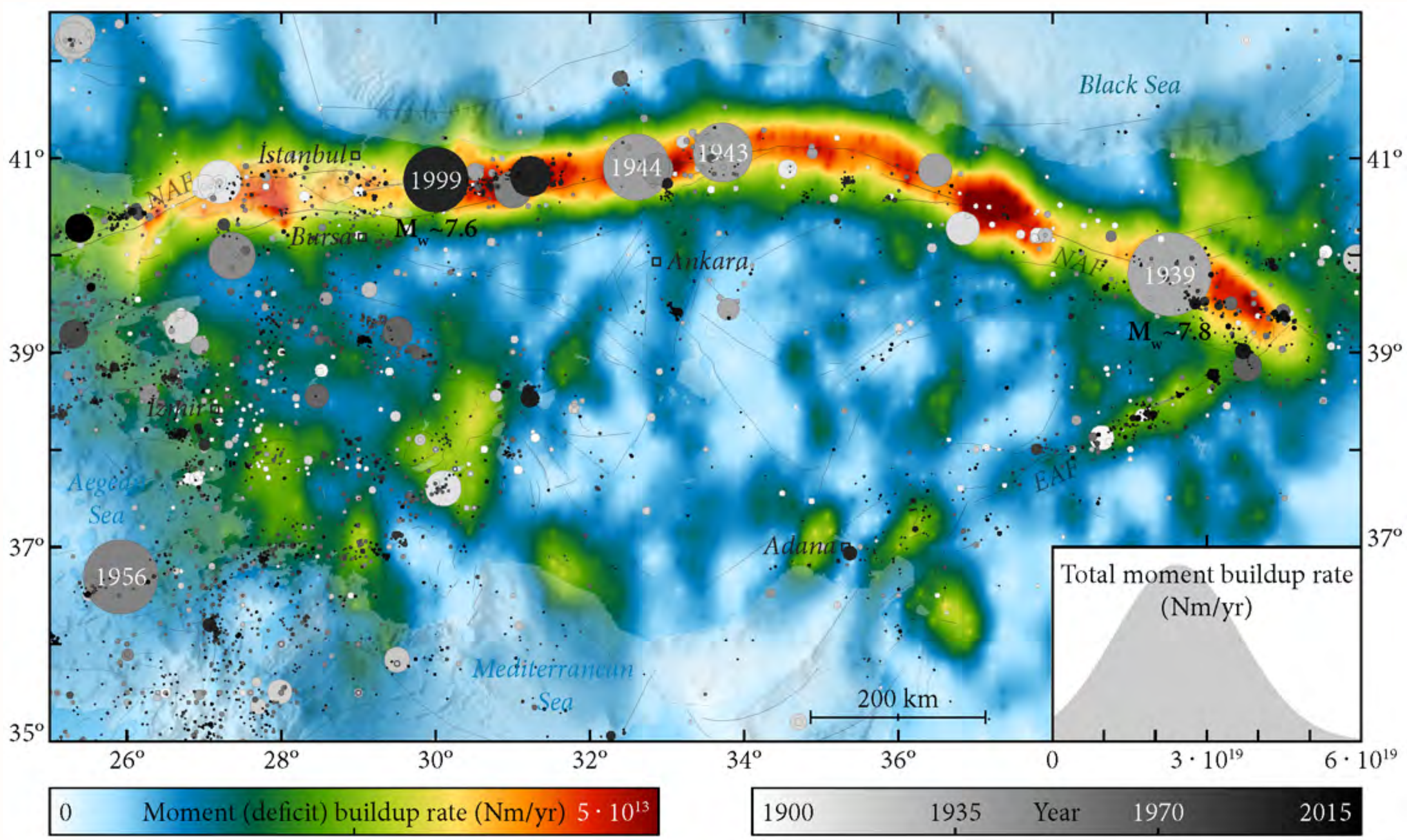
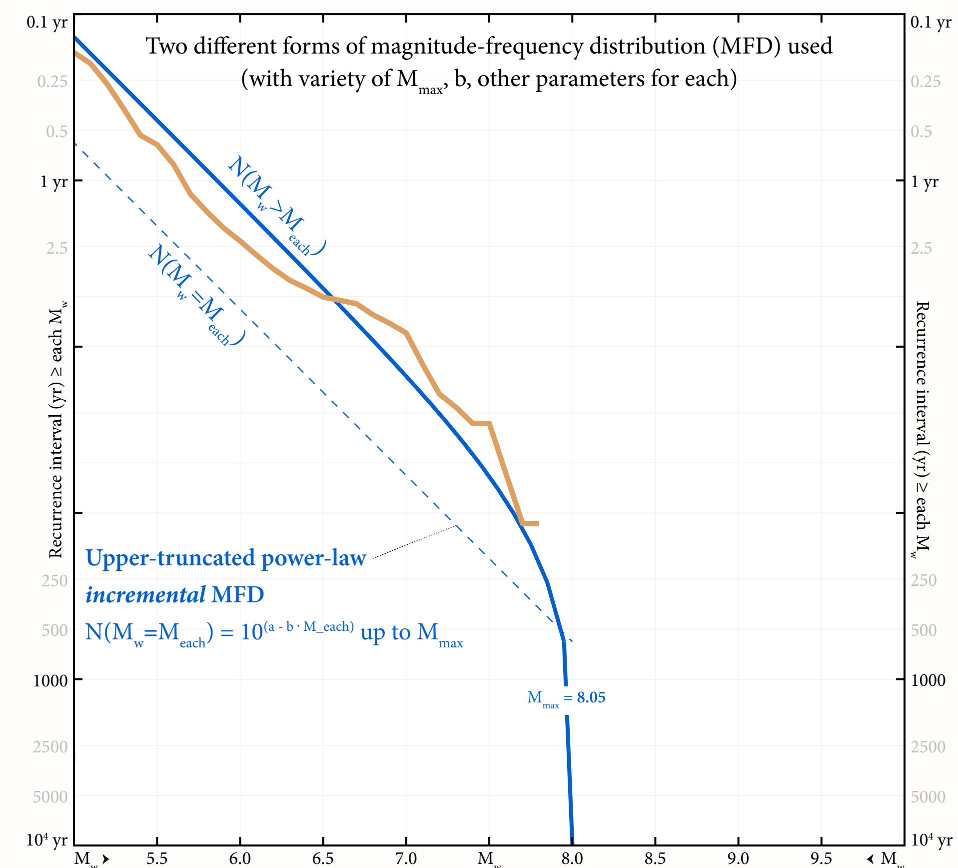
Converting InSAR- and GNSS-derived strain rate maps into earthquake likelihood models for Anatolia





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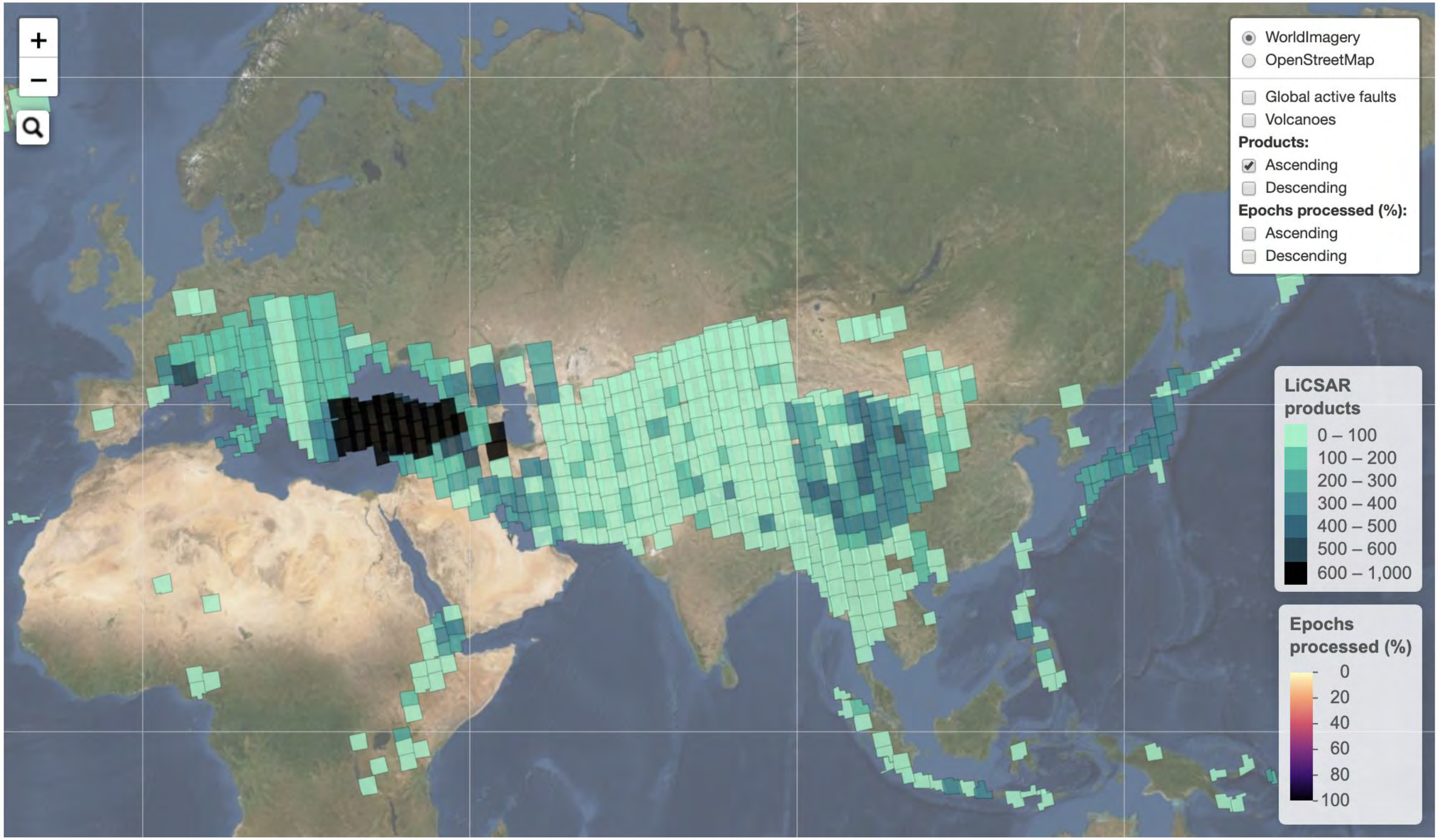
TS5.5: Active Tectonics and Geodynamics of Eastern Mediterranean - EGU General Assembly - May 7, 2020

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



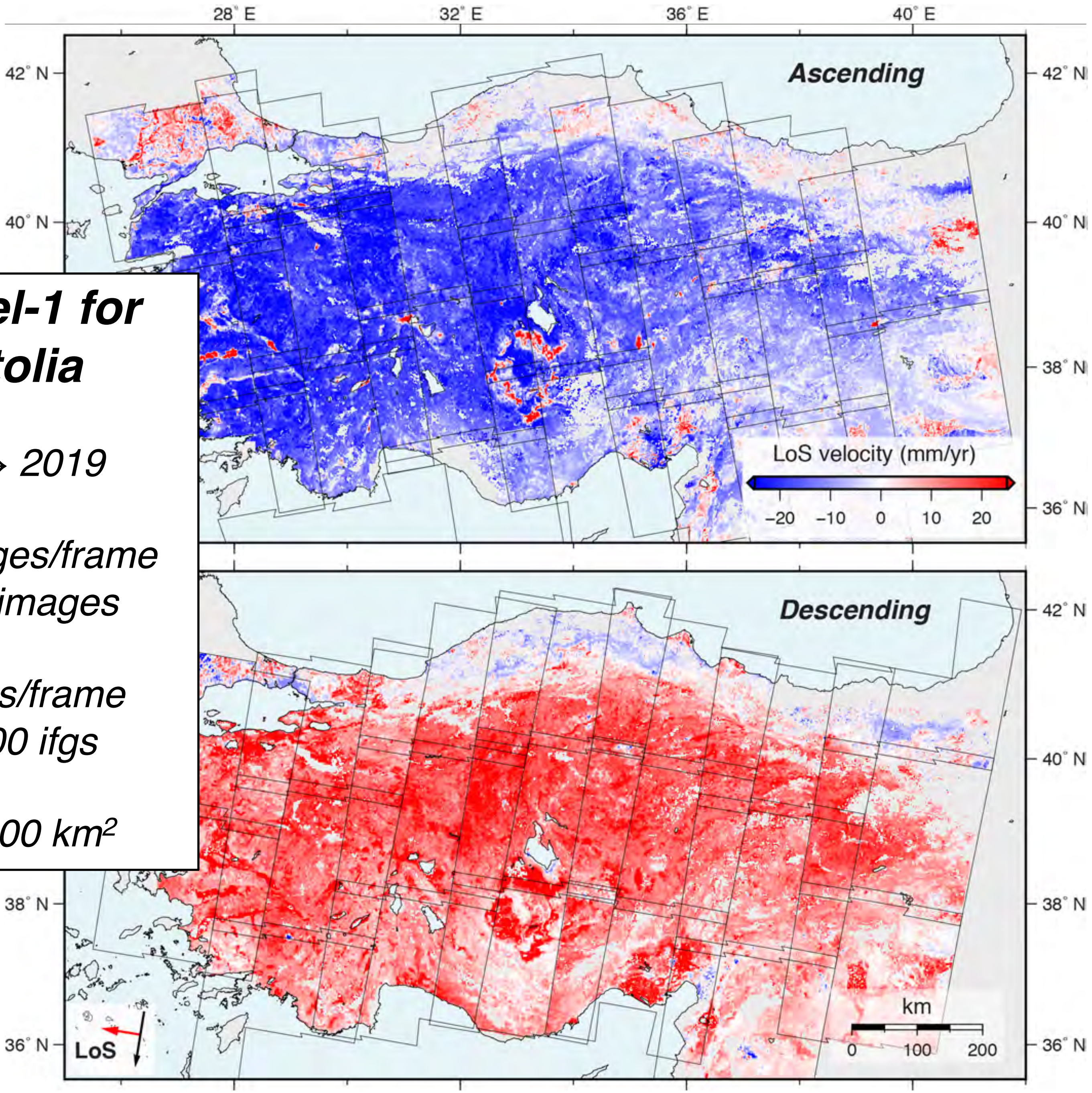
Sentinel-1 for Anatolia

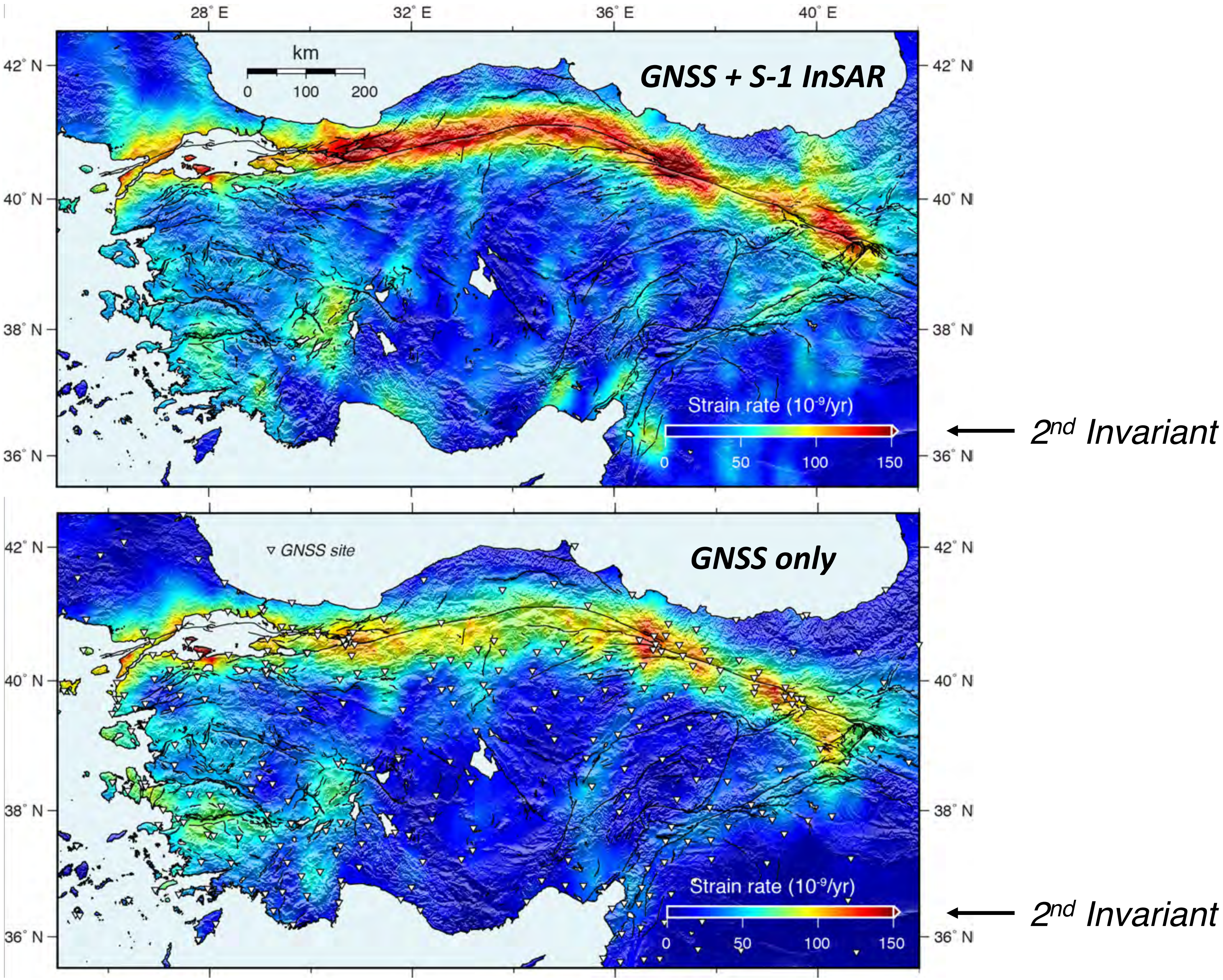
2014 → 2019

~200 images/frame
~8,000 images

~800 ifgs/frame
~30,000 ifgs

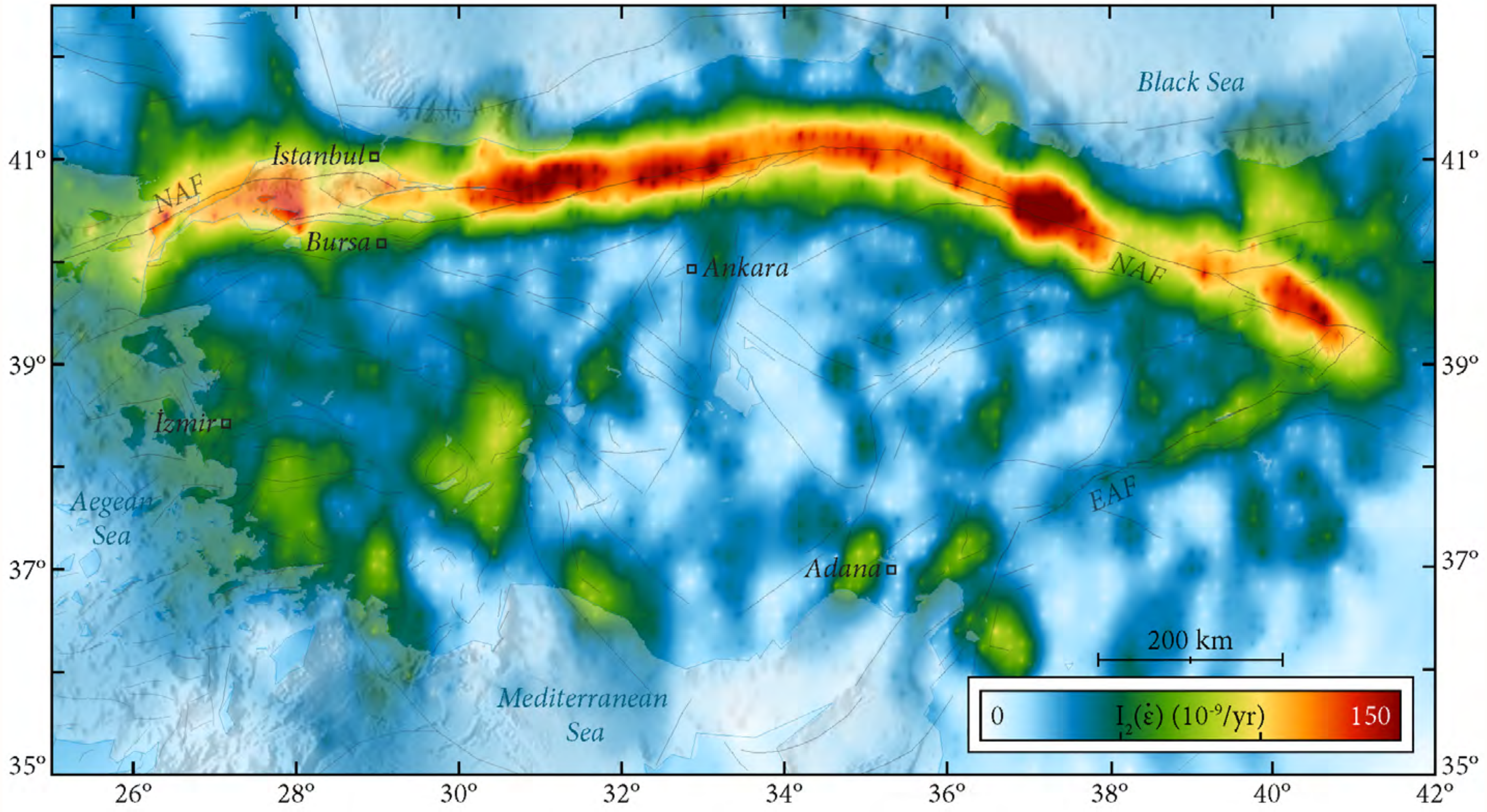
~ 800,000 km²




GNSS + S-1 InSAR
GNSS only
GNSS site
km
0
100
200
28° E
32° E
36° E
40° E
42° N
40° N
38° N
36° N
Strain rate (10^{-9}/yr)
0
50
100
150
2nd Invariant
2nd Invariant

LiCSAR InSAR- and GPS-based **strain rate map** for Anatolia

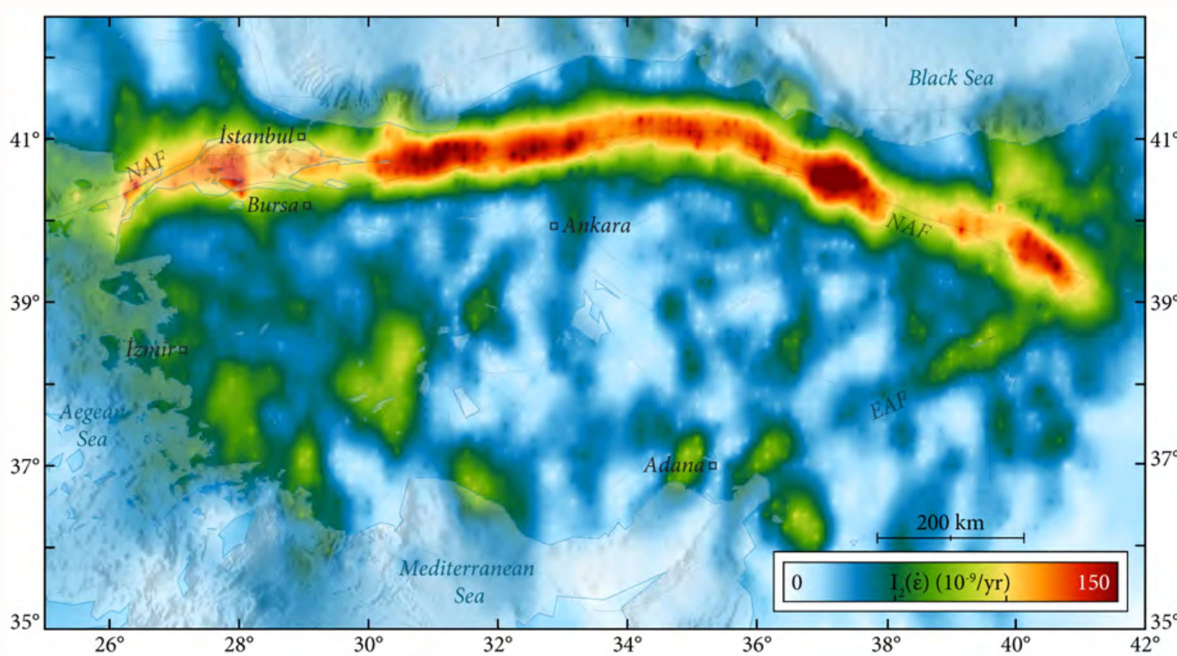
[Jonathan Weiss et al.; see presentation D1225 in this session]



Given a strain map, how can we use it to estimate seismic hazard?

Method: strain rate → Σ(moment buildup rate) $\overset{!}{=}$ Σ(moment release rate in EQs)

- **Moment buildup rate** = **strain rate** · volume · 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 μ: assume **32 GPa** (increases with depth, but may decrease near faults due to damage?)
- Total moment buildup rate in Anatolia: **~2.4 · 10^{19} Nm/yr**
- How might large, moderate and small earthquakes **combine** to collectively release seismic moment at this rate?



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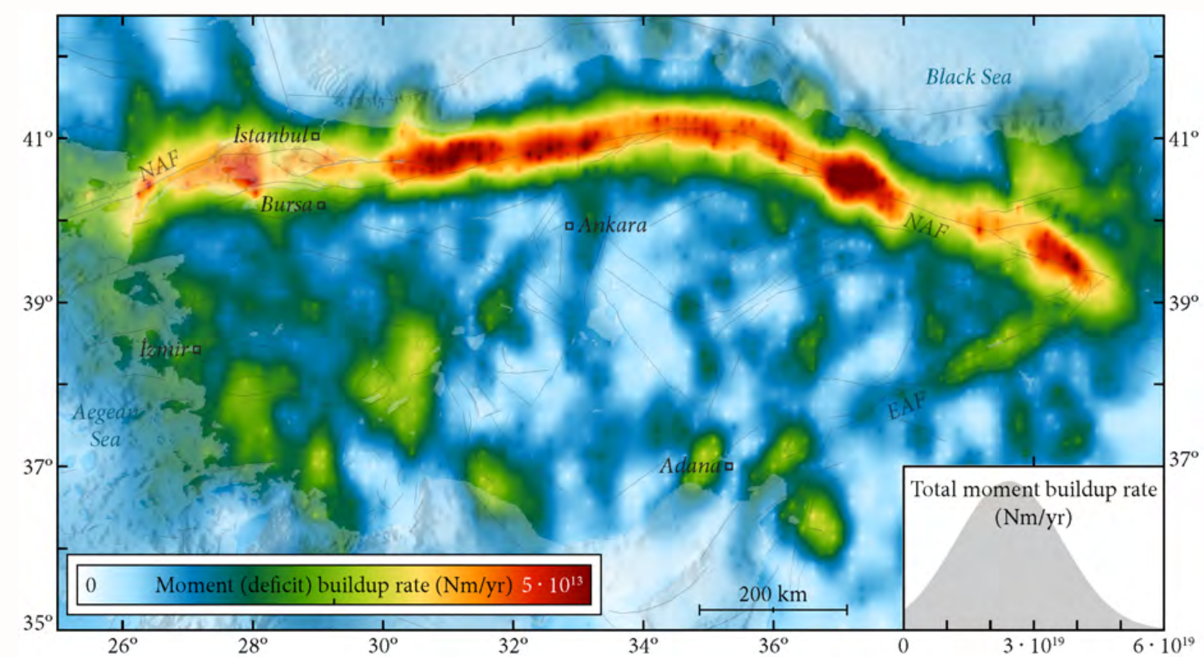
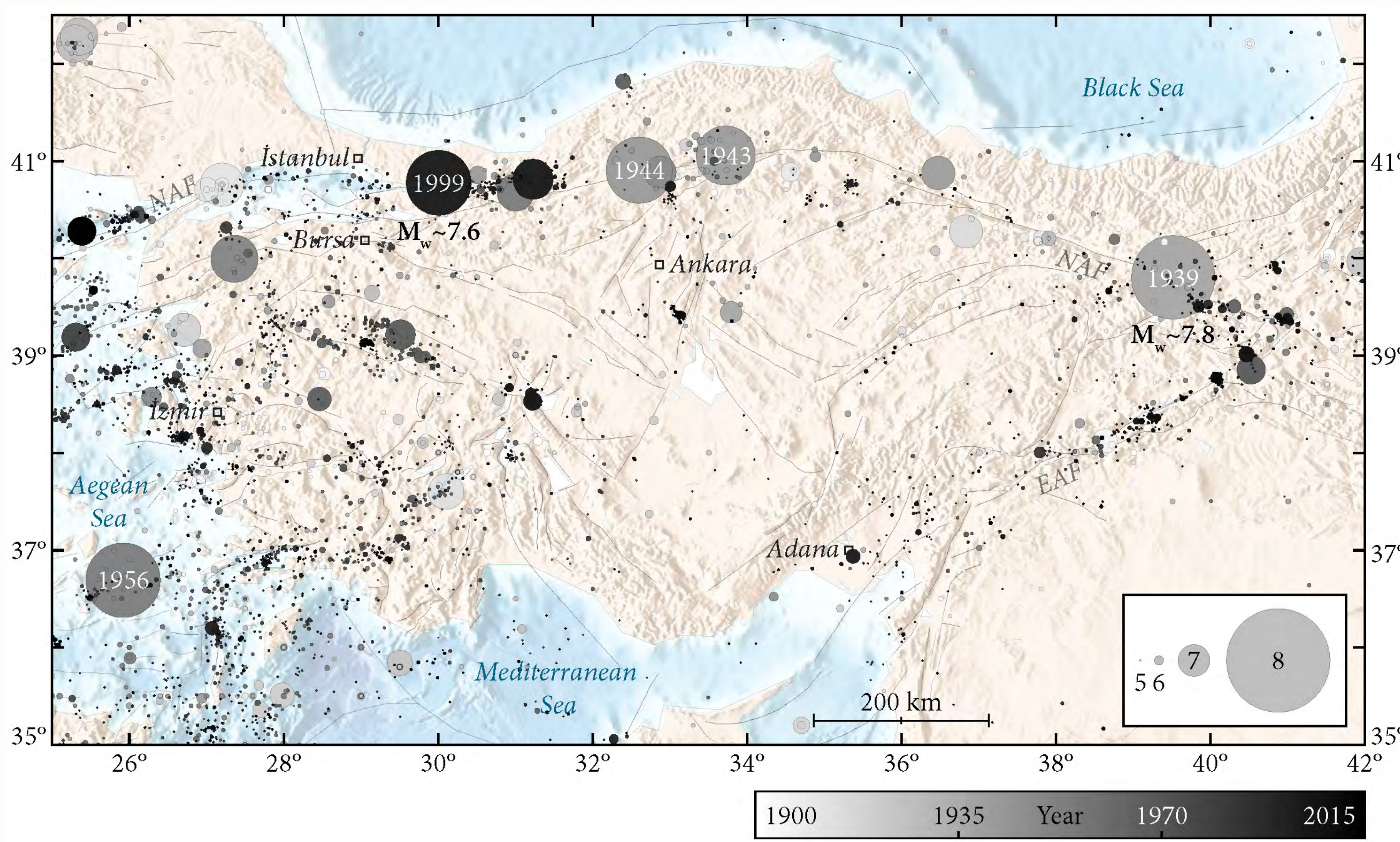


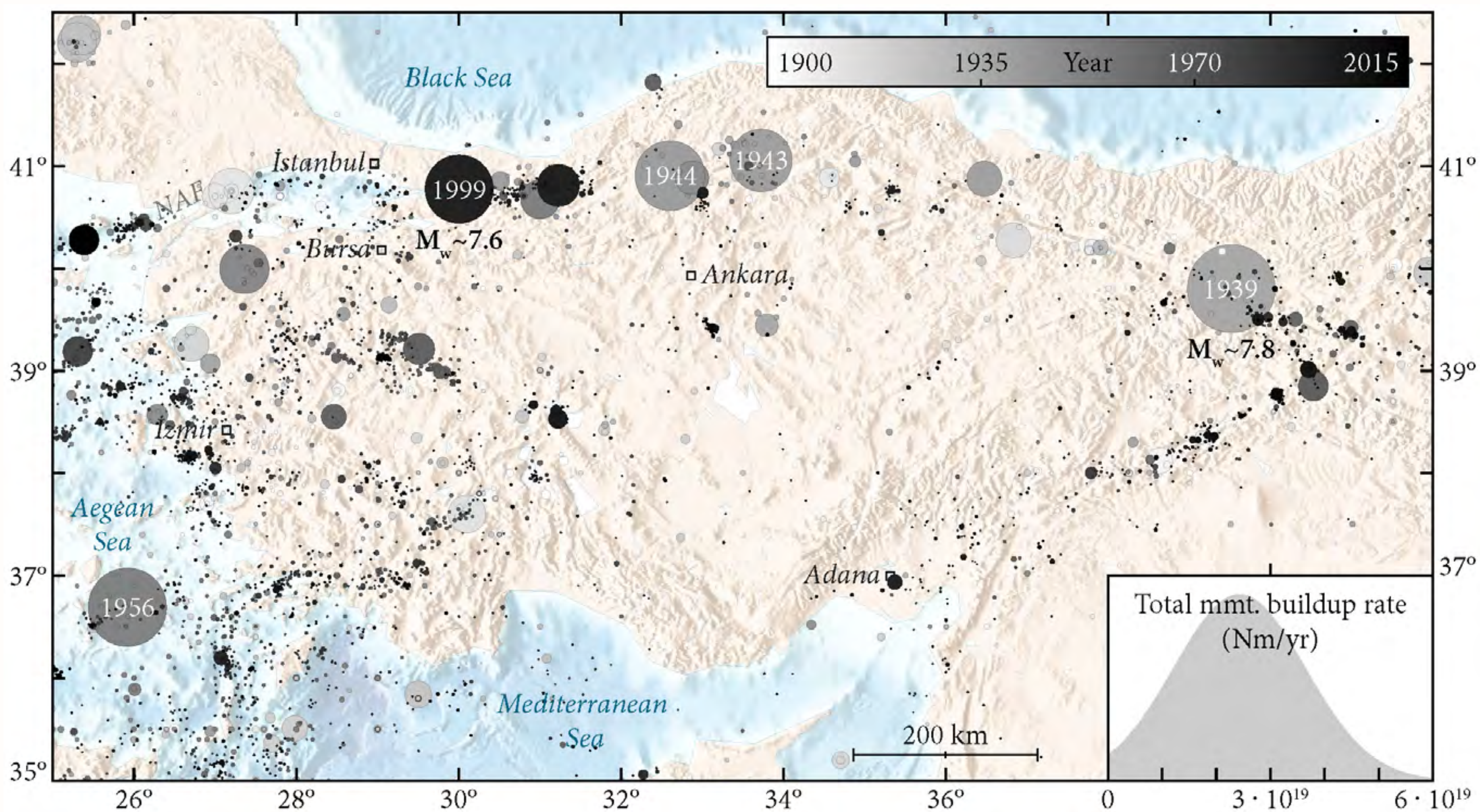
For clues, let's turn the instrumental earthquake catalogue in Anatolia

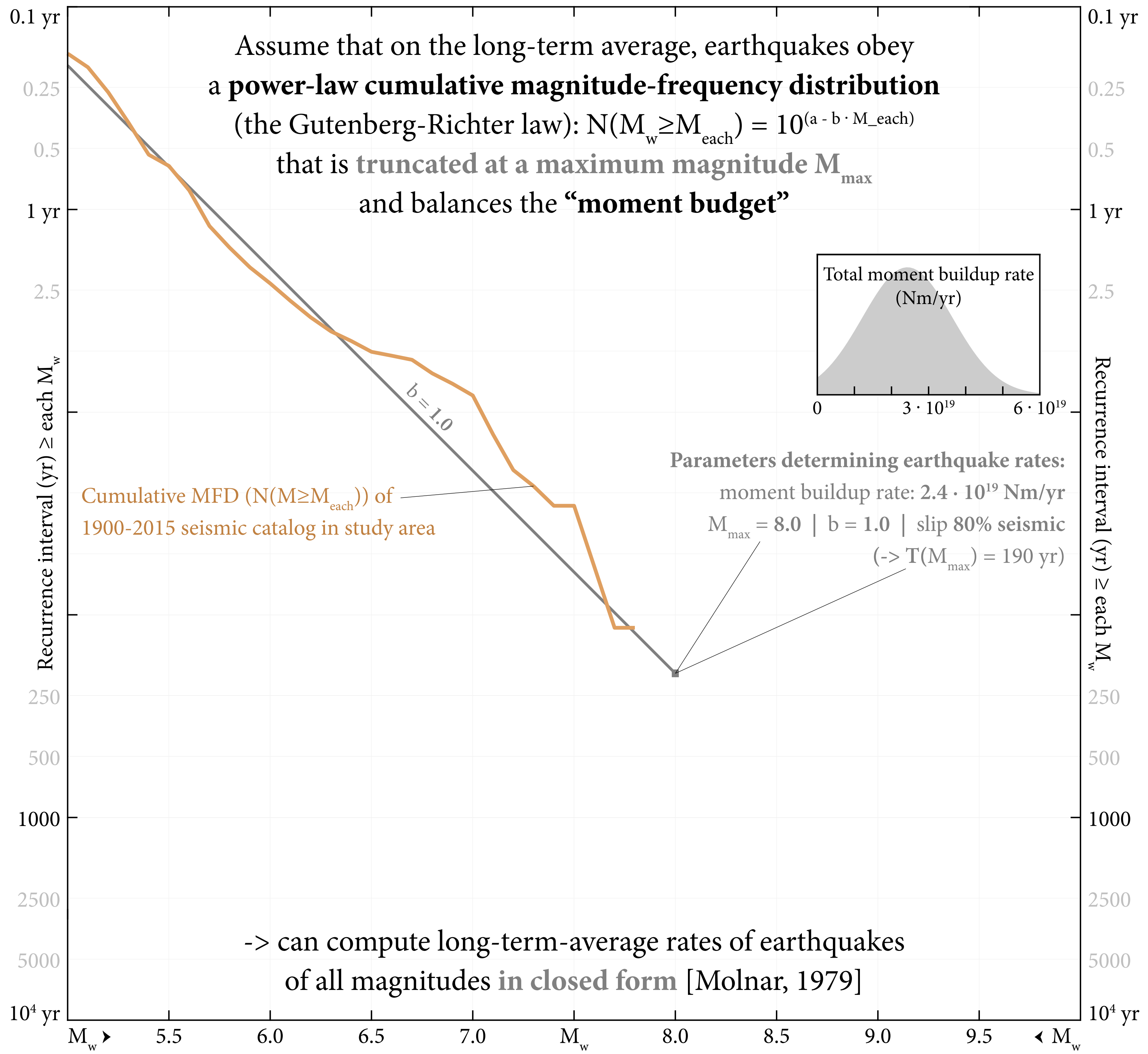


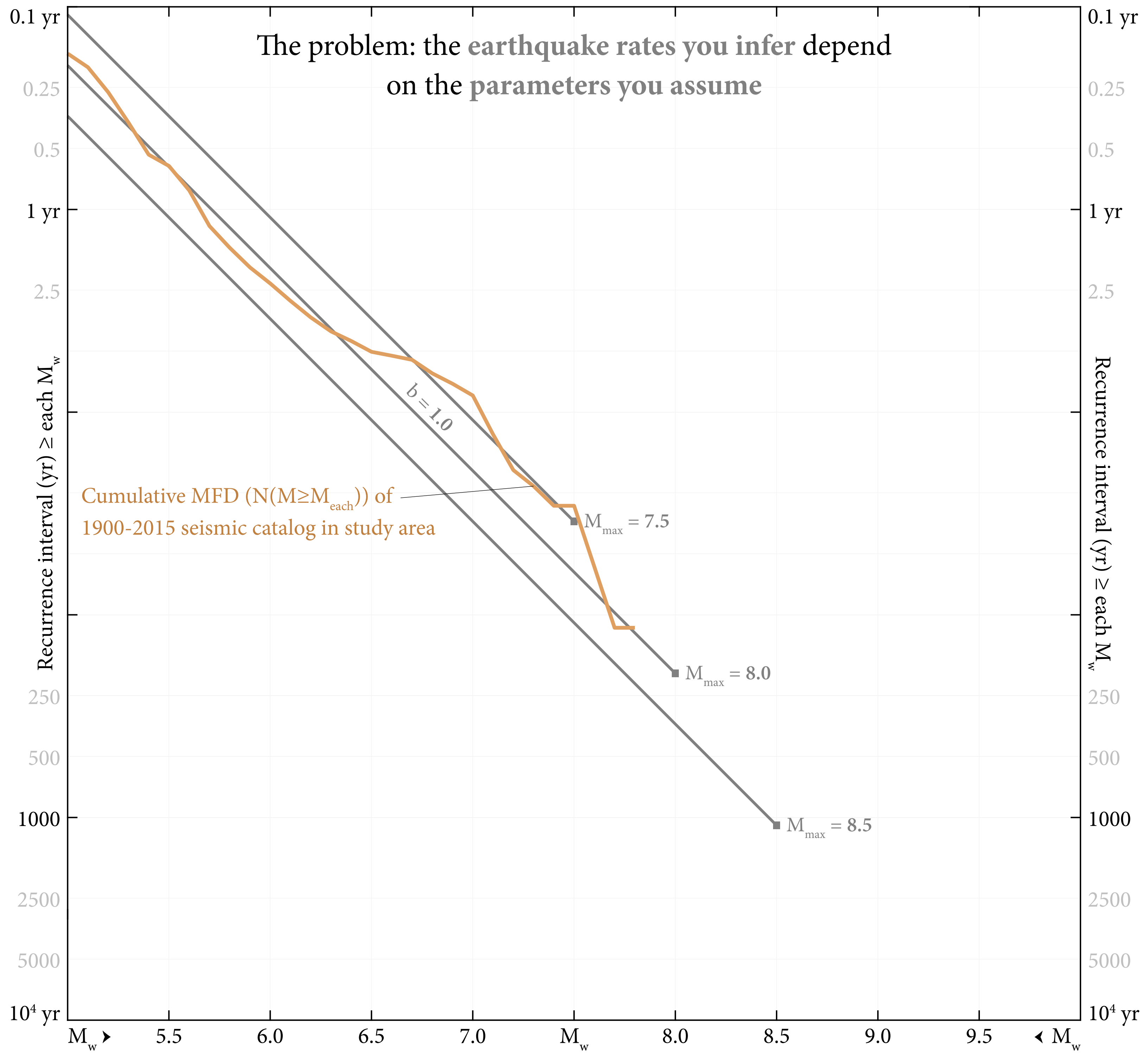
Kadirioğlu et al. [2018] catalogue (≤20 km depth) and ISC-GEM catalogue

Let's *make* a moment-balancing long-term earthquake model, and evaluate the following:

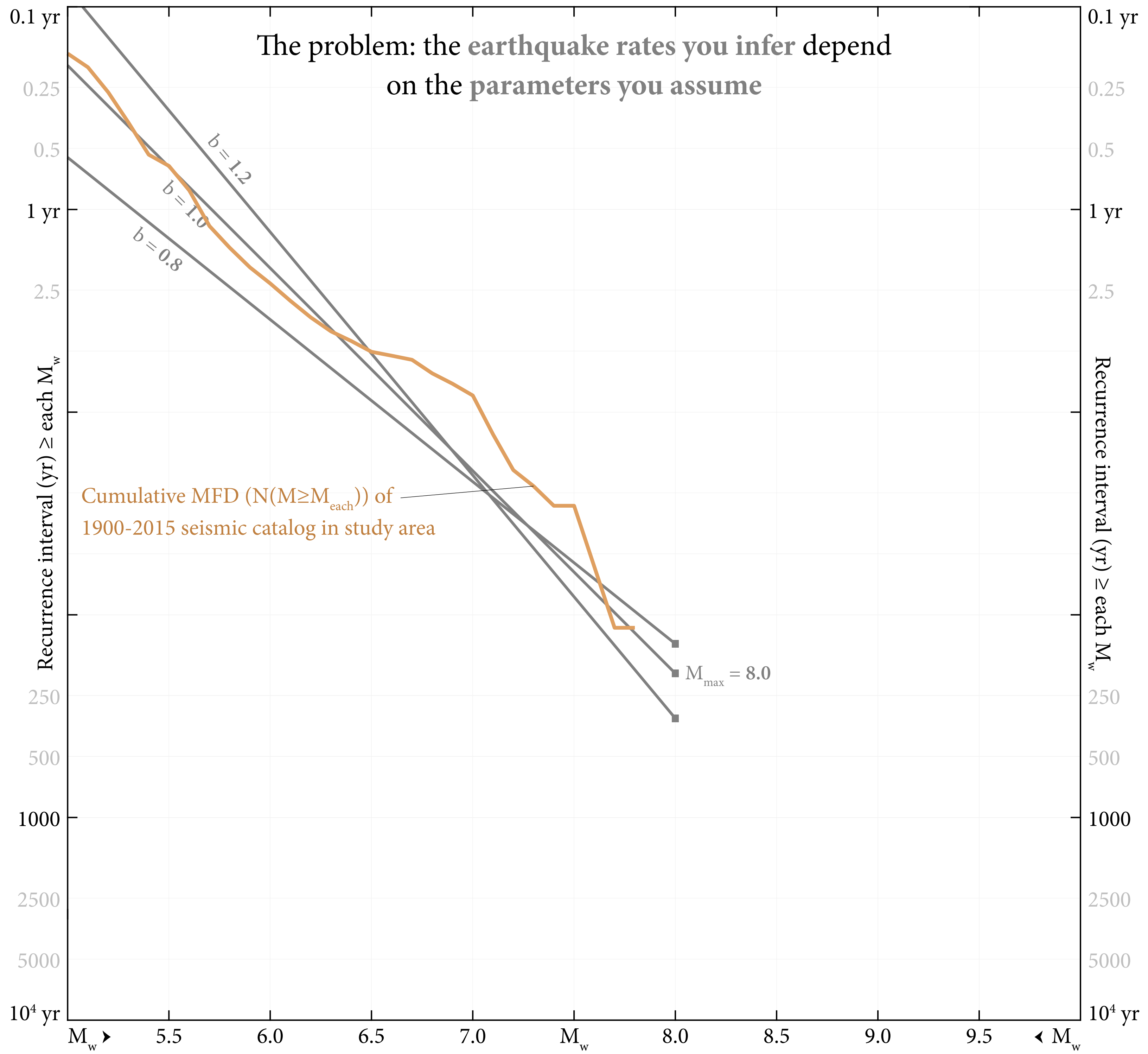
- If you ran this model for 115 yr, would the seismicity from it look anything like the 1900-2015 catalog?
    - In what way? Perhaps in the total **magnitude-frequency distribution**
- More direct: what are the odds that the **exact 1900-2015 magnitude-frequency distribution** would drop out of the model?



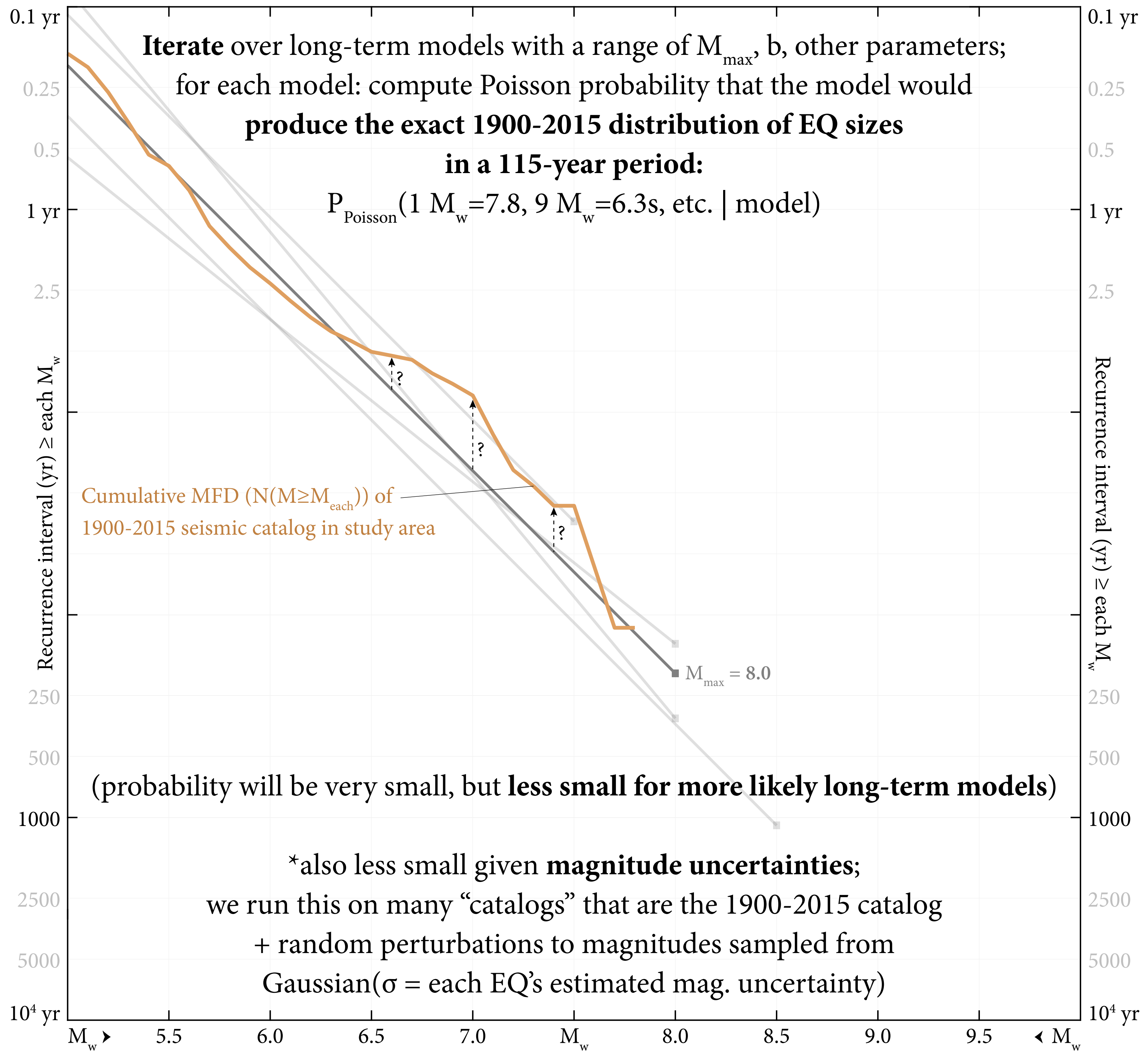

Assume that on the long-term average, earthquakes obey
a power-law cumulative magnitude-frequency distribution
(the Gutenberg-Richter law): N(Mw≥Meach) = 10^(a - b · M_each)
that is truncated at a maximum magnitude Mmax
and balances the “moment budget”
Total moment buildup rate
(Nm/yr)
0
3 · 10^19
6 · 10^19
b = 1.0
Parameters determining earthquake rates:
moment buildup rate: 2.4 · 10^19 Nm/yr
Mmax = 8.0 | b = 1.0 | slip 80% seismic
(-> T(Mmax) = 190 yr)
Cumulative MFD (N(M≥Meach)) of
1900-2015 seismic catalog in study area
Recurrence interval (yr) ≥ each Mw
0.1 yr
0.25
0.5
1 yr
2.5
250
500
1000
2500
5000
10^4 yr
Mw
5.5
6.0
6.5
7.0
8.0
8.5
9.0
9.5
-> 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
0.1 yr
0.25
0.5
1 yr
2.5
250
500
1000
2500
5000
10^4 yr
Recurrence interval (yr) ≥ each M_w
b = 1.0
Cumulative MFD (N(M≥M_{each})) of 1900-2015 seismic catalog in study area
M_{max} = 7.5
M_{max} = 8.0
M_{max} = 8.5
M_w
5.5
6.0
6.5
7.0
8.0
8.5
9.0
9.5



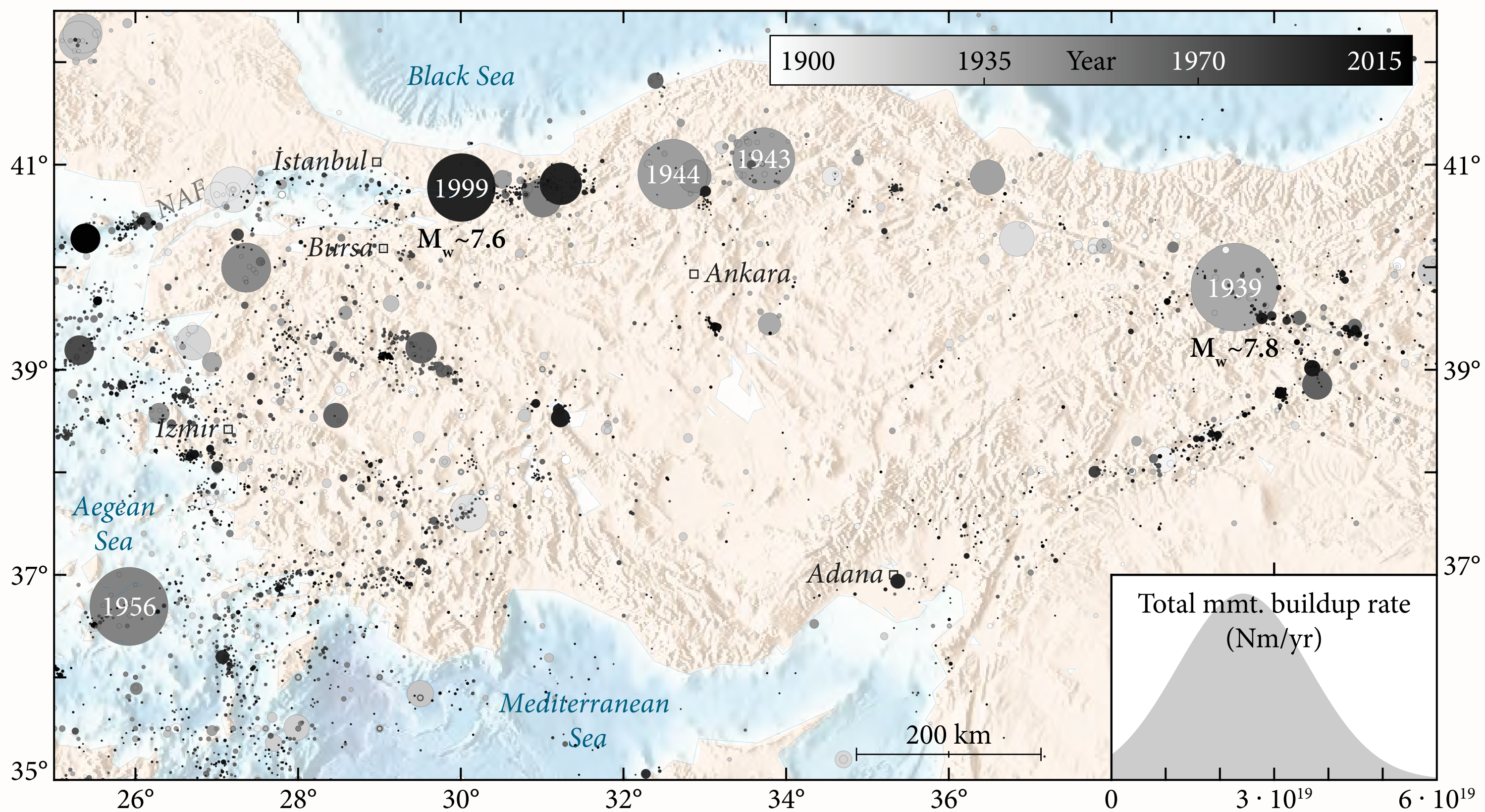
The problem: the earthquake rates you infer depend on the parameters you assume
b = 1.2
b = 1.0
b = 0.8
Cumulative MFD (N(M≥M_each)) of 1900-2015 seismic catalog in study area
M_max = 8.0
Recurrence interval (yr) ≥ each M_w
0.1 yr
0.25
0.5
1 yr
2.5
250
500
1000
2500
5000
10^4 yr
M_w
5.5
6.0
6.5
7.0
8.0
8.5
9.0
9.5

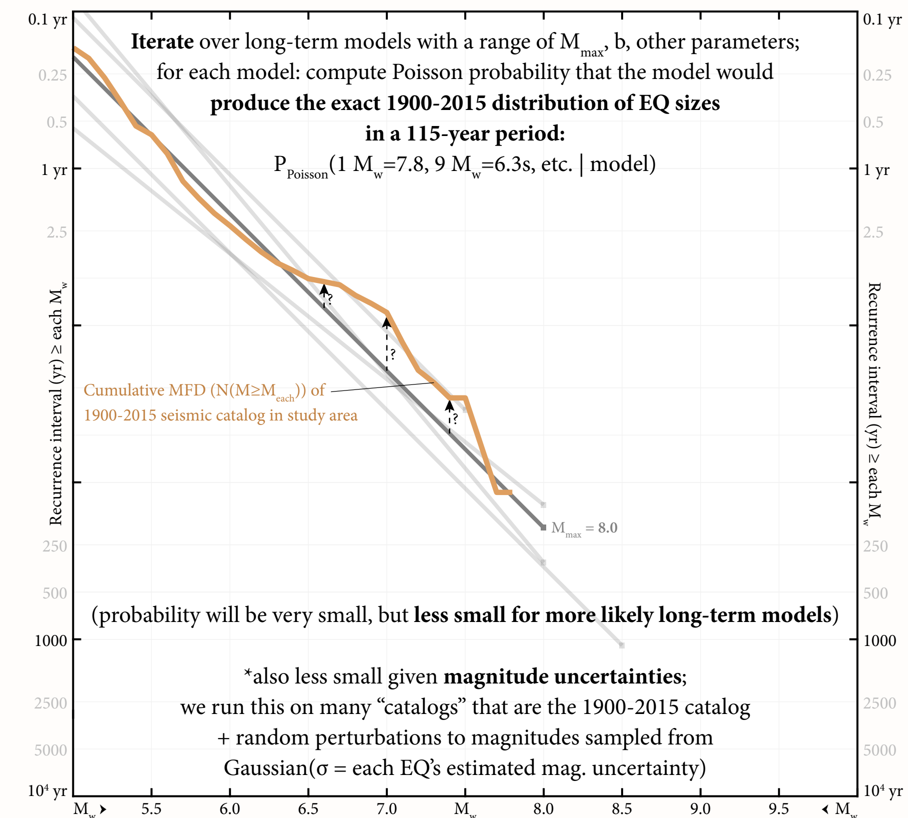


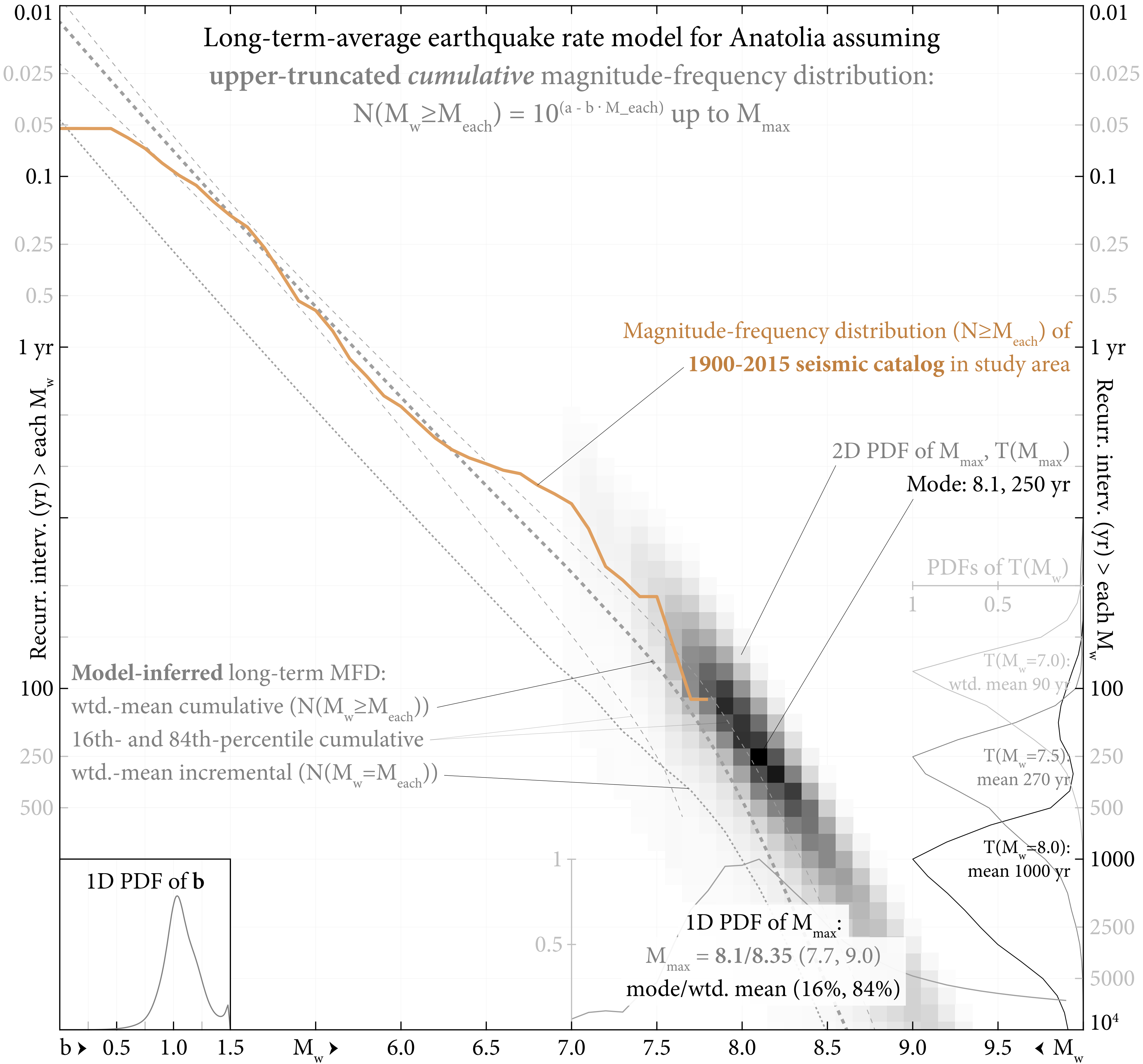
Iterate over long-term models with a range of M_{max}, b, other parameters;
for each model: compute Poisson probability that the model would
produce the exact 1900-2015 distribution of EQ sizes
in a 115-year period:
$P_{Poisson}$(1 M_w=7.8, 9 M_w=6.3s, etc. | model)
Cumulative MFD (N(M≥M_{each})) of
1900-2015 seismic catalog in study area
?
?
?
M_{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(σ = each EQ’s estimated mag. uncertainty)
Recurrence interval (yr) ≥ each M_w
0.1 yr
0.25
0.5
1 yr
2.5
250
500
1000
2500
5000
10^4 yr
M_w
5.5
6.0
6.5
7.0
8.0
8.5
9.0
9.5

$$P(\text{each model}) = P(\textbf{catalog} \mid \text{model}) \cdot P(\text{moment balance}) \cdot P(\text{that buildup rate})$$

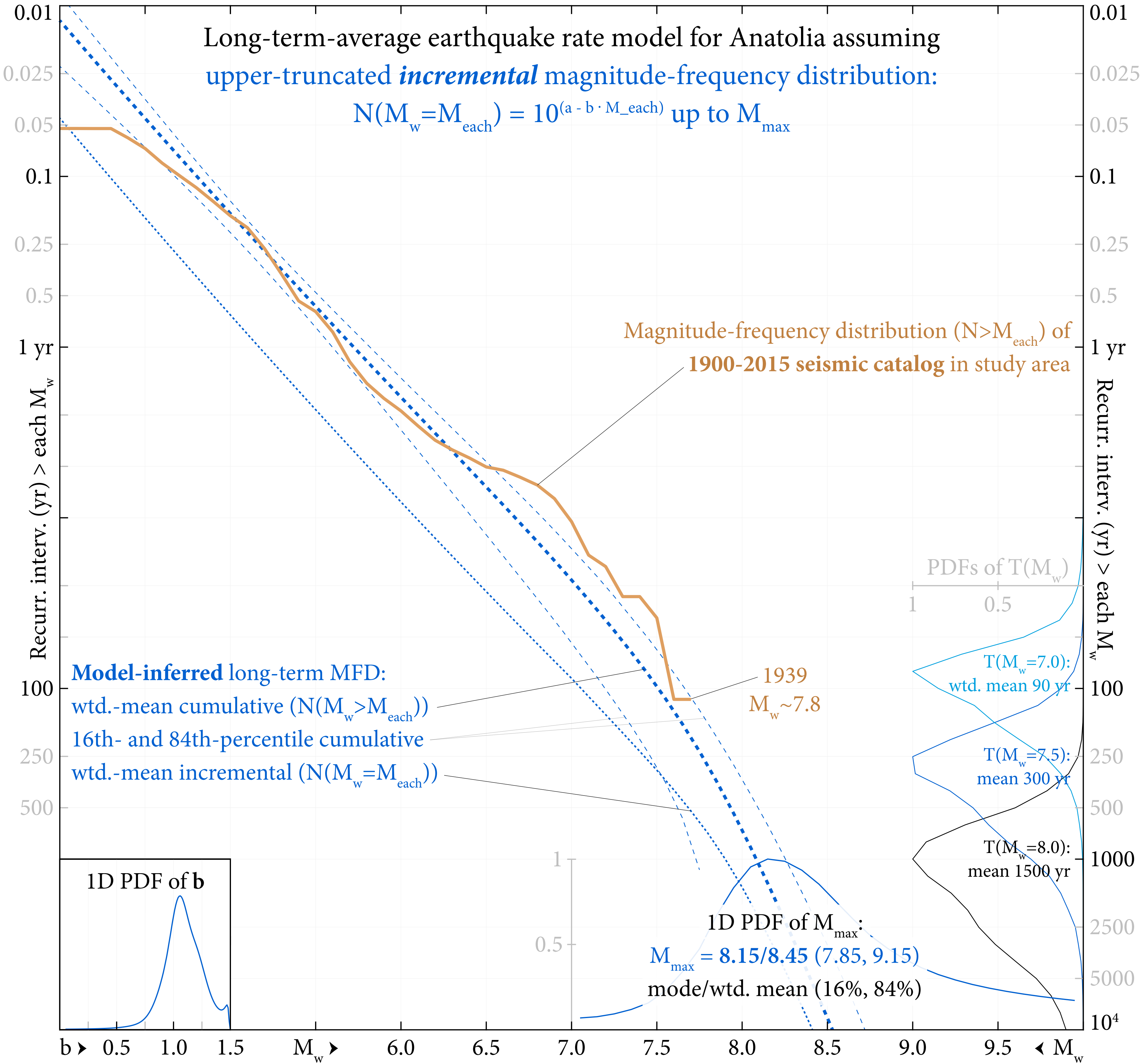
$$= P(\textbf{catalog} \mid \text{model}) \cdot 1 \text{ (by definition)} \cdot \text{PDF}(\text{moment buildup rate})$$







Long-term-average earthquake rate model for Anatolia assuming
upper-truncated cumulative magnitude-frequency distribution:
N(Mw≥Meach) = 10^(a - b · M_each) up to Mmax
Magnitude-frequency distribution (N≥Meach) of
1900-2015 seismic catalog in study area
2D PDF of Mmax, T(Mmax)
Mode: 8.1, 250 yr
PDFs of T(Mw)
T(Mw=7.0): wtd. mean 90 yr
T(Mw=7.5): mean 270 yr
T(Mw=8.0): mean 1000 yr
Model-inferred long-term MFD:
wtd.-mean cumulative (N(Mw≥Meach))
16th- and 84th-percentile cumulative
wtd.-mean incremental (N(Mw=Meach))
1D PDF of b
1D PDF of Mmax:
Mmax = 8.1/8.35 (7.7, 9.0)
mode/wtd. mean (16%, 84%)
Recurr. interv. (yr) > each Mw
0.01
0.025
0.05
0.1
0.25
0.5
1 yr
100
250
500
1000
2500
5000
10^4
b 0.5 1.0 1.5
Mw 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 Mw



Long-term-average earthquake rate model for Anatolia assuming
upper-truncated ***incremental*** magnitude-frequency distribution:
$N(M_w = M_{each}) = 10^{(a - b \cdot M\_each)}$ up to M_{max}
Magnitude-frequency distribution ($N > M_{each}$) of
1900-2015 seismic catalog in study area
1939
M_w~7.8
Model-inferred long-term MFD:
wtd.-mean cumulative ($N(M_w > M_{each})$)
16th- and 84th-percentile cumulative
wtd.-mean incremental ($N(M_w = M_{each})$)
1D PDF of **b**
1D PDF of M_{max}:
M_{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
Recurr. interv. (yr) > each M_w
0.01
0.025
0.05
0.1
0.25
0.5
1 yr
100
250
500
1000
2500
5000
10^4
b
0.5
1.0
1.5
M_w
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5

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