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

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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 ± 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.

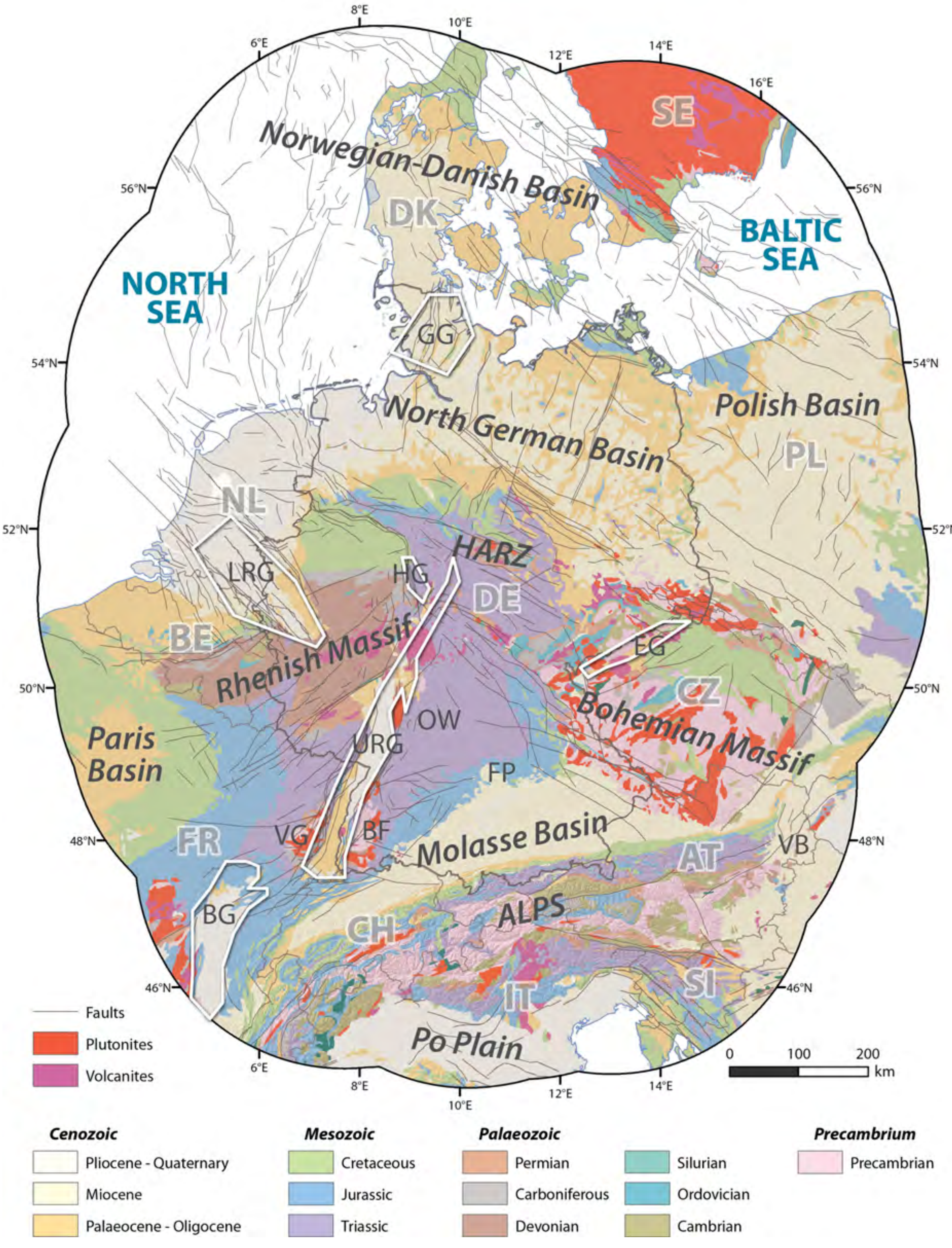


Figure 1. General geological and tectonic framework of Germany and adjacent regions based on the International Geological Map of Europe (IGME5000; Asch, 2005) and fault traces (thin black lines). BF: Black Forest, BG: Bresse Graben, EG: Eger Graben, FP: Franconian Platform, GG: Glückstadt Graben, HG: 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).

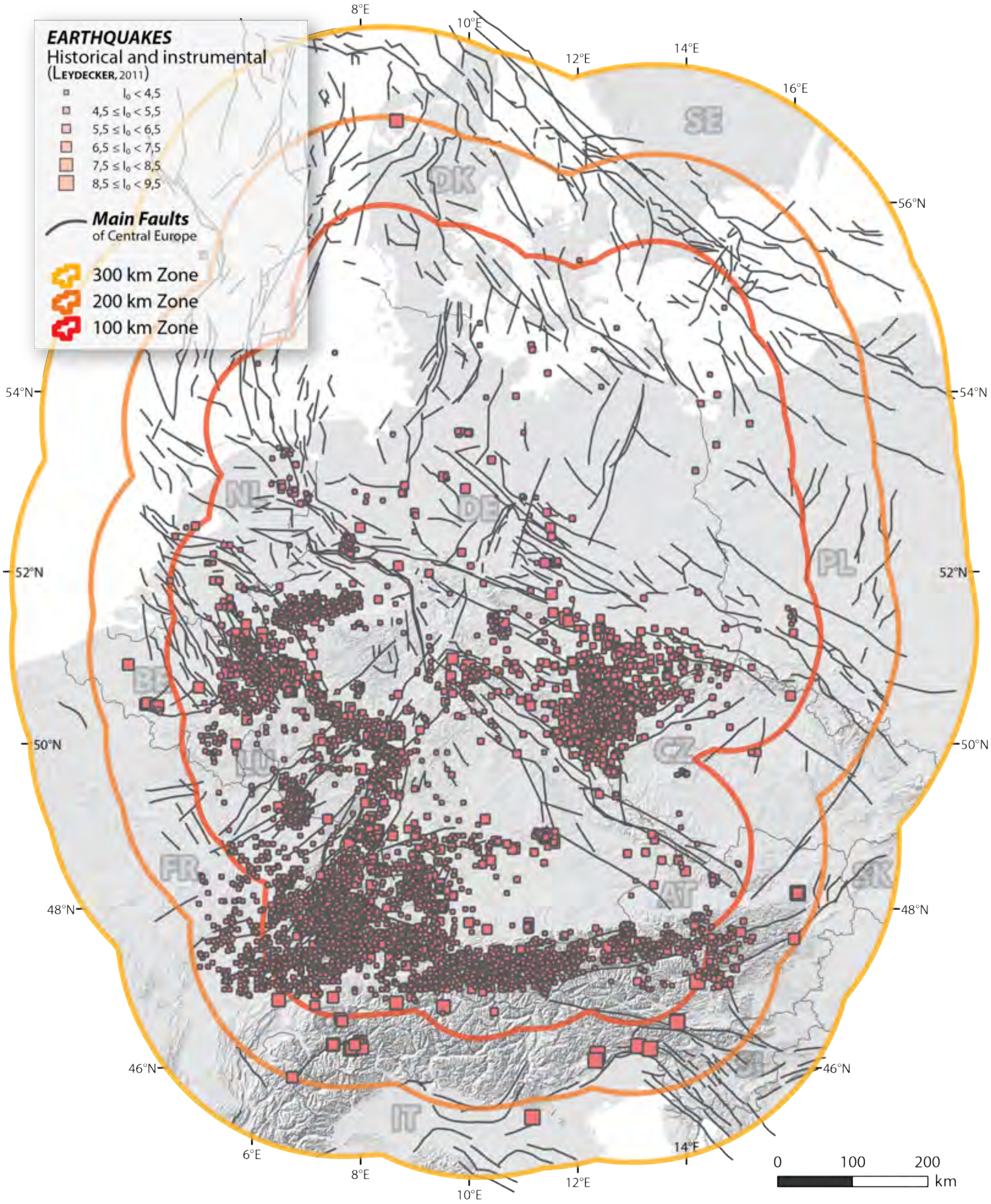


Figure 3. Extent of the study area for the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) showing the main structural framework (main faults, disregarding whether they are active or not, compiled from Dèzes et al. (2004), Kaiser et al. (2005), and Reicherter et al. (2008)) combined 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.

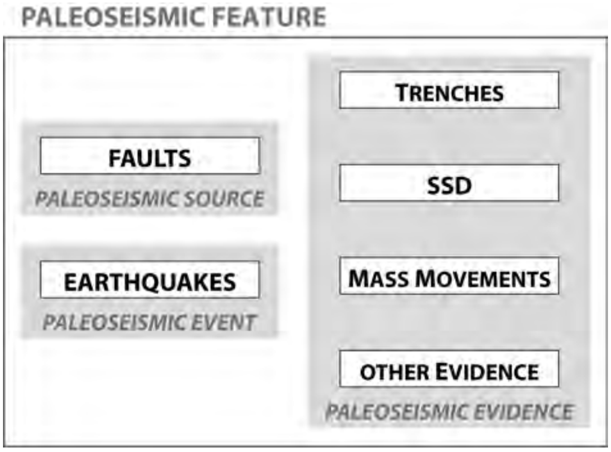


Figure 4. Schematically drawn concept behind the development of PalSeisDB v1.0.

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').

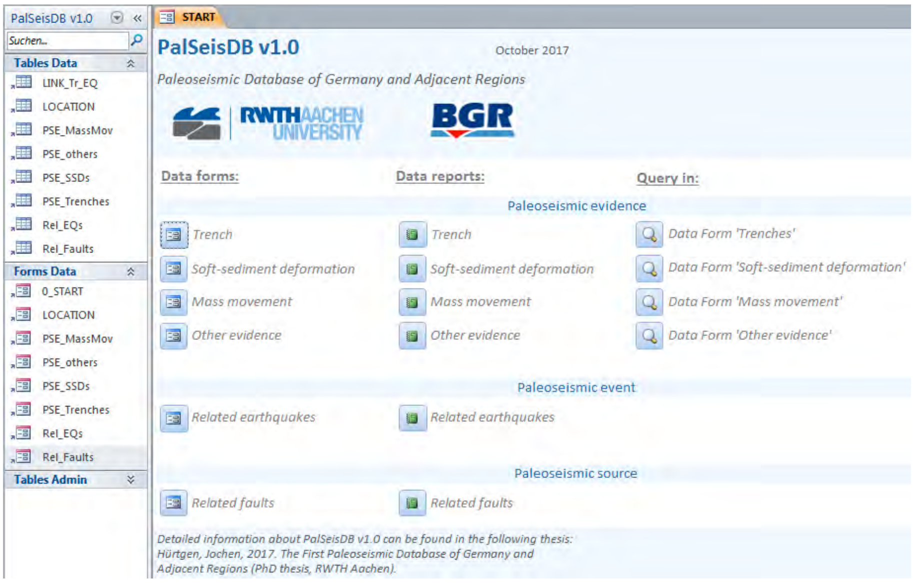


Figure 5. Screenshot of the START window that appears when the Microsoft Access database 'PalSeisDB v1.0.accdb' is opened. It provides direct access to all elements incorporated in the database including data tables, data forms and data reports.

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.

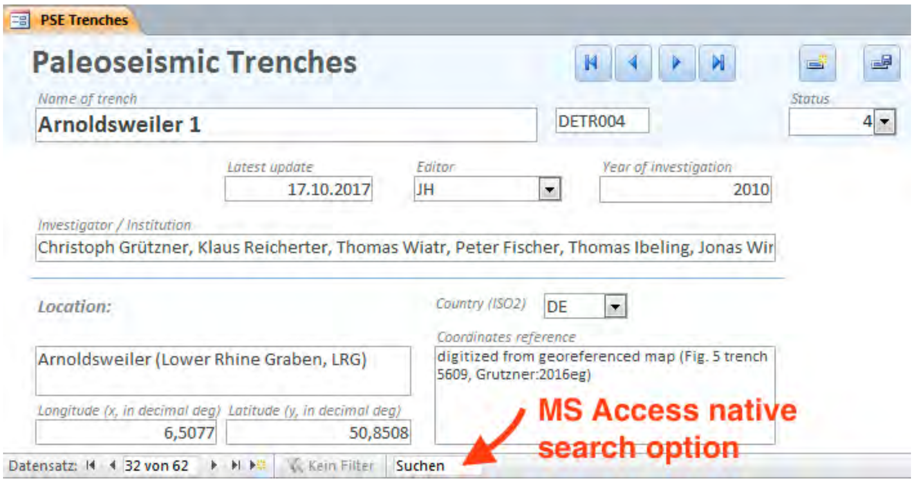


Figure 6. Example of the Microsoft Access natively implemented search option. This search field is available at the bottom of data table and data form view. In this example an extract of the record of a paleoseismic trench close to Arnoldsweiler (Lower Rhine Graben) is shown.

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'.

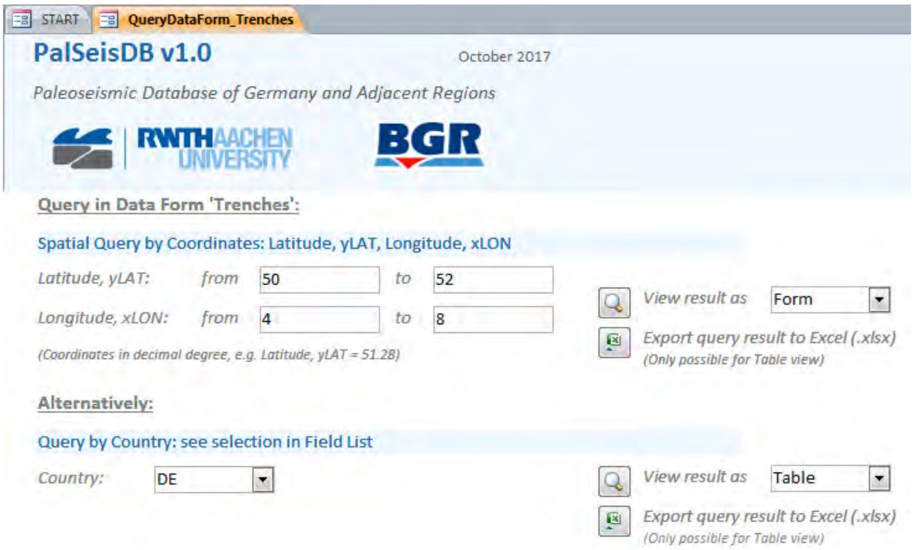
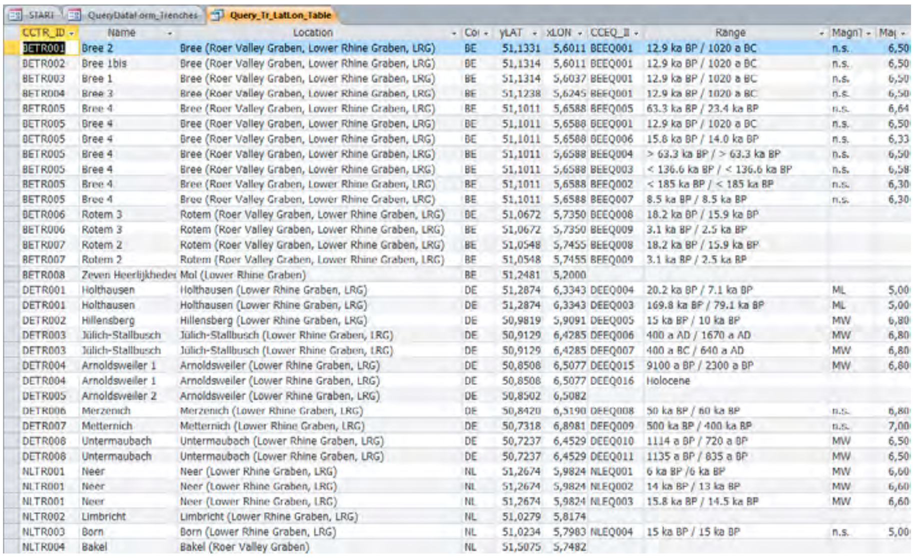


Figure 7. Search mask for 'Trenches' implemented in PalSeisDB v1.0. It provides two options to search and filter for records in the database related to paleoseismic trenches: 1) spatial query by coordinates (ex. Lower Rhine Graben, results as table in Figure 8 and as data form in Figure 9), and 2) spatial 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).

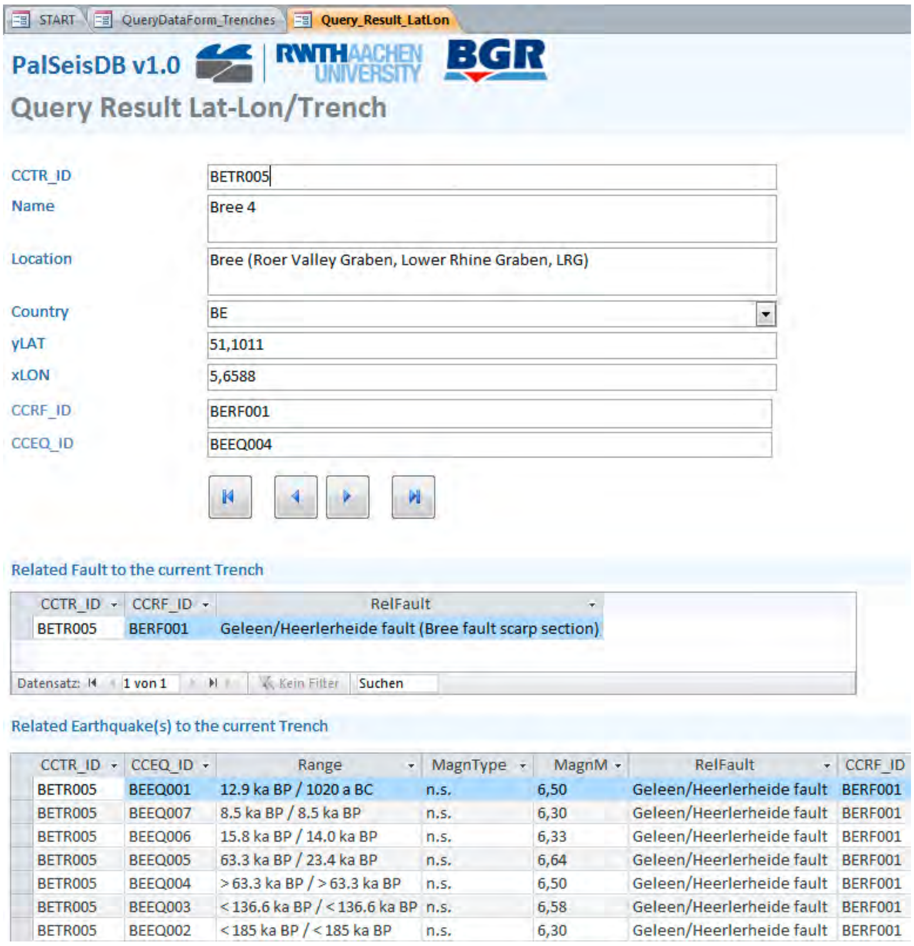
The actual query gets started by clicking the icon with the magnifying glass. Then, a new window will be opened showing the query result in the chosen view ('Table' or 'Form').



START | QueryDataForm_Trenches | Query_Tr_LatLon_Table

CCTR_ID	Name	Location	Col	yLAT	xLON	CCEQ_II	Range	MagnT	Maç
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 RWTHAACHEN UNIVERSITY BGR

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.

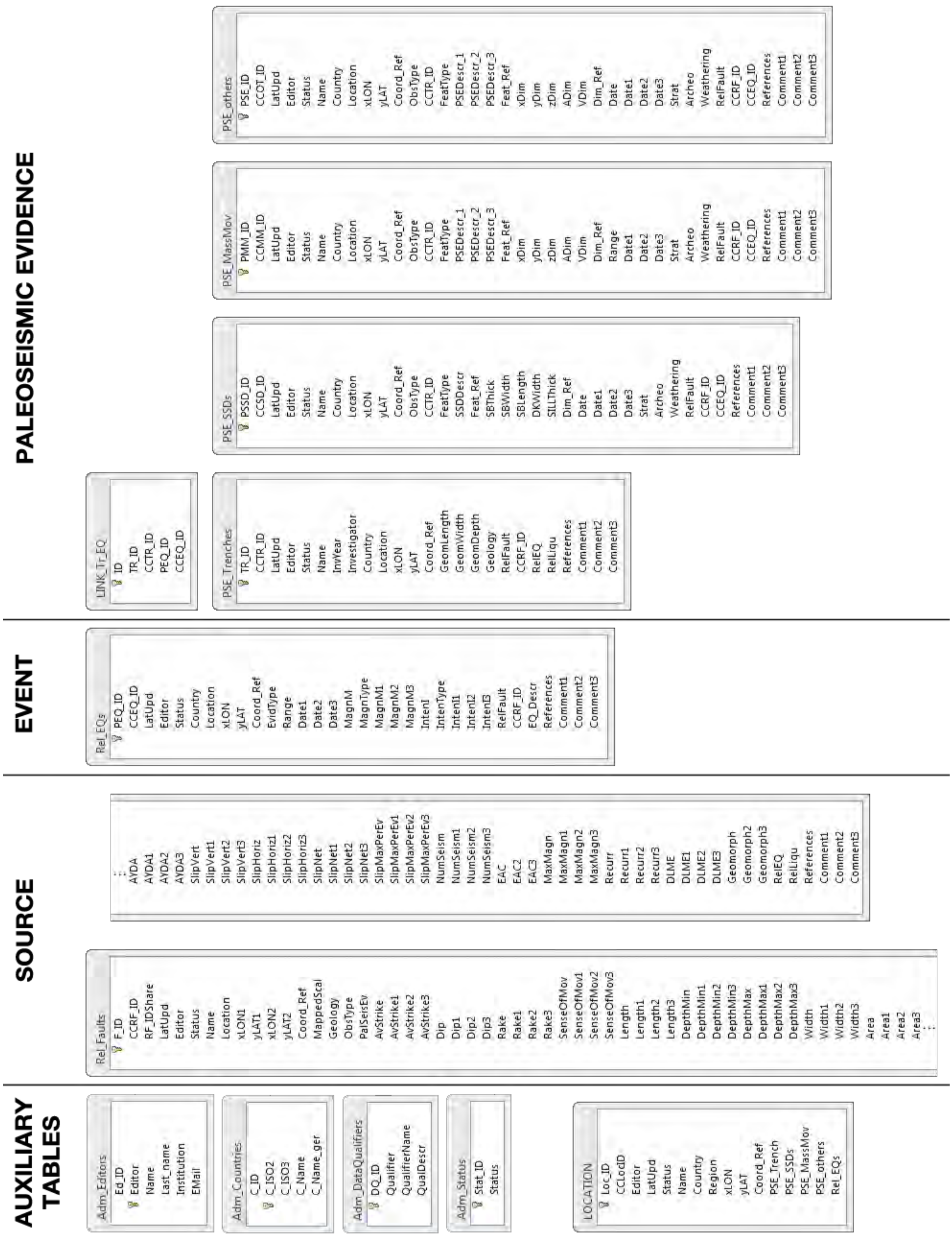


Figure 11. Overview of the data tables and parameters included in the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0). See this and the following Sections for a detailed description of each table and each associated parameter.

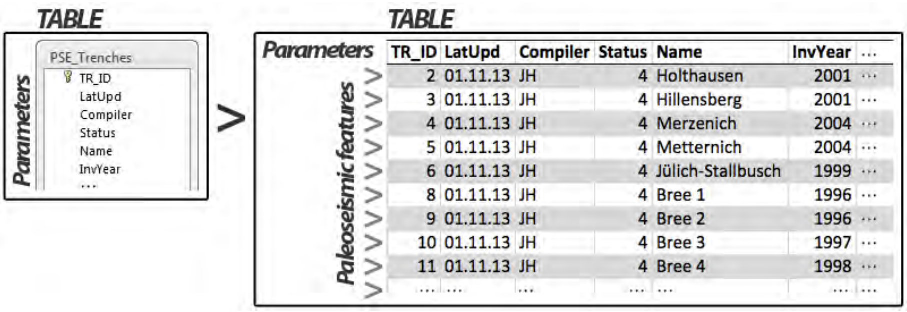


Figure 12. Schematically drawn structure of data tables in PalSeisDB v1.0. Exemplarily shown for the table of paleoseismic trenches. In each data table, each column represents one parameter and each row displays a record of a paleoseismic feature.

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.

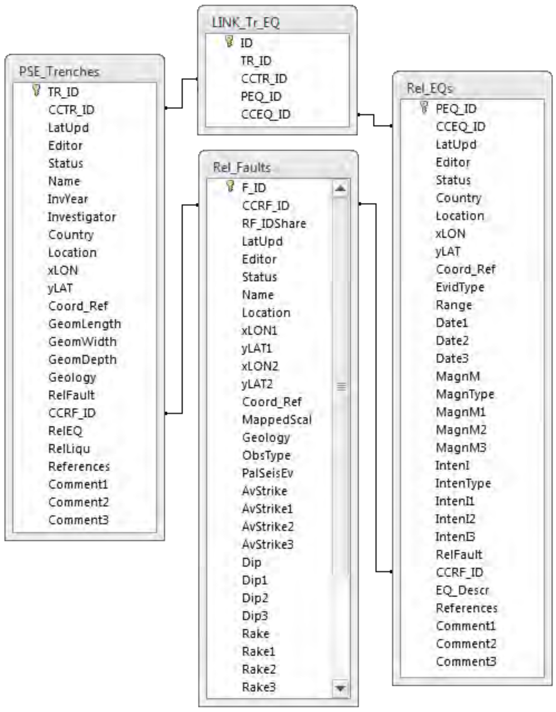


Figure 13. Relational connections in PalSeisDB v1.0 between the elements trenches ('PSE_Trenches'), earthquakes ('Rel_EQs') and faults ('Rel_Faults'). The relation between earthquakes and trenches is realized by an additional table ('LINK_TR_EQs') due to the fact that each trench can document evidence 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).

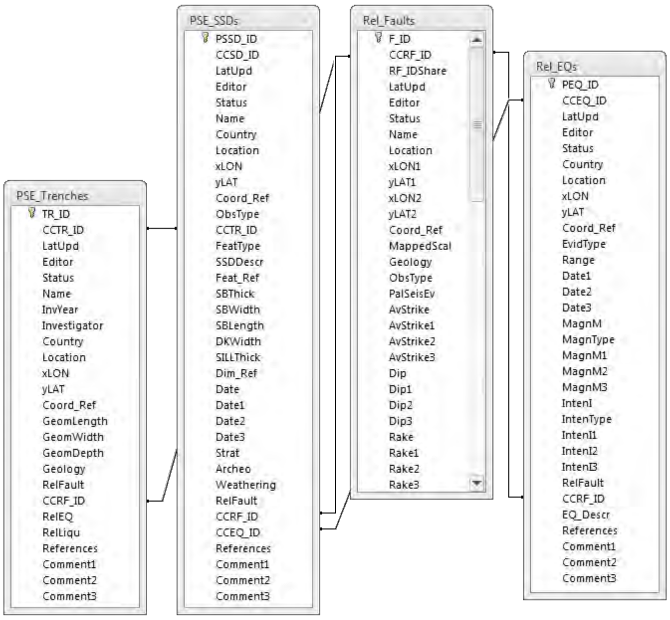


Figure 14. Relational connections in PalSeisDB v1.0 between the elements soft-sediment deformation features (‘PSE_SSDs’), trenches (‘PSE_Trenches’), earthquakes (‘Rel_EQs’) and faults (‘Rel_Faults’). The relation between the tables is realized via the individual ID of a record in PalSeisDB v1.0. The 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.

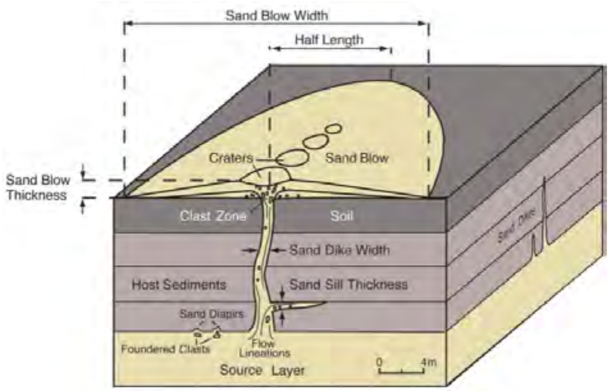


Figure 15. Graphic illustrating the geometric parameters of soft-sediment deformation features including sand blow thickness, width and length, dike width and sill thickness, as well as some of the diagnostic characteristics of these features (Fig. E-2 from Coppersmith et al., 2012, p. E-69). The illustrated 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).

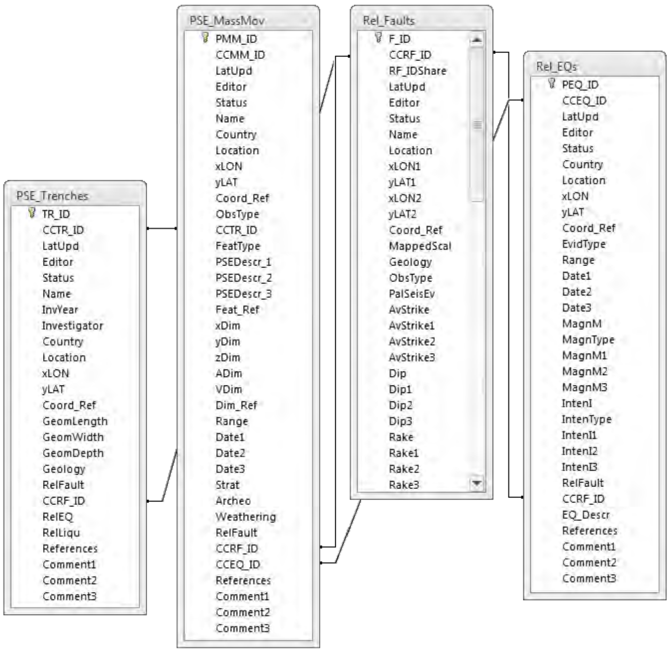


Figure 16. Relational connections in PalSeisDB v1.0 between the elements mass movement features (‘PSE_MassMov’), trenches (‘PSE_Trenches’), earthquakes (‘Rel_EQs’) and faults (‘Rel_Faults’). The relation between the tables is realized via the individual ID of a record in PalSeisDB v1.0. The thin black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

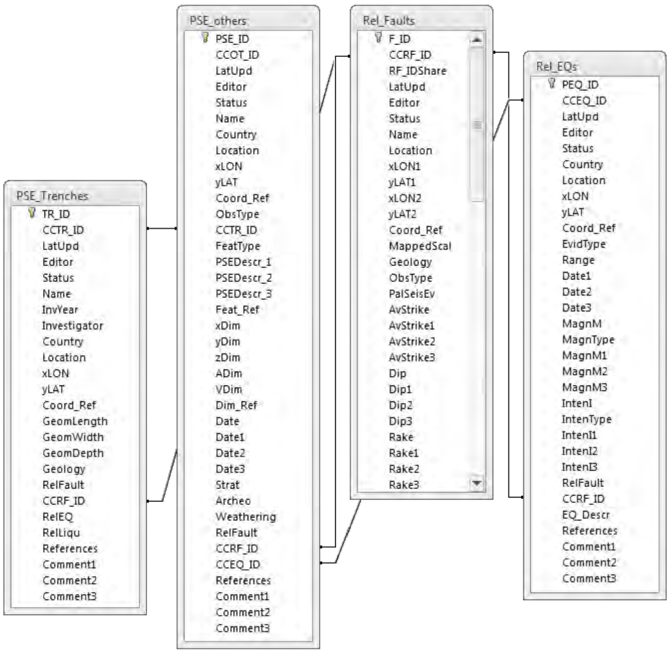


Figure 17. Relational connections in PalSeisDB v1.0 between other paleoseismic evidence features (‘PSE_others’), trenches (‘PSE_Trenches’), earthquakes (‘Rel_EQs’) and faults (‘Rel_Faults’). The relation between the tables is realized via the individual ID of a record in PalSeisDB v1.0. The thin black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

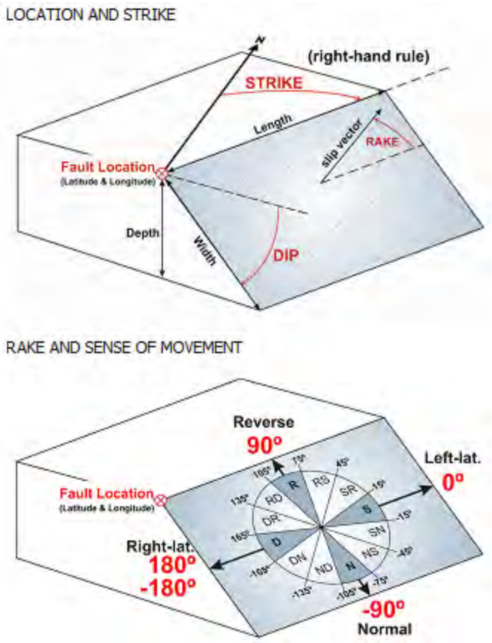


Figure 18. Illustration of the conventions on fault location and sense of movement in PalSeisDB v1.0 (adopted from Aki and Richards, 1980).

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.

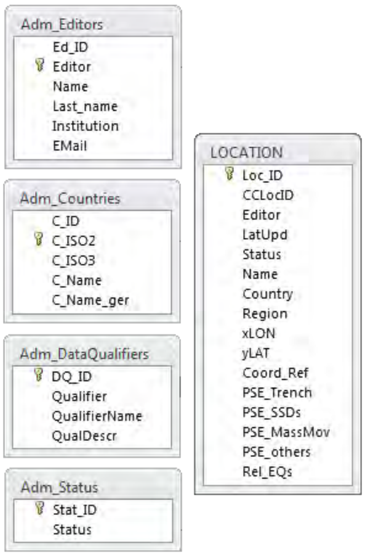


Figure 19. List of auxiliary tables that are used to record secondary information and to support administrative maintaining of PalSeisDB v1.0.

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.

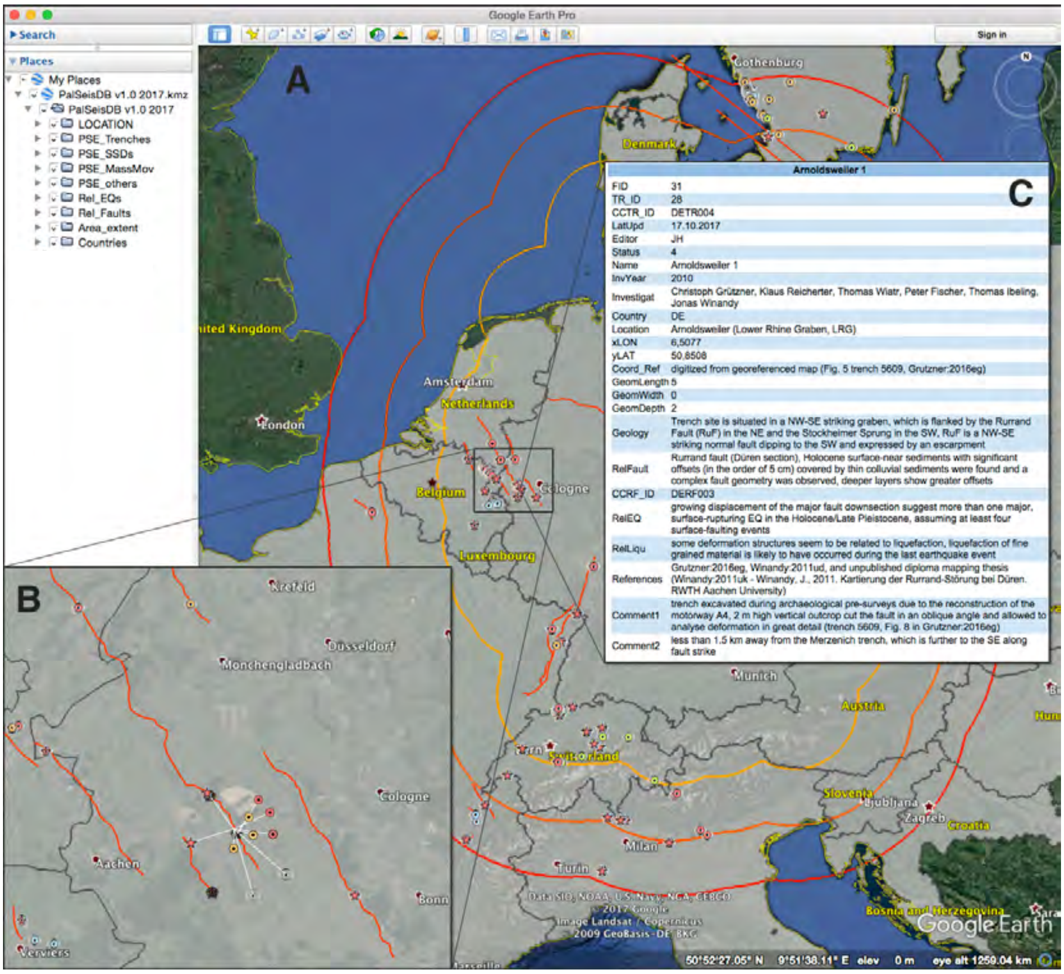


Figure 20. A: The view of PalSeisDB v1.0 in the Google Earth environment. Each data point is selectable and provides further information on the parameterization of each paleoseismic feature (evidence, source, and event). B: Area of the Lower Rhine Graben with expanded data points for a trench study at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

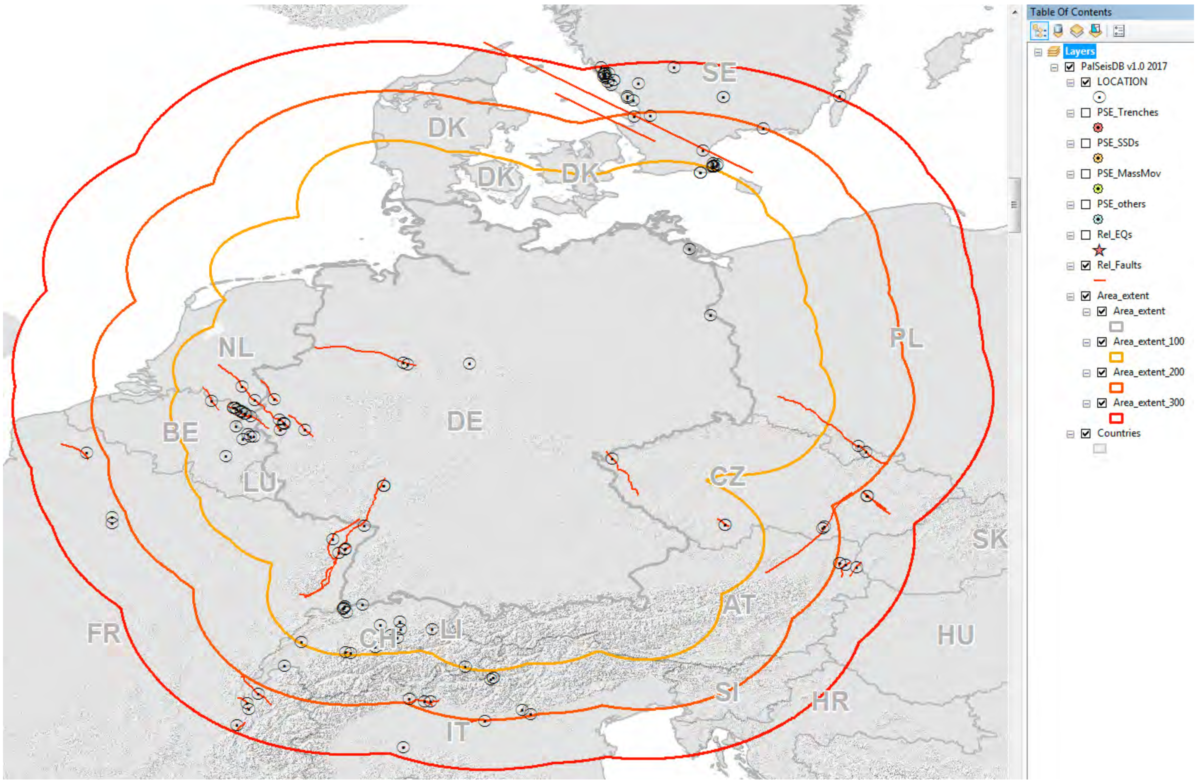


Figure 21. The view of Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) in the ESRI ArcGIS environment. Each data point is selectable and provides information on the parameterization of each paleoseismic feature (evidence, source, and event). Background with topographic imprint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

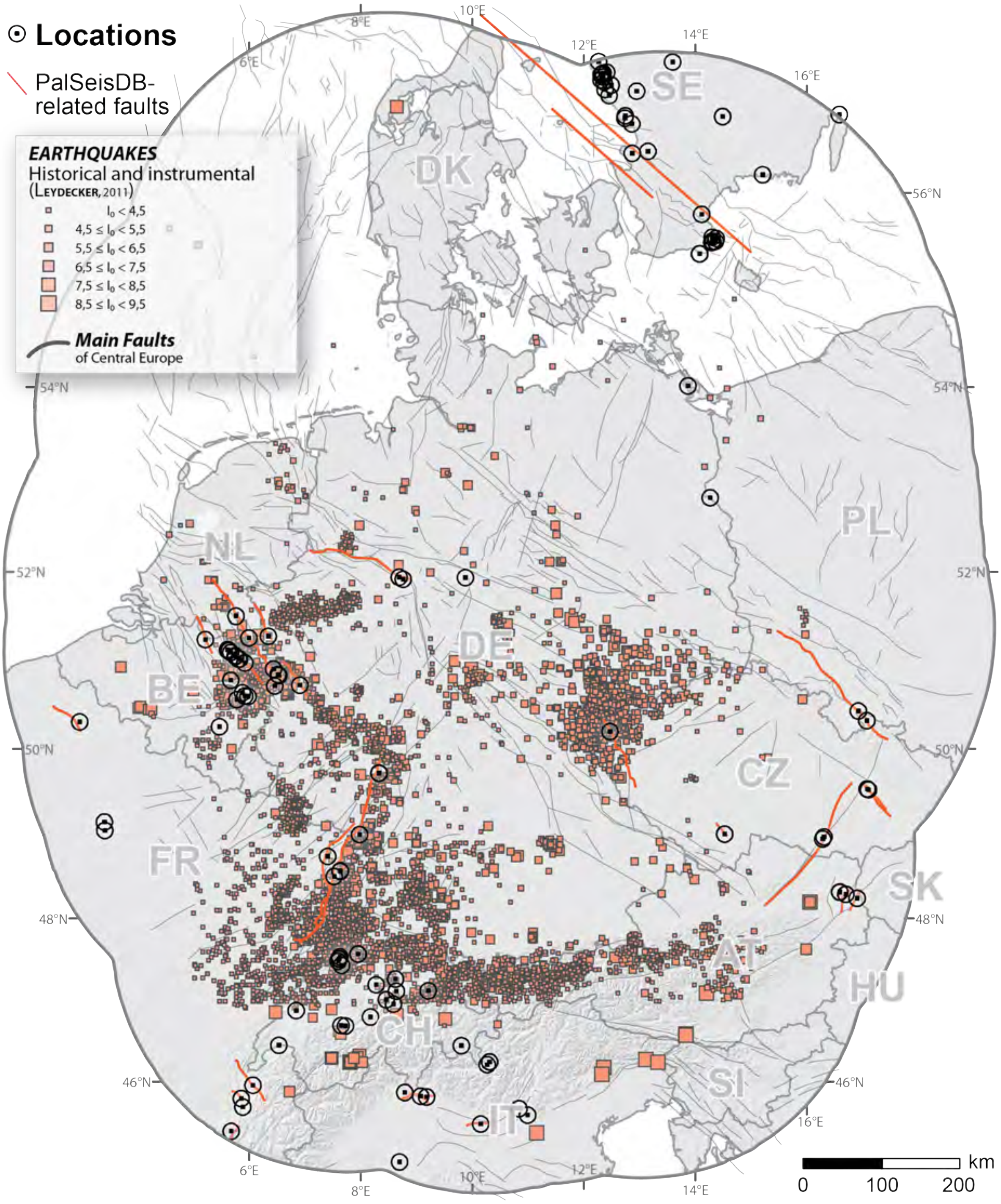


Figure 22. Comprised overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including 129 locations of documented paleoseismic features (black dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, 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).

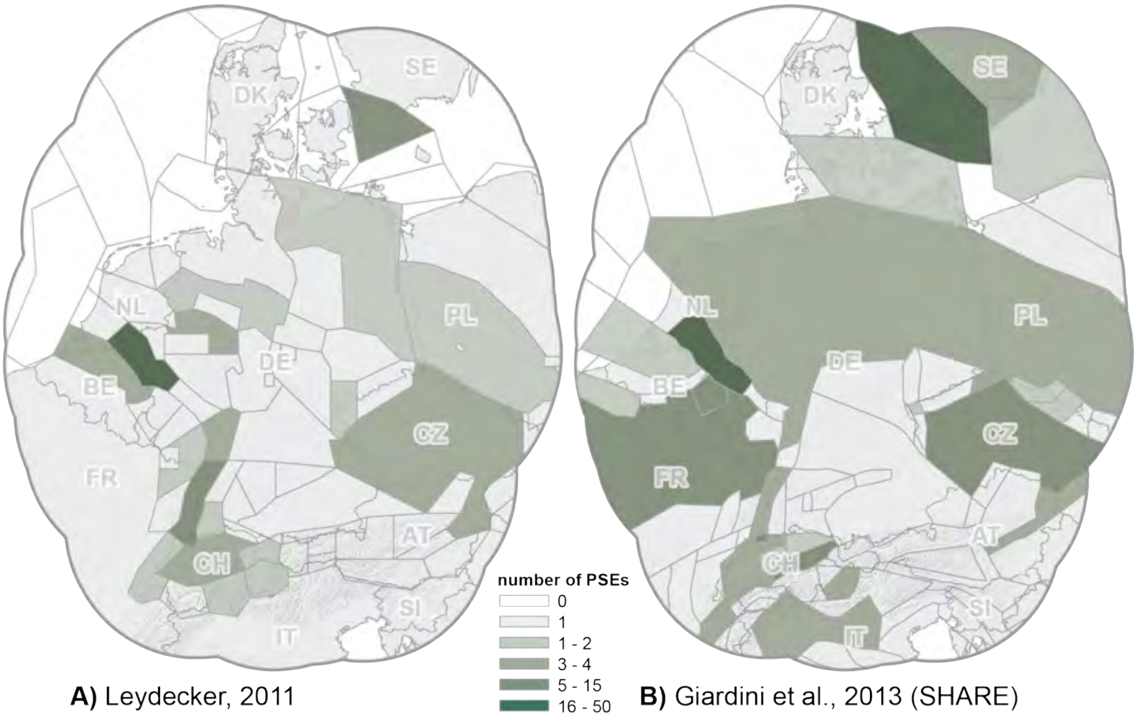


Figure 23. Maps of different seismotectonic zonation schemes after Leydecker (2011) and Giardini et al. (2013, SHARE model). Both models include a color scheme for the distribution of the amount of locations where records of paleoseismic evidence have been found from PalSeisDB v1.0 in each seismotectonic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

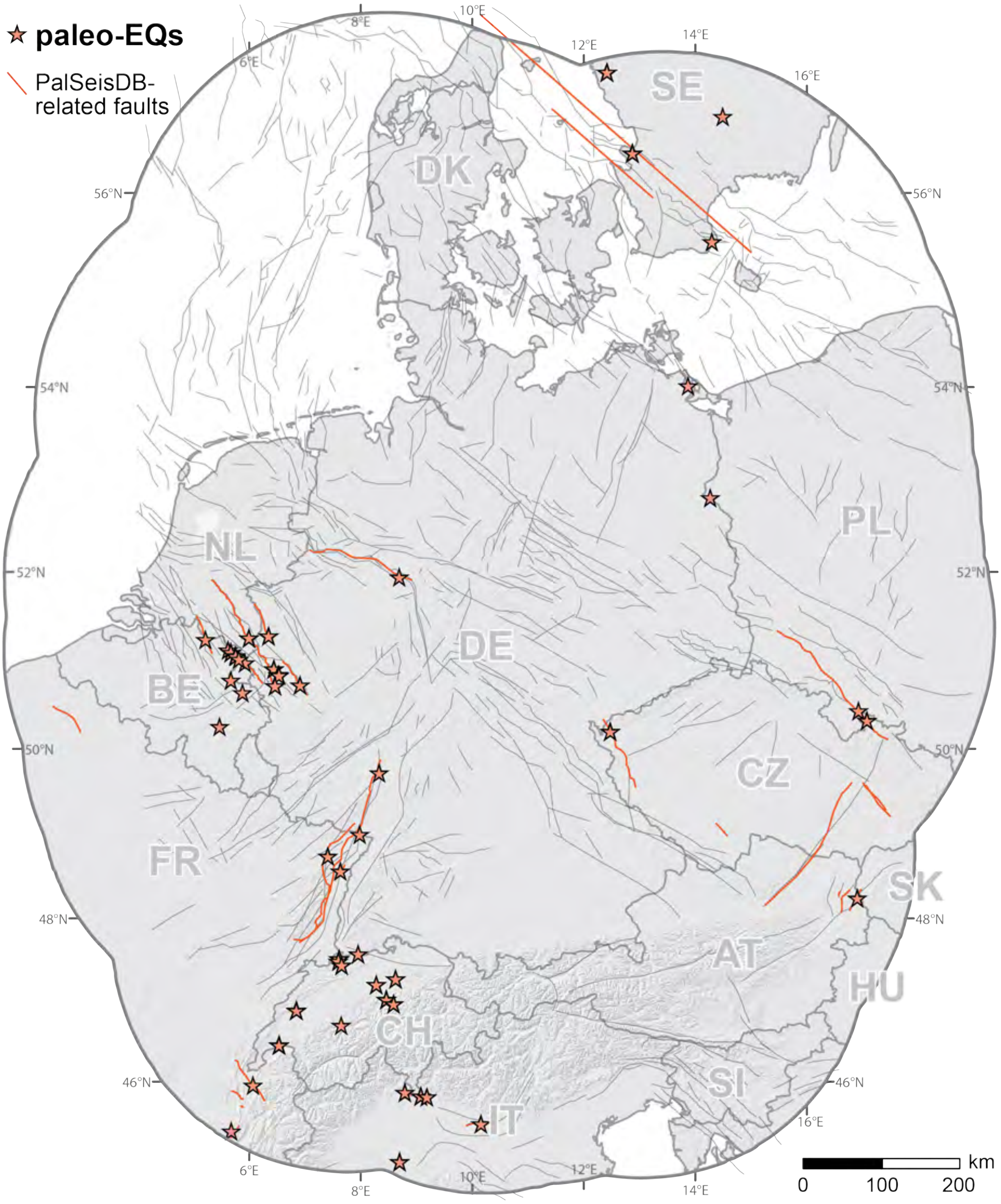


Figure 24. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 105 documented paleoearthquakes (red stars) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, country borders (thick 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.

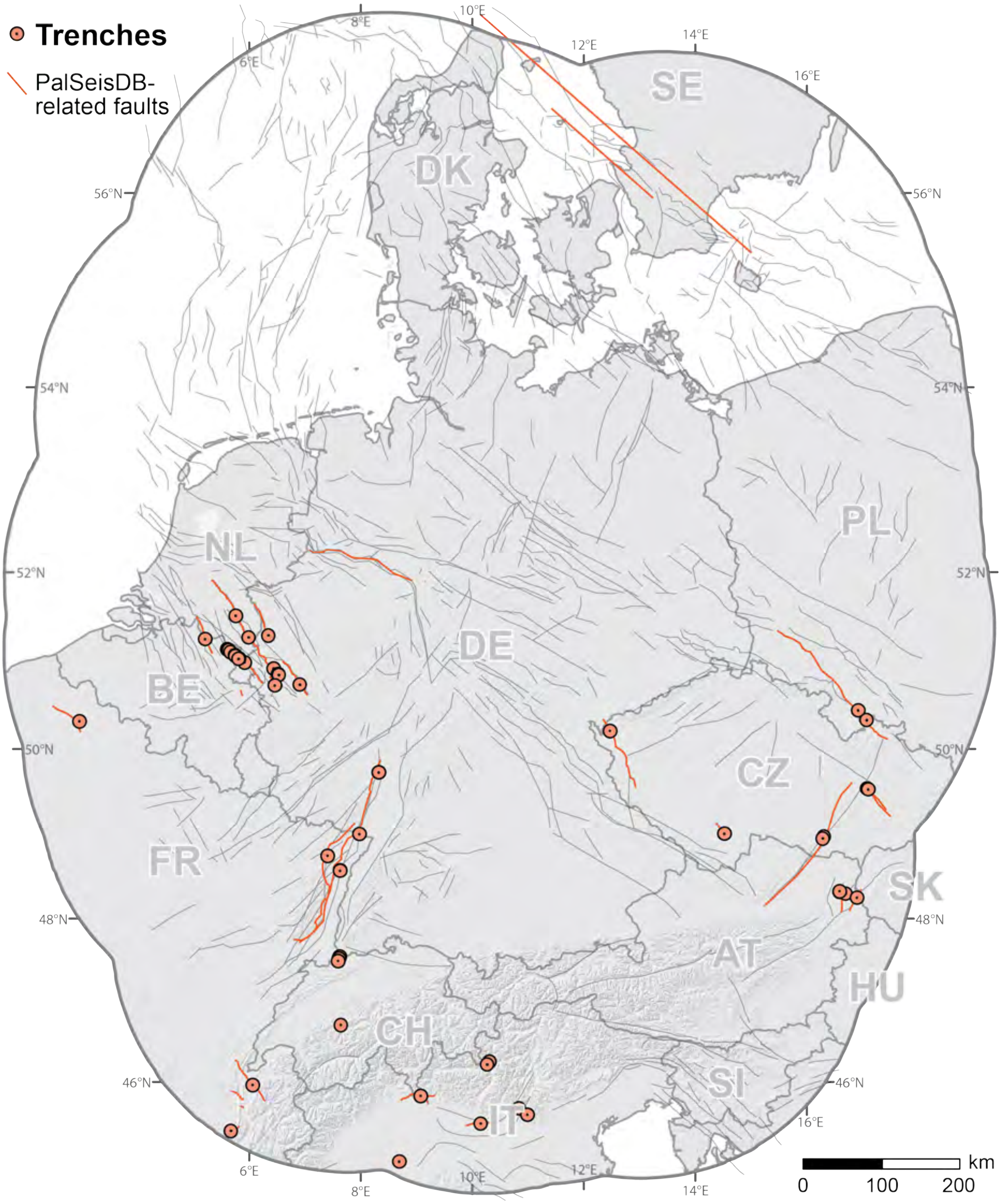


Figure 25. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 62 documented paleoseismic trenches (red dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, country borders (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.

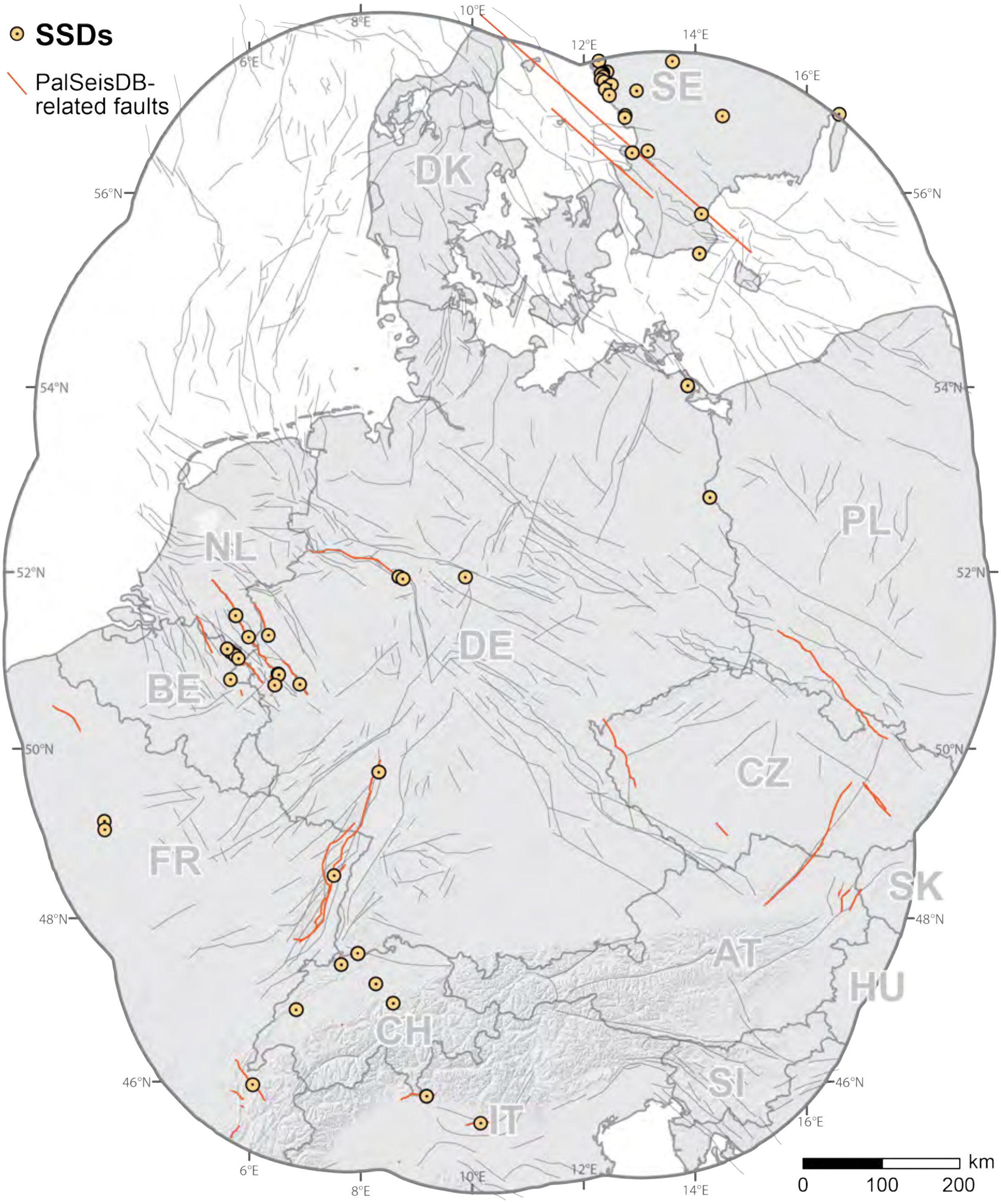


Figure 26. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 116 documented paleoseismic soft-sediment-deformation features (yellow dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). 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.

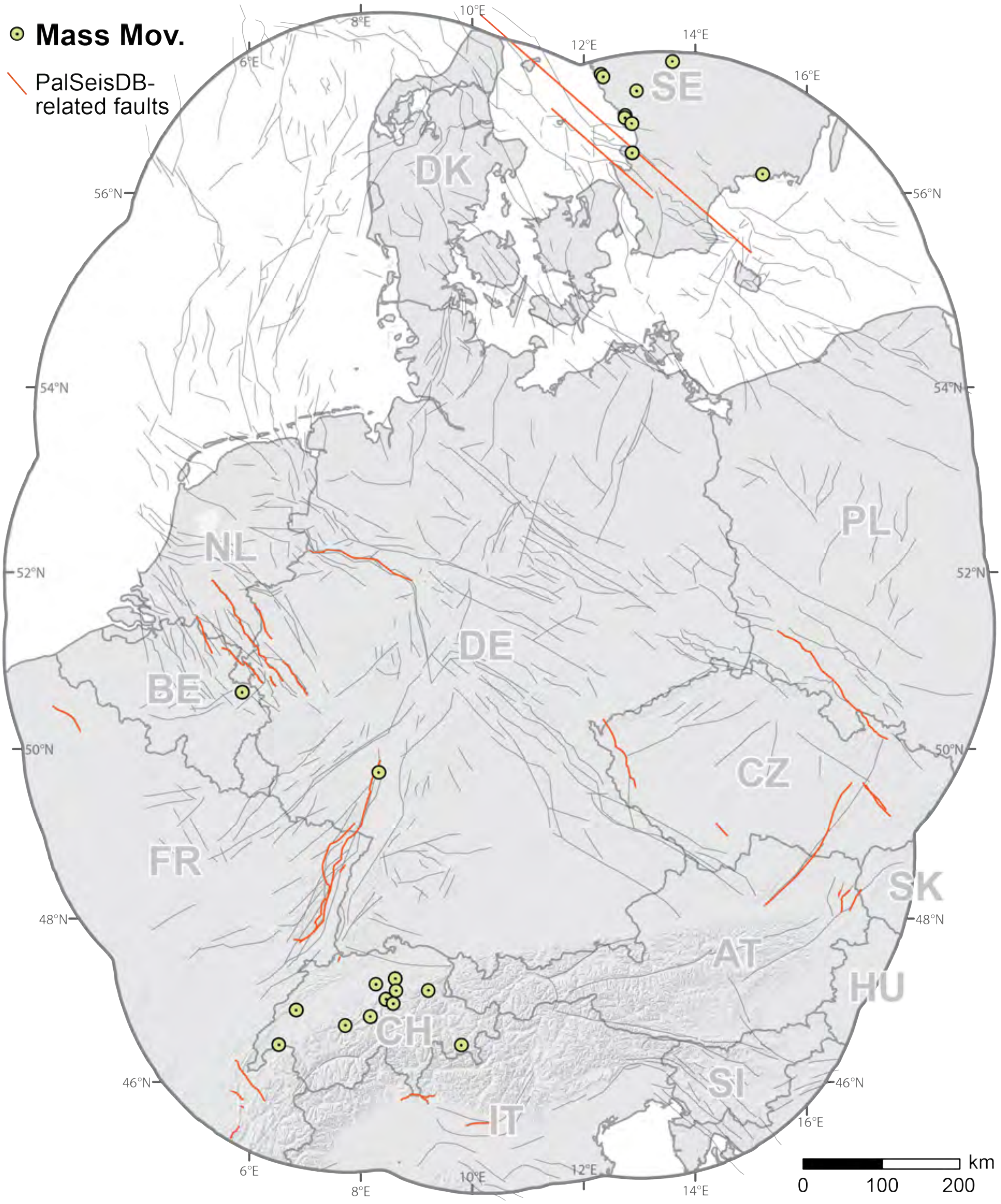


Figure 27. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 61 documented paleoseismic mass movement features (green dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, 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.

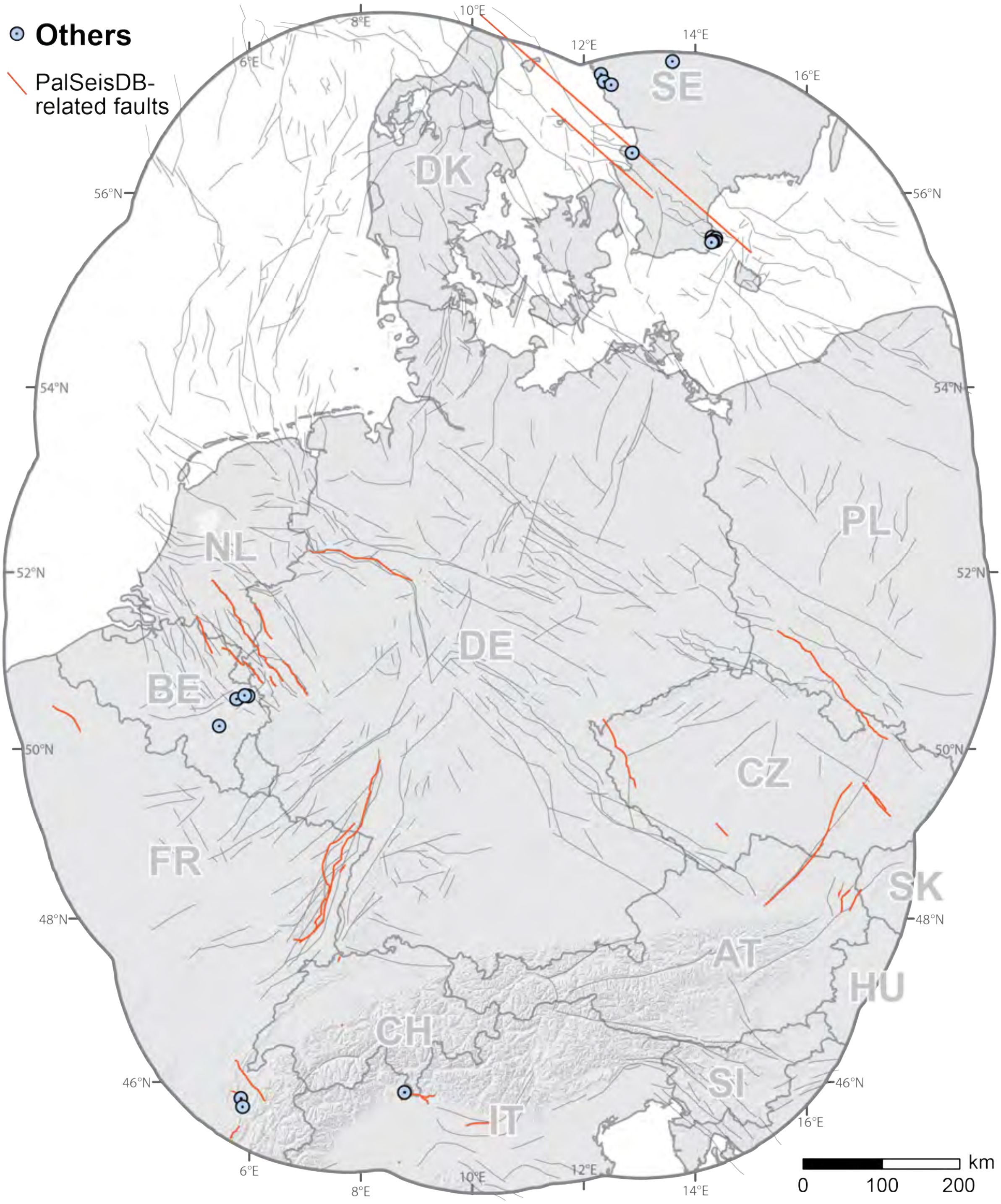


Figure 28. Overview map of the study area of the Paleoseismic Database of Germany and Adjacent Regions (PalSeisDB v1.0) including locations of 21 other documented paleoseismic evidence features (blue dotted circles) and 36 fault traces associated with paleoseismic evidence (thick red lines). Additionally, 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.

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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.

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Ludewig-Meyn-Strasse 10
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