Open Model of Probabilistic Seismic Hazard Assessment for the Indian Subcontinent

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Abstract

Open models encourage peer review and collaboration; open models can be built upon.

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1 Introduction

In this work a seismic hazard model for peninsual India Nath and Thingbaijam (2012) has been implemented under the OpenQuake (Weatherill, 2014; Crowley et al., 2015) platform.

File names in the published model are shown in `typewriter` font, as are keywords specific to OpenQuake, such as `bGRRelative`.

1.1 Seismic hazard in peninsular India

1.2 Open science and OpenQuake

2 Model implemetation

2.1 Seismogenic sources

Thingbaijam and Nath (2011)

2.1.1 Areal sources

As we will see in subsubsection 2.3.1 ground motion prediction logic trees depend on correct assignment of tectonic region types. The main difficulty in implementing the areal source model of Nath and Thingbaijam (2012) was that although their intentions were generally clear, these assignments were not made explicit. Tectonic region type assignments were therefore made using a combination of the representative focal mechanisms reported by Nath and Thingbaijam (2012) and fault maps such as the HimaTibetMap database (Styron et al., 2010). Since the representative focal mechanism was computed as the average of the moment tensors reported in the GCMT database weighted by magnitude it is biased in favour of the larger earthquakes (Thingbaijam and Nath, 2011). The inferred tectonic region assignments assumed are shown in Figure 1.

Potentially problematic tectonic region type assignments:

- zone 906 in the Great Himalayas just north of the Shillong plateau was assigned "active shallow crust strike-slip reverse" even though the main trace of the Himalayan subduction fault runs through it, because the representative focal mechanism is strike-slip.

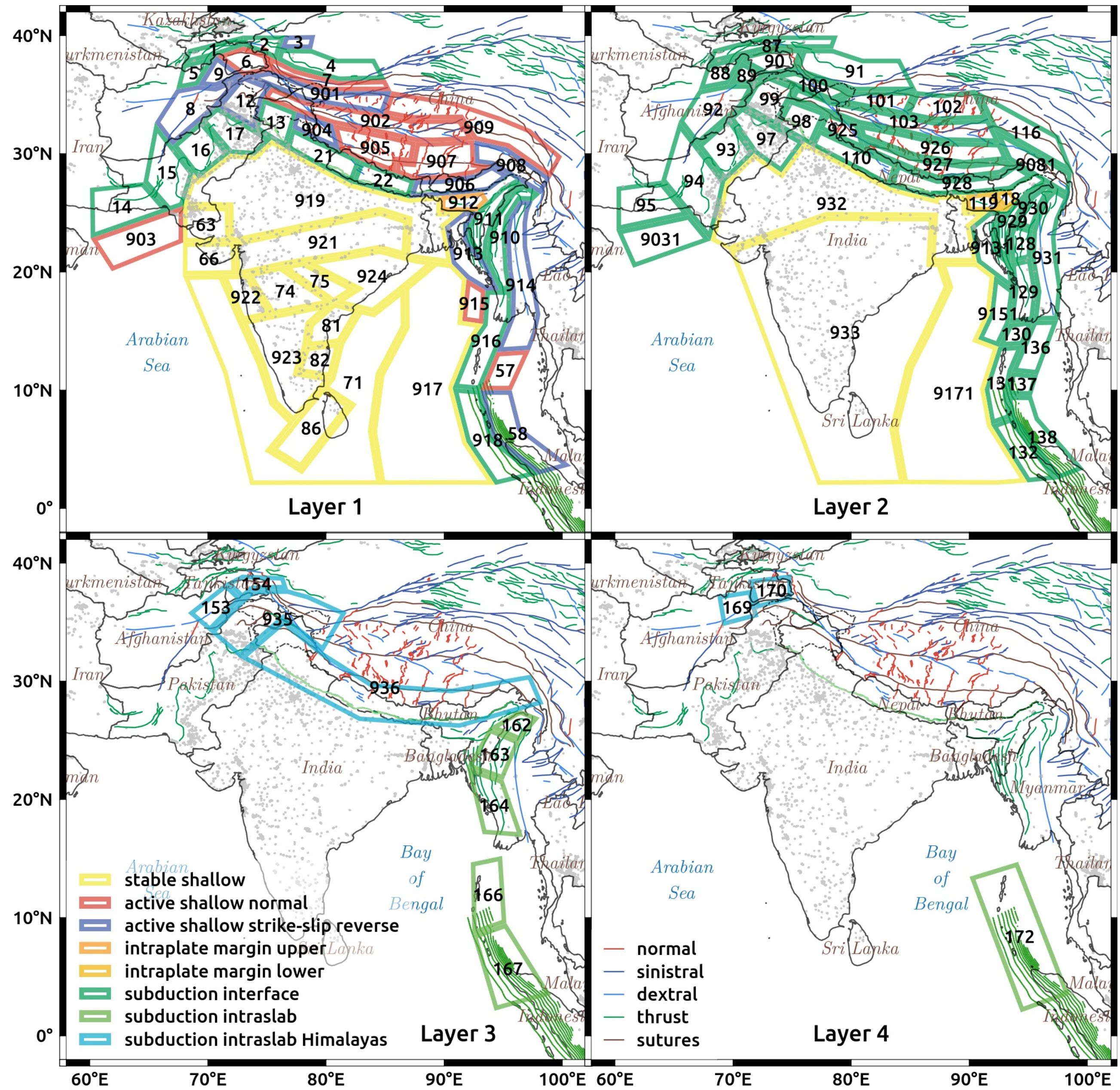

Figure 1: Areal source model tectonic region assignments used in GMPE logic tree. The areal source models is encoded in `areal_source_model.xml`. Zone identification numbers from Nath and Thingbaijam (2012) are indicated. Fault traces are from HimaTibetMap-1.0 (Styron et al., 2010) except the Sumatran subduction fault which is from SLAB 1.0 (Hayes et al., 2012). Fault data from the stable regions of India is lacking. Urban areas, "contiguous patches of built-up land greater than 1 km²" (Schneider et al., 2009), are indicated in darker grey.

- zones 71, 86 on layer 1 and zones 9031, 9081, 9131, 9151 and 9171 on layer 2 have have a values of zero and so were not included in the areal source model

Magnitude-scaling relations were selected based on the same source zonation, since "Wells and Coppersmith (1994) for crustal events and those given by Strasser et al. (2010) for the subduction earthquakes" (Nath and Thingbaijam, 2012, p. 140). For interface and intraslab regions `StrasserInterface` and `StrasserIntraslab` were used, respectively.

The comment that "the fault-rupture area estimated from the magnitude is constrained by a factor of 2" (Nath and Thingbaijam, 2012, p. 140) is interpreted as a width/depth aspect ratio of 2.

The seismogenic depth was assumed to be midway between the minimum and maximum. Is this justified by Thingbaijam and Nath (2011)? Could it stand further refinement?

2.1.2 Smoothed seismicity

Thingbaijam and Nath (2011)

Each point in the smoothed seismicity model was treated as a point source. Nath and Thingbaijam (2012) have provided "spatially varying annual activity rates while b-value and m max remain fixed within the source zone". Thus for the smoothed seismicity model the parameters b and M_{max} of the truncated Gutenberg-Richter magnitude-frequency distributions are to be inferred from the areal source model zonation. For points inside zones with non-zero a values in the areal source model this is trivial; for points outside these zones the zone with the shortest perpendicular distance was chosen.

A point source model in OpenQuake also requires definition of the uncertainty of the probability distribution, as well as the tectonic region type and source mechanism for the selection and implementation of GMPEs, respectively. Thus the same procedure was used to assign σ_b, $\sigma_{m_{max}}$, tectonic subregion, rake, dip, strike and magnitude scaling relations were used.

The electronic supplement to Nath and Thingbaijam (2012) for the smoothed-gridded seismicity models simply gives values for `nu4_5` and `nu5_5` for each latitude and longitude, where "ν_i , is the annual activity rate for ith seismogenic source for a threshold magnitude" (Nath and Thingbaijam, 2012, p. 140).

The truncated Gutenberg-Richter magnitude-frequency distribution in OpenQuake implements

$$\lambda(M \geq m) = 10^{a-bm} = e^{\alpha-\beta m}$$

where, since λ is an annual rate, 10^a is too. If we ignore events below some threshold m_{min} then the annual rate becomes

$$\lambda(M \geq m_{min}) = e^{\alpha-\beta m_{min}} e^{-\beta(m-m_{min})} = \nu e^{-\beta(m-m_{min})}$$

Thus to compute the a value required by OpenQuake from the activity rate ν for a given magnitude threshold, we must also take into account the b value for the zone:

$$a = \log_{10}(\nu) + bm_{min}$$

Applying this formula gives rates for the areal model which agree well with the catalogue, but the rates in the smoothed-gridded seismicity model are on the order of 100x higher. Figure 3.6 of Thingbaijam (2011) shows rates in line with those of Thingbaijam and Nath (2011) and which better agree with the areal rates. In discussion with the author was concluded that the electronic supplement to Nath and Thingbaijam (2012) is in error.

Other assumptions:

Table 1: Comparison of seismicity rates in areal and smoothed-gridded seismicity models to those obtained from the catalogue.

areal 4.5	areal 5.5	smoothed 4.5	smoothed 5.5	ratio 4.5	ratio 5.5	cat 4.5	cat 5.5
79.5	8.4	57.4	3.3	0.72	0.39	54	3
67.5	10.4	85.1	3.9	1.26	0.38	78	3
35.7	2.9	42.9	1.8	1.20	0.62	39	1
11.5	1.6	23.9	1.3	2.08	0.81	10	1
194.2	23.3	209.3	10.3	1.08	0.44	181	8

- zones 9031, 9081, 9131, 9151 and 9171 on layer 2 have m_{max} values values of zero so the the smoothed seismicity points in or nearest to these zones on layer 2 were assigned the m_{max} values from the corresponding zones on layer 1, namely zones 903, 908, 913, 915 and 917.

Note differences in grids: although the hazard maps in the electronic supplement are at 0.2° and the paper says the smoothed-gridded models are also at 0.2° they are in fact at 0.1°. Figure shows the model at just 0.2°.

Note smoothing details. A Gaussian kernel is used, following the methodology of Frankel (1995) with correlation distances of 65 and 85 km for m_{min} of 4.5 and 5.5 respectively. The method involves smoothing event counts, thus events per year, for a given minimum magnitude.

Thingbaijam (2011)

Nath et al. (2010)

2.2 Ground-motion prediction

Importance of models implemented for this study.

The great Assam earthquake of 1897 destroyed buildings within several hundred km. The two main fault structures involved are capable of M > 8 plateau-building events with a recurrence interval of 3-8 kyr each (Bilham and England, 2001).

Nath et al. (2012) notes stress drop apparently increasing with depth and models κ using a database of recent well-recorded micro-earthquakes, and uses this information to develop stochastic models for events in the upper and lower crust. The simulations are of vertical motion at a hard-rock site and no site corrections are attempted.

Sharma et al. (2009) points out that the decay rate of PGA for shallow India-Bangladesh and deep India-Burma border events have different distance scaling. The former leads to the necessity of a GMPE specific to the Shillong plateau Nath et al. (2012) while the latter means interface subduction events need to be treated differently.

Issues encountered while implementing GMPE logic tree:

- layer 4 depth range of 180-300 km is significantly deeper than deepest events used in regression for ATBO03 (100 km), LILE08 (161 km), ZHAO06 (120 km) and GUPT10 (148 km) are specified for. YCSH97 only included events to 229 km. KANN06 is specified to 200 km depth, but is only used for interface events (layer 2).
- Assumed “and Andaman-Sumatra subduction” missing from Figure 3.
- Why is Youngs (1997) not used in the subduction interfaces?

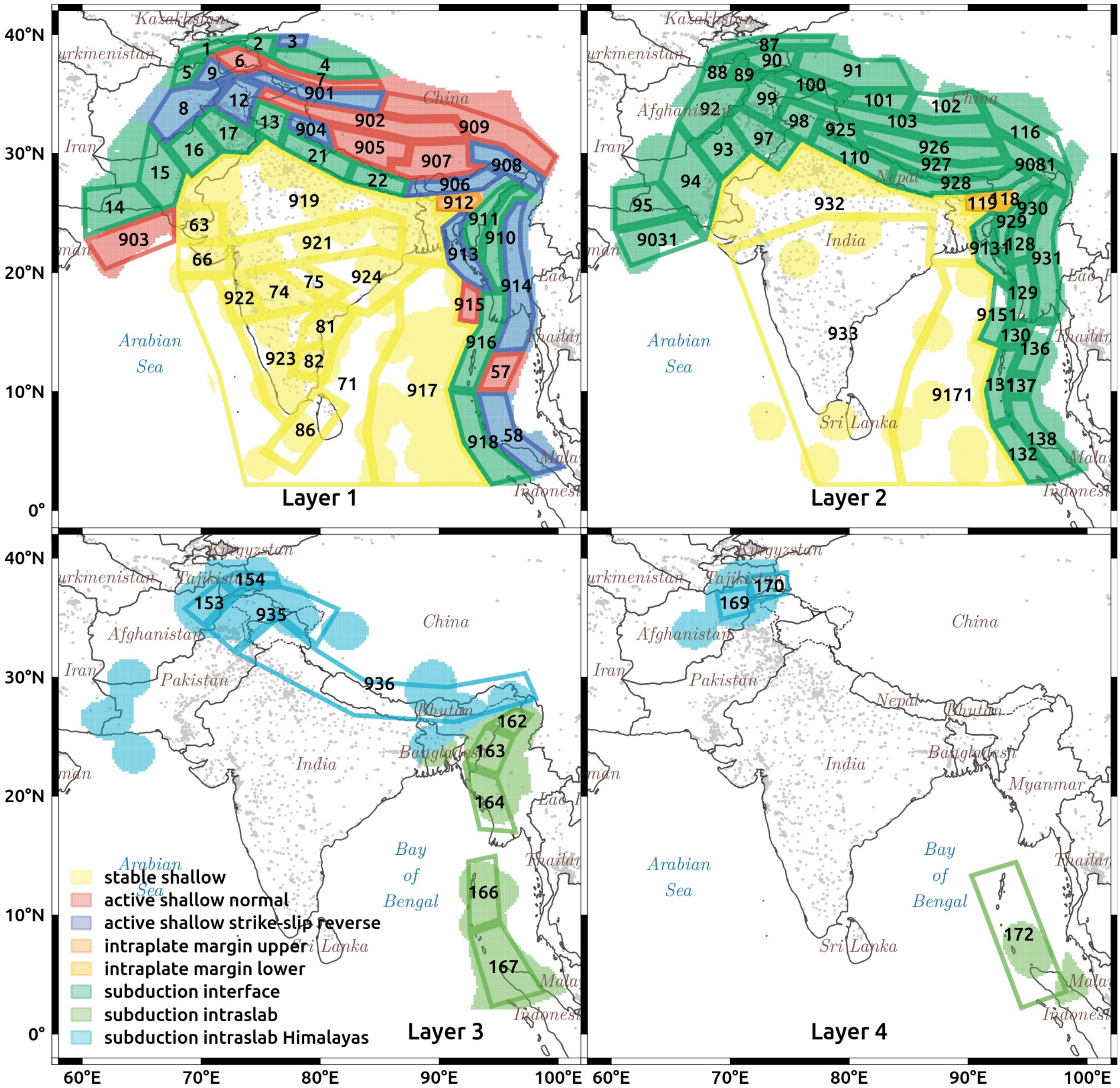

Figure 2: Tectonic region assignments and activity rates for smoothed seismicity point source model. The smoothed seismicity source models are encoded in `smoothed_source_model_mmin4.5.xml` and `smoothed_source_model_mmin5.5.xml`

- Should the Japan/Cascadia distinction not also be used for interface subduction with Atkinson & Boore (2003)?
- Nath and Thingbaijam (2012) doesn't seem to me to follow the recommendations of Nath and Thingbaijam (2011) as far as having two subduction intra-slab sub-regions: the for-

Table 2: Ground motion prediction equations. Models newly implemented in OpenQuake as part of the current work are indicated.

Code	New	Reference
AKBO10		Akkar and Bommer (2010)
BOAT08		Boore and Atkinson (2008)
CABO08		Campbell and Bozorgnia (2008)
ZHAO06		Zhao et al. (2006)
ATBO03		Atkinson and Boore (2003)
ATMA09		Atkinson and Macias (2009)
LILE08		Lin and Lee (2008)
YCSH97		Youngs et al. (1997)
TORO02		Toro (2002)
ATBO06		Atkinson and Boore (2006)
CAMP03		Campbell (2003)
SDBK09	✓	Sharma et al. (2009)
RAIY07	✓	Raghukanth and Iyengar (2007)
NTMN12	✓	Nath et al. (2012)
GUPT10	✓	Gupta (2010)
KNMF06	✓	Kanno et al. (2006)

mer uses Indo-Myanmar and Himalayas while the latter recommends Indo-Myanmar and Hindukush. Nath and Thingbaijam (2012) is followed strictly for for phase 1.

- Assignment of source mechanism (normal or not, matters in shallowest layer only) is tricky. Dip cannot be used to distinguish normal and reverse subduction because the subduction interface angle is not known. different GMPEs use different rake thresholds; a threshold of 30° was chosen, consistent with Boore and Atkinson (2008); Campbell and Bozorgnia (2008) but not Zhao et al. (2006).

Issued encountered while implementing GMPEs:
Sharma et al. (2009)

- lacks a M^2 term Cotton et al. (2006)
- does not define rock vs. soil

Raghukanth and Iyengar (2007)

- typographical errors in coefficient tables: grossest error fixed, 3 other errors causing approximately 10% error not fixed
- actually defines 4 different models: must assume that for all of peninsular India was used by Nath and Thingbaijam (2012), not one of those for sub-regions.

Kanno et al. (2006) -> Douglas (2003)

2.3 Logic Trees

2.3.1 Ground-Motion Prediction

The GMPE logic tree implemented in Nath and Thingbaijam (2012) is shown in Figure 4. Since some of these GMPEs are new to OpenQuake (see Table 2) a comparison was done between that model and that obtained with only the standard GMPEs. For this purpose a ”simplified” GMPE logic tree was constructed which simply omitted the newly-implemented GMPEs and retained equal weighting for the rest.

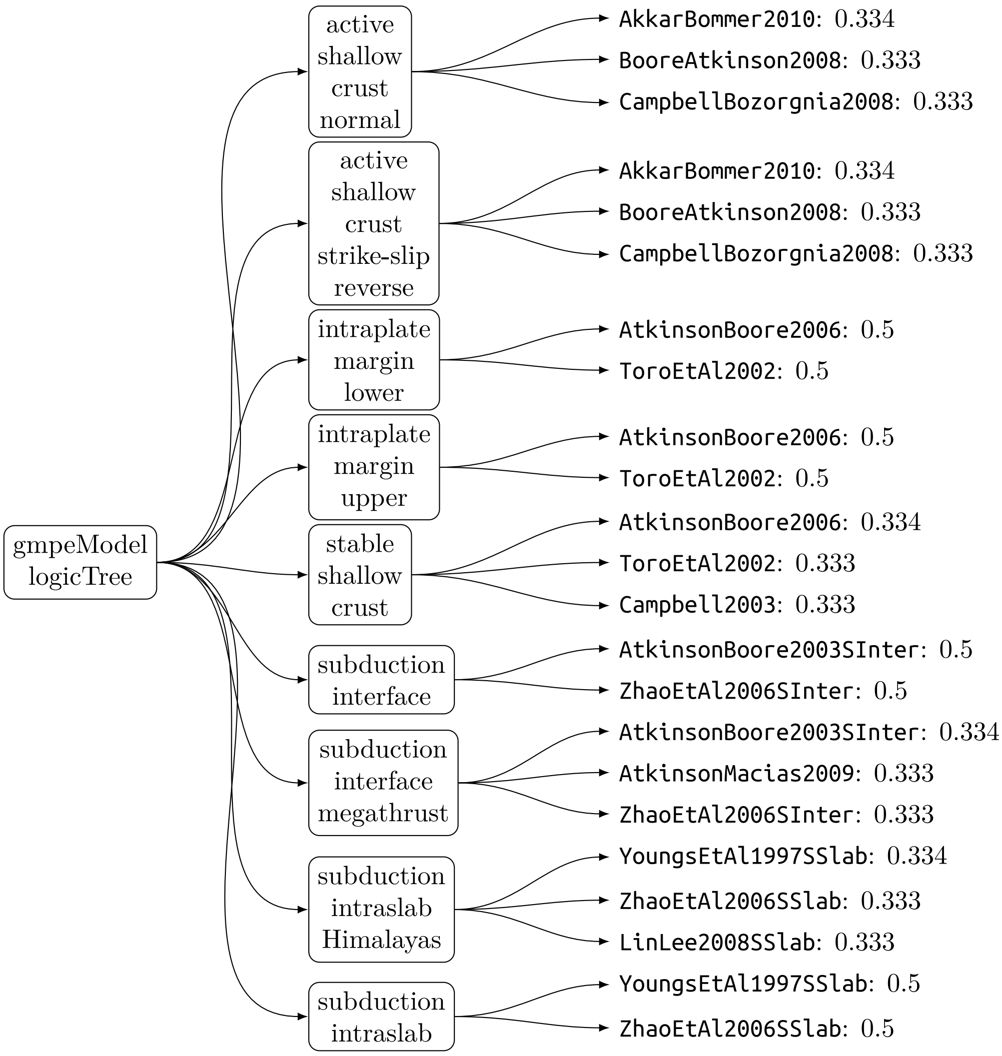

Figure 3: Simplified GMPE logic tree employing only established OpenQuake models, as encoded in `gmpe_logic_tree_omit_new.xml`. Middle column selects tectonic region types as defined in Figure 1. OpenQuake model class names and assigned weights are given on the right side. New and established models are enumerated in Table 2

Moving forward an obvious modification is to replace superseded NGA models with their more up-to-date versions.

[It may also be desirable to rationalize the weighting of the GMPEs or include entirely new ones, such as the new BC Hydro subduction model (Abrahamson et al., 2012). The discussion continues below and is incomplete.]

Anbazhagan et al. (2015) seem to be proposing different weights for different regions based on

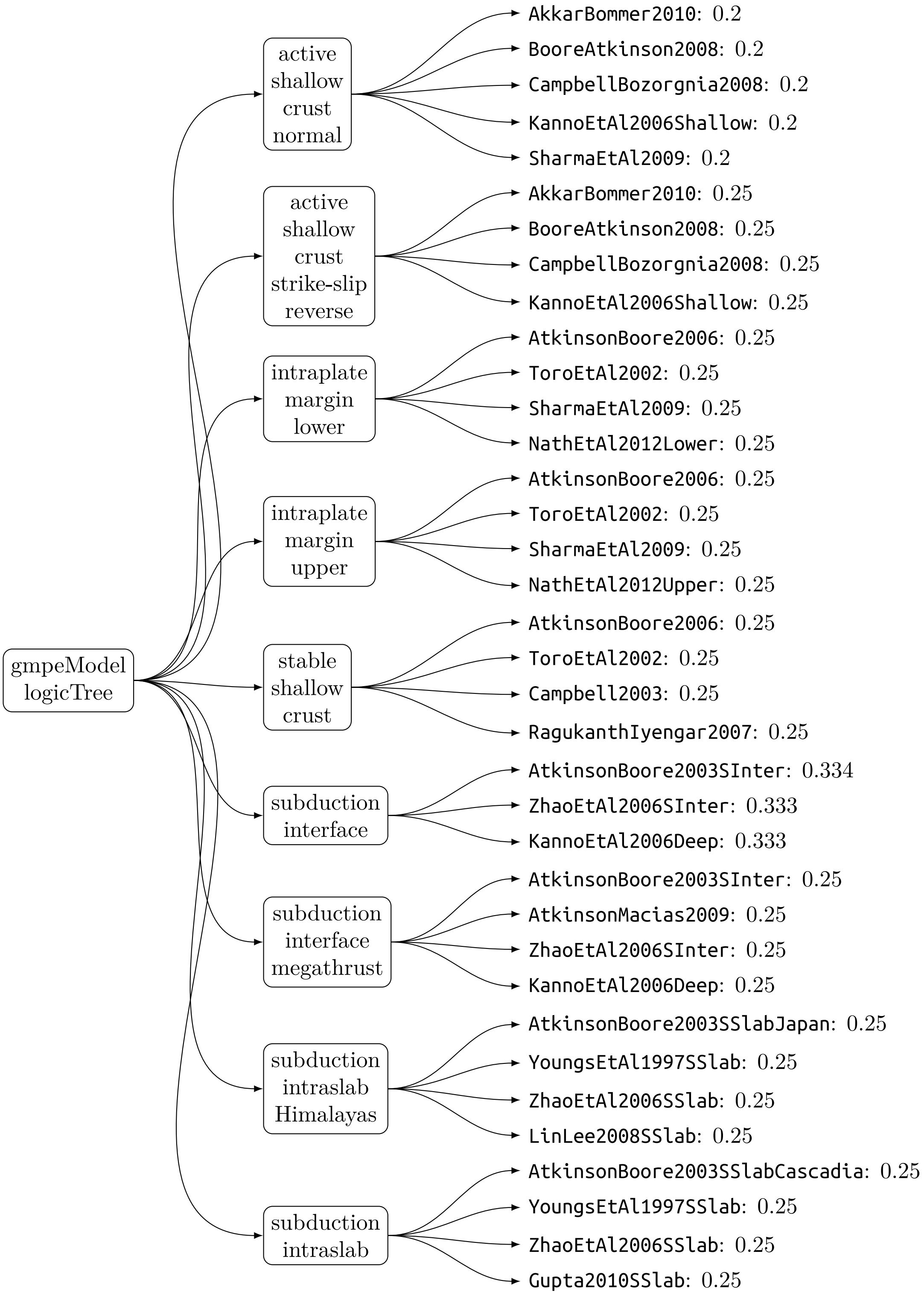

Figure 4: GMPE logic tree of Nath and Thingbaijam (2012), as encoded in `gmpe_logic_tree.xml`. See Figure 3 for complete description

single events in those regions. An extreme example is to define different weights for Anjar, 1956 and Bhuj , 2001 earthquakes even though the epicentres and depths were very close together. In contrast Nath and Thingbaijam (2011) compute LLH for 7 regions (using 38 events total) and state that, “individual events do not have significant number of observations to support a viable ranking basis.”

Anbazhagan et al. (2015) seem to misuse the concept of data support index (DSI) (Delavaud et al., 2012) by setting weights to zero when the DSI is negative. The threshold is arbitrary and is chosen without discussion. As Delavaud et al. (2012) point out “more important than the sign of the DSI is the difference of DSI between two models.”

Both Anbazhagan et al. (2015) and Nath and Thingbaijam (2011) rely on estimating ground motions from macroseismic intensity. I’m sure it is a matter of low seismicity and lack of instrumentation, but I’m still surprised. I would expect the catalogue for peninsular India to be complete for 20 years to magnitude 5 so that one could thus get 10 well-recorded events, at least. There is significant additional (aleatory and epistemic) variability in mapping EMS to PGA which must obscure the true performance of the GMPEs. Perhaps this is part of why Anbazhagan et al. (2015) and Nath and Thingbaijam (2011) arrive at such different LLH scores and rankings for the same events (Anbazhagan et al., 2015, Table 5). It would be interesting to compare the results of LLHs computed using EMS inferred from digitized intensity maps to those computed using instrumental PGA for at least a few events since 1990. Nath and Thingbaijam (2011) take a step towards this by looking at the scatter in their mapping of PGA to EMS but it’s not quite the same.

Many authors (Scherbaum et al., 2009; Nath and Thingbaijam, 2011; Delavaud et al., 2012; Anbazhagan et al., 2015) seem unduly interested in ”ranking”, i.e. constructing an ordered list of GMPEs. This is not a horse race. Scherbaum et al. (2009) suggests a way to turn an LLH score into a logic-tree weight and the formula does not require ranking. Furthermore, in constructing a logic tree one must include factors outside the performance-based scoring, for example an assessment of whether the set is “mutually exclusive and collectively exhaustive” (Bommer and Scherbaum, 2008). For me the question of ranking is just ”noise” which obscures more important questions.

The mutual exclusivity requirement means, to me, that models should be omitted which are redundant in the sense of being too similar to other models in terms of the methodology of their construction, especially if that means they make similar predictions and have similar limitations as a result. For example the exclusion of models which have been superseded (Cotton et al., 2006) can be seen as an application of the requirement that models be mutually exclusive. Another example would be, for a GMPE logic tree intended for the Indian subcontinent, to omit a model such as Hwang and Huo (1997) in favour of Atkinson and Boore (2006) since both are based on stochastic simulation in Eastern North America.

The collective exhaustiveness requirement means, is trickier. It is this requirement which pushes hazard modellers to seek out and evaluate more and complementary types of models. Thus models with broad data support from other regions complement models with poor data support from the target region. Stochastic models supplement data-driven models. Models with different functional forms, distance or magnitude ranges can complement each other.

The process of developing a logic tree to assess epistemic uncertainty is thus a dialectical one. Mutual exclusivity and collective exhaustiveness comprise opposing forces which must be exerted alternately and in tandem.

[Now apply these principles to move forward from Nath and Thingbaijam (2012)!]

2.3.2 Source Models

The source model logic tree is shown in symbolic form in Figure 5.

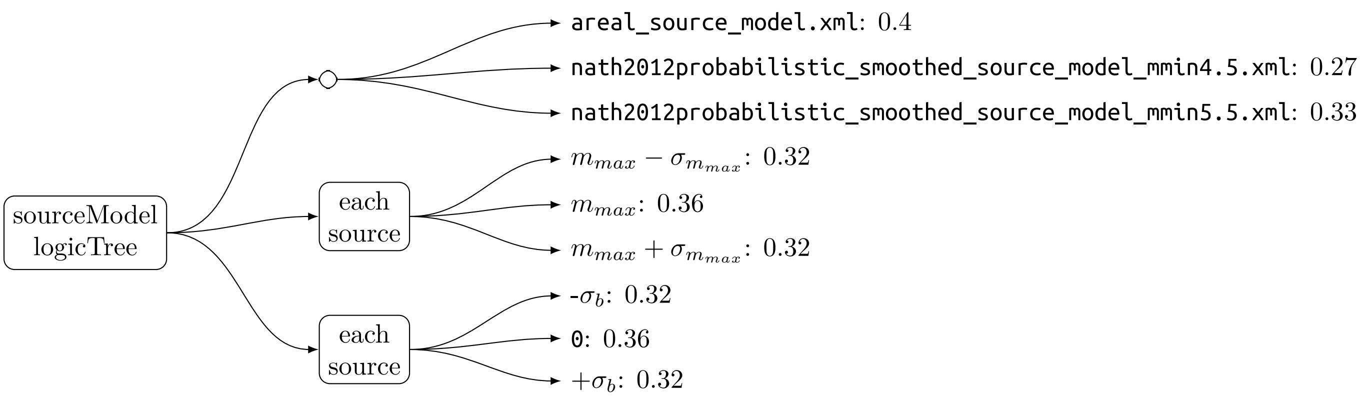

Figure 5: Symbolic source model logic tree of Nath and Thingbaijam (2012).

Nath and Thingbaijam (2012) accounts for the epistemic uncertainty in seismicity model parameters by estimating the standard deviations of b and m_{max} in each source zone and assigning weights to ± 1 standard deviation for each source. This results in a source model logic tree too large to represent on a page; just a portion of it is shown in Figure 6.

Note that although Figure 4 of Nath and Thingbaijam (2012) shows the activity rate ν (and by implication a) varying with b, no estimates of the standard deviation of a or nu. The in OpenQuake happens to recalculate a as b After modifying b using the uncertainty type `bGRRelative` the a value is automatically recalculated to maintain constant total moment rate. It has been assumed that this is the behaviour which Nath and Thingbaijam (2012) implemented.

3 Hazard results

3.1 Verification

3.2 Sensitivity

4 Conclusions

Acknowledgement

Acknowledgements here

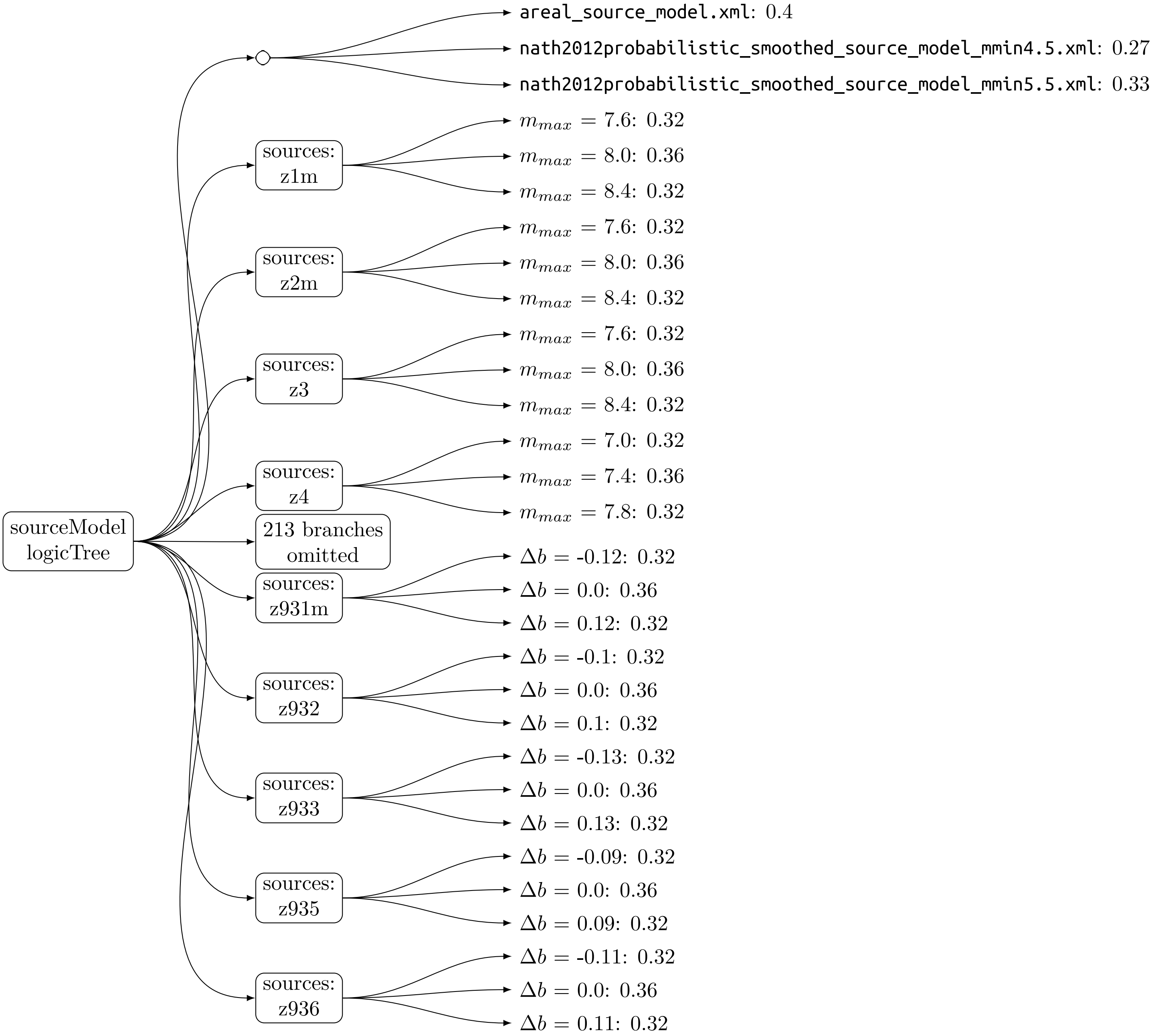

Figure 6: Partial source model logic tree of Nath and Thingbaijam (2012). The full model is encoded in `source_model_logic_tree.xml`

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Appendix A

A.1 Job Configuration Files

Listing 1: phase1–job.ini

```ini
[general]

description = Open Seismic Hazard Model for India - Phase 1
calculation_mode = classical
random_seed = 42

[geometry]

sites_csv = NT2012_Table_3_lon_lat.csv

[logic_tree]

number_of_logic_tree_samples = 1000

[erf]

rupture_mesh_spacing = 5.0
width_of_mfd_bin = 0.1
area_source_discretization = 20.0
```

```
[site_params]

reference_vs30_type = measured
reference_vs30_value = 800.0
reference_depth_to_2pt5km_per_sec = 5.0
reference_depth_to_1pt0km_per_sec = 100.0

[calculation]

source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gmpe_logic_tree_omit_new.xml
investigation_time = 1.0
intensity_measure_types_and_levels = {"PGA": [0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0], "SA(0.2)"
     : [0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0], "SA(1.0)": [0.005, 0.01, 0.02, 0.05, 0.1, 0.2,
     0.5, 1.0, 2.0]}
truncation_level = 3
maximum_distance = 200.0

[output]

export_dir = export
mean_hazard_curves = true
hazard_maps = false
uniform_hazard_spectra = true
poes = 0.002105 0.00040397
```