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Spatial variations of earthquake occurrence and coseismic deformation in the Upper Rhine Graben, Central Europe

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ABSTRACT

Seismic activity in the densely populated Upper Rhine Graben (URG) is an aspect in the public, political, and industrial decision making process. The spatial analysis of magnitude–frequency distributions provides valuable information about local seismicity patterns and regional seismic hazard assessment and can be used also as a proxy for coseismic deformation to explore the seismo-tectonic setting of the URG.

We combine five instrumental and one historic earthquake bulletins to obtain for the first time a consistent database for events with local magnitudes $M_L \geq 2.0$ in the whole URG and use it for the determination of magnitude frequencies. The data processing results in a dataset with 274 Poisson distributed instrumentally recorded earthquakes within the URG between 01/1971 and 02/2012 and 34 historic events since the year 1250. Our analysis reveals significant *b*-value variations along the URG that allow us to differentiate four distinct sections (I–IV) with significant differences in earthquake magnitude distributions: I: Basel region in the Swiss–France–German border region ($b = 0.83$), II: region between Mulhouse and Freiburg in the southern URG ($b = 1.42$), III: central URG ($b = 0.93$), and IV: northern URG ($b = 1.06$). High *b*-values and thus a relatively low amount of high magnitude events in the Freiburg section are possibly a consequence of strongly segmented, small-scale structures that are not able to accumulate high stresses.

We use the obtained magnitude–frequency distributions and representative source mechanisms for each section to determine coseismic displacement rates. A maximum horizontal displacement rate of 41 μm/a around Basel is found whereas only 8 μm/a are derived for the central and northern URG. A comparison with geodetic and geological constraints implies that the coseismic displacement rates cover less than 10% of the overall displacement rates, suggesting a high amount of aseismic deformation in the URG.

1. Introduction

The Upper Rhine Graben (URG) is a NNE–SSW striking continental rift north of the Alpine mountain chain in the German/French/Swiss border region (Fig. 1). Its total length is about 320 km from Basel/Switzerland in the south to Frankfurt/Germany in the north. The URG evolved due to polyphase tectonic activity since Eocene time (Schumacher, 2002) and it is one of the active seismic regions in Central Europe. The crustal extent of the graben is about 6 km (Meier and Eisbacher, 1991), which mostly took place in Oligocene and Miocene time; present deformation appears to be low (Fuhrmann et al., 2013). Within the rift 22 earthquakes with maximum intensities $I_0 \geq$ VII occurred since 1000 A.D. (Grünthal et al., 2009). The largest known event occurred just south of Basel in 1356 with $I_0 =$ IX and M_W 6.9 ± 0.2 (Fäh et al., 2009). The deep geothermal exploitation activity and related induced seismicity within the URG (Evans et al., 2012) cause a demand for local information on recurrence intervals of large tectonic earthquakes, thus providing a measure for the potential of induced seismicity. Furthermore, improved magnitude–frequency relations are an important proxy to estimate the natural seismic hazard in the densely populated URG. Evans et al. (2012) evaluated 41 European injection sites and showed that no induced seismicity occurred at sites with a low seismic hazard potential (less than 10% probability of exceeding 0.08 g within 50 years). On the other hand measures of low magnitude tectonic seismic activity may help to discriminate induced seismicity from natural background seismicity (Dahm et al., 2013). Recent studies on seismic hazard have concentrated on high magnitude earthquakes. The global SHARE-project (e.g. Hiemer et al., 2014) did not take into account magnitudes below M_W 3.7 for calculating magnitude frequencies in Central Europe and the Swiss PEGASOS-project used magnitudes of completeness of $M_W \geq 2.3$ in the URG (Burkhard and Grünthal, 2009). Because of that and the generally low number of earthquakes in the URG used for the determination of magnitude–frequency relations, national or regional hazard estimations do not permit an analysis of local variability in seismicity. To study spatial changes in the seismic activity we found it necessary to include as many data as possible, i.e. to use small magnitude earthquakes as long as they are known completely above a certain magnitude threshold.

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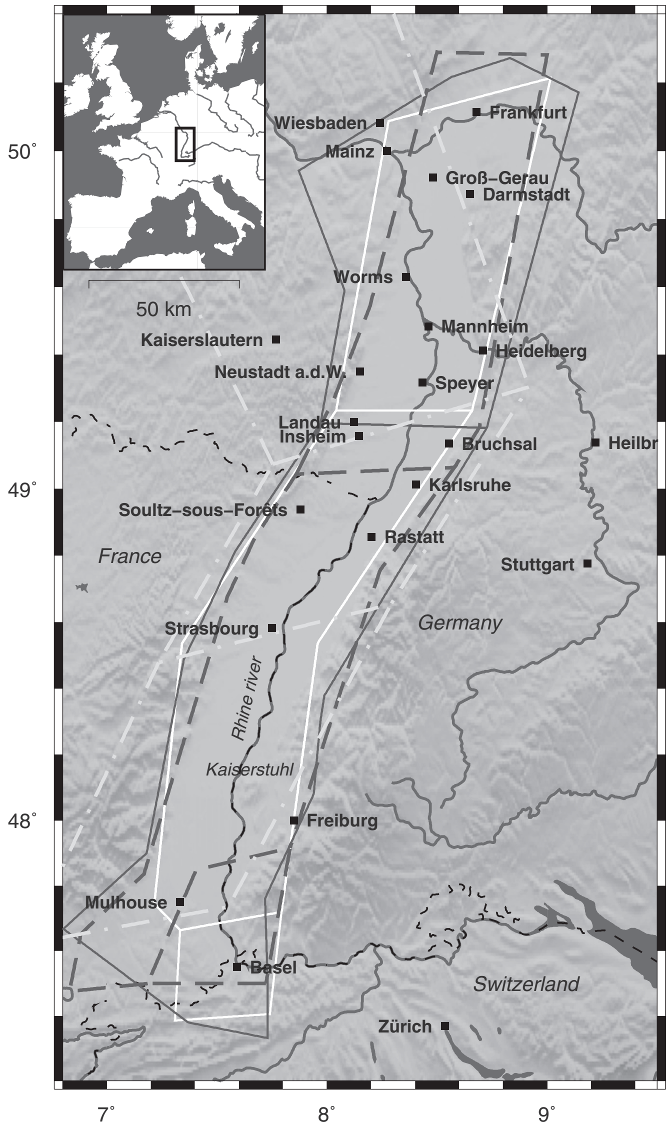

Fig. 1. Seismo-tectonic zones in the Upper Rhine Graben after Leydecker (2011; dark grey solid line), GSHAP (Grünthal et al., 2009, white solid), Helm (1996; light grey dash-dotted), and Burkhard and Grünthal (2009; dashed dark grey).

Spatial seismic zonation is an essential basis for the calculation of magnitude–frequency distributions on a regional scale; however recent studies show a different partitioning especially in the N–S subdivision of the URG (Fig. 1, Section 2.1). New data and a spatial analysis of magnitude–frequency distributions allow us to present an updated systematic zoning of the URG together with an updated determination of recurrence intervals and regional seismic activity.

The oldest documented historic earthquake in the URG is known from 858 A.D. (Leydecker, 2011), with first analogue recordings at the beginning of the 20th century, and a first modern telemetered network installed in 1966 (Bonjer and Fuchs, 1974). Since the 1970s the seismic instrumentation along the URG was constantly improved by state agencies and research institutions. Nowadays, dense seismometer networks with about 40 seismic stations are recording the ground motion of the URG continuously. The seismometers are maintained from different agencies in Germany, France, and Switzerland. This instrumental data has decreased the magnitude threshold of earthquake detection and location, providing a valuable dataset for the subdivision of larger into smaller regions with similar seismogenic behaviour. A non-uniform distribution of epicentres in the URG was first recognised by Hiller et al. (1967), and early work including instrumental recordings was summarised in Ahorner and Schneider (1974) and Bonjer et al. (1984). Partly, seismicity can be assigned to known fault systems (Behrmann et al., 2003; Bonjer, 1997a). Based on eight years of instrumental recordings and modern location, Lippert (1979) divided the URG proper into five seismic provinces with varying seismic activity, which was described with the *b*-value of the Gutenberg–Richter distribution (see Section 4.1): a seismic active northern part ($b = 0.58$), a less seismic active central part ($b = 0.74$), the area north of Freiburg ($b = 0.94$), the very active southern part ($b = 0.92$) and the area around Basel including the Dinkelberg block ($b = 0.88$). For the entire URG Lippert (1979) determined $b = 0.74$, which is nearly identical to the value of $b = 0.73$ for instrumental (1971–1979) and macroseismic (1900–1970) data by Bonjer et al. (1984). Recently Burkhard and Grünthal (2009) assigned a higher *b*-value of 0.858 ± 0.057 to the URG as a large zone and derived a more detailed zone for Basel ($b = 0.894$), the Dinkelberg ($b = 0.920$), the southern URG ($b = 0.810$), and the northern URG ($b = 0.856$). A local study using 56 events with magnitudes $M_L \geq 1.3$ in the vicinity of Groß-Gerau resulted in a *b*-value of 0.9 (Homuth et al., 2014). Of course all these *b*-values depend on the regionalisation used and the treatment of the earthquakes catalogues (completeness estimate, handling of fore- and aftershocks, see Section 3).

The determination of fault plane solutions, their 3-D distribution, and interpretation of the underlying stress field is important for the understanding of recent tectonics and necessary for the calculation of seismic deformation. Generally, mainly strike-slip and normal faulting is observed (Ahorner and Schneider, 1974; Deichmann and Giardini, 2009; Gaßner et al., 2014; Plenefisch and Bonjer, 1997; Ritter et al., 2009). Strike-slip and normal-faulting regimes seem to dominate at different depths: Plenefisch and Bonjer (1997) demonstrate preferred strike-slip in the upper crust and normal faulting in the lower crust of the southern URG, indicating a mechanical decoupling inside the crust.

In the following we combine different earthquake catalogues for the first time to establish a consistent earthquake database for the whole URG. This database reveals spatial changes of earthquake occurrence and permits a revision of existing seismic zonation models. The strain rates in the derived sections of the URG are estimated and discussed in terms of current geodynamic processes. The presented magnitude–frequency distributions are of high relevance for the industry and authorities to estimate the occurrence of local seismicity and might give insights into the recent tectonic development of the URG.

2. Earthquake data and seismic zonations

2.1. Seismic zonations

Several seismic zonations have been suggested for the URG (Fig. 1, see Leydecker, 2011; Burkhard and Grünthal, 2009; Grünthal and Bosse, 1996; Helm, 1996); they mainly differ in their subdivisions along the rift. Some separate the URG in two, others in three sections. For a southernmost section around the city of Basel, a northern boundary at 47.69°N (~15 km north of Basel) is proposed in Grünthal and Bosse (1996) and at 47.88°N (~10 km south of Freiburg) in Burkhard and Grünthal (2009). Helm (1996) used NE–SW striking boundaries as proposed by Grellet et al. (1993) to separate the southern and central part of the URG at about 48.56°N (south of Strasbourg). All authors agree that there is a difference between a northern and a central section of the URG, with a boundary north of Karlsruhe between 49.0°N and 49.3°N. Leydecker (2011) put this boundary at the latitude of Landau (49.19°N) and Helm (1996) used a separating line trending from 49.1°N in the SW to 49.25°N in the NE (Fig. 1). Burkhard and Grünthal (2009) subdivide the central and northern URG at a latitude of about 49.04°N (northern part of Karlsruhe), while Grünthal and Bosse (1996) used a line about 20 km further to the north, south of the city of Speyer (49.23°N). The latter zonation is also used for the German building code DIN 4149 (2005), the official German earthquake zonation, and for the Global Seismic Hazard Assessment Program