Converting InSAR- and GNSS-derived strain rate maps into earthquake likelihood models for Anatolia

Two different forms of magnitude-frequency distribution (MFD) used (with variety of $M_{\text{max}}$, $b$, other parameters for each).

Upper-truncated power-law incremental MFD

$N(M_w > M_{\text{each}}) = 10^{(a - b/M_{\text{each}})}$ up to $M_{\text{max}}$

$N(M_w = M_{\text{each}}) = 10^{(a - b/M_{\text{each}})}$ up to $M_{\text{max}}$

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LiCSAR coverage of Sentinel-I InSAR data for the Alpine-Himalayan Belt
Sentinel-1 for Anatolia

2014 → 2019

~200 images/frame
~8,000 images

~800 ifgs/frame
~30,000 ifgs

~ 800,000 km²
Given a strain map, how can we use it to estimate seismic hazard?
Method: strain rate $\rightarrow \Sigma$(moment buildup rate) = $\Sigma$(moment release rate in EQs)

- **Moment buildup rate** = strain rate $\cdot$ volume $\cdot$ elastic stiffness [e.g., Kostrov, 1974]
  - Locked depth range: assume 16 ± 2 km (average North Anatolian Fault locking depth from Hussain et al. 2018)
  - This is assuming that surface strain rates hold down to 16 km depth
  - Shear modulus $\mu$: assume 32 GPa (increases with depth, but may decrease near faults due to damage?)

- Total moment buildup rate in Anatolia: $\sim2.4 \cdot 10^{19}$ Nm/yr

- How might large, moderate and small earthquakes combine to collectively release seismic moment at this rate?
For clues, let’s turn the instrumental earthquake catalogue in Anatolia

Kadirioğlu et al. [2018] catalogue (≤20 km depth) and ISC-GEM catalogue
Let’s *make* a moment-balancing long-term earthquake model, and evaluate the following:

- If you ran this model for 115 yr, would the seismicity from it look anything like the 1900-2015 catalog?
  - In what way? Perhaps in the total **magnitude-frequency distribution**
- More direct: what are the odds that the **exact 1900-2015 magnitude-frequency distribution** would drop out of the model?
Assume that on the long-term average, earthquakes obey
a **power-law cumulative magnitude-frequency distribution**
(the Gutenberg-Richter law): \( N(M_{w} \geq M_{each}) = 10^{(a - b \cdot M_{each})} \)
that is **truncated at a maximum magnitude** \( M_{max} \)
and balances the “**moment budget**”

\[
\text{Cumulative MFD (} N(M \geq M_{each}) \text{) of 1900-2015 seismic catalog in study area}
\]

- can compute long-term-average rates of earthquakes
  of all magnitudes **in closed form** [Molnar, 1979]
The problem: the earthquake rates you infer depend on the parameters you assume.
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**Iterate** over long-term models with a range of $M_{\text{max}}$, $b$, other parameters;
for each model: compute Poisson probability that the model would
**produce the exact 1900-2015 distribution of EQ sizes**
in a 115-year period:

$$P_{\text{Poisson}}(1 M_w=7.8, 9 M_w=6.3, \text{etc.} \mid \text{model})$$

Cumulative MFD ($N(M \geq M_{\text{each}})$) of
1900-2015 seismic catalog in study area

(probability will be very small, but **less small for more likely long-term models**)

*also less small given **magnitude uncertainties**;
we run this on many “catalogs” that are the 1900-2015 catalog
+ random perturbations to magnitudes sampled from
Gaussian($\sigma = \text{each EQ’s estimated mag. uncertainty}$)
\[
P(\text{each model}) = P(\text{catalog} | \text{model}) \cdot P(\text{moment balance}) \cdot P(\text{that buildup rate})
\]
\[
= P(\text{catalog} | \text{model}) \cdot 1 \text{ (by definition)} \cdot \text{PDF(moment buildup rate)}
\]

Iterate over long-term models with a range of $M_{\text{max}}$, $b$, other parameters; for each model: compute Poisson probability that the model would produce the exact 1900-2015 distribution of EQ sizes in a 115-year period:

\[
P_{\text{Poisson}}(1 \leq M_{w} \leq 7.8, 9 \leq M_{w} \leq 6.3, \text{etc.} | \text{model})
\]

$M_{\text{max}} = 8.0$ (probability will be very small, but less small for more likely long-term models)

*also less small given magnitude uncertainties; we run this on many “catalogs” that are the 1900-2015 catalog + random perturbations to magnitudes sampled from Gaussian($\sigma = \text{each EQs estimated mag. uncertainty}$)

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(Probability will be very small, but less small for more likely long-term models)
Long-term-average earthquake rate model for Anatolia assuming upper-truncated cumulative magnitude-frequency distribution:

\[ N(M_w \geq M_{each}) = 10^{(a - b \cdot M_{each})} \text{ up to } M_{max} \]

Magnitude-frequency distribution \((N \geq M_{each})\) of 1900-2015 seismic catalog in study area

Model-inferred long-term MFD:
- wtd.-mean cumulative \((N(M_w \geq M_{each}))\)
- 16th- and 84th-percentile cumulative wtd.-mean incremental \((N(M_w = M_{each}))\)

1D PDF of \(b\)

1D PDF of \(M_{max}\):

\[ M_{max} = 8.1/8.35 (7.7, 9.0) \]

mode/wtd. mean (16%, 84%)

2D PDF of \(M_{max}, T(M_{max})\)

Mode: 8.1, 250 yr

PDFs of \(T(M_w)\)
- \(T(M_w=7.0)\): wtd. mean 90 yr
- \(T(M_w=7.5)\): mean 270 yr
- \(T(M_w=8.0)\): mean 1000 yr
Long-term-average earthquake rate model for Anatolia assuming upper-truncated incremental magnitude-frequency distribution:

\[ N(M_w = M_{each}) = 10^{(a - b \cdot M_{each})} \text{ up to } M_{\text{max}} \]

Model-inferred long-term MFD:
- wtd.-mean cumulative \((N(M_w > M_{each}))\)
- 16th- and 84th-percentile cumulative wtd.-mean incremental \((N(M_w = M_{each}))\)

Magnitude-frequency distribution \((N > M_{each})\) of 1900-2015 seismic catalog in study area

Recurr. interv. (yr) > each Mw

1939
\(M_w \sim 7.8\)

1D PDF of \(b\)

1D PDF of \(M_{\text{max}}\):
\(M_{\text{max}} = 8.15/8.45 (7.85, 9.15)\)
mode/wtd. mean (16%, 84%)

PDFs of \(T(M_w)\)
- \(T(M_w = 7.0)\): wtd. mean 90 yr
- \(T(M_w = 7.5)\): mean 300 yr
- \(T(M_w = 8.0)\): mean 1500 yr
Upcoming work

- Incorporate **earthquake interactions and sequences** into probabilities
- Move away from drawing a **giant regional box** and enforcing moment balance etc. inside that
  - May be able to do this for individual faults or high-strain regions
- Expand to the rest of the Alpine-Himalayan Belt