USGS Subduction Zone Geometry Models (Slab1.0 & Slab2)

and their use in Probabilistic Seismic Hazard Analysis

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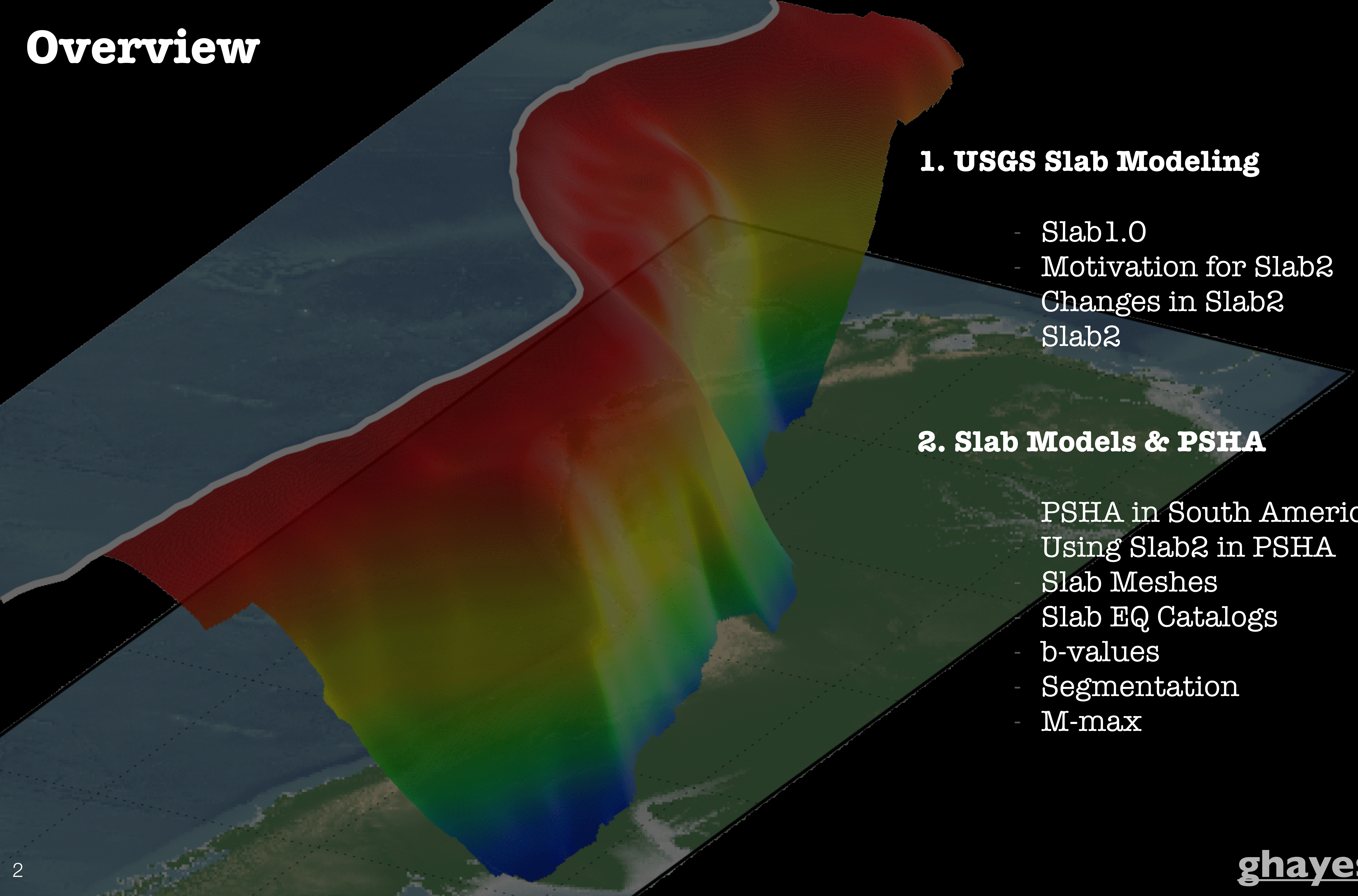
U.S. Geological Survey
National Earthquake Information Center

Overview



1. USGS Slab Modeling

- Slab1.0
- Motivation for Slab2
- Changes in Slab2
- Slab2

2. Slab Models & PSHA

- PSHA in South America
- Using Slab2 in PSHA
- Slab Meshes
- Slab EQ Catalogs
- b-values
- Segmentation
- M-max

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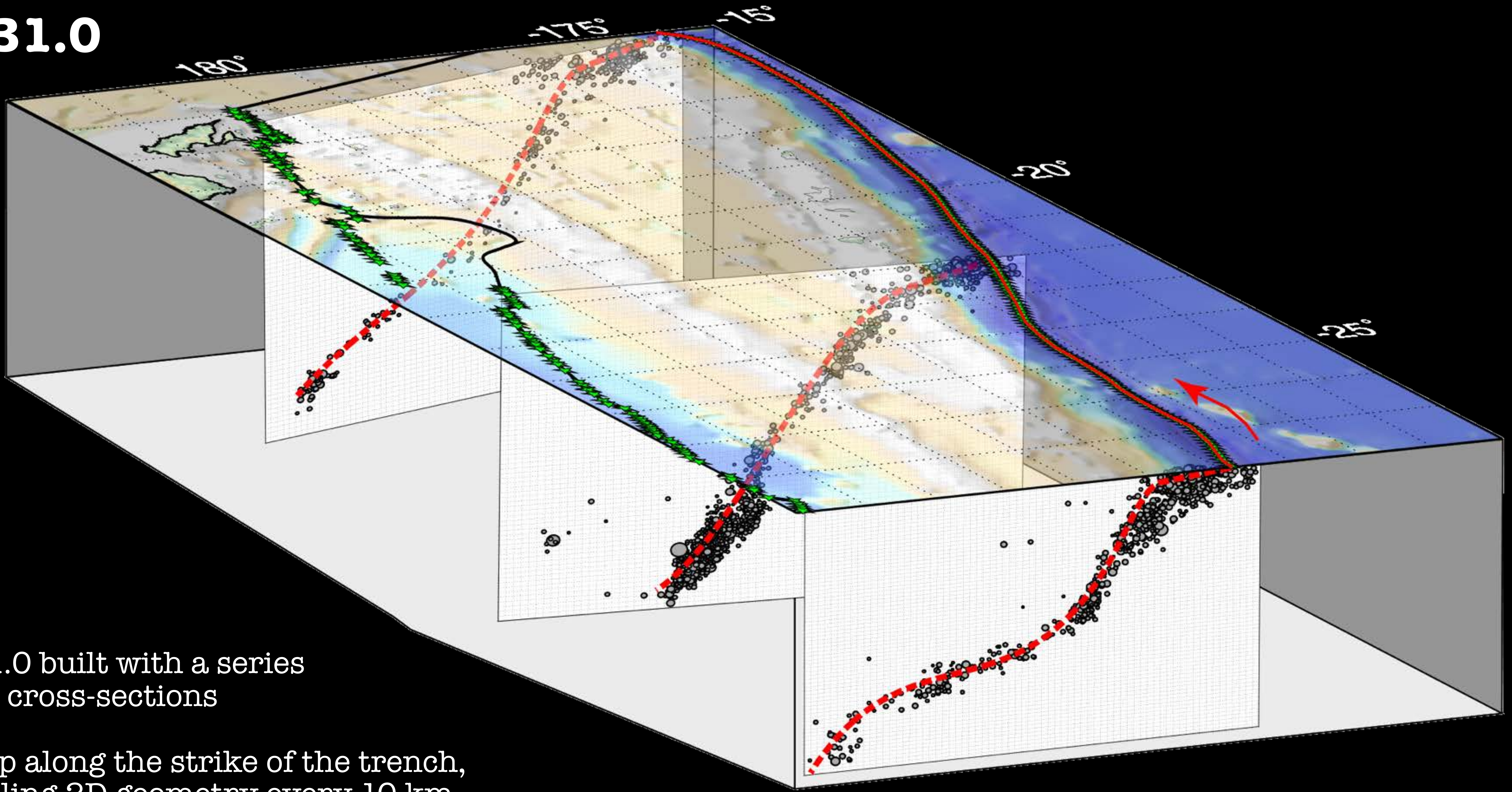
SLAB1.0 - Covers ~85% of global subduction zones

SLAB1.0



Slab1.0 built with a series
of 2D cross-sections

Sweep along the strike of the trench,
sampling 2D geometry every 10 km.

Cross-sections then interpolated into a 3D model.

Slab2 - Why?

The majority of studies that attempt to characterize properties of subduction zone seismicity and hazard require geometry.

How geometry controls subduction zone segmentation and limits earthquake rupture is currently poorly understood.

High-resolution models of subduction zone fault geometry will directly impact the assessment of earthquake hazard

Fault geometry impacts the frequency content of earthquakes generated on that fault

Fault geometry is also a key assumption in any earthquake source inversion

Slab1.0 is inaccurate in some places, and incomplete in others.

Slab2 - What's New?

1. More regional data sets (e.g., earthquake relocations, receiver functions, etc.)

2. More active source seismic data

3. Incorporation of tomographic imaging

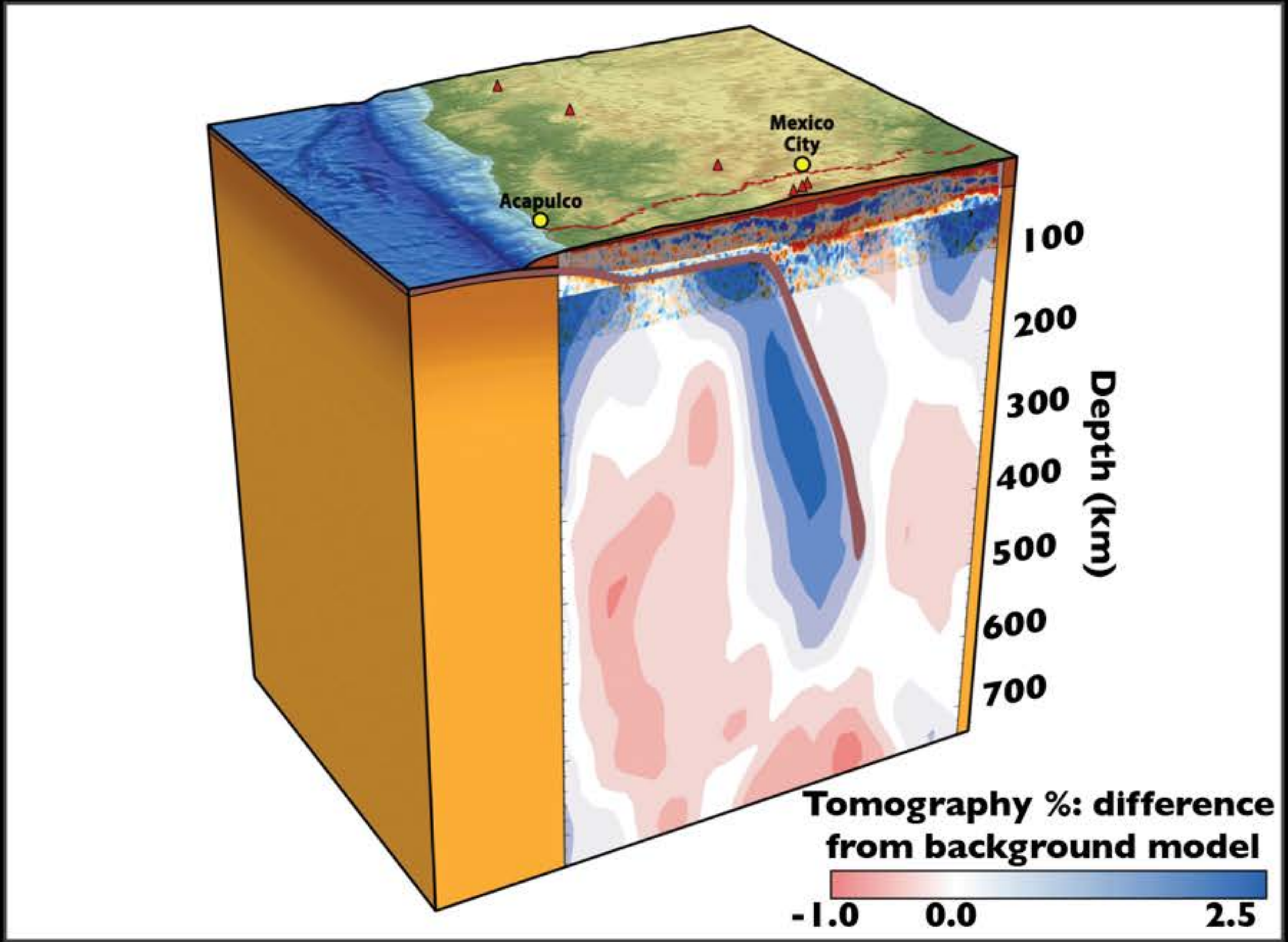
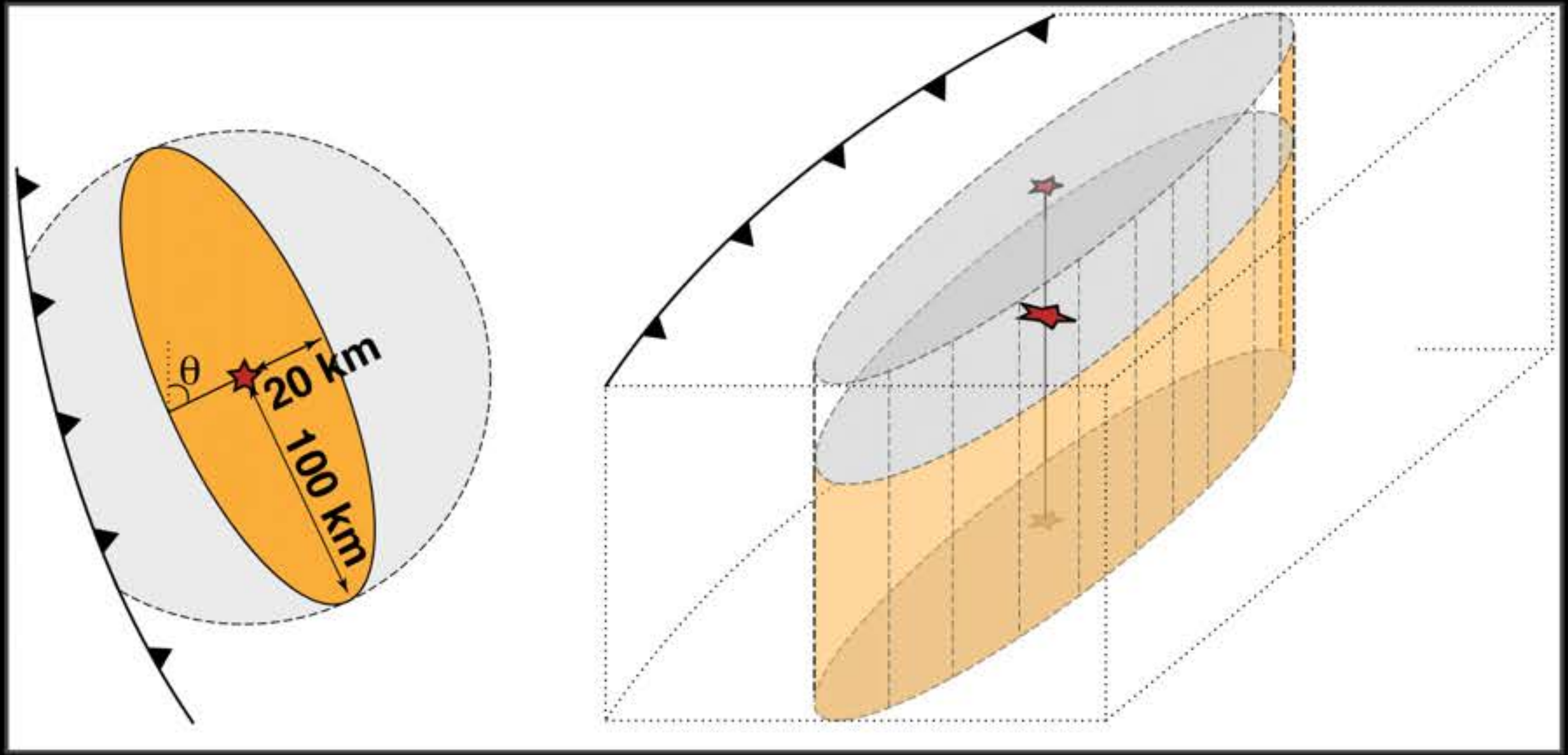


Figure by Robert Clayton, Caltech: http://web.gps.caltech.edu/~clay/MexWeb/MexSubduction.html

4. Improved modeling algorithm



Interpolating data along-strike, rather than radially, facilitates a more accurate representation of slab depth at a point

5. Distributed coding infrastructure (Python based)

6. More data layers (e.g., moment release, coupling, EQ seismotectonics, finite fault models, etc.)

7. Uncertainty assessments

=> Better slab models, covering more of the globe, including more information

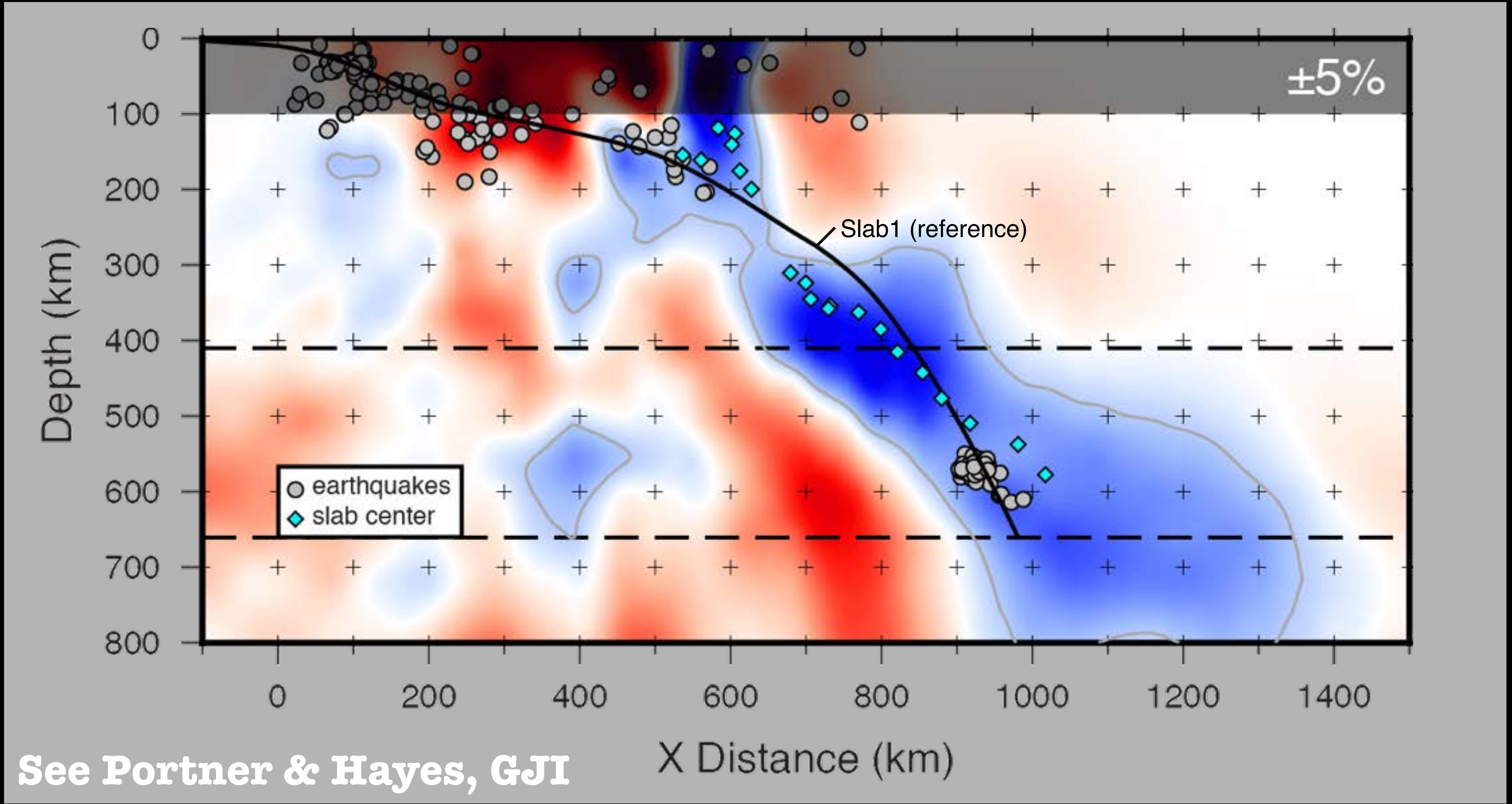
Incorporating Tomography

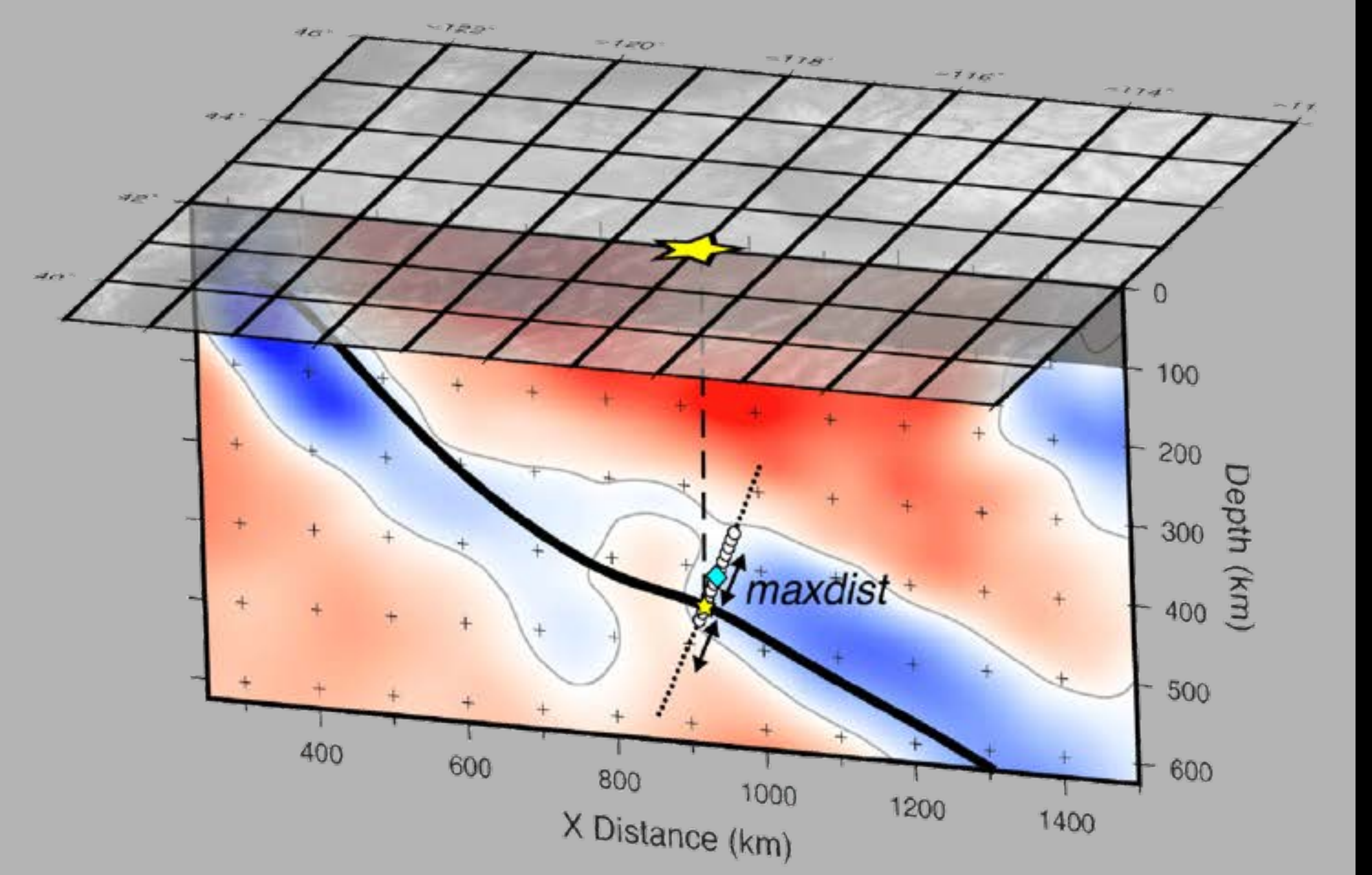
Subducting slabs are relatively cold => fast.

Thus, they are clearly imaged in tomographic studies.

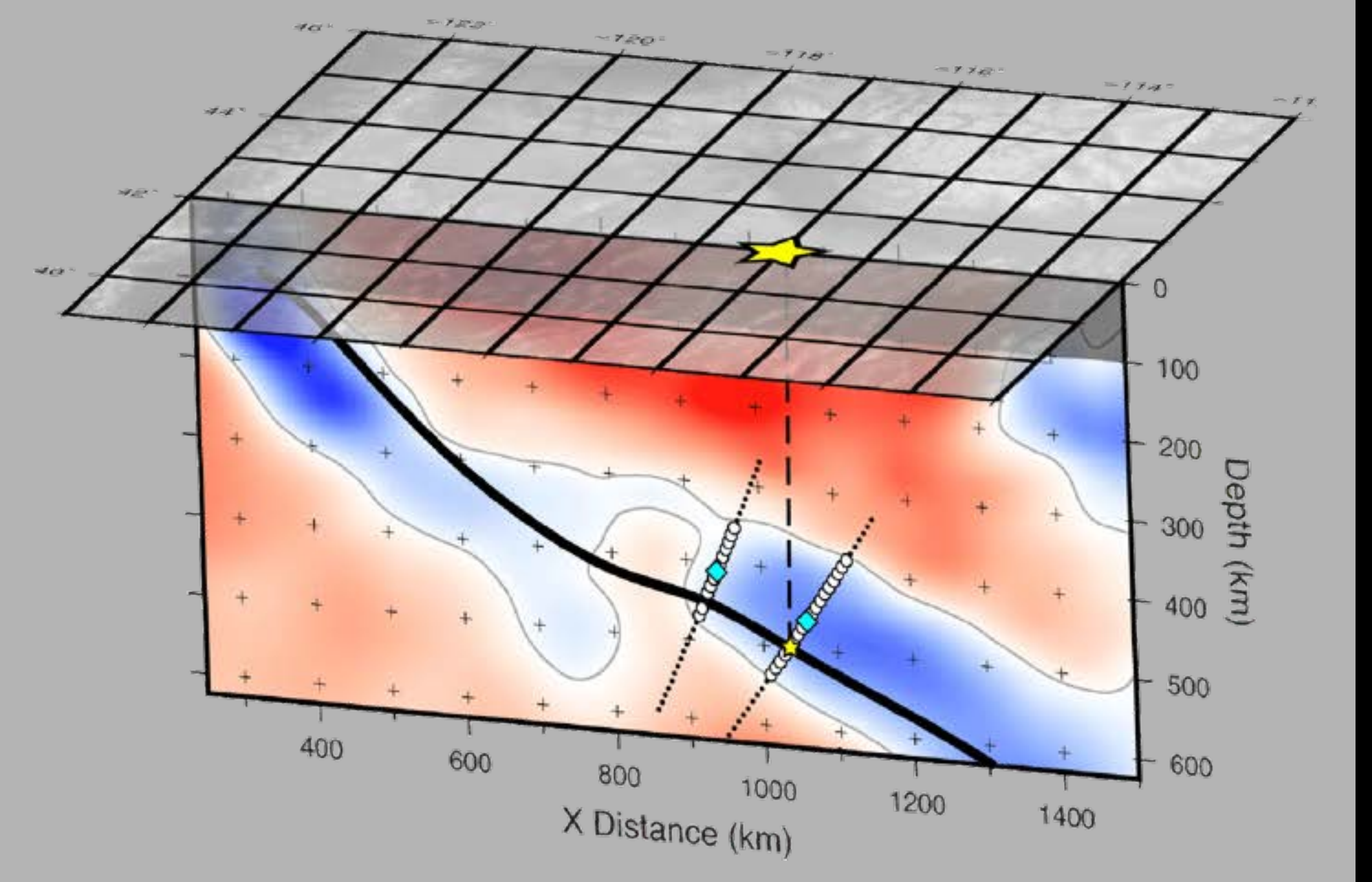
BUT; tomography images a smooth, relative velocity field.

=> identifying accurate location for the slab surface is difficult.





H Step 8: Perform steps 3-7 for each node



 See Portner & Hayes, GJI

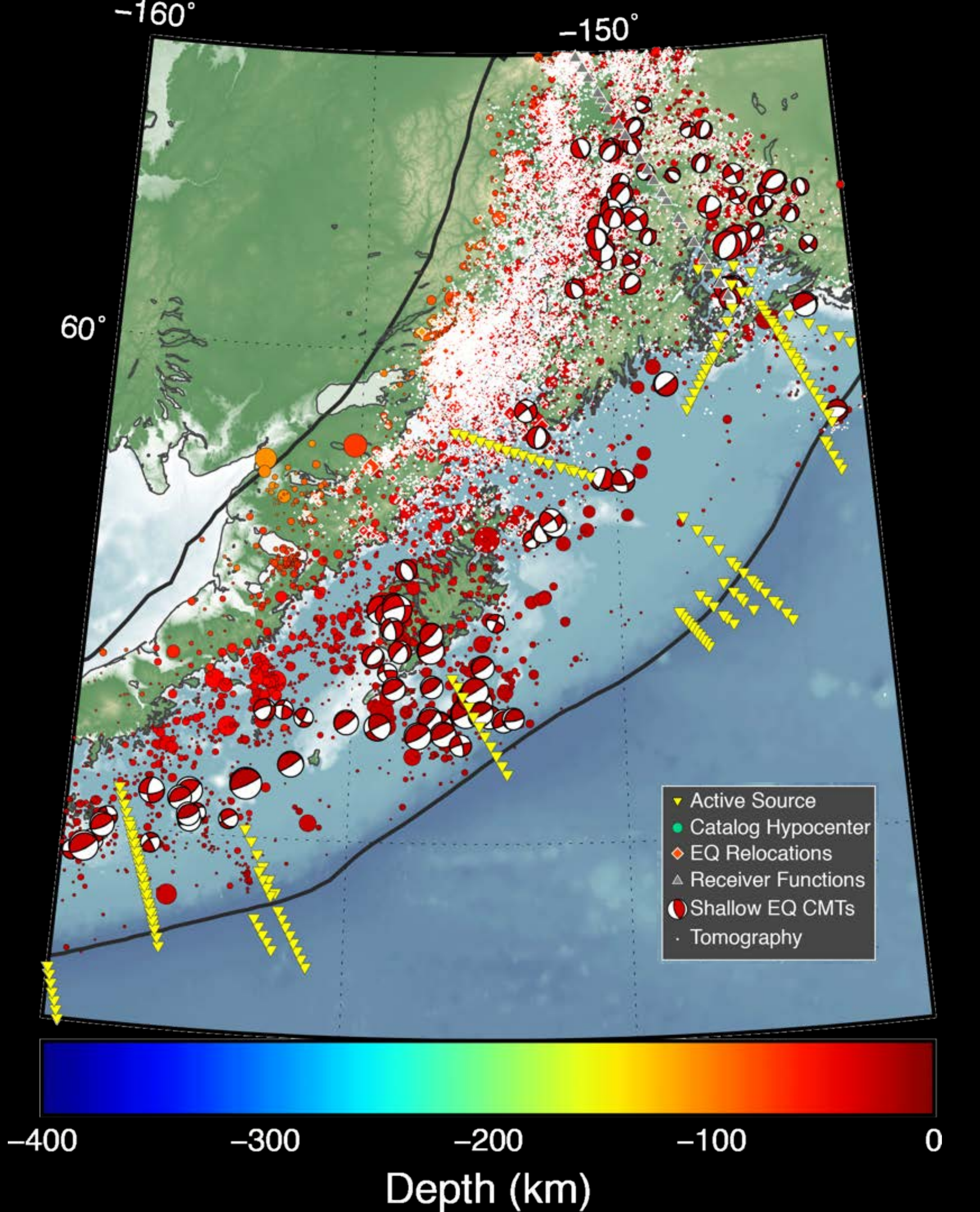
Slab2 - Major Improvements from Regional Data

Slab2 - Adding Active Source Data

Significant effort to add regional active source seismic data imaging the shallow slab.

Example here from Alaska, where the Gulf of Alaska region is not well-imaged by interplate seismicity (post-1964 M 9.2 EQ).

Data from 16 different active source lines in this region alone (plus other constraints from receiver function surveys and relocated microseismicity).

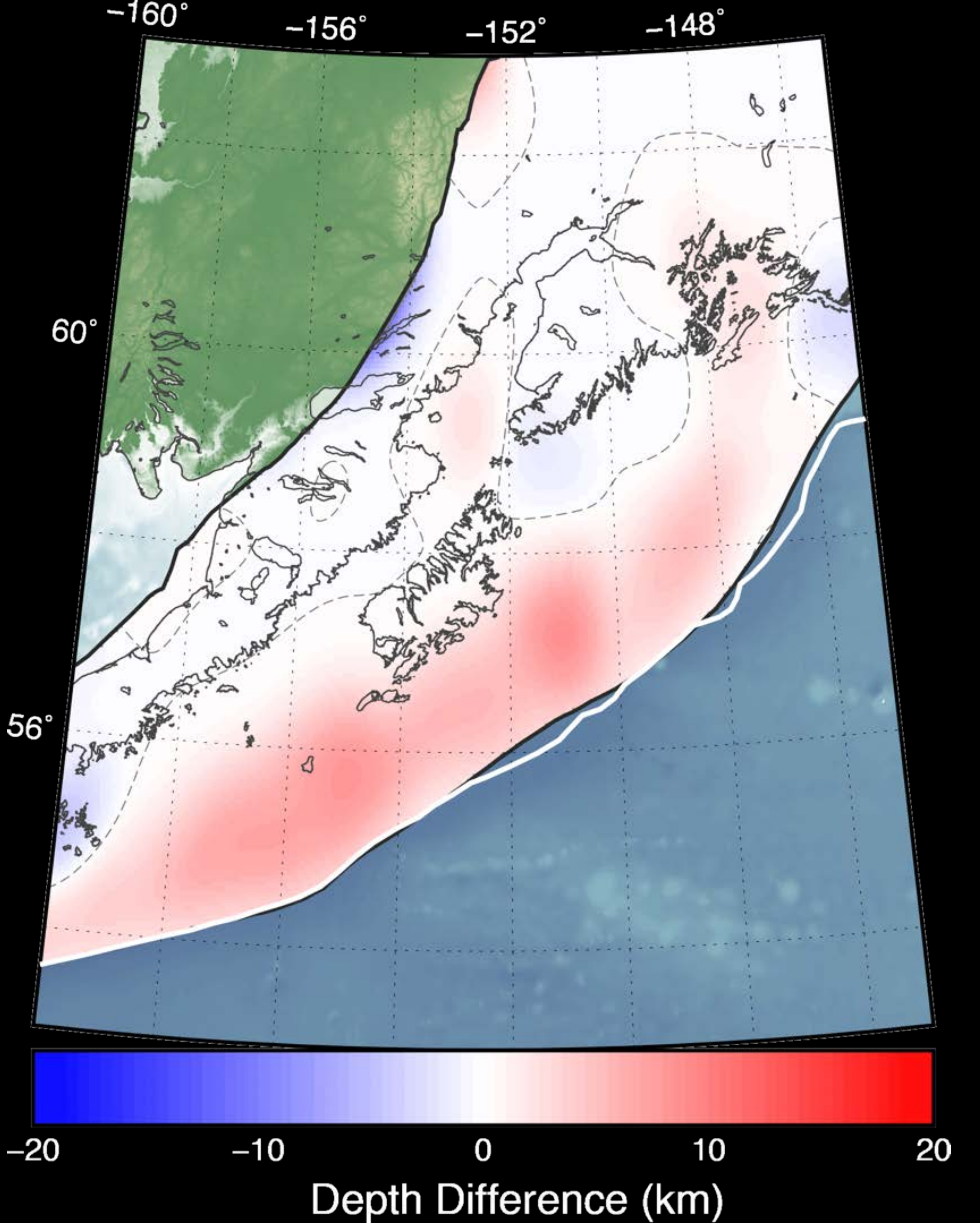


Slab2 - Adding Active Source Data

Active Source data makes a big difference.

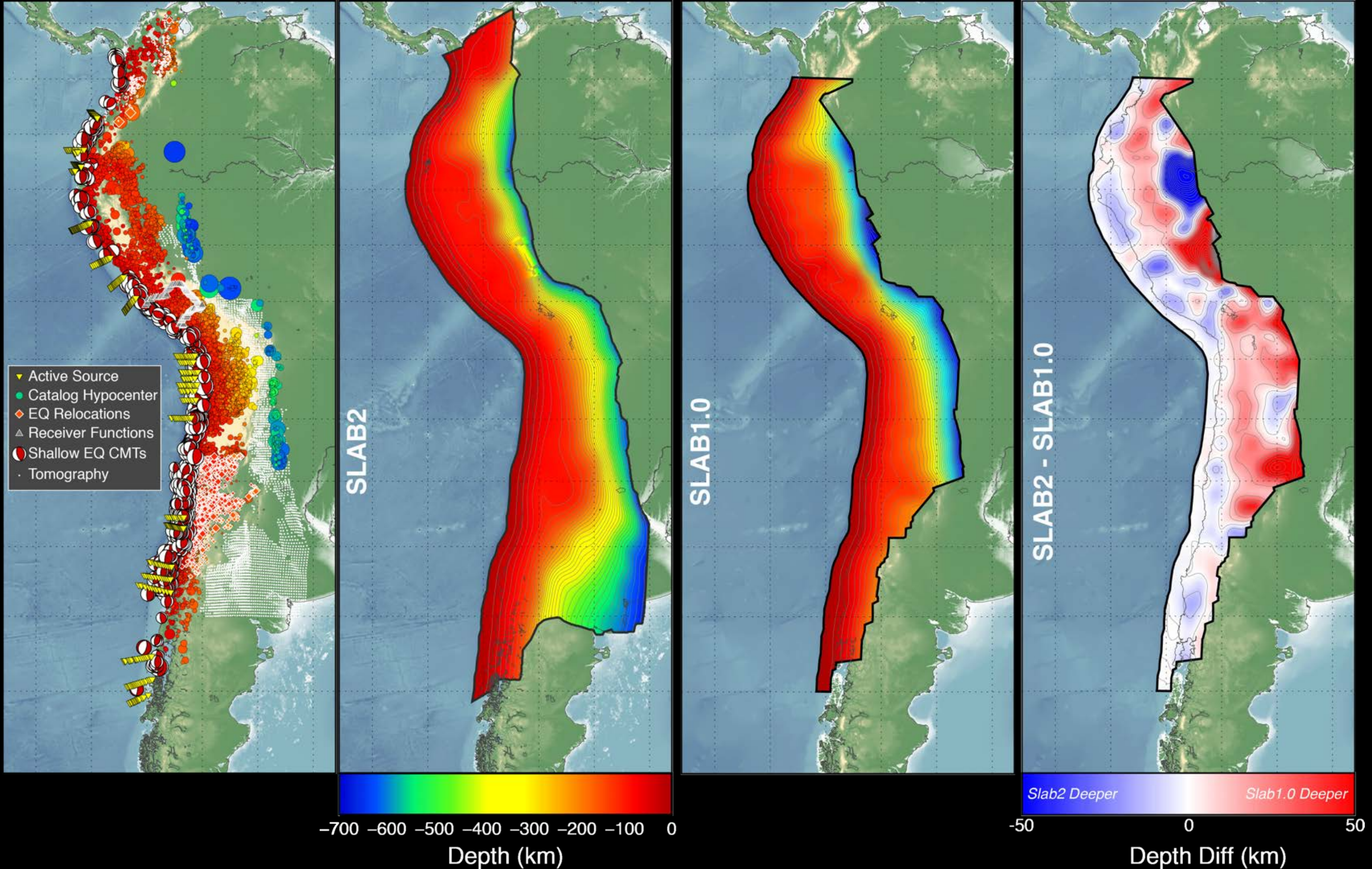
Here, a slab model without the use of AS data is differenced from Slab2 - results in a surface ~10 km deeper in the shallow slab.

To minimize impact of irregular sampling of AS data, we introduced an “average active source profile”, with broader uncertainties, to help constrain the shallow slab in the absence of AS data.



Slab2 Changes in South America

Shift function



SLAB2 - updated model of global subduction zone geometries

Slab2 models the geometry of ALL global subduction zones

This has never been done before


SLAB1.0
100°
−160°
−60°
0
200
400
600
Depth (km)

SLAB2 - updated model of global subduction zone geometries

Slab2 models the geometry of ALL global subduction zones

This has never been done before

SLAB2

Major improvements relative to Slab1.0:

More slabs

More data (active source; regional catalogs & special studies; receiver functions; tomography)

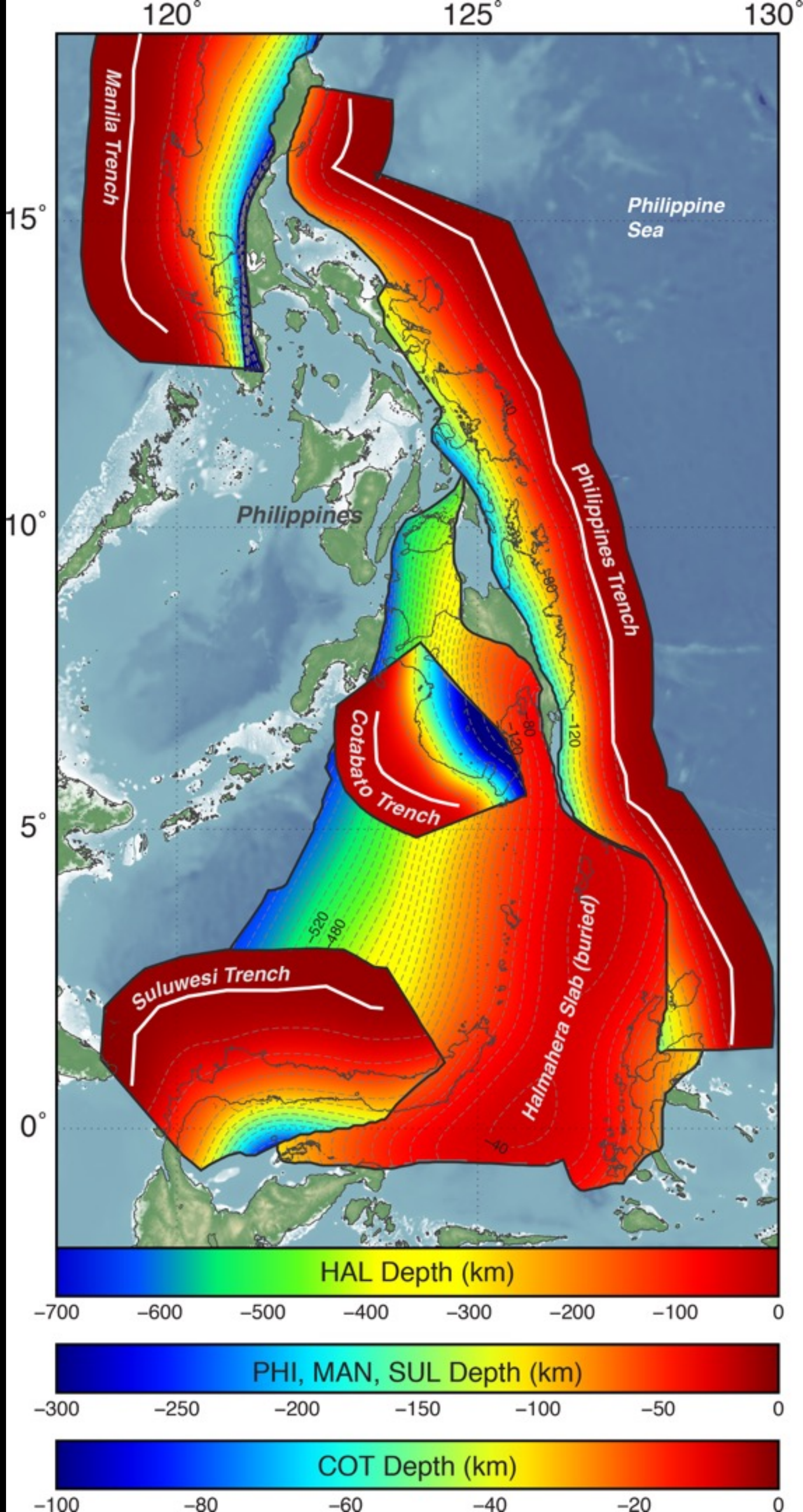
Improved modeling algorithm & code base

Code base freely available (pending publication and USGS approval; check GitHub soon)

Overturned slabs accounted for

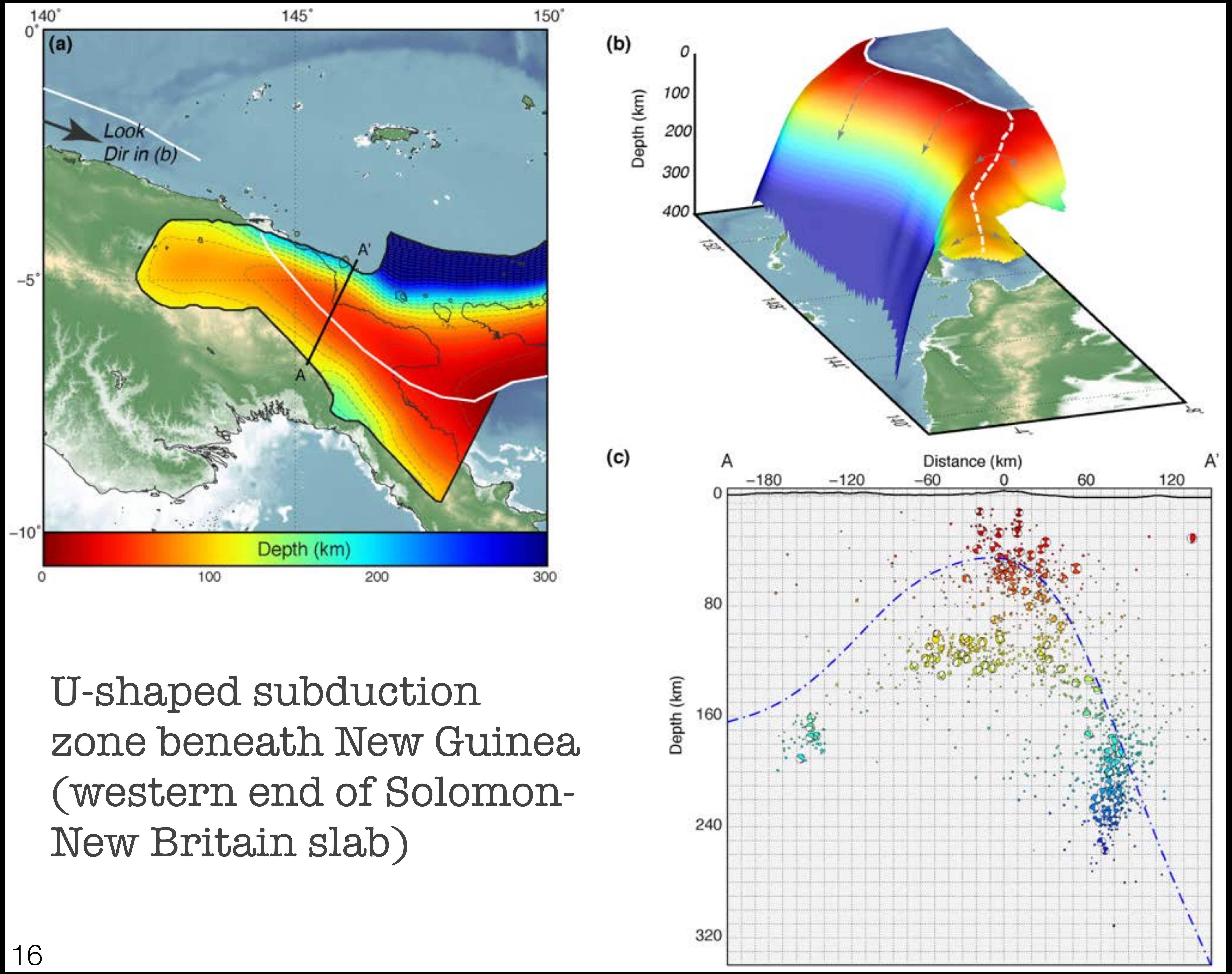
More layers (depth, strike, dip, slab thickness & uncertainty)

Improved seismogenic zone analysis

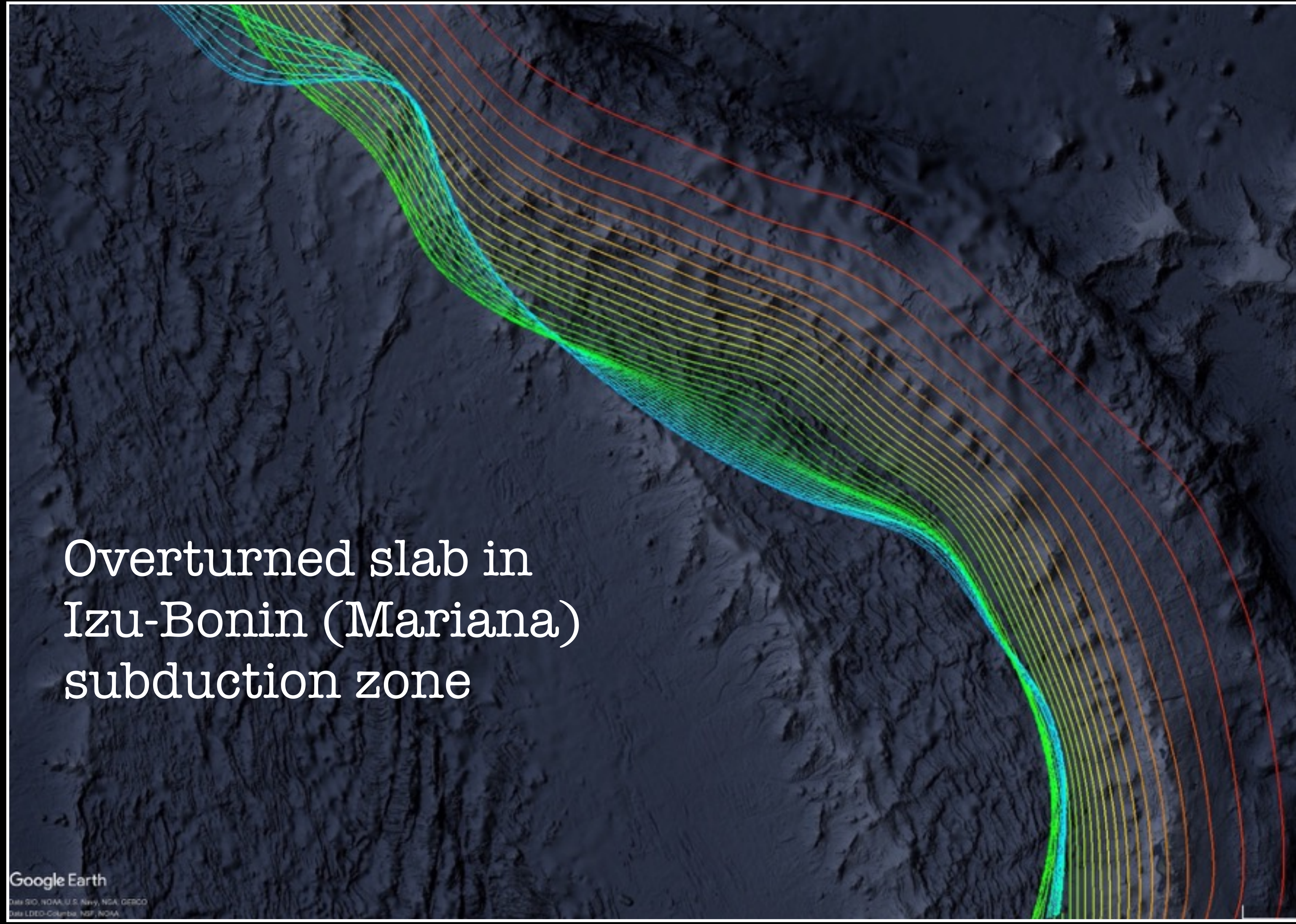


SLAB2

Complex slab structure revealed:



U-shaped subduction zone beneath New Guinea (western end of Solomon-New Britain slab)

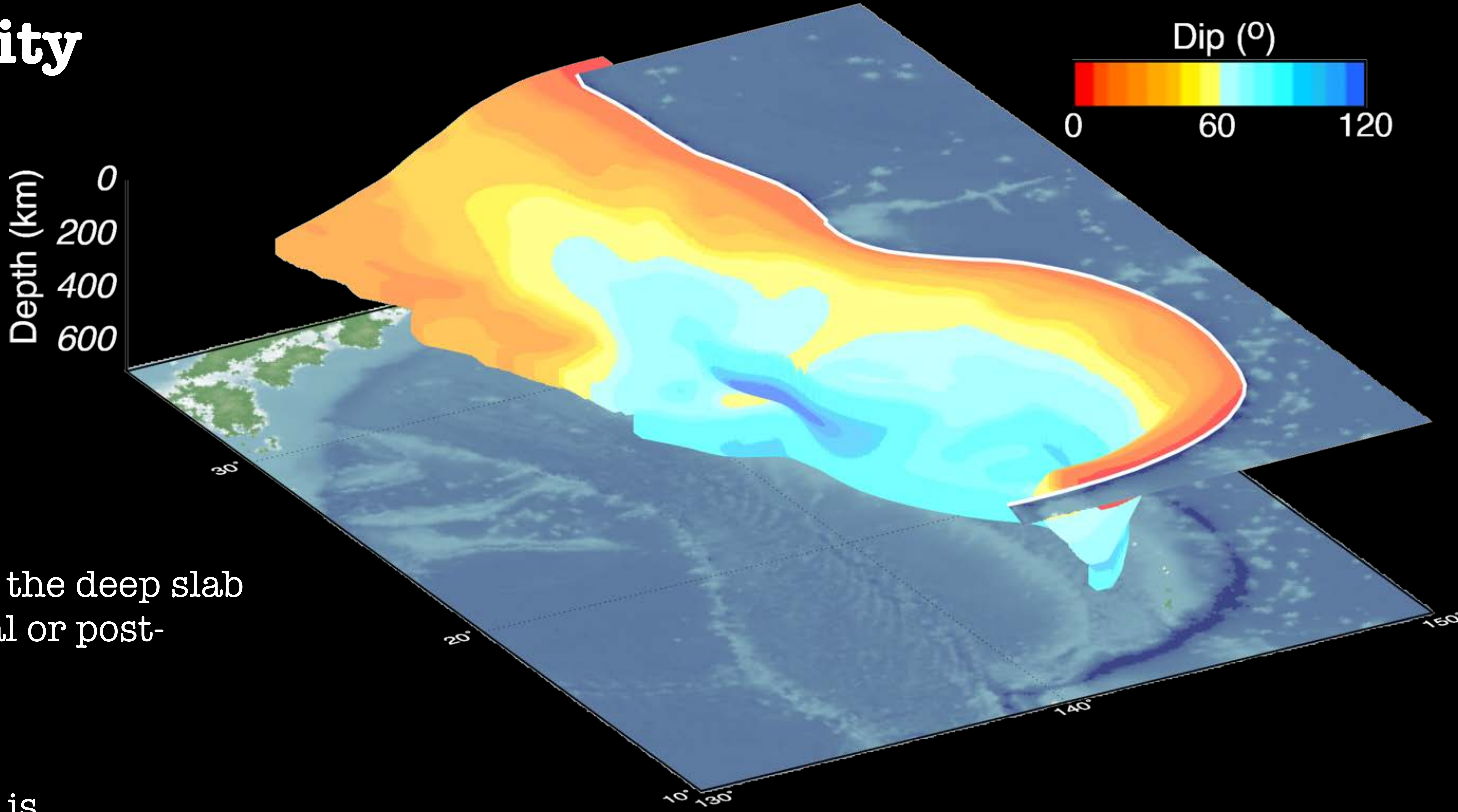


Other overturned or vertical slabs in:

Manila Slab
Solomon Islands/New Britain slab
Kermadec Slab

These slab models include 'supplementary' data files for the deep slab sections.

SLAB2 - Complexity



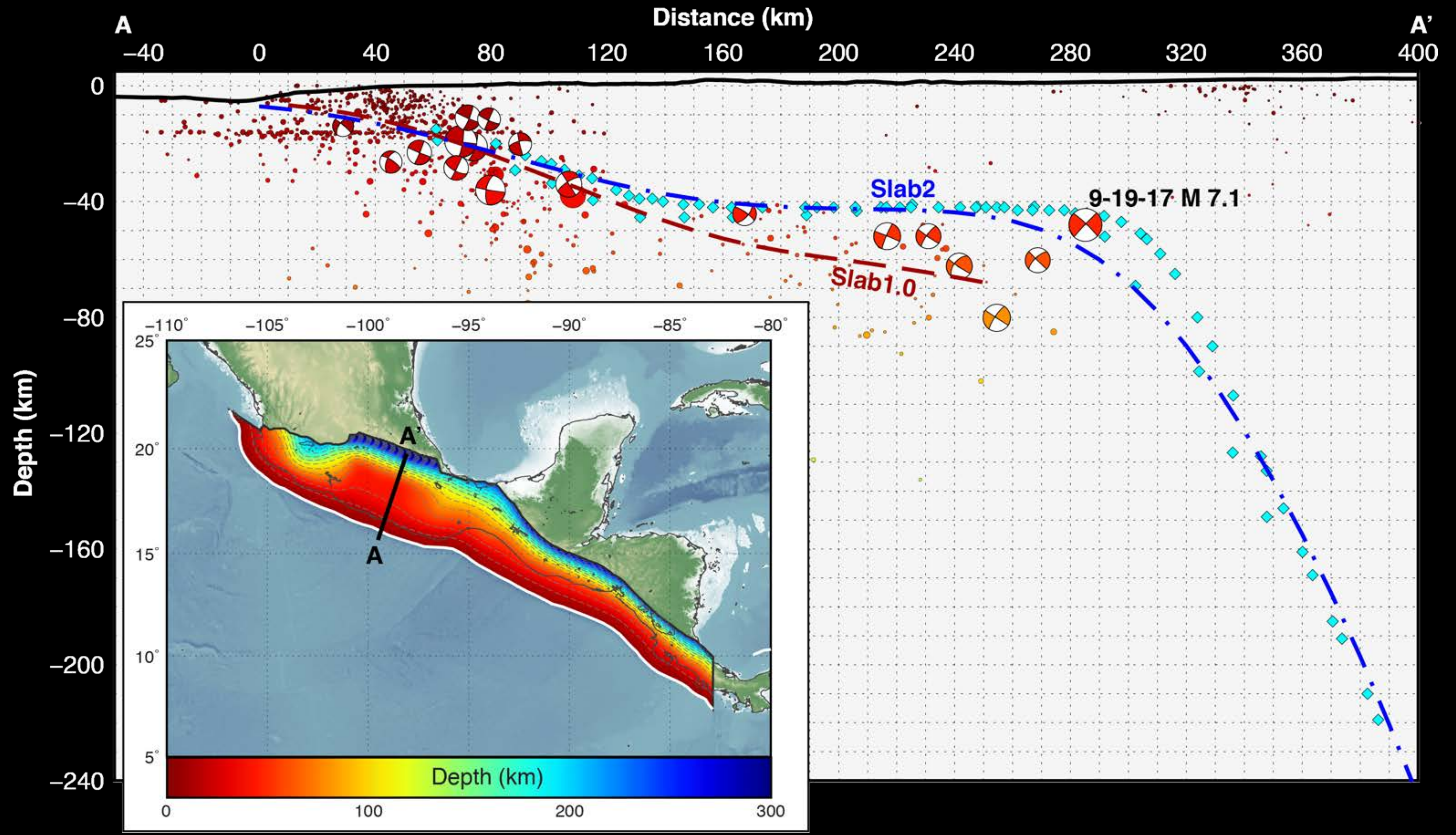
Several slab models include ‘supplementary’ data files for the deep slab sections, where slab is vertical or post-vertical.

For these sections, slab depth is constrained in a rotated reference frame.

Surfaces unavailable because a 3D surface cannot contain multiple data points in the third dimension.

Code is provided to rapidly query supplementary datasets, and return a series of nodes at depth matching a surface node of interest.

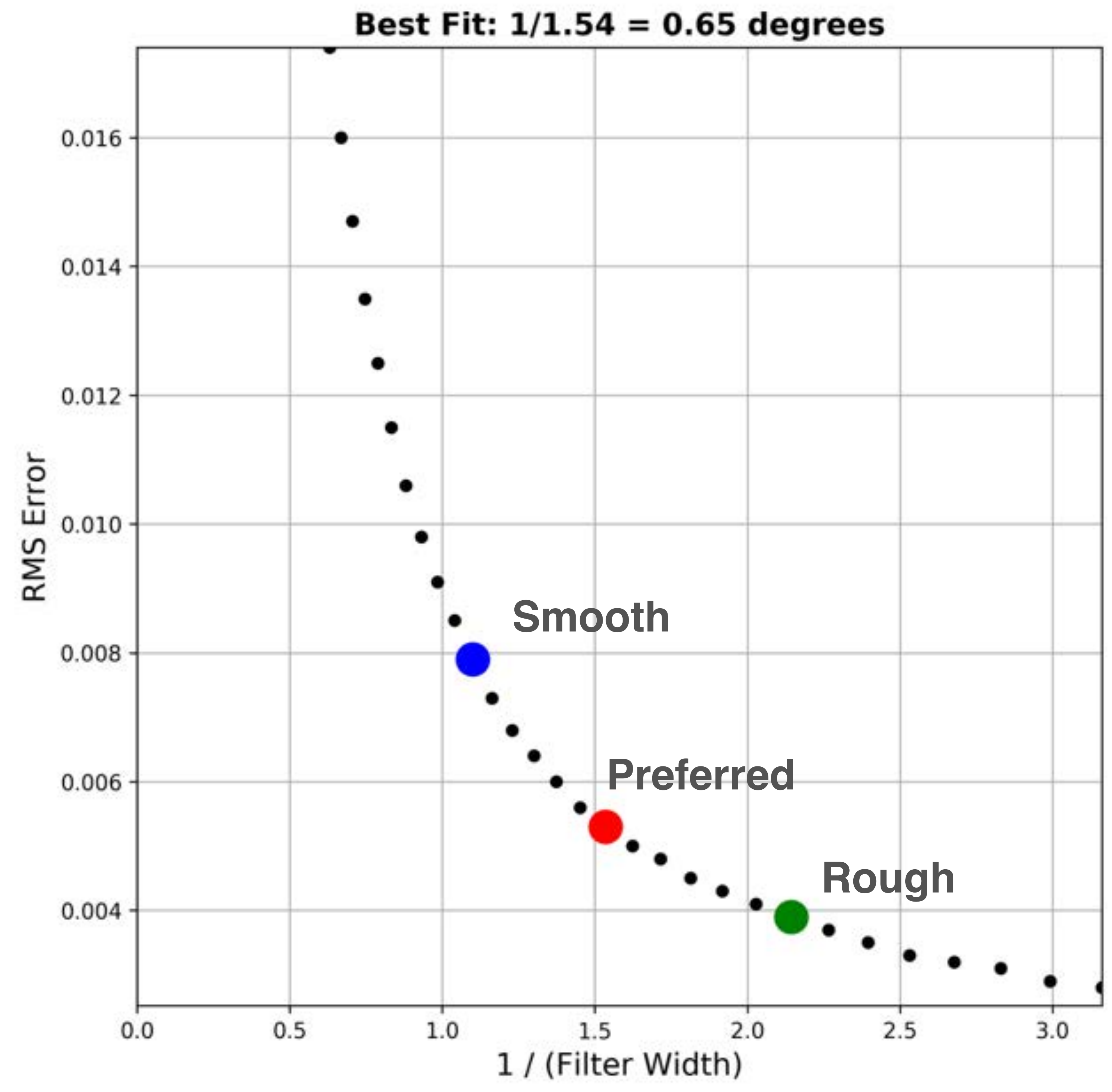
SLAB2

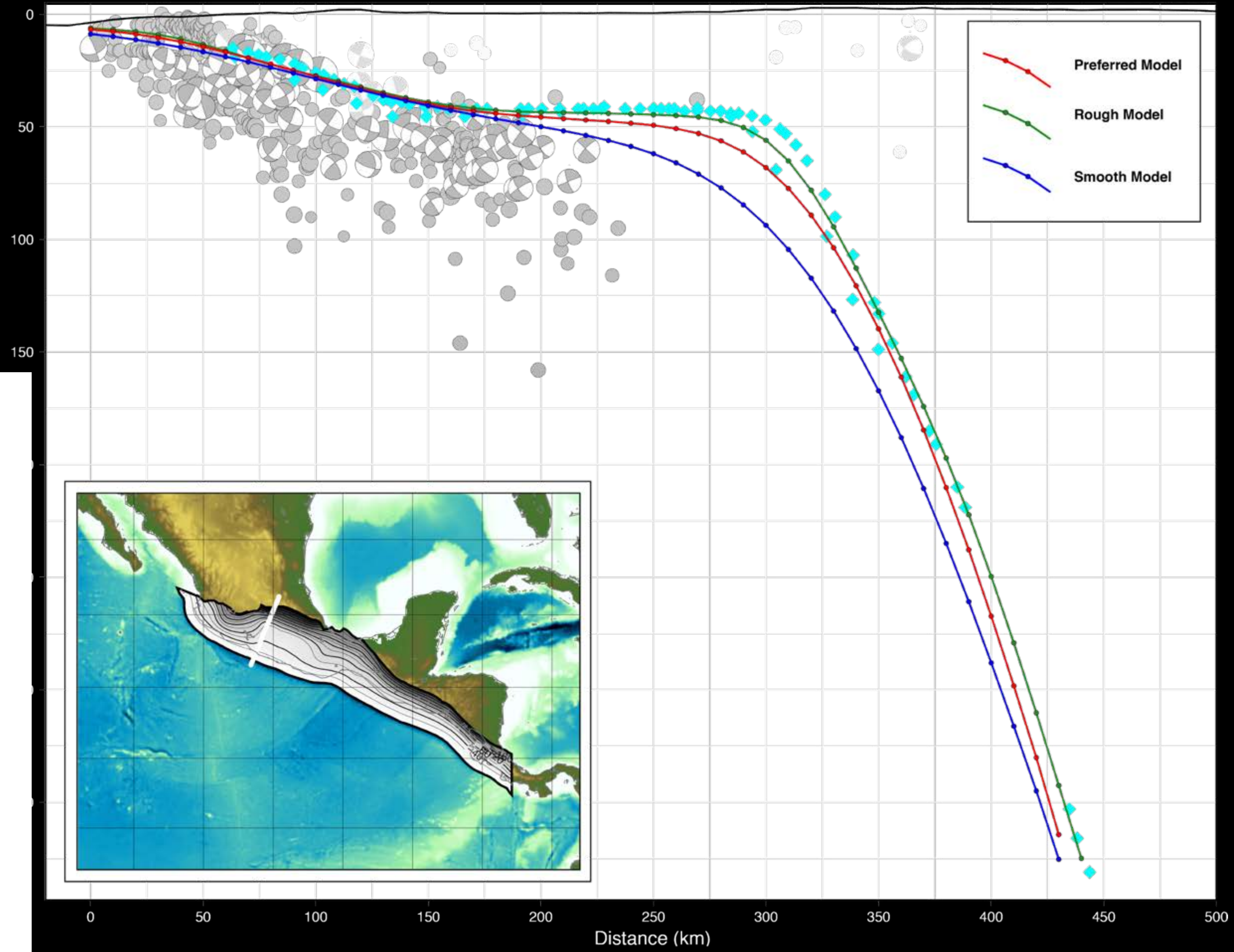


Improved slab resolution in flat slabs (poorly imaged with EQ data alone).

SLAB2 Smoothing

Smoothing chosen objectively, via a least squares & L-Curve approach (e.g., Hansen & O'Leary, 1993).





SLAB2 Smoothing

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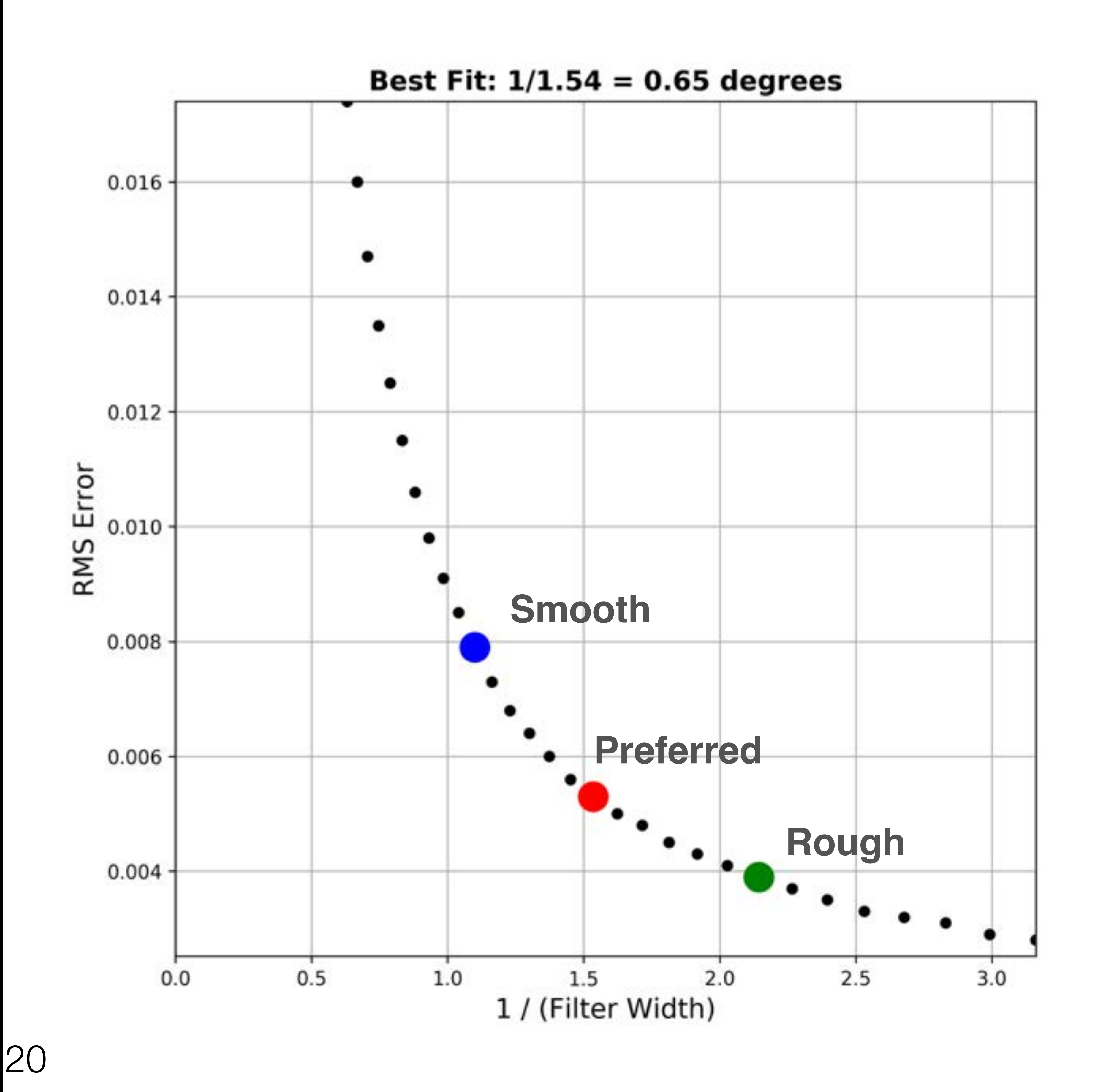
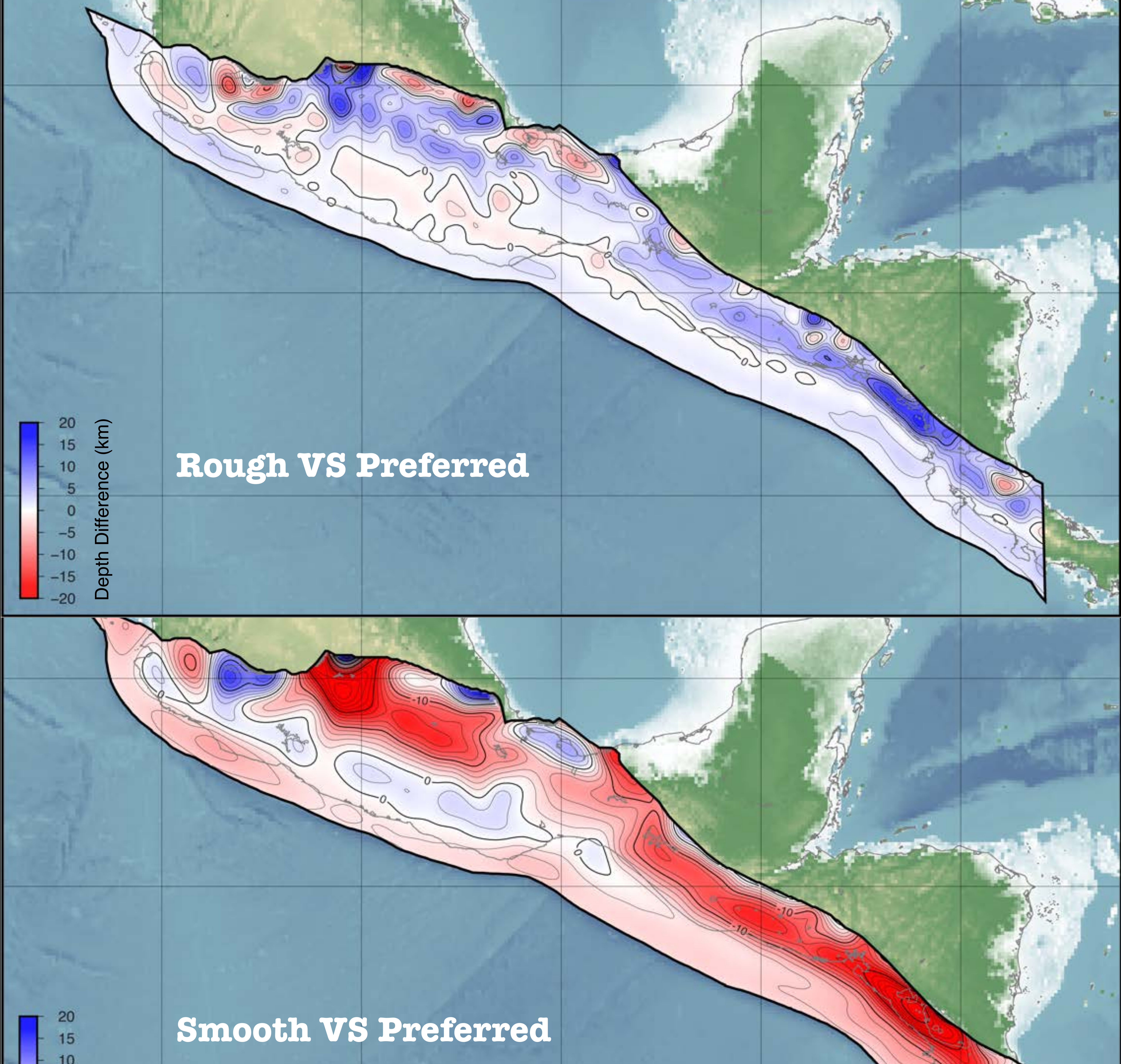
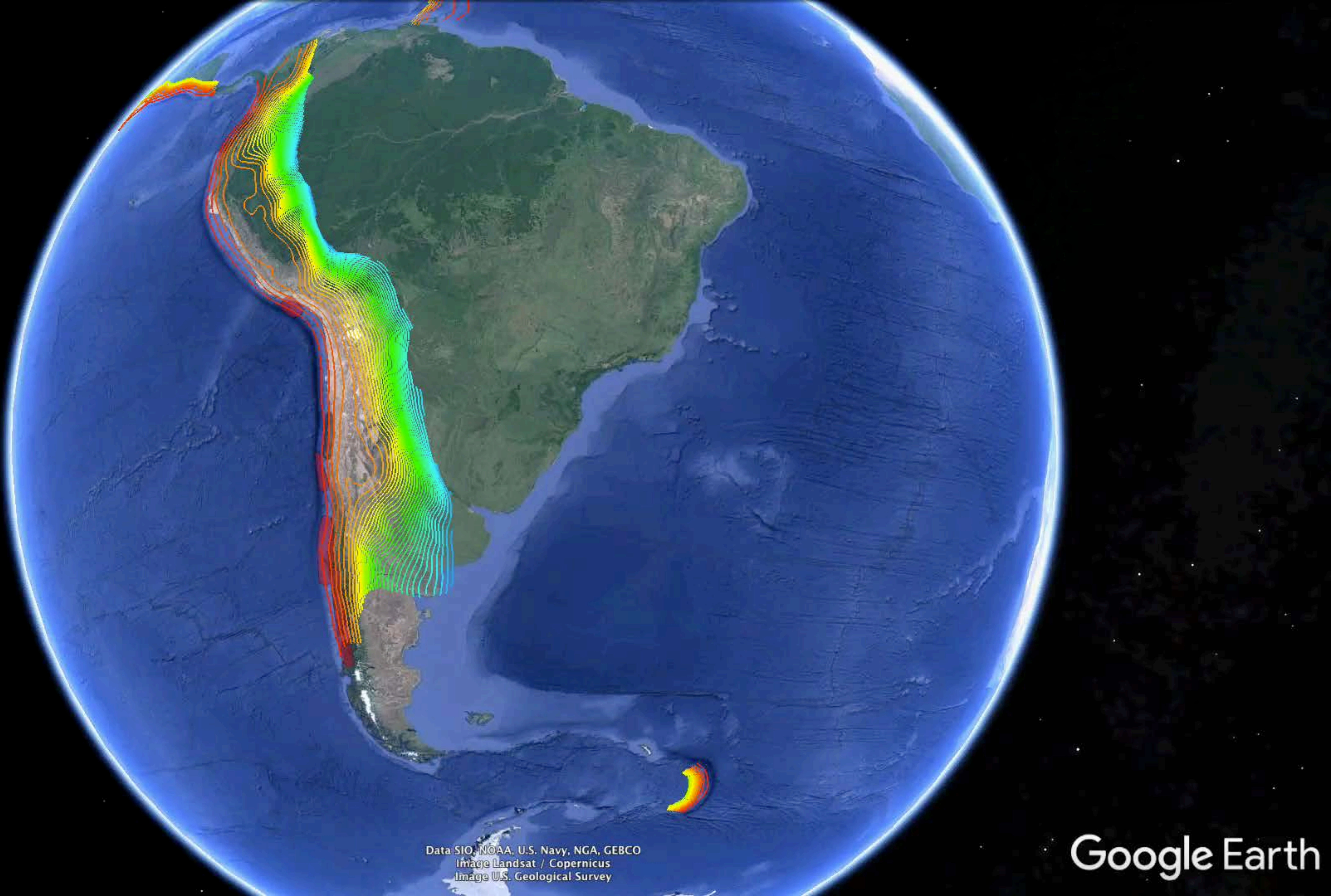




SLAB2



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Slab2 - A Comprehensive Subduction Zone Geometry Model

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Dates

Publication Date : 2018
Start Date : 1900

Citation

Hayes, Gavin, 2018, Slab2 - A Comprehensive Subduction Zone Geometry Model: U.S. Geological Survey, https://doi.org/10.5066/F7PV6JNV.

Summary

Subduction zones are home to the most seismically active faults on the planet. The shallow megathrust interface of subduction zones host our largest earthquakes, and are the only faults capable of M9+ ruptures. Despite these facts, our knowledge of subduction zone geometry - which likely plays a key role in determining the spatial extent and ultimately the size of subduction zone earthquakes - is incomplete. Here we calculate the three- dimensional geometries of all active global subduction zones. The resulting model - Slab2 - provides for the first time a comprehensive geometrical analysis of all known slabs in unprecedented detail.

#####
This distribution includes models of three-dimensional slab geometry under the banner of the U.S. Geological Survey Slab2 project.
#####
Please refer to the paper: "Slab2 - A Comprehensive Subduction Zone Geometry Model", by Hayes, G.P., et al., submitted to Science, March 2018.
#####

... show more ...

Child Items (27)

- Alaska Subduction Zone
- Calabria Subduction Zone
- Caribbean Subduction Zone
- Cascadia Subduction Zone
- Central America Subduction Zone
- Cotobato Subduction Zone
- Halmahera Subduction Zone
- Hellenic Subduction Zone
- Himalaya Main Frontal Thrust
- Hindu Kush Subduction Zone

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Map »

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Categories : Data Release - In Progress
Theme : EHP, Earthquake Hazards Program, GHSC, Geologic Hazards Science Center, USGS, earth science, earthquake hazard, large earthquake ruptures, shallow megathrust interface, subduction zone, subduction zone geometry model
Place : Earth

Provenance

Audit History

All Slab2 models, data, codes, etc., will be available via ScienceBase.

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South America Subduction Zone

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Map »

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Associated Items

Associate an Item

Tags

Categories : Data
Types : Map Service, OGC WFS Layer, OGC WMS Layer, OGC WMS Service

Provenance

Data source : Input directly

Audit History

Additionally, we will add:

- Seismogenic zone mesh
- Inter-, intra-, upper plate catalogs

- Other suggestions…?

Multiple download formats will be available for each model.

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SLAB2

Slab2 is an evolving model

Any model is only
as good as the data that
goes into it (share
your data!)

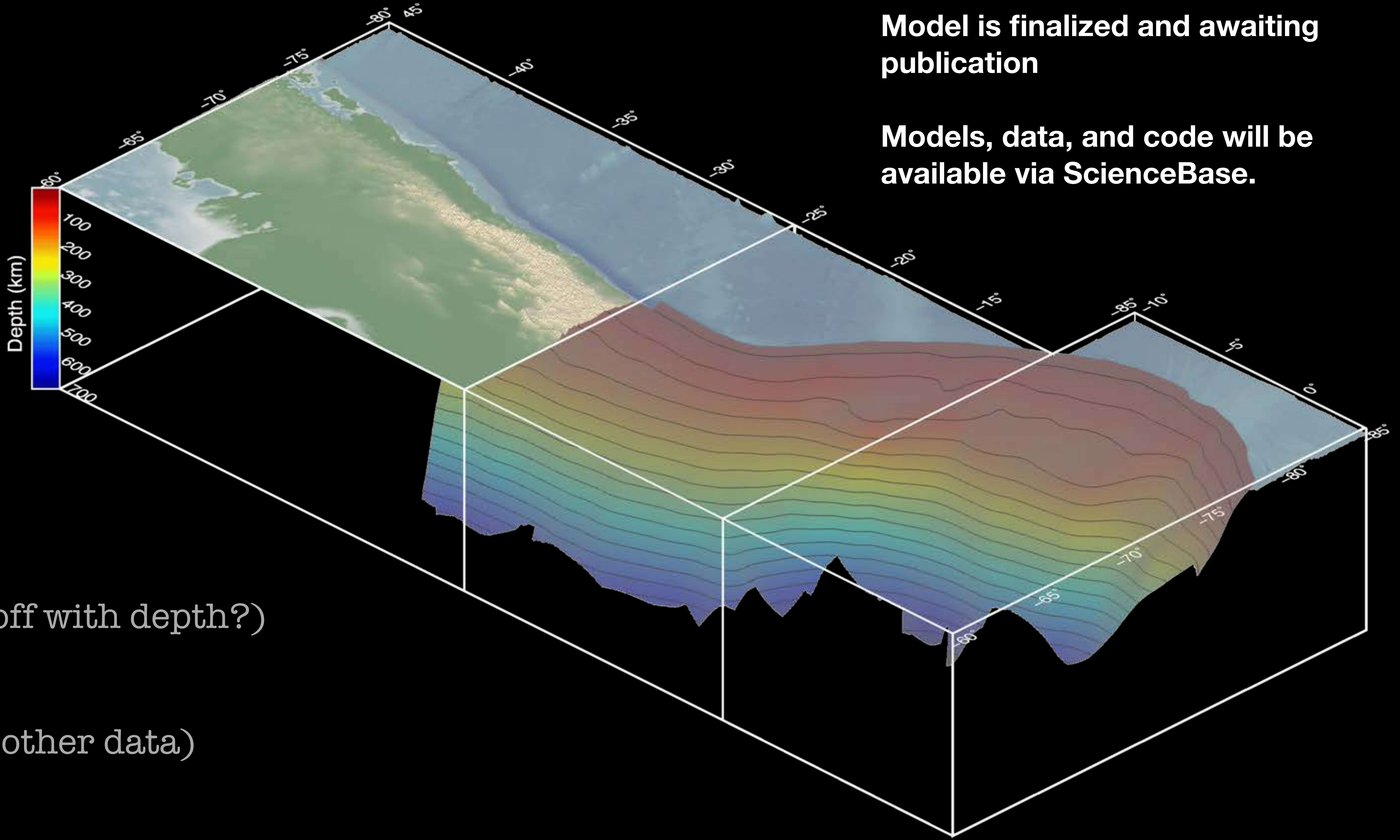
Missing slabs:

Carpathians
(complex, involving break-off with depth?)

Northern Panama
(very sparse seismicity, no other data)

Northern Venezuela
(no seismicity, no other data)

Underthrusted margins like Haida Gwaii, southern Macquarie Ridge,...



Model is finalized and awaiting publication

Models, data, and code will be available via ScienceBase.

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PSHA in Subduction Zones

PSHA in South America

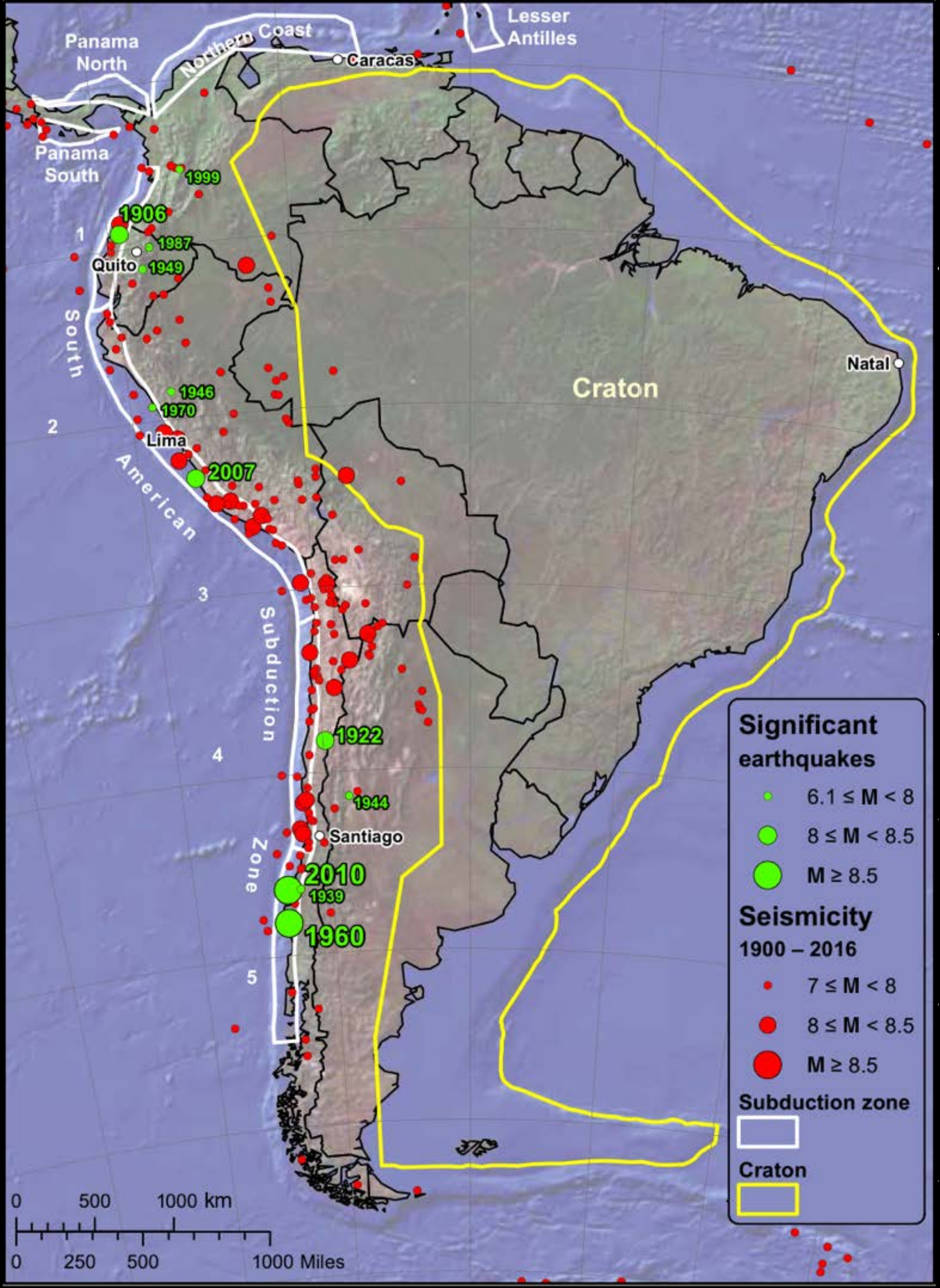


Figure from Petersen et al., BSSA 2018

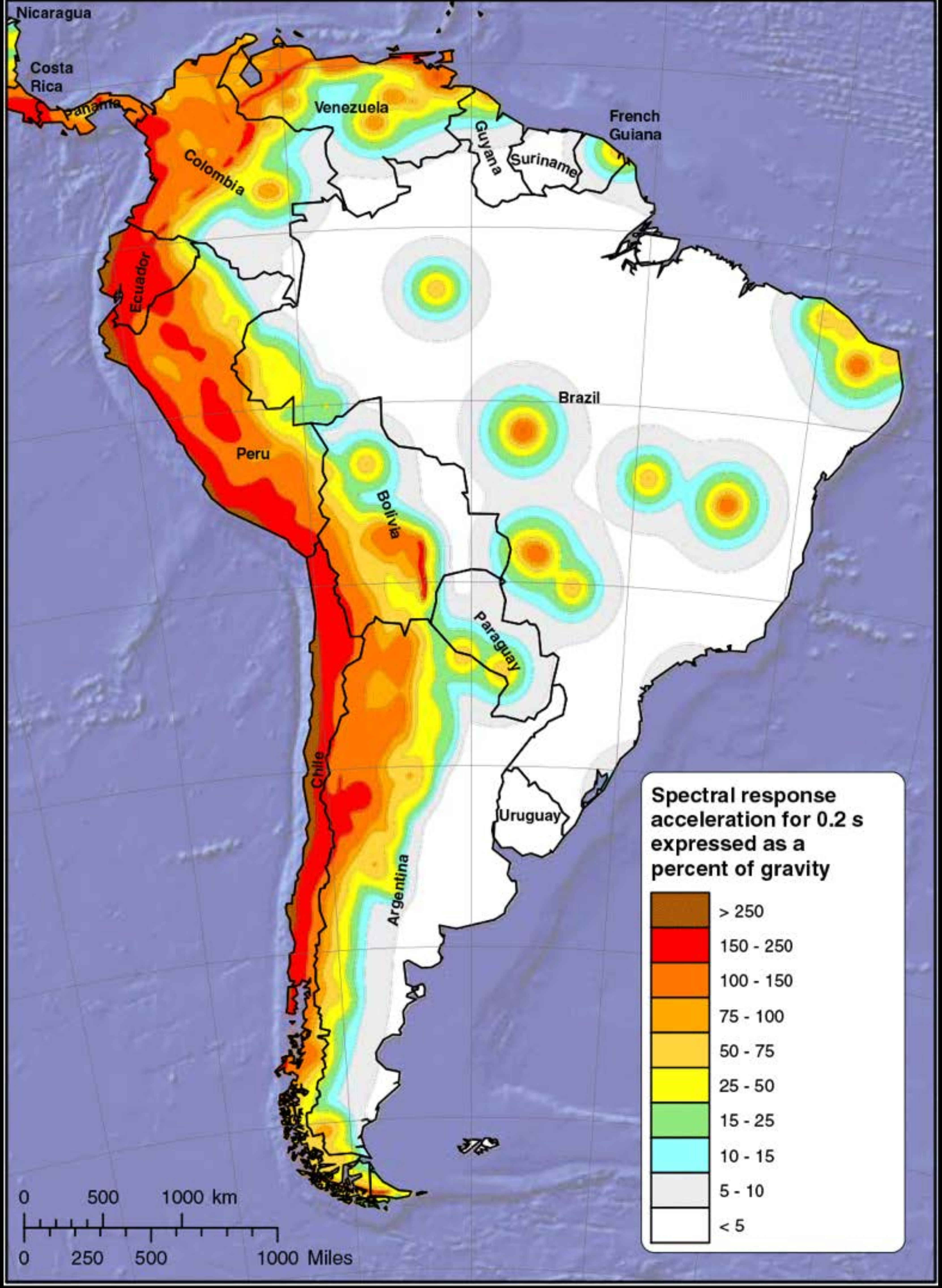


Figure from Petersen et al., BSSA 2018

PSHA in South America

Subduction Model (Interface)

Table 3. Subduction Interface Parameters

Region	Model	Source Name	Input File Name	a-value	b-value	dMag	Mmin	Mmax	Float or Fill Rupture	Dip	Fault Style	Depth (km)	Length (km)	Width (km)	Recurrence Rate	Recurrence Model	Weight
Panama	NA	North Panama Deformation Zone	pan.sub100n.2016.in	5.7	1	0.1	7.3 (0.2)	7.3 (0.2)	float	45	reverse	0 (top), 7-48 (bottom)			1.00E-02	Characteristic	0.4845
							7.7 (0.6)	7.7 (0.6)									
							7.7 (0.2)	7.7 (0.2)									
		South Panama Deformation Zone	pan.sub100s.2016.in	5.3			7.1 (0.2)	7.1 (0.2)				0 (top), 8-54 (bottom)				Characteristic	0.4845
							7.3 (0.6)	7.3 (0.6)									
							7.5 (0.2)	7.5 (0.2)									
South America		Lesser Antilles Subduction Zone	ant78.in	-2.6	0		7.8	7.8	float			-20 (top), -60 (bottom)			2.50E-03	Characteristic	0.2
			ant81.in				8.1	8.1									0.6
			ant84.in				8.4	8.4									0.2
		Northern Coast Subduction Zone	Caribbean.sub78.2016.in				7.8	7.8				5 (top), 50 (bottom)				Gutenberg-Richter	1
			Caribbean.sub81.2016.in				8.1	8.1									1
			Caribbean.sub84.2016.in				8.4	8.4									1
	USGS (1.0 weight)	Zone 1	sub-gr-z1.2016.in	5.026	0.9	0.25	7.5	8.5				10 (top), 50 (bottom)	982		4.32E-02	Gutenberg-Richter	1
			sub-char9p0-z1.2016.in	-2.6	0	1	8.8	8.8					982			Characteristic	0.2
							9	9									0.6
							9.2	9.2									0.2
		Zone 2	sub-gr-z2.2016.in	4.729	0.8	0.25	7.5	8.5					1486		1.31E-01	Gutenberg-Richter	1
			sub-char-z2.2016.in	-2.6	0	0.1	8.8	8.8					1486			Characteristic	0.2
							9	9									0.6
							9.2	9.2									0.2
	USGS (0.5 weight)	Zone 3	sub-gr-z3.2016.in	4.553	0.8	0.25	7.5	8.5					932		8.70E-02	Gutenberg-Richter	0.5
			sub-char9p0-z3.2016.in	-2.6	0	0.1	8.8	8.8					932			Characteristic	0.2
							9	9									0.6
							9.2	9.2									0.2
		Zone 4	sub-gr-z4.2016.in	5.598	0.9	0.25	7.5	9					1395		1.70E-01	Gutenberg-Richter	0.5
		Zone 5	sub-gr-z5.2016.in	4.25	0.8		7.5	9					1217		4.63E-02	Gutenberg-Richter	0.5
		Zone 4 and 5	sub-ch95-z4z5.2016.in	-2.6	0	0.5	9.4	9.4					2612			Characteristic	0.3
							9.5	9.5									0.6
							9.6	9.6									0.1
	Medina et al. (2017) (0.5 weight)	Zones 3, 4, 5 North (-10 to -14.9 S. Lat)	sub_n-gr-z3z4z5.in	4.2181	0.7582	0.1	7.85	9.75								Gutenberg-Richter	0.5
		Combination of Zones 3, 4, and 5 plus southern extension (b = 0.754)	sub-gr-b754N.BC.in	4.1816	0.754											Gutenberg-Richter	0.4
		Combination of Zones 3, 4, and 5 plus southern extension (b = 0.758)	sub-gr-z3z4z5.papazachos.BC.in	4.2181	0.7582											Gutenberg-Richter	0.1

Subduction zone parameters used in Petersen et al (2018) South America Hazard model.

South America slab zones 1-5, and Lesser Antilles slab, based on Slab1.0.

North & South Panama Deformation Zones not defined in Slab1.0, or Slab2. Nor is southern extension of South America model (south of Chile Triple Junction).

PSHA in Subduction Zones

Slab2 can define:

1) Megathrust geometry
    1) Gridded Surface (of entire slab)
    2) 3D mesh (of seismogenic zone)
    3) Planar approximation (of seismogenic zone)

2) Seismogenic Zone Limits

3) Earthquake catalogs filtered for tectonic providence (interplate VS intraplate, etc.)

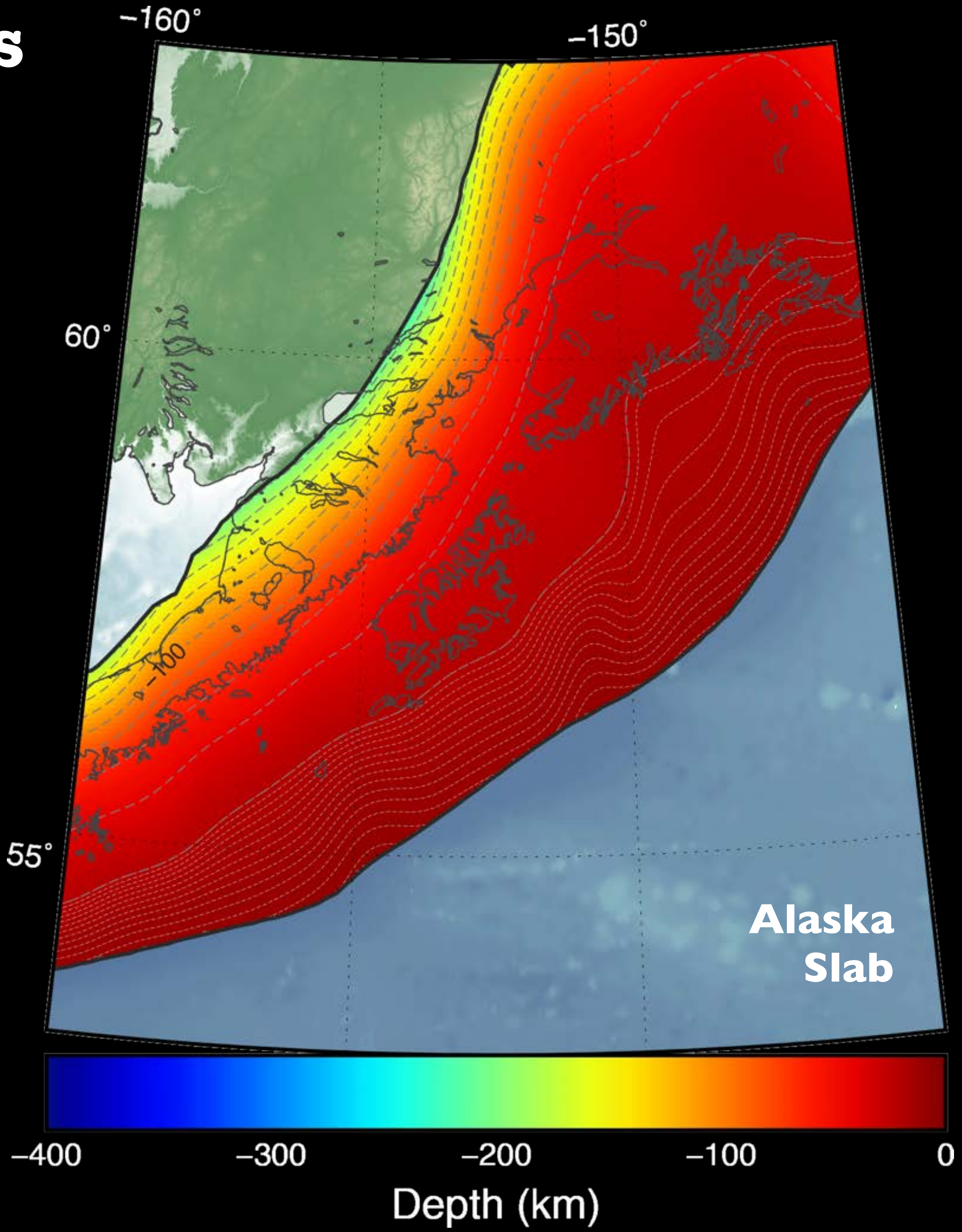
4) Gutenberg-Richter parameters (e.g., b values of mag:freq relationship)

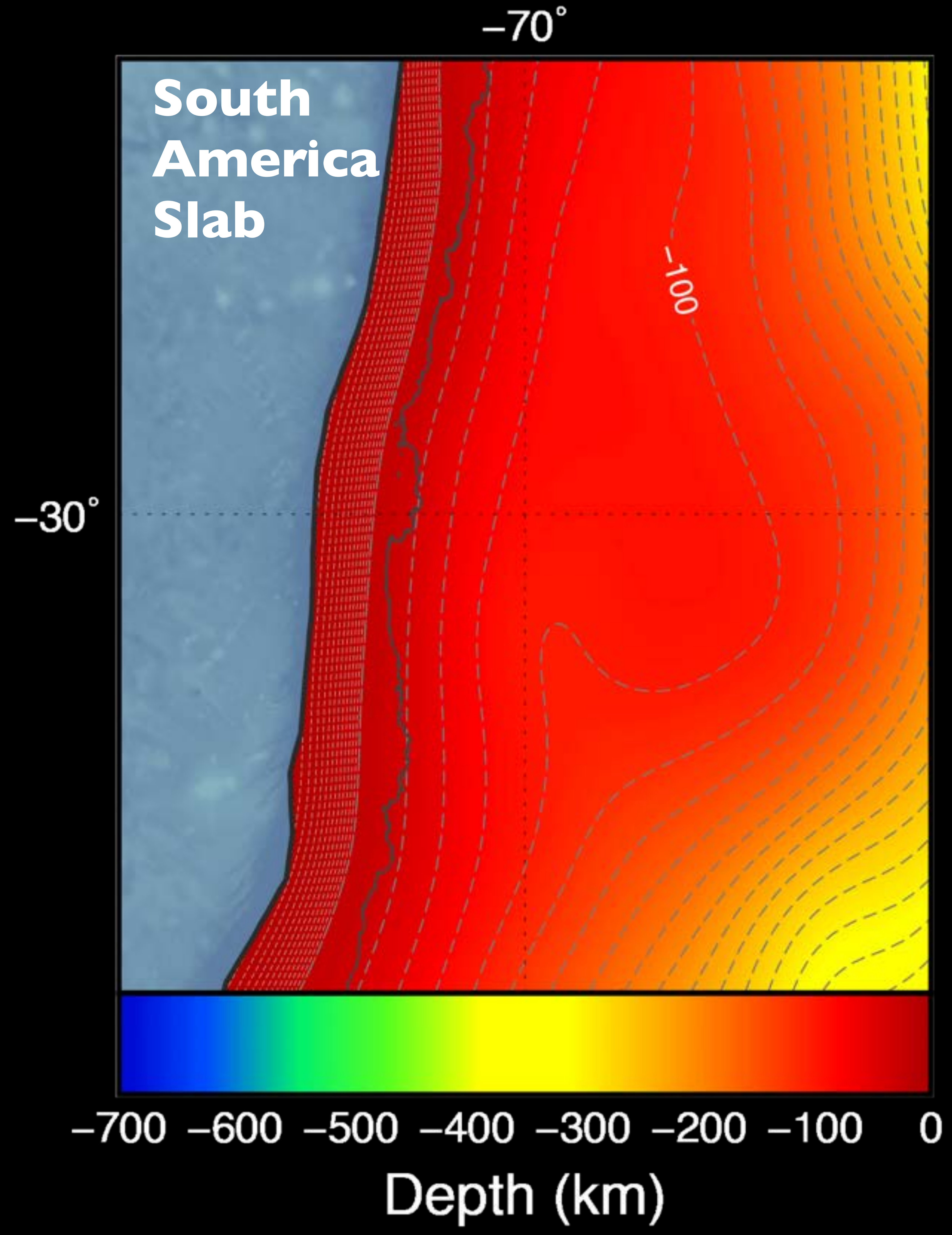
5) Segmentation

7) Maximum magnitude, M-max

Slab Geometries

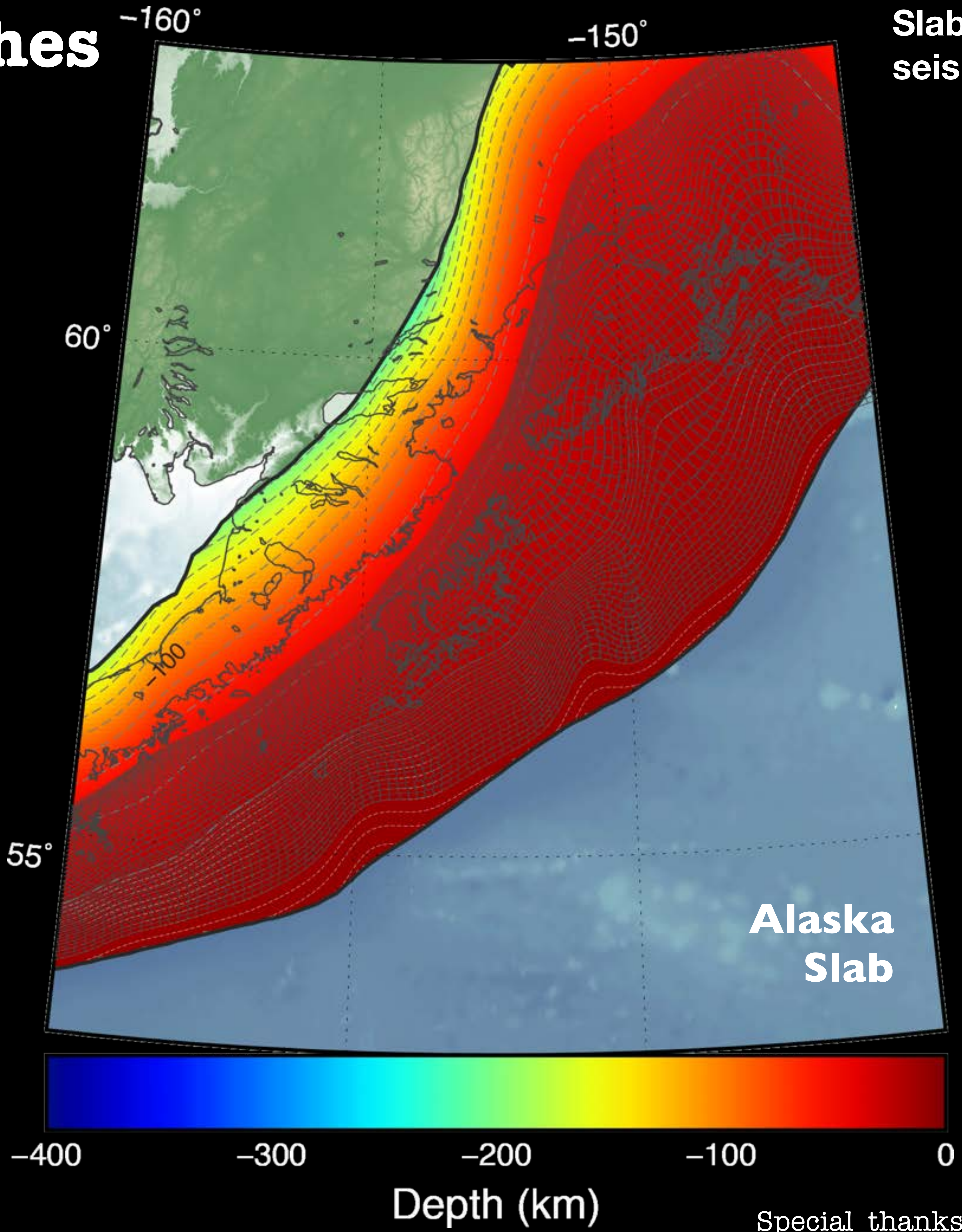
Slab Grids

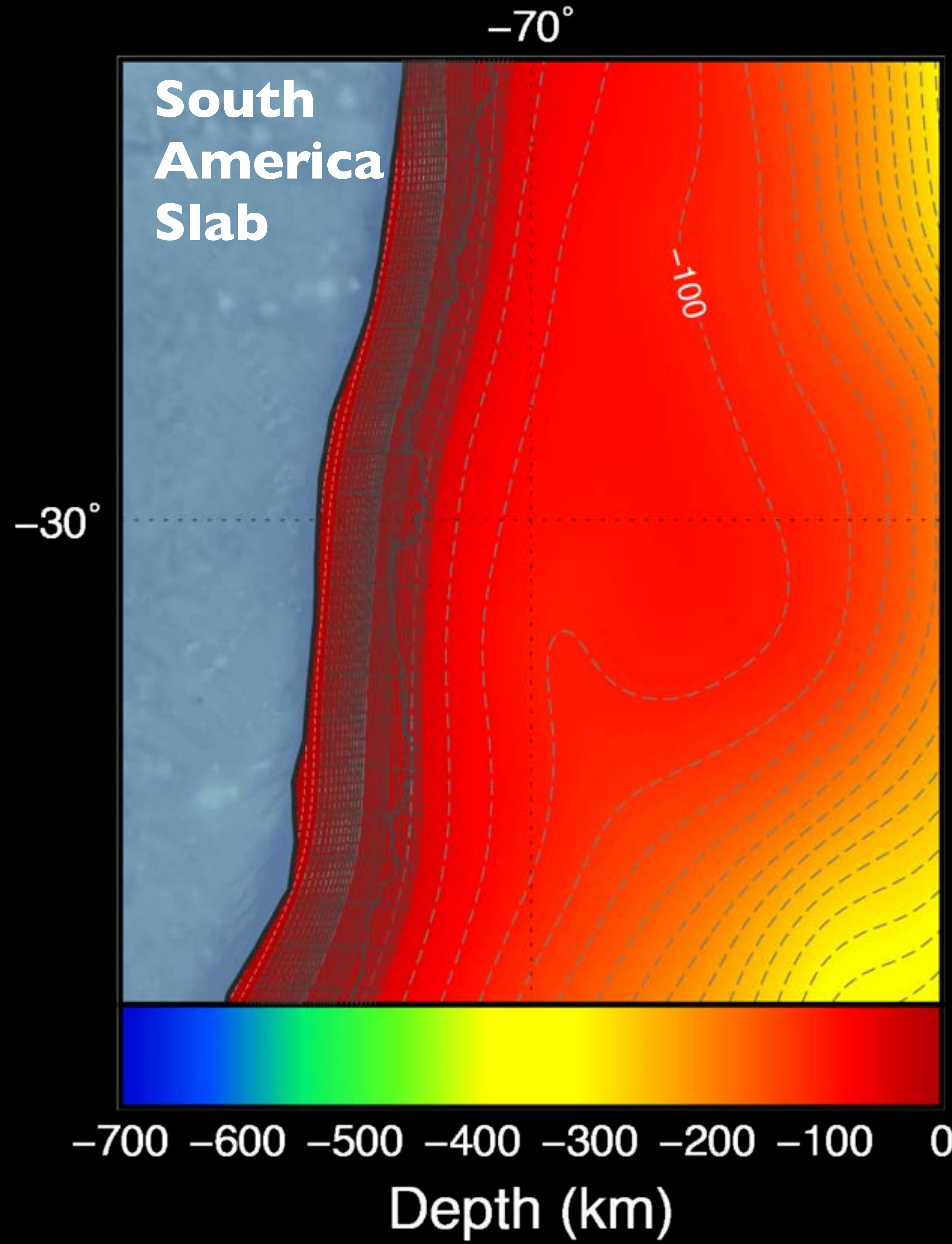

−160°
−150°
60°
55°
−100
Alaska
Slab
−400
−300
−200
−100
0
Depth (km)


−70°
South
America
Slab
−30°
−100
−700
−600
−500
−400
−300
−200
−100
0
Depth (km)

Slab Meshes

Slab2 contains rectangular meshes of all defined seismogenic zones





Special thanks to Dmitry Nicolsky @ University of Alaska Fairbanks for mesh codes

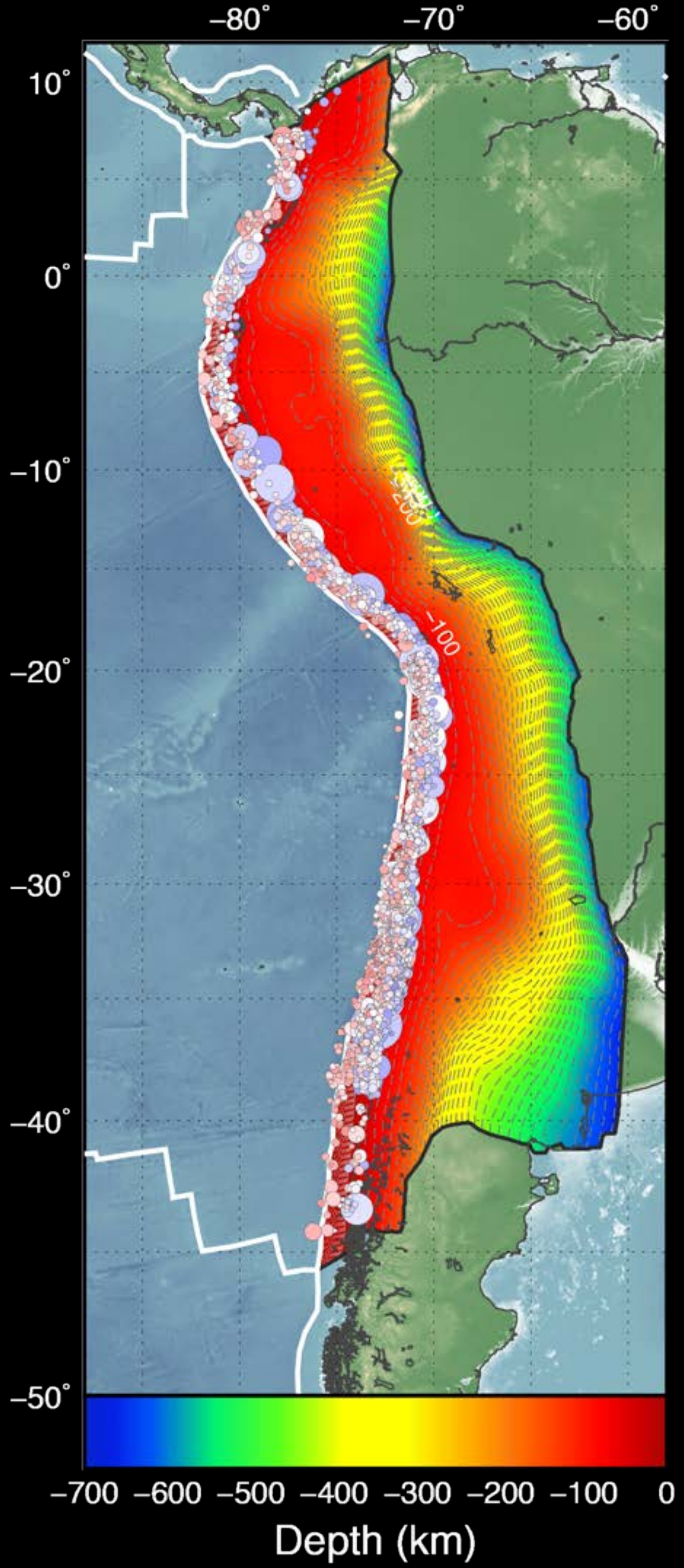
Earthquake Catalogs

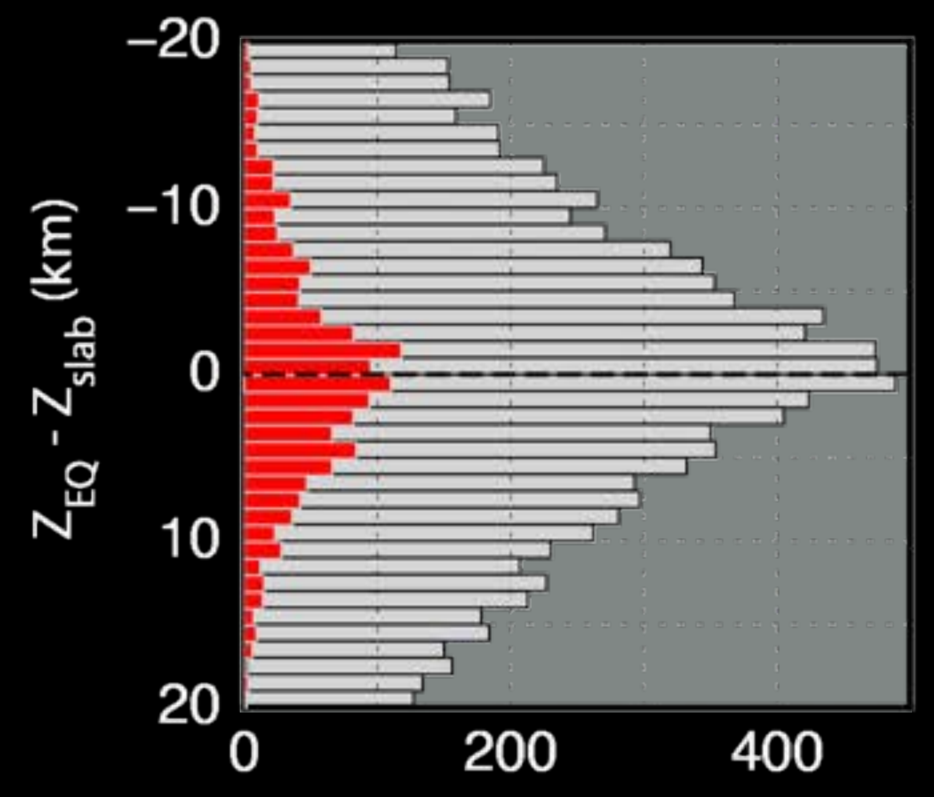
Interplate EQs
South America

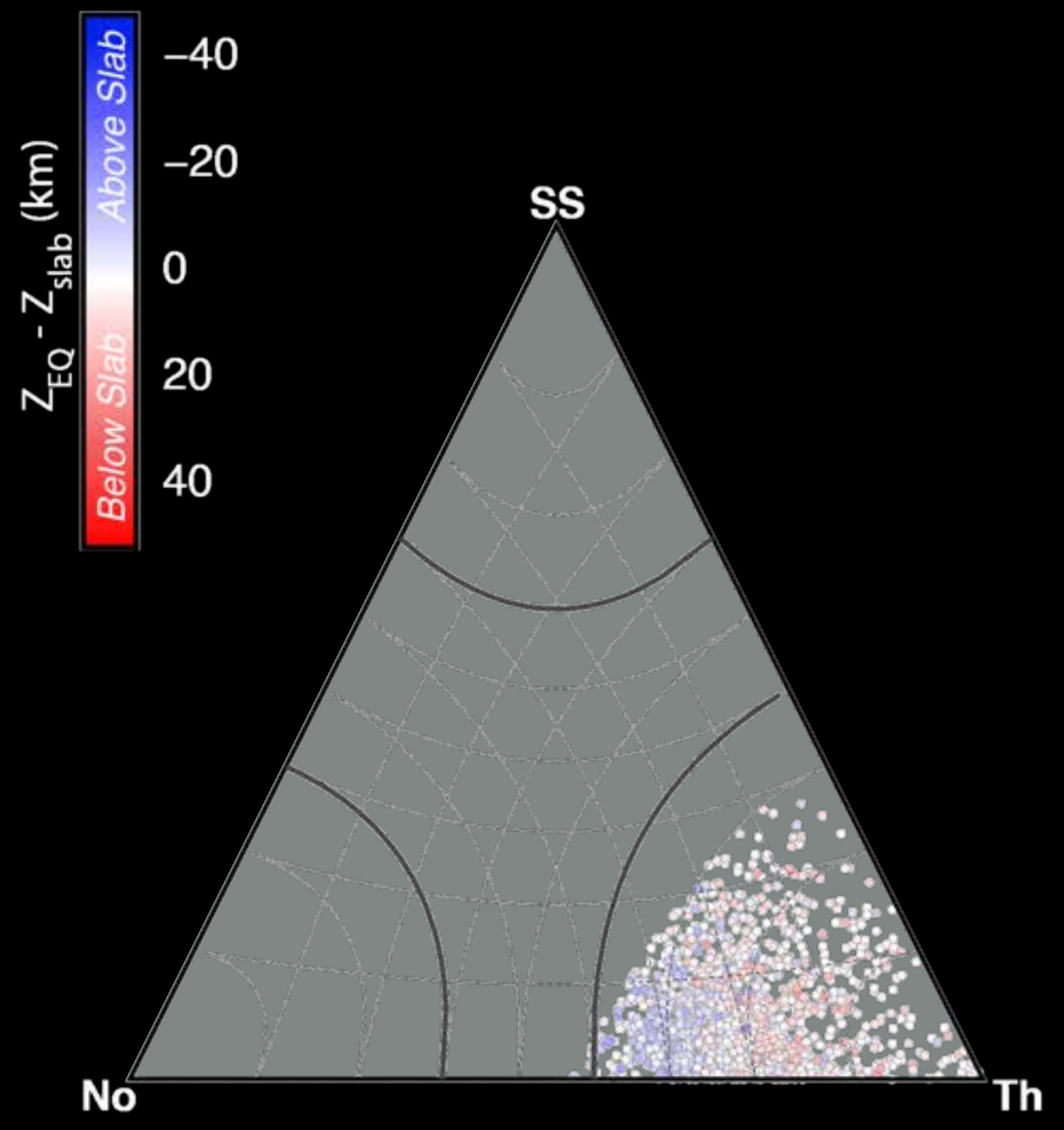
The filtering implicit in the creation of Slab2 allows us to define catalogs of seismicity tagged to the tectonic providence of each earthquake.

i.e., we can easily distinguish earthquakes in interplate, intraplate, and upper plate environments.

Figure on right shows South America interplate seismicity.







Triangle diagrams (after Frohlich, 1992) show the distribution of faulting for the earthquake population (here, all thrust faulting events).

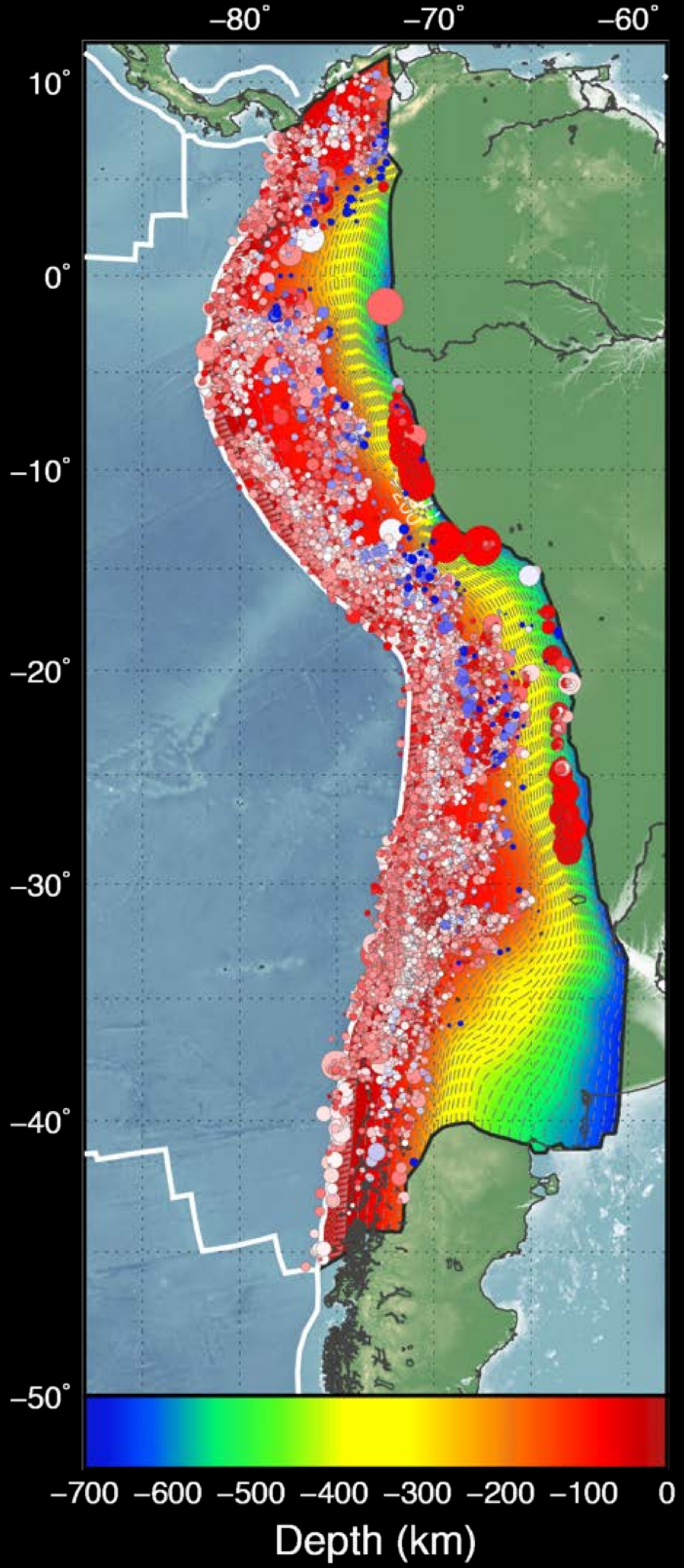
Intraplate EQs

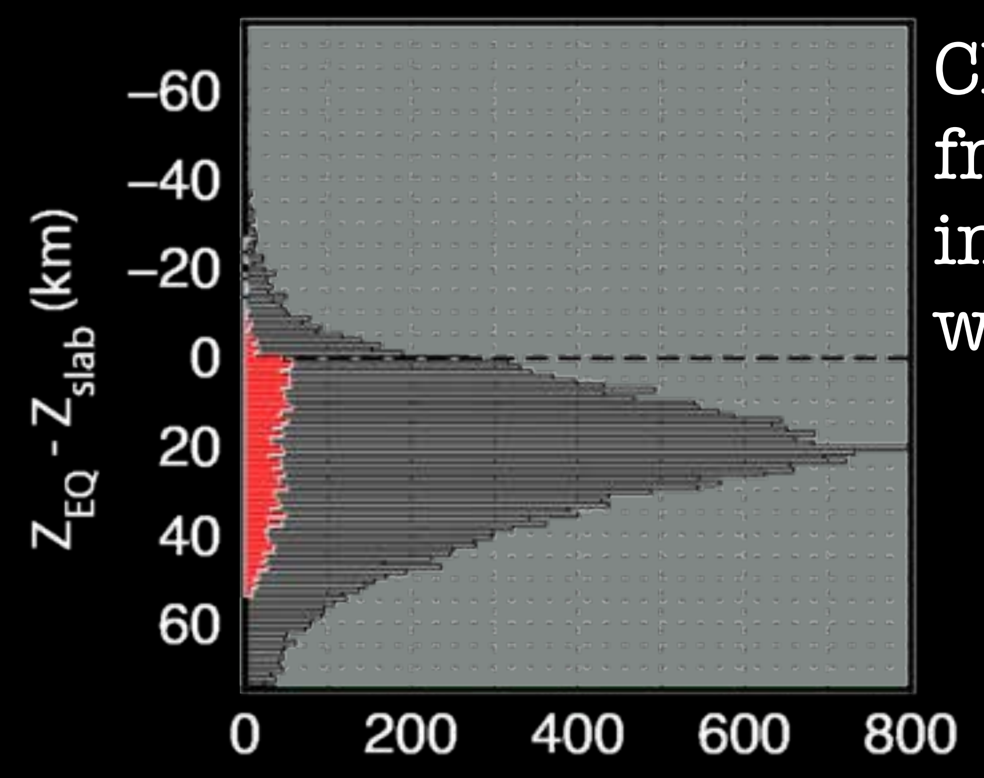
South America

The filtering implicit in the creation of Slab2 allows us to define catalogs of seismicity tagged to the tectonic providence of each earthquake.

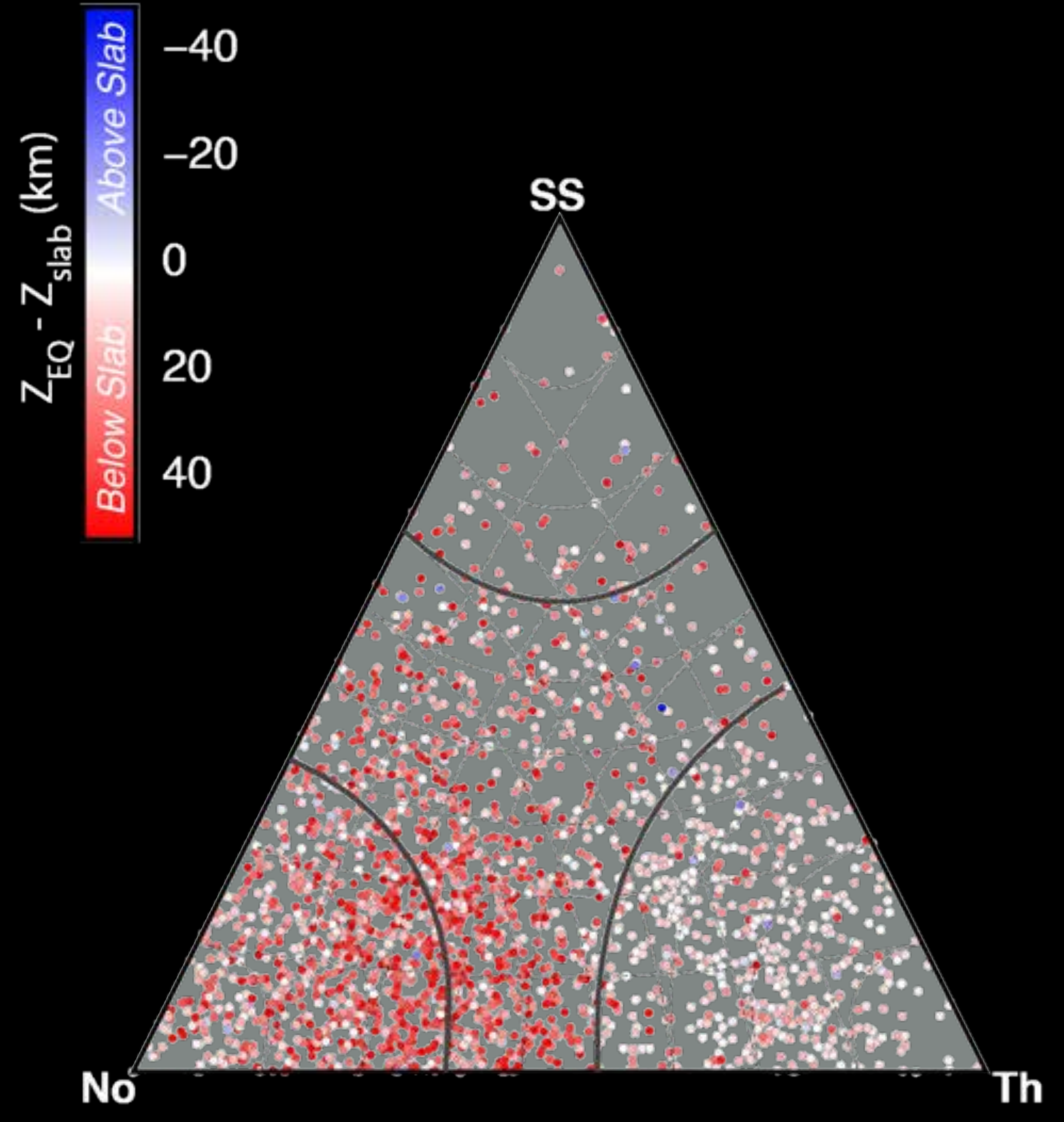
i.e., we can easily distinguish earthquakes in interplate, intraplate, and upper plate environments.

Figure on right shows South America intraplate seismicity.





Clear change from on interface to within plate.

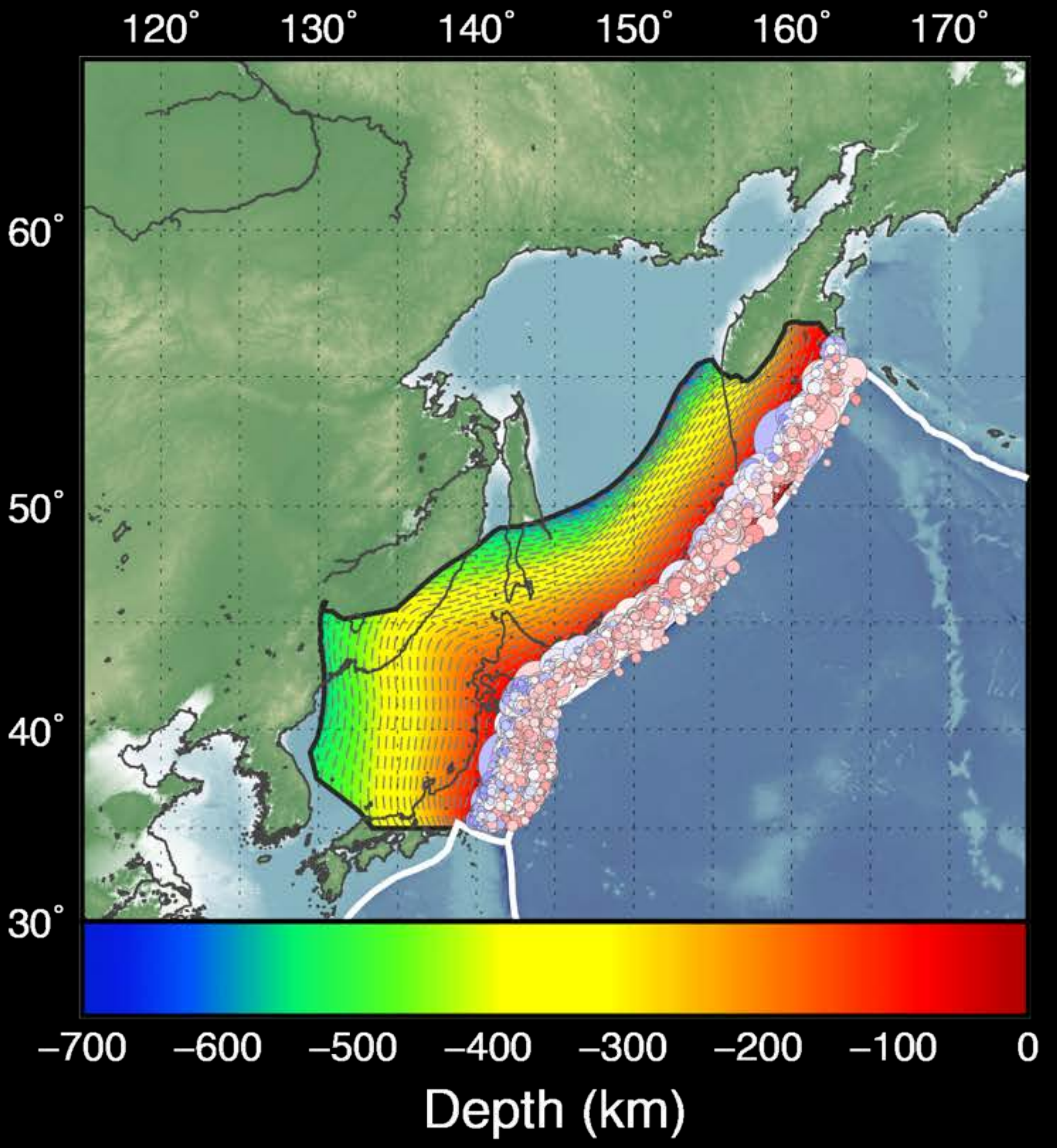


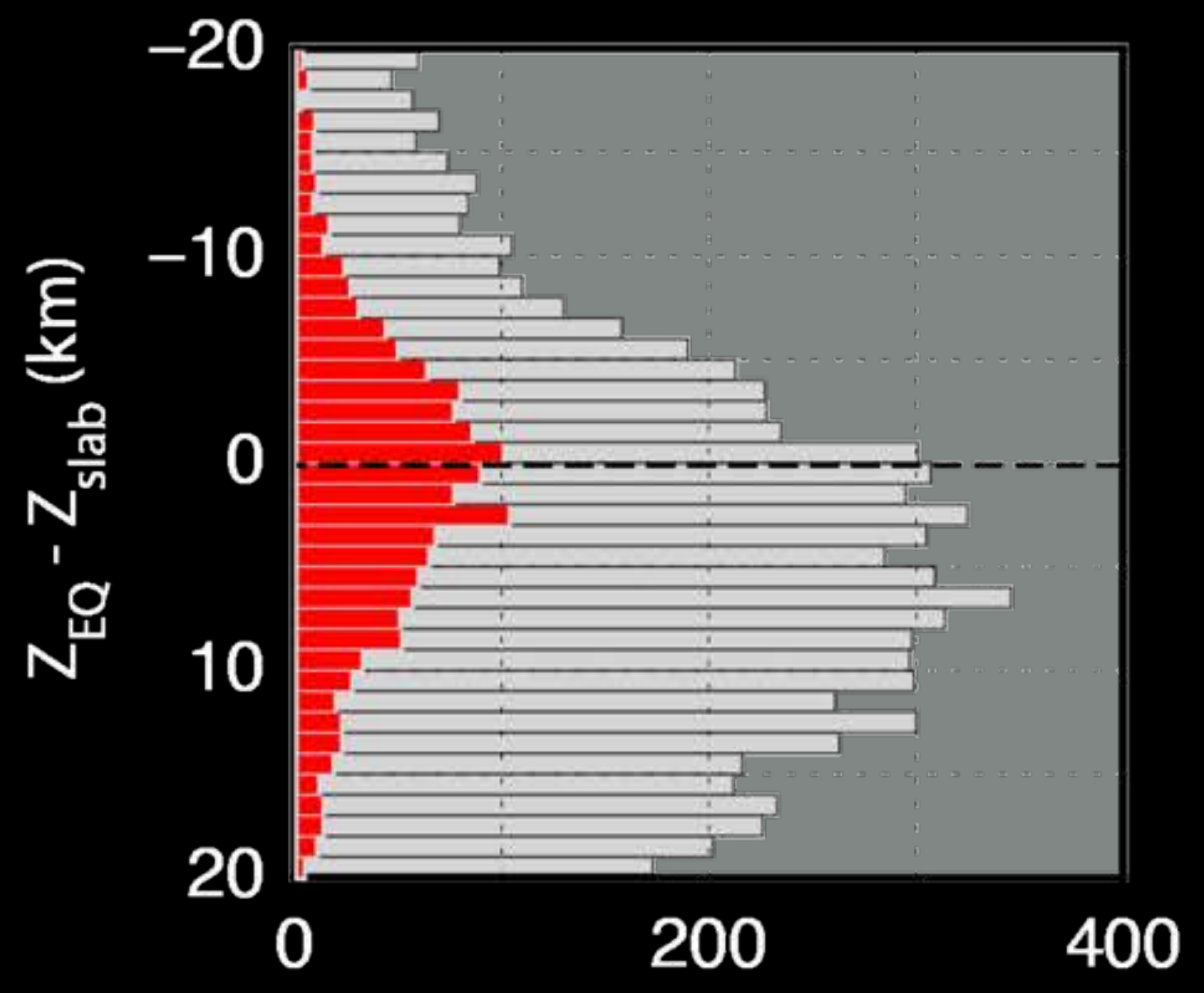
Triangle diagrams (after Frohlich, 1992) show the distribution of faulting for the earthquake population (here, normal faulting events dominate).

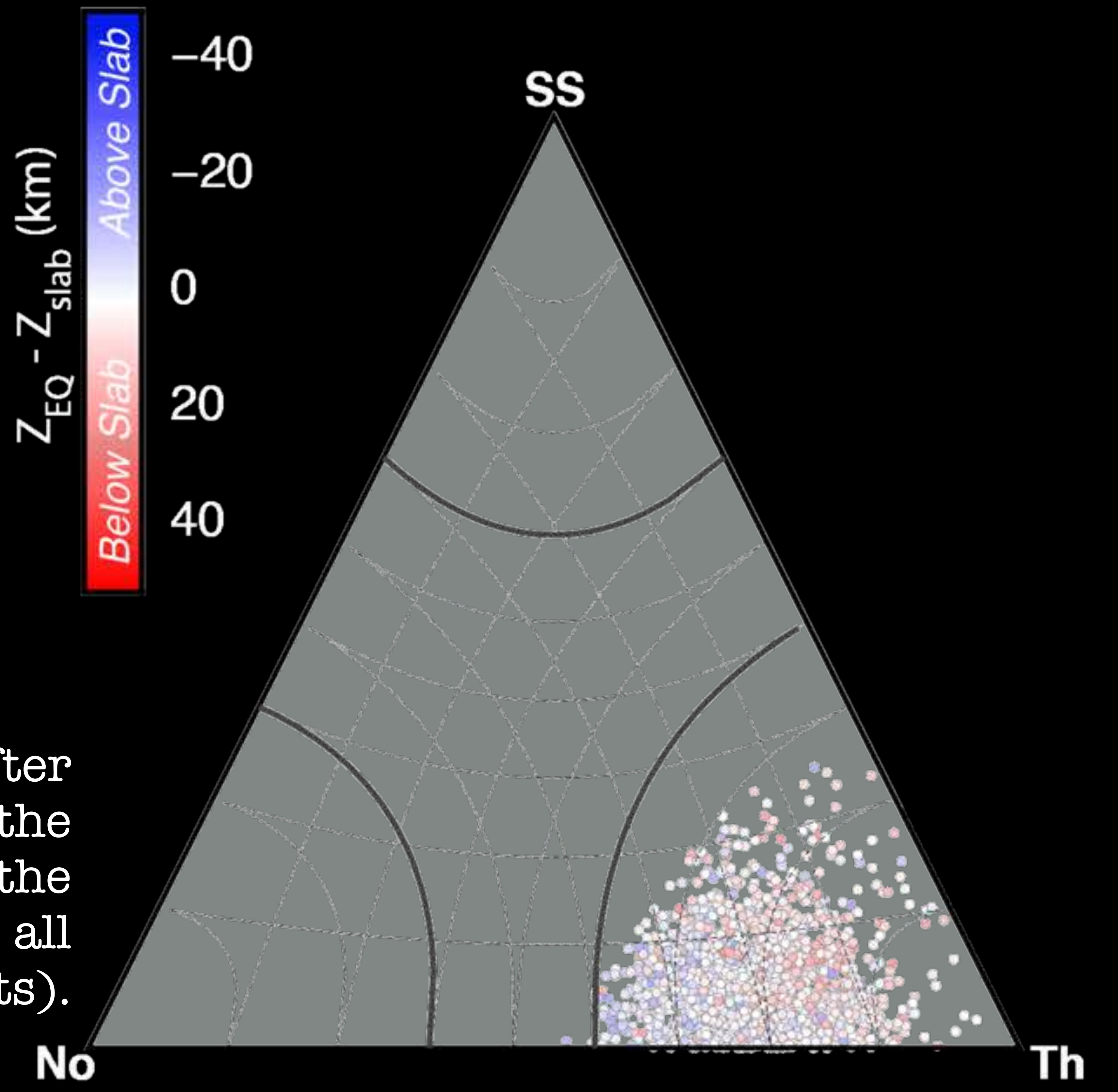
Interplate EQs

Kuril Islands

Figure on right shows Kuril-Japan interplate seismicity.





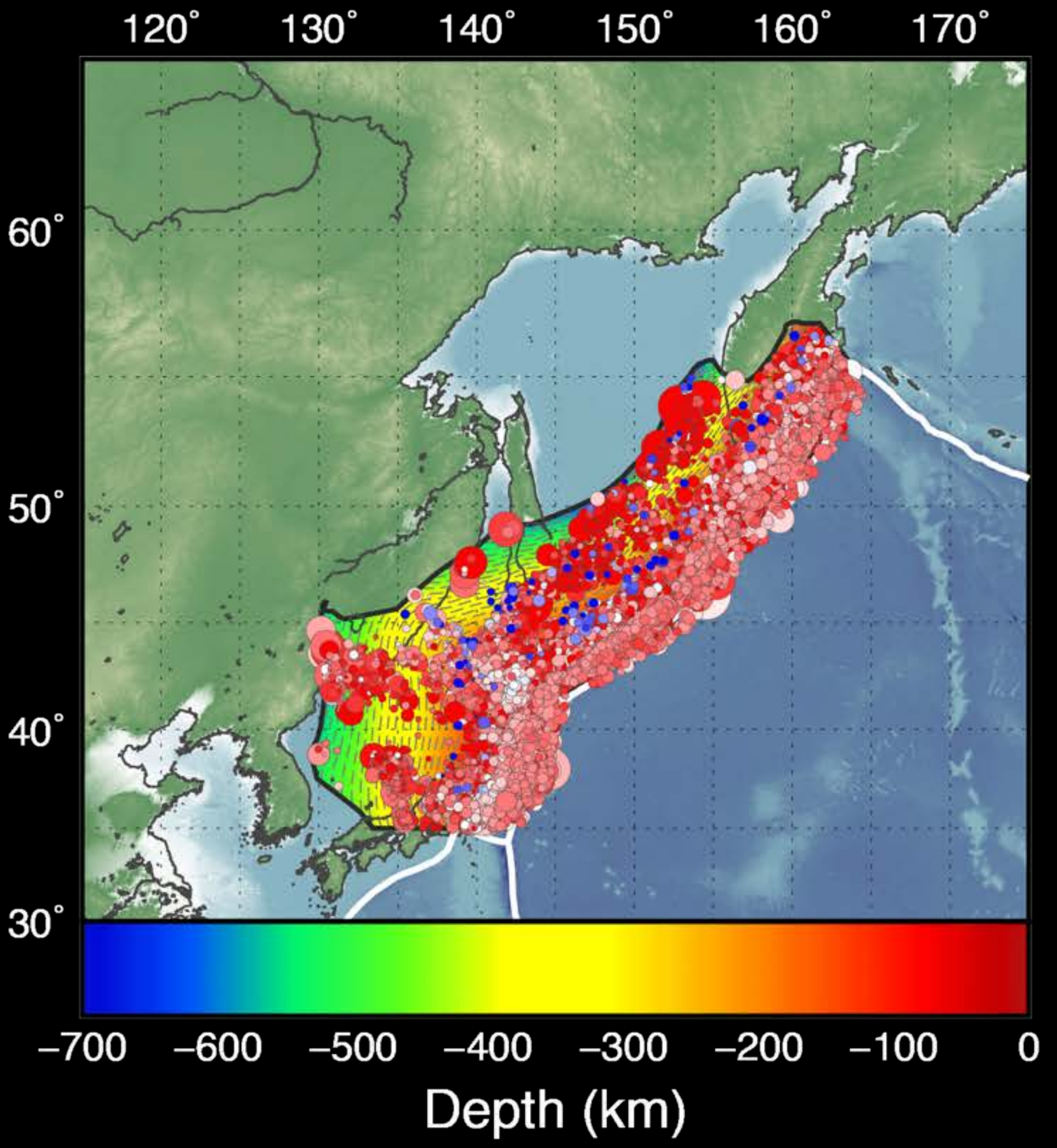


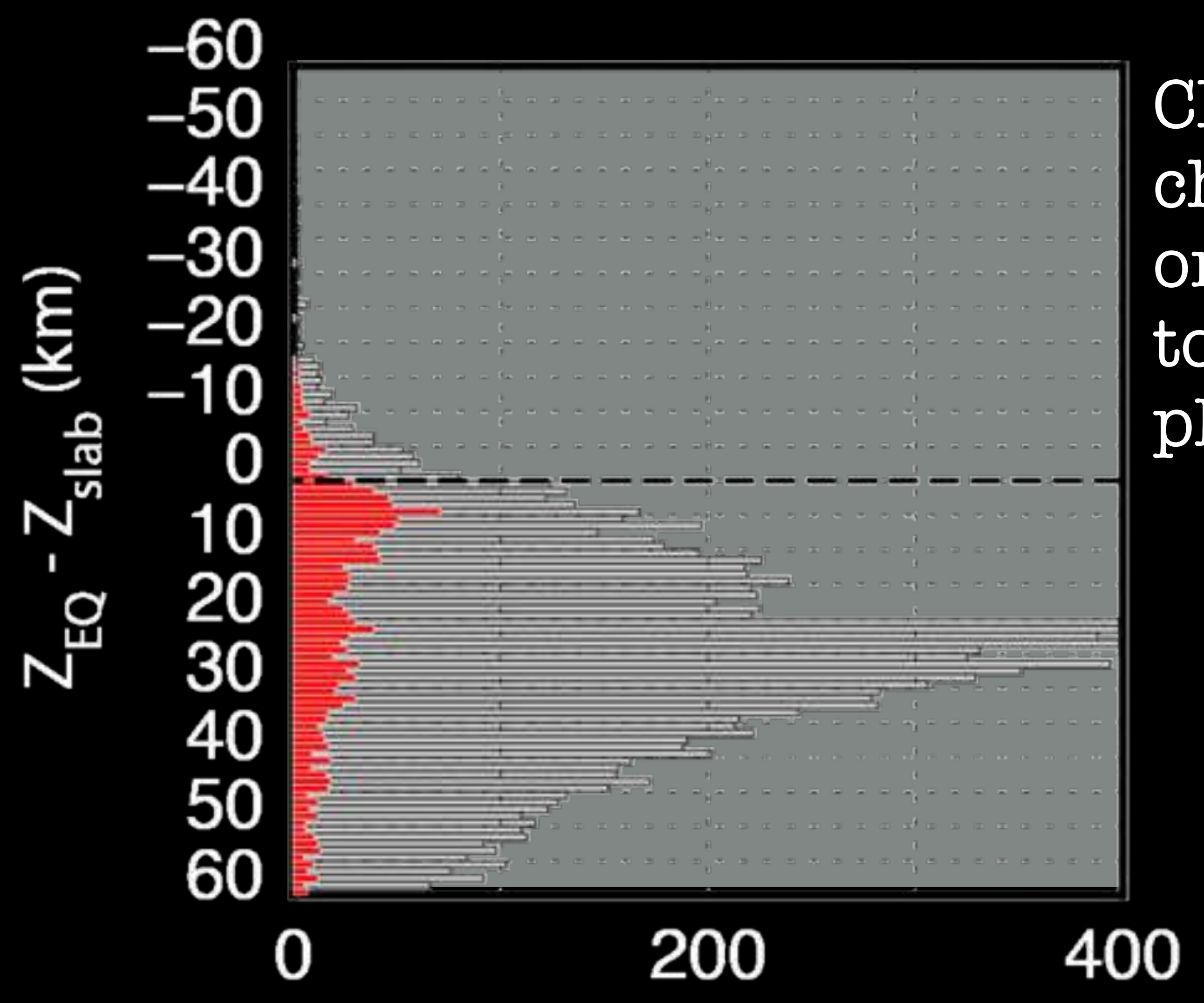
Triangle diagrams (after Frohlich, 1992) show the distribution of faulting for the earthquake population (here, all thrust faulting events).

Intraplate EQs

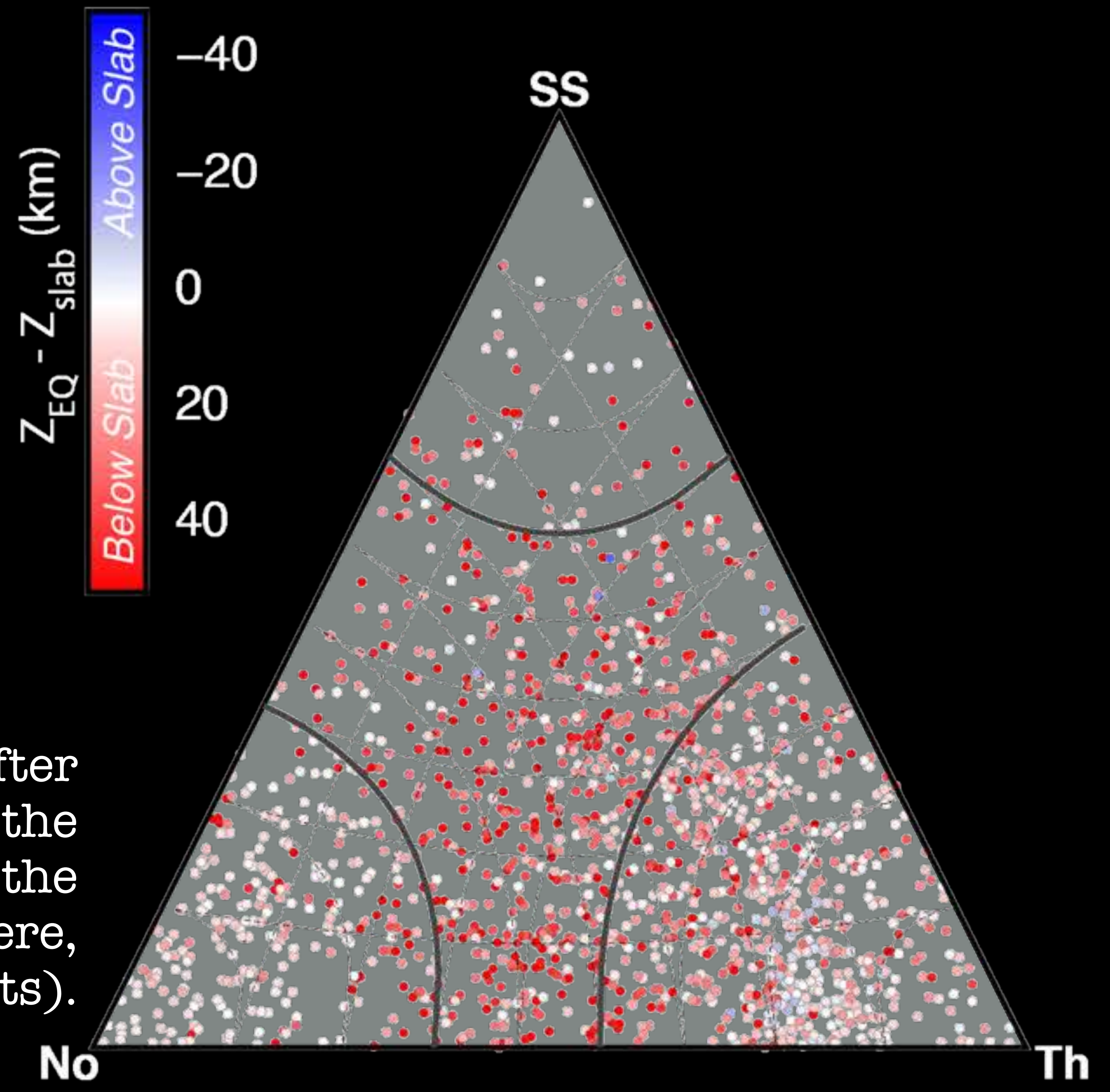
Kuril Islands

Figure on right shows Kuril-Japan intraplate seismicity.





Clear change from on interface to within plate.



Triangle diagrams (after Frohlich, 1992) show the distribution of faulting for the earthquake population (here, even distribution of faults).

The Seismogenic Zone

Seismogenic Zone

For each slab, we have modeled:

Up & Down-dip limits of seismogenic zone

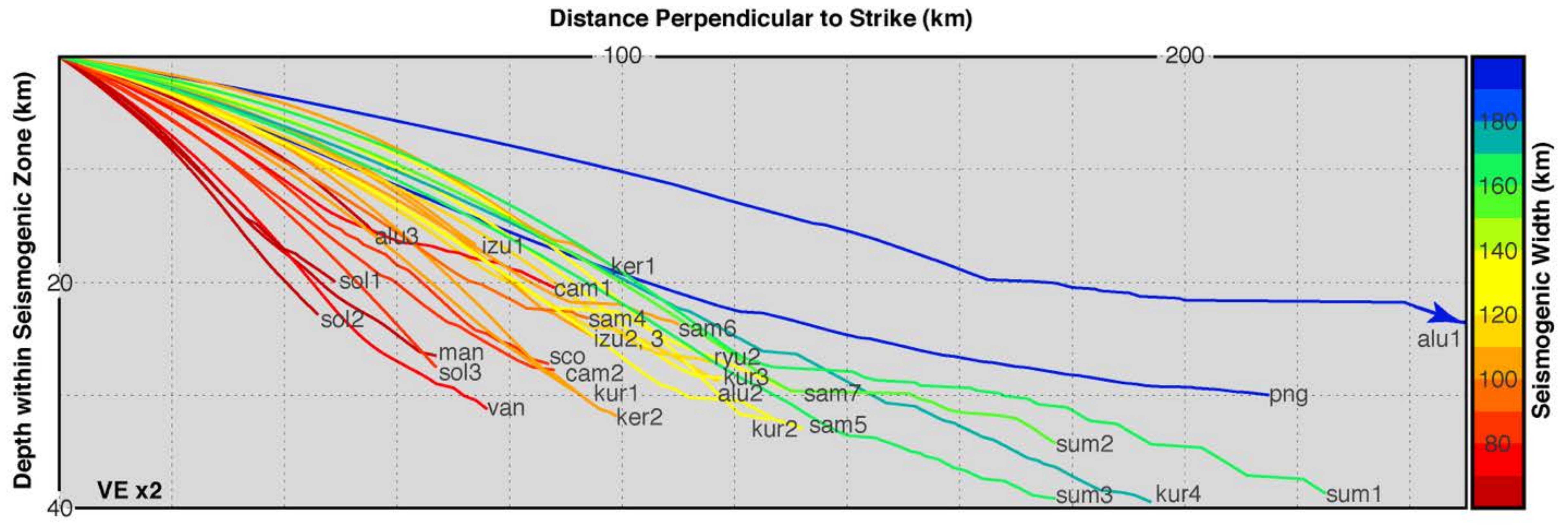
Seismogenic zone width (measured along slab surface)

Average strike, dip, and rake

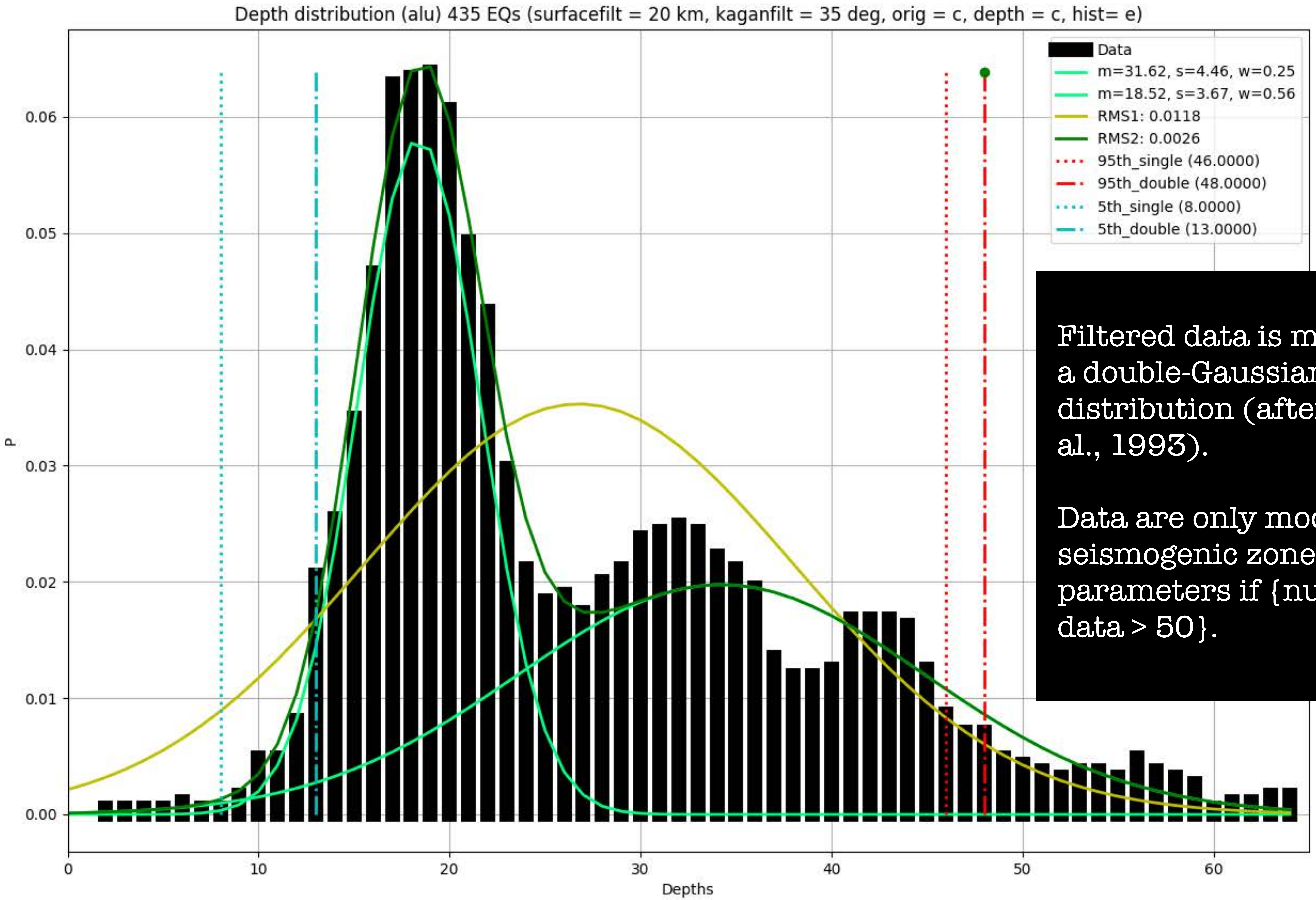
Each slab has also been broken down into smaller regions based on popular ideas of segmentation.

Table 1: **The seismogenic properties of global subduction zones.** This table describes the subduction zone models included in Slab2, and their shallow (S_s) and deep (S_d) seismogenic zone limits, and corresponding seismogenic zone width (S_w). **δ, Φ, and λ** represent the average seismogenic zone interface dip, strike, and rake, respectively. Grey italicized numbers are considered poorly constrained (less than 50 EQs). *[1] = in Slab1.0, this model was named "mex".

#	Subduction Zone Arc	Slab2 Code	N	S_s (km)	S_d (km)	Sw (km)	δ (°)	Φ (°)	λ (°)	Mmax
1	Aleutians	alu	470	12	45	124	14	265	124	9.2
	Alaska	alu1	42	11	45	193	11	233	195	9.2
	Central Aleutians	alu2	345	13	46	110	17	260	104	8.6



Seismogenic Zone - Alaska



Filtered data is modeled with a double-Gaussian distribution (after Pacheco et al., 1993).

Data are only modeled for seismogenic zone parameters if {number of data > 50}.

GR Characteristics
(b-values)

For illustrative purposes only

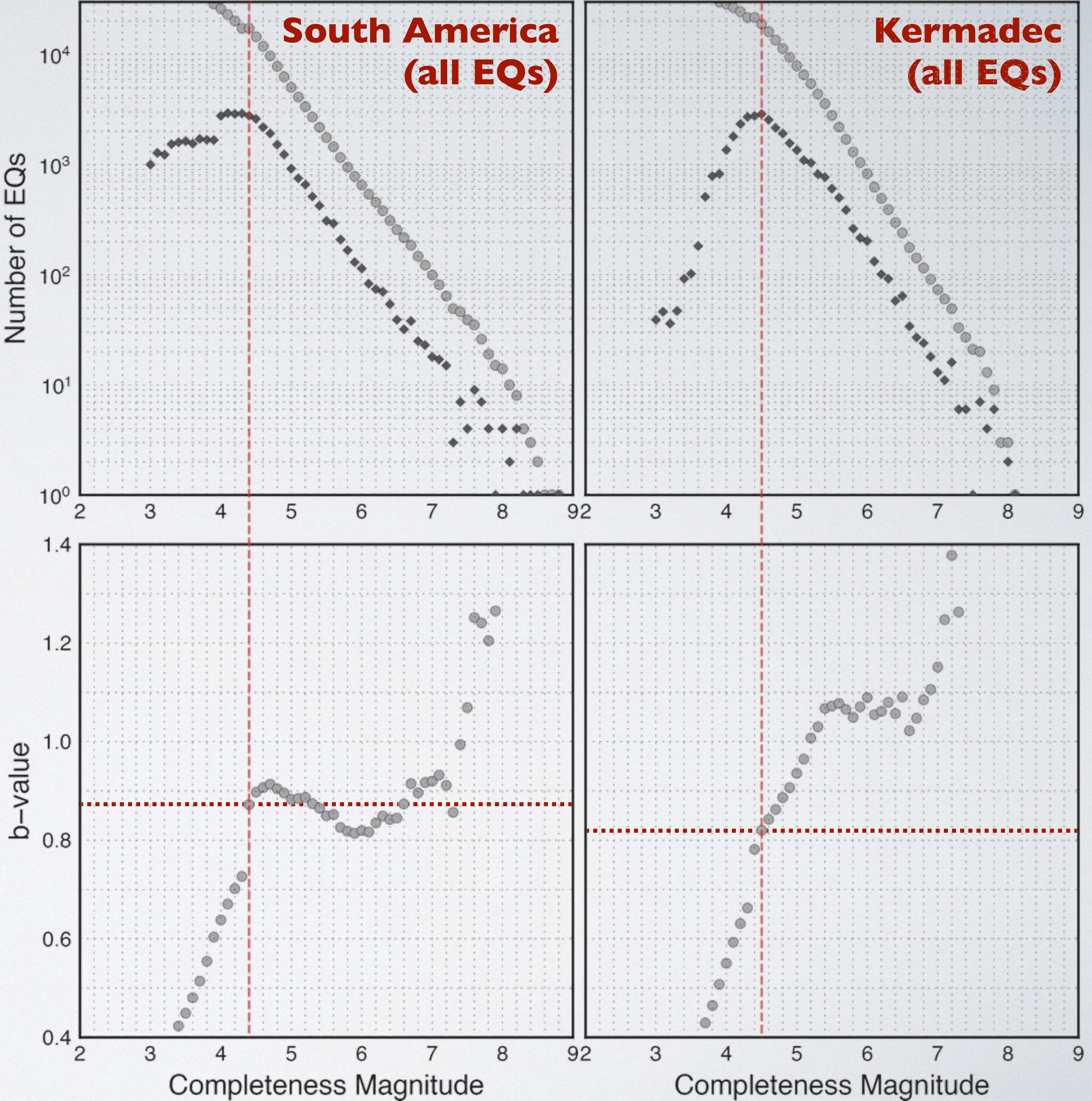
Assessing b-value

South America vs Kermadec

Gutenberg-Richter relations via Maximum Likelihood approach, using all input data for a given subduction zone.

South America b-value ~ 0.87

Kermadec b-value ~ 0.82



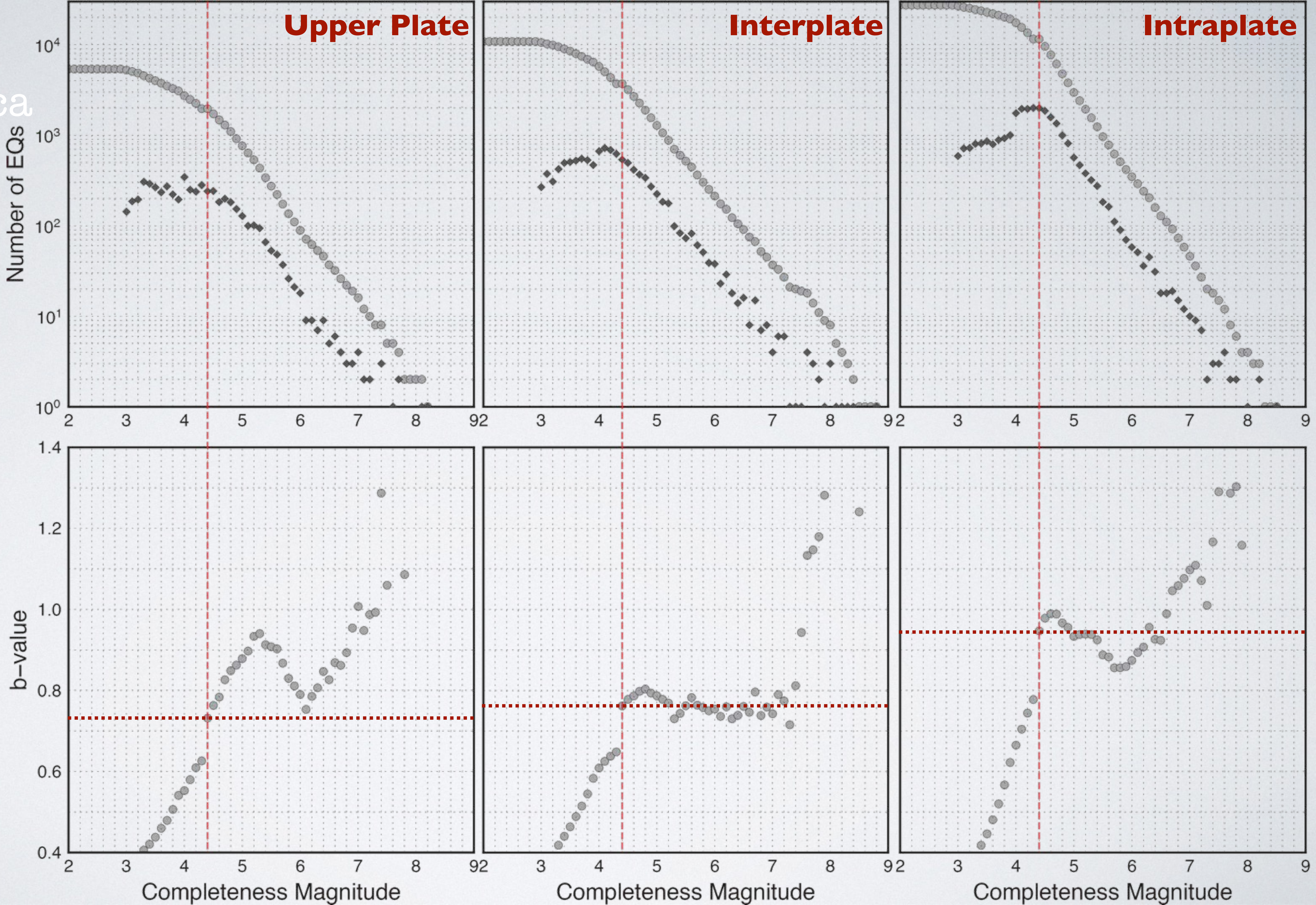
b-values
South America

With Slab2, we can break catalogs down into tectonic environments.

Upper plate:
b-value ~ 0.73

Interplate:
b-value ~ 0.76

Intraplate:
b-value ~ 0.95



b-values

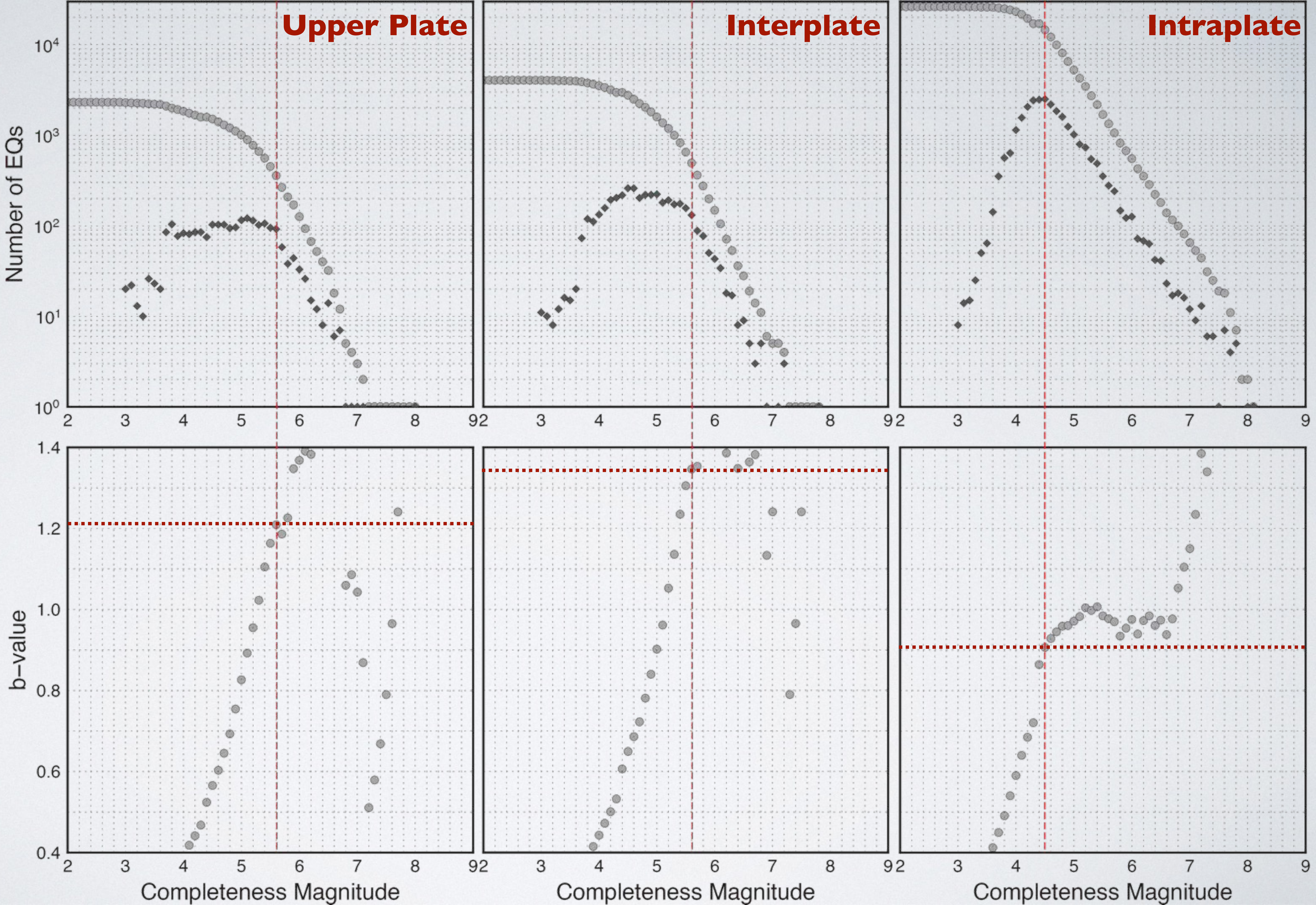
Kermadec

With Slab2, we can break catalogs down into tectonic environments.

Upper plate:
b-value ~ 1.21

Interplate:
b-value ~ 1.34

Intraplate:
b-value ~ 0.91



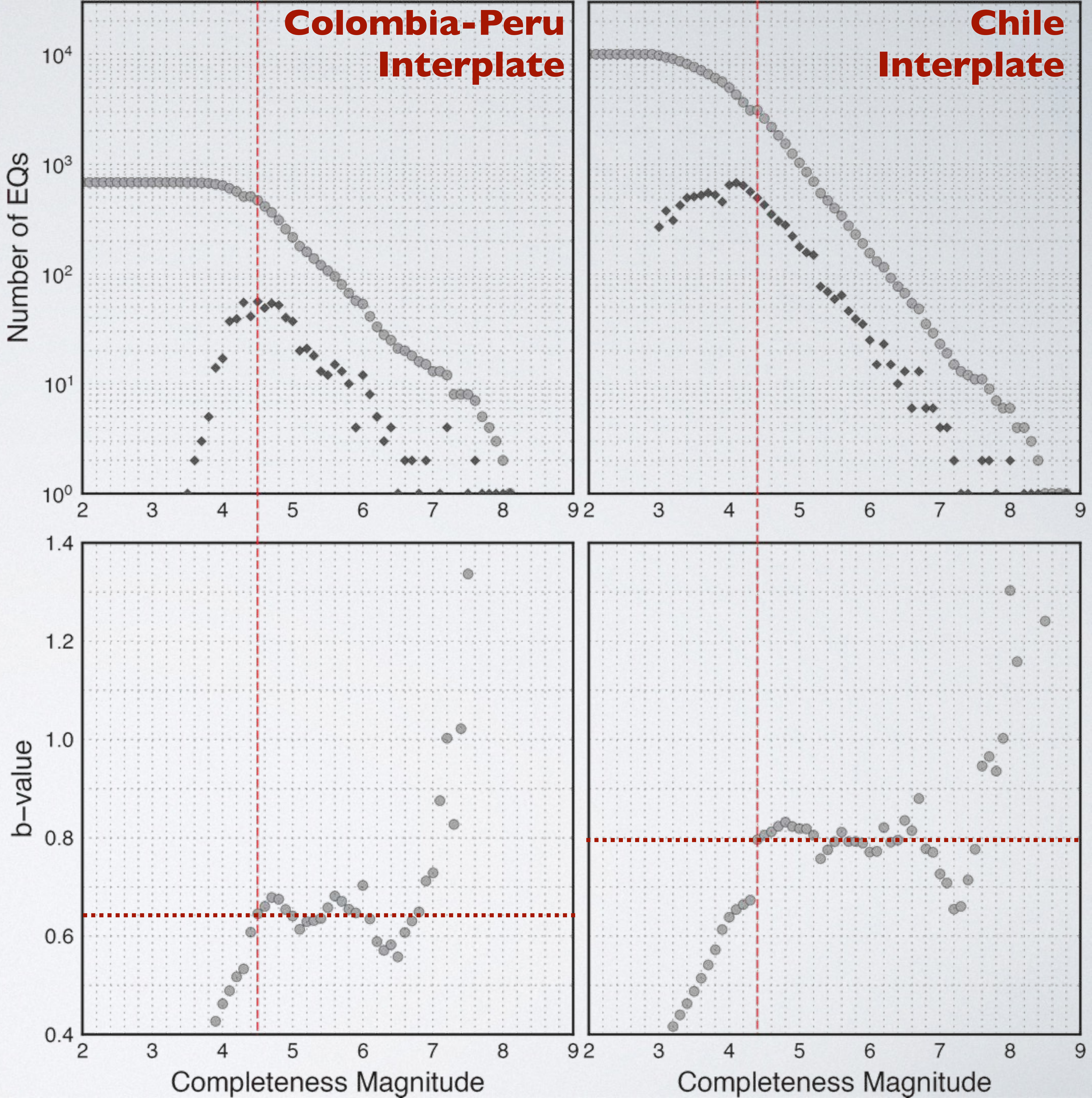
b-values

South America

We can further break catalogs down into segmented tectonic environments.

Colombia-Peru, Interplate:
b-value ~ 0.64

Chile, Interplate:
b-value ~ 0.80

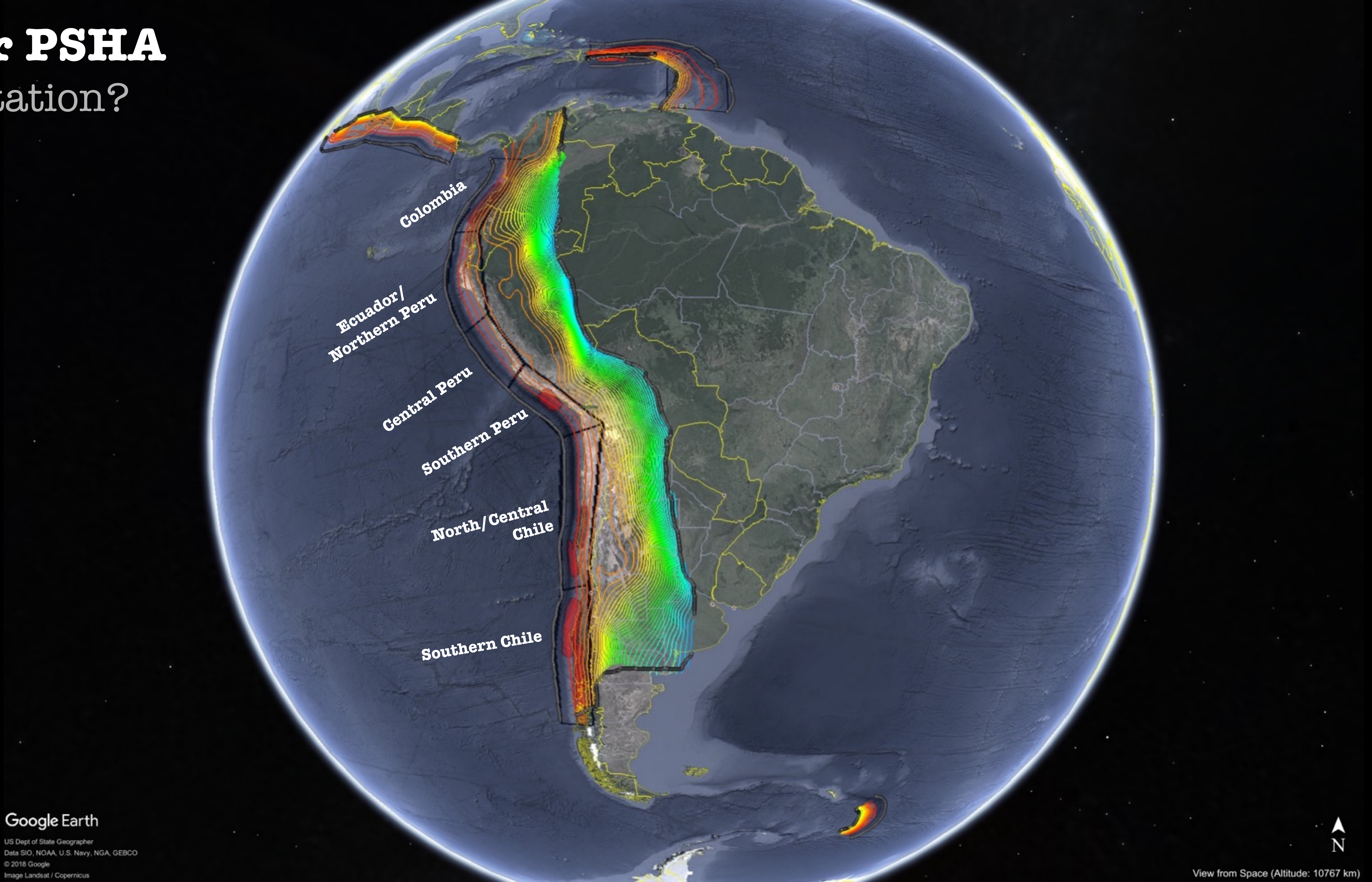


Segmentation & M-max

Work in Progress

Slab2 & PSHA

Segmentation?



Slab2 & PSHA

Segmentation?

Bletery et al. (Science, 2016) postulate that great-sized earthquakes preferentially occur on flat megathrusts, using Slab1.0.

They show a correlation between average 'flatness' (dip gradient) and Mmax for subduction zones in the Slab1.0 model.

GEOPHYSICS

Mega-earthquakes rupture flat megathrusts

Quentin Bletery,[1*] Amanda M. Thomas,[1] Alan W. Rempel,[1] Leif Karlstrom,[1] Anthony Sladen,[2] Louis De Barros[2]

The 2004 Sumatra-Andaman and 2011 Tohoku-Oki earthquakes highlighted gaps in our understanding of mega-earthquake rupture processes and the factors controlling their global distribution: A fast convergence rate and young buoyant lithosphere are not required to produce mega-earthquakes. We calculated the curvature along the major subduction zones of the world, showing that mega-earthquakes preferentially rupture flat (low-curvature) interfaces. A simplified analytic model demonstrates that heterogeneity in shear strength increases with curvature. Shear strength on flat megathrusts is more homogeneous, and hence more likely to be exceeded simultaneously over large areas, than on highly curved faults.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, B01302, doi:10.1029/2011JB008524, 2012

Slab1.0: A three-dimensional model of global subduction zone geometries

Gavin P. Hayes,[1] David J. Wald,[1] and Rebecca L. Johnson[1]

Received 13 May 2011; revised 30 September 2011; accepted 5 October 2011; published 4 January 2012.

[1] We describe and present a new model of global subduction zone geometries, called Slab1.0. An extension of previous efforts to constrain the two-dimensional non-planar geometry of subduction zones around the focus of large earthquakes, Slab1.0 describes the detailed, non-planar, three-dimensional geometry of approximately 85% of subduction zones worldwide. While the model focuses on the detailed form of each slab from their

Slab2 & PSHA

Segmentation?

We can quantify the relationship between flatness and rupture by assessing the gradient of dip in the rupture areas of historic great-sized earthquakes.

Assuming flatness controls where such earthquakes occur, it follows that the flatness of the megathrust within past rupture zones may inform us of where future such EQs can occur.

Gaps between areas of potential rupture may be indicative of persistent geometrical barriers - i.e., segmentation.

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The finite, kinematic rupture properties of great-sized earthquakes since 1990

Gavin P. Hayes

U.S. Geological Survey National Earthquake Information Center, United States

Bulletin of the Seismological Society of America, Vol. 107, No. 3, pp. –, June 2017, doi: 10.1785/0120160255

Alternative Rupture-Scaling Relationships for Subduction Interface and Other Offshore Environments

by Trevor I. Allen* and Gavin P. Hayes

Abstract Alternative fault-rupture-scaling relationships are developed for M_w 7.1–9.5 subduction interface earthquakes using a new database of consistently derived finite-fault rupture models from teleseismic inversion. Scaling relationships are derived for rupture area, rupture length, rupture width, maximum slip, and average slip. These relationships apply width saturation for large-magnitude interface earthquakes (approximately $M_w > 8.6$) for which the physical characteristics of subduction zones limit the depth extent of seismogenic rupture, and consequently, the down-dip limit of strong ground motion generation. On average, the down-dip rupture width for interface earthquakes saturates near 200 km (196 km on average). Accordingly, the reinterpretation of rupture-area scaling for subduction interface earthquakes through the use of a bilinear scaling model suggests that rupture asperity area is less well correlated with magnitude for earthquakes $M_w > 8.6$. Consequently, the size of great-magnitude earthquakes ap-

Slab2 & PSHA

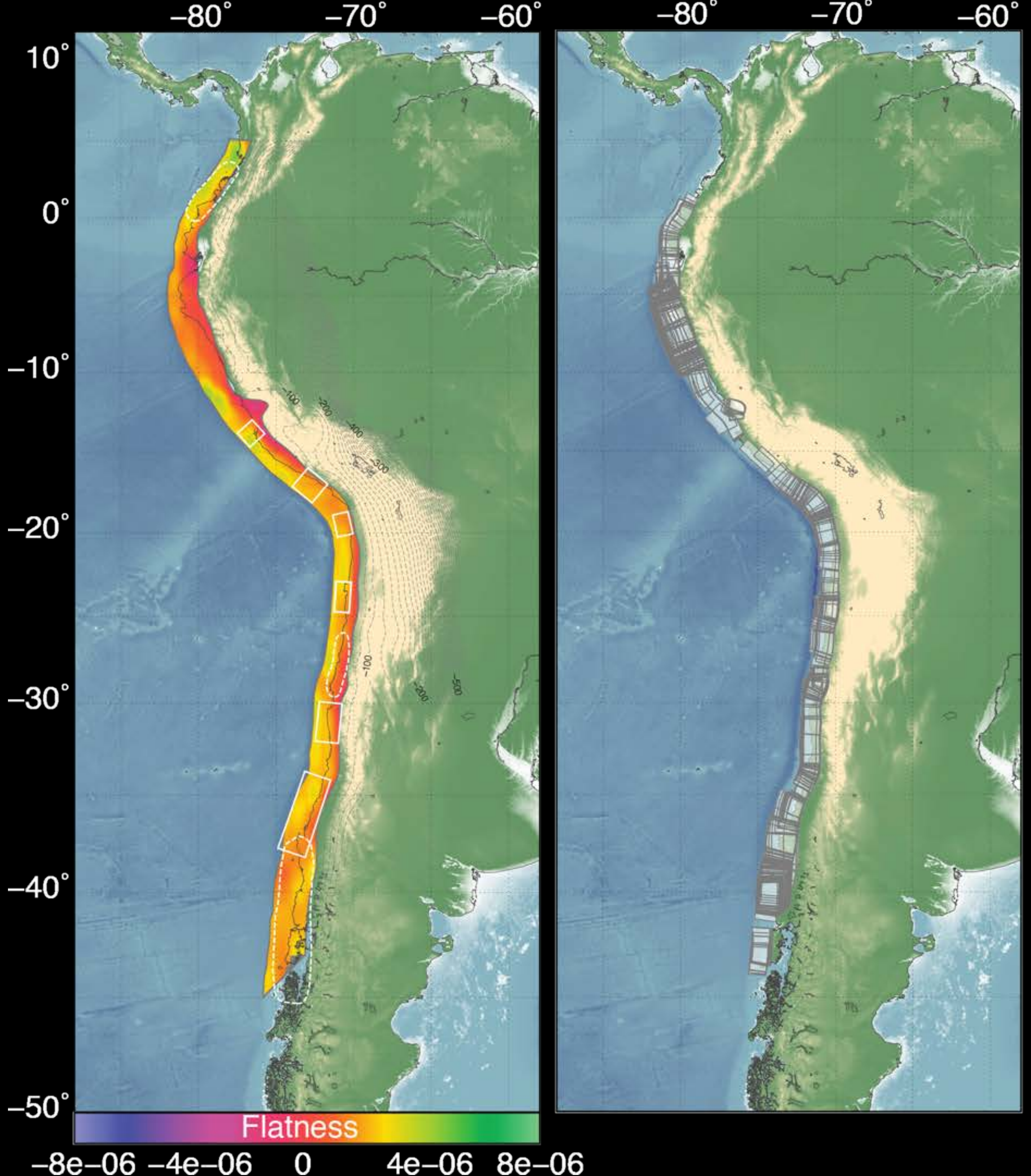
Segmentation?

Flatness (KS), defined as the gradient of the dip, resolved here onto Slab1.0.

Flatness inside rupture areas of historic M8+ EQs defines our “target KS”.

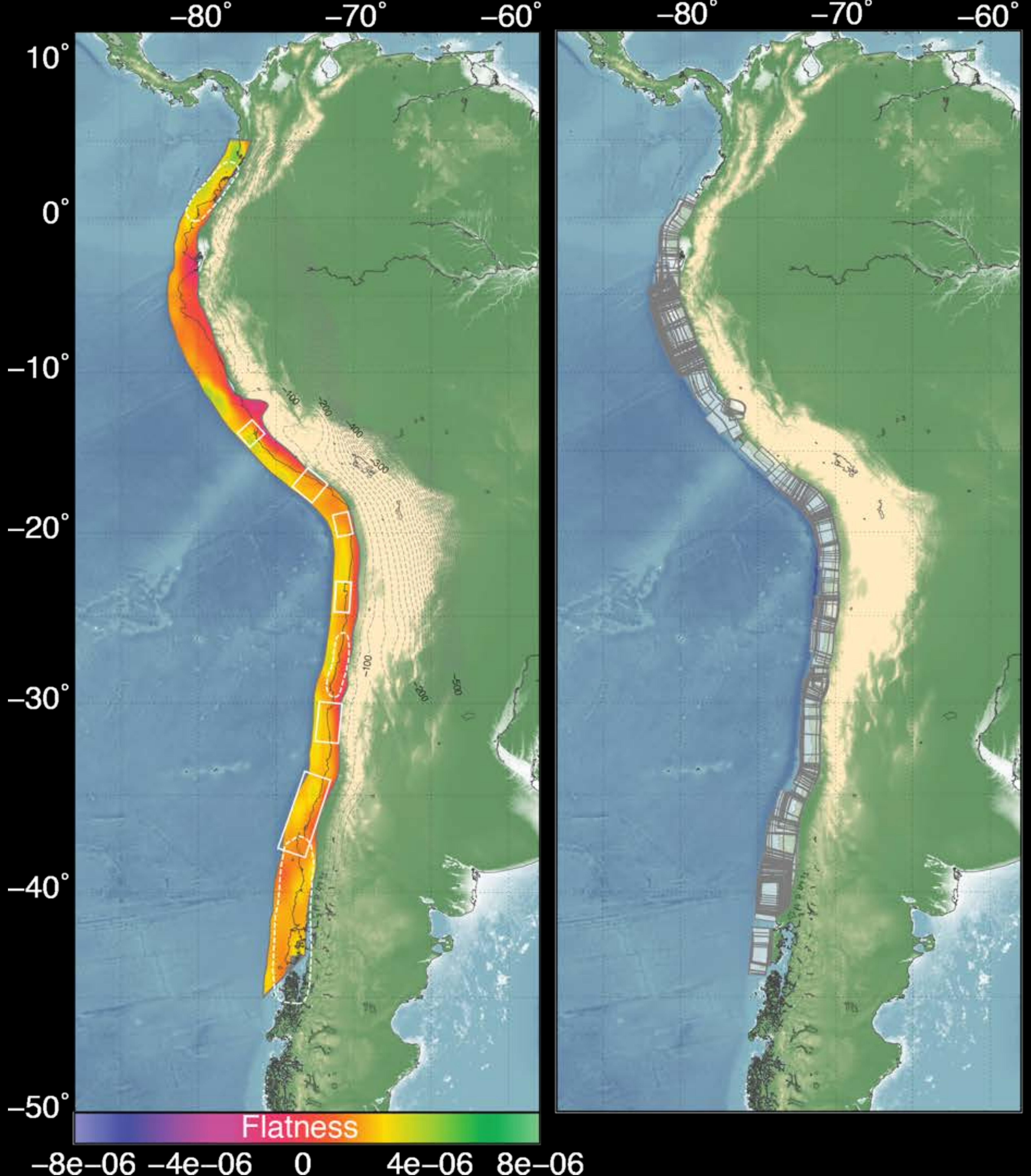
We search for polygons large enough to host a M8+ EQ, whose average flatness < target KS.

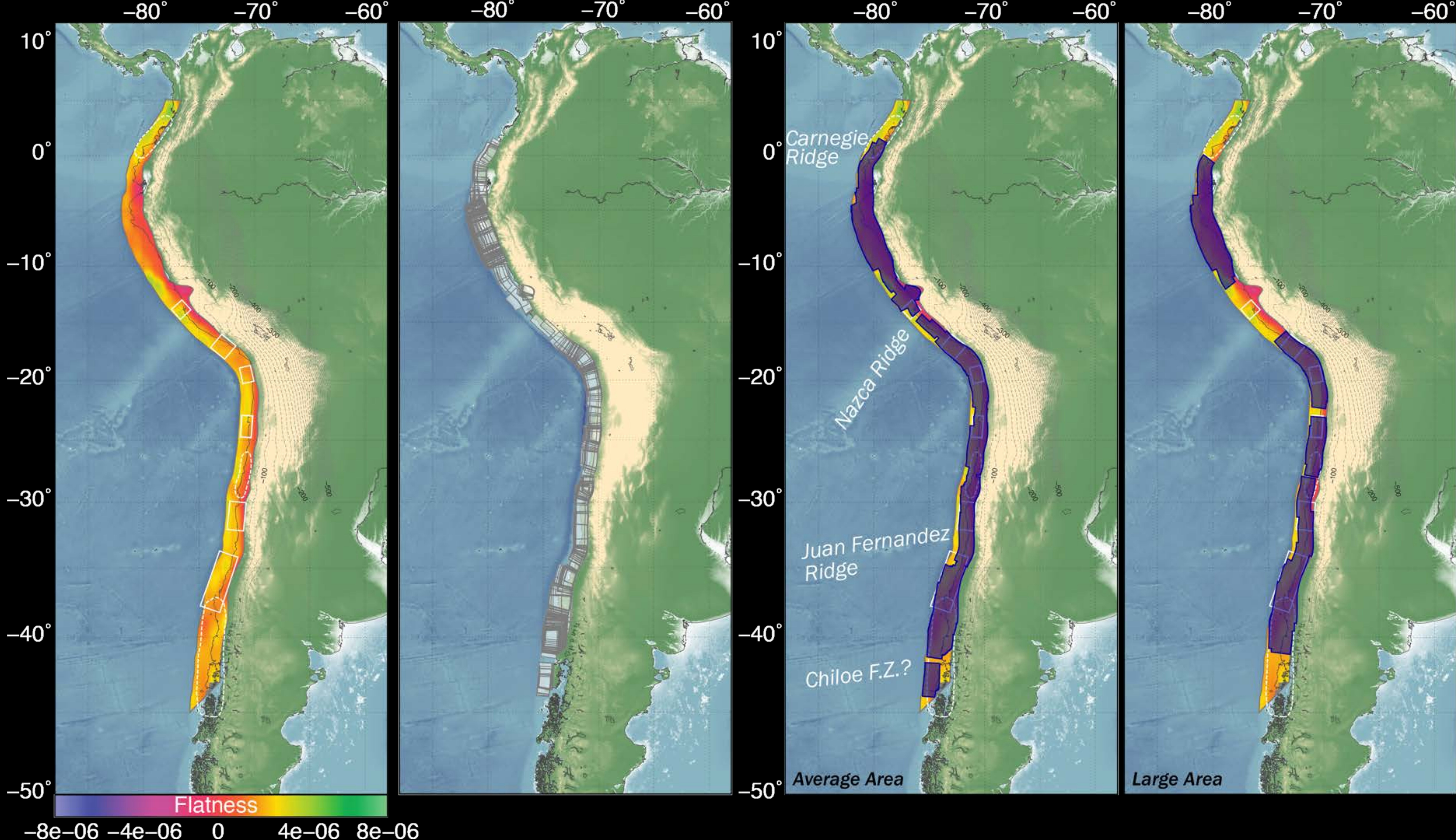
We can then combine overlapping polygons into larger areas to infer how large flatness controlled earthquakes can be.



Slab2 & PSHA

Segmentation?





-80°
-70°
-60°
10°
0°
-10°
-20°
-30°
-40°
-50°
Carnegie Ridge
Nazca Ridge
Juan Fernandez Ridge
Chiloe F.Z.?
Average Area
Large Area
Flatness
-8e-06
-4e-06
0
4e-06
8e-06

Slab2 & PSHA

Segmentation?

Using Allen & Hayes (2017) scaling relations, these areas can be converted to a potential magnitude => Mmax ~ 9.7 for South America.

We call this flatness-related max magnitude, M_{flat}.

Significant uncertainties in this approach, but it allows us to assess intrinsic geometrical differences between subduction zones.

Results imply several subduction zones have large, broad and flat seismogenic zones, capable of hosting massive earthquakes.

Slab	M_{flat}
Sumatra-Java	10+
Alaska-Aleutians	8.9-9.9
South America	9.3-9.7
Cascadia	9.2-9.6
Kuril-Kamchatka-Japan	9.2-9.5
Central America	7.8-8.6
Scotia	7.8-8.1
Izu-Bonin	7.8-8.1
Vanuatu	7.5-8.1
Solomon Islands	8.0
Tonga-Kermadec*1	<8
Philippines	<8
Ryukyu*2	<8

*1 - Slab1.0 did not include Hikurangi Trench region
*2 - Slab1.0 did not include Nankai Trough region

Slab2 & PSHA

Segmentation?

Results also imply unrealistically large M in some cases; perhaps indicating other controlling factors beyond geometry.

With Slab2, we wish to test:

- Effect of seismogenic zone limits on flatness calculations
- Effect of geometry model smoothing
- Patterns of along-strike vs along-dip flatness
- Sensitivity to model parameters (average flatness, standard deviation, etc.)

Slab	M_{flat}
Sumatra-Java	10+
Alaska-Aleutians	8.9-9.9
South America	9.3-9.7
Cascadia	9.2-9.6
Kuril-Kamchatka-Japan	9.2-9.5
Central America	7.8-8.6
Scotia	7.8-8.1
Izu-Bonin	7.8-8.1
Vanuatu	7.5-8.1
Solomon Islands	8.0
Tonga-Kermadec*1	<8
Philippines	<8
Ryukyu*2	<8

*1 - Slab1.0 did not include Hikurangi Trench region
*2 - Slab1.0 did not include Nankai Trough region

Slab2 & PSHA: Summary

Slab2 can define:

1) Megathrust geometry
    1) Gridded Surface (of entire slab) ✓
    2) 3D mesh (of seismogenic zone) ✓
    3) Planar approximation (of seismogenic zone) ✓
2) Seismogenic Zone Limits ✓ (for most slabs, data coverage dependent)
3) Filtered Earthquake catalogs (inter-, intra-, upper plate) ✓
5) Gutenberg-Richter parameters (e.g., b values of mag:freq relationship) ✓ (for most slabs)
6) Segmentation ?
8) Maximum magnitude, M-max ?

further work required to assess efficacy of flatness-based approach

Comments? Questions?

ghayes@usgs.gov