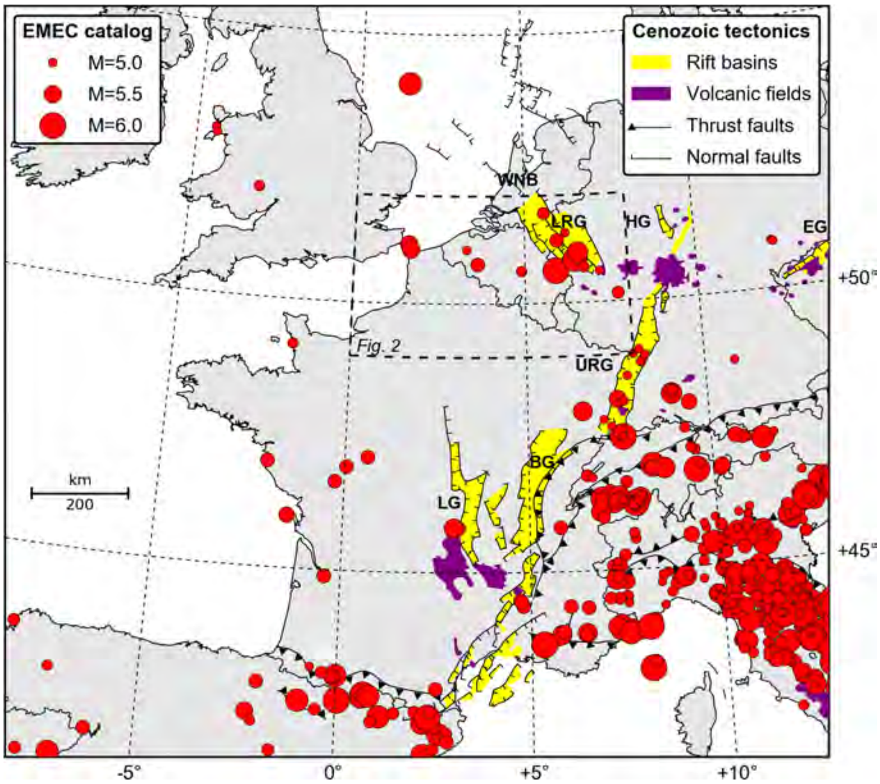


Figure 1. Seismic activity in Western Europe. Epicenters of earthquakes with estimated $M_W \geq 5.0$ as reported in the European Mediterranean Earthquake Catalogue (EMEC) (Grünthal and Wahlström, 2012). WNB for West Netherlands Basin, LRG for Lower Rhine Graben, HG for Hessian Graben, URG for Upper Rhine Graben, BG for Bresse Graben and LG for Limagne Graben. The small rectangle with black dotted line shows the limits of figure 2.

In this paper, we discuss the contribution of the seismology team of the Royal Observatory of Belgium to the study of this issue in the region extending from the Lower Rhine Graben (LRG) to the southern North Sea (dotted rectangle in figure 1). First, we provide the background information on the seismicity in the studied area. Second, we discuss the results of our studies on Holocene and Pleistocene activity of the faults bordering the LRG and their relationship to large earthquakes. Third, we focus on our investigations to evaluate whether tectonic activity is persistent on the geological structures that generated the large 6 April 1580 Strait of Dover and 18 September 1692 Verviers (eastern Belgian Ardennes) historical earthquakes (Figure 2). Finally, we explain some aspects of the seismicity in and outside the LRG based on the comparison of the recent geological seismic moment release with the one released by historical earthquake activity, and we emphasize the need to develop research strategies that allow improving our knowledge on inherited faults that could generate future large earthquakes outside the LRG.

2. Historical seismicity between the Lower Rhine Embayment and southern North Sea

The region extending from the Lower Rhine Graben (LRG) to the Strait of Dover and the southern North Sea is one of the most seismically active areas in Western Europe. Since the 14th century, 14 earthquakes with estimated or measured magnitude $M_W \geq 5.0$ occurred in this area (Figures 1 and 2, Table 1). There is no observed seismic activity to the south of this active cluster in the Paris Basin, nor in the northern prolongation of the LRG in the northwest of the Netherlands and in the southern North Sea.

Table 1. $M_W \geq 5.0$ earthquakes since 1350 in the regions between the LRE and southern North Sea

N°	Date	Lat °N	Long °E	M_W			region
				BE	EM	SH	
1	1382 05 21	51.30	2.00	6	5.5	5.4	Southern North Sea
2	1449 04 23	51.60	2.50	5½	5.0	4.0	Southern North Sea
3	1504 08 23	50.77	6.10	5½	5.0	4.8	Roer Valley Graben
4	1580 04 06	51.00	1.50	6	5.5	5.5	Strait of Dover
5	1640 04 04	50.77	6.10	5½	5.5	5.5	Roer Valley Graben
6	1692 09 18	50.59	5.86	6¼	6.1	5.8	Eastern Belgian Ardenne
7	1755 12 27	50.77	6.10	5¼	5.0	5.1	Roer Valley Graben
8	1756 02 18	50.80	6.50	5¾	5.9	5.7	Roer Valley Graben
9	1828 02 23	50.70	5.00	5	5.1	5.2	Brabant Massif
10	1846 09 27	50.12	7.68	5	5.2	5.2	Middle Rhine Valley
11	1878 08 26	50.95	6.53	5½	5.7	5.5	Roer Valley Graben
12	1938 06 11	50.78	3.58	5.0	5.3	5.3	Brabant Massif
13	1951 03 14	50.63	6.72	5.3	5.1	5.1	Roer Valley Graben
14	1992 04 13	51.16	5.95	5.3	5.3	5.3	Roer Valley Graben

Epicentre location from the earthquake catalog of the Royal Observatory of Belgium
BE: M_W from the earthquake catalog of the Royal Observatory of Belgium
EM: M_W from the EMEC earthquake catalog (Grünthal and Wahlström, 2012)
SH: M_W from the SHEEC earthquake catalog (Stucchi et al., 2013)
In the text, we indicated information from BE, but a comparison with EMEC and SHEEC shows the variability of magnitude estimation for historical earthquakes

Looking at the last 650-700 years, a period in which historical information allows estimating earthquake location and magnitude, the Roer Valley Graben (RVG), the central graben of the LRG that crosses the border region between Belgium, Germany and The Netherlands, appears as the most active area (Hinzen and Oemisch, 2001; Hinzen and Reamer, 2007; Camelbeeck et al., 2007). In the RVG, seismicity occurred uninterrupted (Figure 2). The strongest known earthquake is the 1756 Düren event (Germany) with a magnitude estimated around 5 ¾. Six other earthquakes reached $M_W \geq 5.0$. The two most recent significant events are the $M_W=5.3$ 1951 Euskirchen (Germany) and the $M_W=5.3$ 1992 Roermond earthquakes (the Netherlands) (van Eck and Davenport, 1994). The spatial pattern of earthquake hypocenters agrees with an activity associated to the NNW-SSE trending Quaternary normal fault system displacing the main terraces of the Rhine and Maas rivers, as already suggested by Ahorner (1962, 1975). Earthquake focal mechanisms of the two most recent significant earthquakes, the $M_W=5.3$ 1992 Roermond (Camelbeeck and van Eck, 1994) and the $M_W=4.6$ 2002 Alsdorf earthquake (Hinzen and Reamer, 2007) show quasi-pure normal faulting with one of the nodal planes having similar strike and dip as the faults along which they are supposed to have occurred.

Outside the LRG, the spatial distribution of the current seismic activity is heterogeneous between a large inactive area to the east and a more active area to the west and the southeast of the LRG. To the southeast of the LRG, a zone of moderate seismic activity follows the Middle Rhine Valley across the Rhenish Massif up to the northern limit of the Upper Rhine Graben (Ahorner, 1983; Hinzen and Reamer, 2007). The strongest event in this area is the $M_W \sim 5$ 1846 Sankt Goar earthquake. Another area with a small level of earthquake activity is the SW-NE trending Hunsrück-Taunus zone limiting the Rhenish Massif to the south between the southern part of Grand Duchy of Luxemburg and of the Middle Rhine Valley (Ahorner, 1983).

The major Midi-Eifel thrust, which separates the Brabant parautochton from the Ardenne allochton and represents the northernmost fault zone of the Variscan front, appears as a limit separating different zones in the observed seismicity pattern to the west of the LRG. To the south of this limit and abutted to the LRG, the Ardenne consists of Devono-Carboniferous rocks folded and faulted during the Variscan orogeny (335-300 Ma) (Oncken et al., 1999). Two major units can be distinguished: the Ardenne Massif or Rhenish Shield, and more to the southwest, the Paris Basin. The Paris Basin and the western part of the Ardenne show only little seismic activity. In contrast, seismic activity is more pronounced in the northeastern part of the Belgian Ardenne and the Eifel Mountains in Germany. It is spatially more diffuse and less important than in the RVG even though the most significant event of the earthquake history of the whole region, with an estimated M_W of 6 ¼, occurred here on September 18 1692 near the city of Verviers (Alexandre et al., 2008). By relocating the earthquakes that occurred between 1985 and 2010 in the Ardenne-Eifel area and RVG (Figure 3a), Lecocq (2011) evidenced a remarkable 20 km long NNW-SSE alignment of epicenters already identified by Ahorner (1983) who named it the Hockai Fault Zone (HFZ) (Figures 2 and 4B). The distribution of earthquake focal depths along a perpendicular profile suggests that the HFZ is a narrow zone in which focal depth does not exceed 10 km. To the west of the HFZ, focal depths progressively increase, reaching 25 km depth, while to the east they reach 20 km. The resulting difference of integrated shear strength, which is smaller in the HFZ than in the surrounding area, lead us to consider the HFZ as a weakness zone surrounded by a stronger crust. This is why we suggest that the 1692 earthquake occurred along the HFZ, in its northern part.

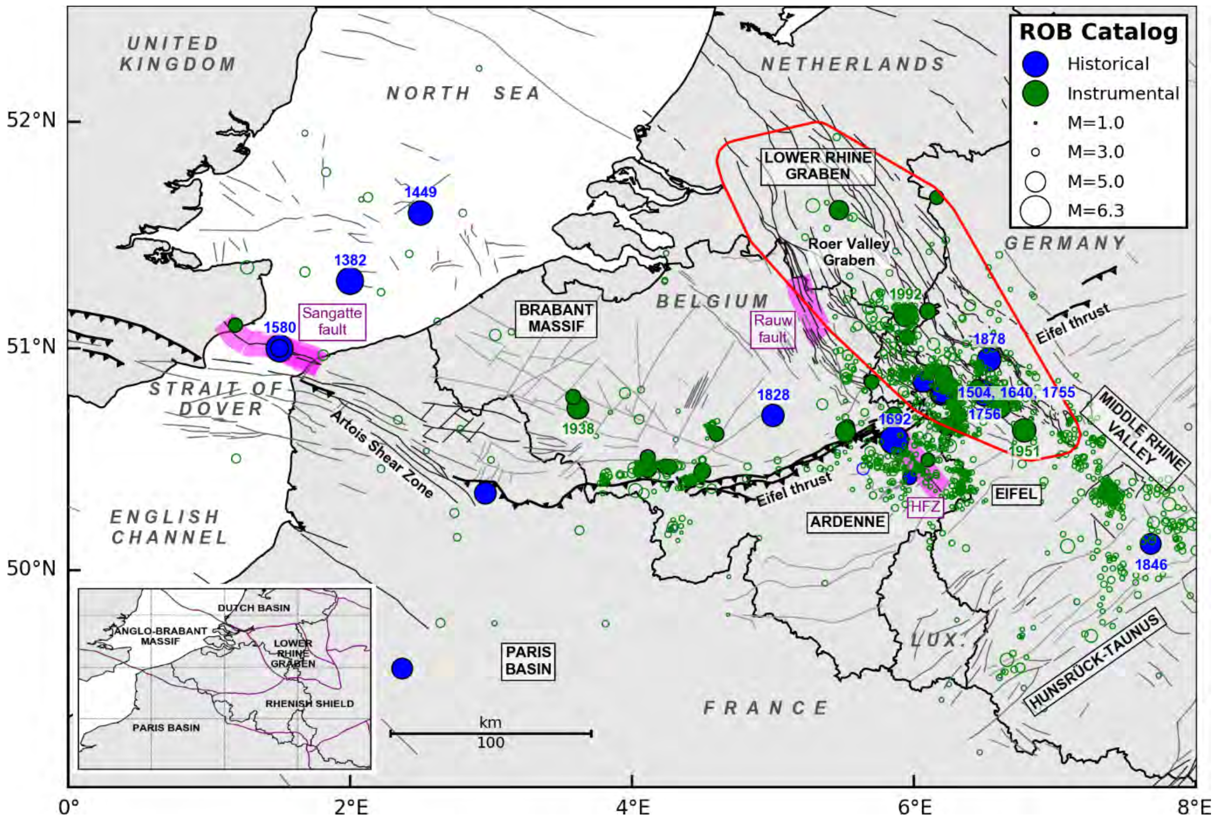


Figure 2. Seismic activity in the region from the Lower Rhine Graben to the southern North Sea from 1350 to 2018 (Catalogue of the Royal Observatory of Belgium). The area inside the red contour is the Lower Rhine Graben. The Sangatte and Rauw faults as well as the Hockai Fault zone (HFZ) are indicated by the magenta-coloured areas.

Moderate earthquake activity also occurs in the Carboniferous basins just north of the Midi-Eifel thrust. The Liège area recently suffered from two earthquakes that occurred on 21 December 1965 ($M_W = 4.3$) and 8 November 1983 ($M_W = 4.6$). More to the west, pronounced seismic activity occurred since the end of the 19th century in the Hainaut zone. Despite the fact that none of these earthquakes exceeded magnitude 4.5, some of them were locally damaging due to their shallowness. An unresolved question about part of this activity is its possible relationship with mining works in this region that begun to be extensive in the 19th century and stopped in the years 1960-1970 (Descamps, 2009). Since the installation of a denser seismic network in Belgium in 1985, a few small earthquakes were also located just south of the Midi-Eifel thrust between the Liège area and the eastern extremity of the Hainaut seismic zone.

North of the Variscan Front, the Anglo-Brabant Massif consists of lower Cambrian to Silurian deposits deformed during the Acadian orogeny (late Llandovery to late Pragian). The Anglo-Brabant Massif witnesses a diffuse seismicity with two damaging M_W=5.0 earthquakes on the Belgian territory on 23 February 1828 and on 11 June 1938 (Table 1). Two other moderate earthquakes occurred below the southern North Sea in the offshore prolongation of the Brabant Massif on 21 May 1382 and 23 April 1449 (Table 1) (Melville et al., 1996). Diffuse seismic activity is also present in the nearby French and southern British territories at the limit between the Artois hills and the Flanders plain and its offshore prolongation across the Strait of Dover. A M_W=6.0 earthquake occurred here on 6 April 1580 (Melville et al., 1996). Camelbeeck et al. (2007) associated this seismicity to faults reactivated during an early Tertiary tectonic inversion and that cut the small Artois anticlinal flexure (Auffret and Colbeaux, 1977). These fault zones are well identified by the horizontal gradient of the gravity Bouguer anomaly (Everaerts, 2000; Camelbeeck et al., 2007).

3. Are the faults that generated moderate and large earthquakes geologically active?

Extending our catalogue of large earthquakes to periods preceding the first written testimonies on earthquake effects requires identifying imprints of large earthquakes in the geomorphology and in the geologic record. However, such earthquake traces are difficult to observe in continental plate interiors because the faults that generated large earthquakes are not very active, if at all, and even low rates of erosion or deposition can erase or hide their traces. Pioneering works of Crone et al. (1990, 1992, and 1997) were the first to relate seismicity with surface faulting evidence recorded in the near-surface geology in stable plate interiors. Their common thread was the clear geomorphic evidence given by the surface ruptures of the 1986 Marryat Creek and 1988 Tennant Creek earthquakes in the Australian craton, and by the fault scarps along the Meers fault in southwest Oklahoma and along the Cheraw fault in southeast Colorado. These geomorphic indicators were ideal geological targets because they precisely indicated where to undertake paleoseismic investigations. These forerunner studies were also the first to highlight past surface rupturing earthquakes by studying fault scarps with no reported seismic activity. Their analyses evidenced the episodic nature of large earthquakes in stable continental regions (SCR).

In Western Europe, there is no identified historical earthquake having ruptured the surface. Of course, the largest ones only reached magnitudes 5 ½ $\leq M_W \leq$6 ¼ which is at the lower limit to produce surface displacement observable without modern geodetic measurements. Furthermore, finding historical documents that mention small surface ruptures is unlikely because possible surface faulting events occurred before the 18th century, a period from which few written records are available. The lack of a historical source of a known surface rupture does not allow defining precisely where to conduct a search for recent or active faulting and to identify the source of the aforementioned earthquakes. Of course, the Quaternary faults of the LRG displace the main terraces of the Rhine and Maas Rivers and are at some places identifiable in the landscape. Nevertheless, their precise fault location needs specific geological and geophysical investigations (Demanet et al., 2001). Until the mid-1990s, as no historical events were mentioned to have ruptured the ground surface, no one would have suspected that the LRG faults could produce large surface faulting earthquakes, especially because Ahorner (1975) considered fault movements in the LRG as purely aseismic.

The M_W=5.3 1992 Roermond earthquake stimulated discussions between Earth scientists about the behaviour of Quaternary faults in the LRG and if earthquakes larger than the Roermond event could happen there. This is why scientists of the Royal Observatory of Belgium addressed these issues from 1995 onwards by undertaking detailed geological and geomorphological investigations of fault scarps in the RVG, searching for the slightest evidence of Holocene and late Pleistocene earthquake activity along Quaternary faults (Camelbeeck and Meghraoui, 1996, 1998). In section 3.1, we present the main quantitative results of our investigations during the last 20 years showing the active character of these border faults and their relationship with large surface rupturing earthquakes.

In parallel, improvements during the last 30 years in our knowledge about historical earthquakes suggest that three large earthquakes with M_W>5.5 occurred to the west of the LRG (Melville et al., 1996; Alexandre et al., 2008). In contrast with surface faulting earthquakes, for which the observed surface break identifies the fault source at the ground surface, the seismogenic source of the moderate historical earthquakes outside the LRG can only be suspected. Therefore, identifying their sources is more complex and needs to incorporate an analysis of the regional geological and geophysical background, a mechanical analysis of the current seismic activity, and the strict application of the methodologies of active faulting studies. We present in section 3.2 a synthesis of investigations on the faults that generated the large 6 April 1580 Strait of Dover and 18 September 1692 Verviers earthquakes, and that suggest that their Quaternary activity would be elusive. The Royal Observatory of Belgium led these investigations in cooperation with universities of Ghent and Liège, respectively.

3.1. The Roer Valley Graben: an active geological source of large earthquakes

Our investigations along the Bree fault scarp (Geleen fault) in Belgium at the western border of the RVG were the first in stable continental Europe to suggest the occurrence of large surface-rupturing earthquakes during the Holocene and the Late Pleistocene (Camelbeeck and Meghraoui, 1996; 1998; Meghraoui et al., 2000; Vanneste et al., 1999, Vanneste and Verbeeck, 2001). Paleoseismic investigations were also conducted along the eastern border faults of the RVG, on the Peel fault near Roermond in the Netherlands and the Rurrand fault near Jülich in Germany (Vanneste and Verbeeck, 2001; van den Berg et al., 2002). Along the Geleen fault, we estimated that the magnitude of the three most recent paleoearthquakes should range between 6.3±0.3 and 6.7±0.3. Evidence suggests that larger earthquakes with M_W approaching 7.0±0.3 could have occurred along the Rurrand fault while the magnitude of the three paleoearthquakes identified along the Peel fault ranges from 6.0±0.3 to 6.5±0.3. Camelbeeck et al. (2007) discuss these interpretations in more detail.

The analysis of the six trenches excavated across the Geleen fault provide invaluable information on the recurrence of large earthquakes along a single seismogenic fault in the RVG. Two large earthquakes occurred during the last 20 kyr while four other similar events have been observed during the previous 80 kyr. The two trenches excavated near Rotem in the Meuse Valley suggest a timing for the most recent event dated between 2.5 ± 0.3 and 3.1 ± 0.3 kyr BP. The average return period for the two and five most recent earthquake cycles is 14 ± 8 kyr and 23 ± 4 kyr, respectively. The average fault slip for the same intervals is 0.050 ± 0.036 mm/yr and 0.031 ± 0.012 mm/yr, respectively. These results suggest significant variability in large earthquake return periods, and possibly in slip rates as well.

Vanneste et al. (2013) compiled all relevant data concerning the Quaternary faults of the LRG and associated seismicity and devised a parameterized model of composite seismic sources, which provides a base for modeling seismic hazard. This data compilation furnishes lower and upper bounds on the activity rates of all the faults in the LRG. Fault slip rates are derived from long-term vertical displacement rates estimated from the age and vertical displacement of the main terraces of the Rhine and Meuse rivers during the last 700 kyr. They range from 0.007 to 0.1 mm/yr.

Other trench exposures provided additional convincing evidence for earthquake surface rupture in the LRG (Skupin et al., 2008, Grützner et al., 2016, Kuebler et al., 2016). Moreover, Gold et al. (2017) evidence an apparent Late Quaternary fault-slip rate increase in the southern LRG by using new main terrace vertical offset measurements.

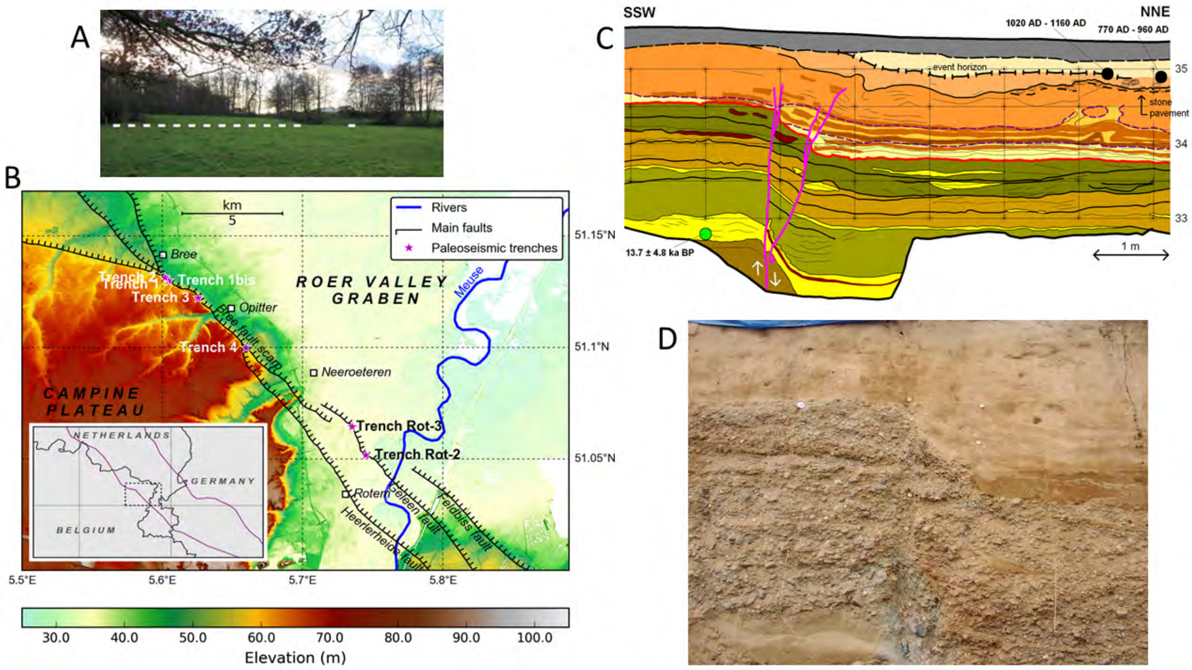


Figure 3. The Geleen fault at the western border of the Roer Valley Graben. (A) Photograph of the frontal scarp - underlined by the white dotted line - near Bree at the trenches 1 and 1bis location and corresponding to the Holocene slip of the fault; (B) Digital Elevation Model of the western border of the RVG in Belgium and location of the excavated paleoseismic trenches; (C) Geological logging of the northwestern wall of the Rotem-2 trench; and (D) photograph in this trench showing the Geleen fault displacing the top of the late Weichselian terrace and overlying eolian sands and silts by 0.75-1 m.

3.2. The stable continental region bordering the Roer Valley Graben

The six moderate and large historical earthquakes located to the west of the RVG occurred on fault zones for which the most recent prolonged activity occurred during the Meso-Cenozoic period. The 1382 and 1449 earthquakes (Table 1) occurred in the offshore extension of the Brabant Massif that contains a sequence of troughs and faults in the Mesozoic and Early Cenozoic cover (Henriet and De Batist, 1989). Such faults and troughs are absent in the sedimentary cover of the onshore Lower Paleozoic Brabant Massif where the 1828 and 1938 earthquakes are located (Table 1), leading to suggest that these onshore earthquakes could result from fault reactivation within the core of the Massif. The 1580 Dover Strait earthquake (Table 1) occurred in the offshore prolongation of an anticlinal flexure defining the limit between the Artois hills and the Flemish Plain onshore, and which is cut by faults resulting from an early Tertiary tectonic inversion phase. The M_W=6 ¼ 18 September 1692 earthquake, which is the largest known earthquake in Western Europe (Alexandre et al., 2008), occurred on a Variscan structure reactivated at different periods during the Mesozoic and the Cenozoic.

As the most recent known tectonic activity of the geological structures associated to the largest known earthquakes is contemporaneous with or older than the early Cenozoicum, we can conclude that the occurrence of large earthquakes is not sufficiently frequent to generate visible imprints of faulting in the geomorphology and in the geologic record. Until recently there were no specific investigations to evaluate whether this assumption was correct. Therefore, we investigated the epicentral areas of the 6 April 1580 and 18 September 1692 earthquakes. Our objectives were to identify the fault zones that generated these historical earthquakes and to evaluate their most recent activity.

3.2.1. The Hockai Fault Zone and the 18 September 1692 earthquake

The Hockai fault zone (HFZ) corresponds to a SSE-NNW oriented fault zone in the northeast Ardenne and its northern foreland (Figures 2 and 4). Its name comes from an alignment of earthquakes identified by Ahorner (1983). Demoulin (1988) reported geomorphological anomalies associated to a

Carboniferous-Permian fault zone nearby and parallel to this seismic alignment. He therefore designated this fault zone as the HFZ, implicitly establishing a link between the seismic events and this inherited fault zone.

The HFZ originated at the end of the Variscan orogeny during the late Carboniferous and early Permian and moved episodically during the Mesozoic and the Cenozoic. Demoulin (2006) mapped the HFZ from geomorphological evidences related to this activity. He succeeded to evidence geomorphological features over a total length of around 40 km, with gaps of several km. Vanneste et al. (2018) furnish a synthesis of the geological background and geomorphological observations along the HFZ.

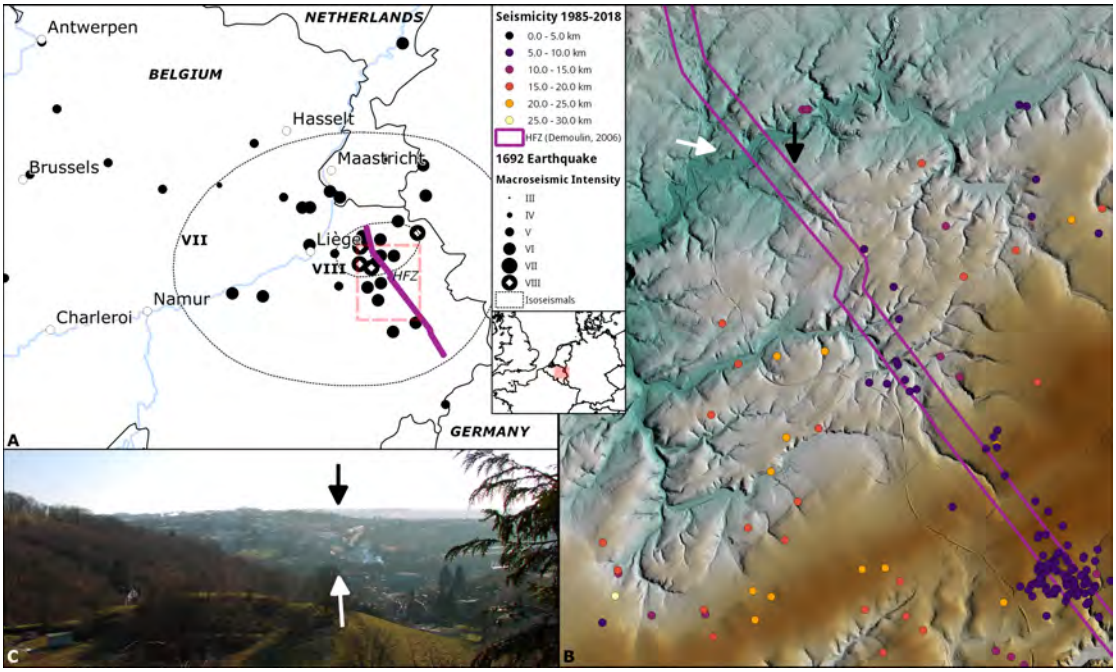


Figure 4. The Hockai fault zone (HFZ). (A) Macroseismic intensities in the epicentral area of the 18 September 1692 Verviers earthquake (Alexandre et al., 2008). The smallest doted curve shows the area with intensities VIII and VII-VIII, the largest is the area with intensity ≥ VII. The mauve line indicates the HFZ (from Demoulin, 2006); (B) Epicenters of earthquakes between 1985 and 2018 in the area indicated by the orange color in (A). The colors differentiate earthquake focal depths. The background map is the new LIDAR Digital Terrain Model of the area where the 7 km long bedrock fault scarp associated with the northern part of the HFZ is well visible. The white and black arrows indicate the position in the DEM of the fault scarp view in the photo (C).

As explained in section 2, compared to other rigid parts of the Ardennes, the HFZ is a weak crustal zone that is more prone to be the source of a more significant seismic activity than the rest of the Massif. The M_W=6 ¼ 18 September 1692 earthquake is the largest known earthquake in Western Europe (Alexandre et al., 2008). It occurred near the city of Verviers and caused important damage corresponding to intensity VIII (EMS-92) in the northeastern part of the Belgian Ardennes (Camelbeeck et al., 2014). The observation that the HFZ crosses the central part of the most affected area suggests that the 1692 earthquake ruptured this fault zone (Figure 4). Suspected Holocene – Late Pleistocene tectonic movements in the northern part of the HFZ corroborate this hypothesis. Indeed, Graulich (1959) observed a 1.7 m vertical displacement of Late Pleistocene loess along a fault associated to the HFZ. Moreover, the LIDAR Digital Terrain Model of the Walloon region evidences a ~ 1-2 m high scarplet in the main scarp prolongation where the HFZ crosses the floodplain of the Vesdre River (Vanneste et al., 2018).

The presence of the Paleozoic bedrock at or near the ground surface explains the long preservation of the Meso-Cenozoic vertical and horizontal fault movements in the landscape along the HFZ. The main geomorphological feature in the northern part of the HFZ is a well-visible 7-km-long linear scarp corresponding to a fault displacing the basement up to 300 m horizontally and 48 m vertically, while the Mesozoic cover is vertically displaced by 23 m (Ancion and Evrard, 1957) (Figure 4). The main question in terms of seismic hazard is to evaluate the part of these movements that could be associated to the current tectonic context and then evaluate the long-term perspectives for large earthquake occurrence. Regional tectonic stresses and current deformation mechanisms are not straightforward to evaluate because the largest earthquakes along the HFZ occurred during the historical period, and their mechanism is unknown. Hence, the only available information comes from the current activity, particularly a seismic sequence that occurred in 1989-1990 during which we deployed mobile instruments. Fault-plane solutions range from sinistral strike-slip to pure normal faulting mechanisms (Camelbeeck, 1993). These mechanisms are compatible with the Meso-Cenozoic vertical and horizontal fault movements observed in the geomorphology, but it remains challenging to evaluate current and recent deformation rates from this long-term geological information.

We evaluated the Quaternary slip rate of the HFZ from geomorphic measurements in the northern portion of the fault, mainly from the terrace levels of the Vesdre River. Petermans et al. (2004) and Demoulin et al. (2007) evaluated a 10 to 20 m vertical displacement of the 2-2.5-Ma-old highest terrace level by the HFZ. This would correspond to an average vertical slip rate around 0.005 mm/yr. Demoulin (2006) suggests a vertical displacement of ~ 1 to 2 m since the deposition of the Weichselian gravels of the Vesdre River, leading to a vertical rate of the order of 0.01 mm/yr. Moreover, Petermans et al. (2004) concluded that the most recent terrace [from 61.5 to 106 kyr BP] was not displaced at the level of the resolution of the observations [a few meters], which suggests a maximum possible slip rate of 0.01 mm/yr.

3.2.2. The fault system across the Strait of Dover and the 6 April 1580 earthquake

To identify the source of the $M_W \geq 5.5$ April 1580 earthquake and evaluate the recent tectonic activity in that area, Garcia-Moreno et al. (2015) collected a large set of bathymetric data and seismic reflection profiles across the width of the Dover Strait.

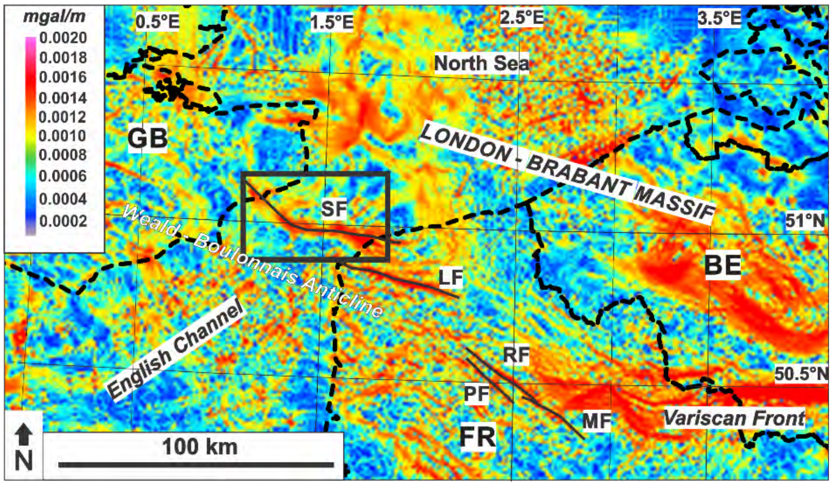


Figure 5. Interpreted horizontal derivative of the Bouguer gravity anomaly (see García-Moreno et al., 2015). Black rectangle: area shown in figure 6; LF: Landrethun Fault; SF: Sangatte fault; RF: Ruitz fault; PF: Pernes fault and MF: Marqueffles fault.

Geophysical data show a broad zone of subparallel WNW-ESE trending faults and folds that offset a series of Cretaceous formations. This zone, named the Sangatte Fault system, is part of the regional North Artois Shear zone (Figure 2). The largest deformations/offsets associated with this fault system correspond to reverse faulting and folding. Offsets along reverse faults reach up to a hundred meters in the center of the Strait of Dover. Normal and strike-slip faulting appears to be also significant.

Importantly, extensional and strike-slip deformations seem to be younger than compressional ones, suggesting the latest tectonic activity of these faults was due to extensional tectonic inversion/reactivation of old compressional structures (Garcia-Moreno et al., 2015).

In the submarine Dover Strait, Quaternary offsets associated with the Sangatte Fault system are poorly constrained. Quaternary erosional and depositional features in this area are limited to: (1) a set of buried deeps known as the Fosse Dangeard, (2) a prominent palaeovalley imprinted on the seafloor known as the Lobourg Channel, and (3) some scattered Holocene sand ridges and sand waves (Garcia-Moreno et al., 2015, 2019). The geophysical data collected from the Strait of Dover show that faults only reach the surface at the top of the Cretaceous bedrock, forming minor scarps. Faults do not seem to extend across the sediment infilling any of the paleo-depressions composing the Fosse Dangeard. They did not produce any deformation or offset exceeding the resolution of 1 m in the bathymetric data across the Lobourg Channel or across the scours carved within it (Figure 6).

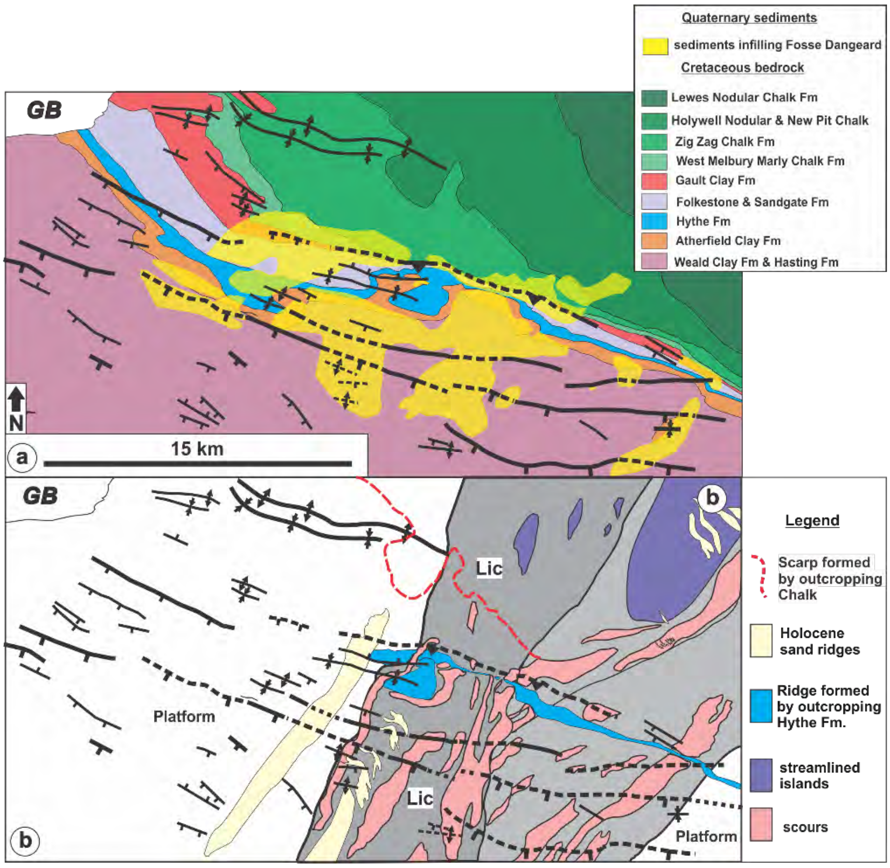


Figure 6. (a) Geological/structural map of the Dover Strait, including Middle–Late Pleistocene buried palaeo-depressions known as "Fosse Dangeard" (modified from García-Moreno et al., 2015, 2019). (b) structural map of the Dover Strait superimposed on geomorphological interpretation of the Lobourg Channel (modified from García-Moreno et al., 2015, 2019). Lic: inner channel formed during the last phase of major fluvial/flood erosion along the Lobourg Channel. Note that fault planes outcrop at the seafloor only across unfilled scours. Note also that neither the morphology of the Lobourg inner channel nor the fluvial/flood scours eroded within it show any distinct deformation/offset along fault planes.

Minor possible offsets (< 5 m) have been identified along some of the faults traversing the paleo-depressions composing the Fosse Dangeard. These are however limited to the lower infill and the basal erosional surfaces of these paleo-depressions. The fact that the possible offsets affect only the basal erosional surfaces of these paleo-depressions precludes to unambiguously assess whether they were formed by tectonic forcing or due to erosional processes or by a combination both (Garcia-Moreno et al., 2015). In any case, this indicates that the cumulated offset along the Sangatte Fault since the formation of the Fosses Dangeard cannot be greater than 5 m.

The absolute age of the formation and infilling of the Fosse Dangeard and the incision of the Lobourg Channel are currently unknown, precluding accurate estimations of possible Quaternary slip rates along the Sangatte Fault. Present consensus holds that the Fosse Dangeard were most likely formed during the Elsterian glacial maximum (i.e., 450,000 years ago). The age of the various seismic units composing their infill is however unknown. Gupta et al. (2017) and Garcia-Moreno et al. (2019) demonstrated that the sediment infilling the Fosse Dangeard are younger than the last phase of major fluvial/flood erosion that imprinted the Lobourg Channel. Indeed, the prominent inner channel and scours excavated into bedrock during that erosional episode truncate the uppermost layers of the Fosse Dangeard's infill. Unfortunately, the time when those erosional features were carved remains unknown. Sedimentary data suggest that the Lobourg Channel may have channelled rivers and flood flows during each of the last three Pleistocene glacial stages, at least until 16,700 year BP (Toucanne et al.,2010; 2015). However, the Dover Strait appears to have remained emerged until early Holocene, which started 12,000 years ago. Consequently, we cannot rule out the occurrence of intense flood and/or fluvial erosion along the Lobourg Channel between 16,700 and 12,000 years ago.

In conclusion, the geophysical investigations undertaken in the Dover Strait demonstrate the existence of a ~40-km-long fault zone traversing the Dover Strait. This study suggests possible maximum tectonic offsets along this fault system of max. 5 m since 450,000 years ago and less than 1 m, the resolution of bathymetric data, since the Holocene, if they exist. An earthquake that would rupture the whole length of the fault zone across the Strait of Dover would reach a M_W=7.0 magnitude, which corresponds to a maximum and average slip of around 2.6 m and 1.2 m respectively (Wells and Coppersmith, 1994). Therefore, if an earthquake of this importance would have occurred during the Holocene, we should find traces of its occurrence in the geomorphology of the Strait of Dover. Moreover, extrapolating the possible maximum 5 m offset of the last 450,000 years to the Holocene gives an offset of the order of 0.1 m, which corresponds to displacements caused by a M_W=6.0 earthquake, similar to the estimated magnitude for the 1580 event, on a fault length of around 10 km. This extrapolation from the longer-term observation is certainly closer to the real tectonic context in the Strait of Dover than the maximum value imposed for the Holocene by the resolution of the observation methods. This analysis enhances the difficulties to assess fault activity rates in this kind of offshore context. In the present case, it is not possible to identify any fault movement at the level of 0.01 mm/year.

4. Seismic strain and moment release

4.1. Seismic moment release at the geological scale

The absence of evidence of tectonic activity on the inherited faults that moved during moderate and large earthquakes in the area surrounding the LRG suggests that the seismic moment released at the geological scale essentially occurred in the LRG. We evaluated the average annual seismic moment release at the geological scale considering that earthquake activity is responsible for the total slip along the LRG faults. Schmedes et al. (2005) suggest such an almost complete seismic coupling in the LRG by combining the earthquake frequency-magnitude distribution over the last 250 years with an upper bound magnitude probability distribution obtained from the integration of seismological and geological information. Moreover, morphometric analyses along the Bree fault scarp and the Peel fault near Roermond suggest that the height of the Holocene scarps of respectively 1.0 and 1.3 m corresponds to slips related to large surface rupturing earthquakes observed in trenches (Camelbeeck et al., 2001). However, we cannot exclude that post-seismic relaxation processes could have also contributed to the total slip.

For these computations, we used the lower and upper bounds of fault slip rates, and surface source lengths of the composite seismic source model of Vanneste et al. (2013). We considered that the thickness of the seismogenic layer is 15 km. Hence, the annual rate of seismic moment in the LRG ranges from 9.0 10^{+15} N.m/yr to 1.7 10^{+16} N.m/yr. Moreover, horizontal rates of extension along the

LRG faults range from 0.07 to 0.13 mm/yr, which corresponds to a long-term horizontal strain rate in the range of 9 10^{-10} /yr – 17 10^{-10} /yr for an average LRG width of 75 km.

Our investigations on the fault zones that generated the 1580 Strait of Dover and 1692 Verviers earthquakes evidence the difficulties to evaluate recent geological activity of faults outside the LRG. However, the most often encountered observation on these faults is the absence of identifiable offset on available geomorphic and young geologic markers. Hence, the information often only provides an upper limit of fault slip rates. As better resolution in terms of slip-rate evaluation corresponds to observed offsets averaged over longer periods, no information can currently be attributed to the most recent periods (Holocene and Late Pleistocene), which is highly problematic due to the episodic character of plate interiors faults. Moreover, we do not know the existence and location of most of the faults that slipped during large earthquakes before the historical period. These different reasons prevent the evaluation of long-term cumulative seismic moment rate outside the LRG.

4.2. Seismic moment release by historical earthquakes

We also evaluated the cumulated released seismic moment in the studied region since 1350. To take into account the uncertainties in the magnitude evaluation for historical earthquakes, we conducted three different estimations using the earthquake catalogs of the Royal Observatory of Belgium (ROB), of the European Mediterranean Earthquakes (EMEC) (Grünthal and Wahlström, 2012), and the SHARE European Earthquake catalog (SHEEC) (Stucchi et al., 2012). In the computation, we simply added the contribution of all the earthquakes in the different catalogs without lower limit of magnitude or completeness analysis. Table 2 reports the results, indicating the cumulated seismic moment in the LRG and the large single zone (SLZ) outside the LRG for the periods 1350-2006 and 1910-2006. For the instrumental period (1910-2006), we present the contributions to the seismic moment release in three magnitude ranges ($3 \leq M_W < 4$, $4 \leq M_W < 5$ and $M_W \geq 5$) with the purpose of estimating their contribution to the total moment release and to verify that the most important contribution comes from the largest earthquakes. As is well evidenced in figure 6, earthquakes with $M_W \geq 5.0$ released most of the seismic moment.

Table 2. Cumulated seismic moment in the region extending from the LRG to southern North Sea

ROB Catalog	EMEC Catalog	SHEEC Catalog
SLZ 1350 - 2006: 3.76 E+18 N.m 1910 - 2006: 1.71 E+17 N.m 3 <= M < 4: 1.85 E+16 N.m 4 <= M < 5: 7.59 E+16 N.m M >= 5: 7.67 E+16 N.m	SLZ 1350 - 2006: 2.71 E+18 N.m 1910 - 2006: 2.38 E+17 N.m 3 <= M < 4: 1.30 E+16 N.m 4 <= M < 5: 7.61 E+16 N.m M >= 5: 1.49 E+17 N.m	SLZ 1350 - 2006: 2.14 E+18 N.m 1910 - 2006: 2.32 E+17 N.m 3 <= M < 4: 1.11 E+16 N.m 4 <= M < 5: 7.27 E+16 N.m M >= 5: 1.49 E+17 N.m
LRG 1350 - 2006: 1.60 E+18 N.m 1910 - 2006: 3.52 E+17 N.m 3 <= M < 4: 8.40 E+15 N.m 4 <= M < 5: 8.08 E+16 N.m M >= 5: 2.62 E+17 N.m	LRG 1350 - 2006: 2.08 E+18 N.m 1910 - 2006: 2.93 E+17 N.m 3 <= M < 4: 5.17 E+15 N.m 4 <= M < 5: 4.35 E+16 N.m M >= 5: 2.42 E+17 N.m	LRG 1350 - 2006: 1.24 E+18 N.m 1910 - 2006: 2.90 E+17 N.m 3 <= M < 4: 4.56 E+15 N.m 4 <= M < 5: 4.35 E+16 N.m M >= 5: 2.42 E+17 N.m

Figure 6 reports the cumulated released seismic moment for the whole region in the map of figure 2 (Total curves), outside the LRG (SLZ curves), and inside the LRG (LRG curves). The total released seismic moment varies from 3.4 to 5.4 10^{+18} N.m. Using the ROB catalogue furnishes the largest value, while the smallest corresponds to the computation with SHEEC. Hence, the annual rate of the seismic moment release ranges between 0.5 and 0.8 10^{+16} N.m/yr, which is about half of the estimated long-term geological annual rate. By considering a 15 km average thickness of the seismogenic layer, it would correspond to an average strain rate released by earthquake activity between 3 and 6 10^{-11}/yr for the whole area.

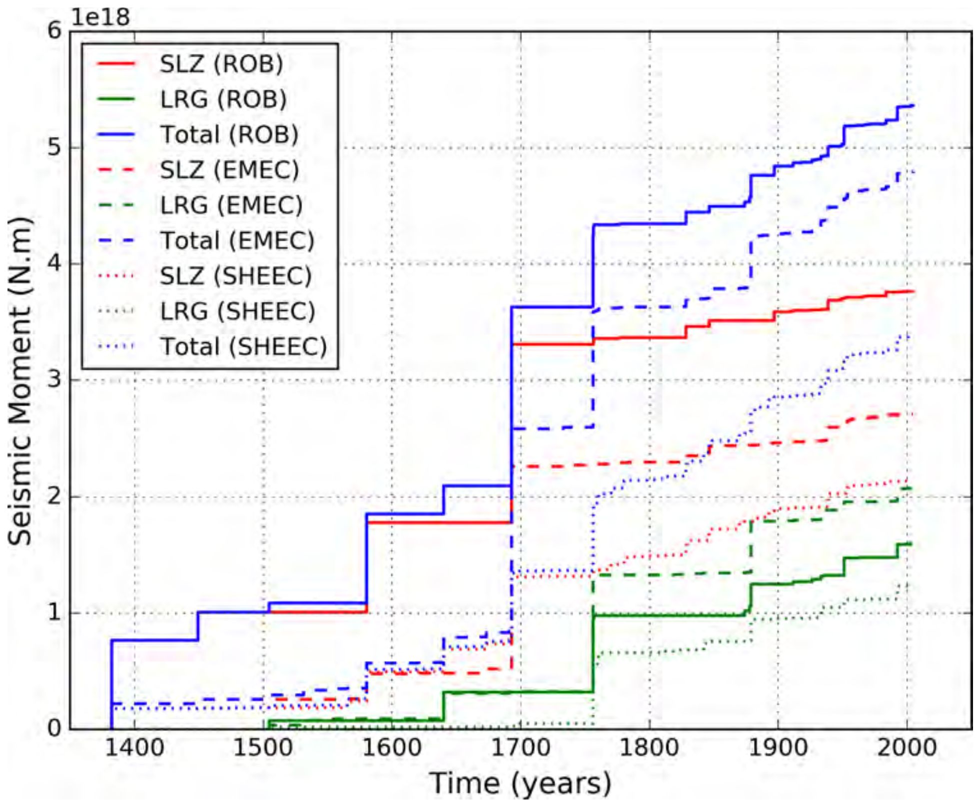


Figure 6. Cumulative released seismic moment since AD 1350 for the whole region mapped in figure 2 (Total curves), outside the LRG (SLZ curves), and inside the LRG (LRG curves) using the earthquake catalogue of the Royal Observatory of Belgium (ROB), the European Mediterranean Earthquake Catalogue (EMEC) (Grünthal and Wahlström, 2012) and the SHARE European Earthquake Catalogue (SHEEC) (Stucchi et al., 2012).

During the period 1350-2006, the seismic moment release in the SLZ is more or less twice the one released in the LRG. Evaluations range from 2.1 to 3.8 10^{+18} N.m in the SLZ and between 1.2 and 2.1 10^{+18} in the LRG, corresponding to respective annual release between 0.3 and 0.6 10^{+16} N.m and 0.17 and 0.3 10^{+16} N.m. The largest discrepancies between the results obtained with the different catalogs concern the period between 1350 and 1700. Table 1 shows that the difference in the magnitude evaluation of four of the largest earthquakes outside the LRG (events 1, 2, 4 and 6 in table 1) is the main factor explaining these differences in moment rates. The SHEEC catalog provides the lowest magnitude estimations for earthquakes in the SLZ, but also in the LRG. Therefore, even if the cumulated moment release between 1350 and 1700 scale differently by using the three catalogs, the region outside the LRG contributes most to the seismic moment release. During this period of 350 years, the moment release rate outside the LRG is 0.94, 0.63 and 0.37 10^{+16} N.m/yr using the ROB, EMEC and SHEEC catalogs respectively, and is comparable to the geological rate ranging from 0.9 to 1.7 10^{+16} N.m/yr resulting from the fault activity in the LRG.

Since 1700, the contribution of the LRG is predominant with moment release rates of 0.5, 0.67 and 0.4 10^{+16} N.m/yr using the ROB, EMEC and SHEEC catalogs respectively. During this period, the differences between the magnitude estimates for the strongest earthquakes strongly diminish (Table 1). It is at the level of the instrumental magnitude uncertainty for events since 1910.

5. Discussion

This fragmented information on the time variation of seismic moment release provides the basis for discussing hypotheses on spatial and temporal distributions of the long-term earthquake activity in the studied area.

In this analysis, we compare seismic moment release in the LRG corresponding to its Late Quaternary WSW-ENE extension with the sum of scalar seismic moments from historical seismicity west of and inside the LRG. This comparison makes sense because despite the lack of information on focal mechanisms for the moderate and large historical earthquakes in that area, Camelbeeck et al. (2007) and Van Noten et al. (2015) determined that many recent earthquakes with $M_L \geq 3.0$ have strike-slip motions coherent with the direction of extension in the LRG.

Seismicity models should take into consideration the following observational facts presented in the previous sections:

- At the geological scale, most of the seismic moment in the whole area would be released along the active faults of the LRG because inherited faults that generated moderate and large historical earthquakes outside the LRG release little cumulative seismic moment over the long-term.

- Depending on the considered earthquake catalogue, 56 to 70 % of the seismic moment released between 1350 and 2006 occurred west of the LRG, while less than 30 to 44 % occurred in the LRG.

- The annual seismic moment release by earthquake activity in the whole area between 1350 and 1700, during which the three largest earthquakes with $M_W \geq 5.5$ occurred to the west of the LRG, is comparable to that release at the recent geological scale in the LRG.

5.1. The clustered and migrating nature of large earthquakes outside the LRG

The lack of large earthquake persistence on the seismogenic sources of the large 1580 and 1692 earthquakes supports the absence of identifiable geological activity of the existing or potential sources of large earthquakes outside the LRG. To explain the observed small moment release at the geological scale ouside the LRG by comparison to the LRG, large earthquakes need to be clustered on some geological structures during limited periods of time, and then need to migrate to other structures. This clustered and migrating character of seismicity is well evidenced by the spatial and temporal pattern of historical seismicity. Indeed, all the earthquakes with $M_W \geq 5.0$ that occurred since 1350 have their epicentre at different places (Figure 2, table 1). Outside of the LRG, they are clustered during relatively short periods of less than a few hundred years and then migrated to other regions. A first group is located in the southern North Sea and the Strait of Dover in 1382, 1449 and 1580. The largest earthquake occurred along the HFZ in 1692, and two earthquakes occurred in the Belgian onshore part of the Brabant Massif in 1828 and 1938.

5.2. Earthquake strain is released along slow active faults in the LRG

Geological information implies that the LRG behaves as a steady-state system, which is predictable over the long-term. Of course, it is difficult to evaluate details of its shorter-term variability. This is well illustrated by historical seismicity during which the average annual seismic moment release in the LRG is five to ten times less important than the average geological release. Moreover, Vanneste and Verbeeck (2001), van den Berg et al. (2002), and Camelbeeck et al. (2007) suggest that the recurrence of large earthquakes during recent geological times along specific faults in the LRG is irregular as observed on the Geleen, Peel and Rurrand faults (Figure 7). This high variability of large earthquake recurrences is associated to the fact that slip rates are less than 0.1 mm/yr, which highlights the role of transient variations of regional crustal stress field or fault strength, compared to the tectonic strain accrual, in the triggering of large earthquakes (Calais et al., 2016).

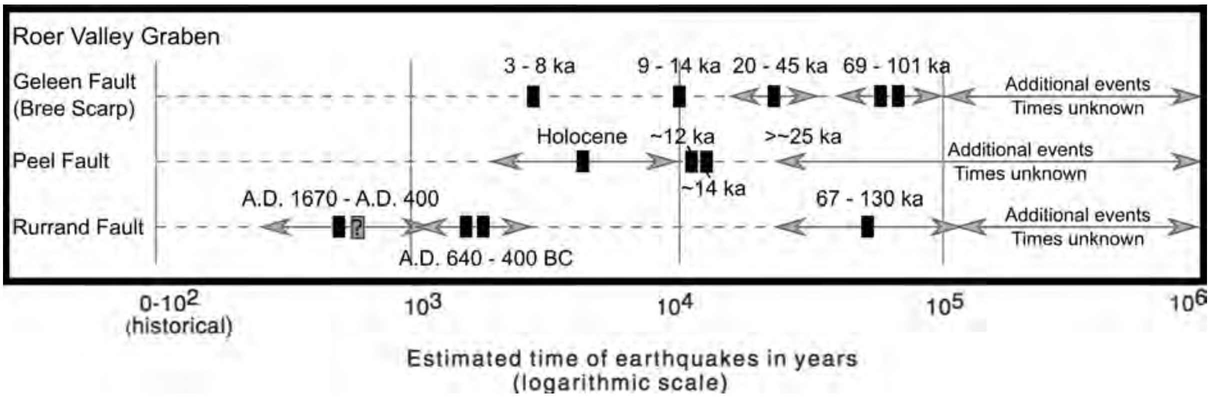


Figure 7. Identified paleoearthquakes and their timing along the Geleen, Peel and Rurrand faults (Vanneste and Verbeeck 2001; van den Berg et al., 2002; and Camelbeeck et al.,2007)

5.3. Large earthquake occurrence would be highly variable over the long-term outside the LRG

The seismic activity outside the LRG during the historical period appears as particularly important in comparison to its weak observed recent geological activity. Hence, during the period between 1350 and 1700, annual seismic moment release is similar to the average geological release rate in the LRG. As the LRG and the region outside the LRG have surfaces of 14,300 and 140,400 km^2, respectively (Figure 2), a similar long-term moment release would represent average activity rates ten times lower outside the LRG than inside the LRG for similar concentrations of seismogenic faults. Geological observations outside the LRG suggest slip rates smaller than 0.01 mm/yr and less dense spatial density of inherited faults capable of generating large earthquakes. Therefore, the geological seismic moment release outside the LRG should only be a small fraction of that in the LRG. Then, if we consider that a maximum of 10% of the geological seismic moment release occurs outside the LRG, the moment release between 1350 and 1700 would correspond to strain accumulation outside the LRG during a few thousand years. Actually, the real accumulation could be of the order of ten or a few tens of thousand years. Therefore, the seismic moment release and the associated occurrence of large earthquakes outside the LRG appear as highly variable with time. This includes few short periods of a high level of seismicity like that observed between 1350 and 1700 with three M_W~5.5-6.0 earthquakes, followed by long periods with a very low seismic moment release comparable to that observed since 1700.

5.4. Earthquake strain release outside the LRG is typical of SCR

As the seismic moment release during the historical period outside the LRG appears as exceptionnally elevated, it is not representative of the real long-term tectonic strain rate, which should be at least an order of magnitude less than the estimated value of 3 to 6 10^{-11}/yr from historical seismicity data. This also suggests that outside the LRG, large historical earthquakes released elastic strain stored in the crust during several thousand to ten thousand years as already discussed in the previous section. In this aspect, seismicity outside the LRG is similar to that observed in typical SCR (Craig et al., 2016; Calais et al., 2016).

5.5. Location of the next moderate and large earthquakes outside the LRG

We presented in section 3.2 our studies on the fault zones that generated the 1580 Strait of Dover and the 1692 Verviers earthquakes. An important conclusion of these investigations is the difficulty of observing fault movements and discriminating between zero and very weak movements. Hence, due to the lack or the very small imprint of their recent geological activity, identifying fault zones west of the LRG where large unknown earthquakes occurred before 1350 is challenging.

Identifying recent geological offsets on inherited faults with no earthquake activity is even more complicated. The fault presenting the largest vertical offset of Late Pliocene sediments to the west of the LRG is the 55-km-long normal Rauw fault (Figure 3). There is no instrumental or historical seismic activity associated to this fault, which also lacks geomorphological expression. Based on high-resolution geological, geotechnical and geophysical investigations finalized by a trench excavation, Verbeeck et al. (2017) provided evidence that the observed 7 m offset occurred between 2.59 Ma and 45 ka. Moreover, the regional observation of alluvial deposits in the hanging wall of the fault suggests that most of the recent fault activity was likely concentrated between 1.0 Ma and 0.5 Ma. This fault is likely one of the rare faults west of the LRG for which applying methodologies of active faulting will furnish information on its episodic activity.

Therefore, to identify structures where large earthquakes could occur in the future, scientists need to develop an understanding of the reasons why specific inherited fault zones are the source of current or historical seismicity. An example west of the LRG is the study of a shallow seismic swarm with 239 low-magnitude (M_L<3.2) earthquakes that occurred 20 km southeast of Brussels between 2008 and 2010. By relocating the earthquakes of the sequence and applying a matched filtering on aeromagnetic data, Van Noten et al. (2015) linked the seismic activity to a limited-size fault, corresponding to an inherited isolated fault structure in the already weakened crust of the Brabant Massif.

6. Conclusions

The only area in the region between the LRG and the southern North Sea where faults present a continuous activity during the Holocene – Late Pleistocene periods and an established relationship with large surface rupturing earthquakes is the LRG. Despite the fact that more research would be necessary to assess the recent geological activity on most of these faults and to evaluate the part of their slippage caused by large earthquake ruptures, the available information briefly presented in this publication make foreseeing future activity over the long-term possible. It allows inferring activity rates and observation-based hypotheses on possible maximum magnitude values for the computation of probabilistic seismic hazard assessment.

Outside the LRG, earthquake activity appears as typical of SCR. Large and moderate earthquakes occur on inherited fault zones presenting little Quaternary activity at best. Large earthquakes and associated seismicity appear episodic and clustered in some areas during periods of a few hundreds of years and then migrate to other regions. Our analysis suggests that historical seismicity data, with the occurrence of several large earthquakes to the west of the LRG between 1350 and 1700, give a false perspective of the real long-term seismicity in this region. On average, seismic moment release in the area would be less important and likely closer to that observed since the 18th century.

Future research should be concentrated on studying the mechanical and structural differences between active faults at plate boundaries or in active intraplate regions and those representing reactivated old structures that survived several tectonic and erosional cycles.

Acknowledgements

We would like to express our thanks to the organizers of the 5th international colloquium on «Historical earthquakes, Paleoseismology, Neotectonics and Seismic Hazard» for their invitation to present an overview of our research.

References

Alexandre, P., Kusman, D., Petermans, T. and Camelbeeck T. (2008). The 18 September 1692 earthquake in the Belgian Ardenne and its aftershocks. *Modern Approaches in Solid Earth Sciences - Historical Seismology: interdisciplinary studies of past and recent earthquakes*, 209-230.

Ahorner, L. (1962). Untersuchungenzur quartären Bruchtektonik der Niderrheinischen Bucht, *Eiszeitalter und Gegenwart*, 13, 24-105.

Ahorner, L. (1975). Present-day stress field and seismotectonic block movements along major fault zones in central Europe.*Tectonophysics*, 29, 233–249, doi: 10.1016/0040-1951(75)90148-1.

Ahorner, L. (1983). Historical seismicity and present-day activity of the Rhenish Massif, central Europe, in Fuchs, K., von Gehlen, K., Mälzer, H., Murawski, H., and Semmel, A., eds., *Plateau Uplift, the Rhenish Shield—A Case History*. Berlin, Springer-Verlag, 198–221.

Ancion, C., and Evrard, P. (1957). Contribution à l'étude des failles Monty, Mouhy et d'Ostende dans la partie orientale du massif de Herve. *Annales de la Société Géologique de Belgique*, 80, B477-B488.

Auffret, J.-P., and Colbeaux, J.-P. (1977). Etude structural du Boulonnais et son prolongement sous-marin en Manche orientale. *Bulletin de la Société Géologique de France*, 19, 1047-1055.

Calais, E., Camelbeeck, T., Stein, S., Liu, M. & Craig, T. J. (2016). A new paradigm for large earthquakes in stable continental plate interiors. *Geophysical Research Letters*, 43, 10621-10637. doi:10.1002/2016gl070815

Camelbeeck, T. (1993). Mécanisme au foyer des tremblements de terre et contraintes tectoniques: Le cas de la zone intraplaque Belge [*Ph.D. thesis*]: Louvain-la-Neuve, Université Catholique de Louvain, 295 p.

Camelbeeck, T., and van Eck, T. (1994). The Roer Valley Graben earthquake in northern Europe of 13 april 1992 and its seismotectonic setting: *Terra Nova*, v. 6, p. 291-300.

Camelbeeck, T., and Meghraoui, M. (1996). Large earthquakes in northern Europe more likely than once thought: Eos (Transactions, American Geophysical Union), v. 77, p. 405–409, doi: 10.1029/96EO00274.

Camelbeeck, T., and Meghraoui, M. (1998). Geological and geophysical evidence for large palaeoearthquakes with surface faulting in the Roer graben (northwestern Europe): Geophysical Journal International, v. 132, p. 347–362, doi: 10.1046/j.1365-246x.1998.00428.x.

Camelbeeck, T., Martin, H., Vanneste, K., Verbeeck, K., and Meghraoui, M. (2001). Morphometric analysis of active normal faulting in slow deformation areas: Examples in the Lower Rhine Embayment: Netherlands Journal of Geosciences, v. 80, p. 95–107.

Camelbeeck, T., Vanneste, K., Alexandre, P., Verbeeck, K., Petermans, T., Rosset, P., Everaerts, M., Warnant, R., Van Camp, M. (2007). Relevance of active faulting and seismicity studies to assessments of long-term earthquake activity and maximum magnitude in intraplate northwest Europe, between the Lower Rhine Embayment and the North Sea, in Stein, S., and Mazzotti, S., ed., Continental Intraplate Earthquakes: Science, Hazard, and Policy issues: *Geological Society of America Special Paper 425*, 193-224.

Camelbeeck T., Alexandre P., Sabbe A., Knuts E., Garcia Moreno D., Lecocq T. (2014). The impact of the earthquake activity in Western Europe from the historical and architectural heritage records. In Talwani P. (Ed) *Intraplate earthquakes*, Cambridge University Press, 198-230.

Craig, T.J., Calais, E., Fleitout, L., Bollinger, L., and Scotti, O. (2016). Evidence for the release of long-term tectonic strain stored in continental interiors through intraplate earthquakes, *Geophysical Research letters*, 43, doi: 10.1002/2016GL069359.

Crone, A.J., and Luza, K.V. (1990). Style and timing of Holocene surface faulting on the Meers fault, southwestern Oklahoma. *Geological Society of America Bulletin*, 102, 117.

Crone, A.J., Machette, M.N., and Bowman, J.R. (1992). Geologic investigations of the 1988 Tennant Creek, Australia, earthquakes – implications for palaeosismicity in stable continental regions. *US Geological Survey Bulletin*, 2032-A.

Crone, A.J., Machette, M.N., and Bowman, J.R. (1997). Episodic nature of earthquake activity in stable continental regions revealed by palaeosismicity studies of Australian and North American Quaternary faults. *Australian Journal of Earth Sciences*, 44, 203-214.

Demanet, D., Renardy, F., Vanneste, K., Jongmans, D., Camelbeeck, T., and Meghraoui, M. (2001). The use of geophysical propecting for imaging active faults in the Roer Graben, Belgium. *Geophysics*, 66, 78-89.

Demoulin, A. (1988). Cenozoic tectonics on the Hautes-Fagnes plateau (Belgium). *Tectonophysics*, 145: 31-41.

Demoulin, A. (2006). La néotectonique de l'Ardenne-Eifel et des régions avoisinantes. *Mémoires de la classe des Sciences, Académie Royale de Belgique*, 25, p252.

Demoulin A., Bovy B., Rixhon G., Cornet Y. (2007). An automated method to extract fluvial terraces from digital elevation models: The Vesdre valley, a case study in eastern Belgium. *Geomorphology* 91, 51-64.

Descamps, L. (2009). Relations entre l'activité sismique dans le Hainaut et l'activité minière. *Travail de fin d'études à la Faculté Polytechnique de Mons*, 52 pp + annexes.

Everaerts, M. (2000). L'interprétation Structurale de la Manche au Rhin: Apport Structural des Champs de Potentiel [Ph.D. thesis]. Louvain-la-Neuve, Université Catholique de Louvain, 167 p.

Garcia Moreno, D., Verbeeck, K., Camelbeeck, T., De Batist, M., Oggioni, F., Zurita Hurtado, O., Versteeg, W., Jomard, H., Collier, J., Gupta, S., Trentesaux, A., Vanneste, K. (2015). Fault activity in the epicentral area of the 1580 Dover Strait (Pas-de-Calais) earthquake (northwestern Europe). *Geophysical Journal International*, vol. 201, 528-542. doi:10.1093/gji/ggv041

Garcia-Moreno, D., Gupta, S., Collier, J., Oggioni, F., Vanneste, K., Trentesaux, A., Verbeeck, K., Versteeg, W., Jomard, H., Camelbeeck, T., De Batist, M. (2009). Middle-Late Pleistocene landscape evolution of the Dover Strait inferred from buried and submerged erosional landforms. *Quaternary Science Reviews*, 203, 209-232, 10.1016/j.quascirev.2018.11.011.

Gold, R.D., Friedrich, A., Kübler, S., and Salamon, M. (2017). Apparent Late Quaternary fault-slip rate increase in the southern Lower Rhine Graben, Central Europe. *Bulletin of the seismological Society of America*, 107, 563-580, doi: 10.1785/0120160197

Graulich, J. (1959). Sur le prolongement meridional du graben de la Minerie (Pays de Herve). *Annales de la Société Géologique de Belgique*, 83, 55-61.

Grünthal, G. & Wahlström, R. (2012). The European-Mediterranean Earthquake Catalogue (EMEC) for the last millennium. *Journal of Seismology*. doi: 10.1007/s10950-0129302-y

Grützner, C., P. Fischer, and K. Reicherter (2016). Holocene surface ruptures of the Rurrand fault, Germany - Insights from palaeoseismology, remotesensing and shallow geophysics, *Geophysical Journal International*, 204, 1662–1677.

Gupta, S., Collier, J., Garcia-Moreno, D., Oggioni, F., Trenteseaux, A., Vanneste, K., De Batist, M., Camelbeeck, T., Potter, G., Van Vliet-Lanoë, B., Arthur, J. (2017). Two-stage opening of the Dover Strait and the origin of island Britain. *Nature Communications,* 8, 10.1038/ncomms15101.

Kuebler, S., R. Streich, E. Lück, M. Hoffmann, A. M. Friedrich, and M. R. Strecker (2016). Active Faulting in a Populated Low-Strain Setting (Lower Rhine Graben, Central Europe) Identified by Geomorphic, *Geophysical and Geological Analysis*, Vol. 432, Geological Society, London, Special Publications.

Henriet, J.-P., and De Batist, M. (1989). The faulted zone of North Hinder (southern North Sea). *Annales de la Société Géologique de Belgique*, 112, 313.

Hinzen KG and Oemisch M (2001) Location and magnitude from seismic intensity data of recent and historic earthquakes in the Northern Rhine area, central Europe. *Bulletin of the Seismological Society of America*, 91, 40-56

Hinzen, K.-G., Reamer, S. (2007). Seismicity, seismotectonics, and seismic hazard in the northern Rhine area, in Stein, S., and Mazzotti, S., ed., Continental Intraplate Earthquakes: Science, Hazard, and Policy issues: *Geological Society of America Special Paper 425*, 225-243.

Lecocq, T. (2011). L'activité sismique en Ardenne et sa relation avec la tectonique active. *Thèse de doctorat, ULB*, 265 pp.

Meghraoui, M., Camelbeeck, T., Vanneste, K., Brondeel, M., and Jongmans, D. (2000). Active faulting and paleoseismology along the Bree fault zone, Lower Rhine graben (Belgium): Journal of Geophysical Research, v. 105, p. 13,809–13,841, doi: 10.1029/1999JB900236.

Melville C., Levret A., Alexandre, P., Lambert, J., and Vogt, J. (1996). Historical seismicity of the Strait of Dover-Pas de Calais: *Terra Nova*, v. 8, p. 626-647.

Oncken, O., von Winterfeld, C.H., Dittmar, U. (1999). Accretion of a rifted passive margin: The Late Paleozoic Rhenohercynian fold and thrust belt (Middle European Variscides). *Tectonics,* 18, 75–91.

Petermans, T., Camelbeeck, T., Alexandre, P., Kusman, D., Verbeeck, K., Vanneste, K., Demoulin, A., Nguyen, F., and Jongmans, D. (2004). The September 18, 1692 earthquake in the Belgian Ardenne and its geologic context. *Final report, SAFE European project (EVG1-2000-00023)*, WP2, p 43.

Schmedes, J., Hainzl, S., Reamer, S.-K., Scherbaum, F., and Hinzen, K.-G. (2005). Moment release in the Lower Rhine Embayment, Germany: seismological perspective of the deformation process. *Geophysical Journal International*, 160, 901-909, doi: 10.1111/j.1365-246X.2005.02525.x

Skupin, K., K. Buschhüter, H. Hopp, K. Lehmann, R. Pelzing, J. Prüfert, M. Salamon, G.Schollmayer, A.Techmer, and V.Wrede (2008). Paläoseismische Untersuchungen im Bereich der Niederrheinischen Bucht, *Geologischer Dienst Nordrhein-Westfalen*, Krefeld, Germany (in German).

Stucchi, M., Rovida, A., Gomez Capera, A., Alexandre, P., Camelbeeck, T., Demircioglu, M.B., Gasperini, P., Kouskouna, V., Musson, R.M.W. & al. (2012). The SHARE European Earthquake Catalogue (SHEEC) 1000 - 1899. *Journal of Seismology*. doi: 10.1007/s10950-012-9335-2

Stein, S., Liu, M., Camelbeeck, T., Merino, M., Landgraf, A., Hintersberger, E., & Kuebler, S. (2015). Challenges in assessing seismic hazard in intraplate Europe. *Geological Society Special Publication 432*, doi.org/10.1144/SP432.7

Swafford, L. & Stein, S. (2007). Limitations of the short earthquake record for seismicity and seismic hazard studies, in Stein, S., and Mazzotti, S., ed., Continental Intraplate Earthquakes: Science

Hazard and Policy issues: *Geological Society of America Special Paper 425*, 49-58. doi: 10.1130/2007.2425(04).

Toucanne, S., Zaragosi, S., Bourillet, J.F., Marieu, V., Cremer, M., Kageyama, M., Van Vliet-Lanoe, B., Eynaud, F., Turon, J.-L., Gibbard, P.L. (2010). The first estimation of Fleuve Manche palaeoriver discharge during the last deglaciation: evidence for Fennoscandian ice sheet meltwater flow in the English Channel circa 20 - 18 ka ago. *Earth and Planetary Sciences Letters*, 290, 459-473.

Toucanne, S., Soulet, G., Freslon, N., Jacinto, R.S., Dennielou, B., Zaragosi, S., Eynaud, F., Bourillet, J.-F., Bayon, G. (2015). Millennial-scale fluctuations of the European Ice Sheet at the end of the last glacial, and their potential impact on global climate. *Quaternary Sciences Review*, 123, 113-133.

Van Noten, K., Lecocq, T., Shah, A., Camelbeeck, T. (2015). Seismotectonic significance of the 2008-2010 Walloon Brabant seismic swarm in the Brabant Massif, Belgium. *Tectonophysics,* 656, 20-38. 10.1016/j.tecto.2015.05.026.

Verbeeck, K., Wouters, L., Vanneste, K., Camelbeeck, T., Vandenberghe, D., Beerten, K., Rogiers, B., Schiltz, M., Burow, C., Mees, F., De Grave, J., Vandenberghe, N. (2017). Episodic activity of a dormant fault in tectonically stable Europe: The Rauw fault (NE Belgium). *Tectonophysics*, doi: 10.1016/j.tecto.2017.01.023

van den Berg, M.W., Vanneste, K., Dost, B., Lokhorst, A., Eijk, M.V., and Verbeeck, K. (2002). Paleoseismic investigations along the Peelrand fault: Geological setting, site selection and trenching results: Geologie en Mijnbouw, v. 81, no. 1, p. 39–60.

van Eck, T., and Davenport, C.A., guest eds. (1994). Special Issue, Seismotectonics and seismic hazard in the Roer Valley Graben; with emphasis on the Roermond earthquake of April 13, 1992: *Geologie en Mijnbouw*, 73 (2-4), 441 p.

Vanneste, K., and Verbeeck, K. (2001). Paleoseismological analysis of the Rurrand fault near Jülich, Roer valley graben, Germany: Geologie en Mijnbouw, v. 80, p. 155–169.

Vanneste, K., Meghraoui, M., and Camelbeeck, T. (1999). Late Quaternary earthquake-related soft-sediment deformation along the Belgian portion of the Feldbiss fault, Lower Rhine graben system: Tectonophysics, v. 309, p. 57–79, doi: 10.1016/S0040-1951(99)00132-8.

Vanneste K., Camelbeeck T., Verbeeck K. (2013). A Model of Composite Seismic Sources for the Lower Rhine Graben, Northwest Europe. *Bulletin of the Seismological Society of America* 103A, 984–1007.

Vanneste, K., Camelbeeck, T., Verbeeck, K., and Demoulin, A. (2018). Morphotectonics and past large earthquakes in eastern Belgium. A. Demoulin (ed.), *Landscapes, Landforms of Belgium, and Luxemburg*, World Geomorphological Landscapes, Springer International Publishing AG 2018, doi: 10.1007/978-3-319-58239-9_13

Vanneste, K., Verbeeck, K., Camelbeeck, T., Renardy, F., Meghraoui, M., Jongmans, D., Paulissen, E., and Frechen, M. (2001). Surface rupturing history of the Bree fault escarpment, Roer valley graben: New trench evidence for at least six successive events during the last 150 to 185 kyr: Journal of Seismology, v. 5, p. 329–359, doi: 10.1023/A:1011419408419.

Wells, D.L., and Coppersmith, K. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, 84, 974-1002.

Historical Earthquakes, Paleoseismology,
Neotectonics and Seismic Hazard:
New Insights and Suggested Procedures

DOI: 10.23689/fidgeo-3867

The Paleoseismic Database of Germany and Adjacent Regions PalSeisDB v1.0

Jochen Hürtgen[1], Klaus Reicherter[1], Thomas Spies[2], Claudia Geisler[2] & Jörg Schlittenhardt[2]

[1] Neotectonics and Natural Hazards Group, RWTH Aachen, Lochnerstr. 4-20, 52056 Aachen, j.huertgen@nug.rwth-aachen.de
[2] Federal Institute for Geosciences and Natural Resources, BGR, Unit 'Engineering Seismology', Stilleweg 2, 30655 Hannover, thomas.spies@bgr.de

Abstract

Central Europe is an intraplate domain which is characterized by low to moderate seismicity with records of larger seismic events occurring in historical and recent times. These records of seismicity are restricted to just over one thousand years. This does not reflect the long seismic cycles in Central Europe which are expected to be in the order of tens of thousands of years. Therefore, we have developed a paleoseismic database (PalSeisDB) that documents the records of paleoseismic evidence (trenches, soft-sediment deformation, mass movements, etc.) and extends the earthquake record to at least one seismic cycle. It is intended to serve as one important basis for future seismic hazard assessments. In the compilation of PalSeisDB, paleoseismic evidence features are documented at 129 different locations in the area of Germany and adjacent regions.

1. Introduction

In the introductory section, we briefly describe the motivational background of the creation of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB), the paleoseismological aspects, that have to be regarded by using results from paleoseismic studies documented in the database, and a rough geological overview of the study area especially focusing on tectonic and paleoseismic aspects.

1.1. General Information

The detection of earthquakes normally proceeds with seismographic networks, which are placed in different densities around the world and today provide a real-time transmission of seismic events. More or less, depending on the country the earthquake activity of the last 100 years was recorded. For earlier periods, historical records, geological and archaeological evidence have to be compiled and evaluated to obtain information on seismicity. Very long (> 10,000 years) and long (about 1,000-10,000 years) recurrences of earthquakes have been studied and evaluated indirectly through complementary indicators to extend the earthquake catalogue into the past. In this study, a summary of the previously presented and partly un-published records of paleoseismic evidence is given for Germany, including the neighbouring countries in Central Europe within a 300-km wide zone. This provides an extension of the combined historical and instrumental earthquake catalog which in this area dates back approximately 1,200 years (e.g. Leydecker, 2011). The events in the published catalog obviously do not represent the needed temporal and spatial distribution of seismicity to be used in seismic hazard assessments as they do not cover the seismic cycle of tectonically active structures, such as faults and folds. As a conclusion, paleoearthquakes identified by paleoseismic investigations in Germany and neighbouring countries which cover extended time periods well beyond 1,200 years, must be taken into account for reliable seismic hazard assessment.

In December 2011, an update of the KTA 2201.1 (Design of Nuclear Power Plants against Seismic Events) came into force. The revised version of this standard explicitly demands the use of paleoseismic studies and their results should be incorporated with respect to the maximum historical or prehistorical earthquake to be considered. The new standard should include the assessment of paleoseismicity up to a distance of 200 km (radius) around the specific site.

- In this framework, the main parameters for the description of earthquakes with paleoseismological methods are determined as a basis for a database to be created.
- The data necessary for the determination of seismic hazard parameters are fully taken into account.
- Also, areas outside of Germany (seismotectonic regions) have to be considered. Due to the requirements of KTA 2201.1 at least the area including a limit distance up to 200 km has to be regarded.
- Development of concept for implementation of database of paleoseismological and presentation in a GIS environment (ArcGIS-based)
- Creation of database and GIS applications
- Description of basic fundamentals of development steps and use of information in the database
- Compilation of the seismotectonic regions for which no sufficient relevant paleoseismic records are available
- development of a strategy to complete the paleoseismic findings that are relevant for the determination of seismic hazard assessments

1.2. Paleoseismological aspects

From a paleoseismic point of view, evidence of paleoearthquakes can be found in different tectonic settings and can have different appearances and effects, which are related to the source of the earthquake. For example, to find evidence in the geological record of a surface rupture in the geologic record, the magnitude of the paleoearthquake must be $Mw > 5.5 \pm 0.5$ (Wells and Coppersmith, 1994). Preservation in the geologic record is strongly determined by erosion and deposition rates (man-made or natural) versus the deformation rates. After McCalpin (2009), it is distinguished between effects found in the vicinity of the fault (on-fault) and effects found at a distance from the fault (off-fault). A very important tool in paleoseismological studies is the excavation of trenches on capable and active faults. Within the trench walls, all on-fault effects, such as offset of strata and colluvial wedges, can be found. These are relevant to determine the age of seismic rupturing on the fault. At a distance from the fault, secondary effects can be observed such as landslides (e.g. Keefer, 1984) or liquefaction features (e.g. Obermeier, 1996). The extent and distribution of these effects are also strongly dependent on earthquake's size and subsurface characteristics. These types of evidence can be used in combination with others such as historical documents and archeoseismic evidence to identify paleoearthquakes on active structures and their associated seismic hazard potential. Through the combined (paleo-) seismological surveys a much more accurate picture of the earthquakes which have struck a region and their associated active faults is created.

The definition of "active" fault is defined differently in different countries; for the German territory, there is no such classification. Nuclear authorities of the United States state that a fault is active if there has been one event in the last 10,000 years or 35,000 years depending on the region; Machette (2000) and Fraser (2001) both state that one event in the last 150,000 years, or two events in the last 500,000 years, makes a fault active; or in New Zealand it is one or more events in the past 120,000 years (McSaveney, 2017).

Even combined studies often do not lead to a clear picture, as diverse sources of error ultimately distort the hazard posed by an area. These errors are firstly the lack of tradition of historical events and also the mixing or confusion of real earthquakes and earthquake-like events. A unique example is the earthquake of 813 AD mentioned in Aachen, but which relates to the impending death of Charles the Great, and yet found its way into the earthquake catalog. A relatively unbroken chain of evidence allows statements and estimations to be made regarding the last (sub)recent earthquake events, the long-term behavior of the active or capable fault(s), recurrence rates or the maximum expected magnitudes. The segmentation of longer fault zones plays an important role regarding total rupture lengths during a quake (individual segment vs. multiple segment ruptures). Empirically, using the rupture length and/or maximum displacement, a magnitude can then be assigned (Wells and Coppersmith, 1994). Are these statements conclusive, there is the possibility to extent an earthquake catalogue into the past and to achieve detailed risk assessments.

During the past decade, the paleoseismological community learned and recognized many new aspects according the temporal and spatial resolution of seismic events in the geological record. Furthermore, the relationship between the intensity and magnitude of events and their damage distribution has been furthered. Paleoseismic investigation methods have also improved considerably, e.g. due to the use of high-resolution DEMs from LiDAR data. In particular, the "diffuse seismicity" detected by environmental effects is increasingly becoming the focus of research, as liquefaction features can also be produced by other geologic processes and are not conclusive as a stand-alone tool for assessing the paleoseismicity of a region.

Another critical aspect for paleoseismology has been demonstrated by the Finale Emilia earthquake series in May 2012, where two events of M ± 6 occurred during 9 days, causing severe damage and extensive liquefaction in an area of several hundreds of squarekilometers (Caputo et al., 2012a; Di Manna et al., 2012; Papathanassiou et al., 2012). Hypothetically speaking, if there is no clear evidence for two individual events in a short period of time, a paleoseismologist would assign a much larger magnitude to this event(s), because empirical relationships are based on the area affected by liquefaction (as outlined by Obermeier in McCaplin, 2009) and would result in larger magnitudes. Finally, all major historical earthquakes in Central Europe (Basel 1356; Verviers 1692, Düren 1756) are hitherto still lacking the finding and excavation of the causative fault, there are some suspicious structures, but no paleoseismic evidence has been proven on-fault.

1.3. Geologic framework of Central Europe

Central Europe is an intraplate domain and is characterized by records of low to moderate seismicity. This is mainly caused by compressional stress from the NW-ward drifting of the African plate and the ridge-push from the North Atlantic Ridge. Other important parameters regarding the tectonic activity in Central Europe are the lithospheric rebound due to the retreat of the ice sheets of the last glacial maximum in the North (Scandinavia) and in the South (Alps) and very localised stresses due to the rise of mantle plumes (i.e. volcanic fields of the Eifel).

In this setting, a large segmented rift system, known as the European Cenozoic Rift System (ECRIS), formed during the late Eocene to Oligocene due to ESE-WNW to E-W directed extension. It comprises, amongst others, the Bresse Graben (BG), the Upper Rhine Graben (URG) and the Lower Rhine Graben (LRG), and extends from west of the Alps to the North Sea. The historical and instrumental seismic record indicates that the areas of the ECRIS, especially the URG and the LRG, are presently the most tectonically active zones of Central Europe and are able to produce larger earthquakes than magnitude 5.5, such as the 1386 Basel earthquake (M 6.0-6.5), the Düren seismic series in 1755/1756 (M 5.8), or the 1992 Roermond earthquake (M 5.9). The neotectonic and recent activity in regions of the North German Basin, the Alps, the Molasse Basin, the Eger Graben (EG), the Vienna Basin (VB), northern Italy, and southern Sweden are also of interest. Figure 1 presents this geological and tectonic setting of Central Europe, focusing on the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB). It is based on the International Geological Map of Europe and Adjacent Areas 1:5,000,000 (IGME5000; Asch, 2005). In agreement with the requirements of the Nuclear Safety Standard (KTA 2201), the compilation of PalSeisDB v1.0 is focused on areas prone to larger earthquakes in Germany, and also in adjacent tectonically active regions in Belgium, Netherlands, Luxembourg, France, Switzerland, Italy, Liechtenstein, Austria, Slovenia, Croatia, Hungary, Czech Republic, Slovakia, Poland, Sweden, and Denmark.

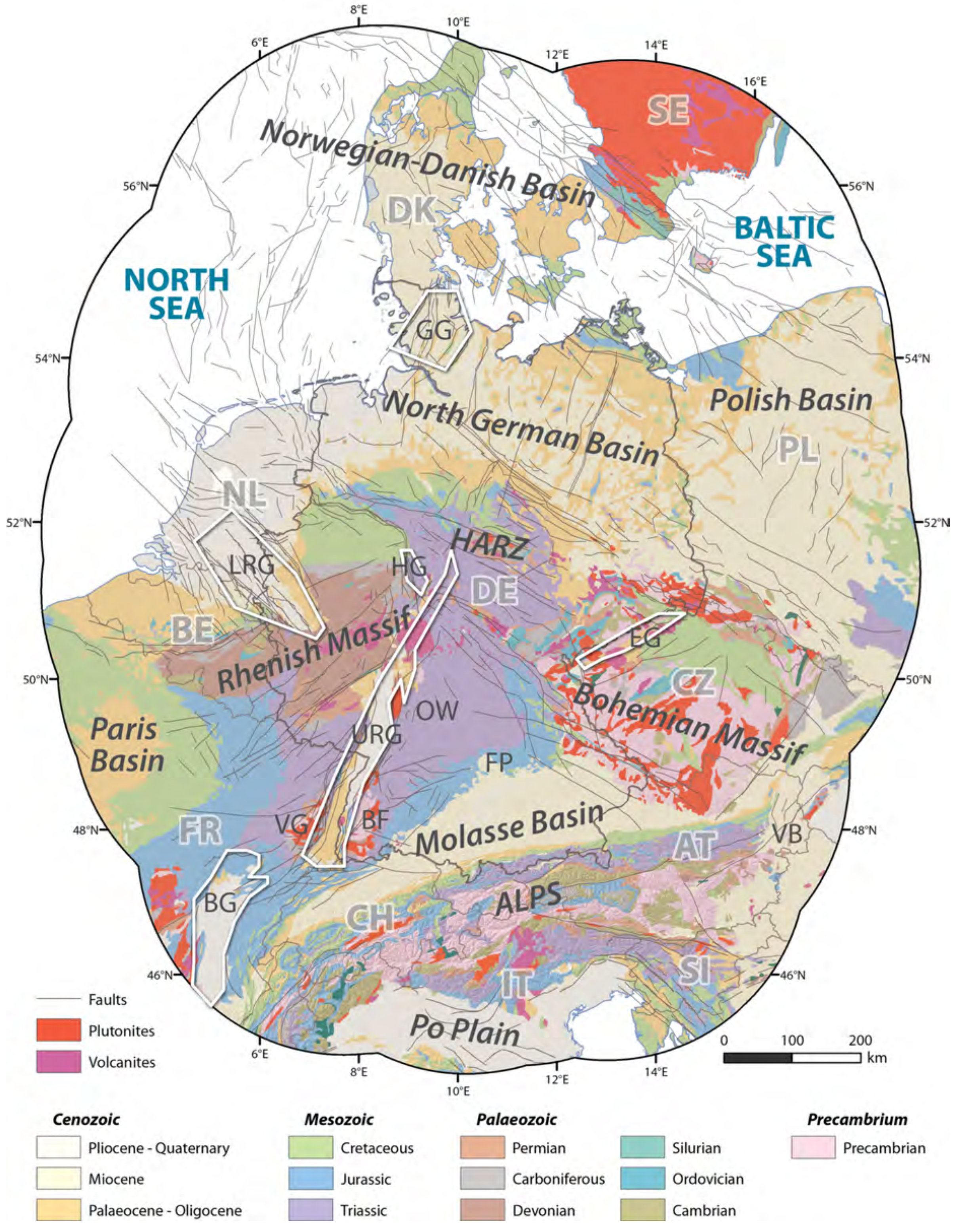


Figure 1. General geological and tectonic framework of Germany and adjacent regions based on the International Geological Map of Europe (IGME5000; Asch, 2005) and fault traces (thin black lines). BF: Black Forest, BG: Bresse Graben, EG: Eger Graben, FP: Franconian Platform, GG: Glückstadt Graben, HG: Hessian Grabens, LRG: Lower Rhine Graben, OW: Odenwald, URG: Upper Rhine Graben, VG: Vogesen, VB: Vienna Basin. Compiled from Dèzes et al. (2004), Kaiser et al. (2005), and Reicherter et al. (2008).

1.4. PalSeisDB-related areas

This section includes geological descriptions of the areas in Central Europe where paleoseismic evidence has been documented. The most relevant regions in Germany and other parts of Central Europe are described in more detail, such as the Lower Rhine Graben and the Upper Rhine Graben. Other regions including the North German Basin, the Osning Thrust zone, the Jura Mountains, the Basel area, Northern and Central Switzerland, Northern Italy and the Southern Alps, the Vienna Basin, the Czech Republic region including the Eger Graben and the Sudetic Marginal Fault zone, and Southern Sweden, are only described briefly covering the main aspects of tectonics and paleoseismic findings.

1.4.1. Lower Rhine Graben

The Lower Rhine Graben (LRG) forms a normal-fault-controlled embayment in the northern flank of the Rhenish Massif (Rheinisches Schiefergebirge). Its structures continue towards the NW in the subsurface of the Dutch–North German plain. The LRG or Lower Rhine Basin is a rift system which has been active since the Tertiary and is bordered by the Rhenish Shield in the west, south and east, and opens to the North Sea in the northwest. It comprises several normal faults that bound SE–NW elongated blocks in a horst and graben style NE-SW extension. The southeastern part of the Lower Rhine Graben is morphologically expressed by the Lower Rhine Embayment (Niederrheinische Bucht), an area of low relief surrounded to the east, south and west by the uplifted plateau of the Rhenish Massif. The northwestern part of the Tertiary rift system is beneath the Dutch–North German plain. Many authors refer to the Lower Rhine Basin as the Roer Valley Graben (RVG) or Roer Valley Rift System (e.g., Michon et al., 2003), which was initiated in Late Permian – Early Triassic and was again active in the Middle Jurassic (Zijerveld et al., 1992). From the Late Cretaceous to present periods of subsidence and inversion were developed (Michon et al., 2003). The main architecture and sediment fill of the Graben developed during the Late Oligocene to present (Schäfer et al., 2005).

During the Quaternary, the subsidence rates in the Lower Rhine Graben significantly increased (Houtgast and Van Balen, 2000) as did the rate of displacement along the main block-bounding normal faults. These faults are generally almost pure dip-slip normal faults and follow two trends, the predominant SE to SSE (135–160°) trend and the subordinate ESE (110–120°) trend. Most tectonic blocks are halfgrabens tilted to the NE, and the main normal faults accordingly dip to the SW. The maximum thickness of Cenozoic sediments, up to 2,000 m, is found in the 20 km wide and 130 km long NW–SE striking Roer Valley Graben.

The Lower Rhine Basin is seismically active and earthquakes with estimated magnitude of 5 have repeatedly occurred. The strongest historical event was the Düren earthquake of 1756 with an estimated magnitude (ML) of 6.1 (Ahorner, 1994). The last major event, the 1992 Roermond earthquake with a local magnitude of 5.9, occurred at a depth of 14 to 18 km on or close to the Peel Boundary normal fault (i.e., the NE boundary fault of the Roer Valley Graben). The present-day stress field in the shallow crust, as determined from earthquake focal mechanisms, is characterized by a subvertical sigma1 and a subhorizontal sigma3 orientated SW–NE (42°; Hinzen, 2003). This probably grades into a strike-slip stress regime (sigma1 horizontal SE–NW) in the lower crust (Hinzen, 2003). This is consistent with the present-day overall European stress field, which is NW–SE directed (Reicherter et al., 2008; Heidbach et al., 2010). Results from a regional GPS net in the southern part of the Lower Rhine Basin suggest ongoing east–west directed separation of the basin shoulders (Campbell et al., 2002). An extensional regime in the Lower Rhine Basin is also indicated by analysis of GPS data in western and central Europe on a larger scale (Tesauro et al., 2005).

The Lower Rhine Graben is the area with the most comprehensive paleoseismic record in Central Europe. Many studies have been undertaken in the last decades with intensive investigations at different fault zones of the LRG. Most of them were paleoseismic trench studies with 22 trenches in total. They have been excavated across the graben system at active faults such as the Feldbiss fault, the Viersen fault, the Rurrand fault, the Swist fault and the Peelrand fault. Detailed descriptions of the trenches and their results can be found in e.g., Camelbeeck and Meghraoui (1996), Camelbeeck and Meghraoui (1998), Camelbeeck et al. (2007), Frechen et al. (2001), Frechen and van den Berg (2002), Grützner et al. (2016), Hinzen et al. (2001), Houtgast et al. (2003), Houtgast et al. (2005), Kübler et al. (2010), Kübler et al. (2011a), Kübler et al. (2011b), Kübler (2013), Kübler et al. (2017a), Kübler et al. (2017b), Lehmann et al. (2001), Meghraoui et al. (2000), Miedema and Jongmanns (2002), Skupin et al. (2008), van Balen et al. (2016), van den Berg et al. (2002), Vandenberghe et al. (2009), Vanneste et al. (1999), Vanneste and Verbeeck (2001), Vanneste et al. (2001), Vanneste et al. (2008), Vanneste et al. (2017), Verbeeck et al. (2017), Winandy et al. (2011).

During these trench studies, other paleoseismic evidence such as soft-sediment deformation and mass movement features was found (e.g., Camelbeeck et al., 2007; Frechen and van den Berg, 2002; Grützner et al., 2016; Houtgast et al., 2003; Kübler, 2013; Skupin et al., 2008; van den Berg et al., 2002; Vandenberghe et al., 2009; Vanneste et al., 1999; Vanneste et al., 2001; Vanneste et al., 2008; Winandy et al., 2011). The results of the trenching campaigns led to the definition of 25 paleoearthquakes in the last 185,000 years in the Lower Rhine Graben, which are lying in a range of magnitudes between 5.0 und 7.0. For a review of the seismic situation in the Lower Rhine Graben, Vanneste et al. (2013) created a model of composite seismic sources in this tectonic setting, which includes 15 different fault zones. The results of this study are also based on the paleoseismic findings from the past decades. The authors determine average return periods of 33,000 years corresponding to the maximum magnitudes of 6.3 - 7.1. With this amount of studies, the Lower Rhine Basin, especially the Feldbiss fault zone, is extensively studied in terms of paleoseismology. But, due to some uncertainties in dating methods and interpretation of paleoseismic evidence, the work in the LRG should be continued.

In the last 5 years, new trench studies have been completed in the LRG, respectively new results of trench studies that already existed are published. Grützner et al. (2016) document new results of two trenches at a site close to Arnoldsweiler (western Germany) where the trench crossing the Rurrand fault. Palaeoseismological data presents evidence for a surface rupturing earthquake in the Holocene and at least one more surface rupturing event. The Rurrand fault is expected to be the seismogenic source of the Düren 1755/1756 earthquake series. But, the trenching results (Grützner et al., 2016) indicate it did not produce surface ruptures at the Rurrand Fault. Kübler et al. (2011a) updated their findings in a trench at the Schafberg fault (western Germany; see also Kübler et al., 2011b). A complex deformation zone in Holocene fluvial sediments was mapped, and evidence for at least one paleoearthquake that resulted in vertical surface displacement of around 1.2 m is documented. van Balen et al. (2016) present preliminary results from a trenching study in Bakel (eastern Netherlands) at the Peelboundary fault zone, which is known to be barriers for horizontal groundwater flow. Two faulting events are recorded in the trench. Verbeeck et al. (2017) identified the Rauw fault in eastern Bakel in a paleoseismic trench. The fault is the largest offset fault west of the Roer Valley Graben and appears as typical of plate interior context with an episodic seismic activity.

1.4.2. Upper Rhine Graben

As part of the European Cenozoic Rift System, the Upper Rhine Graben (URG) belongs to one of the most tectonically active regions in Central Europe. The URG is situated in between two uplifted areas, in the west the Vosges Mountains (VG) and in the east the Black Forest (BF) and the Odenwald (OW). A 300 km long elongated and on average 40km wide rift flanked by the before mentioned uplifted plateaus has developed, initiated in the Miocene. It is bounded by major normal faults striking NNE-SSW with vertical displacements of up to 5 km. Although most faults are normal, horizontal striations on fault planes as well as earthquake focal mechanisms are frequently observed (Plenefisch and Bonjer, 1997), indicating sinistral displacement along both borders of the graben. The graben terminates in the south with the west-east striking frontal thrusts and thrust-bound flexures of the Jura Mountains and in the north with the WSW-ENE striking southern boundary fault of the Rhenish Massif. The formation of the graben was initiated in the Late Eocene with a main rifting phase in the Oligocene (Schumacher, 2002).

In the northern part of the graben, the eastern boundary fault zone shows the greatest displacement and, accordingly, the greatest sediment thickness is located along the eastern margin of the Upper Rhine Graben. The western boundary fault zone was most active and the depocenter is close to the western border. Upper crustal extension across the Upper Rhine Graben amounts to ca. 7 km (Dèzes et al., 2004). So-called 'Vorbergzonen' are formed by blocks with an intermediate position between the uplifted graben shoulders and the lowland of the graben fill. The rocks that crop out in these zones are mainly Mesozoic. To the south of Mulhouse, the graben is subdivided into two sub-basins separated by a central high. Here, the boundary faults are often developed as extensional flexures in the Mesozoic cover rocks (Ustaszewski et al., 2005). In the southernmost part of the Upper Rhine Graben, close to the deformation front of the Jura fold-and-thrust belt, the geometry of the graben was strongly modified by Miocene to recent compressional and transpressional tectonics (Laubscher, 2001; Rotstein et al., 2005).

Earthquake hypocentres in the area of the Upper Rhine Graben occur beneath the graben and its elevated shoulders. Their depth range extends down as far as the Moho and ends abruptly there (Bonjer, 1997). The largest historical earthquake in Central Europe, the Basel 1356 earthquake, occurred at the southern end of the Upper Rhine Graben. The epicentre was located south of Basel, approximately where the eastern border fault/flexure of the Upper Rhine Graben meets the front of the folded Jura. Meghraoui et al., (2001) suggested that a NNE–SSW striking, linear hill slope on the western side of the Birs valley represents the surface rupture of the seismic fault.

Amongst the northern part of the European Continental Rift System, the Upper Rhine Graben is also extensively investigated in terms of paleoseismic work. There, 14 paleoseismic trench studies have been carried out (e.g., Baize et al., 2002; Becker et al., 2002; Becker et al., 2005; Cushing et al., 2000a; Cushing et al., 2000b; David et al., 2011; Ferry et al., 2005; Hibsch et al., 2000; Lemeille et al., 1999; Meghraoui et al., 2001; Monecke et al., 2006; Monninger, 1985; Montenat et al., 2007; Palumbo et al., 2013; Peters et al., 2005; Peters and van Balen, 2007a; Peters and van Balen, 2007b; Peters, 2007; Rotstein and Schaming, 2008). The paleoseismic record of the Western Border fault (e.g., Peters et al., 2005; Peters and van Balen, 2007a; Peters and van Balen, 2007b; Peters, 2007; Baize et al., 2002; Monninger, 1985) and its associated faults, the Vosges fault (Baize et al., 2002) and the Achenheim-Hangenbieten fault (Cushing et al., 2000a; Cushing et al., 2000b; Baize et al., 2002), have both been spatially and temporally studied. These investigations found 4 paleoearthquake events in a time period between 8,000 years to Eemian times. Detailed dating results are currently missing and time constraints are taken from stratigraphic relationships. The interpretations from displaced strata suggest a magnitude of around MW 6.5 for these paleoearthquakes. Montenat et al. (2007) and Hibsch et al. (2000) have described several soft-sediment deformation features (such as hydroplastic faults, injections and sand volcanoes) observed in excavated Quaternary alluvial deposits of the Rhine valley. These were interpreted as seismically induced, but were not described in detail or quantified in age and dimension. The origin of these features could be associated with seismic activity at the Western Border fault. Regarding the historical Basel (1356) earthquake, relatively extensive paleoseismic studies have been undertaken in the broader region of Basel (Switzerland). Meghraoui et al. (2001) and Ferry et al. (2005) have excavated 6 paleoseismic trenches south of Basel and reconstructed a paleoseismic history of 5 different paleoearthquakes including evidence for the 1356 event. The oldest paleoearthquake occurred between 9,500 and 11,200 years BC. The magnitudes range from MW 6.5 - 6.7. The associated source of these paleoearthquakes is the Basel-Reinach fault, which is a 15-km long prolongation of the eastern border of the Upper Rhine Graben to the south. In the broader region of Basel, Becker et al. (2002), Becker et al. (2005), and Monecke et al. (2006) have carried out paleoseismic studies in alpine lakes (Bergsee and Seeween), which support the paleoseismic earthquake history of the trenches excavated to the south of Basel. They have found several soft-sediment deformation and mass movement features that were seismically induced. The other parts of the eastern border of the Upper Rhine Graben (e.g., Eastern Main Border fault and Rhine River fault) are missing detailed paleoseismic studies. Some geophysical, morphological and sedimentological studies have been done (Nivière et al., 2008; Lämmermann-Barthel et al., 2009), which suggest that a Pleistocene reactivation of the Rhine River fault led to the offset of young, near-surface sedimentary deposits. The long-term slip rates of faults in the Freiburg area are estimated to range between 0.04 and 0.1 mm/a Nivière et al., 2008). Lämmermann-Barthel et al. (2009) suppose a SSW-NNE striking fault in the area which forms a morphological step found in an outcrop in the vicinity of Bremgarten. The presence of this so-called Hochgestade-Tiefgestade fault strongly indicates that the step is of tectonic origin and reflects very recent neotectonic movements in the southern Upper Rhine Graben (Lämmermann-Barthel et al., 2009).

1.4.3. North German Basin

The stress field for the North German Basin (NGB) has been almost stable since the Miocene and is oriented NW-SE. Presently, the isostatic rebound of the Fenno-Scandian Shield is the main influence on the stress field in northern Germany (Kaiser et al., 2005; see also Brandes et al., 2015). The Scandinavian post-glacial rebound dome and glacial forebulge has resulted in the formation of a pattern of alternating regions of higher and lower seismicity with respect to the underlying tectonic stress field (Reicherter et al., 2005). The most dramatic evidence of active faulting and seismicity is reported from those areas where icesheets reached their maximum thickness, including the marginal regions of Scotland and the NGB (Wahlstrom, 1989; Arvidsson, 1996; Mörner, 2003, 2004; Stewart et al., 2000). Seismic shocks in the early and probably rapid phase of the Scandinavian shield's post-glacial isostatic rebound are caused by fault reactivation. Present-day crustal deformation is still the consequence of the mantle response to deglaciation (Scherneck et al., 1998).

Seismicity in northern Germany is rather low and of low magnitude. The occurrence of earthquakes larger than EMS intensity > 5 (European Macroseismic Scale, Grünthal and Mayer-Rosa, 1998), as documented in the earthquake catalog for the last 1,000 years (Leydecker, 1986), is also very low and has an expected recurrence interval of 10,000 years (Leydecker et al., 1999). Fault plane solutions indicate N-NW-directed maximum horizontal stress (Henderson, 1991; Reicherter et al., 2005).

A broad zone of subsidence stretches from Hamburg via Berlin to Wroclaw (Poland) (Garetzky et al., 2001) with average subsidence rates of 0.03 mm/a in the deep depocenters. Subsidence and uplift vary across the NGB, mainly as a result of the pre-existing fault zones (Schwab, 1985; Franke and Hoffmann, 1999; Bayer et al., 1999, 2002). All historical and instrumental earthquake data point to magnitudes M < 5. The hypocentral depth of the major portion of the observed earthquakes exceeds the Zechstein base; they are, hence, interpreted as being of tectonic origin. The most prominent geomorphic lineations with an orientation of NW-SE are associated with basement faults or even crustal or lithospheric discontinuities (Reicherter et al., 2005).

The paleoseismic record for the North German Basin is extremely limited. One paleoseismic study has been undertaken at a cliff section on Usedom Island in the southwestern Baltic Sea as part of the intracratonal North German Basin. Hoffmann and Reicherter (2011) found a sequence of sedimentary structures typical of a glacial setting providing a wide range of soft-sediment deformation features. The authors suggest that all observed structures such as faulting, slumping and liquefaction are triggered by earthquake-induced shaking. As discussed before, the seismic activity in the North German Basin was and most probably still is associated with the ongoing isostatic rebound and related forebulge collapse of the crust; however, the locality of the causative fault remains unclear. The age of the related Pleistocene sediments could only be determined by morpho-stratigraphic deglaciation chronologies of Late Weichselian age.

Brandes and Tanner (2012) document a three-dimensional geometry and fabric of shear deformation-bands developed in Middle Pleistocene, unconsolidated, glaciolacustrine delta sands in northern Germany (Winsemann et al., 2007). The deformation bands are very likely the product of young basement tectonics and may be related to movements in the crest of a salt anticline (above the narrow Leine Anticline, between the Hills and Sack Synclines) that exposes Triassic beds at the surface and is cored by Zechstein salt. In the study area, the observation of young basement tectonics is a novelty.

1.4.4. Osning Thrust zone

The Osning Thrust zone (OTZ) comprises the southern margin of the Lower Saxony Basin, which builds an intracratonic basin as part of the complex Central European Basin System (CEBS; Senglaub et al., 2005; Littke et al., 2008). The NW-SE striking fault zone has a length of approximately 115 km and represents, with other faults (e.g., the Aller fault and the Harz Boundary fault), a major fault system which is expressed by the general NW-SE striking structural frame in Central Europe. In the course of the geological development of the OTZ, the fault kinematics changed from a NNW-dipping normal faulting in Early Jurassic times (Baldschuhn and Kockel, 1999) to a low-angle thrust faulting that overthrusts the basin fill of the Lower Saxony Basin onto the Münsterland Block due to the inversion of the Lower Saxony Basin in Coniacian times (Baldschuhn and Kockel, 1999; Keller, 1974; Kockel, 2003). Northern Germany is presently characterized by a compressional and roughly N-S-oriented stress field (Heidbach et al., 2008). The area around the OTZ was affected at different levels by three major glaciations during the Middle and Late Pleistocene (i.e., Elsterian, Saalian and Weichselian). A variety of different deposits has been left in the area, including, amongst others, Pleniglacial to Late

Glacial alluvial fan and aeolian sand-sheet deposits of the upper Senne area in the region of the Osning Thrust zone. Within these glacial deposits, Brandes et al. (2012) and Brandes and Winsemann (2013) have documented evidence for paleoseismic activity along the OTZ. The authors have found numerous soft-sediment deformation structures implying a paleoearthquake during the late Pleistocene with an OSL aged sedimentary succession between 29 and 13 ka BP. In an outcrop in the vicinity of Oerlinghausen, a series of complex meter-scale faults and related fold structures are developed within an alluvial-aeolian complex, 1 km away from the thrust. These structures, also including several dikes, sand blows, flame-like and ball-and-pillow structures, imply a seismic origin caused by earthquakes with a significant magnitude on the Osning Thrust fault, probably due to the generation of a forebulge from the Late Pleistocene-Weichselian ice sheet. The paleoseismic activity of the OTZ is supported by historical earthquake records from autumn of 1612 where an earthquake with an estimated intensity in the range of VI-VII (MSK) occurred in the Bielefeld area (Grünthal and Wahlström 2012; Leydecker 2009; Vogt and Grünthal 1994).

1.4.5. Jura Mountains and Alpine molasse basin

The development of the Jura Mountains is related to the formation of the Alps in an intraplate region. They represent a classic thin-skinned, frontal fold-and-thrust belt (e.g., Sommaruga, 1999) that is not directly connected with the Alps. Instead, the Jura Mountains are decoupled from their basement by the Triassic décollement (Burkhard, 1990; Sommaruga, 1999) and are regionally separated by an apparently undeformed foreland basin called the Swiss Molasse Basin. The Jura Mountains are structurally subdivided into external (Plateau Jura) and internal parts (High or folded Jura). The internal Jura is often characterized by faulted detachment folds. In contrast, the external Jura is dominated by thrusts. Pre- and post-tectonic sediments determine the deformation phase by folding and thrusting of the Jura and Molasse units in Middle Miocene to Pliocene times, starting during Serravallian or Tortonian (11 to 3 Ma, Kälin, 1997, Baize et al., 2011) initiated by rigid indenters that compressed the Jura platform in the Alpine area (e.g., Laubscher, 1992). The Jura Mountains form a pronounced arc shape with a general strike of SSE-NNW in the southern part and a W-E strike in the eastern part. Additional to the structural elements of folds and thrusts, the Jura units are crosscut by several left-lateral strike-slip faults acting as transfer faults during the main phase of shortening.

One of these transfer faults is the Vuache fault, which is a prominent structural feature of 35 km in length transecting the Molasse from the Subalpine nappes up to the internal Jura. On this fault, Delaunay et al. (1981), Jouanne et al. (1994), Baize et al. (2002) and Baize et al. (2011) have documented paleoseismic evidence determined by faulted Upper Pleistocene fluvio-glacial deposits. Historical and instrumental events have also been associated with the Vuache fault. Additionally, secondary earthquake effects have also been recorded such as the occurrence of soft-sediment deformation features (e.g., load-casts, convolute bedding and pillows). La Taille et al. (2015) found in the N-S-elongated lake of Le Bourget two faults that are also expected to be transfer faults in the Jura Mountains and Alpine molasse basin. In high-resolution seismic profiles which have been perfomed across a northern and a southern part of the lake, recent deformation recorded by the Quaternary sediments were detected and characterized. The deformations belong to the northern Culoz fault and to the southern Col du Chat fault.

1.4.6. Northern and Central Switzerland

Switzerland lies in an intraplate setting strongly influenced by the indention of the Adriatic block into the European plate (e.g., Schmid et al., 2004). It is composed of three major tectonic units in its northwestern part. The west and northwest are delimitated by the Upper Rhine Graben, a Late Eocene to early Miocene rift system belonging to the European Cenozoic Rift System. In the Basel area, Pleistocene gravels and loess and Holocene alluvium are mostly exposed at the surface. South of Basel, the N-S-striking Basel-Reinach fault builds the southern prolongation of the Eastern border fault of the Upper Rhine Graben system. To the south, the fold-and-thrust belt of the Folded Jura, consisting of Triassic and Jurassic shales and limestones, has developed in late Miocene times in an E-W direction. To the north, the Tabular Jura extends over a broad area up to the Black Forest and comprises very similar lithologies to the Folded Jura. Both units are characterized by steep cliffs and strong karstification with dolines and caves (Bitterli, 1996). The central part of Switzerland is situated in the north Alpine foreland basin which is north of the North-Alpine front. The Alpine front builds up the front between the Alpine nappes (e.g., Helvetic nappes) and the sub-Alpine Molasse with a general strike of WSW-ENE. In this Alpine range, the Helvetic nappes are thrust over the Molasse basin. Northwestern and central Switzerland is characterized by the existence of several overdeepened and partly elongated troughs that were formed due to glacial erosion during glacier retreat after the Last Glacial Maximum starting around 15,000 y BP (Monecke et al., 2006). These lakes and their continuous lacustrine sedimentation record have the potential to be a natural seismograph (Strasser et al., 2013).

Through the investigation of the AD 1356 Basel earthquake, several geological archives in northwestern Switzerland, such as active faults, lake deposits, slope instabilities and caves, have been studied in Detail to extend the earthquake catalogs to pre-historic times (Becker et al., 2005). Meghraoui et al. (2001) and Ferry et al. (2005) have studied the Basel-Reinach fault in detail with several paleoseismic trenches and determined that this fault is the most likely seismic source of the AD 1356 Basel earthquake. Along with this important earthquake in historic times in Central Europe, the authors found evidence for four more earthquakes in paleoseismic times. The occurrence of the earthquakes is supported by the work of Becker et al. (2002), Becker et al. (2005) and Monecke et al. (2006). The authors found evidence in lake deposits that were seismically deformed. Further studies in central Switzerland (e.g., Kremer et al., 2015; Reusch, 2016; Reusch et al., 2016; Schnellmann et al., 2002; Schnellmann et al., 2006; Strasser et al., 2006; Strasser et al., 2007; Strasser et al., 2013) investigating seismic profiles and deformed lacustrine deposits of 11 prealpine lakes led to several more paleoearthquakes being described in time periods between around 15 ka BP and historic times with estimated magnitudes between Mw 5.7 and 6.7. Kremer et al. (2017) present an overview of these studies and identified striking periods of enhanced occurrence of shaking-induced mass movements and micro deformations in the studied lakes during several phases of the past 10,000 years, centered at 9,700, 6,500 and during the last 4,000 cal yr BP. Fabbri et al. (2017) found evidence for a younger fault activity of the Einigen fault during the Holocene (younger than ~11,000 years BP) combining amphibious geomorphology with subsurface geophysical and geological data. The Einigen fault is considered as a complex fault system with a combination of dextral strike-slip and normal faulting crossing the prealpine Lake of Thun. Kremer et al. (2020) present a composed collection of these geological archives in a database of potential paleoseismic evidence in Switzerland.

1.4.7. Northern Italy

The Po Plain is a flat fluvial foredeep basin elongated in an E-W direction that is characterized by the convergence of two mountain chains, the Southern Alps and the Northern Apennines (e.g., Castellarin et al., 1992; Fantoni et al., 2004; Carminati et al., 2004; Mosca et al., 2009). Both mountain chains do not present a high seismic or high tectonic activity compared with other active mountain belts in the world (e.g., Dolan and Avouac, 2007). The formation of the Southern Alps was controlled by the subduction of Europe underneath the Adriatic plate. The Northern Apennines, in contrast, were formed along the westward subduction of the Adriatic lithosphere below the Tyrrhenian Basin (Michetti et al., 2012). The Insubric Line builds the northern margin of the Southern Alps. The Northern Apennines are not bounded by a topographic mountain front directly, but are limited by a structural front below the Plio-Pleistocene basin deposits of the Po Plain. In between the junction area of the Southern Alps and the Northern Apennines, the structural setting is characterized by several anticline and backthrust systems due to active shallow crustal shortening and uplift in a range of a few mm/yr (Michetti et al., 2012). Four of the most prominent, and also paleoseismically relevant, tectonic elements are, from west to east, the Varese backthrust, the Monte Olimpino back-thrust, the Albese con Cassano anticline, and the Capriano-Castenedolo backthrust.

At the Varese backthrust, Bini et al. (1992) have documented paleoseismic evidence for two paleoearthquakes in a cave (e.g., broken speleothems) in a time range from 350 ka BP for the first event and 52.3-5.5 ka BP for the second. Directly in the city center of Como, at the Borgo Vico site (a formerly construction site), secondary deformation structures associated with the Monte Olimpino backthrust show a centimetric to decimetric movement in drag-folded, glaciolacustrine laminae younger than 17 ka BP (Livio et al., 2011). Chunga et al. (2007) have found several soft-sediment deformation features along the Albese con Cassano anticline, which are clearly associated with a pre-historic earthquake event (dated to Mid-Pleistocene by stratigraphic relationships). Further to the east, Livio et al. (2011) and others describe three different normal faulting events along a gravity-graben between 45 and 5 ka BP due to the tectonic activity of the buried seismogenic backthrust of Capriano-Castenedolo. In the area of the Eastern Monferrato Arc (NW Italy), Frigerio et al. (2017) document the first evidence for earthquake surface displacement in a Late Quaternary pedosedimentary sequence exposed at Pecetto di Valenza. They identified at least two different phases of deformation, and more than five fault scarp-forming events caused a total net displacement of ca. 4.8 m during the past ca. 40 ka.

1.4.8. Vienna Basin

The Vienna Basin is strongly influenced by its NNE-SSW striking left-lateral strike-slip Vienna Basin Transfer Fault (VBTF). It extends from the Alps through the Vienna Basin into the Carpathians and comprises six secondary splay normal faults which branch out and cross the entire basin (Beidinger et al., 2010; Hinsch et al., 2010; Decker et al., 2005; Hinsch et al., 2005). The fault system evolved during the Miocene in a NE-directed movement of a major Alpine-Carpathian crustal block (Linzer et al., 2002; Decker and Peresson, 1998), which is directly linked to the formation of the Vienna Basin consider that the VBTF is rooted on the basal detachment of the Alpine-Carpathian orogenic wedge. The fault zone is segmented by six secondary splay normal faults, which are considered to be reactivated Miocene structures (Decker et al., 2005) and are characterized by varying in kinematic and seismological properties. The southwestern and northeastern part of the fault zone shows moderate to relatively high seismicity (Hinsch et al., 2010), whereas the central part of the VBTF, especially the Lassee segment, did not release significant seismic slip in the last four centuries and appears to be a locked segment (Hinsch and Decker, 2003).

There are, however, several indications for Quaternary movement proposed through geological and morphological data. The movement of the normal faults is considered to be at a very slow vertical velocity level of < 0.1 mm/a. The horizontal slip on the VBTF is considered to be on a higher level (1-2 mm/a, Hintersberger et al., 2018, and Hintersberger et al., 2013). The question arises as to how strongly the VBFT is influencing the kinematics on the normal faults such as the Lassee fault. Hintersberger et al. (2013) have undertaken several paleoseismic trench investigations at the Lassee segment of the VBFT as well as at the Markgrafneusiedl fault, one of the splay normal faults. They have documented 5-6 major surface-rupturing earthquakes correlated between three paleoseismic trenches across the Markgrafneusiedl fault. The events have occurred in the last 120 ka with magnitude estimates ranging from Mw 6.3 and 7.0. In the trenches, the paleoseismologists found several paleoseismic features such as displaced strata, tension cracks and colluvial wedges. The Lassee fault, the Markgrafneusiedl fault and a third normal fault, called Aderklaa-Bockfliess fault, dissecting large river terraces of a minimum IRSL age from about 200 to 300 ka. By paleoseismological trenching and by combining electrical resistivity measurements and the analysis of remote sensing data at the Aderklaa-Bockfliess fault (Gaenserndorf terrace), Weissl et al. (2017) identified the exact fault location and its vertical offset of 10 m.

1.4.9. Western and Eastern Czech Republic

In the Central European structural setting, the Czech Republic has at least three regions that are prone to tectonic activity: the Eger Rift including the Mariánské-Lázne fault in the Cheb basin, the Bohemian Massif with the Sudetic Marginal fault as the northeastern border, and the Nysa-Morava fault zone in the West Carpathian Foreland.

The Cheb Basin belongs to the western intra-continental Cenozoic Eger Rift system and builds a tectonically active basin that is 150 km long and its northern part, which contains the Mariánské-Lázne fault (MLF), is strongly seismically active. During the Late Oligocene and Early Miocene, the Eger rift subsided, and afterwards during the Mid-Miocene it was uplifted and inverted. In the Late Pliocene, the Cheb Basin developed at the NW corner of the Bohemian Massif and experienced widespread subsidence associated with tectonic activity along the MLF (Peterek et al., 2011). The Cheb Basin was initially formed by the reactivation of basement faults and comprises sediment fill of Miocene lignite, clay and sand; and after a gap, Upper Pliocene sand, gravel and kaolinitic clay formations followed (Malkovsky, 1987; Spicakova et al., 2000). The MLF is expressed as a nearly 100 km long escarpment (height of around 50 and 400 m, Bankwitz et al., 2003). The youngest sediments, which are downwarped by the fault, were radiocarbon dated to 4.8 ka BP (Stepančíková, 2012; Stepančíková and Fischer, 2012). With this and another dating result, Stepančíková (2012) supposes two paleoseismic events in the vicinity of Kopanina, one around 260 ka BP (OSL dating) and another around 4.8 ka BP (radiocarbon dating) or even younger. New results from the Kopanina site suppose that the youngest fault cuts and deforms young Holocene deposits of the age interval 5.3 – 1.1 ka BP, which is the youngest proved surface faulting in Central Europe reported so far (Stepančíková et al., 2015).

The Bohemian Massif is bordered by an almost straight mountain front built by the Sudetic Marginal fault zone (SMF), which separates the crystalline rocks of the Sudetic Block and Miocene sediments overlying crystalline rocks of the Fore-Sudetic Block. The SMF is morphologically expressed as more than 130 km long escarpment with a general strike of NW-SE (Badura et al., 2007). The fault zone was initiated during the Variscan orogenesis and was reactivated during the formation of the Alps with alternating kinematics (Oberc and Dyjor, 1969; Grocholski, 1977; Skácel, 2004; Aleksandrowski et al., 1997; Scheck et al., 2002; Badura et al., 2003 a, b). In recent morphological and trenching studies (Badura et al., 2007; Stepančíková et al., 2009; Stepančíková et al., 2012; Stepančíková et al., 2011a; Ste-pančíková et al., 2011b; Stepančíková et al., 2013) provide evidence for Quaternary reactivations of the fault. The youngest paleoseismic event was documented in early Holocene times before the deposition of the youngest datable colluvial sediments (ca. 800 a BP). Stepančíková et al. (2013) suggest that this is a pre-historic earthquake event. Furthermore, the trenching studies indicate that at least four other paleoearthquakes have occurred, which resulted in a surface rupture during the late Quaternary.

The Nysa-Morava fault zone (NMF) is expressed in the NE part of the Bohemian Massif representing the immediate foreland of the Alpine-Carpathian collisional system. It is strongly controlled by a major tectonic structure parallel to the Teisseyre-Tornquist zone, and is also associated with the Elbe fault system (Arthaud and Matte, 1977; Scheck et al., 2002; Spaček et al., 2006). Similar to the Sudetic Marginal fault zone, the Nysa-Morava fault zone, and related smaller faults in the system, express major morphological features as a result of former reactivation (Pliocene to Pleistocene) of NW-SE to NNW-SSE striking boundary faults of related pull-apart type basins (Grygar and Jelínek, 2003; Spaček et al., 2006). The formation of these basins was accompanied with eruptions of alkali basalts during Late Oligocene, Early Miocene, Pliocene and Pleistocene times. Based on historical seismicity records since the 15th century, the NMF has a weak seismicity with only a few events reaching a magnitude between 4 or 5, but it has undergone several pronounced microseismicity events in the instrumental period (Spaček, 2013). In a preliminary trenching study, Spaček (2013) and Spaček et al. (2017) found evidence for one paleoearthquake that was associated with significant slip in the Pleistocene (1.6 to >8 m at individual faults); however, no, or very little, Holocene slip has been evidenced in the trench. Further trench studies have been documented at the NW-SE-striking Hluboká fault and the NNE-SSW-striking Diendorf-Boskovice fault that the tectonic slip is contradicted for the last 15 – 23 ka based on dating of undeformed strata sealing the fault planes. Thus, it is supposed that the two faults were not active in Late Pleistocene at least.

1.4.10. Southern Sweden

Sweden belongs to the Scandinavian Peninsula and builds a part of the Baltic Shield, which is strongly affected and altered by the glaciation periods during the Ice Ages. The Baltic Shield comprises as the basement of Fennoscandia a complex series of magmatic and metamorphic rock formations of very old age (several billions of years). The age of these rocks decreases from north to south. Southern Sweden is structurally characterized by the Sorgenfrei-Tornquist Zone (STZ), that prolongs into the Tesseyre-Tornquist Zone (TTZ) to the SE (e.g., EUGENO-S Working Group, 1988; Babel Working Group, 1991; Mogensen and Jensen, 1994; Mogensen, 1994; Erlström et al., 1997; Plomerová et al., 2002; Babuška and Plomerová, 2004; Bergerat et al., 2007). The entire Tornquist Zone is NW-SE oriented and presents the longest structural lineament in North Central Europe, crossing from the North Sea in the northwest to the Black Sea in the southeast. STZ developed during the Late Carboniferous to Early Permian as a horst and graben structure. According to Mörner (1991), the long-term stress direction in Southern Sweden is in the NW-SE direction. Additional to this long-term trend, the glacial isostatic movements give the region a short-term, but large-scale, overprint in Quaternary times. Regarding glacial retreat and the following rebound of Scandinavia, Southern Sweden had been affected by multiple paleoseismic events (Mörner, 2003). These paleoearthquakes have been documented in several studies (e.g., Mörner, 2003; Mörner, 2004; Mörner, 2005; Mörner, 2009; Mörner, 2011; Mörner, 2014) by different evidence types such as primary fault offsets, fracturing of bedrock, sediment deformation, liquefaction features, mass movement features, tsunami events and turbidites. In total, 15 paleoseismic events have been determined in the region of Southern Sweden during the last 12 ka BP.

1.5. Seismotectonic regions

The region of Central Europe is an area of low seismotectonic activity away from active plate boundaries. The correlation between seismic hypocenters and their tectonic source structures (i.e., faults and folds) often lacks of detailed knowledge about their exact position and the seismic behaviour. The lack of a possible association of earthquake events with a known seismic source is often described as "diffuse seismicity". Therefore, a common approach in seismic hazard assessment is the definition of so-called seismotectonic zones to seismotectonically characterize a specific region. A seismotectonic zone is defined by a partition of main crustal blocks reflecting the major tectonic trend of a homogeneously distributed seismogenic potential by geographically overlying and correlation of other relevant data. The data used for that can be of several different types like geologically (e.g., regional stress regime defined by the World Stress Map provided by Heidbach et al. (2008), a simplified geology, and neotectonic and paleoseismic evidence), and geophysically (e.g., the Moho depth provided by Dèzes et al., 2004) derived data. In other terms, it can be distinguished between the static and dynamic state of Earth's crust. The static state defined by structural and rheological properties is relatively well-known in Central Europe (cf., Dèzes et al., 2004, and Roure et al., 1990). Whereas, the dynamic state of the crust defined by long-term seismicity and Neotectonic, and accordingly paleoseismic deformations is rarely or only locally known. In the course of the dynamic considerations of Earth's crust, the historical and instrumental seismicity is also taken into account as the most important input data for the classification in most seismotectonic zoning models. In seismic hazard assessments, the record of the strongest earthquake event in the seismic catalogs defines for each seismotectonic zone the highest seismic hazard level. Therefore, the role of paleoseismic data for seismic events gets more and more important, although the records of paleoseismology are rare and only locally known and investigated in specific regions (compare for this the state of the database PalSeisDB v1.0 discussed in here). The geological records of paleoseismic events are indicative for a strong earthquake potential and can help by determining the deformation rates of a region at timescales of several tens to hundreds of thousands of years. In consequence, these data of the deformational kinematics during Quaternary times are a reliable key for parameterising and elaboration of seismotectonic zoning models.

For the German and Central European region, several seismotectonic zonation models have been developed in the last decades. The distribution, geometry and boundaries of the polygons describing each seismotectonic zone are strongly dependent on the input parameters (e.g., different earthquake catalogs). Central European examples of seismotectonic zonation schemes outside of Germany are presented, amongst others, by Baize et al. (2013) for France, Burkhard and Grünthal (2009) for Switzerland, Meletti et al. (2008) for Italy, Schenk et al. (2000) for the Czech Republic, Poland and Slovakia, and Verbeeck et al. (2009) for Belgium. For Germany and adjacent regions, two of these models are shown in Figure 2 (Leydecker (2011); Giardini et al., 2013). Previously, further models have been developed, for example by Ahorner and Rosenhauer (1993) and Grünthal and Bosse (1996). All four models do not take paleoseismic earthquake records into account and show all a varying allocation of the polygons describing seismotectonic zones. Thus, uncertainties are mandatory associated with the compilation of seismotectonic zones. In the course of this problem, Coppersmith and Youngs (2006) put forward a fundamental and commonly unanswered question, if the boundaries of seismotectonic source zones represent physical limits to rupture, or if they simply separate regions having differing level of seismicity. Accordingly, the models of seismotectonic zonation should be reconsidered and a more standardized model for Germany or Central Europe should be evaluated to avoid the aforementioned limitations. Furthermore, the availability of paleoseismic data can also lead to a change of seismotectonic zonation. Another option, concerning seismic hazard assessment, could be the consideration of methods without using a seismotectonic zonation as discussed in Golbs (2009).

A) Leydecker, 2011 **B)** Giardini et al., 2013 (SHARE)

Figure 2. Maps of different seismotectonic zonation schemes after Leydecker (2011) and Giardini et al. (2013, SHARE model).

1.6. Aspects of similar projects

Projects collecting data from faults to characterize their seismic potential have been undertaken world-wide and, in most cases, they are still in progress. These projects have been developed on a national basis and some on regional scale. However, they do not collect paleoseismic data directly; data on active faults and seismogenic sources, including their long-term behaviour, is mostly compiled. These faults and seismogenic sources are responsible for the generation of modern, historical and paleo-earthquakes. For seismic hazard assessments, however, not only does this earthquake information have to be considered, but also the geologic relationship between the source of an event (fault) and the effect (earthquake), as concluded by Basili et al., 2008. Some examples of active fault and seismogenic source databases include:

- Italy's 'Database of Individual Seismic Sources' (DISS version 3.2.1, Basili et al., 2008 and DISS Working Group, 2018),
- the 'Quaternary Active Faults Database of Iberia' (QAFI v.3, García-Mayordomo et al., 2012 and IGME 2015),
- France's 'Base de Données des Failles Actives' project (Palumbo et al., 2013 and Jomard et al., 2017),
- the 'U.S. Quaternary Fault and Fold Database' (Haller et al., 2004 and U.S. Geological Survey, 2017),
- the 'Central and Eastern United States Seismic Source Characterization' for Nuclear Facilities (CEUS-SSC, Coppersmith et al., 2012 and CEUS-SSC Working Group, 2015),
- the 'New Zealand Active Faults Database' (Langridge et al., 2016 and GNS Science Limited, 2015),
- the 'Active Fault Database of Japan' (National Institute of Advanced Industrial Science and Technology (AIST), 2016),
- the 'Active Tectonics of the Andes database' (ATA v.1.0, Veloza et al., 2012),

- ‘Mexico Quaternary Fault Database’ (Villegas et al., 2017),
- Quaternary fault database for central Asia (CAFD, Mohadjer et al., 2016), and
- the ‘European Database of Seismogenic Faults’ (EDSF/SHARE compiled in the framework of the Project SHARE, Basili et al., 2013)

The SHARE database includes seismogenic sources (mainly active fault data) and an earthquake catalog (historical and instrumental) for the wider European region. Some entries of fault data are incorporated in PalSeisDB v1.0.

Although the different projects have some common features (e.g. national coverage, completeness, use of available literature data) and a shared main purpose (e.g. use in seismic hazard assessment), there are also several differences mainly in the structural context (e.g. amount of information, visualization style) and the general scientific approach (e.g. main objectives, used parameters). What most of the aforementioned projects have in common is that they represent the result of a significant amount of work. Each project represents several years or decades of research experience, involving researchers and scientists from large working groups (e.g. DISS, CEUS-SSC, SHARE). Additionally, all these projects are still in progress and contain growing databases, which will be subject to change as new information becomes available and new interpretations are developed. To date, no such database has been developed for Germany. Therefore, a project has been started to collect paleoseismic and fault-related data in a similar and, in some parts, extended database structure compared to other project databases.

In the references above, detailed information is provided about some other projects, which have a similar background to the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) in dealing with the collection of data on topics such as active tectonics, paleoseismology and earthquake effects. Some of the used parameters, data and architectural concepts from these databases are incorporated and adapted in the database. Clarification on what is incorporated and adapted is provided in Sections 2 and 3.

2. The Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0)

2.1. Needs, usage and objectives

To date, no systematic documentation of paleoseismic evidence and related paleoseismic events and sources has been developed for Germany. Instead, paleoseismic or tectonically active features are often studied individually by several authors with different approaches or at a very regional scale. Thus, the provided information is hidden in several different studies and, in most cases, inconsistently documented. Therefore, a project has been started to collect paleoseismic and fault-related data in a similar and, in some parts, extended database structure to those in the aforementioned projects (see Section 1.6), providing a consistent archive of harmonized paleoseismic data. As a result, the data of each individual study is comparable to other studies.

There is a wide range of investigations related to paleoseismic evidence. These studies, motivated by many scientists, have provided a large number of publications. The collected material had to be combined and organized in a consistent way containing geographic and parametric data. For this purpose, a newly-built database structure, the so-called Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0), has been produced with data tables including individual parameters and coordinates for the collected features. The database is connected to a GIS-based system via a table export / point shapefile import process. The use of this common format and standard procedure guarantees an updateable system that can also be made publicly available. It should provide new aspects for technical purposes (such as seismic hazard analysis) and scientific purposes (such as finding missing pieces of paleoseismic evidence).

The project is situated in the framework of the updated German Nuclear Safety Standard, called KTA 2201 (Design of Nuclear Power Plants against Seismic Events). In the revised version (latest 2011), the data from paleoseismic studies and their results should be incorporated with respect to the maximum historical or prehistorical deterministic earthquake (paleoearthquake). The new standard should include the assessment of paleoseismicity to a distance of 200 km (radius) from the specific building. The collected information is not only useful in the context of nuclear safety, but also for building regulations in a more general context (e.g. emergency, infrastructural and industrial facilities). To add an additional factor of safety, the study area is expanded to another 100 km wide zone, leading to a study area that includes Germany and the adjacent regions within a radius of 300 km from the German border (see Figure 3).

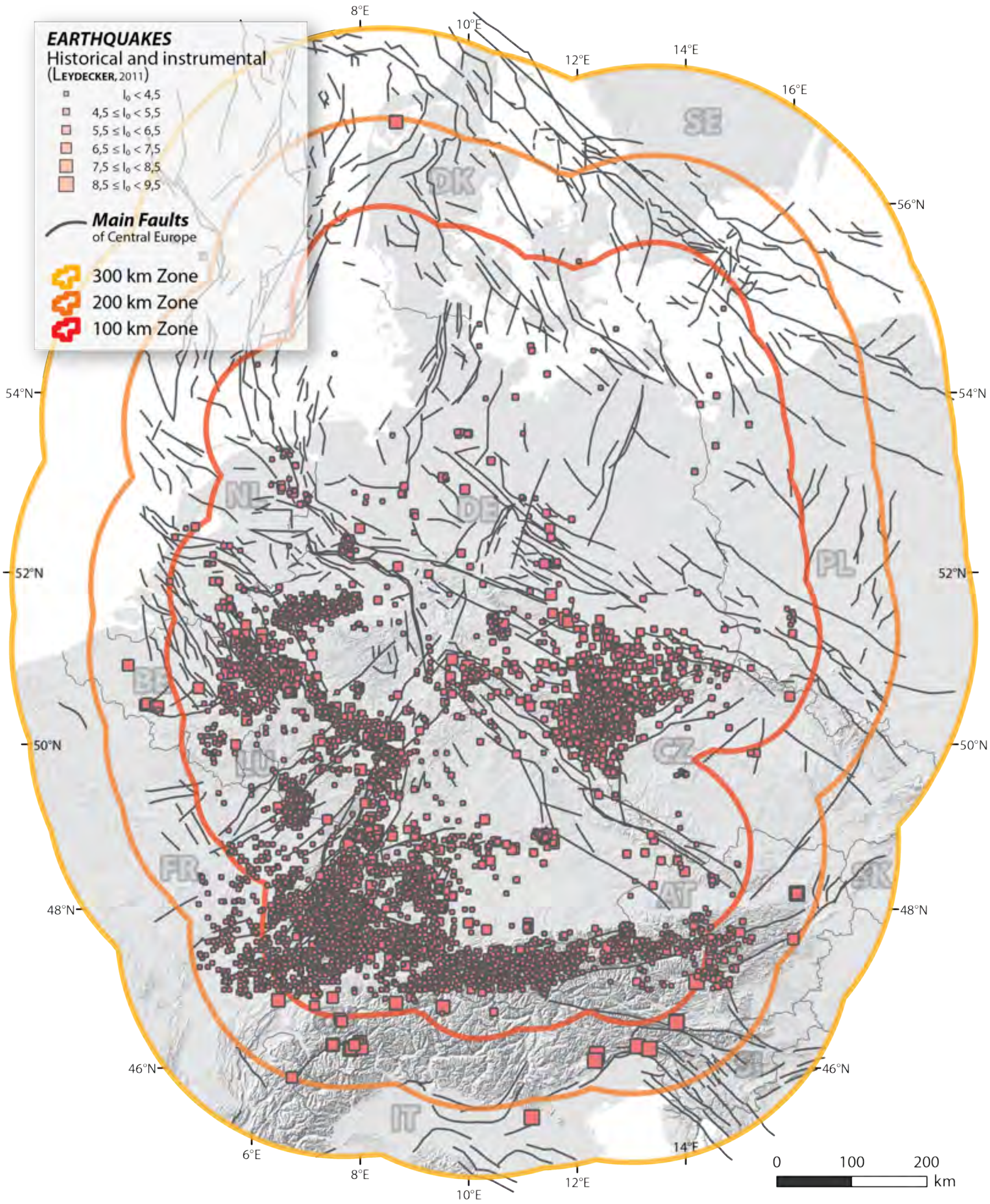


Figure 3. Extent of the study area for the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) showing the main structural framework (main faults, disregarding whether they are active or not, compiled from Dèzes et al. (2004), Kaiser et al. (2005), and Reicherter et al. (2008)) combined with topographic imprint (hillshade of SRTM 90-m-data) and historical and instrumental seismicity (813 – 2009, Leydecker, 2011). The size of the historical and instrumental seismicity squares corresponds to the earthquake's epicentral intensity. The yellow thick line marks the total extent of the study area. Coordinate System: WGS 1984 World Mercator.

2.2. Aims

Regarding the time constraint of the project which is a one year period, a compilation of as many records of paleoseismic evidence as possible can certainly be completed; however, there is not sufficient time to reach the highest level of completeness for the entire study area (ca. 1.46 M km^2) due to its transnational extent and complex geologic and tectonic setting. This cannot be expected particularly in comparison to the previously mentioned databases (see Section 1.6), which have involved several years of collaborative work performed by many researchers and scientists. Some of these projects already had a topic-related background; however, a project requirement was also to develop a framework for systematic documentation of paleoseismic evidence and related features. Such a project should also be seen as ongoing work as it is continuously updated with results from new investigations, or the reinterpretation of previous studies due to progress in the geologic knowledge.

The main expected results for the PalSeisDB development are:

- to develop a structural framework to document paleoseismic records systematically
- to reach the highest level of completeness in terms of paleoseismic evidence, related faults, earthquakes and included information
- to give a geographic representation of the majority of paleoseismic evidence, related faults and earthquakes
- to provide a first data basis for enhancement of seismic hazard assessment (SHA) models including paleoseismicity in Central Europe

Data and information about paleoseismic records that were previously diffusely distributed, and in some cases hidden in a large amount of literature, will be categorized and parameterized, comparable at both local and regional scales.

2.3. Methodology

2.3.1. Concept

After consulting existing databases at national and supranational scales (see examples in Section 1.6), the first step was to build a fundamental concept, which is schematically shown in Figure 4. It consists of the following paleoseismic features (see Section 1.2):

- the **paleoseismic evidence**: This is inferred from the geologic record. Remark: Paleoseismic evidence implies by definition that the geologic evidence can be attributed to a seismic origin.
- the **paleoseismic event**: This is inferred from paleoseismic evidence. It is a paleoearthquake.
- the **paleoseismic source**: The paleoseismic event is attributed to a seismogenic structure or a specific fault, if possible.

For different records of paleoseismic evidence, four categories were distinguished:

- paleoseismic trenches,
- soft-sediment deformation features,
- mass movement features and
- other types of paleoseismic evidence.

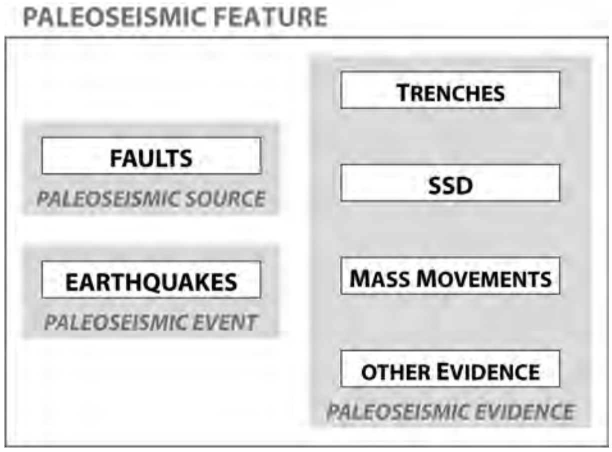


Figure 4. Schematically drawn concept behind the development of PalSeisDB v1.0.

In the ideal case, one or more records of paleoseismic evidence can be related to one paleoseismic event. The paleoseismic event can be caused by a paleoseismic source. In some cases, the conditions of the ideal case do not fit and a relation between event and source or source and evidence cannot be established due to complexity of the geologic record or due to lack of information.

2.3.2. Parameters

After the creation of the fundamental concept, the second step was to find parameters describing the paleoseismic features. These are for instance their location, type, size and seismic implications. The parameters are stored in data tables in the database.

2.3.3. Data from literature

The third step was to collect the available paleoseismic literature in the study area; documents include peer-reviewed scientific articles, publicly available reports, M.S. theses, Ph.D. dissertations, conference proceedings and also in some minor cases unpublished work (e.g., from personal communications and posters). From the literature, the information on paleoseismic evidence, the information on paleoearthquakes and the information on active faults were extracted. They were input into individual data tables with specifications of the origin of the provided data.

The chosen time window of PalSeisDB v1.0 is limited to a period between Eemian age (MIS5, ca. 125 ka) and prehistoric times (ca. 1,000 BP).

2.4. PalSeisDB development procedure

PalSeisDB v1.0 consists of two environments: a database environment and a GIS-based environment. The database environment is mainly used to parameterize each record of paleoseismic evidence, whereas the GIS environment is used to localize and display their fully parameterized paleoseismic features.

The data found in the literature is stored in a Microsoft Access 2010 database. A basic and detailed description of this process is provided in Section 3.1 respectively. All information is stored in data tables using input forms, which had to be created for this purpose. Each paleoseismic feature including all parameters extracted from literature represents an entry in a database table.

The spatial information on an entry was taken by georeferencing figures and maps from published works or by coordinates delivered by personal communications. The records of spatial information are stored in the geodetic datum ETRS 1989 (European Terrestrial Reference System). The extraction of spatial information from figures and maps has been done in ESRI ArcGIS 10.1. Additionally, ArcGIS was used to digitize traces of faults and to visualize the paleoseismic features stored in the database.

From the Microsoft Access database, several different file types have been exported. The structure and type of available data files is described in the following section.

2.5. Structure and use of PalSeisDB

Table 1 lists the data files, which are provided in the frame of PalSeisDB v1.0. The main component is built by the Microsoft Access database ('PalSeisDB v1.0.accdb'). The other files are used to visualize the data and to work with the data independently of the availability of the used operating system and the used applications. The exported data from the Microsoft Access database is also provided in the Microsoft Excel format (xlsx) as individual tables and as an Excel-file of all data in combined format of individual tables ('PalSeisDB v1.0.xlsx').

The data files of PalSeisDB v1.0 are published by Hürtgen et al. (2020) or can be downloaded from the following weblink:

https://www.bgr.bund.de/EN/Themen/Erdbeben-Gefaehrdungsanalysen/Ingenieurseismologische_Gefaehrdungsanalysen/Palaeoseismologie/palaeoseismologie_node_en.html

Table 1. The table presents a list of data files associated with the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0, 2017).

Microsoft Access 2010 Database		
PalSeisDB v1.0	accdb	Paleoseismic Database of Germany and Adjacent Regions (Version 1.0, October 2017) including data tables for paleoseismic features
Microsoft Excel format (containing all paleoseismic data tables from PalSeisDB v1.0)		
PalSeisDB v1.0	xlsx	Excel file comprising all data tables below
LOCATION	xlsx	data from sites where paleoseismic evidence found
PSE_Trenches	xlsx	data from paleoseismic trenches
PSE_SSDs	xlsx	data from soft-sediment deformation features
PSE_MassMov	xlsx	data from mass movement features
PSE_others	xlsx	data from other paleoseismic feature
Rel_EQs	xlsx	data from paleoearthquakes determined by paleoseismic evidence
Rel_Faults	xlsx	data from related faults determined by paleoseismic evidence
LINK_Tr_EQ	xlsx	data table linking paleoseismic trenches to related paleoearthquakes
ESRI ArcGIS 10.1 files (containing all paleoseismic data tables from PalSeisDB v1.0)		
LOCATION	shp	data from sites where paleoseismic evidence found
PSE_Trenches	shp	data from paleoseismic trenches
PSE_SSDs	shp	data from soft-sediment deformation features
PSE_MassMov	shp	data from mass movement features
PSE_others	shp	data from other paleoseismic feature types
Rel_EQs	shp	data from paleoearthquakes determined by paleoseismic evidence
Rel_Faults	shp	data from related faults determined by paleoseismic evidence
Area_extent	shp	ESRI shapefile of the study area extent (German border)
Area_extent_100	shp	ESRI shapefile of the study area extent including a 100 km zone around the German border
Area_extent_200	shp	including a 200 km zone around the German border
Area_extent_300	shp	including a 300 km zone around the German border

Countries	shp	ESRI shapefile of relevant country outlines (based on Natural Earth. Free vector and raster map data @ naturalearthdata.com)
PalSeisDB v1.0 2017	lyr	PalSeisDB v1.0 2017.lyr (Layer Package) includes the above-mentioned Shapefiles with their design appearance in ArcGIS

Google Earth files

PalSeisDB v1.0 2017	kmz	KMZ file comprising all single kmz files below
LOCATION	kmz	data from sites where paleoseismic evidence found
PSE_Trenches	kmz	data from paleoseismic trenches
PSE_SSDs	kmz	data from soft-sediment deformation features
PSE_MassMov	kmz	data from mass movement features
PSE_others	kmz	data from other paleoseismic feature types
Rel_EQs	kmz	data from paleoearthquakes determined by paleoseismic evidence
Rel_Faults	kmz	data from related faults determined by paleoseismic evidence
Area_extent	kmz	study area extent including 100 km, 200 km, and 300 km zones around the German border
Countries	kmz	Relevant country outlines (based on Natural Earth. Free vector and raster map data @ naturalearthdata.com)

2.5.1. Microsoft Access database (start window in ‘PalSeisDB v1.0.accdb’)

Opening the Microsoft Access database file (‘PalSeisDB v1.0.accdb’), a start window displays the overall structure of the database (see Figure 5). The database gives the option to select a specific type of paleoseismic feature – the paleoseismic evidence features, the paleoseismic events, or the paleoseismic sources. These are provided as data forms, which allow both viewing and editing of data, and as data reports, which gives an overview about the data stored of each paleoseismic feature. The left column of the start window (see Figure 5) provides access to all available elements (data tables, data forms and data reports) included in the Microsoft Access database (‘PalSeisDB v1.0.accdb’).

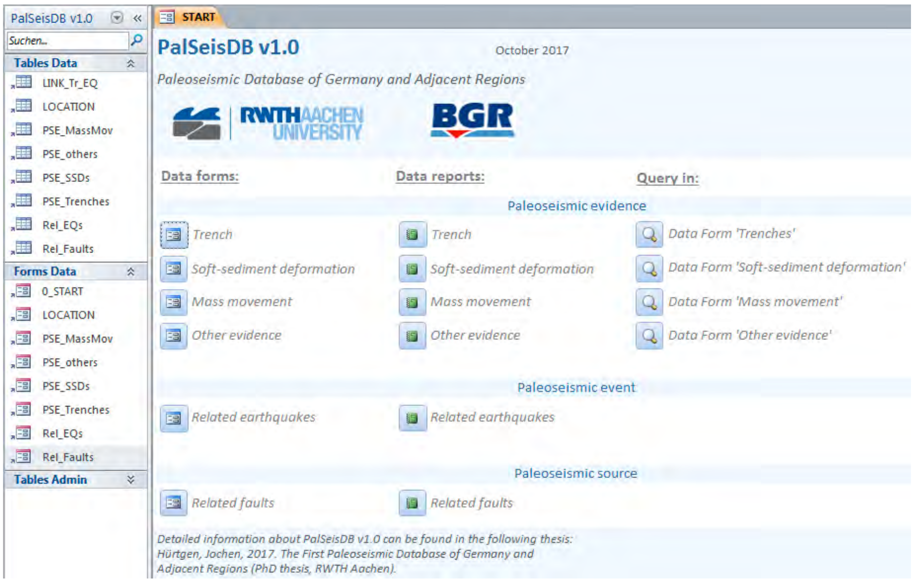


Figure 5. Screenshot of the START window that appears when the Microsoft Access database ‘PalSeisDB v1.0.accdb’ is opened. It provides direct access to all elements incorporated in the database including data tables, data forms and data reports.

2.5.2. *GIS-based data files (*.shp and *.kmz)*

For visualisation purposes, a variety of geographically based files of the different paleoseismic features, are provided in form of shapefiles in a ESRI ArcGIS (shp) and a Google Earth (kmz) file format. They can be selected in the file browser of the operating system. Each geographic file includes the fully parameterized dataset that is also provided in the Microsoft Access database. In the ArcGIS environment, the parameterized data can be viewed by the attribute table feature, or by clicking a specific paleoseismic feature with the identify tool on the map. There are also supplementary files provided to support the user in viewing the paleoseismic features in map view within the ArcGIS environment. This includes the borders of Germany and adjacent regions, extent of study area. The layer package ('PalSeisDB v1.0 2017.lyr') file includes design appearances of all provided shapefiles and their structure. This is only compatible to ESRI ArcGIS. The shapefiles are compatible to other GIS-based software solutions.

In the Google Earth environment, the kmz-files including the paleoseismic data can be loaded and viewed as a separate layer. Each data point on the map is also clickable and opens a pop-up window with all parameters that are included in the database itself.

2.5.3. *Excel-based data files (*.xlsx)*

Additionally, all data tables from the Microsoft Access database are exported as Microsoft Excel format. This allows access for users without an operating version of Microsoft Access 2010 (or similar compatible version).

2.6. Searching the Access database PalSeisDB v1.0

2.6.1. *Searching in general*

The Paleoseismic Database of Germany and Adjacent Regions ('PalSeisDB v1.0.accdb', Microsoft Access format) provides tools to view, search and export the included data (see Figure 5). Records of the database can be viewed as a row in a table (left navigation pane > 'Tables Data' > e.g. 'PSE_Trenches') or as a sheet of a data form (left navigation pane > 'Forms Data' > e.g. 'PSE_Trenches'). All records of a table can also be exported as a data report in pdf-format by clicking on the specific button ('START' navigation form > 'Data reports' > e.g. 'Trench'). In these reports, each record (row of a data table) can be viewed as a data sheet with all parameters listed. The Microsoft Access database PalSeisDB v1.0 provides a natively implemented text search option in data table and data form view (see Figure 6). The user can type in any text and the opened data sheet (either a table or a form) is scanned through, searching for words that include the typed in text partly or completely.

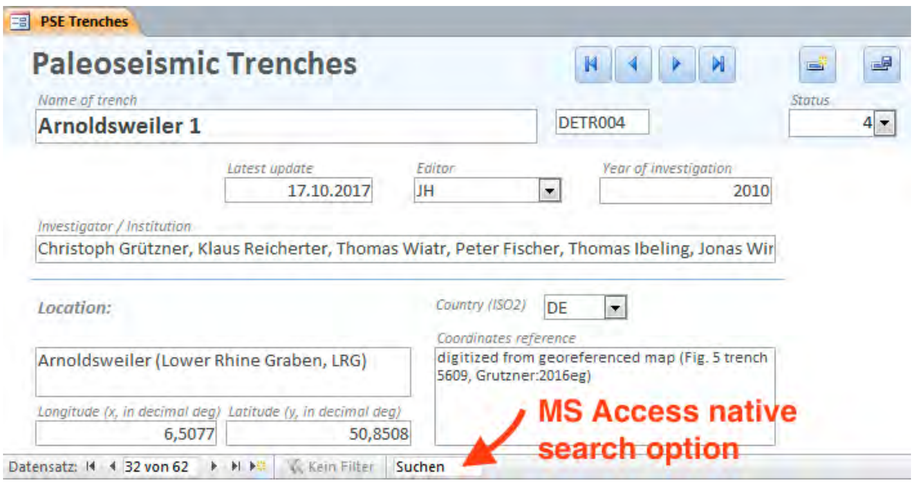


Figure 6. Example of the Microsoft Access natively implemented search option. This search field is available at the bottom of data table and data form view. In this example an extract of the record of a paleoseismic trench close to Arnoldsweiler (Lower Rhine Graben) is shown.

2.6.2. *Use of the implemented search mask and filter tools*

In the following, the use of implemented filter tools as well as the implemented search masks in PalSeisDB v1.0 will be explained to view, search, select and sort palseoseimic records and their parameters according to criteria provided by the user. In the 'START' window (see Figure 5), the search mask related to one of the paleoseismic evidence features is available. The search mask for trenches, soft-sediment deformations, mass movements, and other evidence features can be selected in the column 'Query in'. The search mask is opened by clicking the icon with the magnifying glass. After one of the search masks is chosen by the user, the search mask is used for the input of filter criteria. In PalSeisDB v1.0, the filtering of datasets is based on spatial queries. The user can choose between two variants (see Figure 7):

1. Input of geographic coordinates (latitude and longitude, yLAT and xLON, respectively, in decimal degrees) to limit the search area. The search area is defined by a rectangular that is determined by the input of values for latitude (yLAT) and longitude (xLON).
2. Choose a country from the list. With the symbol '*' all countries are selected.

After the input of the spatial filter criteria, the user needs to choose whether the search result will be shown as 'Table' or as 'Form'.

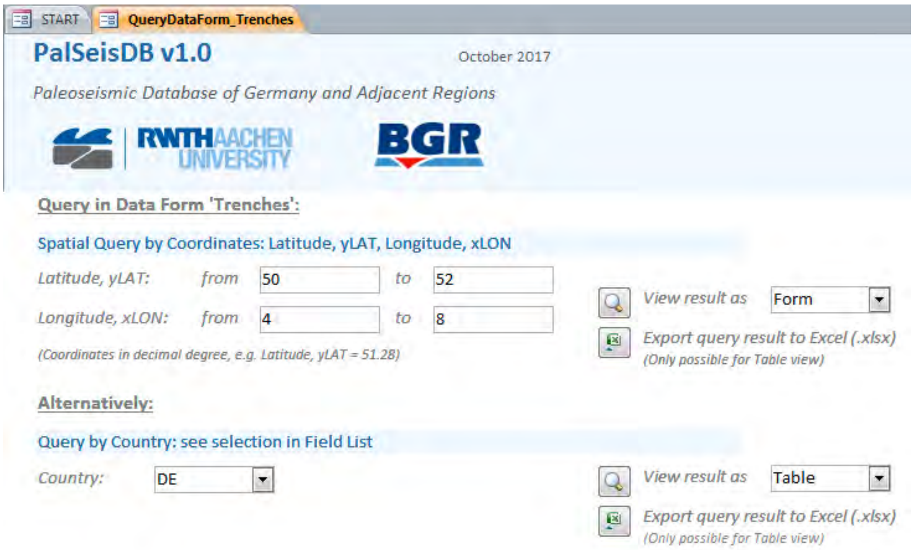
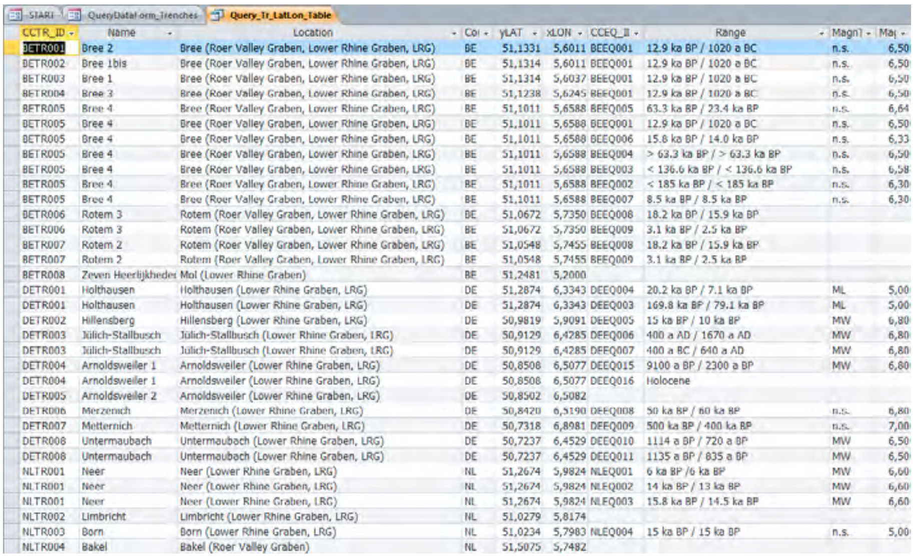


Figure 7. Search mask for 'Trenches' implemented in PalSeisDB v1.0. It provides two options to search and filter for records in the database related to paleoseismic trenches: 1) spatial query by coordinates (ex. Lower Rhine Graben, results as table in Figure 8 and as data form in Figure 9), and 2) spatial query by country (ex. Germany, DE, results as table in Figure 10). The results can be viewed as a data form or table, or can be exported as table in Excel format (*.xlsx).

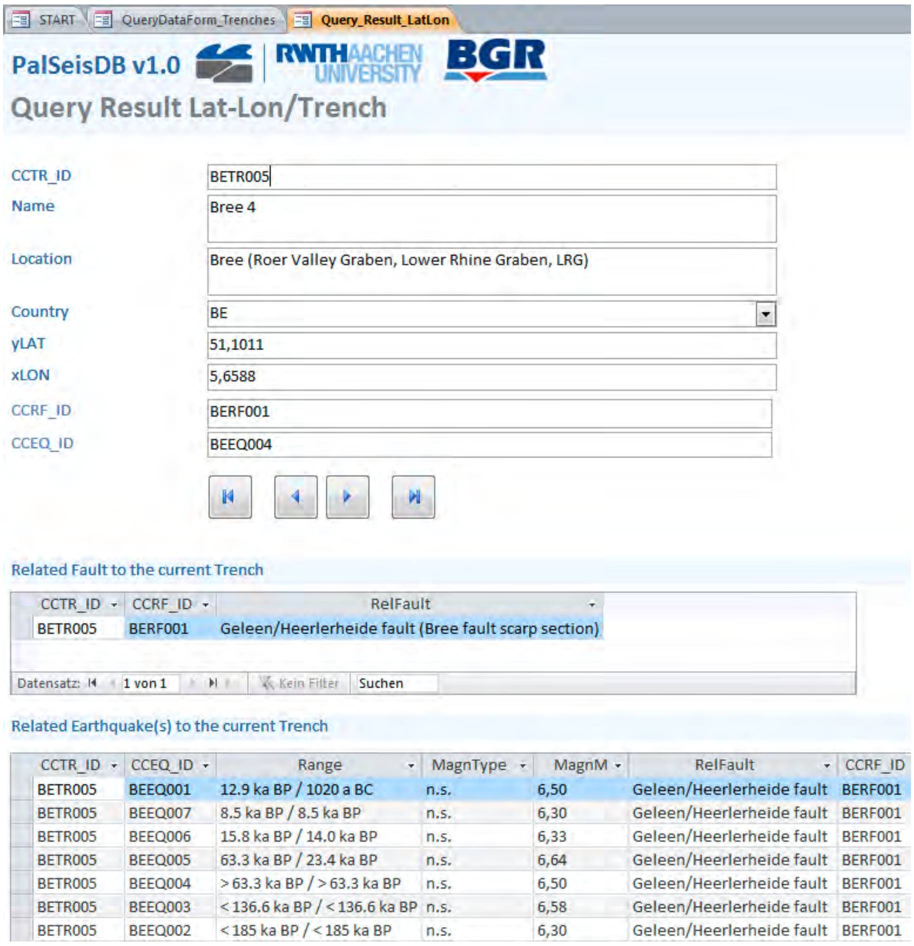
The actual query gets started by clicking the icon with the magnifying glass. Then, a new window will be opened showing the query result in the chosen view ('Table' or 'Form').



START | QueryDataForm_Trenches | Query_Tr_LatLon_Table

CCTR_ID	Name	Location	Coi	yLAT	xLON	CCEQ_II	Range	MagnT	Ma
BETR001	Bree 2	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1331	5,6011	BEEQ001	12.9 ka BP / 1020 a BC	n.s.	6,50
BETR002	Bree 1bis	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1314	5,6011	BEEQ001	12.9 ka BP / 1020 a BC	n.s.	6,50
BETR003	Bree 1	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1314	5,6037	BEEQ001	12.9 ka BP / 1020 a BC	n.s.	6,50
BETR004	Bree 3	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1238	5,6245	BEEQ001	12.9 ka BP / 1020 a BC	n.s.	6,50
BETR005	Bree 4	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1011	5,6588	BEEQ005	63.3 ka BP / 23.4 ka BP	n.s.	6,64
BETR005	Bree 4	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1011	5,6588	BEEQ001	12.9 ka BP / 1020 a BC	n.s.	6,50
BETR005	Bree 4	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1011	5,6588	BEEQ006	15.8 ka BP / 14.0 ka BP	n.s.	6,33
BETR005	Bree 4	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1011	5,6588	BEEQ004	> 63.3 ka BP / > 63.3 ka BP	n.s.	6,50
BETR005	Bree 4	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1011	5,6588	BEEQ003	< 136.6 ka BP / < 136.6 ka BP	n.s.	6,58
BETR005	Bree 4	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1011	5,6588	BEEQ002	< 185 ka BP / < 185 ka BP	n.s.	6,30
BETR005	Bree 4	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,1011	5,6588	BEEQ007	8.5 ka BP / 8.5 ka BP	n.s.	6,30
BETR006	Rotem 3	Rotem (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,0672	5,7350	BEEQ008	18.2 ka BP / 15.9 ka BP		
BETR006	Rotem 3	Rotem (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,0672	5,7350	BEEQ009	3.1 ka BP / 2.5 ka BP		
BETR007	Rotem 2	Rotem (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,0548	5,7455	BEEQ008	18.2 ka BP / 15.9 ka BP		
BETR007	Rotem 2	Rotem (Roer Valley Graben, Lower Rhine Graben, LRG)	BE	51,0548	5,7455	BEEQ009	3.1 ka BP / 2.5 ka BP		
BETR008	Zeven Heerlijkheder	Mol (Lower Rhine Graben)	BE	51,2481	5,2000				
DETR001	Holthausen	Holthausen (Lower Rhine Graben, LRG)	DE	51,2874	6,3343	DEEQ004	20.2 ka BP / 7.1 ka BP	ML	5,00
DETR001	Holthausen	Holthausen (Lower Rhine Graben, LRG)	DE	51,2874	6,3343	DEEQ003	169.8 ka BP / 79.1 ka BP	ML	5,00
DETR002	Hillensberg	Hillensberg (Lower Rhine Graben, LRG)	DE	50,9819	5,9091	DEEQ005	15 ka BP / 10 ka BP	MW	6,80
DETR003	Jülich-Stallbusch	Jülich-Stallbusch (Lower Rhine Graben, LRG)	DE	50,9129	6,4285	DEEQ006	400 a AD / 1670 a AD	MW	6,80
DETR003	Jülich-Stallbusch	Jülich-Stallbusch (Lower Rhine Graben, LRG)	DE	50,9129	6,4285	DEEQ007	400 a BC / 640 a AD	MW	6,80
DETR004	Arnoldsweiler 1	Arnoldsweiler (Lower Rhine Graben, LRG)	DE	50,8508	6,5077	DEEQ015	9100 a BP / 2300 a BP	MW	6,80
DETR004	Arnoldsweiler 1	Arnoldsweiler (Lower Rhine Graben, LRG)	DE	50,8508	6,5077	DEEQ016	Holocene		
DETR005	Arnoldsweiler 2	Arnoldsweiler (Lower Rhine Graben, LRG)	DE	50,8502	6,5082				
DETR006	Merzenich	Merzenich (Lower Rhine Graben, LRG)	DE	50,8420	6,5190	DEEQ008	50 ka BP / 60 ka BP	n.s.	6,80
DETR007	Metternich	Metternich (Lower Rhine Graben, LRG)	DE	50,7318	6,8981	DEEQ009	500 ka BP / 400 ka BP	n.s.	7,00
DETR008	Untermaubach	Untermaubach (Lower Rhine Graben, LRG)	DE	50,7237	6,4529	DEEQ010	1114 a BP / 720 a BP	MW	6,50
DETR008	Untermaubach	Untermaubach (Lower Rhine Graben, LRG)	DE	50,7237	6,4529	DEEQ011	1135 a BP / 835 a BP	MW	6,50
NLTR001	Neer	Neer (Lower Rhine Graben, LRG)	NL	51,2674	5,9824	NLEQ001	6 ka BP /6 ka BP	MW	6,60
NLTR001	Neer	Neer (Lower Rhine Graben, LRG)	NL	51,2674	5,9824	NLEQ002	14 ka BP / 13 ka BP	MW	6,60
NLTR001	Neer	Neer (Lower Rhine Graben, LRG)	NL	51,2674	5,9824	NLEQ003	15.8 ka BP / 14.5 ka BP	MW	6,60
NLTR002	Limbricht	Limbricht (Lower Rhine Graben, LRG)	NL	51,0279	5,8174				
NLTR003	Born	Born (Lower Rhine Graben, LRG)	NL	51,0234	5,7983	NLEQ004	15 ka BP / 15 ka BP	n.s.	5,00
NLTR004	Bakel	Bakel (Roer Valley Graben)	NL	51,5075	5,7482				

Figure 8. Extract of results by using the search mask for 'Trenches' in table view (spatial query by coordinates for the Lower Rhine Graben, see Figure 7). The table gives an overview which sites have been trenched in the queried area and which paleoearthquakes have been found in the specific trench.



START | QueryDataForm_Trenches | Query_Result_LatLon

PalSeisDB v1.0

Query Result Lat-Lon/Trench

CCTR_ID	BETR005
Name	Bree 4
Location	Bree (Roer Valley Graben, Lower Rhine Graben, LRG)
Country	BE
yLAT	51,1011
xLON	5,6588
CCRF_ID	BERF001
CCEQ_ID	BEEQ004

Related Fault to the current Trench

CCTR_ID	CCRF_ID	RelFault
BETR005	BERF001	Geleen/Heerlerheide fault (Bree fault scarp section)

Datensatz: 1 von 1 | Kein Filter | Suchen

Related Earthquake(s) to the current Trench

CCTR_ID	CCEQ_ID	Range	MagnType	MagnM	RelFault	CCRF_ID
BETR005	BEEQ001	12.9 ka BP / 1020 a BC	n.s.	6,50	Geleen/Heerlerheide fault	BERF001
BETR005	BEEQ007	8.5 ka BP / 8.5 ka BP	n.s.	6,30	Geleen/Heerlerheide fault	BERF001
BETR005	BEEQ006	15.8 ka BP / 14.0 ka BP	n.s.	6,33	Geleen/Heerlerheide fault	BERF001
BETR005	BEEQ005	63.3 ka BP / 23.4 ka BP	n.s.	6,64	Geleen/Heerlerheide fault	BERF001
BETR005	BEEQ004	> 63.3 ka BP / > 63.3 ka BP	n.s.	6,50	Geleen/Heerlerheide fault	BERF001
BETR005	BEEQ003	< 136.6 ka BP / < 136.6 ka BP	n.s.	6,58	Geleen/Heerlerheide fault	BERF001
BETR005	BEEQ002	< 185 ka BP / < 185 ka BP	n.s.	6,30	Geleen/Heerlerheide fault	BERF001

Figure 9. Extract of results by using the search mask for 'Trenches' in form view (spatial query by coordinates for the Lower Rhine Graben, see Figure 7). The form gives an overview about the paleoseismic results in trench 'Bree4 (BETR004)' in the Roer Valley Graben. The related fault and the related earthquakes, for which paleoseismic evidence was found in the given trench, are listed in tables.

The view 'Form' is recommended for scanning through the separate datasets (see Figure 9). While the view 'Table' is recommended for getting an overview of the resulting datasets (see Figure 8 and Figure

10) and for further applications, e.g. export query result to a Microsoft Excel table. To export the table of the query result, the user needs to change again to the search mask window. The export of the query result to a Microsoft Excel table is achieved by clicking the icon ‘Export query result to Excel’ (Note: Export to Excel is only possible for a query result in ‘Table’ view).

START | QueryDataForm_Trenches | Query_Tr_Country_Table

CCTR_ID	Name	Location	Co	yLAT	xLON	CCEQ_I	Range	Magi	Ma	IntenType	IntenI	RelFault	CCRF_ID
DETR001	Holthausen	Holthausen (Lower Rhine Graben, LRG)	DE	51,2874	6,3343	DEEQ004	20.2 ka BP / 7.1 ka BP	ML	5,00			Viersen fault	DERF002
DETR001	Holthausen	Holthausen (Lower Rhine Graben, LRG)	DE	51,2874	6,3343	DEEQ003	169.8 ka BP / 79.1 ka BP	ML	5,00			Viersen fault	DERF002
DETR002	Hillensberg	Hillensberg (Lower Rhine Graben, LRG)	DE	50,9819	5,9091	DEEQ005	15 ka BP / 10 ka BP	MW	6,80			Feldbiss fault	NLRF002
DETR003	Julich-Stallbusch	Julich-Stallbusch (Lower Rhine Graben, LRG)	DE	50,9129	6,4285	DEEQ006	400 a AD / 1670 a AD	MW	6,80			Rurrand fault	DERF003
DETR003	Julich-Stallbusch	Julich-Stallbusch (Lower Rhine Graben, LRG)	DE	50,9129	6,4285	DEEQ007	400 a BC / 640 a AD	MW	6,80			Rurrand fault	DERF003
DETR004	Arnoldsweiler 1	Arnoldsweiler (Lower Rhine Graben, LRG)	DE	50,8508	6,5077	DEEQ016	Holocene					Rurrand fault	DERF003
DETR004	Arnoldsweiler 1	Arnoldsweiler (Lower Rhine Graben, LRG)	DE	50,8508	6,5077	DEEQ015	9100 a BP / 2300 a BP	MW	6,80			Rurrand fault	DERF003
DETR005	Arnoldsweiler 2	Arnoldsweiler (Lower Rhine Graben, LRG)	DE	50,8502	6,5082								
DETR006	Merzenich	Merzenich (Lower Rhine Graben, LRG)	DE	50,8420	6,5190	DEEQ008	50 ka BP / 60 ka BP	n.s.	6,80			Rurand fault (Düren section)	DERF003
DETR007	Metternich	Metternich (Lower Rhine Graben, LRG)	DE	50,7318	6,8981	DEEQ009	500 ka BP / 400 ka BP	n.s.	7,00			Swist fault (northern Swist fault section)	DERF004
DETR008	Untermaubach	Untermaubach (Lower Rhine Graben, LRG)	DE	50,7237	6,4529	DEEQ010	1114 a BP / 720 a BP	MW	6,50			Merode/Schafberg fault is covered by <5 r	DERF005
DETR008	Untermaubach	Untermaubach (Lower Rhine Graben, LRG)	DE	50,7237	6,4529	DEEQ011	1135 a BP / 835 a BP	MW	6,50			Merode/Schafberg fault is covered by <5 r	DERF005
DETR009	Osthofen 4	Osthofen/Mettenheim (Upper Rhine Graben, URG)	DE	49,7221	8,3162								
DETR010	Osthofen 1	Osthofen/Mettenheim (Upper Rhine Graben, URG)	DE	49,7218	8,3161	DEEQ012	19 ka BP / 8 ka BP	MW	6,50			Western Border fault (NNE-SSW-trending)	DERF006
DETR011	Osthofen 2	Osthofen/Mettenheim (Upper Rhine Graben, URG)	DE	49,7218	8,3154	DEEQ012	19 ka BP / 8 ka BP	MW	6,50			Western Border fault (NNE-SSW-trending)	DERF006
DETR012	Osthofen 3	Osthofen/Mettenheim (Upper Rhine Graben, URG)	DE	49,7210	8,3151	DEEQ012	19 ka BP / 8 ka BP	MW	6,50			Western Border fault (NNE-SSW-trending)	DERF006

Figure 10. Extract of results by using the search mask for ‘Trenches’ in table view (spatial query by country for the area of Germany, see Figure 7).

3. Technical aspects of PalSeisDB v1.0

3.1. Database environment

3.1.1. General remarks

Based on the methodology described in Section 2.3, the data in the PalSeisDB v1.0 is structured in four categories of different tables. It is distinguished between tables for paleoseismic evidence (see Sections 3.1.3 to 3.1.6), paleoseismic event (see Section 3.1.7), paleoseismic source (see Section 3.1.8), and also some auxiliary tables supporting the functionality of the database (see Section 3.1.9). Figure 11 provides an overview of the included data tables with their assigned parameters. The parameters are organized in tabular form. They each represent a column in the table (see Figure 12). Each entry’s location is identified by a pair of geographic coordinates, latitude and longitude, in decimal degrees with positive values for North and East and negative values for South and West. Precision is set to the fourth decimal, i.e. about 10 meters. Records of geographic information are saved in the geodetic datum ETRS 1989 (European Terrestrial Reference System), which is based on the Geodetic Reference System 1980 (GRS 80). For the faults, two pairs of coordinates are provided defining the start and end tip of a fault trace. A full list of all tables and parameters included in the database with a short description can be found in the appendix of the dissertation Hürtgen (2017); a detailed description of the parameters is presented in the following paragraphs and sections.

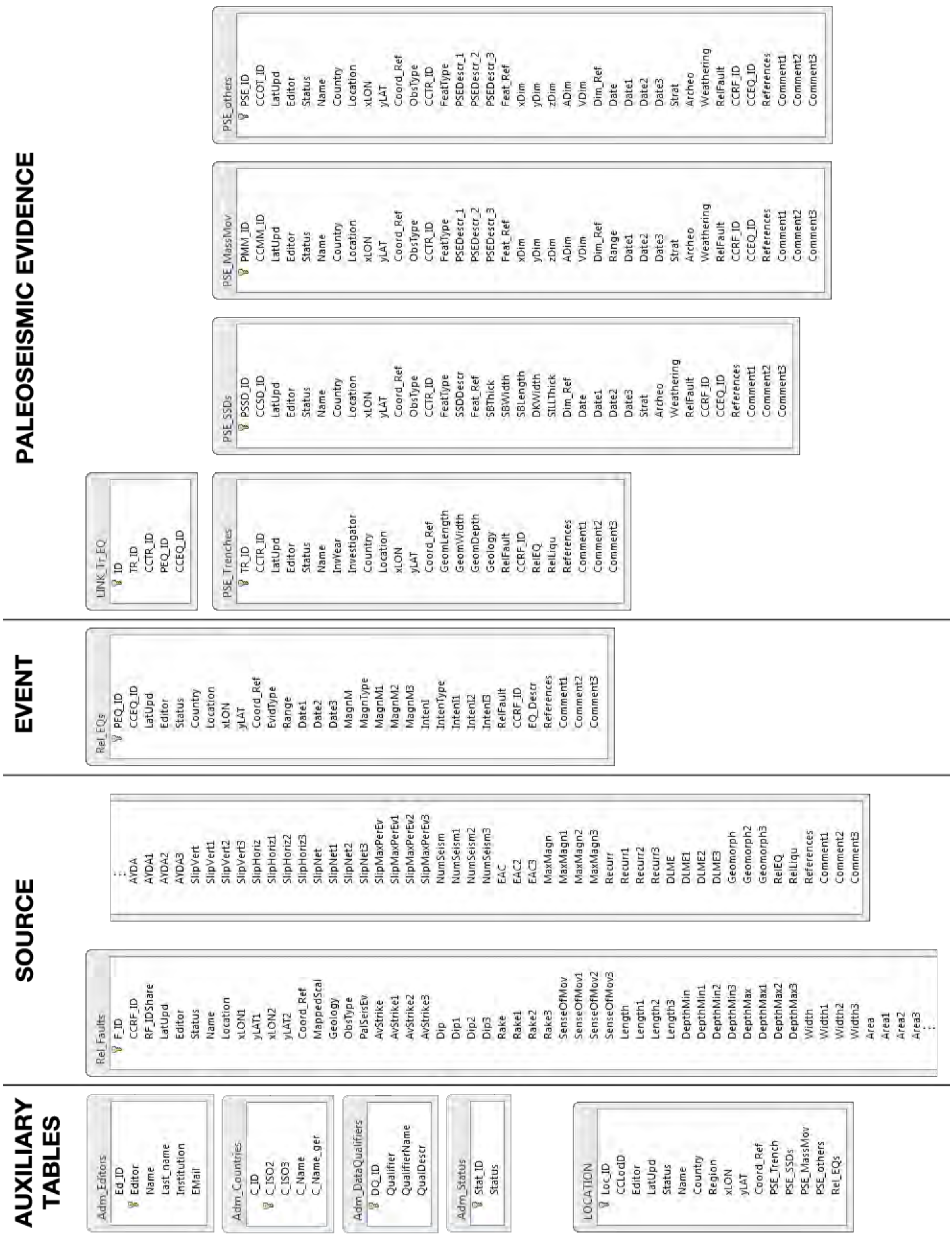


Figure 11. Overview of the data tables and parameters included in the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0). See this and the following Sections for a detailed description of each table and each associated parameter.

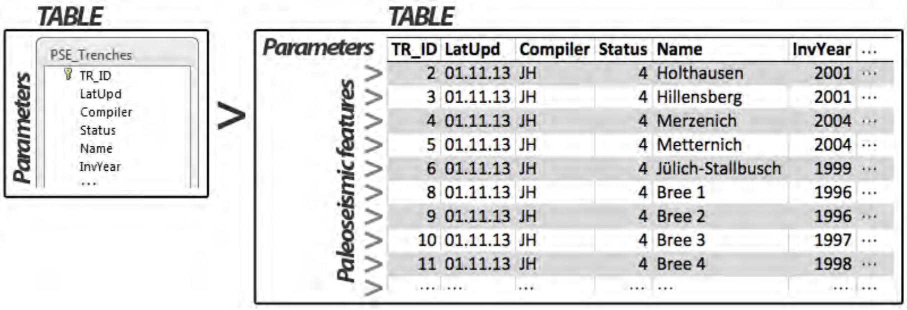


Figure 12. Schematically drawn structure of data tables in PalSeisDB v1.0. Exemplarily shown for the table of paleoseismic trenches. In each data table, each column represents one parameter and each row displays a record of a paleoseismic feature.

In all tables representing data of paleoseismic features ('PSE_Trenches', 'PSE_SSDs', 'PSE_MassMov', 'PSE_others', 'Rel_EQs', 'Rel_Faults'), fifteen parameters are the same. These are:

- **X_ID**: Each entry gets an individually and automatically assigned primary key (ID), which is allocated as a number in ascending order, when a new entry is created. *X* stands for: *TR_ID* for trenches, *PSSD_ID* for soft-sediment deformation, *PMM_ID* for mass movements, *PSE_ID* for other paleoseismic evidence, *PEQ_ID* for paleoearthquakes, and *F_ID* for the related fault. Using this ID, each entry can be uniquely addressed. Also, the entry is linked to other tables by the ID.
- **CCXX_ID**: An individually, manually assigned identifier is defined based on an alphanumeric 7-character code with the format *CCXX###* (adapted from the DISS and SHARE databases). With *CC*: two-character ISO 3166-1 code for the name of the country where data is found; *XX*: two-character code that identifies the type of data; ###: an ordinal between 1 and 999 including leading zeroes. *XX* can be *RF* (related fault), *EQ* (related earthquake), *TR* (trench), *SD* (soft-sediment deformation), *MM* (mass movement), or *PS* (other paleoseismic evidence). For example, the code for a trench in Germany could be: '*DETR004*'.
- **LatUpd**: Date of latest update of an entry.
- **Editor**: An entry can be created or edited by different editors. This data field gives information including the initials of the compiler and it is directly linked to the auxiliary table 'Adm_Editors' which contains more information on the editor, such as initial, name, surname, email address (see Section 3.1.9).
- **Status**: This is used during compilation of entries. Six options ('no status', 'to do', 'first draft', 'revised draft', 'final draft', 'done') can be chosen, which are directly linked to the auxiliary table 'Adm_Status' (see Section 3.1.9).
- **Name**: For each entry, a name is taken from literature or attributed by the editor. In most cases, from local geographical names based on the location. This parameter has not been assigned to related earthquakes (table 'Rel_EQs').
- **Country**: A two-character ISO 3166-1 code for the name of the country where the feature is found. This parameter has not been assigned to related faults (table 'Rel_Faults') due to the possible crossing border character of a fault trace.
- **Location**: Name of location (could include site / region).
- **xLON**: x coordinate (longitude) in decimal degrees (geodetic datum ETRS 1989) of the specific location where the data are found. As mentioned before, for related faults (table 'Rel_Faults') there are two pairs of coordinates defined (start and end tip).
- **yLAT**: y coordinate (latitude) in decimal degrees (geodetic datum ETRS 1989) of the specific location where the data are found. As mentioned before, for related faults (table 'Rel_Faults') there are two pairs of coordinates defined (start and end tip).
- **Coord_Ref**: Comment field short description of how the coordinates were determined and where they come from (e.g. personal communication, digitized from georeferenced map).

- **References**: A list of relevant references (max. 255 characters) which were used to compile the entry. Each reference is documented with a citekey (e.g. 'Grutzner:2016eg'). In the dissertation (Hürtgen 2017), a table is given where the citykey is listed with the full reference (see Appendix Section 8.3).
- **Comment1/2/3**: These three data fields provide the opportunity to leave some short comments (max. 255 characters) on each entry.

For numerical parameters, a qualification system is adopted from the databases (see Section 1.6) of the SHARE project, Italy (DISS) and Spain (QAFI). This allows the user to qualify each assigned parameter according to the type of analyses that were carried out to determine it. The qualification system consists of the assigned value for one parameter (e.g. 'Dip' in table 'Rel_Faults'), an error (e.g. 'Dip1'), a qualifier (e.g. 'Dip2'), and short reference field (e.g. 'Dip3'). The error field shows either the upper and lower limits of the data estimation, or the numerical error of the data measurement. The qualifiers (qualification keys) are defined as follows (see auxiliary table 'Adm_Status', Section 3.1.9): 'LD' for Literature Data, 'OD' for Original Data, 'ER' for Empirical Relationship, 'AR' for Analytical Relationship and 'EJ' for Expert Judgment. 'LD' is the most used qualifier in PalSeisDB v1.0 due to the literature-based character of the study. The other qualifiers can come into play when an evaluation phase of paleoseismic features will be implemented in the database. The detailed definition of the qualifiers is described as follows:

- **Literature Data** ('LD'): Data taken from studies published in scientific journals, Master or PhD theses, technical reports of research projects or internal reports of major research institutions or universities.
- **Original Data** ('OD'): Unpublished original measurements and interpretations for the purposes of this database.
- **Empirical Relationship** ('ER'): Values derived from empirical relationships such as those of moment magnitude vs. either fault size (Wells and Coppersmith, 1994) or seismic moment (Hanks and Kanamori, 1979; Kanamori and Anderson, 1975).
- **Analytical Relationship** ('AR'): Values derived from simple equations relating the geometric properties of a rectangular fault plane, or equations relating seismic moment with rigidity, fault area and average displacement.
- **Expert Judgment** ('EJ'): Assignments made by the compiler on the basis of tectonic information or established knowledge at a scale broader than that of the seismogenic source under consideration.

The reference field (max. 255 characters) describes the type of observation or empirical relationship used to determine each parameter and the uncertainties involved; bibliographic references related to the parameter are also given.

For all parameters where no data is available the database entry field is left blank. This is applied throughout the whole database. Interconnections between features are realized through relational links between table parameters (see the following Sections for details).

3.1.2. Parametrization of dates and ages in PalSeisDB v1.0

Dating paleoearthquakes is the major, and even a challenging, task in paleoseismic investigations. The quality and reliability of determined age brackets of a geologic feature is strongly influenced by climatic variabilities during and after the formation of the feature and by the occurrence of datable material or structures in or around the feature. Climatic effects cause changes in erosion and deposition, of sea-level, and ice and vegetation cover. These have to be considered in terms of the precision of the determined age. In paleoseismic studies, dating ideally enables the paleoseismologist to determine the age of an event layer directly (datum when the fault was active). In many cases, this is not possible and the age can only be bracketed by dating layers below and above the event horizon.

In consequence, the precision of the determination of dates for individual records of paleoseismic evidence in PalSeisDB v1.0 can vary in a wide range. Five different cases are implemented:

1. minimum and maximum age + error (e.g. '80 ± 3 – 70 ± 2 ka BP')

2. age range without error (e.g. ‘80 – 70 ka BP’)
3. only minimum or maximum age (e.g. ‘< 80 ka BP’, or ‘> 70 ka BP’)
4. age determination by stratigraphic correlations (e.g. ‘Mid Pleistocene’)
5. no entry (if determination of an age is not possible)

These definitions are considered in the age determination for the parametrization of ‘Range/Date’ in tables ‘PSE_SSDs’ (see Section 3.1.4), ‘PSE_MassMov’ (see Section 3.1.5), ‘PSE_others’ (see Section 3.1.6) and ‘Rel_EQs’ (see Section 3.1.7), and for the parametrization of ‘AYDA’ (age of youngest deposits affected by fault) and ‘DLME’ (date of last maximum earthquake) in table ‘Rel_Faults’ (see Section 3.1.8).

3.1.3. Paleoseismic evidence: trenches

A very important tool in paleoseismic studies is the excavation of trenches on capable and active faults. Within the trench walls, all on-fault effects, such as offset of strata and colluvial wedges, can be found. These are relevant to determine the age of seismic rupturing on the fault. As the data from paleoseismic trenches can give the most reliable information on the occurrence of paleoseismic events, a data table for the excavated trenches (‘PSE_Trenches’) is implemented into the database in the study area with some basic information on location, geometry, geological framework, the excavated fault, the record of seismic events and soft-sediment deformation.

In the frame of the PalSeisDB v1.0, a paleoseismic trench can be both any natural outcrop crossing faults (such as a riverbank cut or a cliff) or any artificial excavated outcrop ideally crossing perpendicular or parallel to a fault zone irrespective of any originally planned paleoseismic purpose (e.g. open pit mines incidentally crossing an active fault). From paleoseismic trenching, information on paleoearthquakes and active faults is extracted, if possible, and then input into the corresponding individual data tables (for ‘Rel_EQs’ see Section 3.1.7, and for ‘Rel_Faults’ see Section 3.1.8). The relation between paleoseismic trenches and paleoearthquakes is realized by a linking table called ‘LINK_Tr_EQ’, due to the fact that each trench can document several earthquakes and each earthquake can be possibly found in more than one trench. The linking table associates the earthquake events documented in a trench with the entry of a paleoseismic trench in the database (see Figure 13). A paleoseismic trench can also include other paleoseismic evidence features (soft-sediment deformation, mass movements, and others) that are then documented in the specific data table. The data table should, therefore, mainly be used as an archive for paleoseismic trenches excavated so far, as a reference for future paleoseismic investigations, and also to aid in selecting new trenching sites. No parameters are given here which are directly useful for seismic hazard assessments. Instead, they are given in the other data tables.

Amongst the common parameters described in Section 3.1.1, the following parameters are included into the paleoseismic trench data table (‘PSE_Trenches’):

- **InvYear**: Year of investigation (or year of publication, if not assignable).
- **Investigator**: Name of investigators or institution who were involved in the excavation of the trench.
- **GeomLength**: Numerical value for length of trench in m.
- **GeomWidth**: Numerical value for width of trench in m.
- **GeomDepth**: Numerical value for depth of trench in m.
- **Geology**: Short description of the geological framework (max. 255 characters).
- **RelFault**: Short description of related/excavated fault or tectonic framework (max. 255 characters). Each described fault is documented in detail in the table ‘Rel_Fault’.
- **CCRF_ID**: Key for specific related fault (‘CCRF_ID’) found in trench described in the parameter field to the left (‘RelFault’). This is also the direct link to the table ‘Rel_Faults’ where the detailed parameterization can be found (e.g. ‘DERF001’).
- **RelEQ**: Short description of earthquake evidence or paleoseismic framework (max. 255 characters). Relations between trenches and earthquakes are reached by a link table that associates the evidence with an event.

- **RelSSD**: Short description of soft-sediment deformation features (max. 255 characters). Each described feature is documented in detail in the table 'PSE_SSDs' and re-linked to the trench.

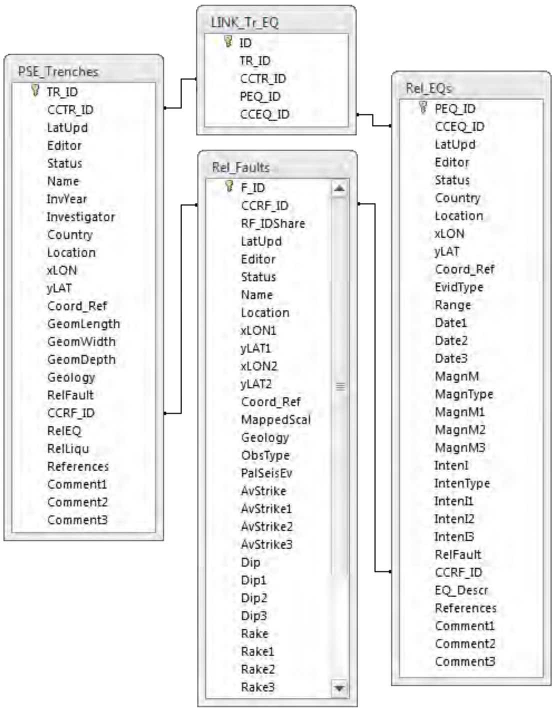


Figure 13. Relational connections in PalSeisDB v1.0 between the elements trenches ('PSE_Trenches'), earthquakes ('Rel_EQs') and faults ('Rel_Faults'). The relation between earthquakes and trenches is realized by an additional table ('LINK_TR_EQs') due to the fact that each trench can document evidence of several earthquakes and records of the same earthquake can be possibly found in more than one trench. The thin black lines indicate by which parameters the tables are linked to each other.

3.1.4. Paleoseismic evidence: soft-sediment deformation

A few seismically induced soft-sediment deformation (SSD) features have, at present, been documented in Central Europe; however, studies in other areas (e.g. CEUS project in Central and Eastern United States) indicate that these are useful when evaluating the seismic hazard potential in areas with low to moderate seismicity. For the documentation of soft-sediment deformation features, parameters mainly based on the CEUS project (Paleoliquefaction Database, see Section 1.6.1) are adopted. In terms of PalSeisDB v1.0, all soft-sediment deformation features are meant to be as features in non-consolidated deposits (such as sand, silt or clay) that were deformed due to seismic shaking. These features can develop close to the seismic source (fault), but they can also occur at a larger distance as secondary earthquake effects (e.g. McCalpin, 2009; Michetti et al., 2007; Obermeier, 1996). If soft-sediment deformation features do not occur directly at faults, it is difficult to find the responsible source for seismic shaking, particularly in terms of paleoseismic investigations. Nevertheless, from the paleoseismic evidence of soft-sediment deformation features in PalSeisDB v1.0, information on paleoearthquakes and, at best, on faults (paleoseismic source) is extracted and then input into the corresponding individual data tables (for 'Rel_EQs' see Section 3.1.7, and for 'Rel_Faults' see Section 3.1.8). The relation between paleoseismic events, sources and soft-sediment deformation features is realized by connecting the tables via the associated IDs of each entry in the database, if possible (see Figure 14).

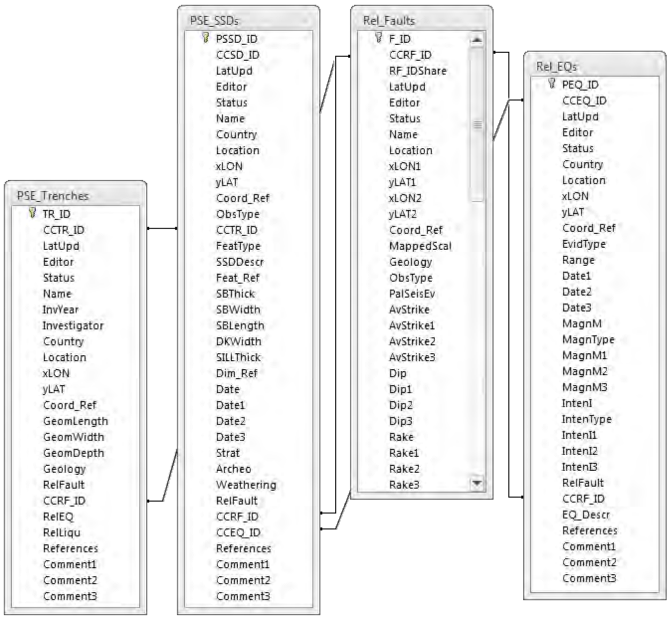


Figure 14. Relational connections in PalSeisDB v1.0 between the elements soft-sediment deformation features ('PSE_SSDs'), trenches ('PSE_Trenches'), earthquakes ('Rel_EQs') and faults ('Rel_Faults'). The relation between the tables is realized via the individual ID of a record in PalSeisDB v1.0. The thin black lines indicate by which parameter the tables are linked to each other.

Amongst the common parameters described in Section 3.1.1, the following parameters are included into the data table of paleoseismic evidence from soft-sediment deformation features ('PSE_SSDs'). The parameters preceded by a hash (#) are individually assigned for the SSD features. The others, not preceded by a hash (#), are also used in the tables for the mass movement features (in table 'PSE_MassMov', see Section 3.1.5) and other paleoseismic evidence features (in table 'PSE_others', see Section 3.1.5).

- **ObsType**: Alphabetic description (max. 255 characters) of observation type (including e.g. riverbank cut, trench, field mapping, test pit, test pit/auger, cave, lake, drilling).
- **CCTR_ID**: Key for a specific trench ('CCTR_ID') with a documented SSD feature defined in table 'PSE_Trenches' (e.g. 'DETR001'). This is also the direct link to the table 'PSE_Trenches', where the detailed description can be found.
- # **FeatType**: Alphabetic description of feature type by a selective field restricted to crater fill, dike, sand blow, sill, and SSD (see CEUS project for detailed description).
- **SSDDescr**: Short description (max. 255 characters) of the paleoseismic evidence feature.
- **Feat_Ref**: Reference for paleoseismic evidence feature.
- # **SBThick**: Sand blow thickness (in cm), see Figure 15 for reference.
- # **SBWidt**h: Sand blow width (in cm), see Figure 15 for reference.
- # **SBLength**: Sand blow length (in cm), see Figure 15 for reference.
- # **DKWidth**: Dike width (in cm), see Figure 15 for reference.
- # **SILLThick**: Sill thickness (in cm), see Figure 15 for reference.
- **Dim_Ref**: Dimension reference (max. 255 characters) with annotations on dimension measurement methods and bibliographic references.
- **Range** (Date): Numeric value from dating with lower and upper boundary (if given) or stratigraphic determination of preferred age estimate (e.g. 15 ka BP / 13 ka BP or Late Pleistocene); + Date1 (uncertainty), Date2 (qualifier key) and Date3 (alphabetic description of reference). The determination of the dating range or age of a paleoseismic feature is described in detail in Section 3.1.2.
- **Strat**: Alphabetic description (max. 255 characters) of qualitative age data from stratigraphic relationships, if any; also includes shorthand reference information.

- **Archeo**: Alphabetic description (max. 255 characters) of archeological age data, if any; also includes shorthand reference information.
- **Weathering**: Alphabetic description (max. 255 characters) of degree of weathering of feature (not weathering of surrounding sediments), if available; also includes shorthand reference information.
- **RelFault**: Name of related fault causing the paleoseismic evidence feature, if applicable. Each named fault is documented in detail in the table 'Rel_Fault'.
- **CCRF_ID**: Key for specific related fault ('CCRF_ID') described in the parameter field to the left (RelFault). This is also the direct link to the table Rel_Faults where the detailed parameterization can be found (e.g. 'DERF001').
- **CCEQ_ID**: Key for specific related earthquake event ('CCEQ_ID') with evidenced paleoseismic feature as defined in table 'Rel_EQs' (e.g. 'DEEQ001'). This is also the direct link to the table 'Rel_EQs', where the detailed parameterization can be found.

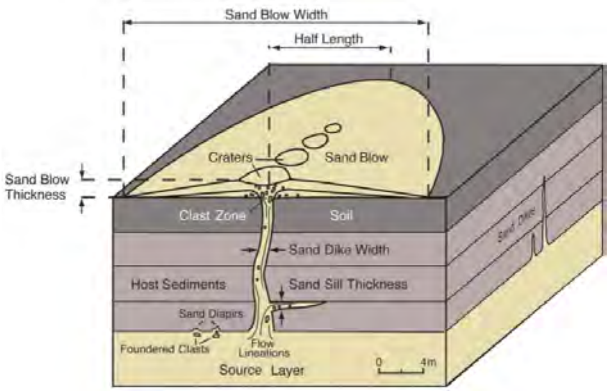


Figure 15. Graphic illustrating the geometric parameters of soft-sediment deformation features including sand blow thickness, width and length, dike width and sill thickness, as well as some of the diagnostic characteristics of these features (Fig. E-2 from Coppersmith et al., 2012, p. E-69). The illustrated features are not only restricted to sands, but they can also, in parts, occur associated with other grain size materials, such as gravels (e.g. gravel venting), silts and clays.

3.1.5. Paleoseismic evidence: mass movements

The documentation of seismically induced mass movement features has, so far, been sparsely distributed in Central Europe, some features have been found and documented in the Battice area in Belgium (Demoulin and Pissart, 2000; Demoulin et al., 2003) and some subaquateous ones in Central Switzerland in lakes (Strasser et al., 2013). In PalSeisDB v1.0, however, these paleoseismic evidence features are implemented because, as stated by Keefer (1984), McCalpin (2009), and Michetti et al. (2007), they can also be used to evaluate the seismic potential in areas with low to moderate seismicity. Nevertheless, it is both difficult to find them and to determine their seismic origin (fault), at least in frame of paleoseismology. They can be used in terms of evaluation of historical reports considering environmental earthquake effects (EEE, see Guerrieri et al. (2007) and (2009)), and even though historical events are not implemented yet in PalSeisDB v1.0, this could be planned as a future task.

The appropriate parameters for mass movement features in terms of seismic evaluation are the type of material involved (soil or rock), type of movement (slide, fall, etc.) and the dimensions (e.g. volume of landslide mass). These are essential to assess the magnitude of landslide triggering events (Keefer, 1984). From the paleoseismic evidence of mass movement features in PalSeisDB v1.0, information on paleoearthquakes and, at best, on faults (paleoseismic source) is extracted and then input into the corresponding individual data tables (for 'Rel_EQs' see Section 3.1.7, and for 'Rel_Faults' see Section 3.1.8). The relation between paleoseismic events, sources and mass movement features is realized by connecting the tables via the associated IDs of each entry in the database, if possible (see Figure 16).

Amongst the common parameters described in Section 3.1.1 and the defined ones in the previous Section 3.1.4 without a preceding hash (#), the following parameters are included into the data table of paleoseismic evidence from mass movement features (‘PSE_MassMov’):

- **FeatType**: Alphabetic description of feature type by a selective field restricted to rock fall, rock slide, rock avalanches, rock slumps, rock block slides, soil falls, disrupted soil slides, soil avalanches, subaqueous landslides, mass movement (modified after classification from Keefer, 1984).
- **PSEDescr_2**/**PSEDescr_3**: Additional fields for short description (max. 255 characters) of mass movement feature.
- **xDim**: Axis length of feature (in cm) in the direction of mass movement.
- **yDim**: Feature dimension (in m) measured perpendicular to the direction of movement.
- **zDim**: Maximum vertical dimension (in m, e.g. height, thickness).
- **ADim**: 2-dimensional (in m^2, mappable area).
- **VDim**: 3-dimensional (in m^3, volume).

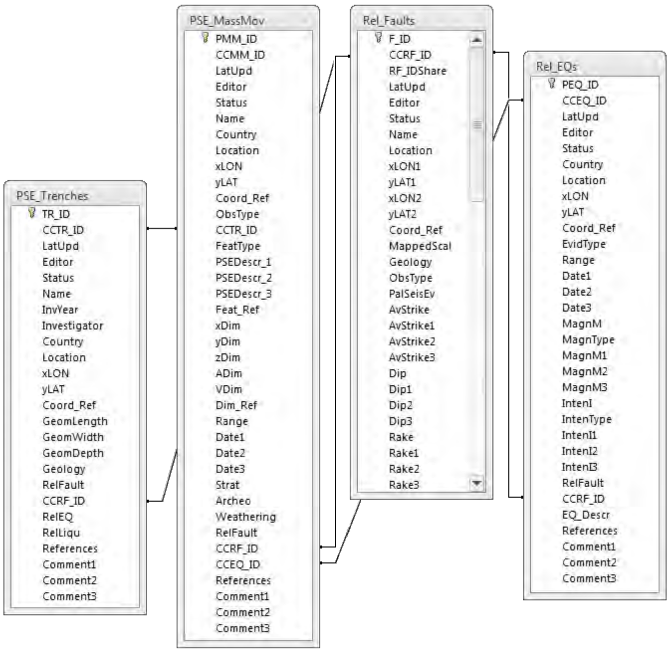


Figure 16. Relational connections in PalSeisDB v1.0 between the elements mass movement features (‘PSE_MassMov’), trenches (‘PSE_Trenches’), earthquakes (‘Rel_EQs’) and faults (‘Rel_Faults’). The relation between the tables is realized via the individual ID of a record in PalSeisDB v1.0. The thin black lines indicate by which parameter the tables are linked to each other.

3.1.6. Paleoseismic evidence: others

This data table (‘PSE_others’) comprises all other paleoseismic evidence features that do not fit into the other three categories. It contains more specialized paleoseismic features, such as investigations on seismically ruptured speleothem structures, and records of layers deposited by tsunamis, amongst others. In future steps, an implementation of archeoseismological records in terms of historical seismicity could also be conceivable. This data table has the most potential to be split into further individual tables with new parameterization concerning the different, aforementioned categories; however, to date there are only a few implemented records that fall into this category.

Information on paleoearthquakes and active faults (paleoseismic source) is extracted from paleoseismic evidence of other features and then input into the corresponding individual data tables (for ‘Rel_EQs’ see Section 3.1.7, and for ‘Rel_Faults’ see Section 3.1.8). The relation between paleoseismic events, sources and other paleoseismic features is realized by connecting the tables via the associated IDs of each entry in the database, if possible (see Figure 17).

Amongst the common parameters described in Section 3.1.1 and the defined ones in the previous Section 3.1.4 without a preceding hash (#), the following parameters are included into the data table of other paleoseismic evidence features (‘PSE_others’):

- **FeatType**: Alphabetic description of feature type by a selective field that includes speleothems, tsunamigenic deposits, archeoseismological evidence, and freely assignable categories.
- **PSEDescr_2/PSEDescr_3**: Additional fields for a short description (max. 255 characters) of other paleoseismic features.
- **xDim**: Feature width/diameter (in cm) in cross section.
- **yDim**: Feature dimension (in cm) measured perpendicular to cross section.
- **zDim**: Vertical dimension (in cm, e.g. height, thickness).
- **ADim**: 2-dimensional (in m^2, mappable area).
- **VDim**: 3-dimensional (in m^3, volume).

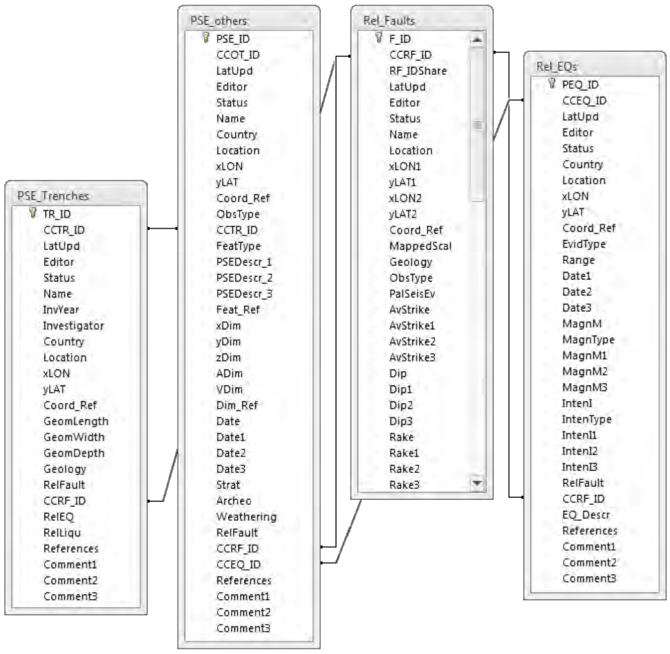


Figure 17. Relational connections in PalSeisDB v1.0 between other paleoseismic evidence features (‘PSE_others’), trenches (‘PSE_Trenches’), earthquakes (‘Rel_EQs’) and faults (‘Rel_Faults’). The relation between the tables is realized via the individual ID of a record in PalSeisDB v1.0. The thin black lines indicate by which parameter the tables are linked to each other.

3.1.7. Related earthquakes

The table ‘Rel_EQs’ is essential when considering the seismic hazard potential of an area. It provides information on the date and the magnitude or intensity of paleoevents. The information on paleoearthquakes is extracted from the studies documenting paleoseismic evidence features described in the previous sections (see Sections 3.1.1 to 3.1.6). Thus, there is always at least one related paleoseismic evidence record for each paleoearthquake documented in the database PalSeisDB v1.0. With all evidence types, it is tried to determine a paleoearthquake. This is possible for most paleoseismic trenches, but limited for soft-sediment deformation, mass movement and other evidence features due to the eventually missing accurate dating or the uncertainty for seismic triggering mechanism. In none of the implemented paleoseismic studies documented in PalSeisDB v1.0, the determination of the paleoearthquakes’ epicenter is possible due to the lack of a sufficient amount of coevally documented, found, or even occurred, paleoseismic records. Ideally, an earthquake event can be directly connected to a specific fault, the seismic source, but in some cases, this can be very difficult and in others it is even not possible. The distribution and development of paleoseismic evidence records can help to quantify the paleoearthquake and to expand the historical and instrumental earthquake catalogs with a broader temporal and spatial distribution of seismic events.

Amongst the common parameters described in Section 3.1.1, the following parameters are included into the data table of related earthquakes ('Rel_EQs'):

- **EvidType**: Method of identification (e.g. paleoseismology, archeoseismology, historical seismology, instrumental seismology).
- **Range** (Date): Numeric value from dating with lower and upper boundary (if given) or stratigraphic determination of preferred age estimate (e.g. 15 ka BP / 13 ka BP or Late Pleistocene). Date is determined by dating methods (e.g. radiocarbon or OSL dating) or stratigraphic relations of evidenced paleoseismic features (e.g. offsets in trenches, soft-sediment deformation, mass movements or others); + Date1 (error/uncertainty), Date2 (qualifier key), and Date3 (alphabetic description of reference). The determination of the dating range or age of a paleoearthquake is described in detail in Section 3.1.2.
- **MagnM**: Maximum magnitude determined from paleoseismic evidence; + MagnM1 (uncertainty), MagnM2 (qualifier key), and MagnM3 (alphabetic description of reference).
- **MagnType**: Alphabetic description of magnitude type by a selective field restricted to MW (moment magnitude), ML (local magnitude), MS (surface magnitude) and n.s. (not specified).
- **IntenI**: Maximum intensity determined from paleoseismic evidence; + IntenI1 (uncertainty), IntenI2 (qualifier key), and IntenI3 (alphabetic description of reference).
- **IntenType**: Alphabetic description of intensity type by a selective field restricted to EMS (European Macro-Seismic scale), ESI (Environmental Seismic Intensity scale), MCS (Mercalli-Cancani-Sieberg scale), MM (Modified Mercalli scale), MSK (Medvedev–Sponheuer–Karnik scale) and n.s. (not specified).
- **RelFault**: Name of related fault causing the paleoearthquake, if applicable. Each named fault is documented in detail in the table 'Rel_Fault'.
- **CCRF_ID**: Key for specific related fault ('CCRF_ID') which is assumed to be the source of earthquake event described in the parameter field to the left ('RelFault'). This is also the direct link to the table 'Rel_Faults' where the detailed parameterization can be found (e.g. 'DERF001').
- **EQ_Descr**: Alphabetic description (max. 255 characters) of the paleoearthquake and bibliographic references for related earthquake.

3.1.8. Related faults

The structure of the data table 'Rel_Faults' describing the active faults is mainly adopted from Italy's Database of Individual Seismic Sources (DISS) and the Quaternary Active Faults Database of Iberia (QAFI) including physical properties such as geometric (length, width, strike, dip), kinematic (rake, stress field), and seismic properties (single-event displacement, maximum magnitude, slip rate, recurrence interval, elapsed time). PalSeisDB v1.0 includes only faults, which are directly associated with paleoseismic evidence. This means each entry of a fault requires at least one record of paleoseismic evidence in one of the tables 'PSE_Trenches', 'PSE_SSDs', 'PSE_MassMov' or 'PSE_others'. From these tables, a direct link to a record of a fault is addressed by the fault ID ('CCRF_ID'). The concept of three different types of seismogenic sources (Individual Seismogenic Sources, Composite Seismogenic Sources, and Debated Seismogenic Sources) from the DISS project is for now not implemented in PalSeisDB v1.0. This could be an implemented future step for a better understanding of uncertainties on active faults. Information on active faults (paleoseismic source) is extracted from the paleoseismic evidence features in the database and from literature about specific fault-related studies. This information is then input into the corresponding individual data table ('Rel_Faults') with specifications on the quality of the provided data. For the parameterization of faults, data from several other databases is incorporated into PalSeisDB v1.0. Thus, PalSeisDB v1.0 incorporates data from SHARE, DISS and BDFA (see Section 1.6).

The geographical definition of fault traces follows the right-hand rule (c.f Aki and Richards, 1980). Figure 18 illustrates the adopted conventions on fault location and sense of movement. In PalSeisDB v1.0, only point data is saved for the faults (start and end point of fault trace), but the geographical information and the parameterized data set is linked through an ESRI shapefile.

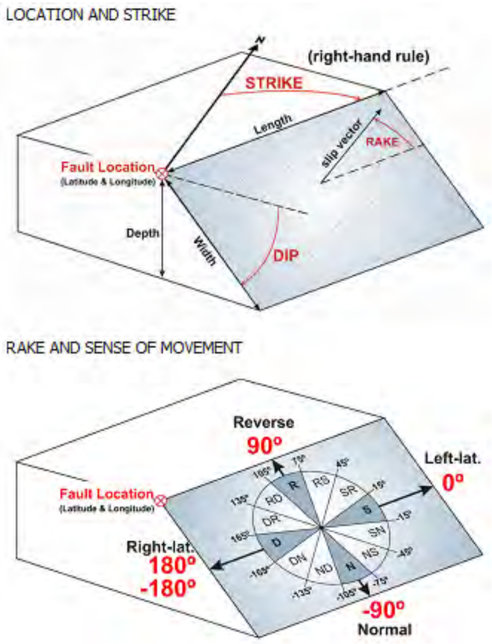


Figure 18. Illustration of the conventions on fault location and sense of movement in PalSeisDB v1.0 (adopted from Aki and Richards, 1980).

Amongst the common parameters described in Section 3.1.1, the following parameters are included into the data table of related faults ('**Rel_Faults**'):

- **RF_IDShare**: Manually assigned 7-character ID for each entry (e.g. 'DECS001') from the ID in the SHARE database, if the specific fault is also included in the SHARE database, otherwise the field is left blank.
- **MappedScal**: a thousand of the Scale as in which the feature was digitized in the GIS environment (e.g. for a scale of 1:25,000, a value of 25 would be set).
- **xLON1/2**: x coordinate (longitude) in decimal degrees (geodetic datum ETRS 1989) of the start and end point of the fault trace.
- **yLAT1/2**: y coordinate (latitude) in decimal degrees (geodetic datum ETRS 1989) of the start and end point of the fault trace.
- **Geology**: Larger geological unit (e.g. North Sea, Lower Rhine Graben, etc.) or short description of geological framework (max. 255 characters).
- **ObsType**: Observation type (e.g. field mapping, paleoseismic trench, geophysics, etc.)
- **PalSeisEv**: A true/false field determining whether paleoseismic evidence is found or not at the particular fault. At this stage, only faults with related paleoseismic evidence are included; however, in a future step, faults without any records of paleoseismology will also be considered.
- **AvStrike**: Average strike in degrees.
- **Dip**: Dip in degrees.
- **Rake**: Rake in degrees.
- **SenseOfMov**: Sense of movement. Possible entries: 'R' (Reverse), 'N' (Normal), 'D' (Dextral), 'S' (Sinistral), a combination of two ('DN', 'ND', 'NS', 'SN', 'SR', 'RS', 'RD', 'DR'), 'ANT' (Anticline) and 'SYN' (Syncline).
- Length: Length of fault trace in km.
- **DepthMin**: Minimum depth in km.
- **DepthMax**: Maximum depth in km.
- **Width**: Width in km.
- **Area**: Area in sq-km.
- **AYDA**: Age of youngest deposits affected by fault ('AYDA', e.g. Quaternary, Lower-Middle Pleistocene, 80-100 ka, etc.).
- **SlipVert**: Vertical slip rate in m/ka (VSR).

- **SlipHoriz**: Horizontal slip rate in m/ka (HSR).
- **SlipNet**: Net slip rate in m/ka (NSR).
- **SlipMaxPerEv**: Maximum slip per event in m.
- **NumSeism**: Number of seismic events (in PalSeisDB v1.0, only the number of paleoseismic events are recorded).
- **EAC**: Evidence of Aseismic Creep (EAC).
- **MaxMagn**: Maximum magnitude (Mw).
- **Recurr**: Recurrence interval in years.
- **DLME**: Date of last maximum earthquake (DLME).
- **Geomorph**: short description (max. 255 characters) of geomorphic evidence (e.g. straight mountain front, clear topographic lineament in remote sensing and DEMs, colluvial wedges, paleosols, channel offset, drainage pattern, triangular facets, etc.).
- **RelEQ**: Short description (max. 255 characters) of earthquake evidence (paleoseismic framework).
- **RelSSD**: Short description (max. 255 characters) of observed soft-sediment deformation features.

3.1.9. Auxiliary tables

Some auxiliary tables are included in PalSeisDB v1.0. They provide additional or supporting information in terms of the database architecture or on content-related issues. The tables 'Adm_Countries', 'Adm_DataQualifier's (see Section 3.1.1), and 'Adm_Status' include basic information and administrative support on maintaining the database. The table 'Adm_Countries' contains a list of countries, which are relevant for the project. These are the countries achieving the criteria located within a 300 km radius around the German border. The table 'Adm_Status' comprises a list of different statuses that helps the editor to input data and to get organized when compiling several records at once. Additionally, it will help in the future when more than one editor is working with the database. Each record of the data tables gets a parameter containing the status ('no status', 'to do', 'first draft', 'revised draft', 'final draft', or 'done'). The table 'Adm_Editors' provides a list of editors who were involved in composing a record in the database. Besides the tables helping to compile and organize data input, there is another table called 'LOCATION'. This table summarizes all sites, where records of paleoseismic evidence features have been found and incorporated in terms of PalSeisDB v1.0.

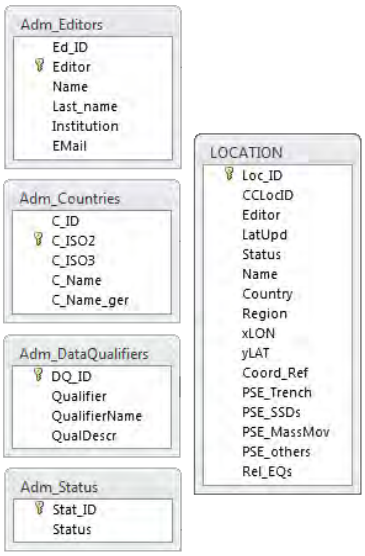


Figure 19. List of auxiliary tables that are used to record secondary information and to support administrative maintaining of PalSeisDB v1.0.

In Figure 19, the parameters of the auxiliary tables are presented. See below for a full list of parameters with a short description of each one.

‘**Adm_Countries**’

- **C_ID**: Automatically assigned country's ID for each entry.
- **C_ISO2**: ISO-Code 3166 for country (2-characters).
- **C_ISO3**: ISO-Code 3166 for country (3-characters).
- **C_Name**: Full name of country (English).
- **C_Name_ger**: Full name of country (German).

‘**Adm_DataQualifiers**’

- **DQ_ID**: Automatically assigned data qualifier's ID for each entry.
- **Qualifier**: 2-character qualifier.
- **QualifierName**: Qualifier's name.
- **QualDescr**: Short description of qualifier.

‘**Adm_Status**’

- **Stat_ID**: Manually assigned status' ID for each entry (0-5).
- **Status**: Name of the status.

‘**Adm_Editors**’

- **Ed_ID**: Automatically assigned editor's ID for each entry.
- **Editor**: Editor's initials.
- **Name**: Name of editor.
- **Last_Name**: Last name of editor.
- **Institution**: Institution of editor.
- **Email**: Editor's email-address.

‘**LOCATION**’

- **Loc_ID**: Automatically assigned location's ID for each entry.
- **CCLocID**: An individually, manually assigned identifier is defined based on an alphanumeric 7-character code with the format CCLC### (adapted from the DISS and SHARE databases). With CC: two-character ISO 3166-1 code for the name of the country where data is found; LC: abbreviation for location; ###: an ordinal between 1 and 999 including leading zeroes. For example, the code for a location in Germany could be: ‘DELC008’.
- **Editor**: Editor's initials.
- **LatUpd**: Latest update of entry.
- **Status**: Status of the entry (with selective elements from table ‘Adm_Status’).
- **Name**: Short name of location/site.
- **Country**: ISO-Code 3166 for country (2-characters)
- **Region**: Short name of region.
- **xLON**: x coordinate (longitude) in decimal degrees.
- **yLAT**: y coordinate (latitude) in decimal degrees.
- **Coord_Ref**: Reference and/or method of coordinate determination.
- **PSE_Trench**: Determines whether there is any paleoseismic evidence (trenches) found at this location.
- **PSE_SSDs**: Determines whether there is any paleoseismic evidence (seismic-induced soft-sediment deformation features) found at this location.
- **PSE_MassMov**: Determines whether there is any paleoseismic evidence (seismic-induced mass movements) found at this location.

- **PSE_others**: Determines whether there is any paleoseismic evidence (others, e.g. speleothems) found at this location.
- **Rel_EQs**: Determines whether there is any evidence for paleoearthquakes found at this location.

3.2. GIS-based environment

Even though the main development of PalSeisDB v1.0 has been evolved in a Microsoft Access 2010 environment, it was mandatory to use also a geographic-supported system as spatial distributed data is used in the database records. For that reason, the map-based environment is a supporting tool to be used during compilation of data records, and also during the evaluation of data in terms of spatial analyses, such as seismic hazard assessments. All information is organized as GIS and Google Earth layers (see Section 2.5 for a detailed list of provided files) that enables the user to explore all data types at different scales and to perform spatial and statistical computations. Data from the tables 'PSE_Trenches', 'PSE_SSDs', 'PSE_MassMov', 'PSE_Others', 'Rel_EQs' are provided as point features, whereas the data from table 'Rel_Faults' is provided as polyline feature in the GIS and Google Earth environment. Section 2.5 describes how to make the included data visible. ArcGIS and other GIS environments provide the possibility to view attribute tables of shapefiles. This corresponds to a similar view of data tables in PalSeisDB v1.0 as presented in Microsoft Access environment. The Figure 20 and Figure 21 show the view of the data from PalSeisDB v1.0 in the Google Earth and the ESRI ArcGIS environment.

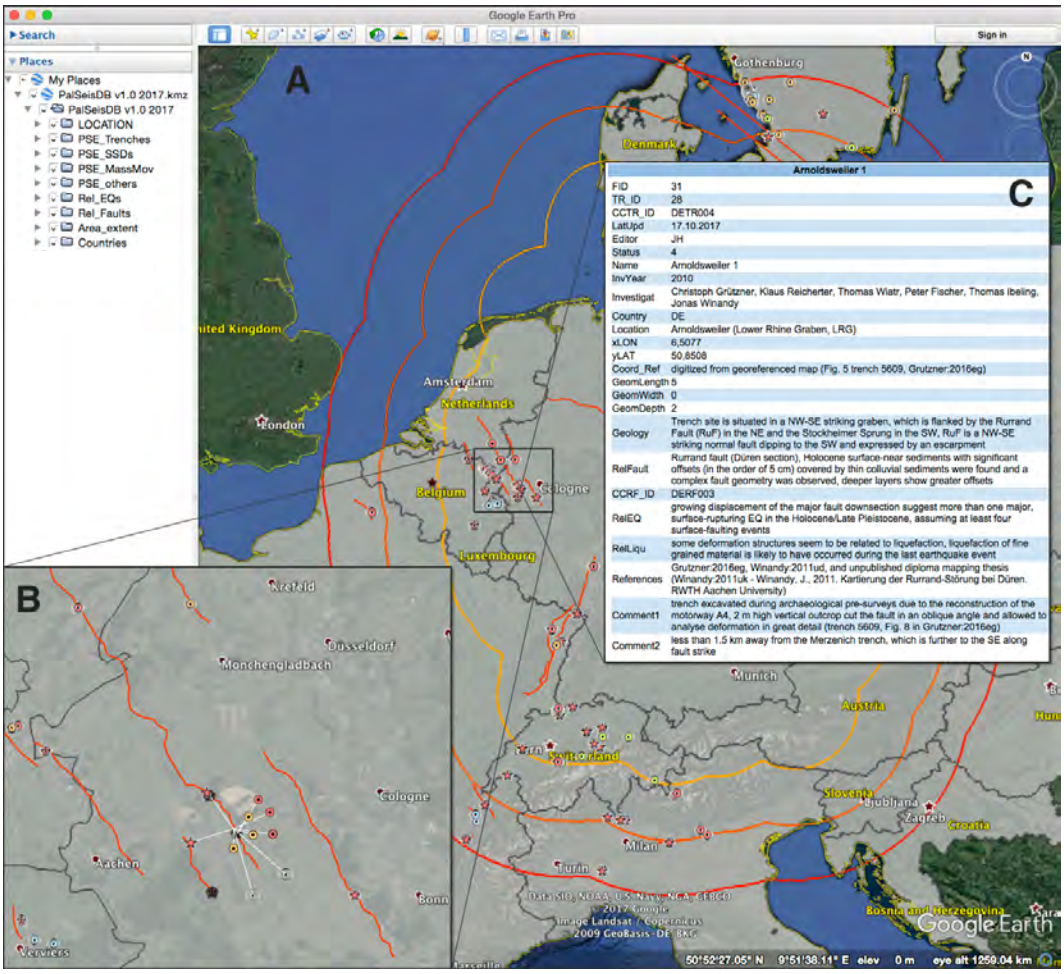


Figure 20. A: The view of PalSeisDB v1.0 in the Google Earth environment. Each data point is selectable and provides further information on the parameterization of each paleoseismic feature (evidence, source, and event). B: Area of the Lower Rhine Graben with expanded data points for a trench study at the Rurrand fault ('Arnoldsweiler 1', 'DETR004'). C: Detailed information from the record of the paleoseismic trench 'Arnoldsweiler 1' ('DETR004').

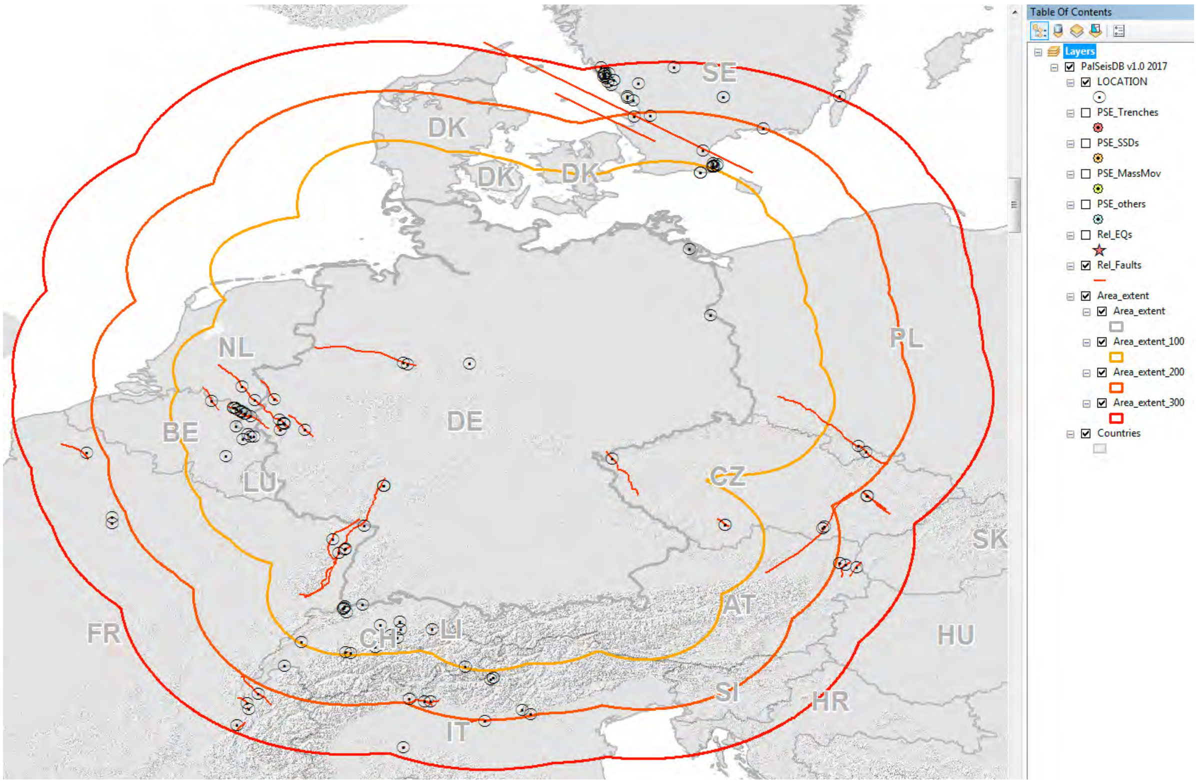


Figure 21. The view of Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) in the ESRI ArcGIS environment. Each data point is selectable and provides information on the parameterization of each paleoseismic feature (evidence, source, and event). Background with topographic imprint (hillshade of SRTM 90-m-data).

4. Results

The compilation of PalSeisDB v1.0 shows that paleoseismic evidence features have been documented at 129 different locations unequally distributed in the area of Germany and adjacent regions (see Figure 22 and Table 2). Of these, 17 locations are from investigations in Germany. Further paleoseismic evidence features have been found at a number of locations in the PalSeisDB-relevant regions of Austria (4), Belgium (14), Czech Republic (9), France (12), Italy (10), Netherlands (4), Poland (1) Switzerland (20), and Sweden (38). In total, 105 paleoearthquakes have been determined (see Figure 24), mostly from paleoseismic trench studies, but also from other paleoseismic studies regarding soft-sediment deformation and mass movement features, as well as other paleoseismic evidence features (e.g. tsunamigenic deposits, broken speleothems, etc.). Evidence for most of the paleoearthquakes (a number of 94 events) has been dated within a time period between 25,000 years BP and historical times. The oldest earthquakes even date back to a time period between Eemian and Mid-Pleistocene times. 71 paleoearthquakes have values of magnitudes higher than MW 5.5 and 43 earthquakes higher than MW 6.5. The other paleoearthquakes document events with magnitudes higher than 5.0. This is meant as the lowest threshold to produce and preserve paleoseismic evidence features. The magnitudes have been mostly determined by relationships between magnitudes and rupture length or surface displacement (Wells and Coppersmith, 1994).

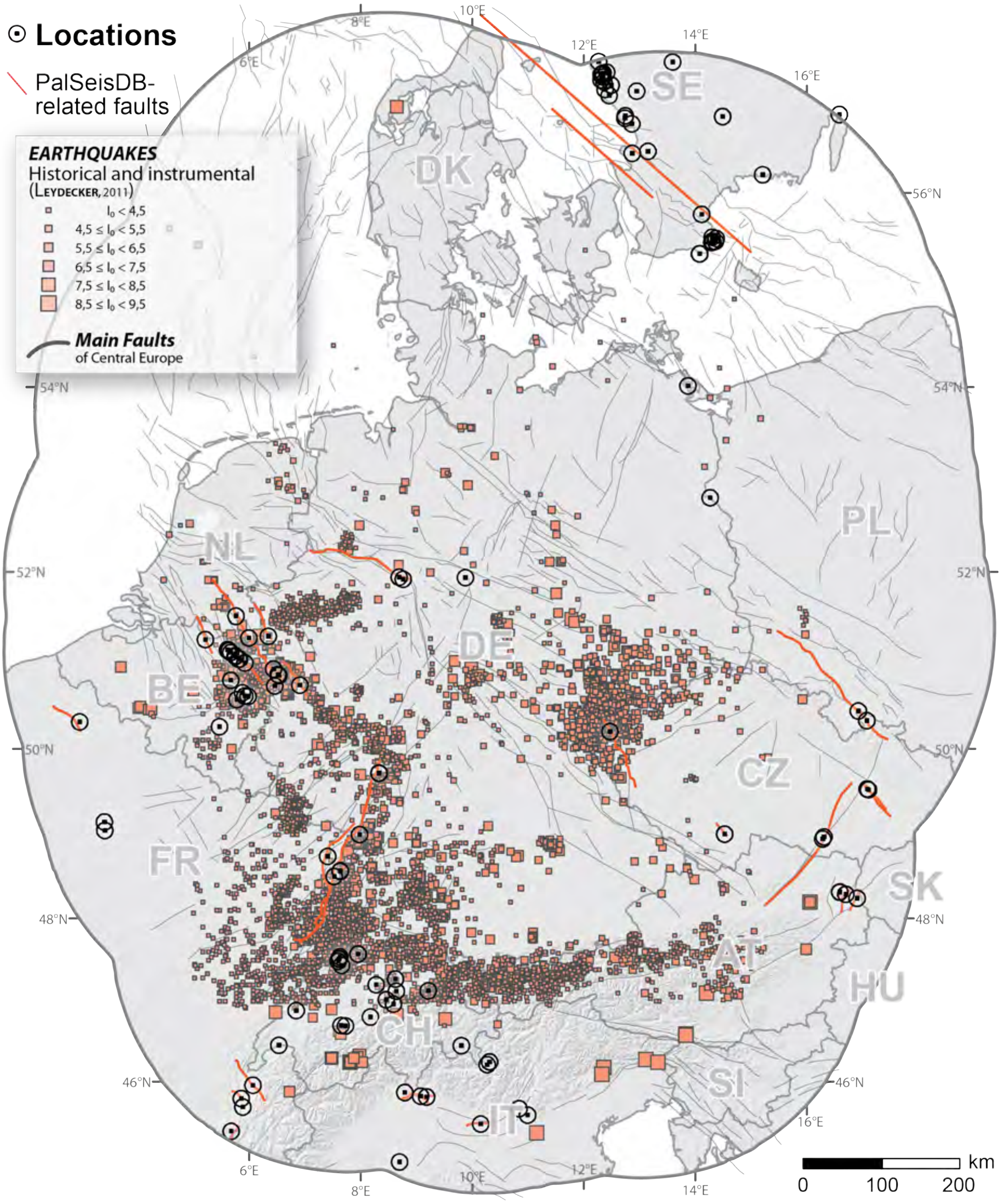


Figure 22. Comprised overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including 129 locations of documented paleoseismic features (black dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, fault traces of the main structural framework of Central Europe (thin gray lines) are shown as described in caption of **Figure 3** combined with topographic imprint (hillshade of SRTM 90-m-data). Classified red squares represent historical and instrumental documented earthquake data from Leydecker (2011).

Paleoseismic data from 62 trenching studies have been documented and implemented in PalSeisDB v1.0 (see Figure 25). These give the most reliable information on the determination of seismic rupturing on a fault and on the occurrence of paleoseismic events. The areas with the most paleoseismic trenches are the Lower and Upper Rhine Graben systems. In Germany, 12 trenches have been excavated until today which provide detailed information of the displacement rates of the investigated fault systems and the related paleoseismic events.

Furthermore, 116 seismically induced soft-sediment deformation features (see Figure 26), 61 mass movement features (see Figure 27), and 21 other paleoseismic evidence features (see Figure 28) have been documented. These features have been found in both natural and human-made outcrops. They provide only an indirect evidence for seismic activity in geological times. They are defined as secondary or off-fault effects that could also be observed in distance to the seismogenic source. As result, a seismogenic source could not be determined for each paleoseismic evidence feature. But in total, 36 faults are related to paleoseismic evidence and have been parameterized in PalSeisDB v1.0. The parameterization is not completely done due to a knowledge gap about the faults' seismic characteristics.

Table 2. Number of records documented in PalSeisDB v1.0 for LC ('LOCATION'), TR ('PSE_Trenches'), SD ('PSE_SSDs'), MM ('PSE_MassMov'), OT ('PSE_others'), EQ ('Rel_EQ) sorted by country (CC, AT Austria, BE Belgium, CH Switzerland, CZ Czech Republic, DE Germany, FR France, IT Italy, NL The Netherlands, PL Poland, SE Sweden) and sum.

CC	LC	TR	SD	MM	OT	EQ
AT	4	4	0	0	0	1
BE	14	8	9	13	4	13
CH	20	7	18	34	0	34
CZ	9	9	0	0	0	5
DE	17	12	32	1	0	16
FR	12	7	4	0	2	5
IT	10	11	9	0	2	10
NL	4	4	5	0	0	4
PL	1	0	6	0	0	1
SE	38	0	33	13	13	16
Sum	129	62	116	61	21	105

The definition of so-called seismotectonic regions or zones to seismotectonically characterize a specific region have been discussed in Section 1.5. For the study of PalSeisDB v1.0, we can assign each record of the database, that is paleoseismic evidence, to one specific zone relying on the model provided by Leydecker (2011), which is based on considerations of Leydecker and Aichele (1998). The zonation scheme of Leydecker (2011) does not cover the entire study area of PalSeisDB v1.0. Subsequently, several records (strictly speaking, a number of 29 locations with documented paleoseismic evidence) are located outside of the model. Herein, paleoseismic records are only documented in 24 of a total number of 89 regions (see Table 3). All other zones (65) lack on published documented paleoseismic evidence. Especially, as already mentioned in Sections 1.4.1 and 1.4.2, the Rhine Graben system has been strongly investigated in terms of paleoseismology and, thus, paleoseismic evidence has been found at 19 different locations in the zone of the Lower Rhine Area (NB) and at 12 different locations in the zone of the Middle and Southern Upper Rhine Graben (SR).

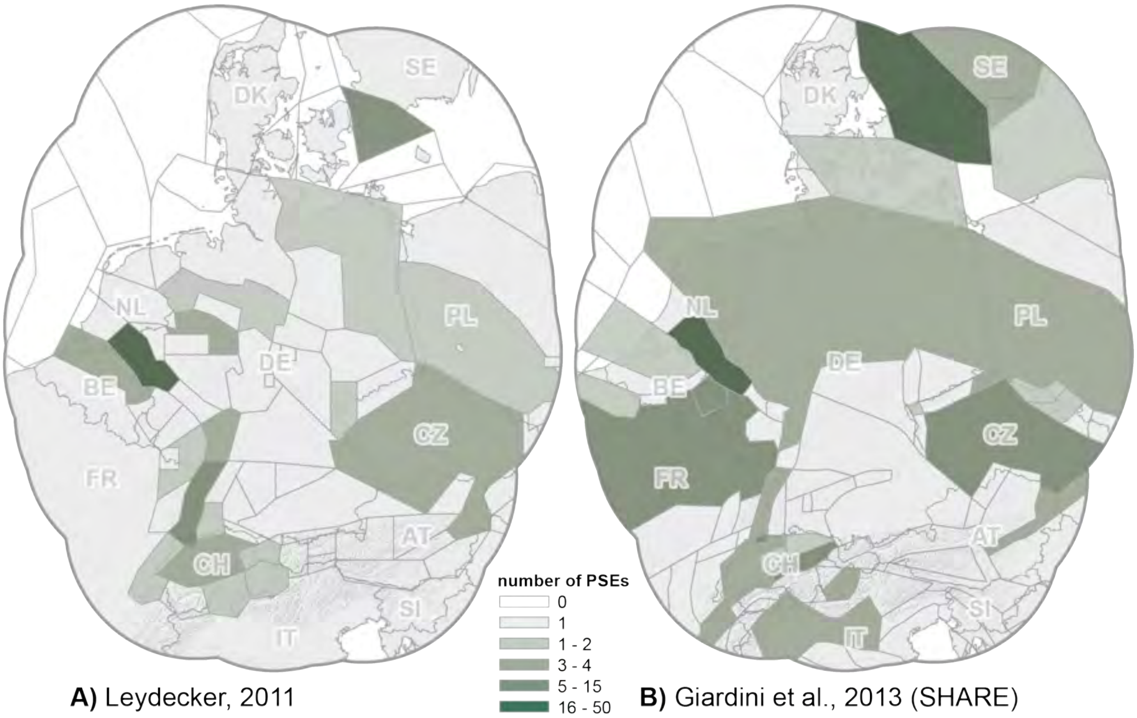


Figure 23. Maps of different seismotectonic zonation schemes after Leydecker (2011) and Giardini et al. (2013, SHARE model). Both models include a color scheme for the distribution of the amount of locations where records of paleoseismic evidence have been found from PalSeisDB v1.0 in each seismotectonic zone. PSEs: PaleoSeismic Evidence features.

Table 3. List of seismotectonic zones after Leydecker (2011) with locations of recorded paleoseismic evidence (PSE) in PalSeisDB v1.0. Abb.: Abbreviation of the English name of seismotectonic zones.

Abb.	English name of seismotectonic zones	Nr. of PSEs
BR	Brabant Massif	2
CM	Central Bohemian Massif	4
CC	Central Switzerland	4
EH	Eastern Part of West European Platform	1
SF	Eastern Swiss Alpine Foreland	2
EA	Eastern Swiss Alps	1
NB	Lower Rhine Area (Roer Valley Graben)	19
MH	Malmoehus	11
SR	Middle and Southern Upper Rhine Graben	12
MU	Muensterland	2
ND	Northeastern Germany	1
NR	Northern Upper Rhine Graben	4
PS	Pfalz-Saar Area	1
SW	Southern Black Forest	1
SB	Southern Bohemian Massif	2
SX	Southern Lower Saxony	1
GV	St. Gall - Vorarlberg	1
SU	The Sudeten	2
TC	Ticino	1
VE	Venn Area	4
VB	Vienna Basin	4
VG	Vogtland Region	1
WJ	Western Jura	1
-	Outside of Seismotectonic Regions	29

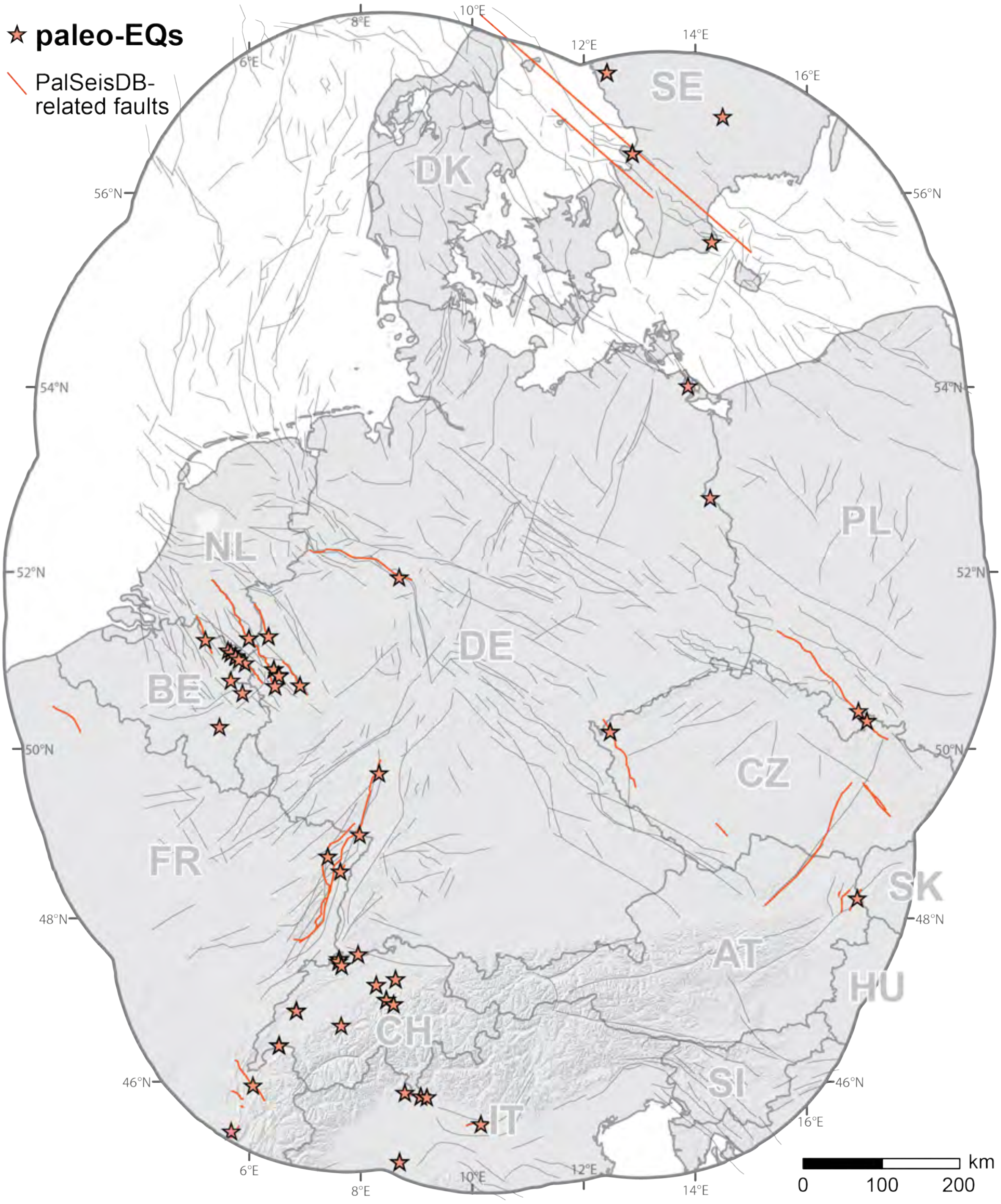


Figure 24. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 105 documented paleoearthquakes (red stars) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, country borders (thick gray lines) and fault traces of the main structural framework of Central Europe (thin gray lines) are shown as described in caption of Figure 3 combined with topographic imprint (hillshade of SRTM 90-m-data). Coordinate System: WGS 1984 World Mercator.

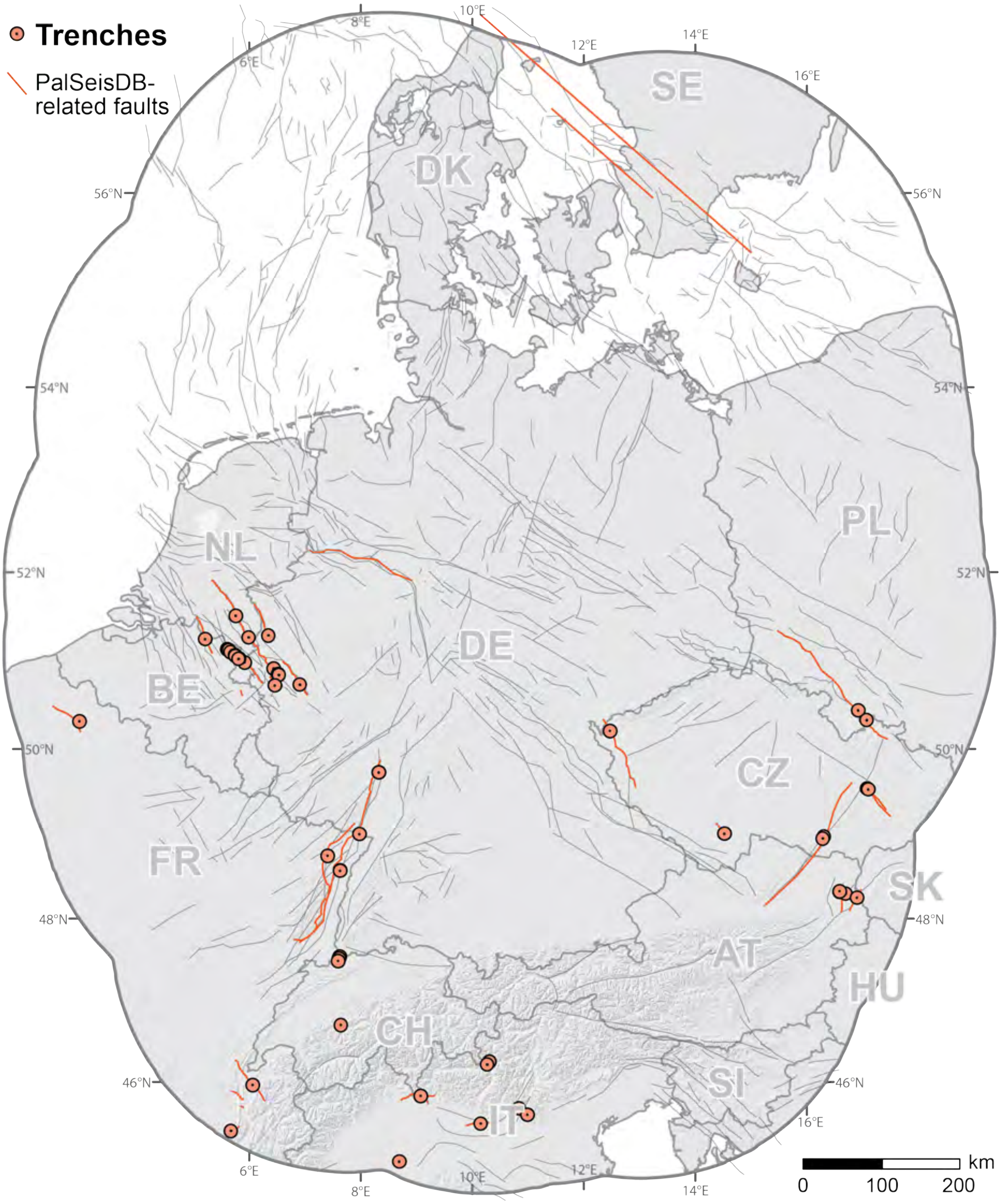


Figure 25. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 62 documented paleoseismic trenches (red dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, country borders (thick gray lines) and fault traces of the main structural framework of Central Europe (thin gray lines) are as described in caption of Figure 3 shown combined with topographic imprint (hillshade of SRTM 90-m-data). Coordinate System: WGS 1984 World Mercator.

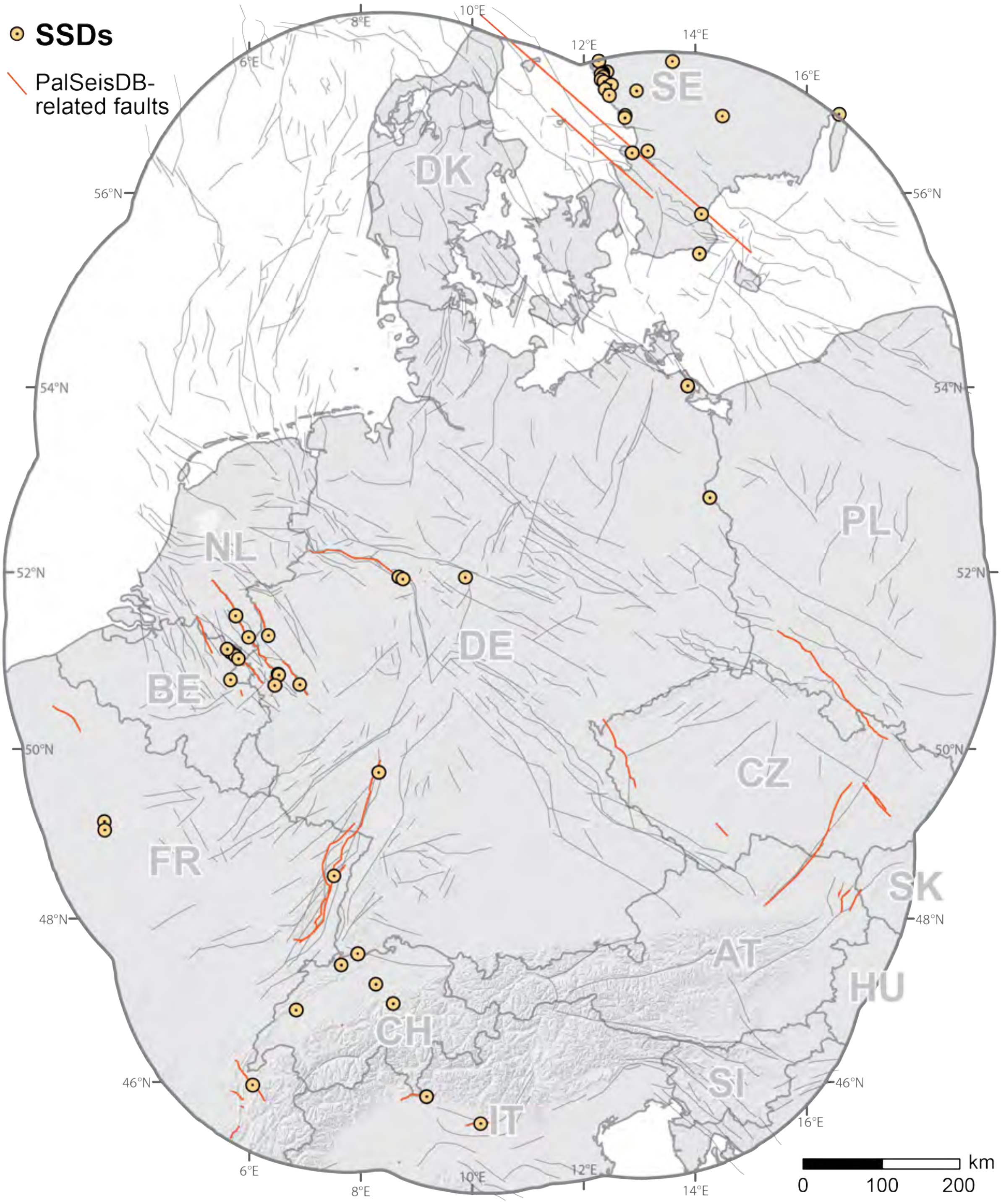


Figure 26. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 116 documented paleoseismic soft-sediment-deformation features (yellow dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, country borders (thick gray lines) and fault traces of the main structural framework of Central Europe (thin gray lines) are shown as described in caption of Figure 3 combined with topographic imprint (hillshade of SRTM 90-m-data). Coordinate System: WGS 1984 World Mercator.

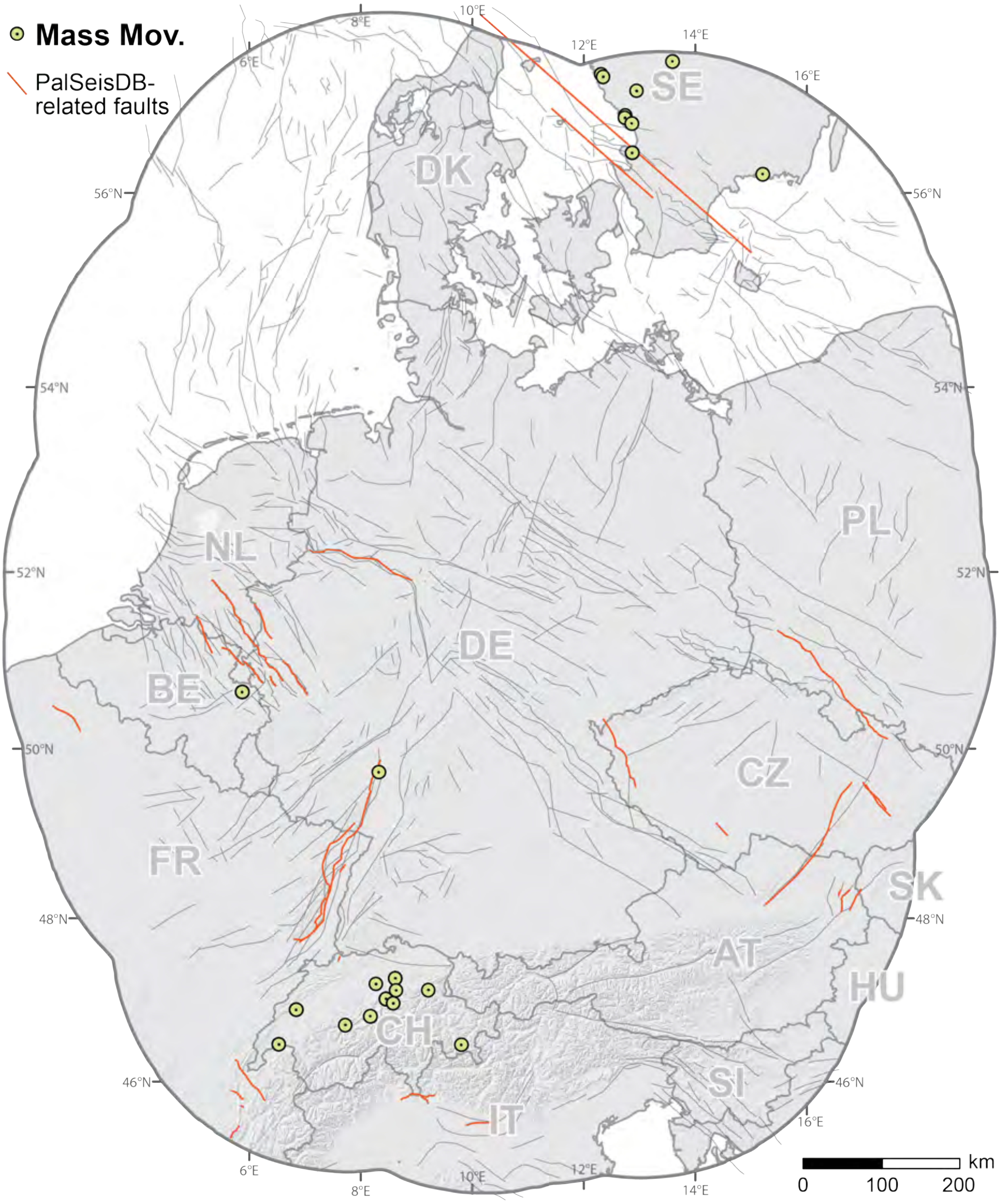


Figure 27. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 61 documented paleoseismic mass movement features (green dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, country borders (thick gray lines) and fault traces of the main structural framework of Central Europe (thin gray lines) are shown as described in caption of Figure 3 combined with topographic imprint (hillshade of SRTM 90-m-data). Coordinate System: WGS 1984 World Mercator.

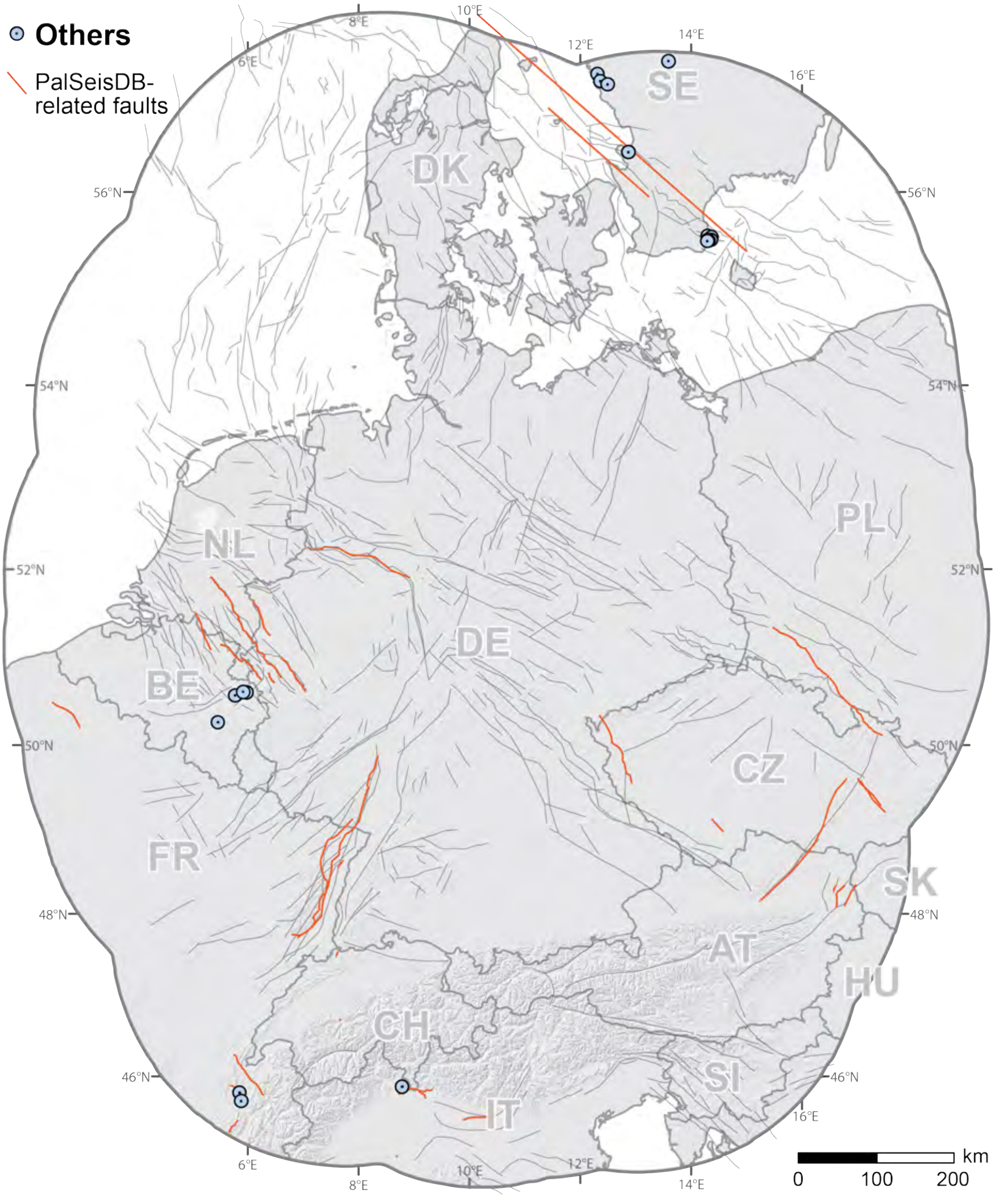


Figure 28. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 21 other documented paleoseismic evidence features (blue dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, country borders (thick gray lines) and fault traces of the main structural framework of Central Europe (thin gray lines) are shown as described in caption of Figure 3 combined with topographic imprint (hillshade of SRTM 90-m-data). Coordinate System: WGS 1984 World Mercator.

5. Future steps of PalSeisDB v1.0

The PalSeisDB project began with no previous work having been undertaken by other parties. Other paleoseismic databases exist throughout the world; however, in Germany and the adjacent regions, nothing regarding the systematic collection of paleoseismic evidence had been carried out. The tasks involved in the production of the database have included the development of a structural framework, the definition of relevant parameters, the collection of relevant literature and the compilation of records in terms of paleoseismic findings for new standards in seismic hazard assessment. During the expansion and finalization of the first version of the 'Paleoseismic Database of Germany and Adjacent Regions' (PalSeisDB v1.0, 2017), some ideas for improvements were developed. These can be implemented as part of future versions of the database. The following steps would be possible:

- The potential to search by different queries within the database is realized in a basic way. A variety of queries will help the user to find relevant information very quick, such as searches by location, fault, or earthquake directly in the Microsoft Access environment.
- An error field for locations could be added to enforce the uncertainty in seismic hazard assessments. At this stage, the uncertainties on the location are included in the comments of the location.
- Paleoseismic studies provide a huge variety of age determinations of paleoseismic events, e.g. from stratigraphy or different dating methods. In the database, this variety of age determinations makes the temporal comparison of documented events difficult. A standardizations scheme of ages should be encountered for a better comparison in the future.
- To add supplementary material to each record (such as figures from literature, maps, references, etc.) would allow better visualization and understanding and be hugely advantageous.
- The presented data table 'PSE_others' (see Section 3.1.6) could be split in several sub-tables regarding the provided categories (e.g. speleothems' findings and tsunamigenic deposits).
- Using mainly trench data, information on displaced strata along faults could be derived. This displacement data could be recorded in a separate table.
- By extending the dataset to faults that have been active through neotectonic or recent times, an active faults database, such as in other countries, could be created. To date this compilation of data is missing in Germany and also in most of the surrounding countries.
- A reevaluation of historical seismic events in terms of environmental earthquake effects (EEE, see Guerrieri et al. (2007) and (2009)) could provide a broader view on the spatial and temporal distribution of seismicity in Central Europe.
- The public release of PalSeisDB v1.0 as a web-hosted map could be interesting for a variety of professional groups (such as scientists, administrators, technicians, or insurers).
- In this frame, it is also possible to provide a web-based input form for compiling new data from a co-working platform for paleoseismologists and regional experts in active tectonics.

These points are only ideas for how PalSeisDB v1.0 will evolve in the future and how to keep it up-to-date. PalSeisDB v1.0 will be a project under constant revision and updating as a consequence of the advances in the knowledge about paleoseismic records of paleoearthquakes and seismogenic sources that can generate these.

6. Final remarks

The paleoseismic record in Central Europe is relatively sparsely distributed. The area with the most available paleoseismic evidence is the Lower Rhine Graben (LRG), which has been intensively investigated by paleoseismologists over the last two decades (e.g. Camelbeeck et al., 2007; Grützner et al., 2016; Kübler et al., 2017a; Skupin et al., 2008; Vanneste et al., 2013). Nevertheless, in this area a limited number of trenches (17) in relation to the number of active faults have been excavated. The most well-investigated fault is the Feldbiss fault zone, which builds up the south-eastern border of the LRG. Distributed on its segments, it comprises nine paleoseismic trenches. The other eight trenches are distributed across other individual fault segments in the LRG (e.g. Viersen fault, Rurrand fault, Swist fault, Peelrand fault). In the Upper Rhine Graben (URG), 14 paleoseismic trench investigations have been undertaken, e.g. at the Western Border fault in the vicinity of Osthofen (Peters et al., 2005) and at the Basel-Reinach fault south of Basel (Ferry et al., 2005; Meghraoui et al., 2001). Amongst others, further trenches have been carried out in France (e.g. Baize et al., 2002; 2011), in Czech Republic (e.g. Spaček et al., 2017; Stepančíková et al., 2015), in Northern Italy (e.g. Livio et al., 2013; Frigerio et al., 2017), and in the Vienna Basin (e.g. Hintersberger et al., 2013; Weissl et al., 2017). From these studies, paleoearthquakes have been identified and incorporated in PalSeisDB v1.0. Furthermore, paleoseismic evidence features were also documented from several sites, for example soft-sediment deformation features in Germany (e.g. Brandes and Winsemann, 2013; Hoffmann and Reicherter, 2011), Poland (e.g. Van Loon & Pisarska-Jamroży, 2014), in Northern Italy (e.g. Chunga et al., 2007), in Switzerland (e.g. Becker et al., 2005; Monecke et al., 2006; Reusch et al., 2016), in Belgium (e.g. Vanneste et al., 1999; Demoulin, 1996), and widely present in Sweden (e.g. Mörner, 2005; Mörner, 2014). Seismically triggered mass movement and other paleoseismic features are only documented in Belgium (e.g. Demoulin et al., 2003), Switzerland (e.g. Strasser et al., 2013; Kremer et al., 2017), Sweden (e.g. Mörner, 2009), and Italy (e.g. Bini et al., 1992). In conclusion, several studies have searched for paleoseismic evidence in Central Europe, mainly on a national basis. These studies can help determine paleoearthquakes, but there is definitely more research needed to understand the seismic cycle of these active faults and to assess their seismic hazard. The records of paleoseismic features are only sparsely spatial distributed in Central Europe. Especially, the missing record of a sufficient amount of paleoseismic studies characterizing potential active faults as seismogenic sources of significant earthquake events is a problem and reflects the missing parameterization of related faults in PalSeisDB v1.0.

The Paleoseismic Database of Germany and Adjacent Regions in its current version PalSeisDB v1.0 comprises all paleoseismic work that has been undertaken and published until December 2017. Figure 22 provides an overview of the locations where paleoseismic evidence features have been documented in terms of the current version of PalSeisDB v1.0. White areas, where paleoseismic data and historical and instrumental seismicity is missing, should not be taken as sign of absence of active tectonics, merely as sign of lack of field investigations. Therefore, these areas have great potential as trenching or investigation sites for future paleoseismic studies. Moreover, the included collection of paleoearthquakes in PalSeisDB v1.0 could be used to extend recent historical and instrumental earthquake catalogs.

The project was also meant to develop a new framework for systematic documentation of the aforementioned records of paleoseismic evidence and related features. Such a project should also be seen as an ongoing work that is continuously updated with regard to new investigations or reinterpretation of previous studies due to progress and evolution in geological knowledge and technical improvements.

Acknowledgements

This work has been supported by the BGR (Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany) - Commission from 16th of May 2012 (Best. Nr. 212-450007223382).

We would like to thank all the scientific experts in paleoseismology - Stéphane Baize, Marc Cushing, Kurt Decker, Matthieu Ferry, Gottfried Grünthal, Christoph Grützner, Luca Guerrieri, Esther Hintersberger, Gösta Hoffmann, Luca Guerrieri, Hervé Jomard, Simon Kübler, Klaus Lehmann, Günter Leydecker, Franz Livio, James P. McCalpin, Mustapha Meghraoui, Alessandro M. Michetti, Nils-Axel Mörner, Luigi Palumbo, Małgorzata (Gosia) Pisarska-Jamroży, Martin Salamon, Pablo Silva, Petr Spaček, Petra Stepančíková, Michael Strasser, Roland van Balen, A.J. (Tom) Van Loon, Kris Vanneste, Koen Verbeeck, and many more - who supported this project with their knowledge, advice and their 'data' to develop and fill PalSeisDB v1.0 with records of paleoseismic evidence.

References

Ahorner, L., Rosenhauer, W., 1993. Seismische Risikoanalyse. Naturkatastrophen und Katastrophenvorbeugung. Bericht zur IDNDR, Deutsche Forschungsgemeinschaft, und identisch in DGEB-Publikation Nr. 6, 177–190, VCH-Verlag, Weinheim.

Ahorner, L., 1994. Fault-plane solutions and source parameters of the 1992 Roermond, the Netherlands, mainshock and its stronger aftershocks from regional seismic data. Geologie en Mijnbouw, 73, 199–214.

Aki, K., Richards, P.G., 1980. Quantitative Seismology: Theory and Methods. W.H. Freeman and Company.

Aleksandrowski, P., Kryza, R., Mazur, S., Żaba, J., 1997. Kinematic data on major Variscan strike-slip faults and shear zones in the Polish Sudetes, northeast Bohemian Massif, Geol. Mag., Vol. 134, 727-739.

Arthaud, F., Matte, P., 1977. Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Result of a right-lateral shear zone between the Appalachians and the Urals. Geol. Soc. Am. Bull., 88, 1305−1320.

Arvidsson, R., 1996. Fennoscandian earthquakes: whole crustal rupturing related to postglacial rebound. Science, 274, 744–746.

Asch, K., 2005. The 1 : 5 Million International Geological Map of Europe and Adjacent Areas. BGR (Hannover), 1 map.

Babel Working Group, 1991. Deep seismic survey images the structure of the Tornquist Zone beneath the South Baltic Sea. Geophys. Res. Lett. 18, 1091–1094.

Babuška, V., Plomerová, J., 2004. The Sorgenfrei-Tornquist Zone as the mantle edge of Baltica lithosphere: new evidence from three-dimensional seismic anisotropy. Terra Nova 16, 243–249.

Badura, J., Zuchiewicz, W., Górecki, A., Sroka, W., Przybylski, B., 2003a. Morphometric characteristics of the Sudetic Marginal Fault between Złoty Stok and Dobromierz, SW Poland (in Polish, with English summ.), Przegląd Geologiczny, Vol. 51, No. 12, 1048-1057.

Badura, J., Zuchiewicz, W., Górecki, A., Sroka, W., Przybylski, B., Żyszkowska, M., 2003b. Morphotectonic properties of the Sudetic Marginal Fault, SW Poland, Acta Montana IRSM AS CR, Ser. A, Vol. 24 (131), 21-49.

Badura, J., Zuchiewicz, W., Stepančíková, P., Przybylski, B., Kontny, B., Cacón, S., 2007. The Sudetic Marginal Fault - a young morphotectonic feature at the NE margin of the Bohemian Massif, Central Europe. Acta Geodynamica Et Geomaterialia 4, 7–29.

Baize, S., Cushing, M., Lemeille, F., Granier, B., Grellet, B., Carbon, D., Combes, P., Hibsch, C., 2002. Inventaire des indices de rupture affectant le Quaternaire, en relation avec les grandes structures connues, en France métropolitaine et dans les régions limitrophes. Mémoires de la Société Géologique de France 175.

Baize, S., Cushing, M., Lemeille, F., Gelis, C., Texier, D., Nicoud, G., Schwenninger, J.L., 2011. Contribution to the seismic hazard assessment of a slow active fault, the Vuache fault in the southern Molasse basin (France). Bulletin de la Société géologique de France 182, 347–365, doi: 10.2113/gssgfbull.182.4.347.

Baize, S., Scotti, O., 2013. An outline of the geological contribution to seismic hazard assessment (SHA) for nuclear facilities, in: Presented at the 4th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA), 9-14 October 2013, Aachen, Germany, pp. 11–13.

Baldschuhn, R., Kockel, F., 1999. Das Osning-Lineament am Südrand des Niedersachsen-Beckens. Zeitschrift der Deutschen Geologischen Gesellschaft 150, 673-695.

Bankwitz, P., Schneider, G., Kämpf, H., Bankwitz, E., 2003. Structural characteristics of epicentral areas in Central Europe: study case Cheb Basin (Czech Republic). Journal of Geodynamics 35, 5–32.

Basili, R., Kastelic, V., Demircioglu, M.B., García Moreno, D., Nemser, E.S., Petricca, P., Sboras, S., Besana-Ostman, G.M., Cabral, J., Camelbeeck, T., Caputo, R., Danciu, L., Domac, H., Fonseca, J., García-Mayordomo, J., Giardina, D., Glavatovic, B., Gulen, L., Ince, Y., Pavlides, S., Sesetyan, K., Tarabusi, G., Tiberti, M.M., Utkucu, M., Valensise, G., Vanneste, K., Vilanova, S., Wössner, J., 2013. The European Database of Seismogenic Faults (EDSF) compiled in the framework of the Project SHARE, http://diss.rm.ingv.it/share-edsf/, doi: 10.6092/INGV.IT-SHARE-EDSF.

Basili, R., Valensise, G., Vannoli, P., Burrato, P., Fracassi, U., Mariano, S., Tiberti, M.M., Boschi, E., 2008. The Database of Individual Seismogenic Sources (DISS), version 3: Summarizing 20 years of research on Italy's earthquake geology. Tectonophysics 453.

Bayer, U., Scheck, M., Rabbel, W., Krawczyk, C.M., Gotze, H.J., Stiller, M., Beilecke, T., Marotta, A.M., Barrio-Alvers, L., Kuder, J., 1999. An integrated study of the NE German Basin. Tectonophysics 314, 285–307.

Bayer, U., Grad, M., Pharaoh, T.C., Thybo, H., Guterch, A., Banka, D., Lamarche, J., Lassen, A., Lewerenz, B., Scheck, M., Marotta, A.M., 2002. The southern margin of the East European Craton: new results from seismic sounding and potential fields between the North Sea and Poland. Tectonophysics 360, 301–314, doi: 10.1016/S0040-1951(02)00359-1.

Becker, A., Davenport, C.A., Giardini, D., 2002. Palaeoseismicity studies on end-Pleistocene and Holocene lake deposits around Basle, Switzerland. Geophysical Journal International 149, 659–678, doi: 10.1046/j.1365-246X.2002.01678.x.

Becker, A., Ferry, M., Monecke, K., Schnellmann, M., Giardini, D., 2005. Multiarchive paleoseismic record of late Pleistocene and Holocene strong earthquakes in Switzerland. Tectonophysics 400, 153–177, doi: 10.1016/j.tecto.2005.03.001.

Beidinger, A., Decker, K., Roch, K.H., 2010. The Lassee segment of the Vienna Basin fault system as a potential source of the earthquake of Carnuntum in the fourth century a.d. International Journal of Earth Sciences 100, 1315–1329, doi: 10.1007/s00531-010-0546-x.

Bergerat, F., Angelier, J., Andreasson, P.-G., 2007. Evolution of paleostress fields and brittle deformation of the Tornquist Zone in Scania (Sweden) during Permo-Mesozoic and Cenozoic times. Tectonophysics 444, 93–110, doi: 10.1016/j.tecto.2007.08.005.

Bini, A., Quinif, Y., Sules, O., Uggeri, A., 1992. Les mouvements tectoniques recents dans les Grottes du Monte Campo dei Fiori (Lombardie, Italie). Karstologia 19, 23–30.

Bitterli, T., 1996. Höhlen der Region Basel-Laufen. Speläolog. Inventar Schweiz 3. 328 pp.

Bonjer, K.-P., 1997. Seismicity pattern and style of seismic faulting at the eastern borderfault of the southern Rhine Graben. Tectonophysics, 275, 41–69.

Brandes, C., Steffen, H., Steffen, R., Wu, P., 2015. Intraplate seismicity in northern Central Europe is induced by the last glaciation. Geology, 43, 611–614, doi: 10.1130/G36710.1.

Brandes, C., Winsemann, J., 2013. Soft-sediment deformation structures in NW Germany caused by Late Pleistocene seismicity. International Journal of Earth Sciences 102, 2255–2274, doi: 10.1007/s00531-013-0914-4.

Brandes, C., Tanner, D.C., 2012. Three-dimensional geometry and fabric of shear deformation-bands in unconsolidated Pleistocene sediments. Tectonophysics, 518-521, 84–92, doi: 10.1016/j.tecto.2011.11.012.

Brandes, C., Winsemann, J., Roskosch, J., Meinsen, J., Tanner, D.C., Frechen, M., Steffen, H., Wu, P., 2012. Activity along the Osning Thrust in Central Europe during the Lateglacial: ice-sheet and lithosphere interactions. Quaternary Science Reviews 38, 49–62, doi: 10.1016/j.quascirev.2012.01.021.

Burkhard, M., 1990. Aspects of the large-scale Miocene deformation in the most external part of the Swiss Alps (Subalpine Molasse to Jura fold belt). Eclogae geologicae Helvetiae, 83, 559–583.

Burkhard, M., Grünthal, G., 2009. Seismic source zone characterization for the seismic hazard assessment project PEGASOS by the Expert Group 2 (EG1b). Eclogae geol. Helv. 102, 149–188. doi: 10.1007/s00015-009-1307-3.

Camelbeeck, T., Meghraoui, M., 1996. Large earthquake in northern Europe more likely than once thought. EOS, Transactions American Geophysical Union 77, 405, doi:10.1029/96EO00274.

Camelbeeck, T., Meghraoui, M., 1998. Geological and geophysical evidence for large palaeo-earthquakes with surface faulting in the Roer Graben (northwest Europe). Geophysical Journal International 132, 347–362, doi: 10.1046/j.1365-246x.1998.00428.x.

Camelbeeck, T., Vanneste, K., Alexandre, P., Verbeeck, K., Petermans, T., Rosset, P., Everaerts, M., Warnant, R., Van Camp, M., 2007. Relevance of active faulting and seismicity studies to assessments of long-term earthquake activity and maximum magnitude in intraplate northwest Europe, between the Lower Rhine Embayment and the North Sea. Geological Society of America Special Paper 425, 193–224, doi: 10.1130/2007.2425(14).

Campbell, J., Kümpel, H. J., Fabian, M., Fischer, D., Görres, B., Keysers, C. J., Lehmann, K., 2002. Recent movement pattern of the Lower Rhine embayment from tilt, gravity and GPS data. Geologie en Mijnbouw - Netherlands Journal of Geosciences, 81, 223 – 230.

Caputo, R., Iordanidou, K., Minarelli, L., Papathanassiou, G., Poli, M.E., Rapti-Caputo, D., Sboras, S., Stefani, M., Zanferrari, A., 2012. Geological evidence of pre-2012 seismic events, Emilia-Romagna, Italy. Annals of Geophysics, 55, 4, doi: 10.4401/ag-6148.

Carminati, E., Doglioni, C., Scrocca, D., 2004. Alps vs. Apennines, Special volume of the Italian Geological Society for the IGC 32, Florence 2004, 141-151.

Castellarin, A., Cantelli, L., Fesce, A. M., Mercier, J. L., Ricotti, V., Pini, G. A., Prosser, G., Selli, L., 1992. Alpine compressional tectonics in the Southern Alps; relationships with the N-Apennines, Annales Tectonicae, 6 (1), 62-94.

CEUS-SSC Working Group, 2015. 'Central and Eastern United States Seismic Source Characterization' for Nuclear Facilities (CEUS-SSC), accessed June 2020, http://www.ceus-ssc.com/.

Chunga, K., Livio, F., Michetti, A.M., Serva, L., 2007. Synsedimentary deformation of Pleistocene glaciolacustrine deposits in the Albese con Cassano Area (Southern Alps, Northern Italy), and possible implications for paleoseismicity. Sedimentary Geology 196, 59–80, doi: 10.1016/j.sedgeo.2006.08.010.

Coppersmith, K.J., Youngs, R., 2006. Seismic source zones in PSHA: aleatory or epistemic? 1st European Conference on earthquake engineering and seismology, Geneva, 3–8 September 2006.

Coppersmith, K.J., Salomone, L.A., Slayter, D.L., CEUS-SSC Working Group, 2012. Central and Eastern United States Seismic Source Characterization for Nuclear Facilities. Technical Report. Electrical Power Research Institute EPRI, U.S. Department of Energy DOE, and U.S. Nuclear Regulatory Commission NRC.

Cushing, M., Lemeille, F., Cotton, F., Grellet, B., Audru, J.-C., Renardy, F., 2000a. Paleo-earthquakes investigations in the Upper Rhine Graben (URG) in the framework of the PALEOSIS project. Paleosis project (ENV4-CT97-0578 EC Environment and Climate Research Programme) 1–9.

Cushing, M., Lemeille, F., Cotton, F., Grellet, B., Audru, J.-C., Renardy, F., 2000b. Paleo-earthquakes investigations in the Upper Rhine Graben in the framework of the PALEOSIS project, in: PALEOSIS - HAN2000 - potential for large earthquakes in low seismic activity regions of Europe, 39–43.

David, C., Cushing, M., Baize, S., Jomard, H., Baumont, D., 2011. Vers une base de données des failles actives en Francemétropolitaine pour l'évaluation de l'aléa sismique, in: 8ème Colloque National AFPS 2011, Marne-la-Vallée, 11–20.

Decker, K., Peresson, H., 1998. Miocene to present-day tectonics of the Vienna Basin transform fault. In: Links between the Alps and the Carparthians, XVI congress of the Carparthian-Balkan geological association. Geologische Bundesanstalt, Vienna, pp 33–36.

Decker, K., Peresson, H., Hinsch, R., 2005. Active tectonics and Quaternary basin formation along the Vienna Basin Transform fault. Quaternary Science Reviews 24, 305–320. doi: 10.1016/j.quascirev.2004.04.012.

Delaunay, A., Rampnoux, J.-P., 1981. Les déformations au front des massifs des Bornes et des Bauges: analyse de la tectonique cassante de l'avant-pays savoyard. Bulletin de la Société géologique de France XXIII, 203–212.

Demoulin, A., 1996. Clastic dykes in east Belgium: evidence for upper Pleistocene strong earthquakes west of the Lower Rhine rift segment. Journal of the Geological Society 153, 803–810.

Demoulin, A., Pissart, A., 2000. Past landslides in the Verviers (E Belgium) area, in: Presented at the PALEOSIS - HAN2000 - potential for large earthquakes in low seismic activity regions of Europe, pp. 49–51.

Demoulin, A., Pissart, A., Schroeder, C., 2003. On the origin of late Quaternary palaeo-landslides in the Liège (E Belgium) area. International Journal of Earth Sciences 92, 795–805.

Dèzes, P., Schmid, S. M., Ziegler, P. A., 2004. Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. Tectonophysics, 389, 1–33.

Di Manna, P., Guerrieri, L., Piccardi, L., Vittori, E., Castaldini, D., Berlusconi, A., Bonadeo, L., Comerci, V., Ferrario, F., Gambillara, R., Livio, F., Lucarini, M., Michetti, A., 2012. Ground effects induced by the 2012 seismic sequence in Emilia: implications for seismic hazard assessment in the Po Plain. Annals of Geophysics, 55, 4, doi: 10.4401/ag-6143.

DISS Working Group, 2018. Database of Individual Seismogenic Sources (DISS), Version 3.2.1: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas, accessed June 2020, http://diss.rm.ingv.it/diss/, Istituto Nazionale di Geofisica e Vulcanologia, doi: 10.6092/INGV.IT-DISS3.2.1.

Dolan, J. F., Avouac, J., 2007. Active fault-related folding; structural evolution, geomorphologic expression, paleoseismology, and seismic hazards, Journal of Geophysi-cal Research, 112 (B3).

Erlström, M., Thomas, S. A., Deeks, N., Sivhed, U., 1997. Structure and tectonic evolution of the Tornquist Zone and adjacent sedimentary basins in Scania and the southern Baltic Sea area. Tectonophysics 271, 191–215.

EUGENO-S Working Group, 1988. Crustal structure and tectonic evolution of the transition between the Baltic Shield and the North German Caledonides (the EUGENO-S Project). Tectonophysics 176, 253–348.

Fabbri, S.C., Herwegh, M., Horstmeyer, H., Hilbe, M., Hübscher, C., Merz, K., Schlunegger, F., Schmelzbach, C., Weiss, B., Anselmetti, F. S., 2017. Combining amphibious geomorphology with subsurface geophysical and geological data: A neotectonic study at the front of the Alps (Bernese Alps, Switzerland). Quaternary International, 451, 101–113, doi: 10.1016/j.quaint.2017.01.033.

Fantoni, R., Bersezio, R., Forcella, F., 2004. Alpine structure and deformation chronology at the Southern Alps-Po Plain border in Lombardy, Bollettino della Società Geologica Italiana, 123, 463-476.

Ferry, M., Meghraoui, M., Delouis, B., Giardini, D., 2005. Evidence for Holocene palaeoseismicity along the Basel-Reinach active normal fault (Switzerland): a seismic source for the 1356 earthquake in the Upper Rhine graben. Geophysical Journal International 160, 554–572. doi: 10.1111/j.1365-246X.2005.02404.x.

Franke, D., Hoffmann, N., 1999. Das Elbe-Lineament – bedeutende Geofraktur oder Phantomgebilde? Teil 1: Die Referenzgebiete. Zeitschift für geologische Wissenschaften, 27, 279–314.

Fraser, W.A., 2001. California Division of safety of dams (DSOD) - Fault activity guidelines.

Frechen, M., Vanneste, K., Verbeeck, K., Paulissen, E., Camelbeeck, T., 2001. The Deposition History of the Coversands along the Bree Fault Escarpment, NE Belgium. Netherlands Journal of Geosciences 80, 171–185.

Frechen, M., van den Berg, M.W., 2002. The coversands and timing of Late Quaternary earthquake events along the Peel Boundary Fault in the Netherlands. Netherlands Journal of Geosciences 81, 61–70.

Frigerio, C., Bonadeo, L., Zerboni, A., Livio, F., Ferrario, M. F., Fioraso, G., Irace, A., Brunamonte, F., Michetti, A. M., 2017. First evidence for Late Pleistocene to Holocene earthquake surface faulting in the Eastern Monferrato Arc (Northern Italy). Quaternary International, 451, 143–164, doi: 10.1016/j.quaint.2016.12.022.

García-Mayordomo, J., Insua-Arévalo, J.M., Martínez-Díaz, J.J., Jimenez-Díaz, A., Martín-Banda, R., Martín-Alfageme, S., Álvarez-Gómez, J.A., Rodríguez-Peces, M., Pérez-López, R., Rodriguez-Pascua, M.A., Masana, E., Perea, H., Martín-González, F., Giner-Robles, J., Nemser, E.S., Cabral, J., QAFI Compilers, 2012. The Quaternary Active Faults Database of Iberia (QAFI v. 2.0). Journal of Iberian Geology 38, 285–302.

Garetzky, R. G., Ludwig, A. O., Schwab, G., Stackebrandt, W., 2001. Neogeodynamics of the Baltic Sea depression and adjacent areas, results of IGCP project 346. Brandenburgische Geowissenschaftliche Beiträge, 8.

Giardini, D., Wössner, J., Danciu, L., Valensise, G., Grünthal, G., Cotton, F., Akkar, S., Basili, R., Stucchi, M., Rovida, A., Stromeyer, D., Arvidsson, R., Meletti, F., Musson, R., Sesetyan, K., Demircioglu, M.B., Crowley, H., Pinho, R., Pitilakis, K., Douglas, J., Fonseca, J., Erdik, M., Campos-Costa, A., Glavatovic, B., Makropoulos, K., Lindholm, C., Camelbeeck, T., 2013. Seismic Hazard Harmonization in Europe (SHARE): Online Data Resource, doi: 10.12686/SED-00000001-SHARE.

GNS Science Limited, 2015. New Zealand Active Faults Database, accessed June 2020, http://data.gns.cri.nz/af/.

Golbs, C., 2009. Probabilistische seismische Gefährdungsanalysen auf der Grundlage von Epizentrendichten und ihre ingenieurpraktischen Anwendungsgebiete. Bauhaus-Universität Weimar, Weimar.

Grocholski, A., 1977. The marginal Sudetic fault against the Tertiary volcanotectonics (in Polish, with English summ.), Acta Universitatis Wratislaviensis, Vol. 378, Prace Geologiczno-Mineralogiczne, Vol. 6, 89-103.

Grünthal, G., Bosse, C., 1996. Probabilistische Karte der Erdbebengefährdung der Bundesrepublik Deutschland – Erdbebenzonierungskarte für das nationale Anwendungsdokument zum Eurocode 8, Scientific Technical Report STR 96/10.

Grünthal, G., Mayer-Rosa, D., 1998. Einheitliche Erdbebengefährdungskarte für Deutschland, Österreich und die Schweiz (D-A-CH). Schweizerischer Pool für Erdbebendeckung, Geschäftsbericht, 1997, 11- 24.

Grünthal, G., Wahlström, R., 2006. New Generation of Probabilistic Seismic Hazard Assessment for the Area Cologne/Aachen Considering the Uncertainties of the Input Data. Natural Hazards 38, 159–176. doi: 10.1007/s11069-005-8611-7.

Grünthal, G., Wahlström, R., 2012. The European-Mediterranean Earthquake Catalogue (EMEC) for the last millennium. J Seis 16, 535–570.

Grützner, C., Fischer, P., Reicherter, K., 2016. Holocene surface ruptures of the Rurrand Fault, Germany – insights from palaeoseismology, remote sensing and shallow geophysics. Geophysical Journal International, 204, 1662–1677, doi: 10.1093/gji/ggv558.

Grygar, R., Jelínek, J., 2003. The Upper Morava and Nysa pull-apart grabens - the evidence of neotectonic dextral transtension on the sudetic faults system. Acta Montana, Ser. A, 24, 51−59.

Guerrieri, L., Tatevossian, R., Vittori, E., Comerci, V., Esposito, E., Michetti, A.M., Porfido, S., Serva, L., 2007. Earthquake environmental effects (EEE) and intensity assessment: the INQUA scale project. Bollettino Societa Geologica Italiana 126, 375.

Guerrieri, L., Porfido, S., Esposito, E., Blumetti, A.M., Michetti, A.M., Giulianelli, M., Vittori, E., 2009. Cataloguing Earthquake Environmental Effects: a tool for the comparison of recent, historical and paleo earthquakes, in: Presented at the 1st INQUA-IGCP-567 International Workshop on Earthquake Archaeology and Palaeoseismology, pp. 39–42.

Haller, K.M., Machette, M.N., Dart, R.L., Rhea, B.S., 2004. U.S. Quaternary Fault and Fold Database Released. Eos Trans. AGU 85, 213.

Hanks, T.C., Kanamori, H., 1979. A moment magnitude scale. Journal of Geophysical Research 84, 2348.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., Müller, B., 2008. The Release 2008 of the World Stress Map. Available online at. www.world-stress-map.org.

Henderson, J. R., 1991. An estimate of the stress tensor in Sweden using the earthquake fault-plane solution. Tectonophysics, 192, 213–244.

Hibsch, C., Malartre, F., Durand, M., Huault, V., Cushing, M., Lemeille, F., 2000. Analysis of Quaternary soft-sediment deformation features in the Upper Rhine graben, in: PALEOSIS - HAN2000 - potential for large earthquakes in low seismic activity regions of Europe, 79–82.

Hinsch, R., Decker, K., 2003. Do seismic slip deficits indicate an underestimated earthquake potential along the Vienna Basin Transform Fault System? Terra Nova 15 (5), 343–349.

Hinsch, R., Decker, K., Wagreich, M., 2005. 3-D mapping of segmented active faults in the southern Vienna Basin. Quaternary Science Reviews 24, 321–336.

Hinsch, R., Decker, K., 2010. Seismic slip rates, potential subsurface rupture areas and seismic potential of the Vienna Basin Transfer Fault. International Journal of Earth Sciences 100, 1925–1935. doi: 10.1007/s00531-010-0613-3.

Hintersberger, E., Decker, K., Lomax, J., Fiebig, M., Lüthgens, C., 2013. Fault linkage model of strike-slip and normal faults in the Vienna Basin based on paleoseismological constraints. EGU General Assembly Conference Abstracts 15, EGU2013–12755.

Hintersberger, E., Decker, K., Lomax, J., Lüthgens, C., 2018. Implications from palaeoseismological investigations at the Markgrafneusiedl Fault (Vienna Basin, Austria) for seismic hazard assessment. Natural Hazards and Earth System Sciences, 18(2), 531–553, doi: 10.5194/nhess-18-531-2018.

Hinzen, K.G., Reamer, K., Rose, T., 2001. Results of Analysis of Digital Elevation Models Used Site Selection for Paleoseismological Investigations at the Rurrand Fault. Netherlands Journal of Geosciences 80.

Hinzen, K.-G., 2003. Stress field in the Northern Rhine area, Central Europe, from earthquake fault plane solutions. Tectonophysics 377, 3-4, 325-356.

Hoffmann, G., Reicherter, K., 2011. Soft-sediment deformation of Late Pleistocene sediments along the southwestern coast of the Baltic Sea (NE Germany). International Journal of Earth Sciences 101, 351–363. doi: 10.1007/s00531-010-0633-z.

Houtgast, R. F. Van Balen, R. T., 2000. Neotetonics of the Roer Valley Rift System, the Netherlands. Global and Planetary Change, 27, 131–146.

Houtgast, R.F., van Balen, R.T., Kasse, C., Vandenberghe, J., 2003. Late Quaternary tectonic evolution and postseismic near surface fault displacements along the Geleen Fault (Feldbiss Fault Zone - Roer Vally Rift System, the Netherlands), based on trenching. Netherlands Journal of Geosciences 82, 177–196.

Houtgast, R.F., van Balen, R.T., Kasse, C., 2005. Late Quaternary evolution of the Feldbiss Fault (Roer Valley Rift System, the Netherlands) based on trenching, and its potential relation to glacial unloading. Quaternary Science Reviews 24, 489–508. doi: 10.1016/j.quascirev.2004.01.012.

Hürtgen, J., 2017. The First Paleoseismic Database of Germany and Adjacent Regions PalSeisDB v1.0. RWTH Aachen University, Aachen, doi: 10.18154/RWTH-2018-223292.

Hürtgen, J.; Reicherter, K.; Spies, T.; Geisler, C.; Schlittenhardt, J. (2020): The Paleoseismic Database of Germany and Adjacent Regions PalSeisDB. V. 1.0. GFZ Data Services, doi: 10.5880/fidgeo.2020.040.

IGME, 2015. QAFI v.3: Quaternary Faults Database of Iberia. accessed June 2020, from IGME web site: http://info.igme.es/QAFI.

ISO 3166-1: Codes for the representation of names of countries and their subdivisions. International Organization for Standardization (ISO), Geneva, Switzerland. accessed September 2014, http://www.iso.org/iso/home/standards/country_codes.htm.

Jomard, H., Cushing, E.M., Palumbo, L., Baize, S., David, C., Chartier, T., 2017. Transposing an active fault database into a seismic hazard fault model for nuclear facilities. Natural Hazards and Earth System Sciences Discussions, 1–18, doi: 10.5194/nhess-2017-96.

Jouanne, F., Ménard, G., Jault, D., 1994. Present-day deformation of the French northwestern Alps/southern Jura mountains: comparison between historical triangulations. Geophysical Journal International 119, 151–165. doi:10.1111/j.1365-246X.1994.tb00919.x.

Kaiser, A., Reicherter, K., Hübscher, C., Gajewski, D., 2005. Variation of the present-day stress field within the North German Basin – insights from thin shell FE modeling based on residual GPS velocities. Tectonophysics 397, 55–72.

Kälin, D., 1997. Litho- und Biostratigraphie der mittel- bis obermiozänen Bois de Raube – Formation (Nordwestschweiz). Eclogae geologicae Helvetiae, 90, 97–114.

Kanamori, H., Anderson, D.L., 1975. Theoretical basis of some empirical relations in seismology. Bulletin of the Seismological Society of America 65, 1073–1095.

Keefer, D.K., 1984. Landslides caused by earthquakes. Geological Society of America Bulletin 95, 406–421.

Keller, G., 1974. Die Fortsetzung der Osningzone auf dem Nordwestabschnitt des Teutoburger Waldes. Neues Jahrbuch für Geologie und Paläontologie Monatshefte, 72-95.

Kockel, F., 2003. Inversion structures in Central Europe – Expressions and reasons, an open discussion. Netherlands Journal of Geosciences/Geologie en Mijnbouw, 82, 367–382.

Kremer, K., Hilbe, M., Simpson, G., Decrouy, L., Wildi, W., Girardclos, S., 2015. Reconstructing 4000 years of mass movement and tsunami history in a deep peri-Alpine lake (Lake Geneva, France-Switzerland). Sedimentology, 62, 1305–1327, doi: 10.1111/sed.12190.

Kremer, K., Wirth, S.B., Reusch, A., Fäh, D., Bellwald, B., Anselmetti, F. S., Girardclos, S., Strasser, M., 2017. Lake-sediment based paleoseismology: Limitations and perspectives from the Swiss Alps. Quaternary Science Reviews, 168, 1–18, doi: 10.1016/j.quascirev.2017.04.026.

Kremer, K., Gassner-Stamm, G., Grolimund, R., Wirth, S. B., Strasser, M., Fäh, D., 2020. A database of potential paleoseismic evidence in Switzerland. Journal of Seismology 24, 247–262, doi: 10.1007/s10950-020-09908-5.

KTA 2201.1, 2011. Auslegung von Kernkraftwerken gegen seismische Einwirkungen, Teil 1: Grundsätze; Fassung 2011/11. Kerntechnischer Ausschuss (KTA).

Kübler, S., Friedrich, A.M., Strecker, M.R., 2010. Paleoseismic evidence for seismogenic faulting in the epicentrical area of the 1755/56 Düren earthquake series, Lower Rhine Embayment, NW Germany. Geophysical Research Abstracts 12.

Kübler, S., Friedrich, A.M., Strecker, M.R., 2011a. Seismogenic surface faulting in the area of Germany's strongest historical earthquake, Lower Rhine Embayment, NW Germany. Freiberger Forschungshefte C 538, 13–16.

Kübler, S., Friedrich, A.M., Strecker, M.R., 2011b. Coseismic surface rupturing in the epicentral area of Germany's strongest historical earthquake, in: 2nd INQUA-IGCP-567 International Workshop on Active Tectonics, Earthquake Geology, Archaeology and Engineering, Corinth (Greece), 111–113.

Kübler, S., 2013. Active Tectonics of the Lower Rhine Graben (NW Central Europe) Based on New Paleoseismological Constraints and Implications for Coseismic Rupture Processes in Unconsolidated Gravels. Ludwig-Maximilians University Munich, Munich.

Kübler, S., Friedrich, A.M., Gold, R.D., Strecker, M.R., 2017a. Historical coseismic surface deformation of fluvial gravel deposits, Schafberg fault, Lower Rhine Graben, Germany. International Journal of Earth Sciences, 1–15, doi: 10.1007/s00531-017-1510-9.

Kübler, S., Streich, R., Lück, E., Hoffmann, M., Friedrich, A.M., Strecker, M.R., 2017b. Active faulting in a populated low-strain setting (Lower Rhine Graben, Central Europe) identified by geomorphic, geophysical and geological analysis. Geological Society, London, Special Publications, 432, 127–146, doi: 10.1144/SP432.11.

La Taille, de, C., Jouanne, F., Crouzet, C., Beck, C., Jomard, H., de Rycker, K., Van Daele, M., 2015. Impact of active faulting on the post LGM infill of Le Bourget Lake (western Alps, France). Tectonophysics, 664, 31–49, doi: 10.1016/j.tecto.2015.08.024.

Lämmermann-Barthel, J., Neeb, I., Hinderer, M., Frechen, M., 2009. Last Glacial to Holocene Fluvial Aggradation and Incision in the Southern Upper Rhine Graben: Climatic and Neotectonic Controls. Quaternaire 20, 25–34.

Langridge, R. M., Ries, W. F., Litchfield, N. J., Villamor, P., Van Dissen, R. J., Barrell, D. J. A., Rattenbury, M. S., Heron, D. W., Haubrock, S., Townsend, D. B., Lee, J. M., Berryman, K. R., Nicol, A., Cox, S. C., Stirling, M. W., 2016. The New Zealand Active Faults Database. New Zealand Journal of Geology and Geophysics, 59, 86–96, doi: 10.1080/00288306.2015.1112818.

Laubscher, H., 1992. Jura kinematics and the Molasse basin. Eclogae geol. Helv., 85, 653-675.

Laubscher, H., 2001. Plate interactions at the southern end of the Rhinegraben. Tectonophysics, 343, 1–19.

Lehmann, K., Klostermann, J., Pelzing, R., 2001. Paleoseismological Investigations at the Rurrand Fault, Lower Rhine Embayment. Netherlands Journal of Geosciences 80, 139–154.

Lemeille, F., Cushing, M., Cotton, F., Grellet, B., Ménillet, F., Audru, J.-C., Renardy, F., Flehoc, C., 1999. Evidence for Middle to Late Pleistocene faulting within the northern Upper Rhine Graben (Alsace Plain, France). Earth and Planetary Science Letters 328, 839–846.

Leydecker, G., 1986. Erdbebenkatalog für die Bundesrepublik Deutschland mit Randgebieten für die Jahre 1000–1981. Geologisches Jahrbuch Reihe E, 36, 3–8.

Leydecker, G., Aichele, H., 1998. The Seismogeographical Regionalisation for Germany: The Prime Example of Third-Level Regionalisation. Geologisches Jahrbuch E 55, 85–98.

Leydecker, G., Kopera, J. R., Rudloff, A., 1999. Abschätzung der Erdbebengefährdung in Gebieten geringer Seismizität am Beispiel eines Standortes in Norddeutschland. In: Savidis, S. A. (ed.) Entwicklungsstand in Forschung und Praxis auf den Gebieten des Erdbebeningenieurwesens, der Boden- und Baudynamik. DGEB Berlin, Publikation 10, 89–97.

Leydecker, G., 2009. Erdbebenkatalog für die Bundesrepublik Deutschland mit Randgebieten für die Jahre 800-2007. Datenfile www.bgr.de/quakecat, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover.

Leydecker, G., 2011. Erdbebenkatalog für Deutschland mit Randgebieten für die Jahre 800 bis 2008. Geologisches Jahrbuch Reihe E, 59.

Linzer, H.-G., Decker, K., Peresson, H., Dell'Mour, R., Frisch, W., 2002. Balancing lateral orogenic float of the Eastern Alps. Tectonophysics 354 (3–4), 211–237.

Littke, R., Scheck-Wenderoth, M., Brix, M. R., Nelskamp, S., 2008. Subsidence, inversion and evolution of the thermal field. In: Littke, R., Bayer, U., Gajewski, D., Nelskamp, S. (Eds.), Dynamics of Complex Intracontinental Basins: The Central European Basin System. Springer-Verlag, Berlin-Heidelberg, pp. 125-141.

Livio, F., Berlusconi, A., Chunga, K., Michetti, A.M., Sileo, G., 2011. New stratigraphic and structural evidence for Late Pleistocene surface faulting along the Monte Olimpino Backthrust (Lombardia, N Italy). Rendiconti Online della Società Geologica Italiana 14, 17–25. doi:10.3301/ROL.2011.03.

Livio, F., Berlusconi, A., Michetti, A.M., Zerboni, A., Trombino, L., Spötl, C., Rodnight, H., 2013. Paleoseismicity at the Monte Netto site (Southern Alps, N Italy): blind thrust activity deduced from secondary fold-related faults. in: 4th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA), 9-14 October 2013, Aachen, Germany, 141–143.

Machette, M.N., 2000. Active, capable, and potentially active faults - a paleoseismic perspective. Journal of Geodynamics 29, 387–392.

Malkovsky, M., 1987. The Mesozoic and Tertiary basins of the Bohemian Massif and their evolution. Tectonophysics 137, 31–42.

McCalpin, J., 2009. Paleoseismology, 2nd ed. Academic Press.

McSaveney, E., 2017. 'Active faults - What is an active fault?', Story by Eileen McSaveney, published 12 Jun 2006, reviewed and revised 1 Aug 2017, Te Ara - the Encyclopedia of New Zealand, accessed June 2020, http://www.TeAra.govt.nz/en/active-faults/page-1.

Meghraoui, M., Camelbeeck, T., Vanneste, K., Brondeel, M., Jongmans, T., 2000. Active faulting and paleoseismology along the Bree fault, lower Rhine graben, Belgium. Journal of Geophysical Research 105, 13809–13841.

Meghraoui, M., Delouis, B., Ferry, M., Giardini, D., Huggenberger, P., Spottke, I., Granet, M., 2001. Active normal faulting in the upper Rhine Graben and Paleoseismic Identification of the 1356 Basel earthquake. Science 293, 2070–2073. doi:10.1126/science.1010618.

Meletti, C., Galadini, F., Valensise, G., Stucchi, M., Basili, R., Barba, S., Vannucci, G., Boschi, E., 2008. A seismic source zone model for the seismic hazard assessment of the Italian territory. Tectonophysics, 450, 85-108.

Michetti, A.M., Esposito, E., Guerrieri, L., Porfido, S., Serva, L., Tatevossian, R., Vittori, E., Audemard, F., Azuma, T., Clague, J., Comerci, V., Gurpinar, A., McCalpin, J., Mohammadioun, B., Mörner, N.-A., Ota, Y., Roghozin, E., 2007. Intensity Scale ESI 2007, in: Guerrieri, L., Vittori, E. (Eds.), Memorie Descrittive Carta Geologica d'Italia. Servizio Geologico d'Italia – Dipartimento Difesa del Suolo, APAT, Roma, p. 53 pp.

Michetti, A.M., Giardina, F., Livio, F., Mueller, K., Serva, L., Sileo, G., Vittori, E., Devoti, R., Riguzzi, F., Carcano, C., Rogledi, S., Bonadeo, L., Brunamonte, F., Fioraso, G., 2012. Active compressional tectonics, Quaternary capable faults, and the seismic landscape of the Po Plain (northern Italy). Annals of Geophysics 55, 969–1001. doi:10.4401/ag-5462.

Michon, L., van Balen, R.T., Merle, O., Pagnier, H., 2003. The Cenozoic evolution of the Roer Valley Rift System integrated at a European scale. Tectonophysics 367, 101–126. doi:10.1016/S0040-1951(03)00132-X.

Miedema, R., Jongmans, T., 2002. Soil formation in Late Glacial Meuse sediments related to the Peel Boundary Fault activity. Netherlands Journal of Geosciences 81, 71–81.

Mogensen, T. E., 1994. Paleozoic structural development along the Tornquist Zone, Kattegat area, Denmark. Tectonophysics 240, 191–214.

Mogensen, T. E., Jensen, L. N., 1994. Cretaceous subsidence and inversion along the Tornquist Zone from Kattegat to the Egersund Basin. First Break 12 (4), 211–222.

Mohadjer, S., Ehlers, T.A., Bendick, R., Stübner, K., Strube, T., 2016. A Quaternary fault database for central Asia. Natural Hazards and Earth System Science, 16, 529–542, doi: 10.5194/nhess-16-529-2016.

Monecke, K., Anselmetti, F.S., Becker, A., Schnellmann, M., Sturm, M., Giardini, D., 2006. Earthquake-induced deformation structures in lake deposits: A Late Pleistocene to Holocene paleoseismic record for Central Switzerland. Eclogae geol. Helv. 99, 343–362. doi:10.1007/s00015-006-1193-x.

Monninger, R., 1985. Neotektonische Bewegungsmechanismen im mittleren Oberrheingraben. Karlsruhe University, Karlsruhe.

Montenat, C., Barrier, P., Ott d Estevou, P., Hibsch, C., 2007. Seismites: An attempt at critical analysis and classification. Sedimentary Geology 196, 5–30. doi: 10.1016/j.sedgeo.2006.08.004.

Mörner, N.-A., 1991. Intense earthquakes and seismotectonics as a function of glacial isostasy. Tectonophysics 188, 407-410.

Mörner, N.-A., 2003. Paleoseismicity of Sweden. Paleogeophysics & Geodynamics, Stockholm University, Stockholm, Sweden.

Mörner, N.-A., 2004. Active faults and paleoseismicity in Fennoscandia, especially Sweden. Primary structures and secondary effects. Tectonophysics 380, 139–157. doi: 10.1016/j.tecto.2003.09.018.

Mörner, N.-A., 2005. An interpretation and catalogue of paleoseismicity in Sweden. Tectonophysics 408, 265–307. doi: 10.1016/j.tecto.2005.05.039.

Mörner, N.-A., 2009. Late Holocene earthquake geology in Sweden. Geological Society, London, Special Publications 316, 179–188. doi:10.1144/SP316.11.

Mörner, N.-A., 2011. Paleoseismology: The application of multiple parameters in four case studies in Sweden. Journal of Structural Geology 242, 65–75. doi: 10.1016/j.quaint.2011.03.054.

Mörner, N.-A., 2014. An M > 6 Earthquake ~750 BC in SE Sweden. Open Journal of Earthquake Research, 03, 66–81, doi: 10.4236/ojer.2014.32008.

Mosca, P., Polino, R., Rogledi, S., Rossi, M., 2009. New data for the kinematic interpretation of the Alps-Apennines junction (Northwestern Italy), Int. J. Earth. Sci.; doi: 10.1007/s00531-009-0428-2.

National Institute of Advanced Industrial Science and Technology (AIST), 2016. Active Fault Database of Japan, October 4, 2016 version. Research Information Database DB095, National Institute of Advanced Industrial Science and Technology. accessed June 4, 2020, https://gbank.gsj.jp/activefault/index_e_gmap.html.

Nivière, B., Bruestle, A., Bertrand, G., Carretier, S., Behrmann, J., Gourry, J.C., 2008. Active tectonics of the southeastern Upper Rhine Graben, Freiburg area (Germany). Quaternary Science Reviews 27, 541–555. doi: 10.1016/j.quascirev.2007.11.018.

Oberc, J., Dyjor, S., 1969. Marginal Sudetic Fault (in Polish, with English summ.), Biuletyn Instytutu Geologicznego, Vol. 236, 41-142.

Obermeier, S.F., 1996. Use of liquefaction-induced features for paleoseismic analysis - An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. Engineering Geology 44, 1–76.

Palumbo, L., Baize, S., Cushing, M., Jomard, H., David, C., 2013. Devising BDFA: a new active fault database conceived behind nuclear safety assessment in France, in: 4th International INQUA Meeting on Paleoseismology, Active Tectonics and Ar-cheoseismology (PATA), 9-14 October 2013, Aachen, Germany, 181–184.

Papathanassiou, G., Caputo, R., Rapti-Caputo, D., 2012. Liquefaction phenomena along the paleo-Reno River caused by the May 20, 2012, Emilia (northern Italy) earthquake. Annals of Geophysics, 55, 4. doi:10.4401/ag-6147.

Peterek, A., Reuther, C.-D., Schunk, R., 2011. Neotectonic evolution of the Cheb Basin (Northwestern Bohemia, Czech Republic) and its implications for the late Pliocene to Recent crustal deformation in the western part of the Eger Rift. Zeitschrift für Geologische Wissenschaften 39, 335–365.

Peters, G., 2007. Active tectonics in the Upper Rhine Graben. Amsterdam.

Peters, G., Buchmann, T.J., Connolly, P., van Balen, R.T., Wenzel, F., Cloetingh, S.A.P.L., 2005. Interplay between tectonic, fluvial and erosional processes along the Western Border Fault of the northern Upper Rhine Graben, Germany. Tectonophysics 406, 39–66. doi: 10.1016/j.tecto.2005.05.028.

Peters, G., van Balen, R.T., 2007a. Tectonic geomorphology of the northern Upper Rhine Graben, Germany. Global and Planetary Change 58, 310–334. doi: 10.1016/j.gloplacha.2006.11.041.

Peters, G., van Balen, R.T., 2007b. Pleistocene tectonics inferred from fluvial terraces of the northern Upper Rhine Graben, Germany. Tectonophysics 430, 41–65. doi: 10.1016/j.tecto.2006.10.008.

Plenefisch, T., Bonjer, K.-P., 1997. The stress field in the Rhine Graben area inferred from earthquake focal mechanisms and estimations of frictional parameters. Tectonophysics, 275, 71–97.

Plomerová, J., Babuška, V., Vecsey, L., Kouba, D., TOR Working Group, 2002. Seismic anisotropy of the lithosphere around the Trans-European Suture Zone (TESZ) based on teleseismic body-wave data of the TOR experiment. Tectonophysics 360, 89–114.

Reicherter, K., Kaiser, A., Stackebrandt, W., 2005. The post-glacial landscape evolution of the North German Basin: morphology, neotectonics and crustal deformation. International Journal of Earth Sciences 94, 1083–1093. doi:10.1007/s00531-005-0007-0.

Reicherter, K., Froitzheim, N., Jarosiński, M., Badura, J., Franzke, H.J., Hansen, M., Hübscher, C., Müller, R., Poprowa, P., Reinecker, J., Stackebrandt, W., Voigt, T., Eynatten, von, H., Zuchiewicz, W., 2008. Alpine tectonics II - Central Europe north of the Alps, in: McCann, T. (Ed.), Geology of Central Europe. Geological Society of London.

Reusch, A., Moernaut, J., Anselmetti, F. S., Strasser, M., 2016. Sediment mobilization deposits from episodic subsurface fluid flow – A new tool to reveal long-term earthquake records? Geology, 44, 243–246, doi: 10.1130/G37410.1.

Reusch, A.M., 2016. Sublacustrine Paleoseismology and Fluid Flow in the Western Swiss Molasse Basin. doi: 10.3929/ethz-a-010638214.

Rotstein, Y., Schaming, M., Rousse, S., 2005. Structure and Tertiary tectonic history of the Mulhouse High, Upper Rhine Graben: Block faulting modified by changes in the Alpine stress regime. Tectonics, 24(1), TC1012.

Rotstein, Y., Schaming, M., 2008. Tectonic implications of faulting styles along a rift margin: The boundary between the Rhine Graben and the Vosges Mountains. Tectonics 27, 1–19. doi:10.1029/2007TC002149.

Roure, F., Heitzmann, P., Polino, R., (eds) 1990. Deep structure of the Alps. Mém. Soc. géol. Fr., Paris, 156; Mém. Soc. Géol. Suisse, Zürich, 1; Vol. spec. Soc. Geol. It., Roma, 1, 350 pages.

Royden, L. H., Horvath, F., Rumpler, J., 1983. Evolution of the Pannonian basin system, 1. Tectonics. Tectonics 2, 63–90.

Royden, L. H., 1988. Late Cenozoic tectonics of the Pannonian basin system. In: Roy-den, L.H., Horvath, F. (eds) The Pannonian basin: a study in basin evolution. AAPG Memoir 45. American Association of Petroleum Geologists and Hungarian Geological Society, Tulsa, pp 27–48.

Schäfer, A., Utescher, T., Klett, M., Valdivia-Manchego, M., 2005. The Cenozoic Lower Rhine Basin – rifting, sedimentation, and cyclic stratigraphy. International Journal of Earth Sciences, 94, 621 – 639.

Scheck, M., Bayer, U., Otto, V., Lamarche, J., Banka, D., Pharaoh, T., 2002. The Elbe Fault System in North Central Europe - a basement controlled zone of crustal weakness. Tectonophysics, 360, 281−299.

Schenk, V., Schenkova, Z., Kottnauer, P., Guterch, B., Labak, P., 2000. Earthquake Hazard for the Czech Republik, Poland and Slovakia – Contribution to the ILC/IASPEI Global Seismic Hazard Program. Natural Hazards, 21, 331-345.

Scherneck, H. G., Johansson, J. M., Mitrovica, J. X., Davis, J. L., 1998. The BIFROST project: GPS determined 3-D displacement rates in Fennoscandia from 800 days of continuous observations in the SWEPO network. Tectonophysics, 294, 305–321.

Schmid, S. M., Fügenschu, B., Kissling, E., Schuster, R., 2004. Tectonic map and overall architecture of the Alpine orogen. Eclogae Geol. Helv., 97, 93–117.

Schnellmann, M., Anselmetti, F.S., Giardini, D., Mckenzie, J.A., Ward, S.N., 2002. Pre-historic earthquake history revealed by lacustrine slump deposits. Geology 30, 1131. doi: 10.1130/0091-7613(2002)030.

Schnellmann, M., Anselmetti, F.S., Giardini, D., Mckenzie, J.A., 2006. 15,000 Years of mass-movement history in Lake Lucerne: Implications for seismic and tsunami hazards. Eclogae geol. Helv. 99, 409–428. doi: 10.1007/s00015-006-1196-7.

Schumacher, M. E., 2002. Upper Rhine Graben: Role of preexisting structures during rift evolution. Tectonics, 21(1). doi: 10.1029/2001TC900022.

Schwab, G., 1985. Paläomobilität der Norddeutsch-Polnischen Senke. Dissertation, Akademie der Wissenschaften der DDR, Potsdam.

Senglaub, Y., Brix, M. R., Adriasola, A. C., Littke, R., 2005. New information on the thermal history of the southwestern Lower Saxony Basin, northern Germany, based on fission track analysis. International Journal of Earth Sciences 94, 876-896.

Skácel, J., 2004, The Sudetic Marginal Fault between Bílá Voda and Lipová Lázně, Acta Geodyn. Geomater., Vol. 1, No. 3 (135), 31-33.

Skupin, K., Buschhüter, K., Hopp, H., Lehmann, K., Pelzing, R., Prüfert, J., Salamon, M., Schollmayer, G., Techmer, A., Wrede, V., 2008. Paläoseismische Untersuchungen im Bereich der Niederrheinischen Bucht. Scriptum - Arbeitsergebnisse aus dem Geologischen Dienst Nordrhein-Westfalen, 1–73.

Sommaruga, A., 1999. Décollement tectonics in the Jura foreland fold and thrust belt. Mar. Petrol. Geol., 16, 111-134.

Spaček, P., Sykorová, Z., Pazdírková, J., Svancara, J., Havik, J., 2006. Present-day seismicity of the south-eastern Elbe Fault System (NE Bohemian Massif). Studia Geophysica et Geodaetica 50, 233–258.

Spaček, P., 2013. Active tectonics in the West Carpathian Foreland: Nysa-Morava Zone and Upper Morava Basin System (Czech Republic), in: 4th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA), 9-14 October 2013, Aachen, Germany, 255–257.

Spaček, P., Valenta, J., Tábořík, P., Ambrož, V., Urban, M., Stepančíková, P., 2017. Fault slip versus slope deformations: Experience from paleoseismic trenches in the region with low slip-rate faults and strong Pleistocene periglacial mass wasting (Bohemian Massif). Quaternary International, 451, 56–73, doi: 10.1016/j.quaint.2017.05.006.

Spicakova, L., Ulicny, D., Koudelkova, G. C., 2000. Tectonosedimentary evolution of the Cheb Basin (NW Bohemia, Czech Republic) between late Oligocene and Pliocene: a preliminary note. Studia Geophysica et geodaetica 44, 556–580.

Stepančíková, P., Hók, J., Nyvlt, D., 2009. Trenching survey on the south-eastern section of the Sudetic Marginal fault (NE Bohemian Massif, intraplate region of Central Europe), in: 1st INQUA-IGCP-567 International Workshop on Earthquake Archaeology and Palaeoseismology, Baelo Claudia (Cadíz, Spain), 149–151.

Stepančíková, P., Dohnal, J., Pánek, T., Łój, M., Smolková, V., Šilhán, K., 2011a. The application of electrical resistivity tomography and gravimetric survey as useful tools in an active tectonics study of the Sudetic Marginal Fault (Bohemian Massif, central Europe). Journal of Applied Geophysics 74, 69–80. doi: 10.1016/j.jappgeo.2011.03.007.

Stepančíková, P., Nyvlt, D., Hók, J., Dohnal, J., 2011b. Paleoseismic study of the Sudetic marginal Fault at the locality Bílá Voda (Bohemian Massif), in: 2nd INQUA-IGCP-567 International Workshop on Active Tectonics, Earthquake Geology, Archaeology and Engineering, Corinth (Greece), 243–246.

Stepančíková, P., 2012. Stop 7 - Fault scarp morphology within the Mariánské Lázně fault zone, in: Stepančíková, P., Peterek, A., Marek, T. Field trip guide - Int. Conference Czech Association of Geomorphologists 18-20th April 2012, Sokolov, Prague, 24–25.

Stepančíková, P., Fischer, T., 2012. Late Quaternary activity within the Mariánské Lázně Fault zone as revealed by trenching survey (Cheb basin, Kopanina site), in: Geomorfologický sborník 10, Int. Conference Czech Association of Geomorphologists, 18.-20. April 2012, Sokolov, Prague, 51–52.

Stepančíková, P., Rockwell, T.K., Hartvich, F., Tábořík, P., Stemberk, J., Ortuño, M., Wechsler, N., 2013. Late Quaternary Activity of the Sudetic Marginal Fault in the Czech Republic: A signal of Ice Loading? In: 4th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA), 9-14 October 2013, Aachen, Germany, 259–262.

Stepančíková, P., Táborík, P., Fischer, T., Hartvich, F., Karousová, M., Stemberk, J., Nováková, L., 2015. Holocene activity of the Mariánské Lázne Fault (Cheb basin, Bohemian Massif): youngest proved surface faulting in central Europe? 6th International INQUA Meeting on Paleoseismology, Active Tectonics and Archaeoseosmology in Pescina, Fucino Basin, Italy, 1–3.

Stewart, I. S., Sauber, J., Rose, J., 2000. Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. Quaternary Science Reviews, 19, 1367–1389.

Strasser, M., Anselmetti, F.S., Fäh, D., Giardini, D., Schnellmann, M., 2006. Magnitudes and source areas of large prehistoric northern Alpine earthquakes revealed by slope failures in lakes. Geology 34, 1005. doi: 10.1130/G22784A.1.

Strasser, M., Stegmann, S., Bussmann, F., Anselmetti, F.S., Rick, B., Kopf, A., 2007. Quantifying subaqueous slope stability during seismic shaking: Lake Lucerne as model for ocean margins. Marine Geology 240, 77–97. doi: 10.1016/j.margeo.2007.02.016.

Strasser, M., Monecke, K., Schnellmann, M., Anselmetti, F.S., 2013. Lake sediments as natural seismographs: A compiled record of Late Quaternary earthquakes in Central Switzerland and its implication for Alpine deformation. Sedimentology 60, 319–341. doi: 10.1111/sed.12003.

Tesauro, M., Hollenstein, C., Egli, R., Geiger, A., Kahle, H.-G., 2005. Continuous GPS and broad-scale deformation across the Rhine Graben and the Alps. International Journal of Earth Sciences, 94, 525–537.

U.S. Geological Survey, 2017. Quaternary fault and fold database for the United States, accessed June 2020, at: https://www.usgs.gov/natural-hazards/earthquake-hazards/faults.

Ustaszewski, K., Schumacher, M. E., Schmid, S. M., 2005. Simultaneous normal faulting and extensional flexuring during rifting: an example from the southernmost Upper Rhine Graben. International Journal of Earth Sciences, 94, 680–696.

van Balen, R.T., Bakker, M.A.J., Kasse, C., 2016. New observations of an old fault: preliminary trenching results at the Peelboundary Faultzone. Abstract Peribaltic, 1–2.

van den Berg, M., Vanneste, K., Dost, B., Lokhorst, A., van Eijk, M., Verbeeck, K., 2002. Paleoseismic investigations along the Peel Boundary Fault- geological setting, site selection and trenching results. Netherlands Journal of Geosciences 81, 39–60.

Van Loon, A.J.T., Pisarska-Jamroży, M., 2014. Sedimentological evidence of Pleistocene earthquakes in NW Poland induced by glacio-isostatic rebound. Sedimentary Geology, 300, 1–10, doi: 10.1016/j.sedgeo.2013.11.006.

Vandenberghe, D., Vanneste, K., Verbeeck, K., Paulissen, E., Buylaert, J.-P., De Corte, F., Van den haute, P., 2009. Late Weichselian and Holocene earthquake events along the Geleen fault in NE Belgium: OSL age constraints. Quaternary International 199, 56–74. doi: 10.1016/j.quaint.2007.11.017.

Vanneste, K., Meghraoui, M., Camelbeeck, T., 1999. Late Quaternary earthquake-related soft-sediment deformation along the Belgian portion of the Feldbiss Fault, Lower Rhine Graben system. Tectonophysics 309, 57–79.

Vanneste, K., Verbeeck, K., 2001. Paleoseismological analysis of the Rurrand fault near Jülich, Roer Valley graben, Germany: Coseismic or aseismic faulting history? Netherlands Journal of Geosciences 80, 155–169.

Vanneste, K., Verbeeck, K., Camelbeeck, T., Paulissen, E., Meghraoui, M., Renardy, F., Jongmans, T., Frechen, M., 2001. Surface-rupturing history of the Bree fault scarp, Roer Valley graben: Evidence for six events since the late Pleistocene. Journal of Seismology 5, 329–359.

Vanneste, K., Mees, F., Verbeeck, K., 2008. Thin-section analysis as a tool to aid identification of palaeoearthquakes on the “slow”, active Geleen Fault, Roer Valley Graben. Tectonophysics 453, 94–109. doi: 10.1016/j.tecto.2007.10.011.

Vanneste, K., Camelbeeck, T., Verbeeck, K., 2013. A Model of Composite Seismic Sources for the Lower Rhine Graben, Northwest Europe. Bulletin of the Seismological Society of America 103, 984–1007.

Vanneste, K., Camelbeeck, T., Verbeeck, K., Demoulin, A., 2017. Morphotectonics and Past Large Earthquakes in Eastern Belgium. In: Demoulin, A. (ed.) Landscapes and Landforms of Belgium and Luxembourg. Cham, Springer International Publishing, World Geomorphological Landscapes, 215–236. doi: 10.1007/978-3-319-58239-9_13.

Veloza, G., Styron, R., Taylor, M., Mora, A., 2012. Open-source archive of active faults for northwest South America. GSAT 22, 4–10.

Verbeeck, K., Vanneste, K., Camelbeeck, T., 2009. Seismotectonic zones for probabilistic seismic-hazard assessment in Belgium (No. NIROND TR-2008-31 E). ONDRAF/NIRAS Report.

Verbeeck, K., Wouters, L., Vanneste, K., Camelbeeck, T., Vandenberghe, D., Beerten, K., Rogiers, B., Schiltz, M., Burow, C., Mees, F., De Grave, J., Vandenberghe, N., 2017. Episodic activity of a dormant fault in tectonically stable Europe: The Rauw fault (NE Belgium). Tectonophysics, 699, 146–163, doi: 10.1016/j.tecto.2017.01.023.

Villegas, G.C., Mendoza, C., Ferrari, L., 2017. Mexico Quaternary Fault Database. Terra Digitalis, 1, 1–9, doi: 10.22201/igg.terradigitalis.2017.1.3.68.

Vogt, J., Grünthal, G., 1994. Die Erdbebenfolge vom Herbst 1612 im Raum Bielefeld. Geowissenschaften 12:236–240.

Wahlstrom, R., 1989. Seismodynamics and postglacial faulting in the Baltic Shield. In: Gregersen, S. & Basham, P. W. (eds) Earthquakes at the North Atlantic Passive Margins: Neotectonics and Postglacial Rebound. Kluwer, Dordrecht, 467–482.

Weissl, M., Hintersberger, E., Lomax, J., Lüthgens, C. & Decker, K., 2017. Active tectonics and geomorphology of the Gaenserndorf Terrace in the Central Vienna Basin (Austria). Quaternary International, 451, 209–222, doi: 10.1016/j.quaint.2016.11.022.

Wells, D.L., Coppersmith, K.J., 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America 84, 974–1002.

Wessely, G., 1993. Der Untergrund des Wiener Beckens. In: Brix F, Schulz O (eds) Erdöl und Erdgas in Österreich. Naturhistorisches Museum Wien und F. Berger, Horn, pp 249–280.

Winandy, J., Grützner, C., Reicherter, K., Wiatr, T., Fischer, P., Ibeling, T., 2011. Is the Rurrand Fault (Lower Rhine Graben, Germany) Responsible for the AD 1756 Düren earthquake series?, in: 2nd INQUA-IGCP-567 International Workshop on Active Tectonics, Earthquake Geology, Archaeology and Engineering, 286–289.

Winsemann, J., Asprion, U., Meyer, T. & Schramm, C., 2007. Facies characteristics of Middle Pleistocene (Saalian) ice-margin subaqueous fan and delta deposits, glacial Lake Leine, NW Germany. Sedimentary Geology, 193, 105–129, doi: 10.1016/j.sedgeo.2005.11.027.

Zijerveld, L., Stephenson, R., Cloething, S., Duin, E. & van den Berg, M. W., 1992. Subsidence analysis and modelling of the Roer Valley Graben (SE Netherlands). Tectonophysics, 208, 159–171.