A Probabilistic Seismic Hazard Model for Sub-Saharan Africa

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June 29, 2016, Addis Ababa - Ethiopia

working together
to assess risk

GEM GLOBAL EARTHQUAKE MODEL

OQ OPENQUAKE

Introduction and Motivation

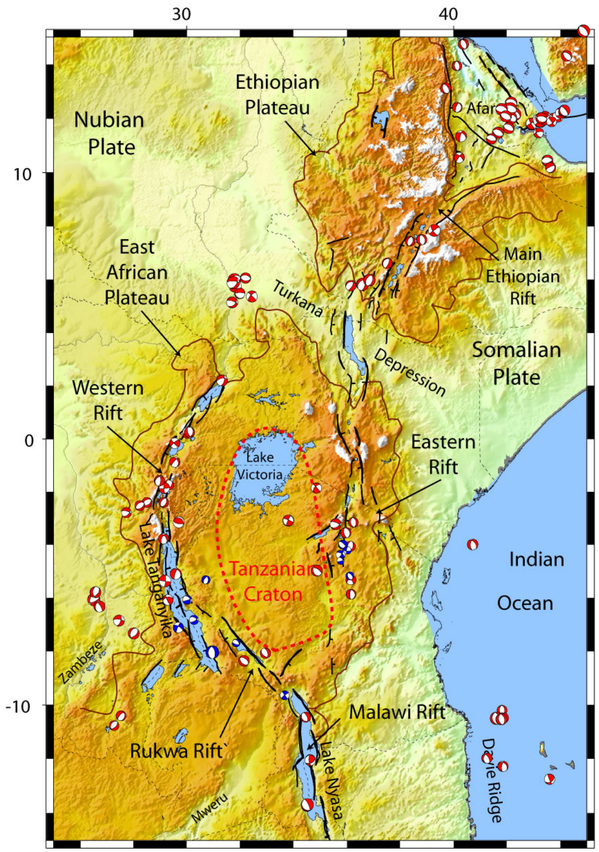
Introduction

① The **East African Rift System** (EARS) is the major active tectonic feature of the **Sub-Saharan Africa** (SSA) region

② Several past large earthquakes caused a non-negligible level of damage

③ A reliable risk assessment is therefore essential, which requires a state-of-art hazard assessment for the region

④ We propose an new **probabilistic seismic hazard model** for SSA based on the most recent and up to date available information



GEM's Philosophy

The Sub-Saharan Africa Hazard Model (as for all GEM products) is meant to be:

1) Collaborative

Although the initial pilot model has been proposed by GEM, we promote its development through collaboration between scientists from African institutions and worldwide

2) Open and transparent

All input information (e.g. catalogue), data (configuration files) and results are openly accessible to the community for verification, improvement or any use

GEM – SSA Hazard Model

Presently available PSHA Model Components:

- Earthquake Catalogue
  - Agency Selection
  - Magnitude Homogenization
  - Declustering
- Source Zonation
- Seismicity Analysis (for area sources):
  - Completeness & MFD Parameters
  - Depth Distribution
  - Source Mechanism
  - Rate Balance
- GMPE Selection
- Logic Tree Implementation & Uncertainty
- PSHA Calculations & Results

The new SSA Earthquake Catalogue

Merging Earthquake Catalogues

Input Catalogues:

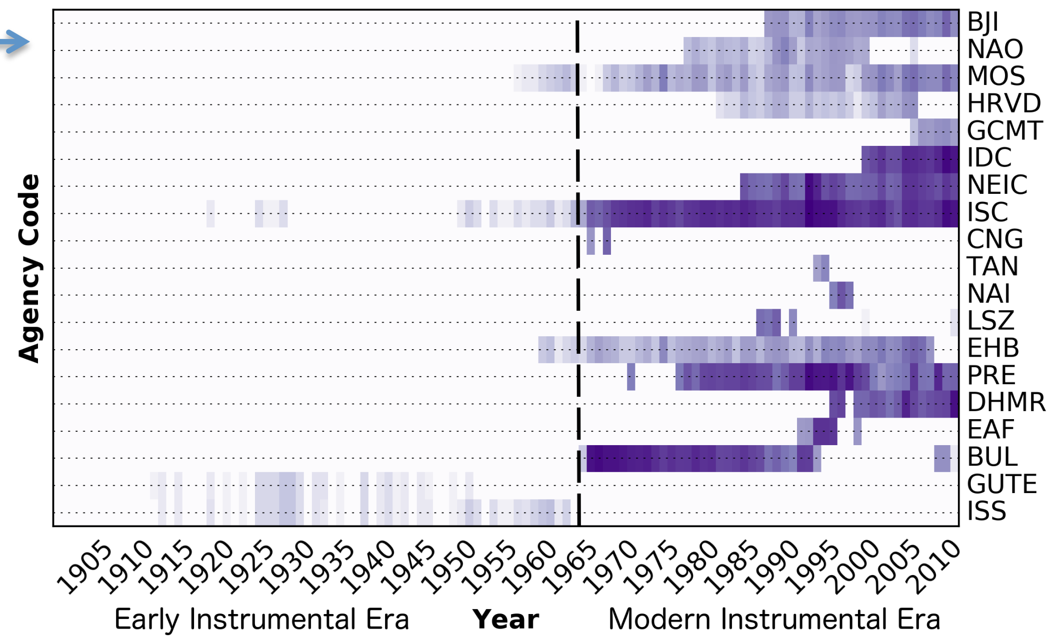
- ISC-REV
- ISC-GEM
- GCMT
- GEH
- AfricaArray

  - Tanzanian Broadband Seismic Experiment (TZB)
  - Ethiopian Plateau Catalogue (ETP)
  - AfricaArray Eastern Africa Seismic experiment (AAE)

Agency Prioritization

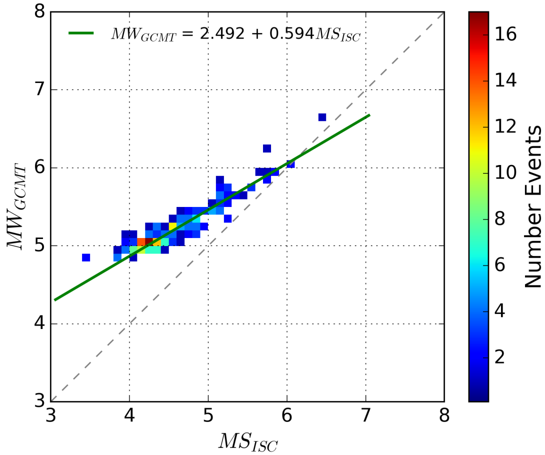
Period	Agency selection
1000 - 1900	GEH
1901 - 1959	ISC-GEM, ISC, ISS, GUTE, GEH
1960 - 1964	ISC-GEM, EHB, ISC, ISS, GEH
1965 - 1980	ISC-GEM, EHB, ISC, NEIC, IDC, GCMT, HRVD, GCMT-NDK, BUL, PRE, LSZ, TAN, CNG, GEH
1981 - 2015	ISC-GEM, EHB, ISC, NEIC, IDC, GCMT, HRVD, GCMT-NDK, AAE, ETP, TZB, PRE, LSZ, NAI, TAN, CNG, EAF, GEH

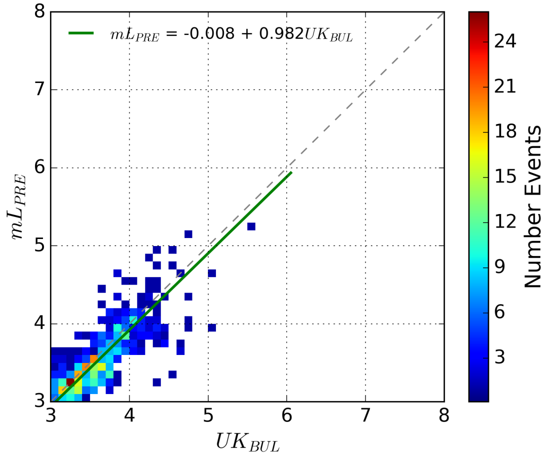
Agency Selection



Magnitude Homogenization

Examples

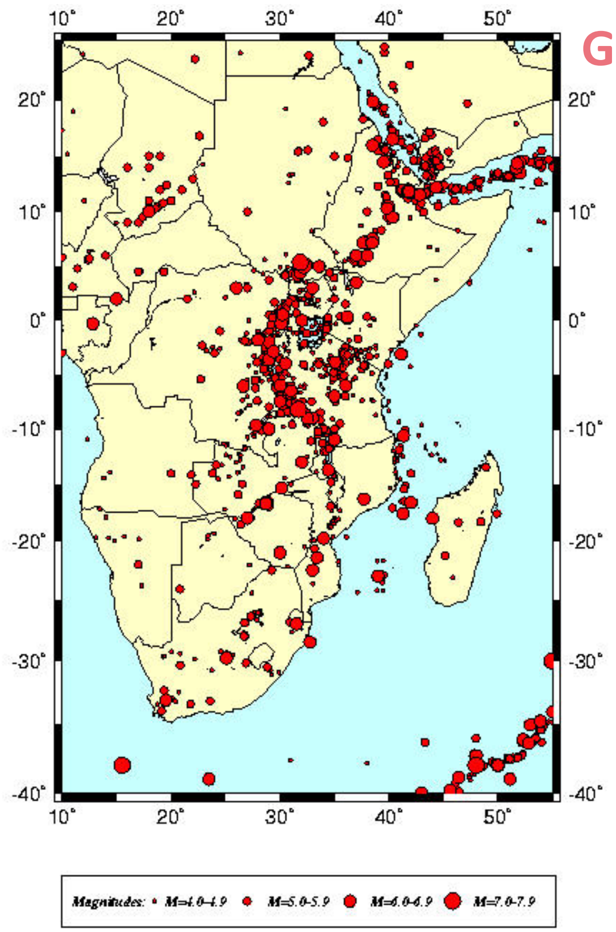


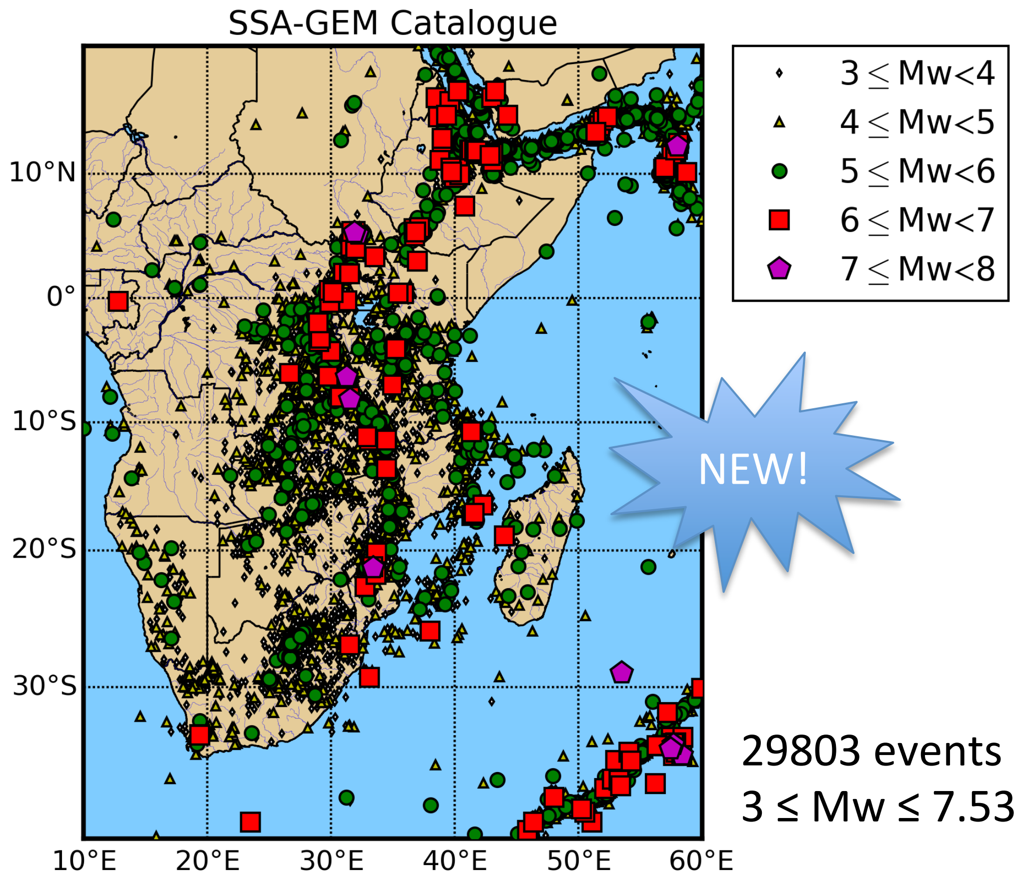


Agency	Type	Mw Conversion Rule	Range	Note
GCMT	Mw	None	–	–
ISC-GEM	Mw	None	–	–
NEIC	Mw	None	–	–
ISC	Ms	0.616*Ms+2.369	Ms<6	(Reference Weatherhill)
		0.994*Ms+0.1	Ms>6	
ISC	mb	1.084*mb-0.142	mb<6.5	(Reference Weatherhill)
NEIC	Ms	0.723*Ms+1.798	Ms<6.5	(Reference Weatherhill)
		1.005*Ms-0.026	Ms>6.5	
NEIC	mb	1.159*mb-0.659	mb<6.5	(Reference Weatherhill)
PRE	Ml	Ml	Ml<6	Assuming linear scaling to Mw and arbitrary large uncertainty (0.3 units)
BUL	Mblg	Ml	Ml<6	Assuming equivalence to PRE-Ml
TZB	Ml	$1.02+0.47*Ml+0.05*Ml^2$	Ml<5	Edwards et al., 2010
ETP	Ml	$1.02+0.47*Ml+0.05*Ml^2$	Ml<5	Edwards et al., 2010
AAE	Ml	$1.02+0.47*Ml+0.05*Ml^2$	Ml<5	Edwards et al., 2010
PAS	Ms	0.616*(Ms-0.2)+2.369	Ms<6	
		0.994*(Ms-0.2)+0.1	Ms>6	Using ISC-Ms conversion scaled by factor 0.2 (according to Engdahl and Villaseñor, 2002 - *Centennial Catalogue*)

SSA Earthquake Catalogue

GSHAP

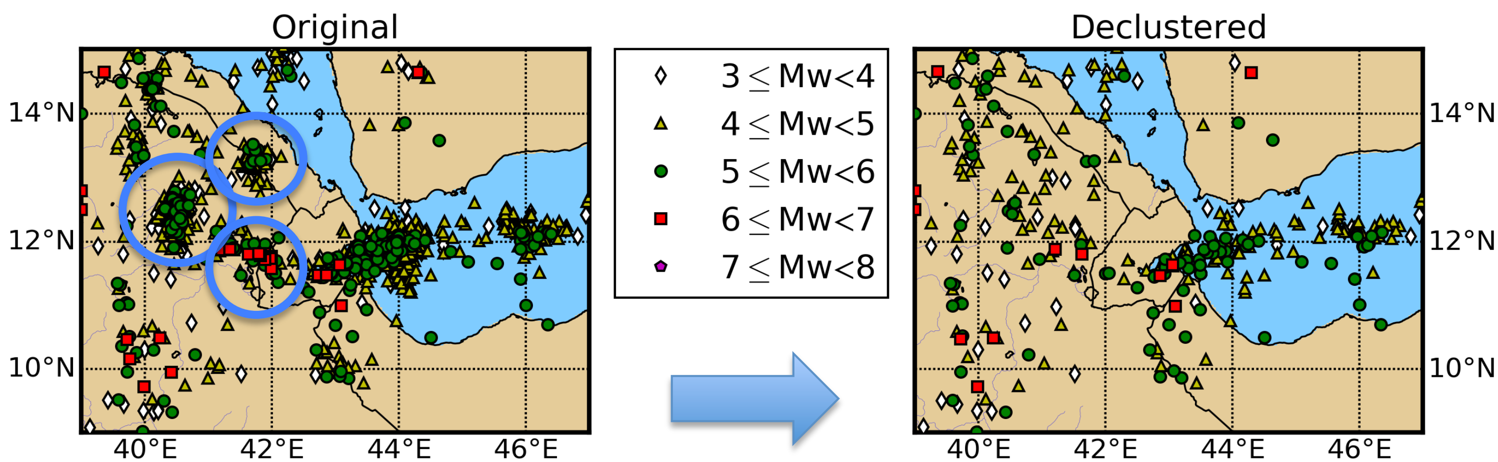




29803 events
$3 \leq Mw \leq 7.53$

SSA Catalogue Declustering

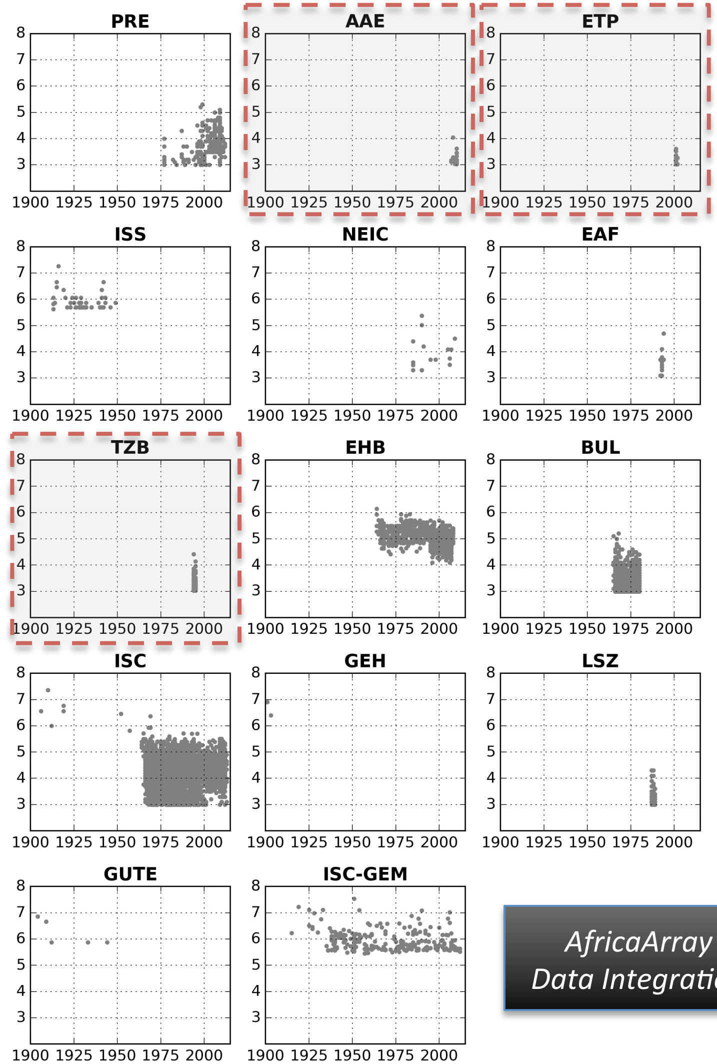
To obtain estimates of stationary seismicity rates the recurrence models need to be fit to earthquake catalogues that are purged of non-Poissonian Events (i.e. foreshocks and aftershocks) which are dependent



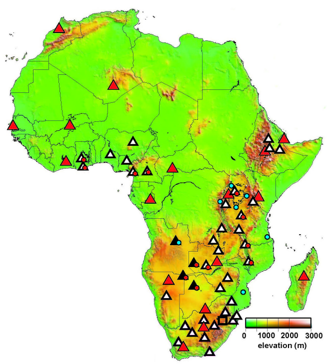
- We use Gardner & Knopoff (1974) algorithm
- 7259 events out of the original 29803 (3 ≤ Mw ≤ 7.5)

Accessing Relative Agency Contribution

DECLUSTERED
SSA CATALOGUE



Were AfricaArray data of any significance?

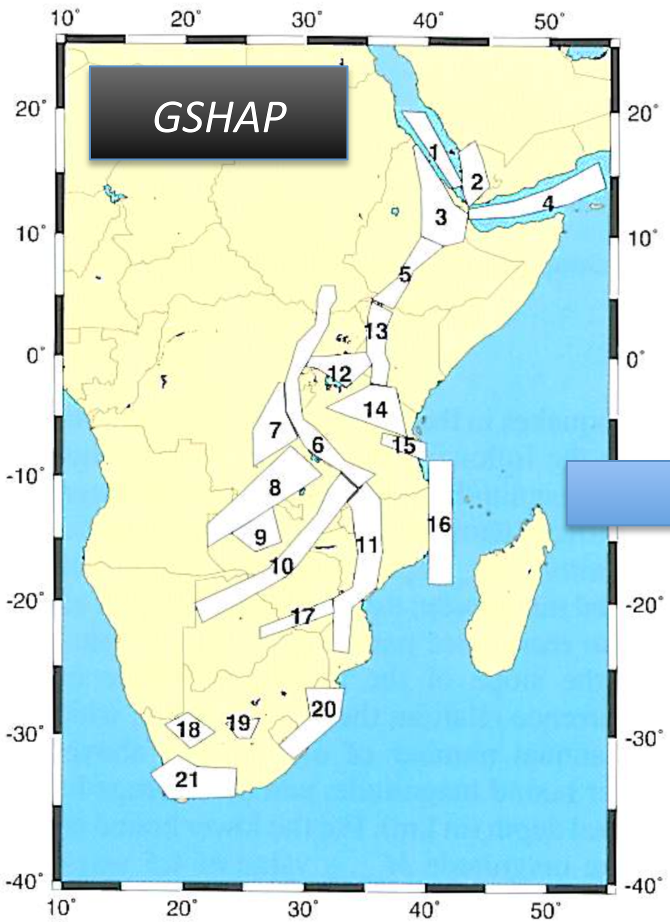


YES, but not for seismicity analysis…..

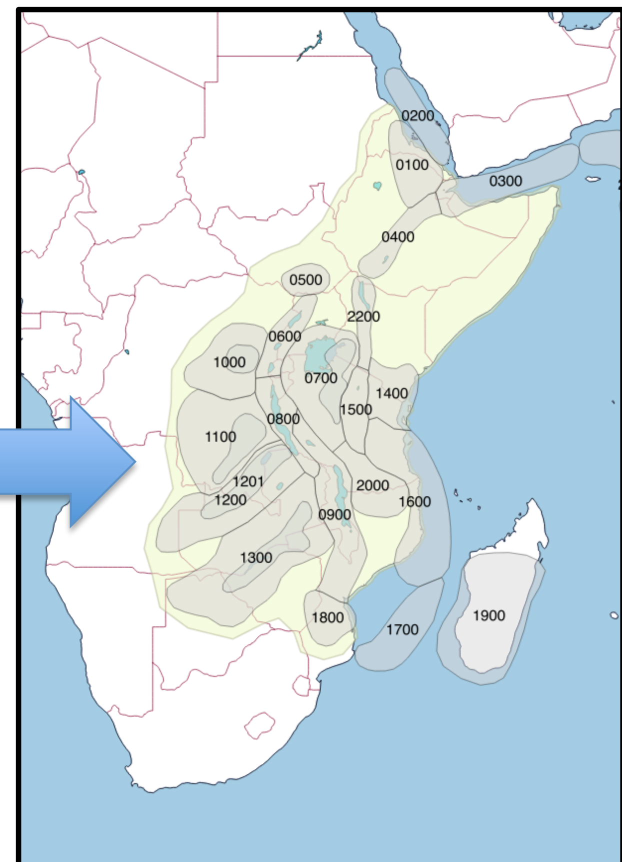
AfricaArray Data Integration

Area Source Zonation

Area Source Zonation



GEM - Version 6.0

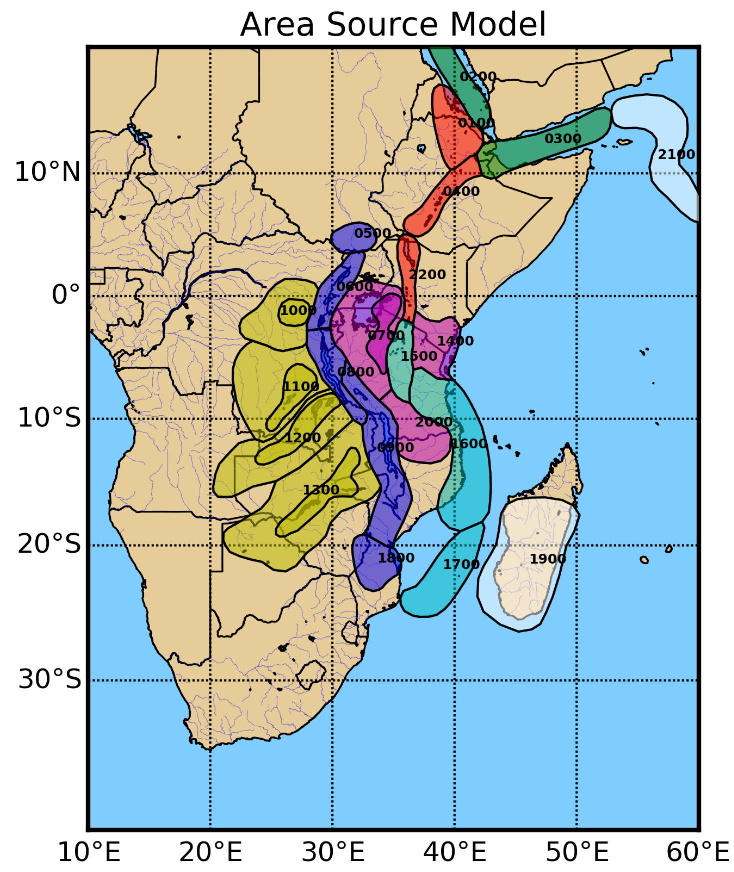


Based on:

- Previous studies
- Seismicity
- Surface Faults
- Plate boundaries
- Strain models

Source Groups

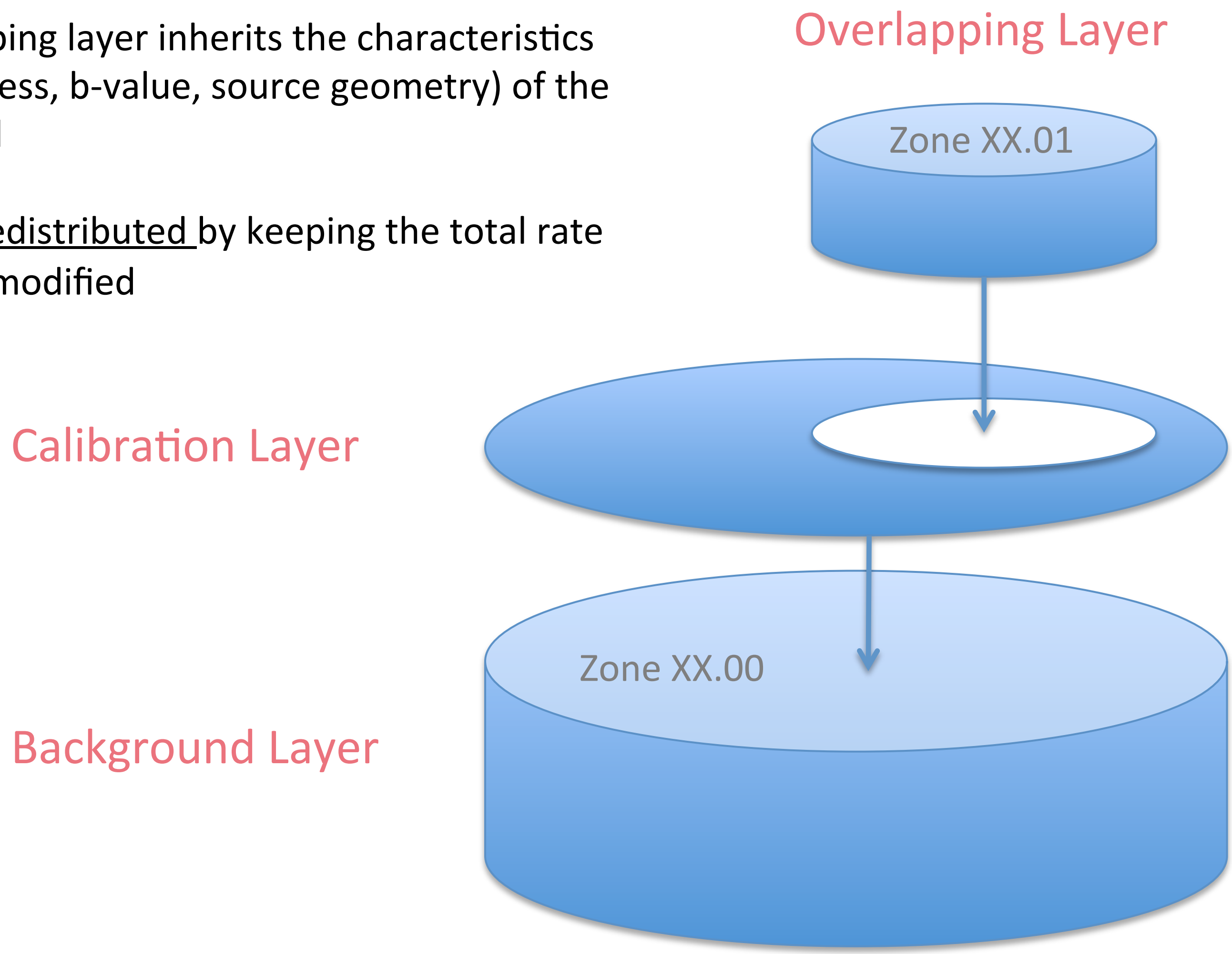
Group ID	Source ID	Name - Decription
1	02-00	South Read Sea
	03-00	Aden Gulf
2	01-00	Afar Depression - Eritrea
	04-00	Main Ethiopian Rift
	22-00	North Kenya - Lake Turkana
3	05-00	South Sudan
	07-00/01	Lake Victoria
	14-00	South Kenya
	20-00	Rowuma Basin
4	06-00	Western Rift - Lake Edward, Albert and Kivu
	08-00	Western Rift - Tanganika
	09-00	Malawi - Nyasa Rift
	18-00	South Mozambique
5	10-00/01	Walikale and Masisi
	11-00/01	Luama Rift
	12-00/01	Mweru - Katanga - Upemba
	13-00/01	Kariba - Okavango
6	15-00	Eastern Rift
	16-00	Davie Ridge
	17-00	Mozambique Channel



Multiple Layer Strategy

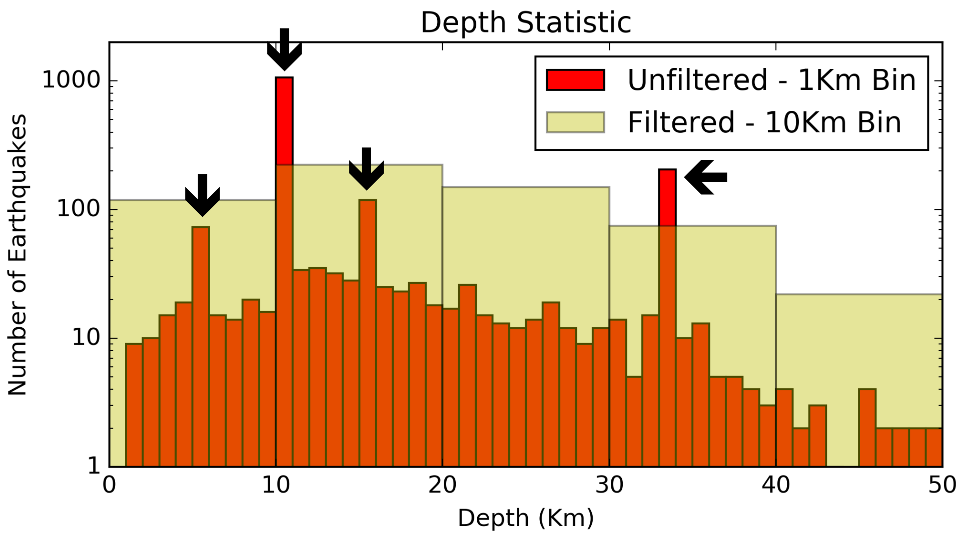
An overlapping layer inherits the characteristics (completeness, b-value, source geometry) of the background

<u>Rates are redistributed</u> by keeping the total rate balance unmodified



Source Parameters

Depth Solution Distribution



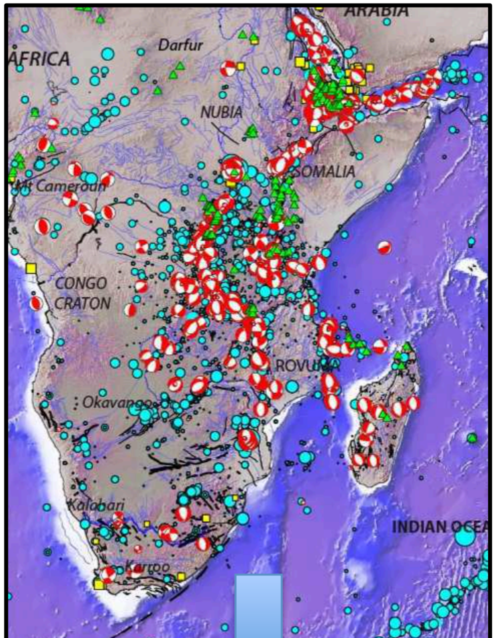
Fix-Depth Solutions Removed

Uncertain Large-Depth Solutions Removed

Final Statistic

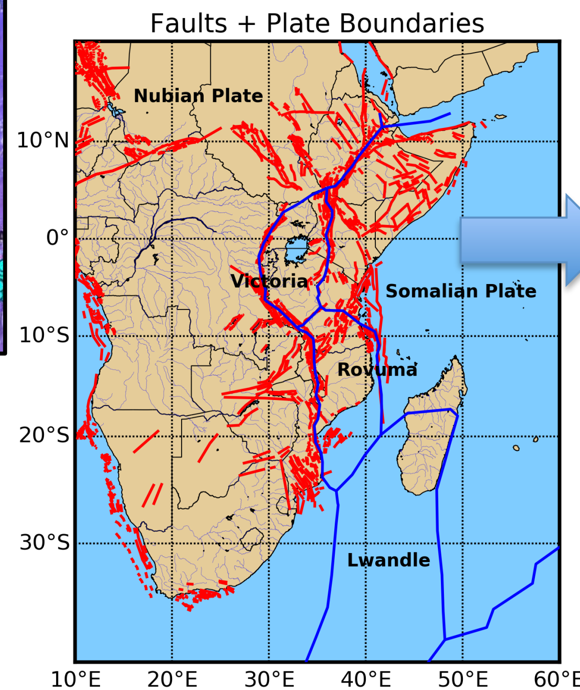
ID	N^{tot}	5Km	15Km	25Km	35Km
1	182	37	80	51	14
2	50	15	21	8	6
3	26	5	11	4	6
4	163	28	58	53	24
5	77	22	24	17	14
6	69	12	30	16	11

Source Mechanism Statistic

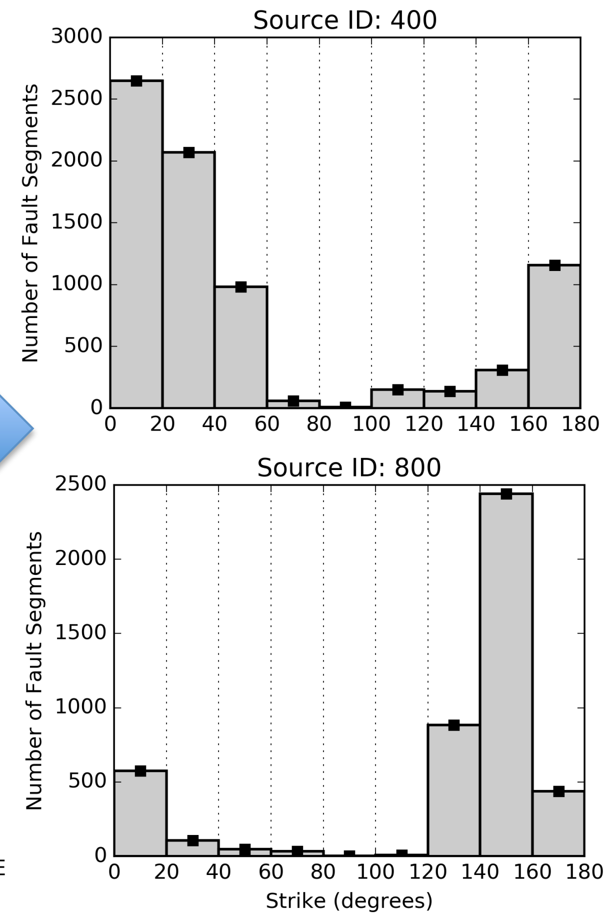


Bibliographic information
+ open datasets

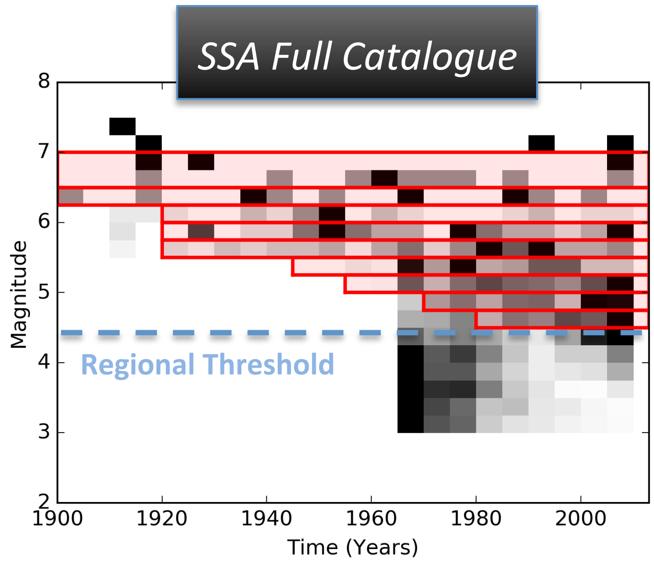
Fault Style (Dip+Rake)



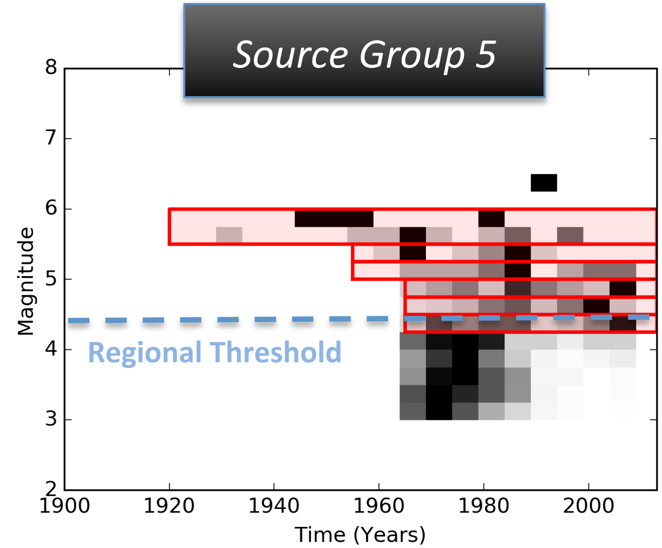
Strike Distribution



Catalogue Completeness Analysis

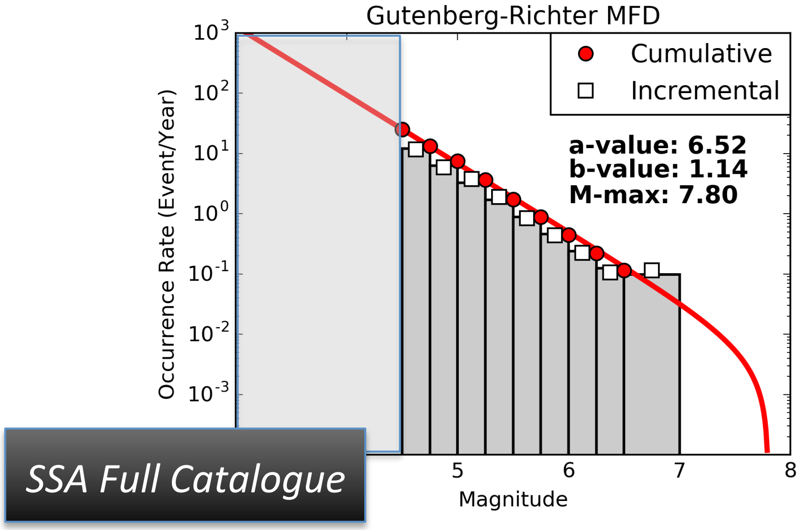


- First, a regional completeness analysis was performed
- Source groups have been subsequently refined to account for spatial variability
- Alternative methods (e.g. Stepp, 1997) were also tested




```
comp_table = [[4.50, 0.25, 1967., 2013.],
              [4.75, 0.25, 1967., 2013.],
              [5.00, 0.25, 1967., 2013.],
              [5.25, 0.25, 1967., 2013.],
              [5.50, 0.50, 1951., 2013.],
              [6.00, 0.50, 1901., 2013.],
              [6.50, 1.00, 1901., 2013.]]
```

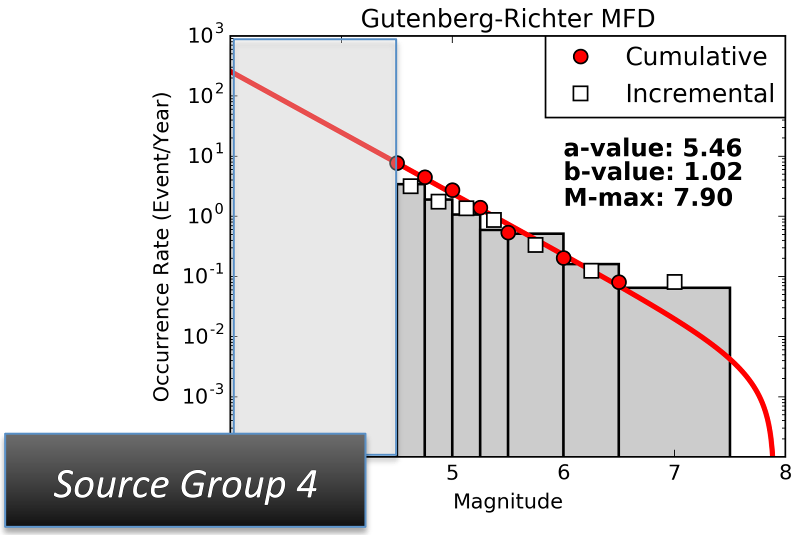
MFD – Seismicity Analysis



Using a **truncated Gutenberg- Richter** magnitude occurrence relation with $Mw^{min} = 4.5$

New strategy based on direct inversion of observed **incremental occurrences rates**

- Not affected by data correlation
- Bins of arbitrary width / completeness
- Either *a*, *b* or Mw^{max} can be fixed



MFD – Seismicity Analysis

- The b-values were kept constant within source groups, while the rates have been calibrated separately for each source zone
- Rates have been redistributed between overlapping layers by preserving the total balance of the zone
- Maximum magnitude was defined based on the maximum observed magnitude for the zone, plus about 0.5 magnitude units

Group	a	b	Mw^{max}
1	5.4629809325	1.0233537813	7.2
2	4.7012917208	0.9472904903	7.5
3	4.6964659876	1.0215313804	6.9
4	5.4566139474	1.0154006974	7.9
5	4.9062300341	0.9914650334	6.9
6	5.7370738808	1.1585298966	7.4

Could be improved using strain models!

Logic Tree Implementation

GMPE Selection - Introduction

Given the unfortunate lack of **calibration recordings**, GMPE selection can only be made based on general considerations about:

- The tectonic context of validity
- Type and quality of data used for calibration
- Suitability of the functional form

However, African regions interested by the rift system are in a quite peculiar seismotectonic setting

Seismicity can hardly be classified as just of stable continental or active shallow type, but **hybrid behavior** might be expected

GMPE Selection – Weighting Strategy

We have selected four suitable GMPEs, two per seismotectonic setting:

1. Chiou & Youngs (2014)
2. Akkar et al. (2014)
3. Atkinson & Boore (2006)
4. Pezeshk et al. (2011)

1–2 → Active Shallow Crust

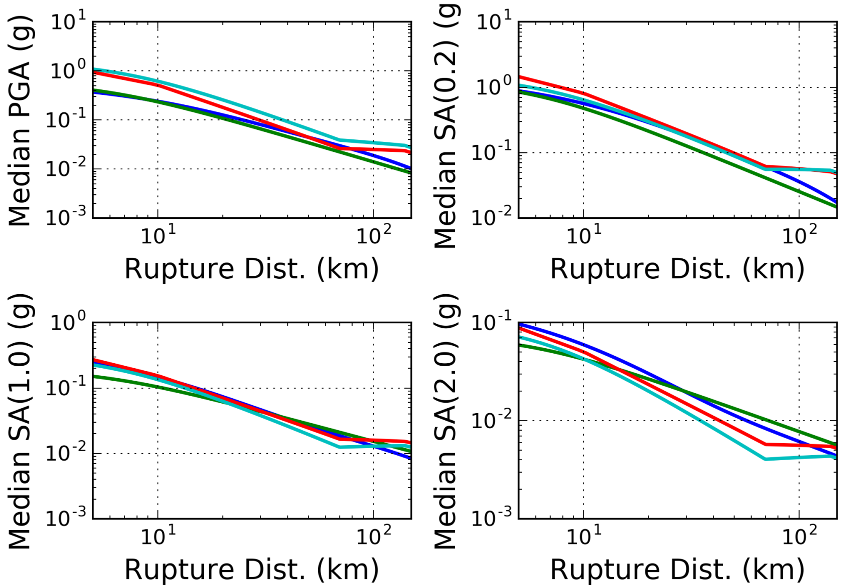
3–4 → Stable Continental Crust

Four main tectonic categories have then been identified, which allows the assignment of different **weight combinations** to the GMPEs

Group ID	Source ID	CY	AK	AB	PZ
A	100 200 300 400 1700	0.5	0.5	0	0
B	500 600 800 900 1800 2200	0.375	0.375	0.125	0.125
C	1500	0.25	0.25	0.25	0.25
D	700 701 1000 1001 1100 1101 1200 1201 1300 1301 1400 1600 2000	0.125	0.125	0.375	0.375

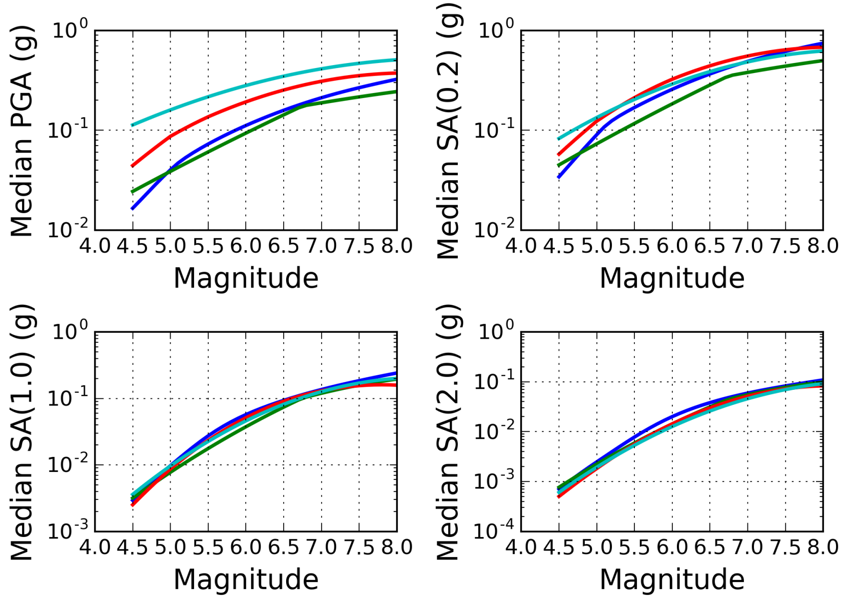
GMPE Selection – Mapping GM Variability

Distance Scaling

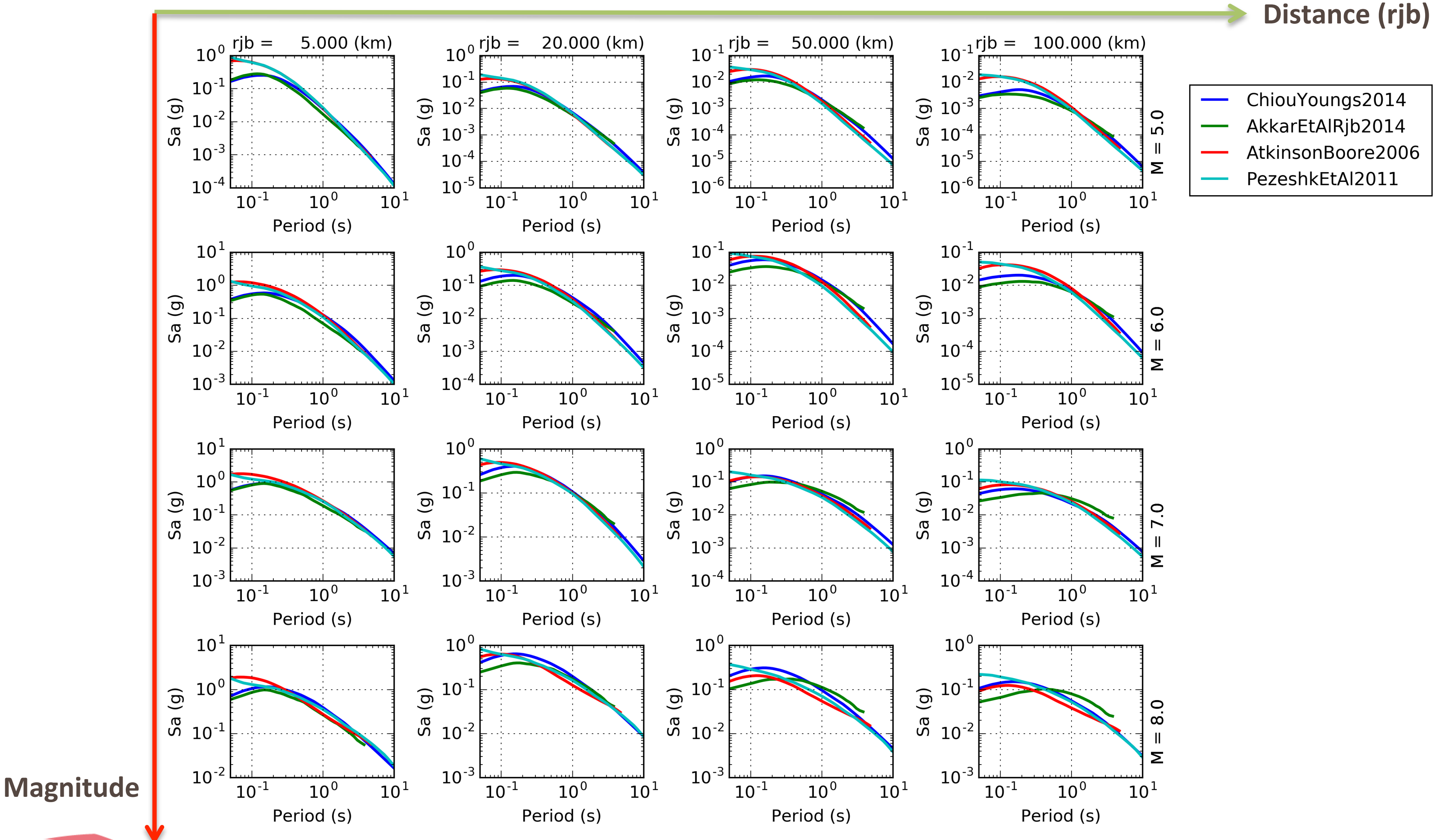


The selection was performed with the goal of best representing the **epistemic variability** of the ground motion models

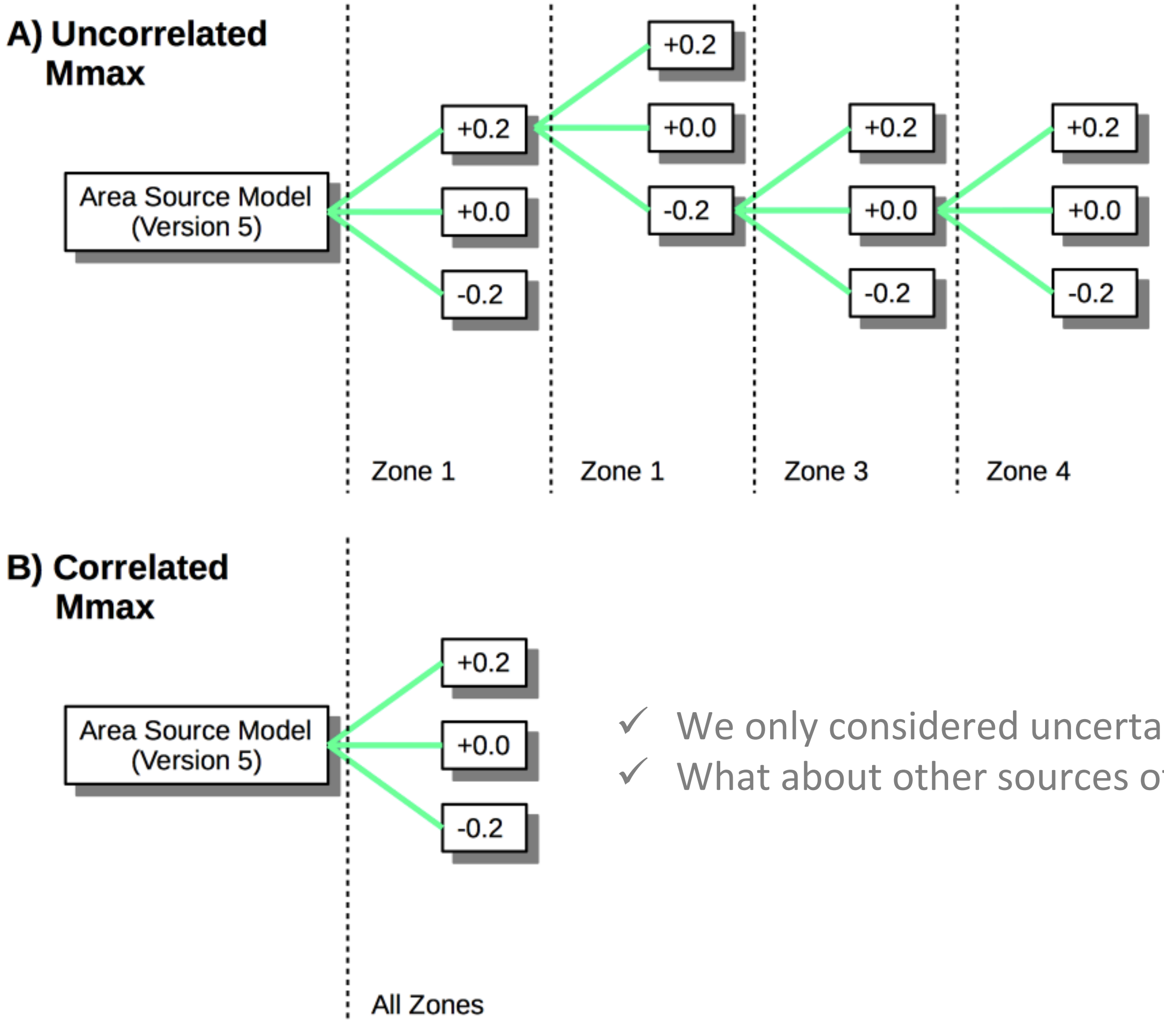
Magnitude Scaling



GMPE Selection – Comparing Spectra



Source Parameter Uncertainty - Regionalization



- ✓ We only considered uncertainty on M^{max}
- ✓ What about other sources of uncertainty?

PSHA Results using OpenQuake Engine

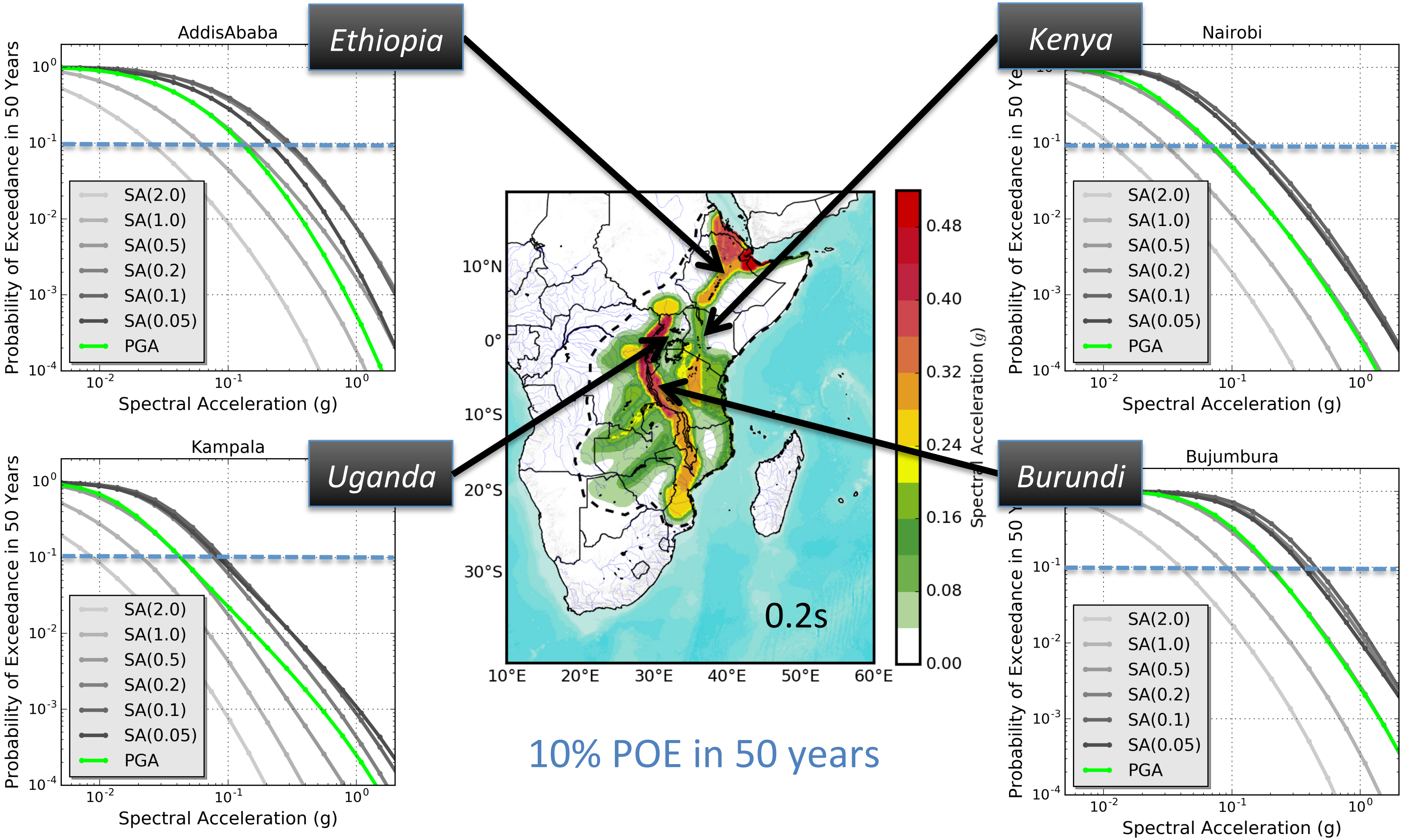
Hazard Calculation Using OpenQuake

The Sub-Saharan Africa Hazard model has been calculated for:

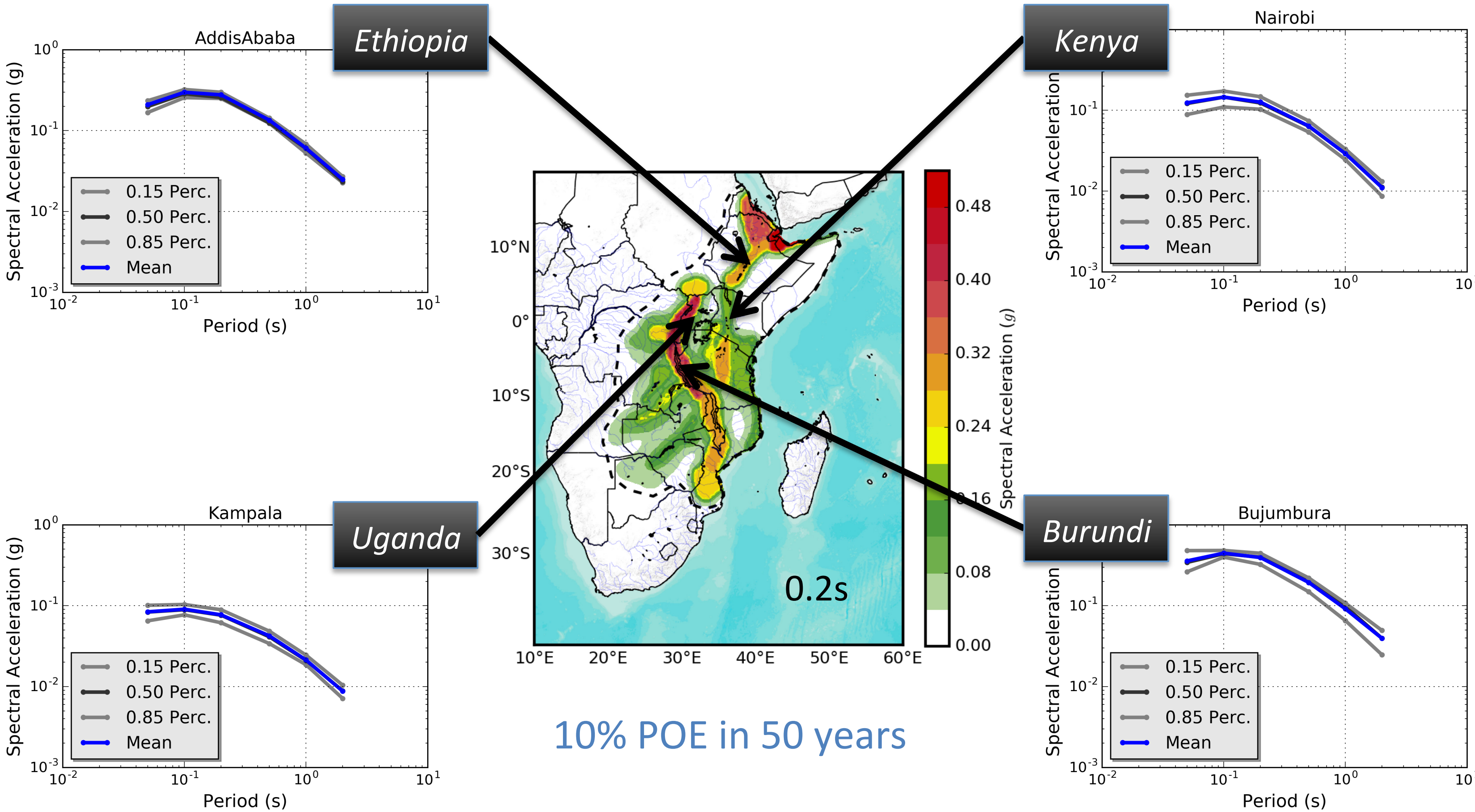
- 2722 sites (about 50km resolution), 192426 ruptures
- 2% and 10% PoE in 50 Years (R.P. of 2474 and 474 years, respectively)
- Outputs: hazard curves, uniform hazard spectra (UHS), hazard maps
- Spectral periods: PGA, 0.05*s*, 0.1*s*, 0.2*s*, 0.5*s*, 1*s* and 2s
- Statistic: mean hazard and percentiles (0.15, 0.5 and 0.85)
- Rock reference conditions (Vs^{30}=600m/s); no site-specific response

6.3 hours on 256 cores

Hazard Curves @ African Capitals

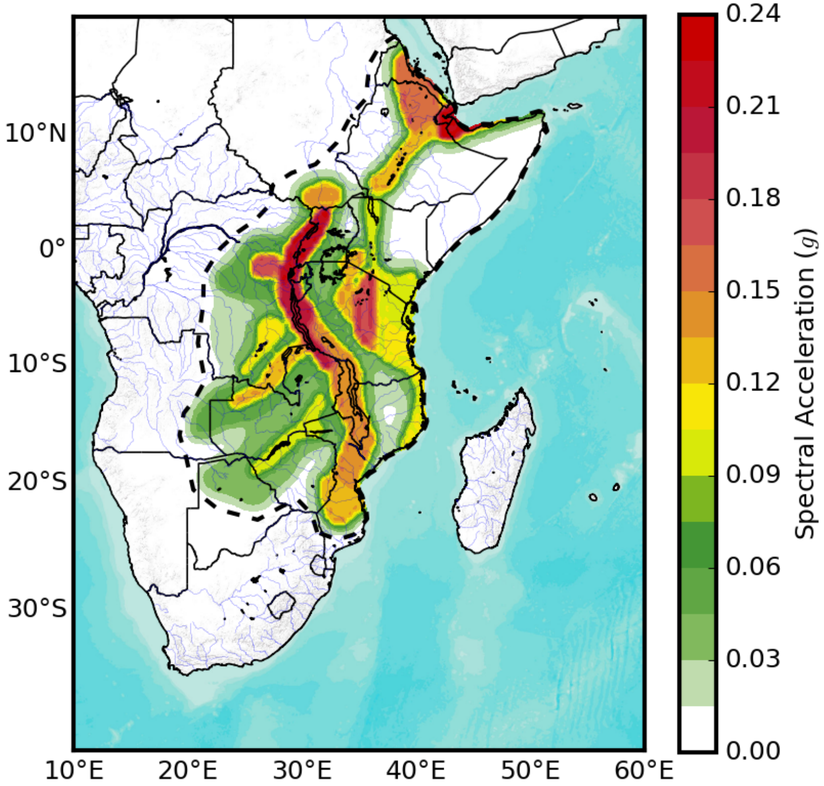


Uniform Hazard Spectra @ African Capitals

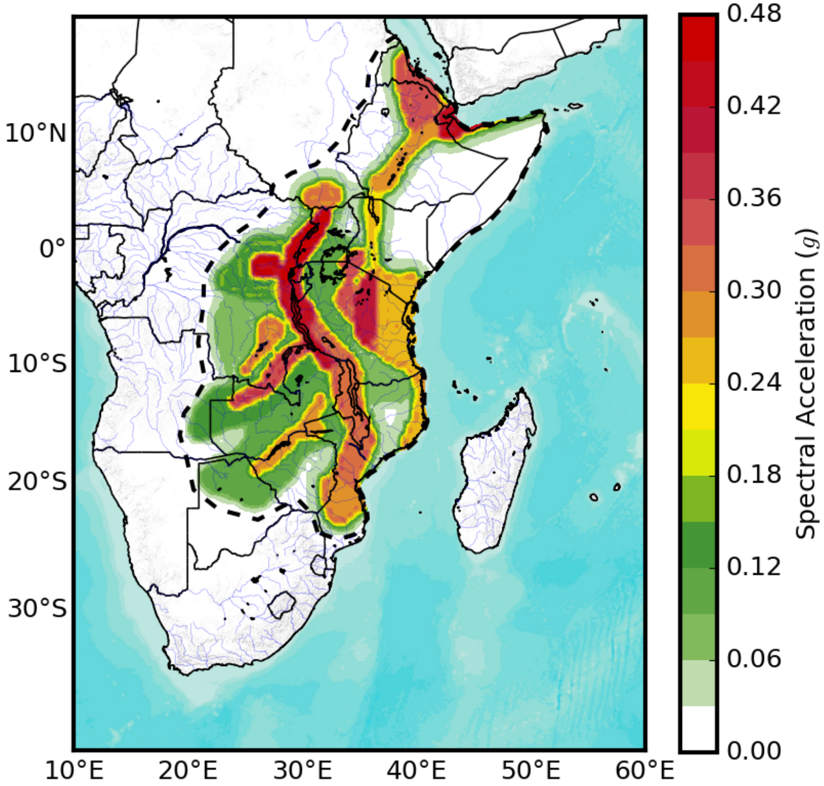


Hazard Maps @ PGA

10% POE in 50 years

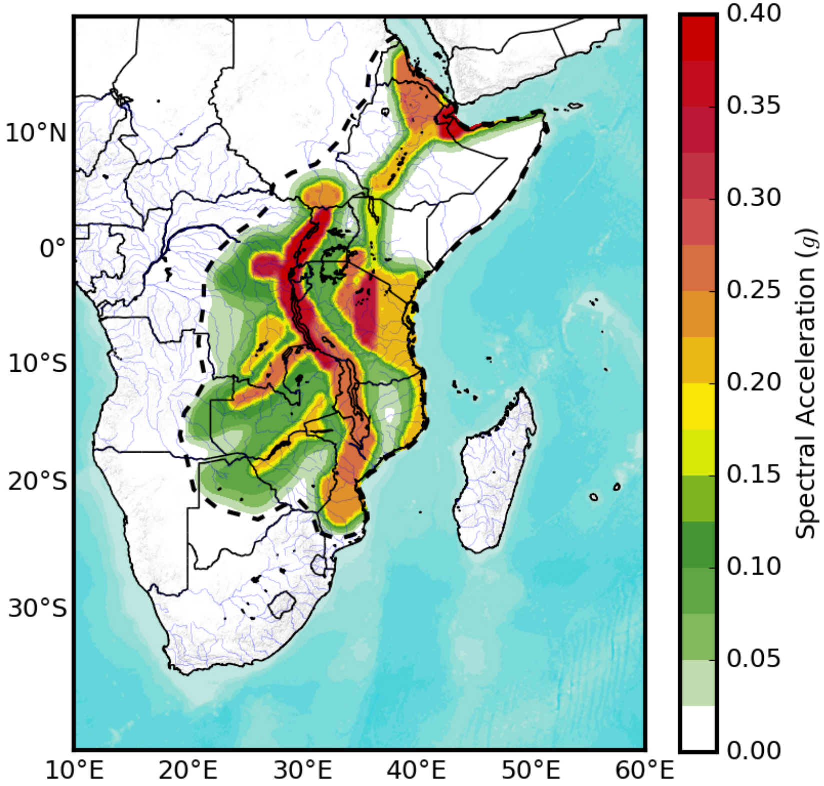


2% POE in 50 years

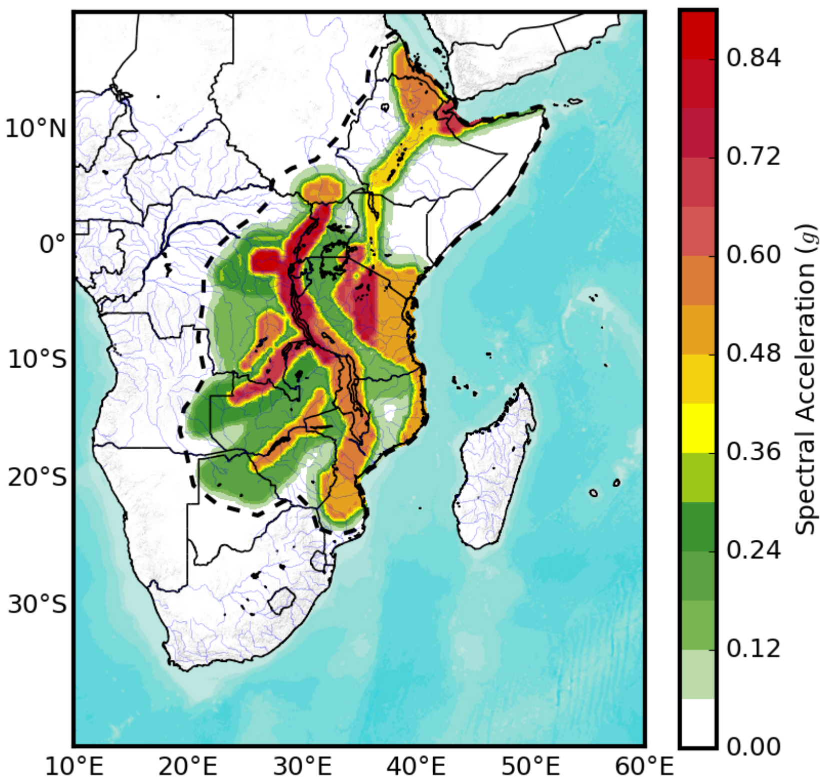


Hazard Maps @ 0.05s

10% POE in 50 years

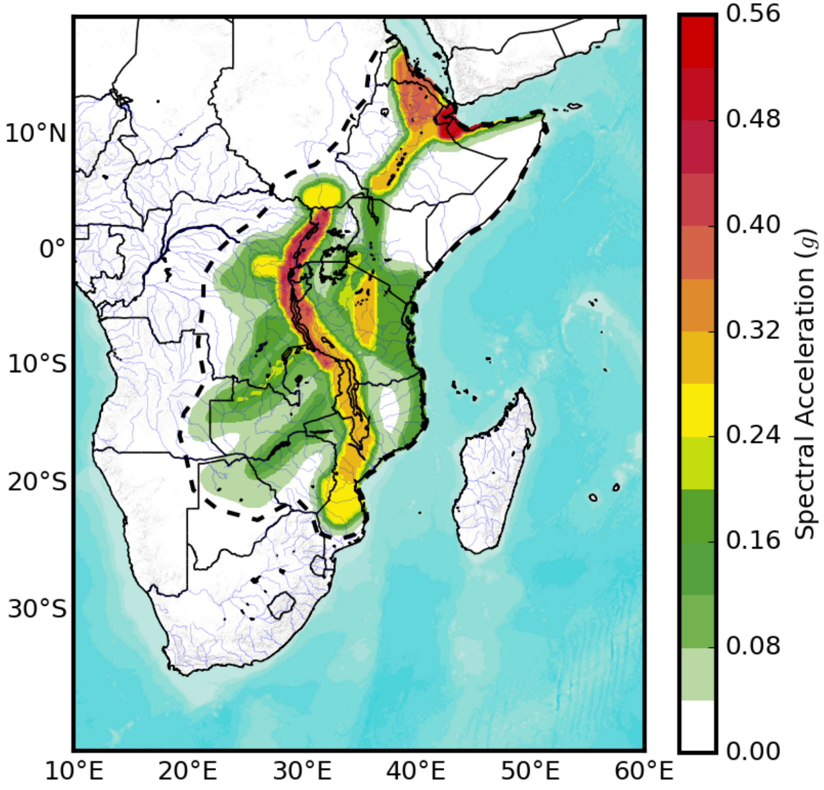


2% POE in 50 years

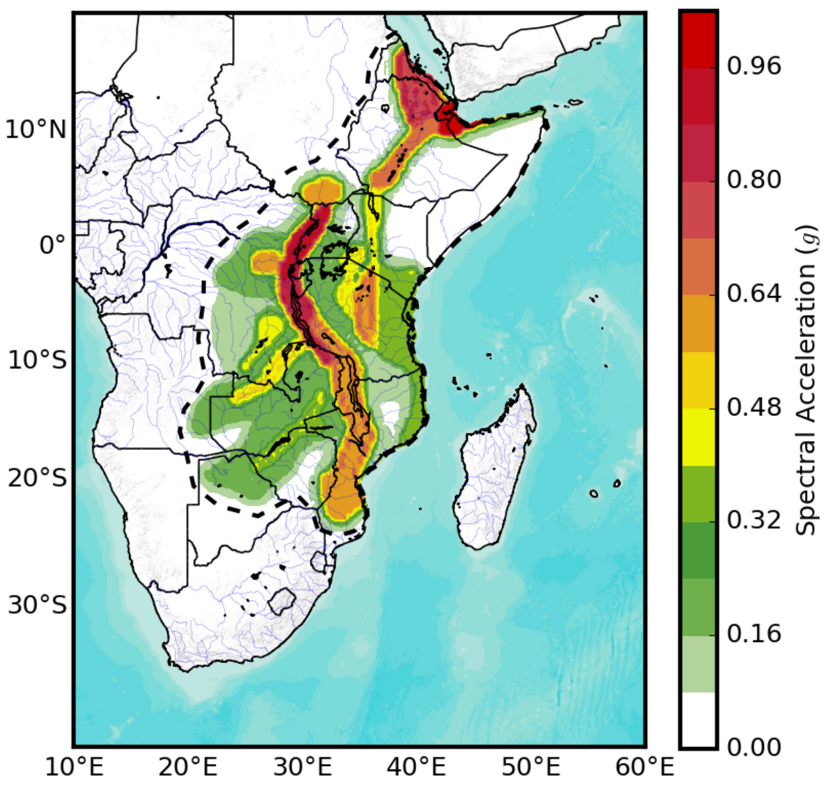


Hazard Maps @ 0.2s

10% POE in 50 years

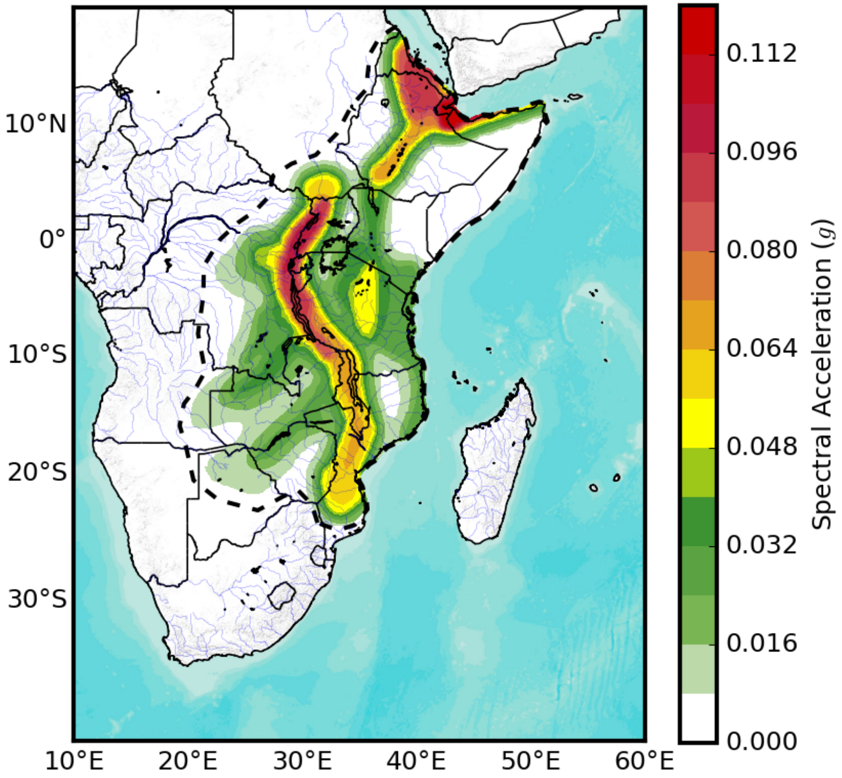


2% POE in 50 years

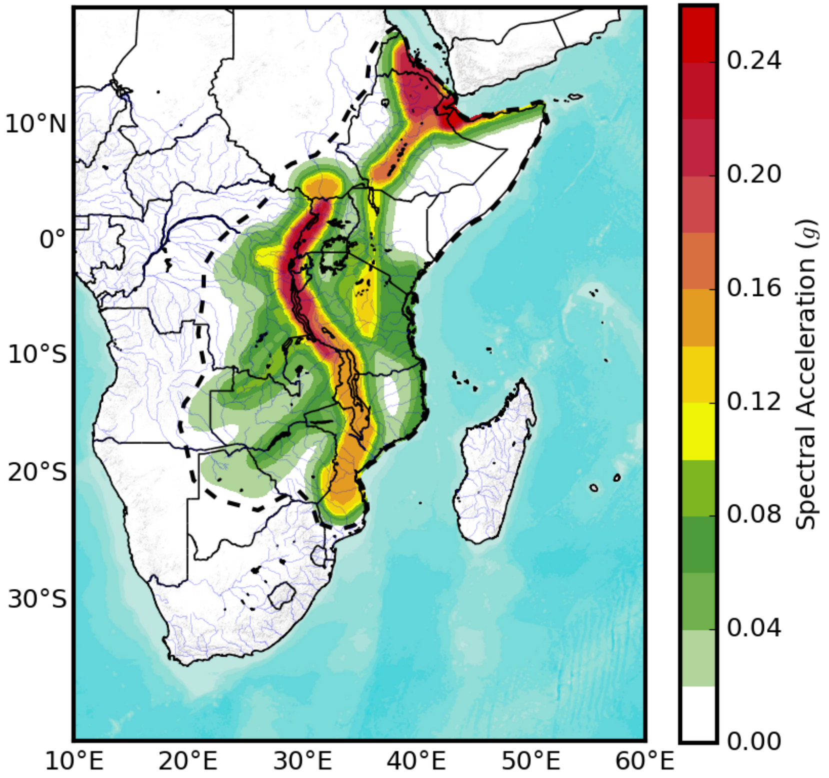


Hazard Maps @ 1s

10% POE in 50 years



2% POE in 50 years



Moving Forward

Although SSA Hazard model has been finalized, several issues still remain open…

Missing PSHA Model Components:

- Fault Models → Information is fragmented; how to proceed?
- Strain Rates → Strain model already available, but not used so far
- Strong Motion Data → AfricaArray, IRIS?
- Alternative Seismicity Models → Smoothed Seismicity?
- Disaggregation Scenario → Focusing on major cities? Ongoing…..
- Site-specific response → Possible microzonation studies?

Food for thought…

Thank you!