Update of the Seismogenic Potential of the Upper Rhine Graben Southern Region

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TEXT S1: DECLUSTERING FROM MARSAN ET AL. (2017)

Marsan et al. (2017) approach for declustering is based on the space-time Epidemic-Type Aftershock Sequence (ETAS) model (Ogata, 1998). We first estimate M_c by fitting the magnitude frequency distribution (MFD) of earthquakes by the following model (Ogata and Katsura, 1993; Daniel et al., 2008): $N(m) = A \times 10^{-bm} \times q(m)$. $N(m)$ is the number of events of magnitude m, $q(m)$ corresponds the probability of an event of magnitude m to occur during the time period of the analyzed catalog, b correspond to the b-value of the MFD, and A is a constant. Events below the maximum curvature, roughly indicating M_c (Wiemer and Wyss, 2000), are also included in the fit. $q(m)$ is defined by Ogata and Katsura (1993) equation:

$$q(m) = \frac{1}{2} + \frac{1}{2}\ erf(\frac{m - \mu}{\sqrt{2\sigma}})$$

where erf is the error function. The parameters μ, σ, b, and A are evaluated from the data and M_c is estimated using $M_c = \mu + 2\ \sigma$ (i.e. with 97.7% confidence). M_c is estimated at 2.2 and 3.2 for the instrumental (>1994) and historical (>1850) catalogs. The results of the declustering of the instrumental and historical catalogs are shown in Figure S6 and S7.

TEXT S2: DECLUSTERING FROM ZALIAPIN & BEN ZION (2013)

We use the declustering from Zaliapin and Ben-Zion (2013) on the same catalogs and magnitude of completeness as for Marsan et al. (2017) (Section 3.2 in main text and Text S1). The parameters for Zaliapin and Ben-Zion (2013) method contains two parameters to tune: the fractal dimension of epicenters that we chose equal to 1.6, the default value used by Zaliapin and Ben-Zion (2013) in southern California; and the b-value. We tested three different b-values (0.5, 1.0 and 1.5). The results of the declustering are shown in Figure S9 and S10, and its impact on the probabilities of M_{max}, the b-value and $P(\tau \mid M_w = M_{Mode})$ are shown in Figure S11. The three different b-values tested provide very similar results (Figure S11).

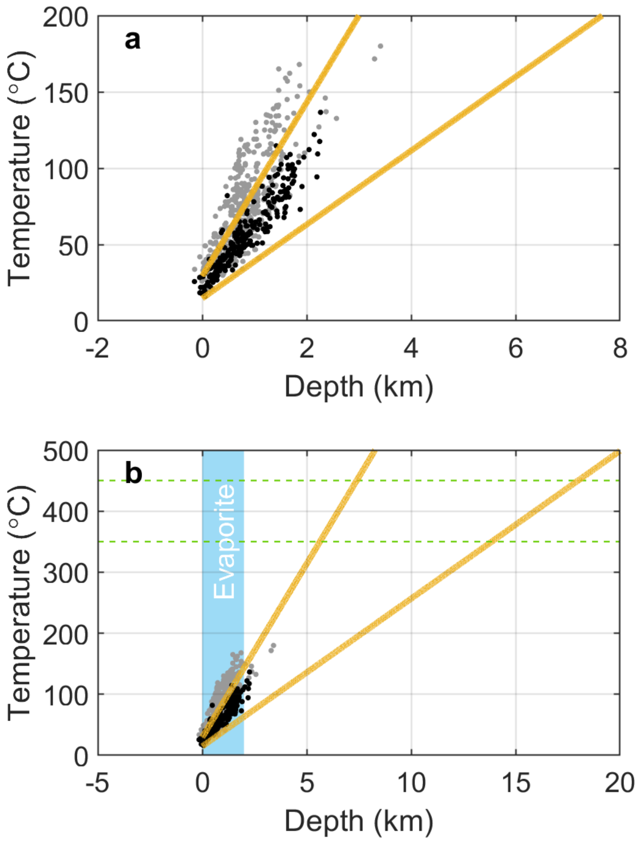

Figure S1: (a) Temperature as a function of depth based on borehole data from Guillou-Frottier et al. (2013) (grey dots). The black dots indicate the borehole data south of the city of Strasbourg, within the region of interest. The envelope of the black dots is roughly indicated by the the yellow lines. (b) Same is (a) but with larger depth and temperature ranges. The green dashed horizontal lines indicate the 350°C and 450°C isotherms, between which a transition in frictional properties occurs for quartzo-feldspathic rocks (Blanpied et al., 1995). The blue shaded area highlight the potential depth range of the potash-salt evaporitic basin.

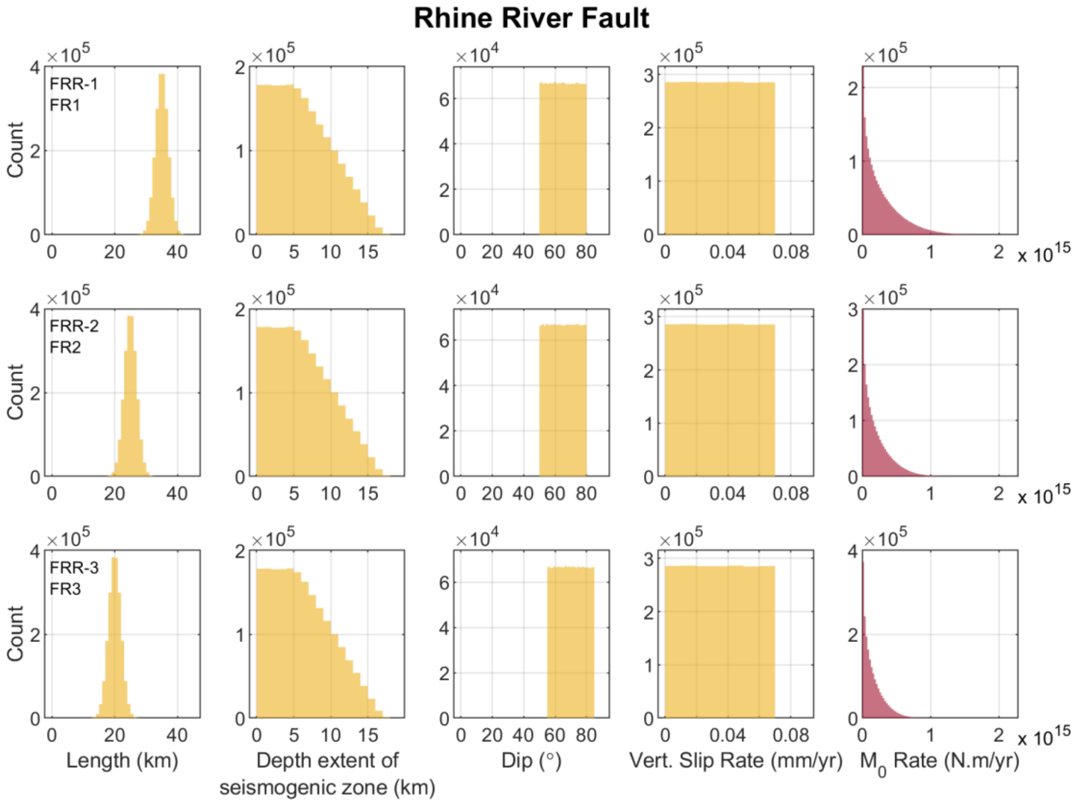

Figure S2: Constitutive parameter PDFs of each segment of the Rhine River Fault. Note that the samples are identical for each segment for the depth extent of the seismogenic zone and for the vertical slip rate. The details of the PDFs are given in Table 1.

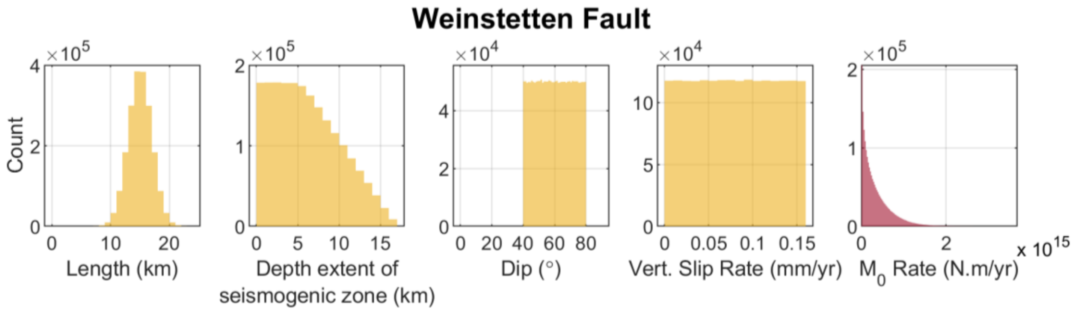

Figure S3: Same as Figure S2 but for the Weinstetten Fault.

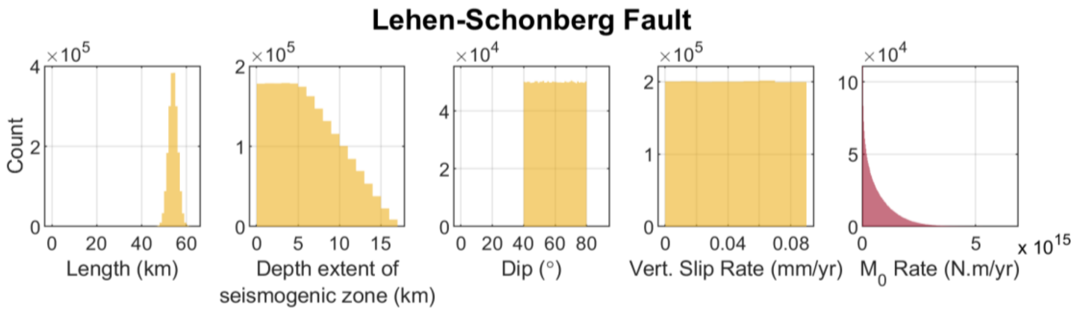

Figure S4: Same as Figure S2 but for the Lehen-Schonberg Fault.

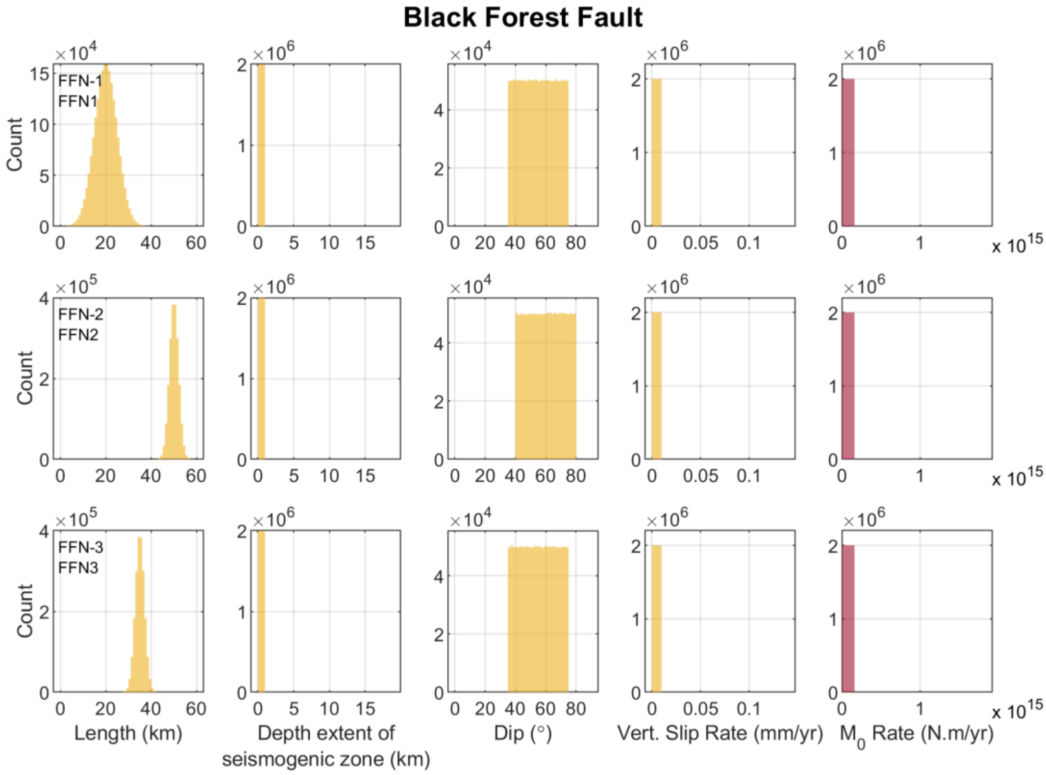

Figure S5: Same as Figure S2 but for the Black Forest Fault.

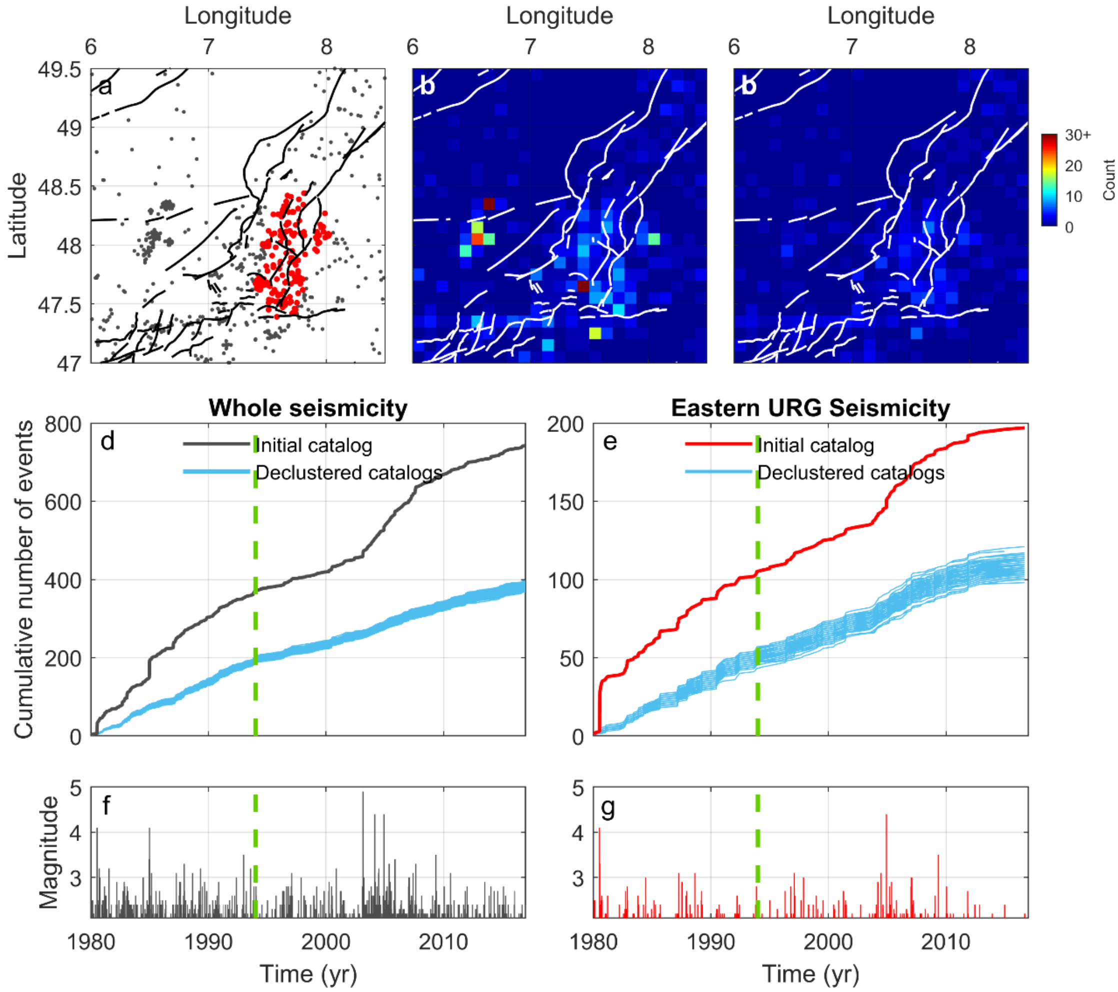

Figure S6: (a) Seismicity in the southern Upper Rhine Graben region from Drouet et al. (2020) catalog between 1980 and 2016 ($M_c = 2.2$). Events represented with red dots indicate the ones selected for the seismic potential analysis. (b) Earthquake density map with $M_w \geq 2.2$. (c) Background earthquake density map from the declustering of events with $M_w \geq 2.2$ (Marsan et al., 2017). The number of earthquakes per cell (0.1° x 0.1° in longitude and latitude) indicates the mean number of events based on 100 catalogs created from sampling for each event the probability to be part of the background seismicity. (d) Cumulative number of events since 1980 using the whole earthquake catalog. The gray and blue curves indicate the results before and after declustering, respectively. A hundred declustered catalogs are shown to illustrate the effect of sampling the probability of events to be mainshocks. The vertical green dashed line indicate the date from which we assume the catalog to be complete. (e) Same as (d) but for the selected events (red dots in (a)). (f) and (g) show the magnitude of the events through time for the whole catalog and for the selected events, respectively.

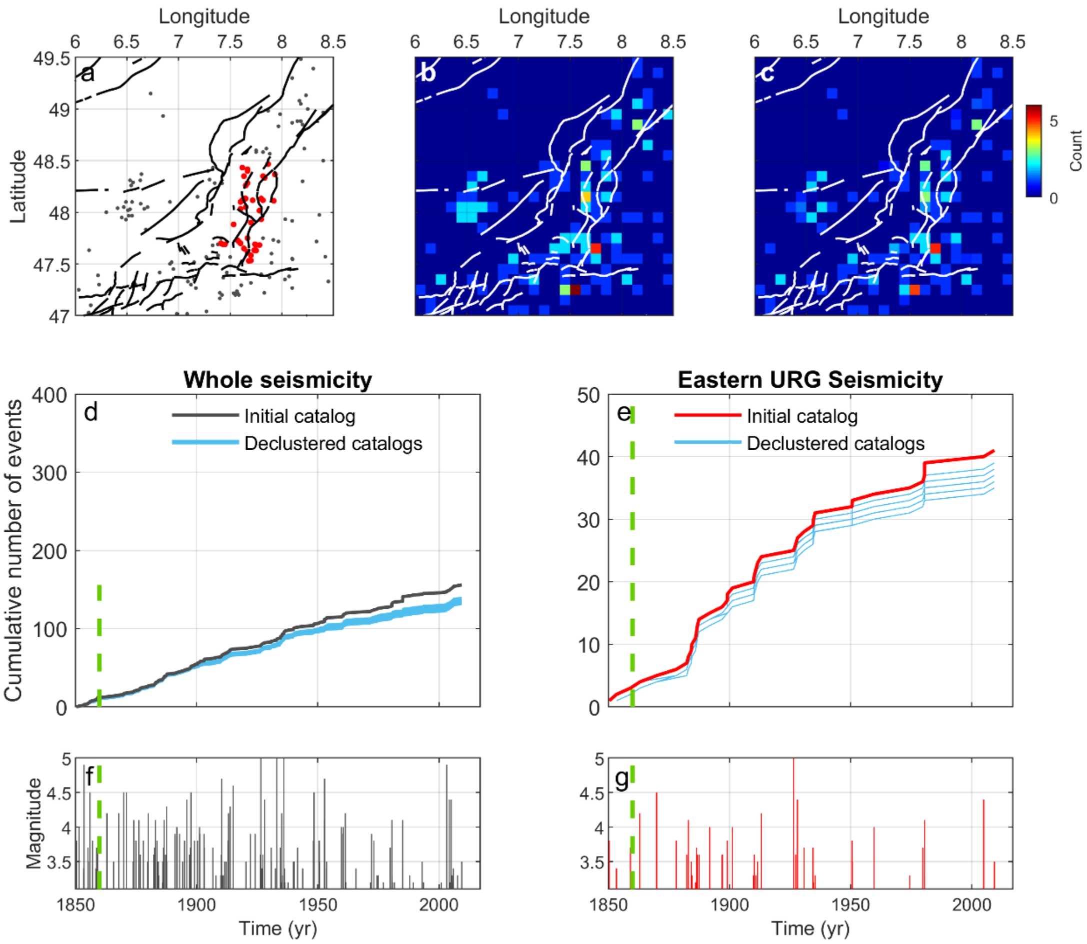

Figure S7: Same as Figure S6 but for the period between 1850 and 2016, taking $M_c = 3.2$.

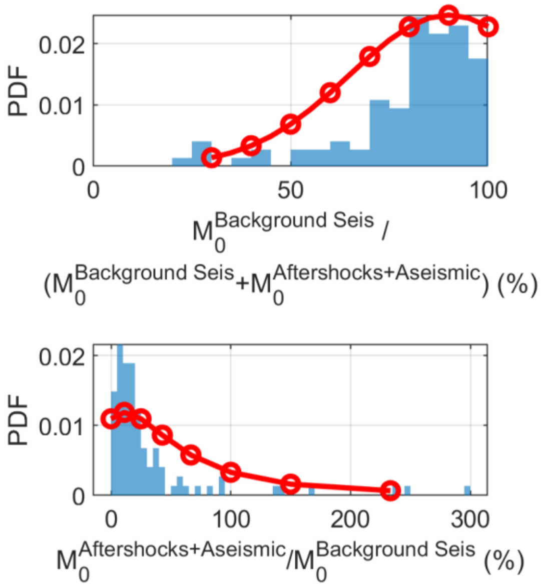

Figure S8: Afterslip and aftershock contribution. Blue histograms are based on Churchill et al. (2022) dataset. The red lines and dots correspond to the PDFs used and values explored for the seismicity models in Section 3.3.

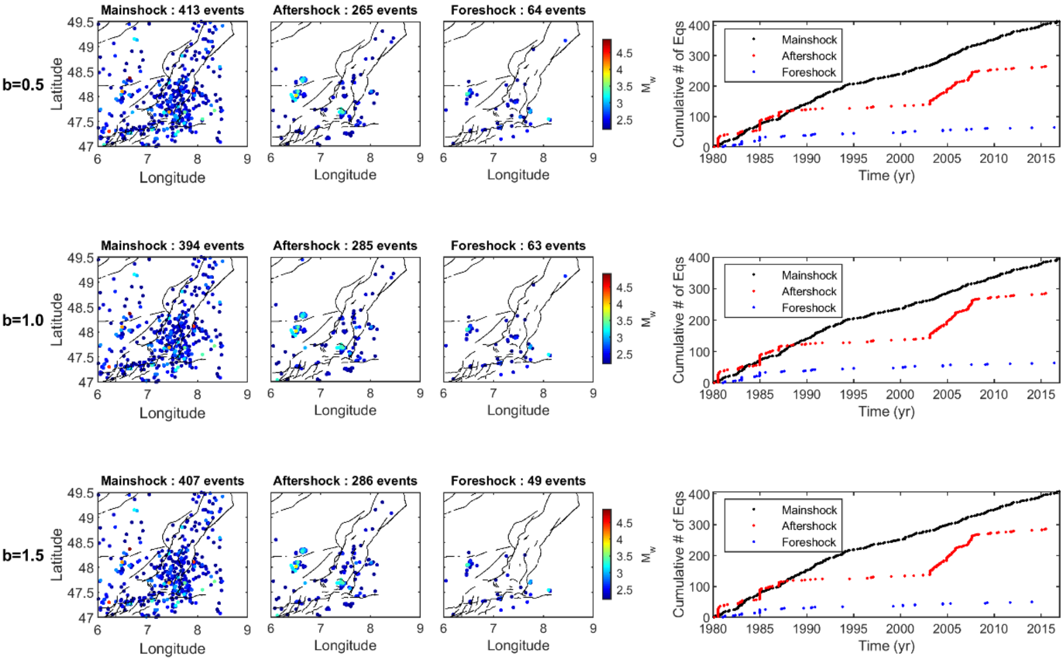

Figure S9: Results from the declustering method of Zaliapin and Ben-Zion (2013) on $M_w \geq 2.2$ events between 1980 and 2016, for different imposed b-values.

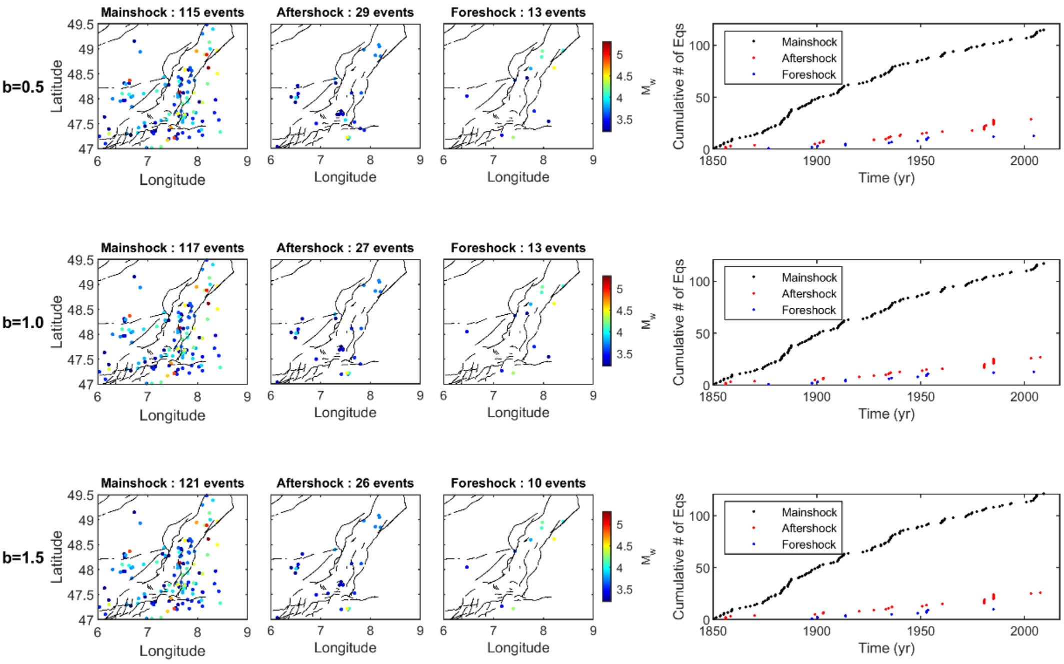

Figure S10: Results from the declustering method of Zaliapin and Ben-Zion (2013) on $M_w \geq 3.2$ events between 1850 and 2016, for different imposed b-values.

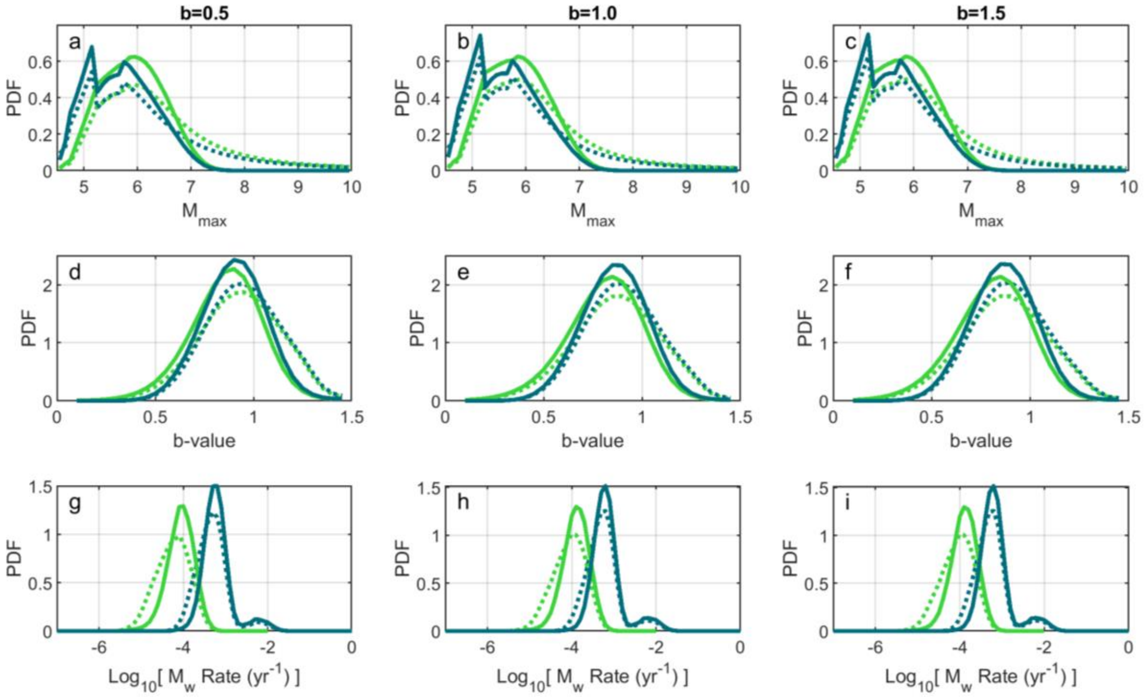

Figure S11: Results using the declustering method from Zaliapin and Ben-Zion (2013) instead of Marsan et al. (2017). In this scenario, no probabilities of events to be mainshocks are defined. (a), (b) and (c) M_{max} PDF. (d), (e) and (f) b-value PDF. (g), (h) and (i) $P(\tau \mid M_w = M_{Mode})$ PDF. (a), (d) and (g) correspond to the results using a declustering with b=0.5. (b), (e) and (f) correspond to the results using a declustering with b=1.5. (c), (f) and (i) correspond to the results using a declustering with b=1.5. Solid lines correspond to the results using all constraints while the dotted lines use only the moment budget and earthquake catalogs constraints. Green and blue lines indicate results from the tapered and truncated models, respectively.

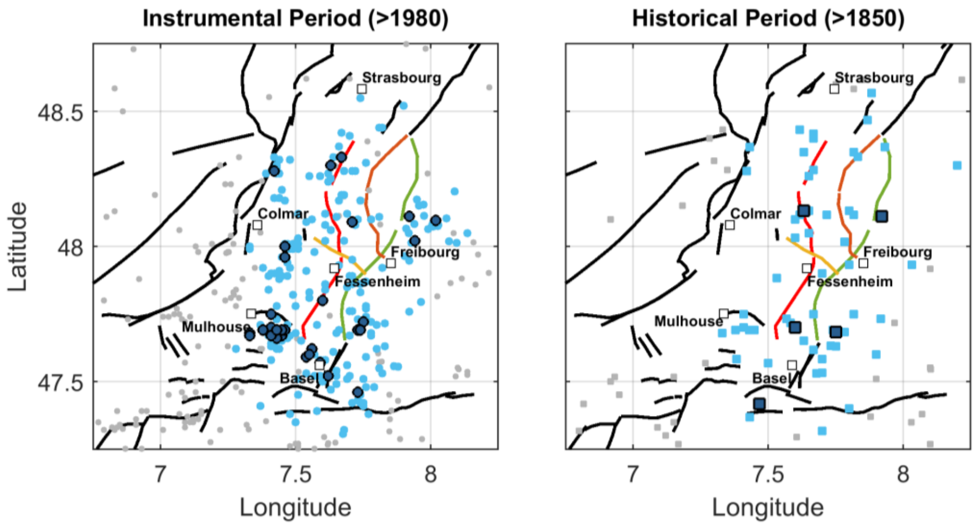

Figure S12: Earthquake selection for the instrumental (>1994) and historical (>1850) periods. Gray dots and squares indicate all earthquakes with $M_c = 2.2$ and 3.2 for the instrumental and historical catalogs, respectively. Light blue dots and squares indicate earthquakes within 20-km of the faults, taken into account for the seismogenic potential analysis in Figure S13 (Section 5.2). Dark blue dots and squares indicate $M_w > 2.75$ and 4.25 earthquakes taken into account for the seismogenic potential analysis.

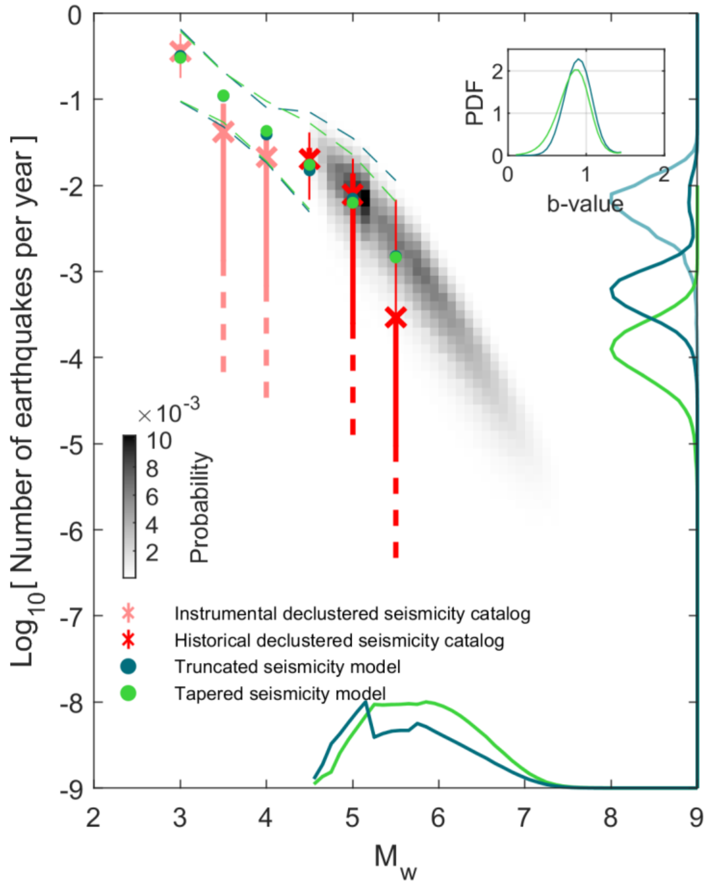

Figure S13: Seismogenic potential of the URG using all constraints, but taking events within 20 km of the faults, instead of 10 km as defined initially (Section 3.2). The rate of occurrence of historical and instrumental earthquakes, within their observation period, are indicated by red and pink crosses and error bars, respectively. The thick and thin error bars indicate the 15.9-84.1% (1-sigma) and 2.3-97.7% (2-sigma) quantile of the MFDs. The dashed lines indicate that within the 2500 catalog built to explore uncertainties, at least some catalogs do not have any events within the magnitude bin and observation period considered. The green and blue colors are associated to the tapered and truncated long-term seismicity model. Green and blue dots show the mean of the marginal PDF of the long-term seismicity. Green and blue dashed lines indicate the spread of the 1% best seismicity models. The marginal probabilities of M_{max}, $P_{M_{max}}$, are indicated by the solid lines on the M_w axis . The dotted lines on the earthquake frequency axis indicate the probability of the rate of events, τ, with magnitude $M_w = M_{Mode}$, thus $P(\tau \mid M_w = M_{Mode})$, with M_{Mode}=5.85 and 5.15 for the tapered and truncated models, respectively. It considers all magnitudes in the seismicity models and not only the recurrence rate of M_{max}. The solid blue line on the earthquake frequency axis indicates $P(\tau_{max} \mid M_{max} = 5.15)$ (only for the truncated seismicity model). The top-right inset shows the marginal probability of the b-value. Note that the seismicity MFDs in the figure are not in the cumulative form.

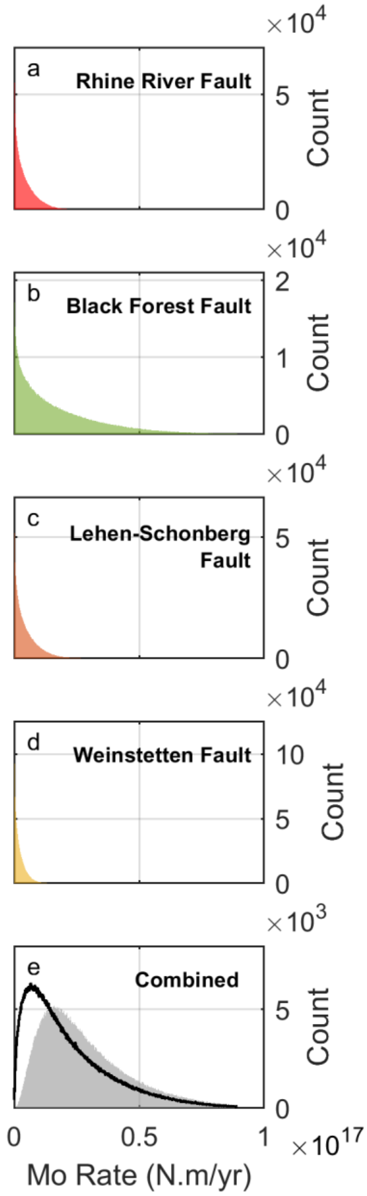

Figure S14: Moment deficit rate PDF (expressed in counts) of each four considered fault (colors are indicative of the faults in the left panel), and of their combination (in grey), considering a strike-slip slip rate component equivalent to 6.6 times the dip-slip estimate, and assuming the Black Forest Fault maximum long-term vertical slip rate is 0.18 mm/yr (as proposed by Jomard et al., 2017) (Section 5.3). The black line in panel (e) indicates the MDR combination of solely the Rhine River and Black Forest faults, scenario as proposed by Chartier et al. (2017).

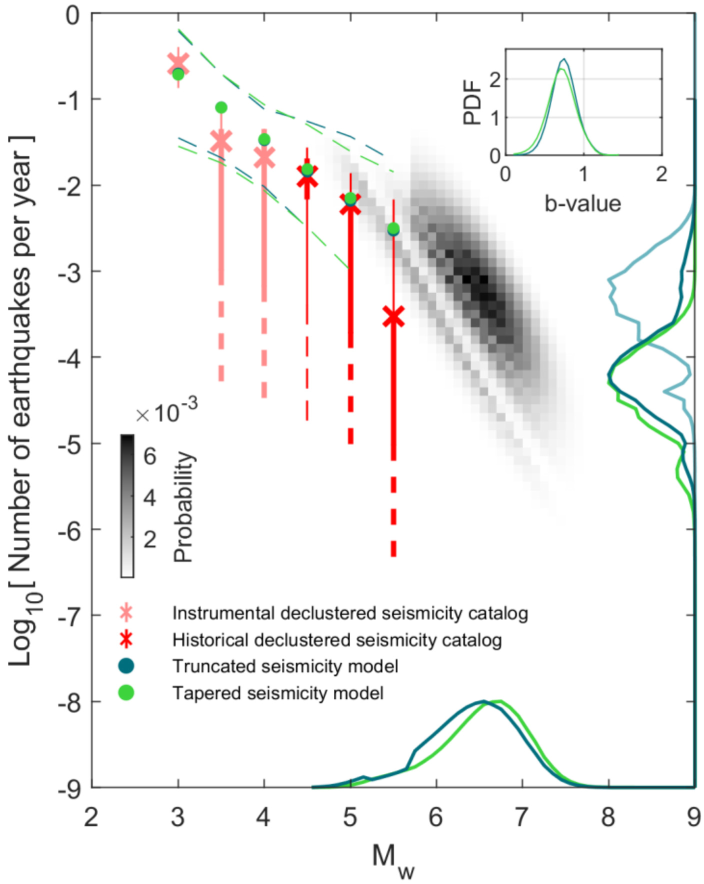

Figure S15: Seismogenic potential of the URG using all constraints, taking into account only the Rhine River and Black Forest faults (as in Chartier et al., 2017), considering a strike-slip slip rate component equivalent to 6.6 times the dip-slip estimate, and assuming the Black Forest Fault maximum long-term vertical slip rate is 0.18 mm/yr (as proposed by Jomard et al., 2017) (Section 5.3). Leonard et al. (2010) strike-slip moment-area scaling law is used here for the scaling law constraint, even though it is very similar to the dip-slip version. The rate of occurrence of historical and instrumental earthquakes, within their observation period, are indicated by red and pink crosses and error bars, respectively. The thick and thin error bars indicate the 15.9-84.1% (1-sigma) and 2.3-97.7% (2-sigma) quantile of the MFDs. The dashed lines indicate that within the 2500 catalog built to explore uncertainties, at least some catalogs do not have any events within the magnitude bin and observation period considered. The green and blue colors are associated to the tapered and truncated long-term seismicity model. Green and blue dots show the mean of the marginal PDF of the long-term seismicity. Green and blue dashed lines indicate the spread of the 1% best seismicity models. The marginal probabilities of M_{max}, $P_{M_{max}}$, are indicated by the solid lines on the M_w axis . The dotted lines on the earthquake frequency axis indicate the probability of the rate of events, τ, with magnitude $M_w = M_{Mode}$, thus $P(\tau \mid M_w = M_{Mode})$, with M_{Mode}=6.75 and 6.55 for the tapered and truncated models, respectively. It considers all magnitudes in the seismicity models and not only the recurrence rate of M_{max}. The solid blue line on the earthquake frequency axis indicates $P(\tau_{max} \mid M_{max} = 6.55)$ (only for the truncated seismicity model). The top-right inset shows the marginal probability of the b-value. Note that the seismicity MFDs in the figure are not in the cumulative form.

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