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Seismicity pattern and magnitude frequencies of the Upper Rhinegraben

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Abstract

The Upper Rhinegraben (URG) is one of the active seismic regions in Germany. Due to the dense population and a high concentration of industrial sites (not least active or planned geothermal power-plants) the seismicity is of common interest on a regional to local scale. We use the magnitude-frequency distribution of instrumentally recorded earthquakes to study the seismicity along the URG. The analysis of 237 declustered events $M_L \geq 2.0$ reveals an increased *b*-value in the region around Freiburg and relatively higher event rates for $M_L \geq 2.0$ compared with the central and northern sections of the URG. Taking into account the occurrence of lower crustal seismicity in the very southern and northern part of the URG, we suggest a separation of the URG in a northern, central and southern seismic zone.

Introduction

The seismicity of the URG is moderate. Only 22 earthquakes with maximum intensities $I_0 \geq$ VII occurred since 1000 AD within the rift (Grünthal et al., 2009). The largest known event occurred just south of Basel in 1356 with I_0=IX. Because of its higher quantity of earthquakes most seismicity studies cover the southern part of the URG (e.g. Bonjer, 1997a). Nevertheless, the local seismic activity in the whole URG is of importance for public, political, and industrial interests. The growing geothermal exploitation activity within the URG requests local information on recurrence intervals of tectonic earthquakes embedded in a regional context. Seismic hazard zonations can be used to answer these questions on magnitude-frequency distributions on a regional scale. Unfortunately, various recent studies disagree in the partitioning of the URG. In their official seismogeographical regionalisation adopted by the IASPEI Leydecker & Aichele (1998) regard the whole URG as one seismo-tectonic unit including Basel.

However, a recent study by Burkhard & Grünthal (2009) subdivides the URG in three sections: the region of Basel, the southern and northern URG with a boundary at a latitude of around 49.04°N (northern part of Karlsruhe). The Global Seismic Hazard Assessment Program (GSHAP, Grünthal et al., 1999) puts this border approximately 20 km further north (49.24°N, near Phillipsburg). The latter is also the basis for the German Building Code (DIN 4149) and the official German earthquake zonation.
Most of the URG belongs to earthquake zone 1 (DIN 4149), i.e. 10% probability of a maximum intensity I_0=VI-VII earthquake within 50 years. The region south of Freiburg is part of zone 2 (10% prob. of I_0=VII per 50 a), and zone 3 (10% prob. of I_0=VII-VIII per 50 a) is assigned to Basel and its surrounding (Grünthal et al., 1998).

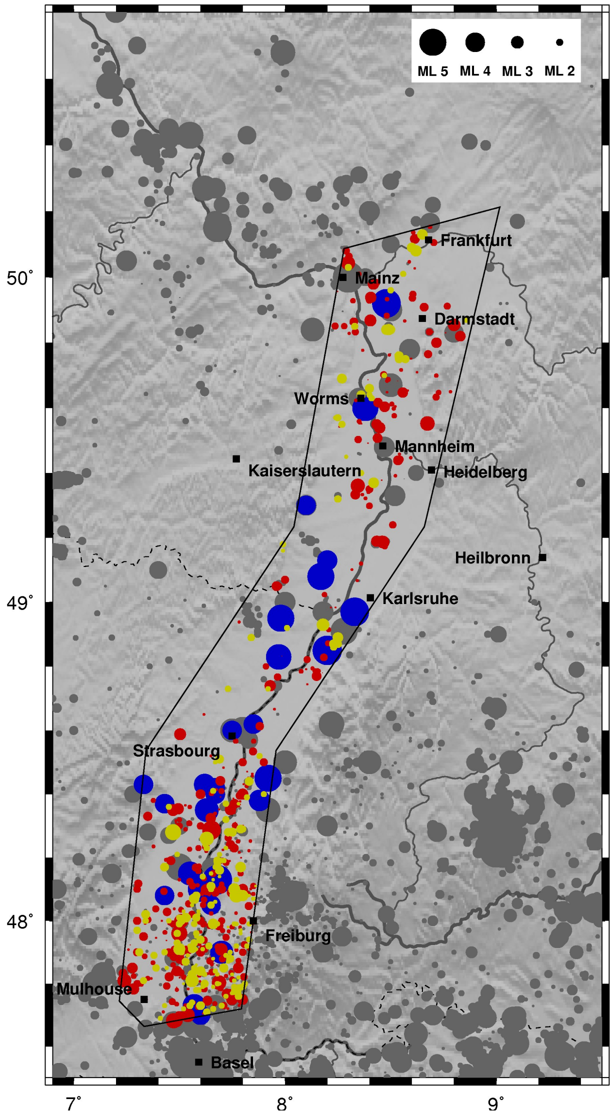

Figure 1: Seismicity in the URG. Instrumental observations: Bonjer (1997a,b, red dots, 1971-1996) and LGRB Baden-Württemberg (yellow dots, 1997-2009). Blue dots show historic data (CENEC, Grünthal et al., (2009), 1869-1970). Gray dots fall outside the URG (solid frame, as used in this study) or are aftershocks, part of event series or related to man-made activity. Size scales with M_L.

Earthquake data

Figure 1 shows the earthquake distribution in the URG. South of Strasbourg the quantity of seismicity is higher than north of it. The analysis of earthquake depths reveals lower crustal activity approximately south of Freiburg (Bonjer, 1997a) and north of Karlsruhe (Ritter et al., 2009).
To analyse the seismicity of the URG we use two instrumental catalogues covering the whole rift (Fig. 1):

- nrift-catalogue, 1971-1996 (Bonjer, 1997a,b)
- Bulletin of the Landesamt für Geologie, Rohstoffe und Bergbau (LGRB) Baden-Württemberg (digital data: 1997-2009).

For calculating Gutenberg-Richter (G-R) distributions, we use the boundary of the URG after DIN 4149. We decluster the dataset, excluding aftershocks, earthquake series (except the strongest event), and seismicity related to man-made activity. This results in a reduction from 1118 to 647 events between 1971 and 2009. The maximum magnitude contained in our dataset within the rift occurred on 27 October 1979 between Sélestat/F and Lahr/D with a magnitude M_L 3.9.
In contrast to former studies, which use both, historic and instrumental data, we include instrumental observations only, since historic data are affected by uncertainties up to half a

magnitude (Grünthal et al., 2009). In addition to a more reliable dataset, this allows us to compare those historic magnitudes with predictions from instrumentally based frequency-magnitude distributions.

Magnitude-frequency distribution

To analyse the magnitude-frequency or G-R distribution we apply the maximum-likelihood estimation after Aki (1965) and Utsu (1965):

$$b=(\bar{M}-M_0)^{-1}\cdot\log e \,, \qquad (1)$$

with the mean magnitude $\bar{M}$ and a magnitude level of data completeness M_0. Under the assumption that the datasets are samples from a population obeying the G-R relation, this formulation is equivalent to the classical G-R distribution

$$\log N(M)=a-bM \,. \qquad (2)$$

Cumulative statistics for the event numbers are less affected by short time-intervals (as in this study) than incremental representations. Thus the maximum-likelihood estimation is preferable to a linear regression because of its validity for analysing dependent data. The level of completeness M_0 is determined to M_L 2.0 and reduces the data set to 237 seismic events in the whole URG (Fig. 3a).
We subdivide the dataset into groups that extend over the whole width of the URG and that contain 50 events each. These regions are shifted by 0.01 degree in latitude to each other to obtain a continuous mapping of the G-R parameters. Independent G-R parameters exist for four of the regions (4 × 50 events per region ≤ 237 events total). For each region we determine *b*-values following eq. 1, and we use eq. 2 to calculate the absolute level of seismicity *a*. Figure 2 shows an example for the G-R relation of the southernmost part of the study region. Clearly, magnitude frequencies for $M_L < 2.0$ do not meet the logarithmic trend, because the data are not complete. For magnitudes $M_L \geq 3.3$ the data are not representative because of the short time span. The maximum likelihood estimation results in a *b*-value of 0.98 and an absolute number of 1.48 events with $M_L \geq 2.0$ per year.

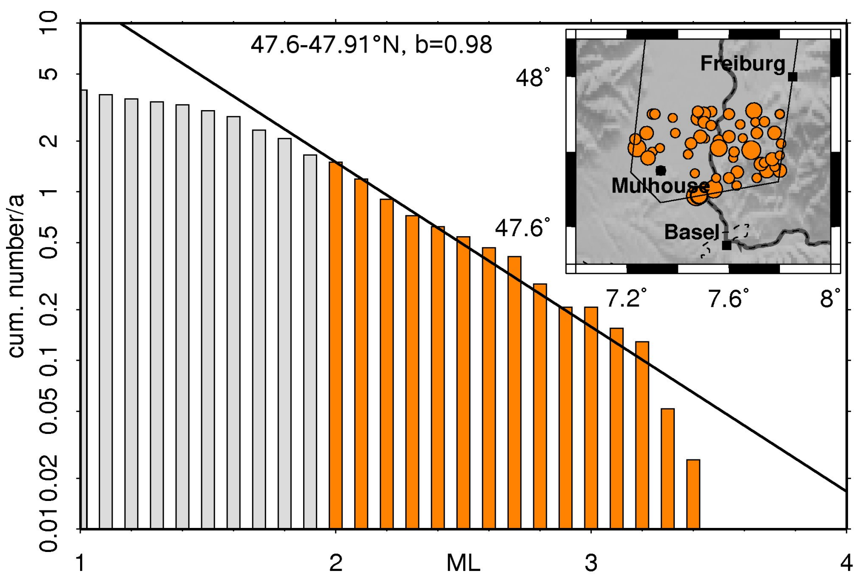

Figure 2: Magnitude frequency distribution for the southernmost part of the study area. 50 events with $M_L \geq 2.0$ (coloured) are used for the maximum-likelihood estimation in this region (solid line, eq. 2).

Results

The maximum-likelihood estimation for 185 overlapping regions (Fig. 3) – each containing 50 events – results in a stable b-value in the central and northern part of the URG (north of 48.25°N). The average of those regions is b=0.98. However, the southern part shows a maximum b=1.43 at the region 47.9-48.06°N, that is around the latitude of Freiburg. The average value south of 48.25°N is b=1.18, and thus it is clearly increased with respect to the northern and central URG. Standard deviations after Utsu (1965) depend on the b-value and range from 0.13 to 0.20 for the minimum and maximum b-value, respectively.

Event rates for magnitudes $M_L \geq 2.0$ are highest around the latitude of Freiburg with $\mu(2.0)$=1.8 events per year per 1000 km^2. For a better comparability we use normalised areas, since the single subregions do have different lateral extensions. The minimum event rate is found for a wide region from 48.41°N to 49.71°N (approximately Strasbourg to Mannheim) with $\mu(2.0)$=0.21/a/1000 km^2. These rates for $M_L \geq 2.0$ result directly from the observed input data and show a variation within the URG of one order.

However, rates for $M_L \geq 1.0$ can be estimated based on the higher magnitude data. This extrapolation allows us a quantity estimation even for regions with an observational detection level higher than M_L 1.0. The curve for $\mu(1.0)$ (no figure) shows a similar shape than that for $\mu(2.0)$ with a maximum of $\mu(1.0)$=50/a/1000 km^2 and a minimum of $\mu(1.0)$=2/a/1000 km^2 (at latitudes as for $\mu(2.0)$), i.e. a span of 1.5 orders.

A correlation of the occurrence estimations for $M_L \geq 4.0$ with historic earthquake data is difficult, since only 53 events are listed in the CENEC-catalogue (Grünthal et al., 2009) that occurred within the URG and do not belong to an event series (except the strongest event). For $M_L \geq 4.0$ occurrence maxima are predicted north and south of Freiburg. North of Strasbourg the event rates are quite stable. The most interesting property of the $\mu(4.0)$ prediction is that it spans over less than one order (0.2-1.4 events $M_L \geq 4.0$/100 a/1000 km^2) and thus it is less heterogeneous than it might be expected from the instrumentally observed seismicity (Fig. 1).

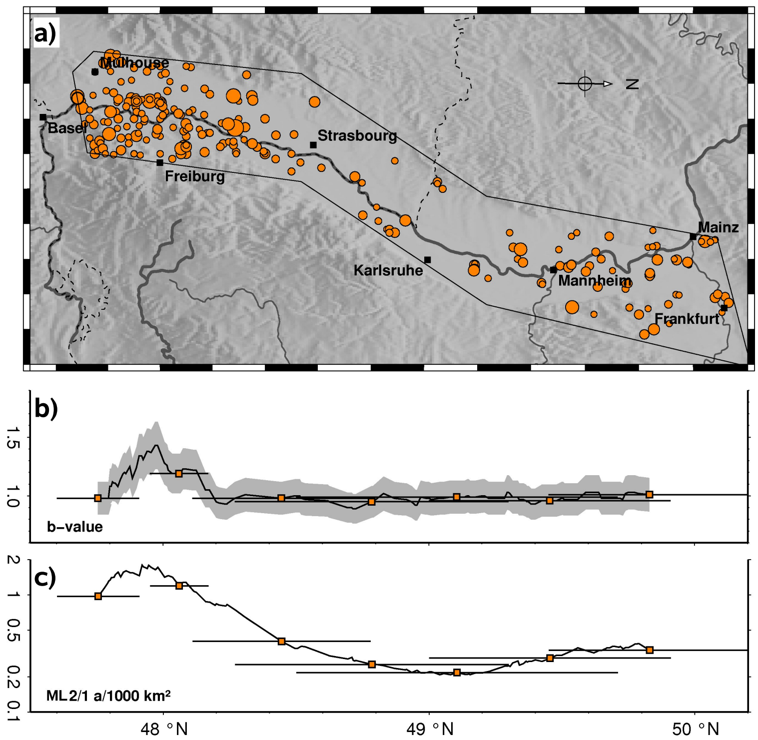

Figure 3: Result of the regional magnitude-frequency analysis for the URG. a) Earthquake dataset $M_L \geq 2.0$ (237 events, 1971-2009). b) b-values for overlapping regions (each containing 50 events). The shaded area gives the standard deviations after Utsu (1965). c) Event rates normalised to one year and 1000 km^2. Coloured squares give exemplary centres of regions, the horizontal lines indicate the lateral extend of the regions.

Conclusions

The maximum-likelihood estimation for subregions of the URG and the earthquake depth distribution reveal a seismogenic separation of the rift in three sections:

- *Northern URG* (north of 49.1-49.3°N, border between Karlsruhe and Mannheim) $b\approx1.0$, $\mu(2.0)\approx0.3$/a/1000 km^2, lower crust seismicity
- *Central URG* (between Northern and Southern section) $b\approx1.0$, $\mu(2.0)\approx0.2$/a/1000 km^2, no lower crust seismicity
- *Southern URG* (south of 48.1-48.2°N, border north of Freiburg) $b\approx1.2$, $\mu(2.0)\approx1.4$/a/1000 km^2, lower crust seismicity

Our findings contain important parameters for the estimation of the natural, background seismicity in specific regions of the URG. The spatial event rates can be of use for seismic hazard analysis in general and especially in terms of future geothermal exploitation activity.

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