

A New Probabilistic Approach for Fault-Based Crustal Earthquake Evaluation Using Width- Limit Effect Source Scaling Models: Transitioning from Regional to Fault-Specific Analysis

Bob J.-Y. Huang

Norman A. Abrahamson

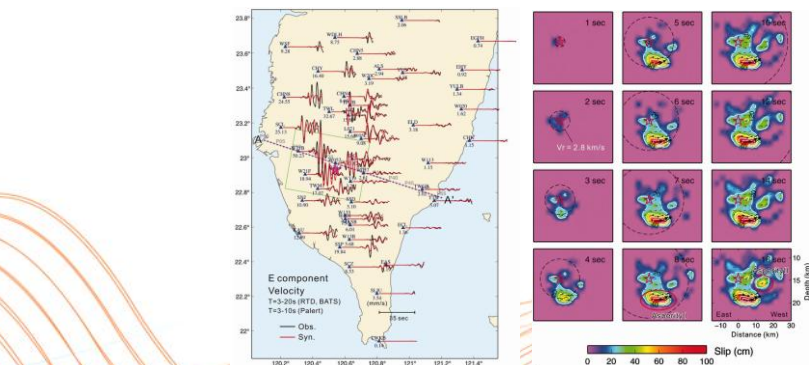
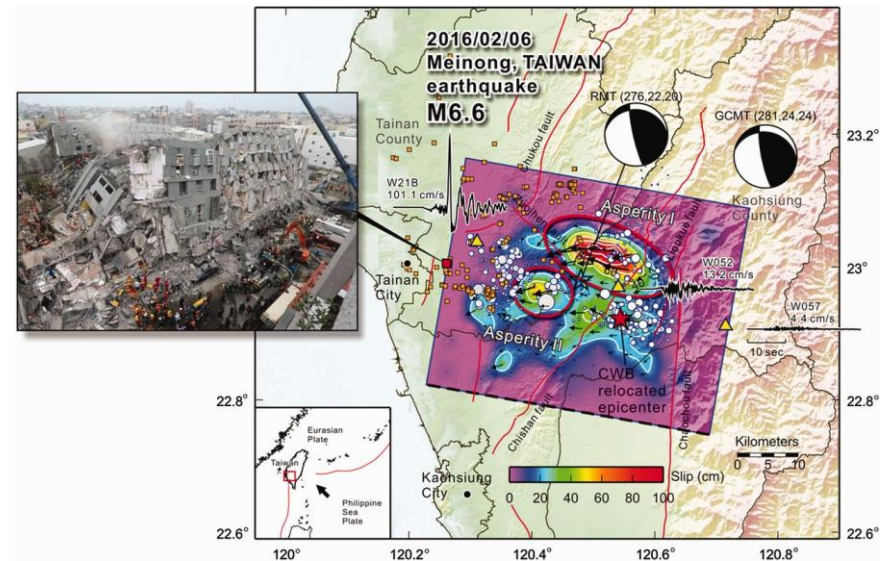
2026.05.08

Introductions

- What were the purposes of source-scaling models?

Source inversion

- ✓ $M_0 = \mu \cdot A \cdot \bar{D}$
- ✓ $M_w = 2/3 * \log M_0 - 10.7$
(Hanks and Kanamori, 1979)

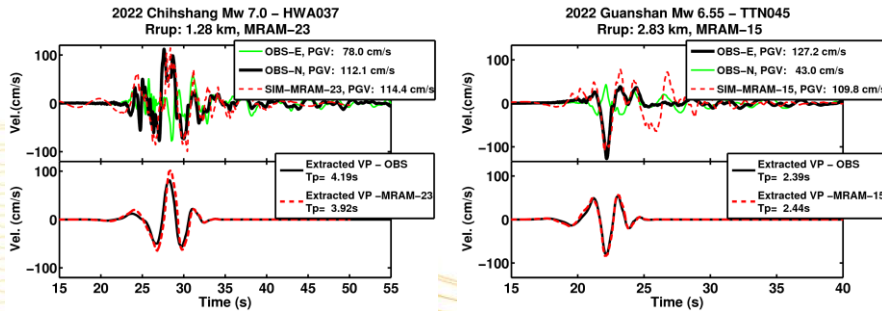
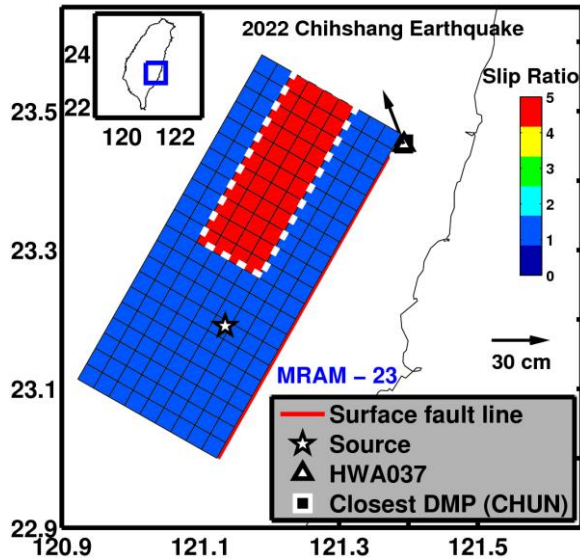


(Lee et al., SRL, 2016)

Introductions

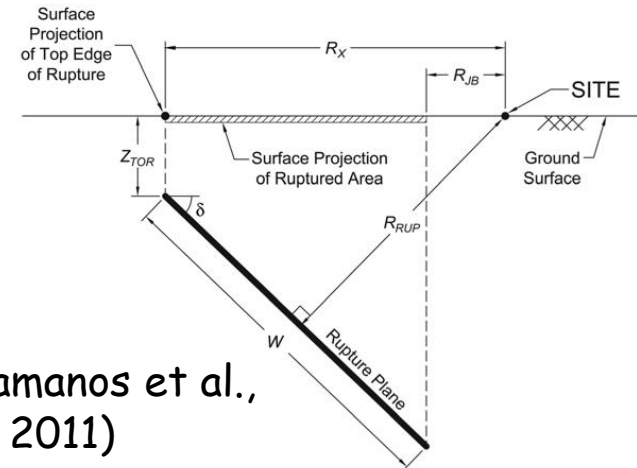
- What were the purposes of source-scaling models?

Ground motion simulation

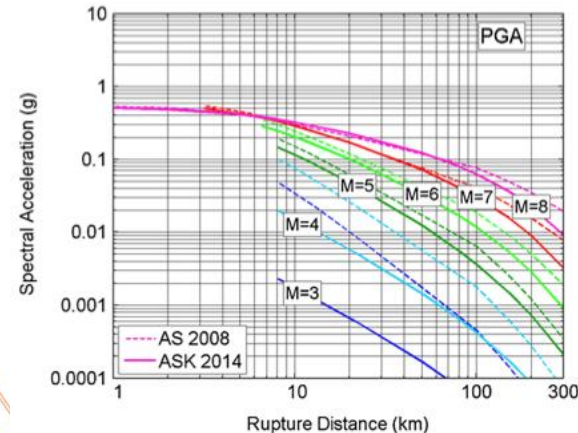


(Huang et al., EESD, 2024)

Ground motion predictions



(Kaklamanos et al., EQS, 2011)

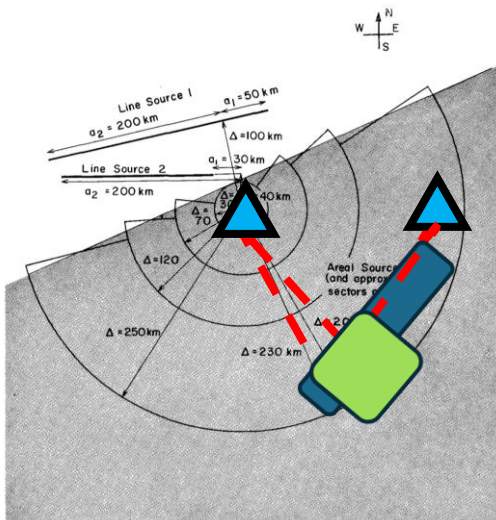


(Abrahamson et al., EQS, 2014)

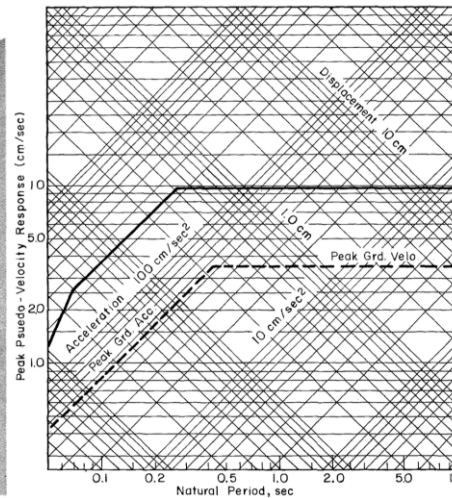
Introductions

- What were the purposes of source-scaling models?

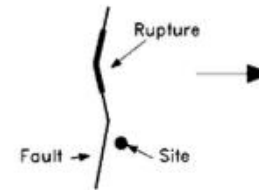
Probabilistic/ Deterministic seismic/ fault-displacement hazards



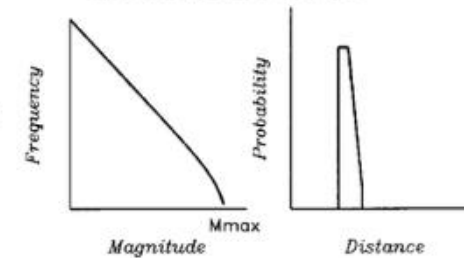
(Cornell, BSSA, 1968)



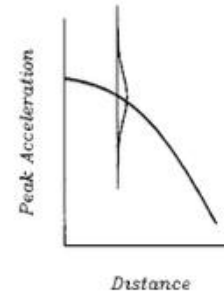
(1) Identify seismic sources



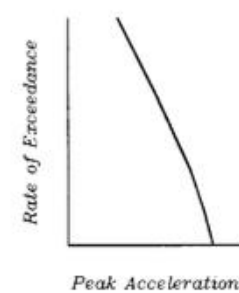
(2) Characterize earthquake frequency and distance distributions



(3) Characterize ground motion distribution



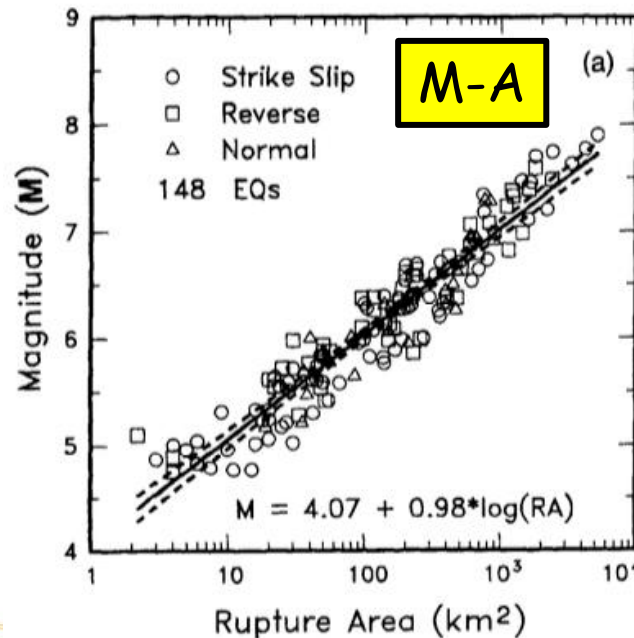
(4) Compute ground motion hazard curve



(Youngs et al., EQS, 2003)

Introductions

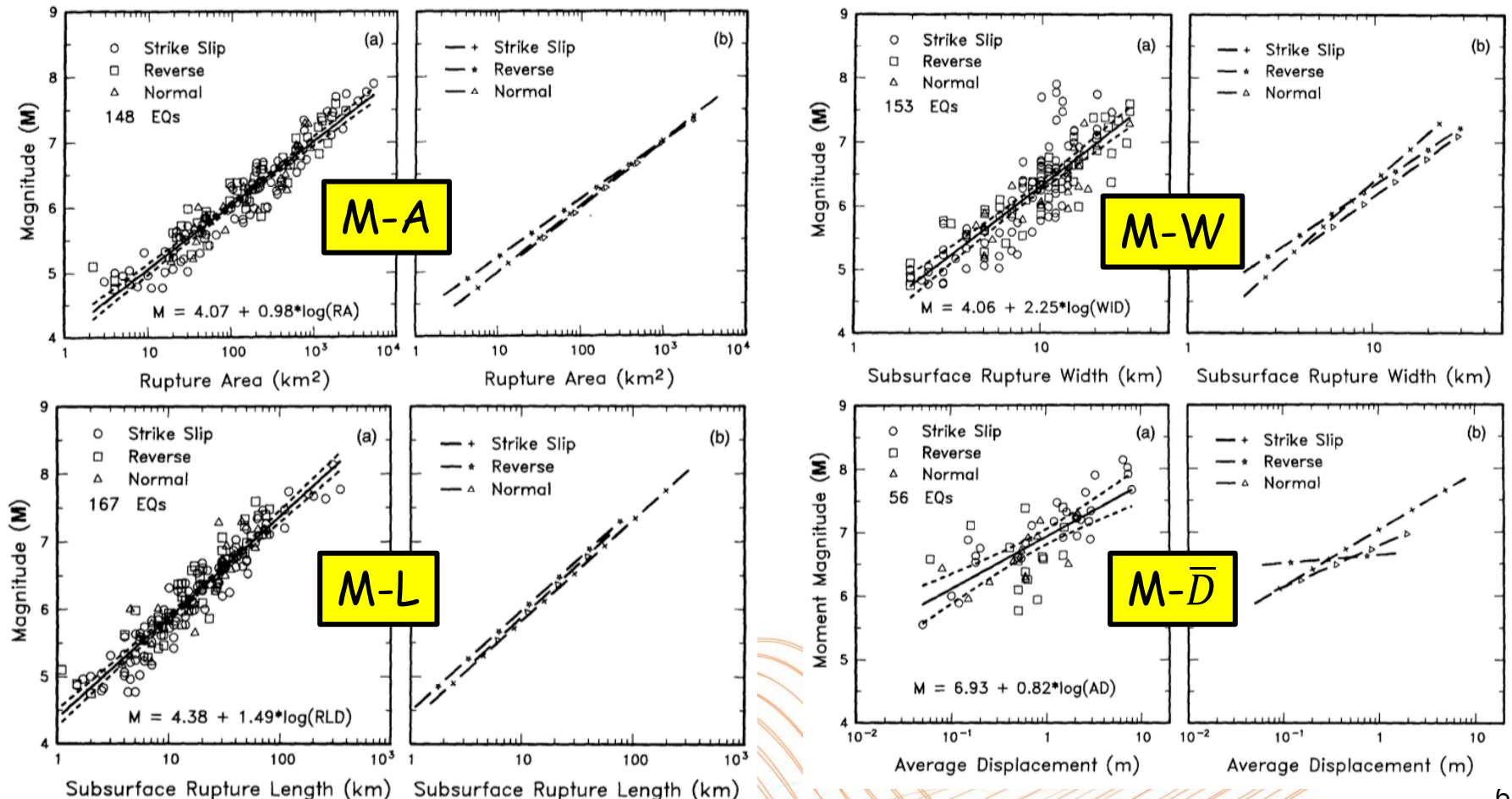
- Available information for determining the dimensions of the fault rupture:
 - Area of aftershocks
 - Field observations of the surface rupture
 - Finite-fault source inversions



(Wells and Coppersmith, BSSA, 1994)

Introductions

- Typical source scaling Laws (models)
 - Style of faulting (SoF)-dependent

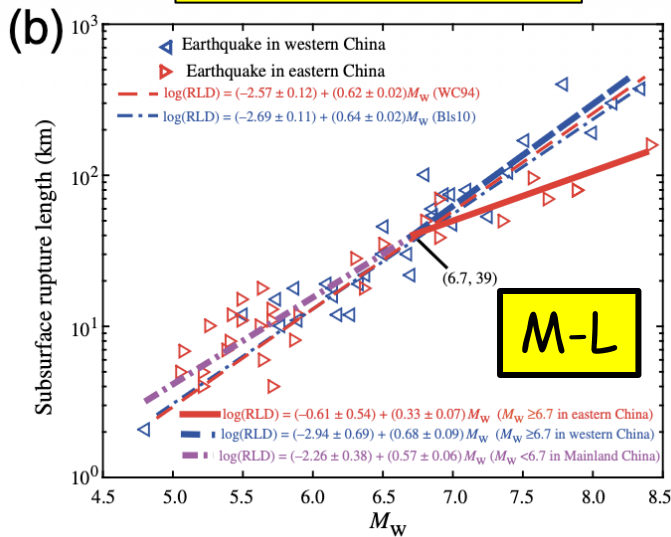


(Wells and Coppersmith, BSSA, 1994)

Introductions

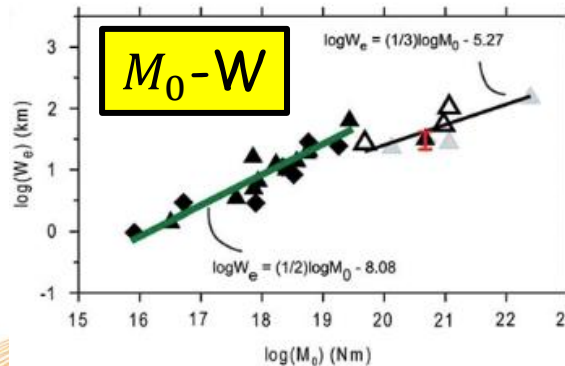
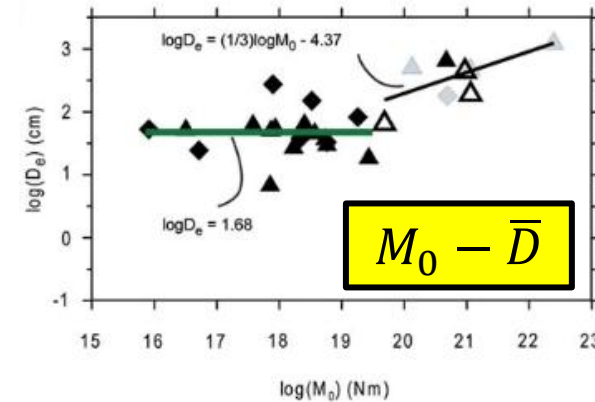
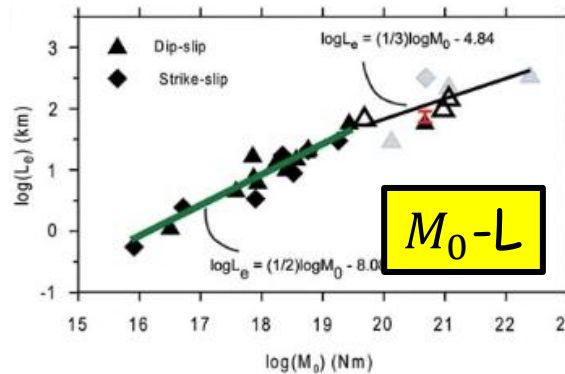
- Typical source scaling Laws (models)
 - Regional differences

W vs E China, SS



(Cheng et al., SRL, 2019)

Taiwan vs Global

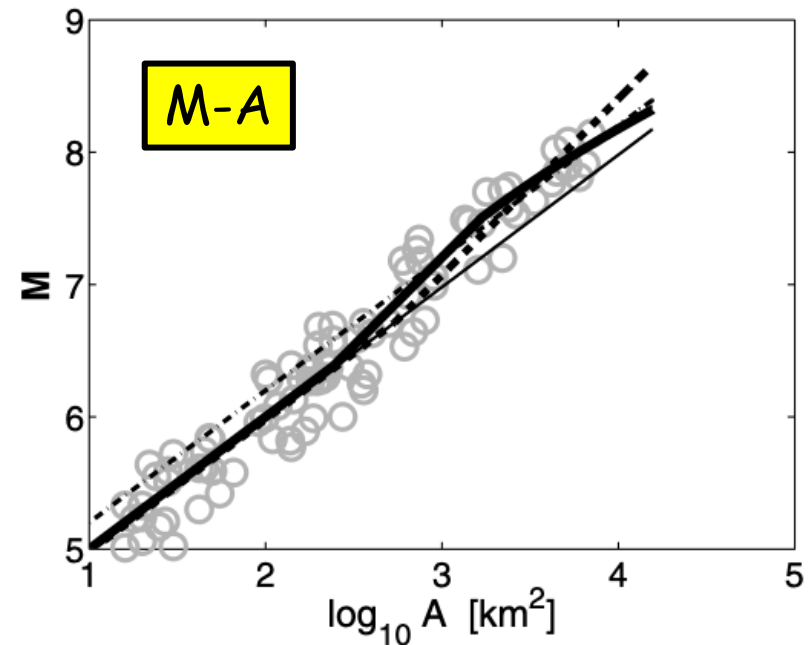
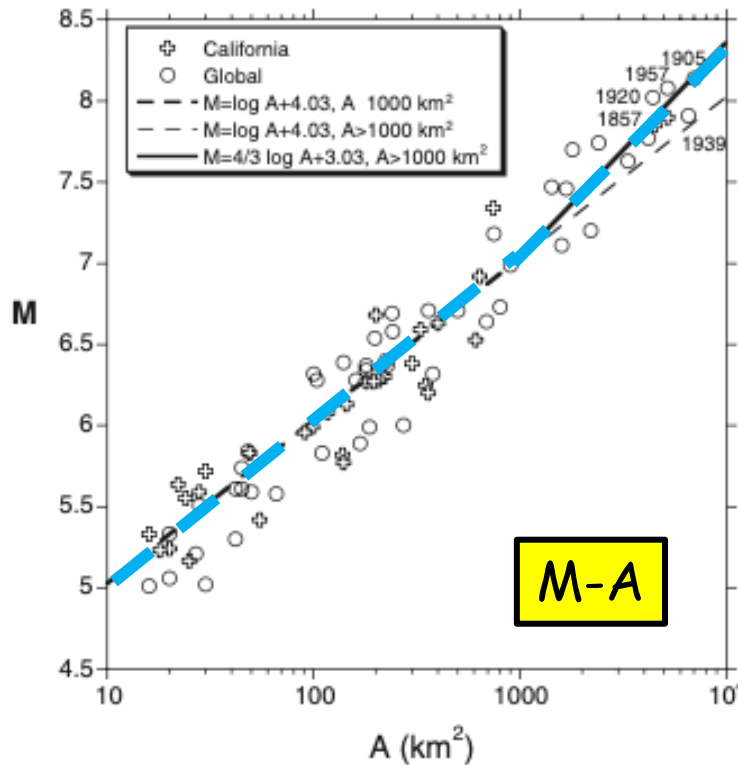


* Subduction included

(Yen and Ma, BSSA, 2011)

Introductions

- Typical source scaling Laws (models):
 - **Width-limit effect** for crustal earthquakes



$$M = \log_{10} A + \frac{2}{3} \log_{10} \frac{\max\left(1, \sqrt{\frac{A}{H^2}}\right)}{\left[1 + \max\left(1, \frac{A}{H^2\beta}\right)\right]/2} + \text{const.}$$

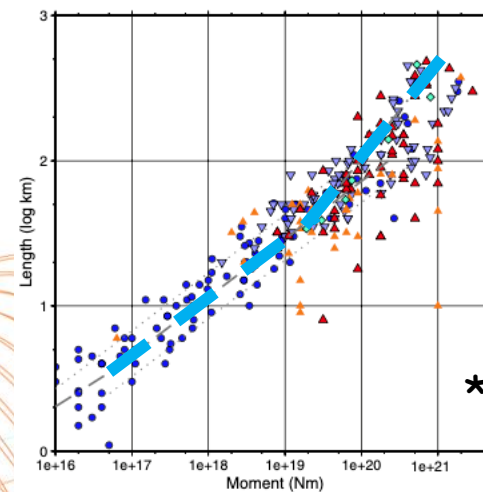
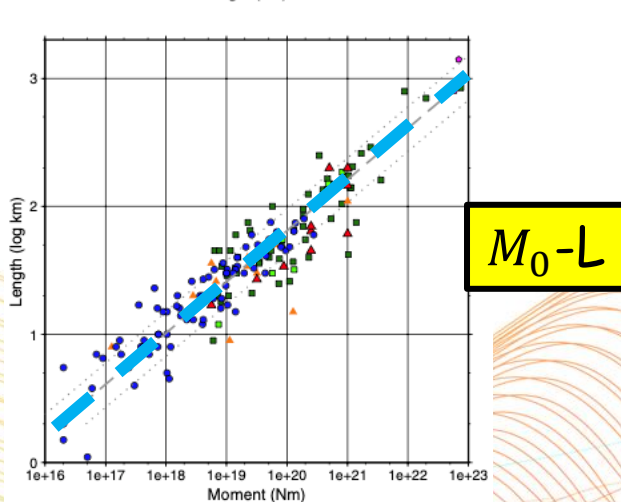
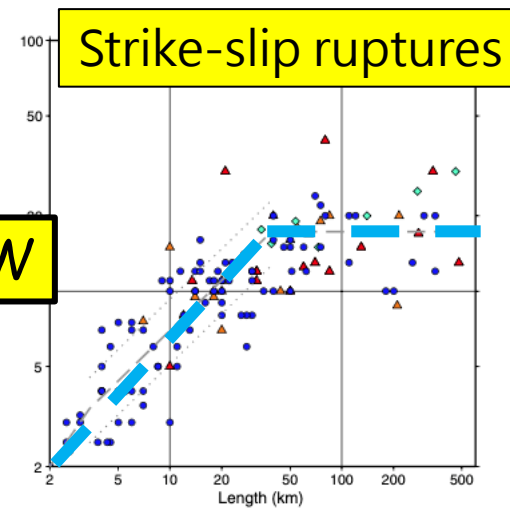
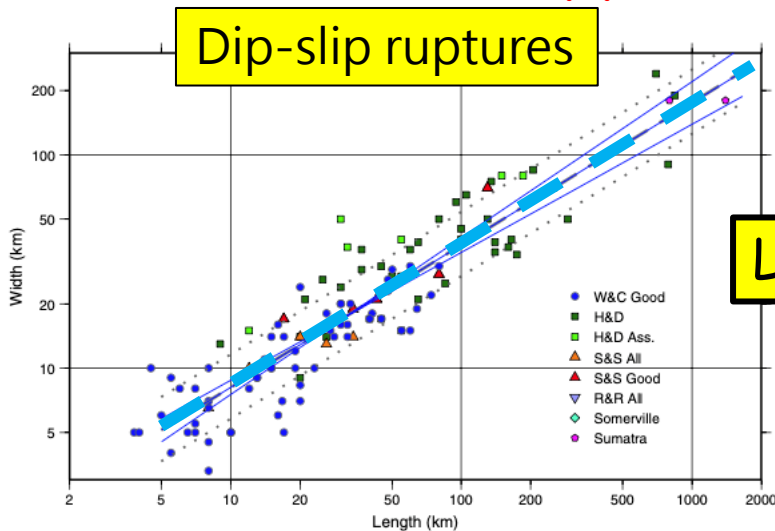
➤ H: siesmogenic thickness

(Hanks and Bakun, BSSA, 2002)

(Shaw, BSSA, 2009)

Introductions

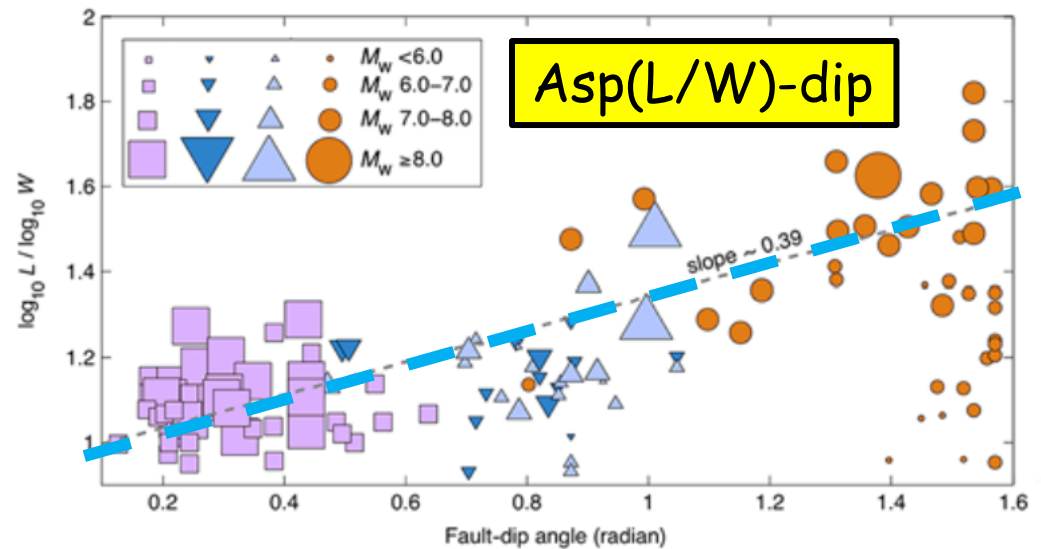
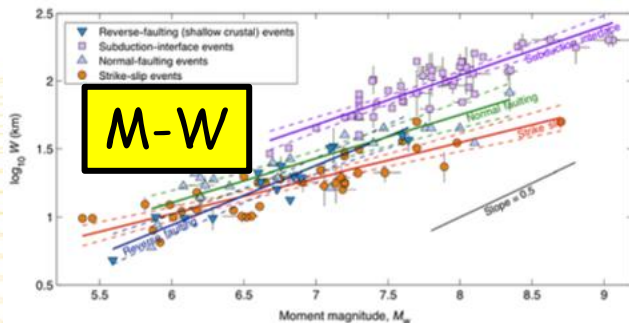
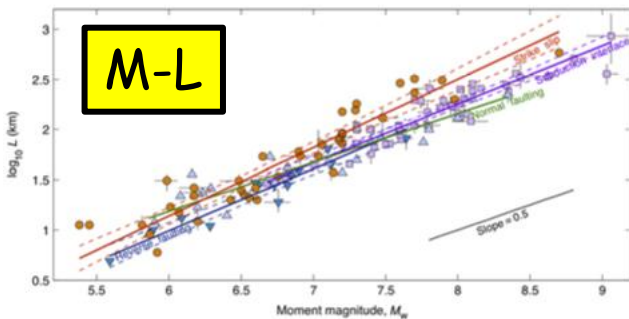
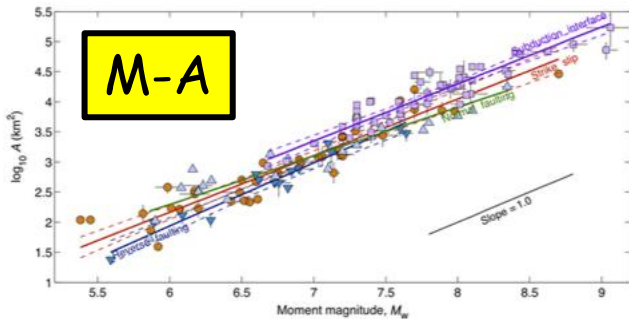
- Typical source scaling Laws (models):
 - **Width-limit effect** for crustal earthquakes



* Subduction included
10
(Leonard, BSSA, 2010)

Introductions

- Typical source scaling Laws (models):
 - Fault-dip angle difference

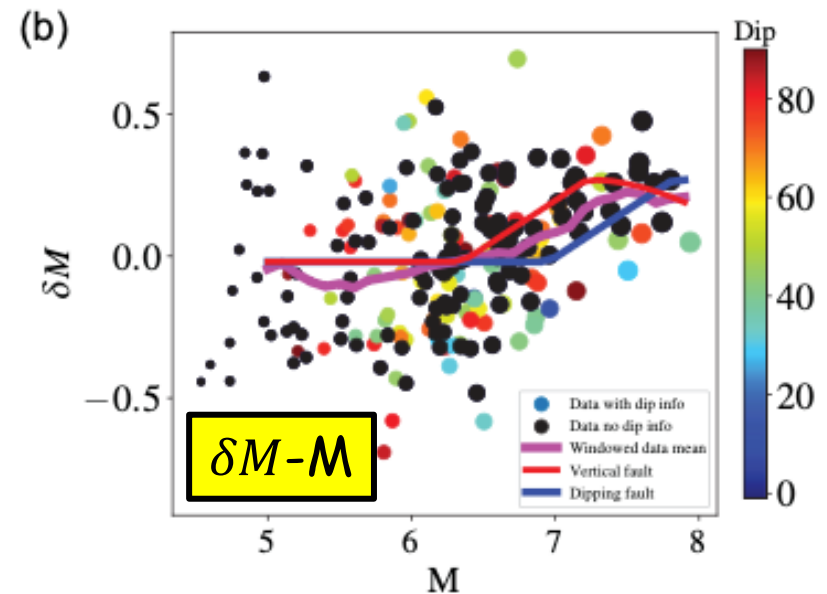
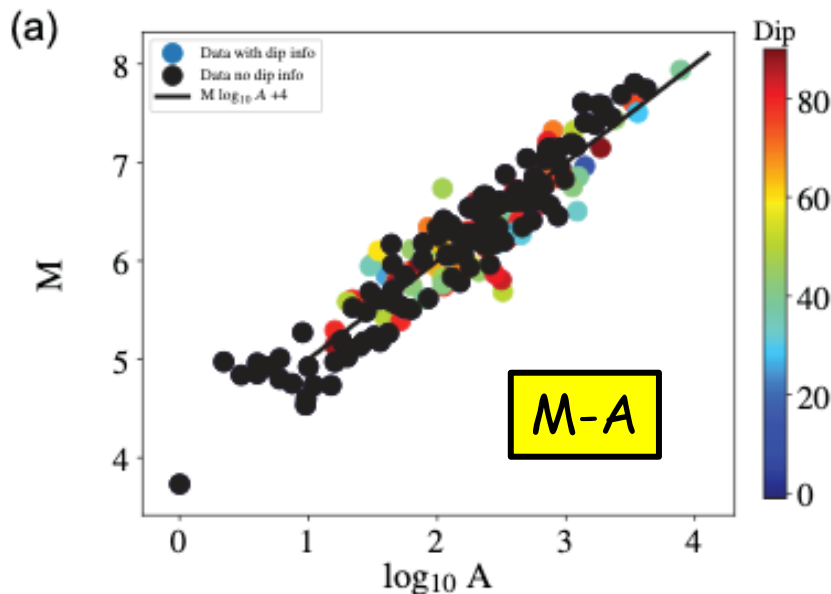


* Subduction included

(Thingbaijam et al., BSSA, 2017)

Introductions

- Typical source scaling Laws (models):
 - Fault-dip angle difference

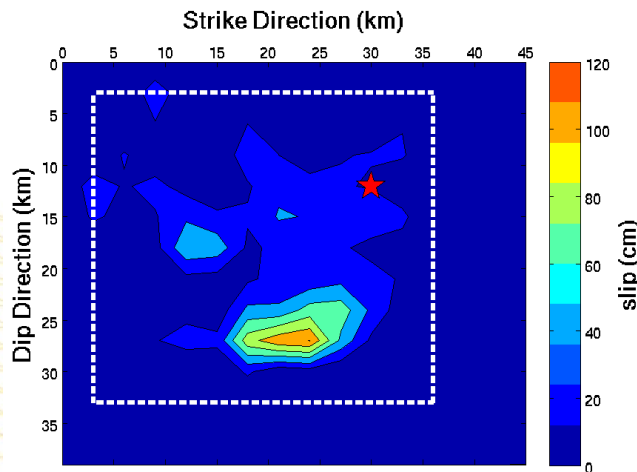


Introductions

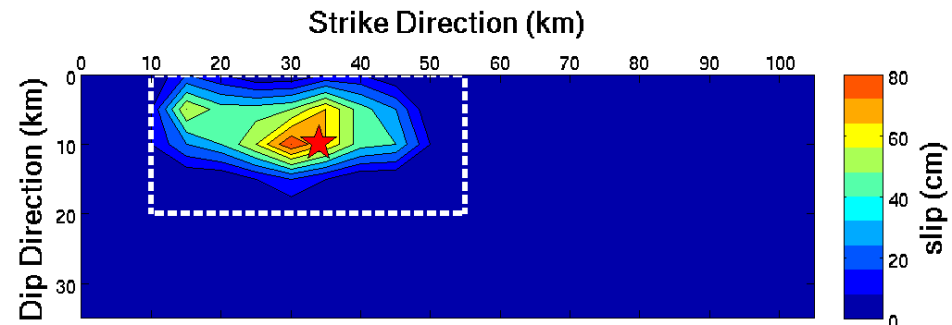
- Issues of applying typical models
 - ✓ Regional scaling -> Fault-based scaling

	Mw	Length (km)	Width (km)	Asp	SoF [Rake]
2016 Meinong	6.52	33	30	1.1	SS [27]
2022 Guanshan	6.57	45	20	2.25	SS [29]

2016 Feb. 6 Meinong, Mw: 6.52
Ztor: 7.93 km, HypoD: 14.6 km
 L_e : 33 km, W_e : 30 km

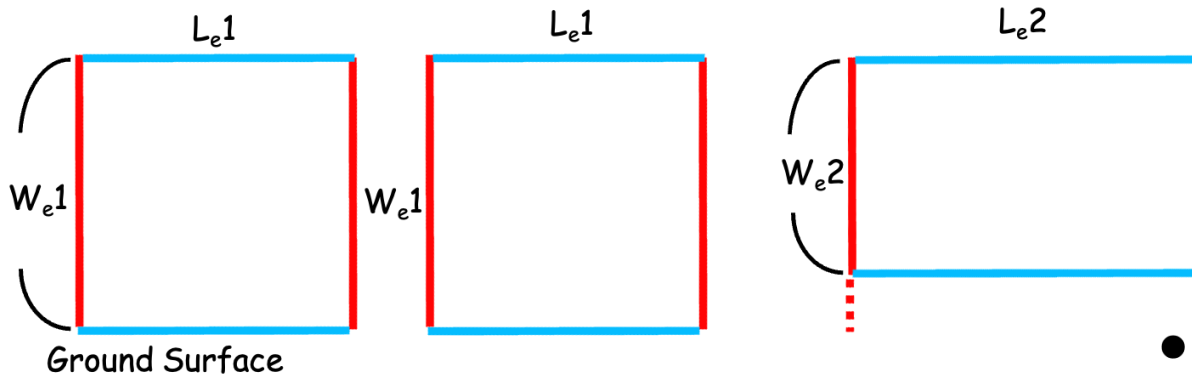


2022 Sep. 17 TTN (foreshock) CRF, Mw: 6.6
Ztor: 0 km, HypoD: 8.61 km
 L_e : 45 km, W_e : 20 km

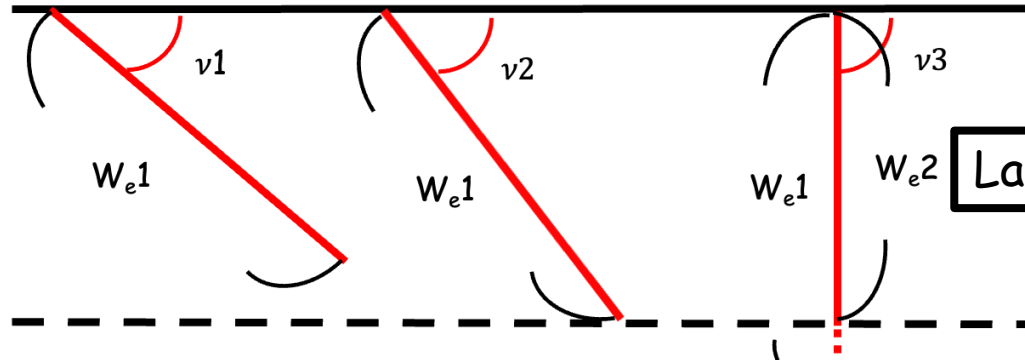


Concepts of Modeling the Width-Limit Effect in the SSM

Fault Plane View



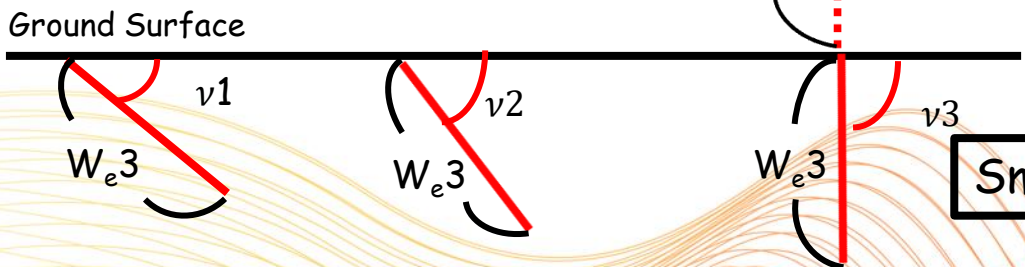
- $v1 < v2 < v3$
- $W_{e1} = L_{e1}$
- $W_{e2} < W_{e1}$
- $L_{e2} > L_{e1}$



Larger M



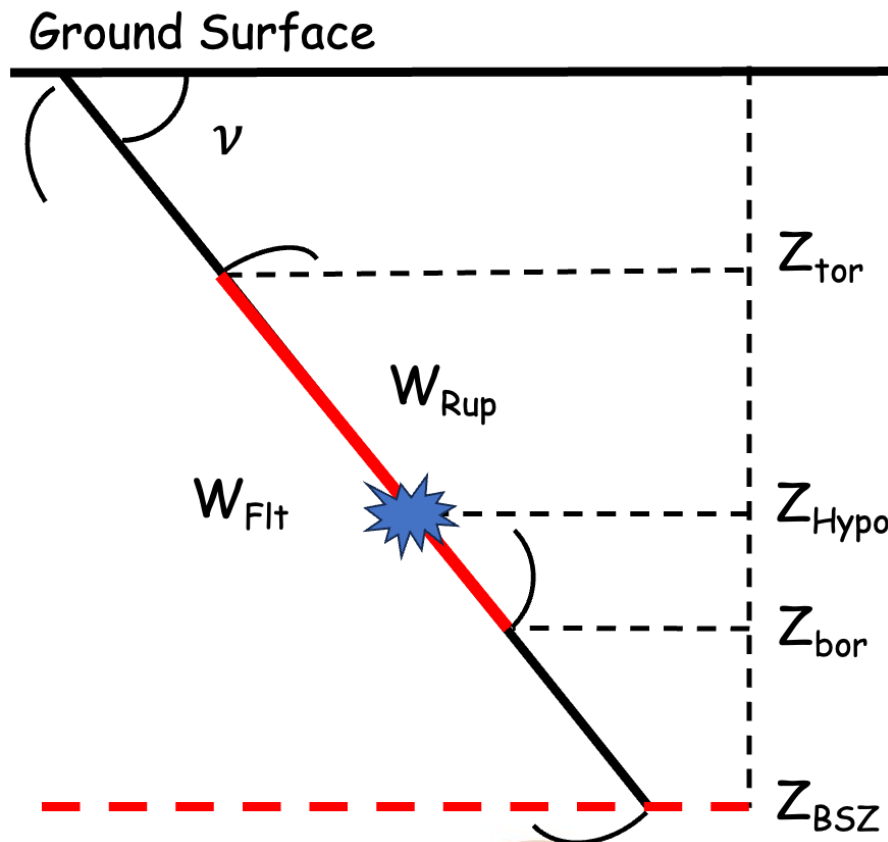
Aspect ratio (Asp) scaling:
 $L_{e2}/W_{e2} \gg 1$ (L_{e1}/W_{e1})



Smaller M

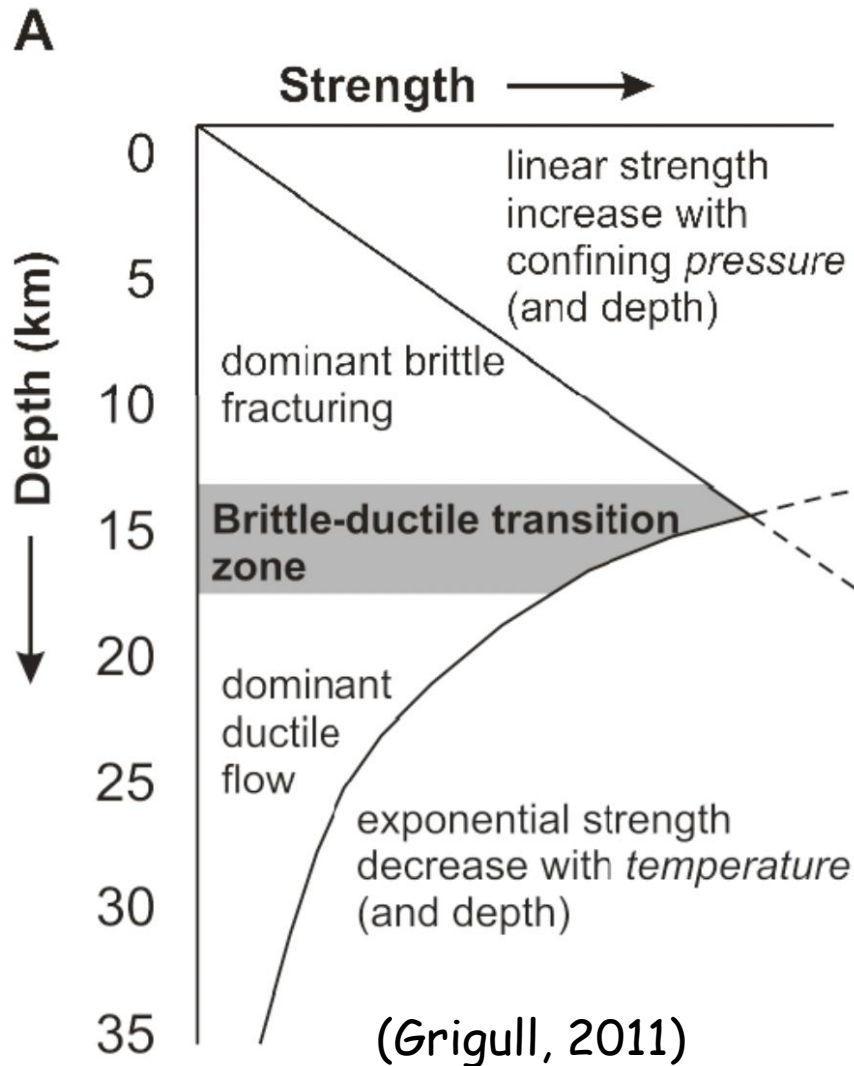
Bottom of seismogenic Zone

Concepts of Modeling the Width-Limit Effect in the SSM



- A depth term NZ_{bor} is applied for a depth-dependent feature.

Concepts of Modeling the Width-Limit Effect in the SSM



Depth-Dependent feature



Asp scaling:
Shallow > Deep



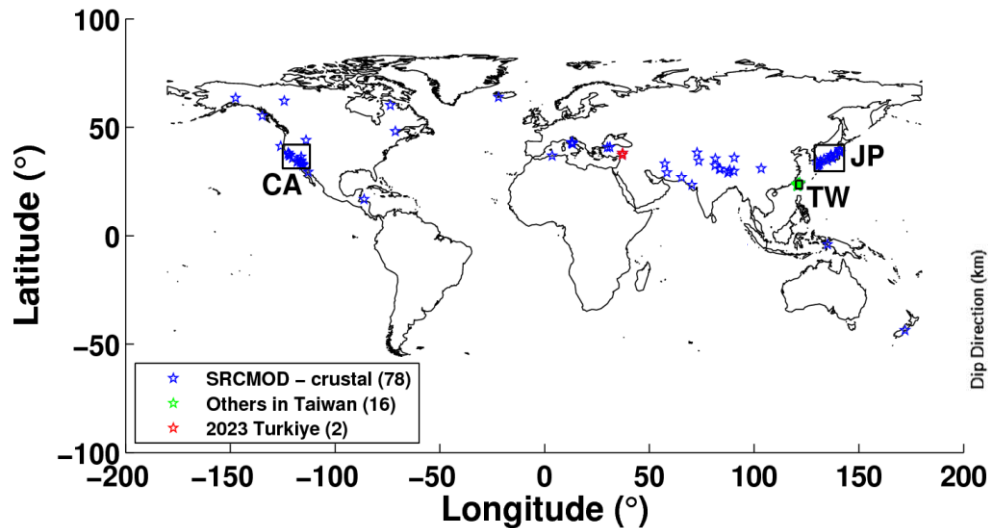
Free-Surface Effect



Asp scaling:
Buried > Surface

Database

- Crustal earthquakes: 96
 - CA: 17; TW: 20; JP: 17;
 - 2023 Turkiye: 2

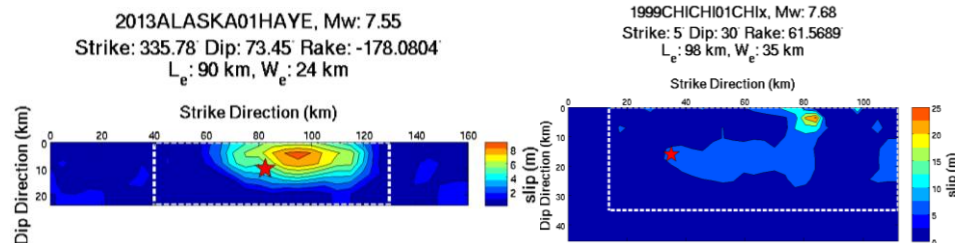


SRCMOD, Mai and Thingbaijam (2014)

- Trimming Process Applied

- Effective fault dimensions rely on an **Autocorrelation width function**

(Mai and Beroza, 2000; Thingbaijam and Mai, 2016; Yen and Ma, 2011)



- Fault parameters of multiple segments finite-fault models were combined using area as the weighting scheme.

USGS (2023) Lee et al. (2013; 2014; 2015; 2016; 2019; 2020; 2023); Yen and Ma (2011)

Model Construction (Regional scaling)

➤ Aspect ratio scaling relation

$$\checkmark \log_{10}(Asp_e) = S4_{ASP}(M, \nu, NZ_{bor}, region)$$

S1
S2
S3
S4

- Width-limit effect: $M, \nu, region$
(RT(M) for large-M)
- Depth-Dependent and Free-surface effects: NZ_{bor}

➤ Area scaling relation

$$\checkmark \log_{10}(A_e) = S3_A(M, \nu, NZ_{bor})$$

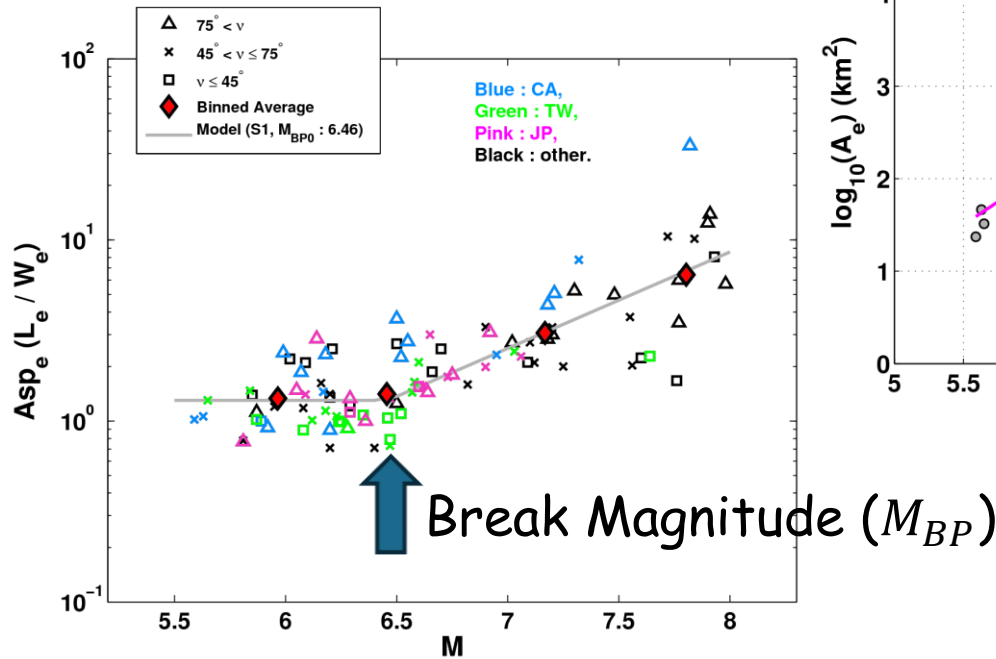
S1
S2
S3

- Width-limit effect: M, ν
- Depth-Dependent and Free-surface effects: NZ_{bor}

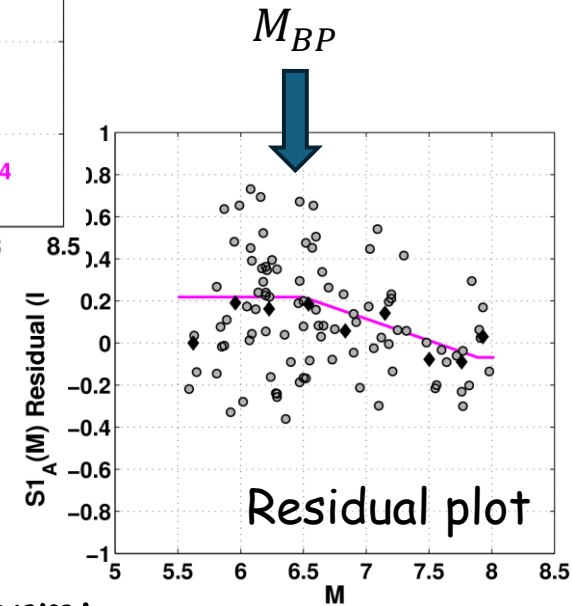
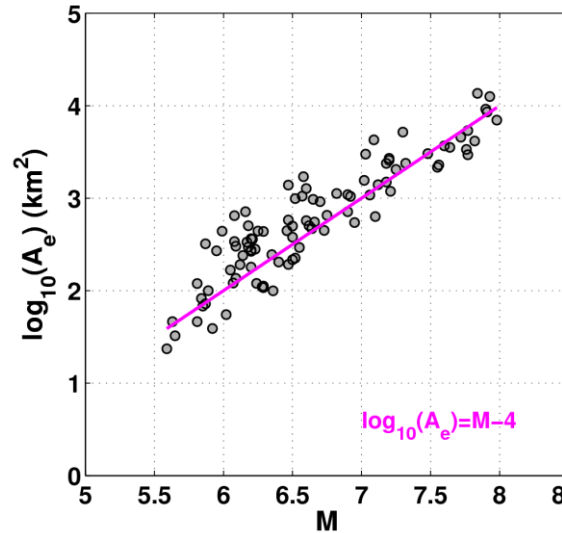
Model Construction (Regional scaling)

➤ Width-limit effect in $S1(M)$ model

Aspect ratio



Area



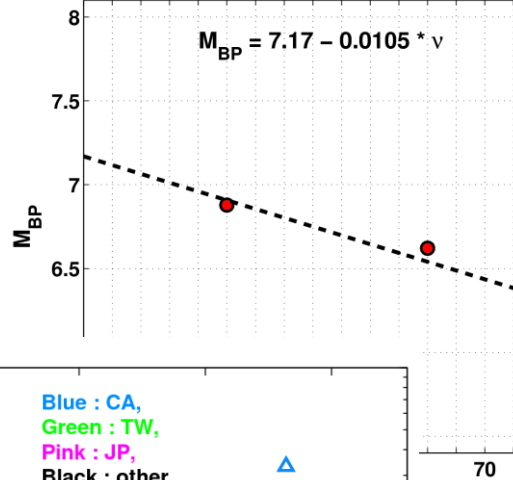
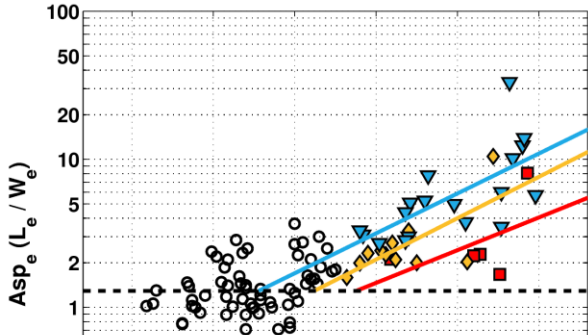
- Bilinear form:
 - constant (smaller M)
 - M dependent (large M)

- Trilinear form:
 - M dependent (intermediate M)
 - constant (small and large M)

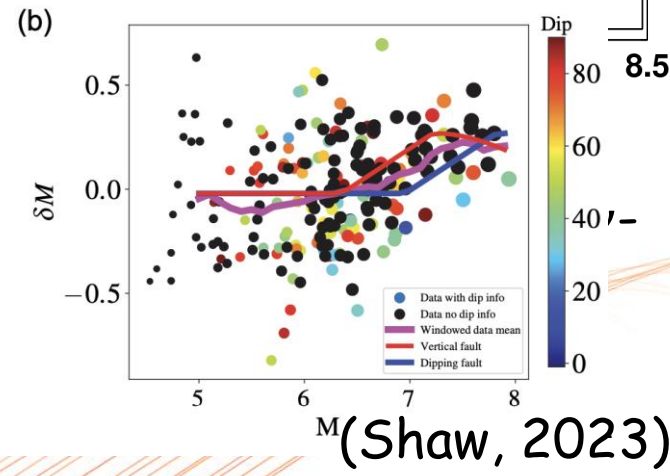
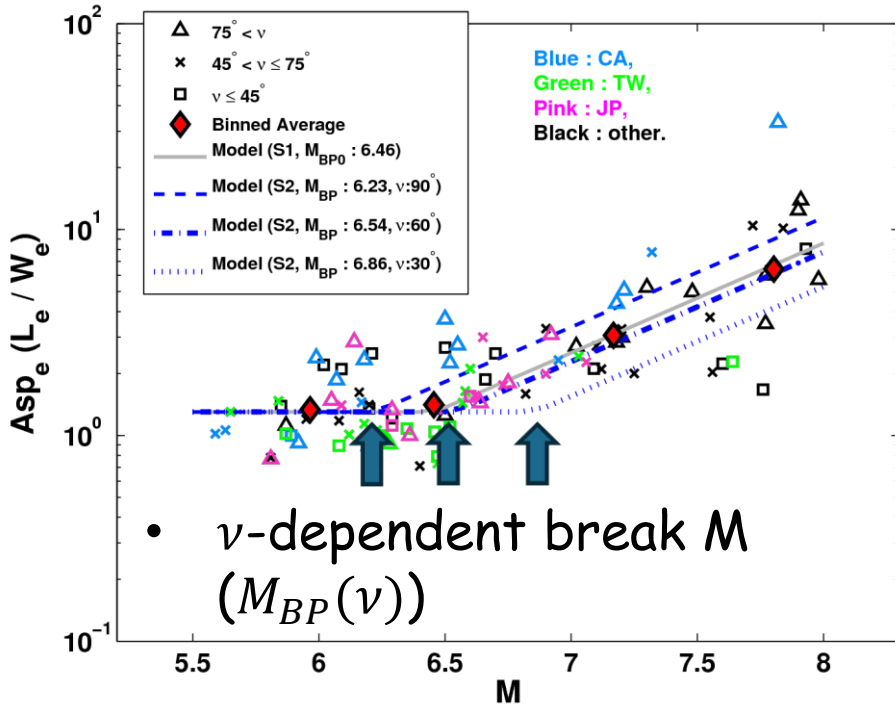
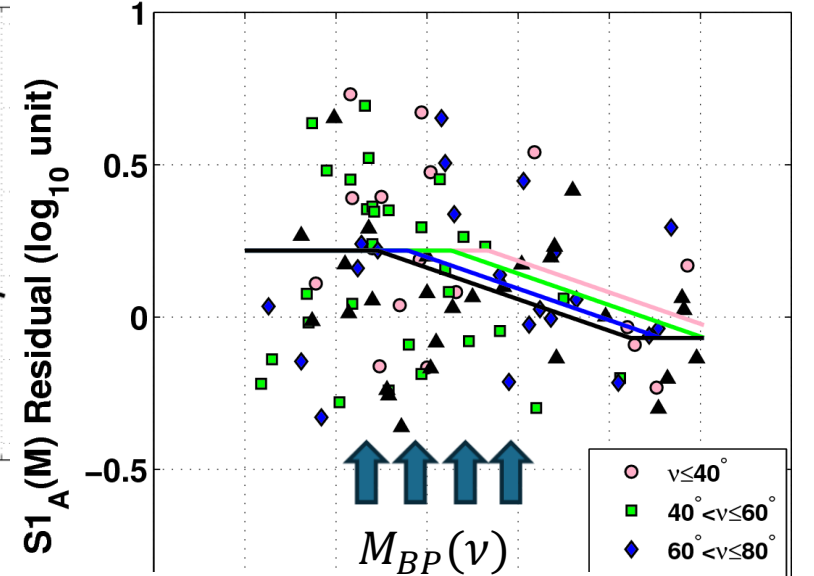
Model Construction (Regional scaling)

➤ Width-limit effect in $S2(M, \nu)$ model

Aspect ratio



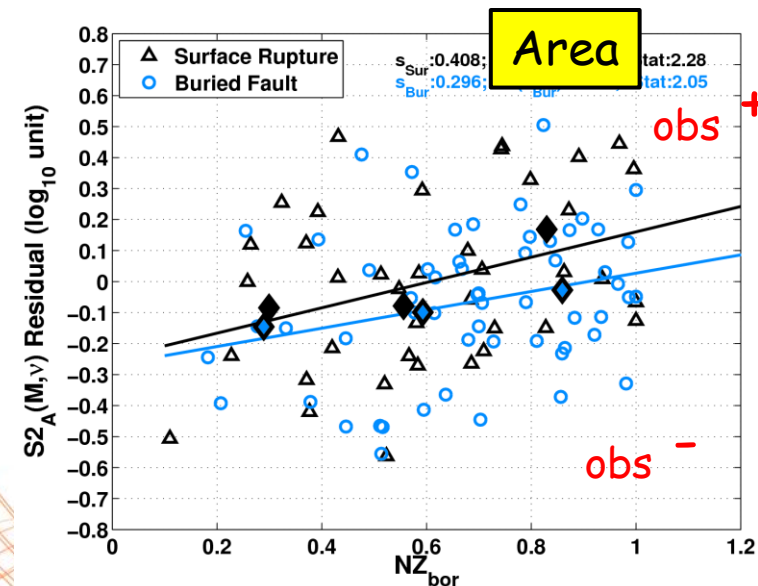
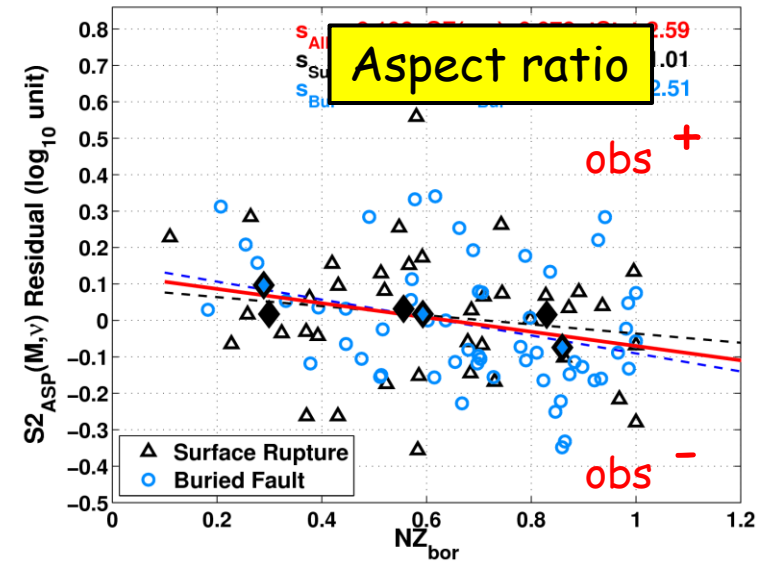
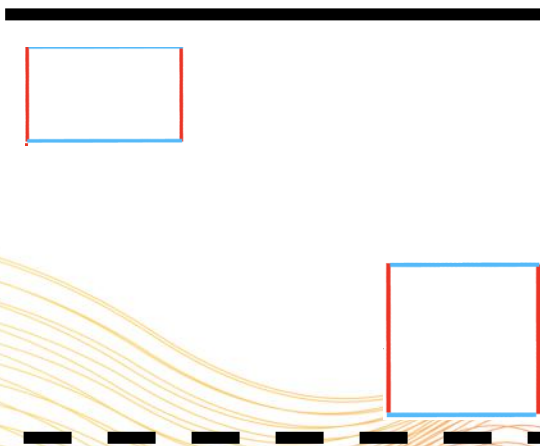
Area



Model Construction (Regional scaling)

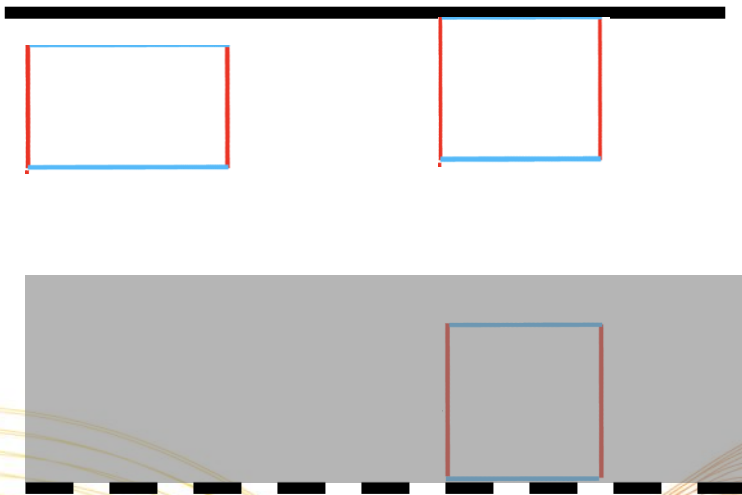
$$\text{Residual} = \log_{10}(\text{Obs}) - \log_{10}(\text{Model})$$

- Depth-dependent feature in $S3(NZ_{\text{bor}})$ model
- ✓ A depth-dependent stress condition restricts the downdip fault rupture because the deeper structure has a higher brittle strength.
 - Higher confining pressure and stress (brittle strength) in the deeper part.
 - **Negative slope in Asp and positive slope in A.**

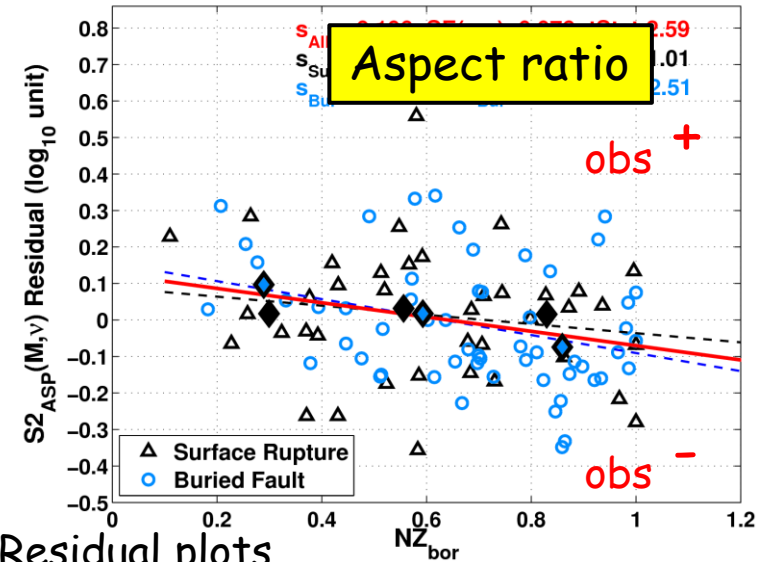


Model Construction (Regional scaling)

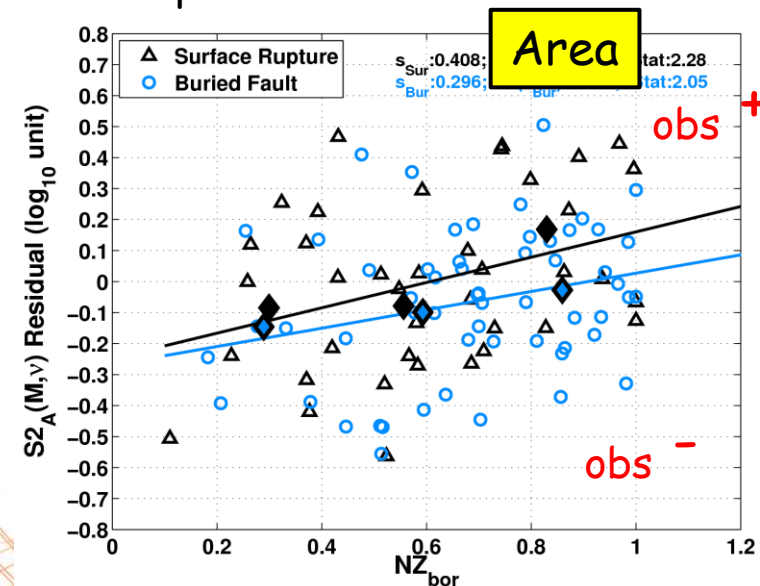
- Free-surface effect in $S3(NZ_{bor})$ model
- ✓ Higher fracture energy was expended if there was a surface rupture. (Difference between surface and buried fault)



$$\text{Residual} = \log_{10}(\text{Obs}) - \log_{10}(\text{Model})$$



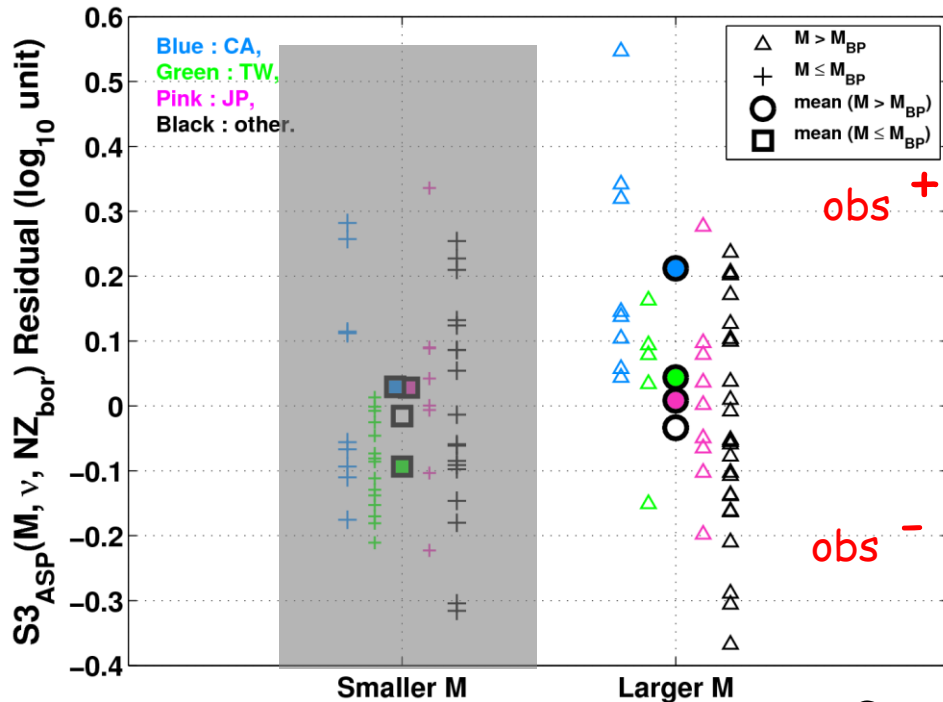
*Residual plots



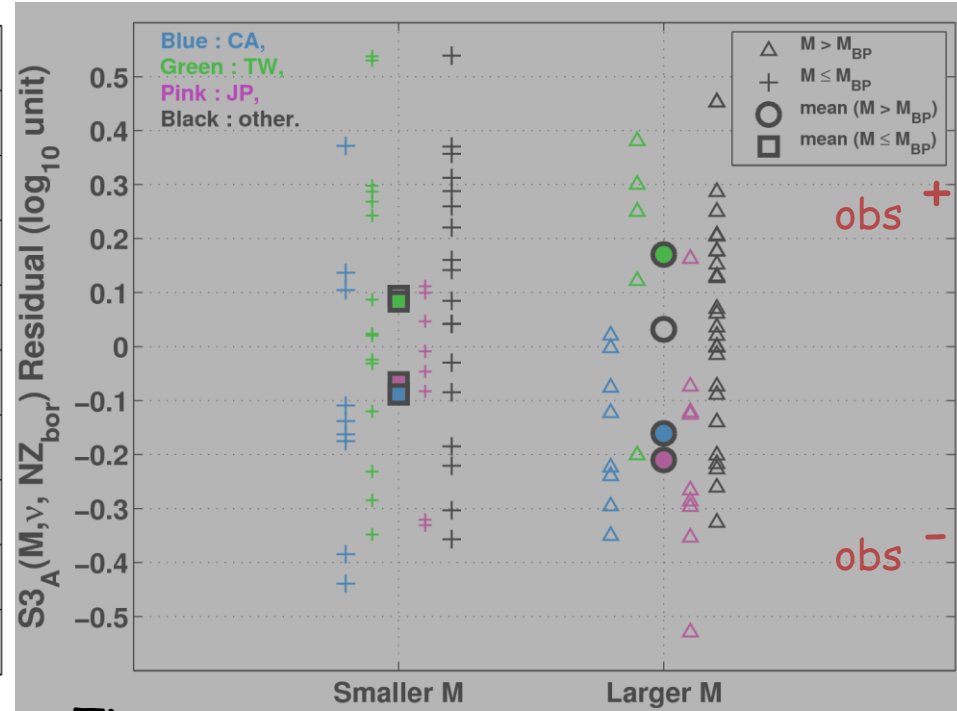
Model Construction (Regional scaling)

➤ Width-limit effect in $S4(RT(M))$ model

Aspect ratio



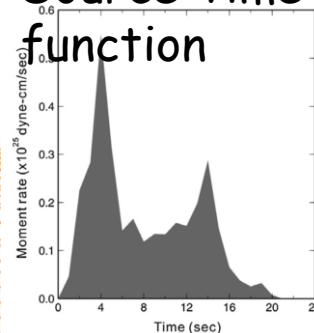
Area



*Residual plots

- Unclear physical basis for smaller M.

Source Time function



Rupture Velocity (β)

$$\text{➤ } M_0 = \mu \cdot A \cdot D$$

$$\text{➤ } \Delta\sigma = \frac{7}{16} \left(\frac{f_c}{k\beta} \right)^3 M_0$$

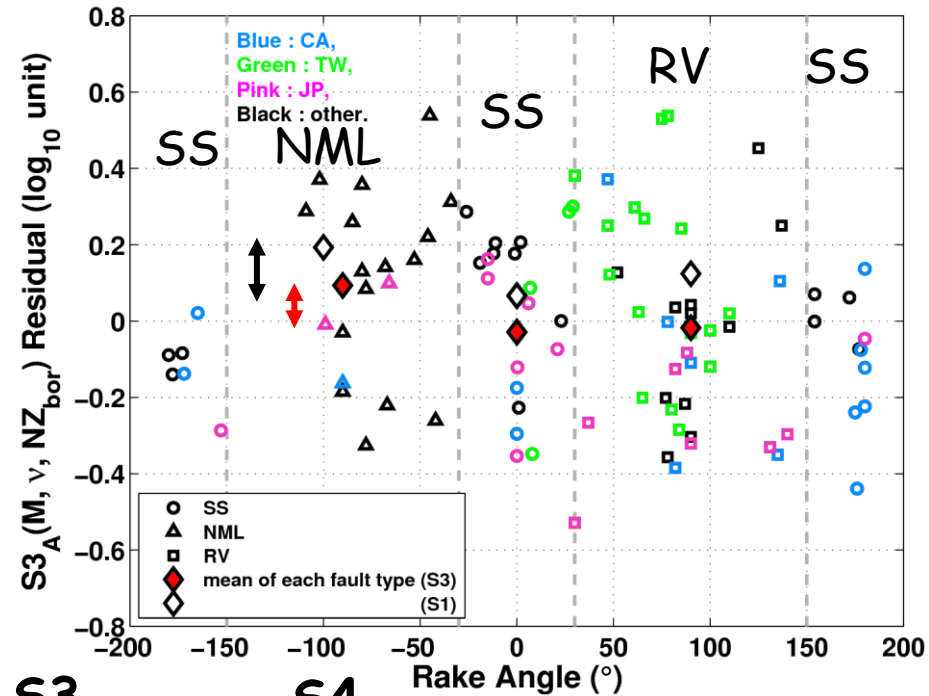
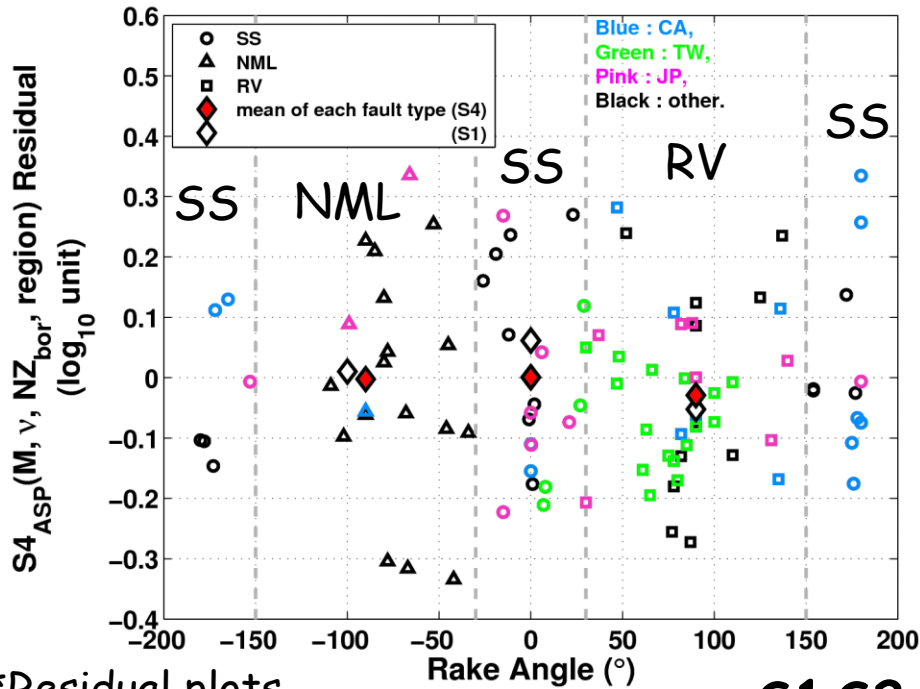
(Brune, 1970) 24

Model Construction (Regional scaling)

➤ Style-of-faulting scaling in **Final residual**

Aspect ratio

Area



*Residual plots

S1 S2

S3

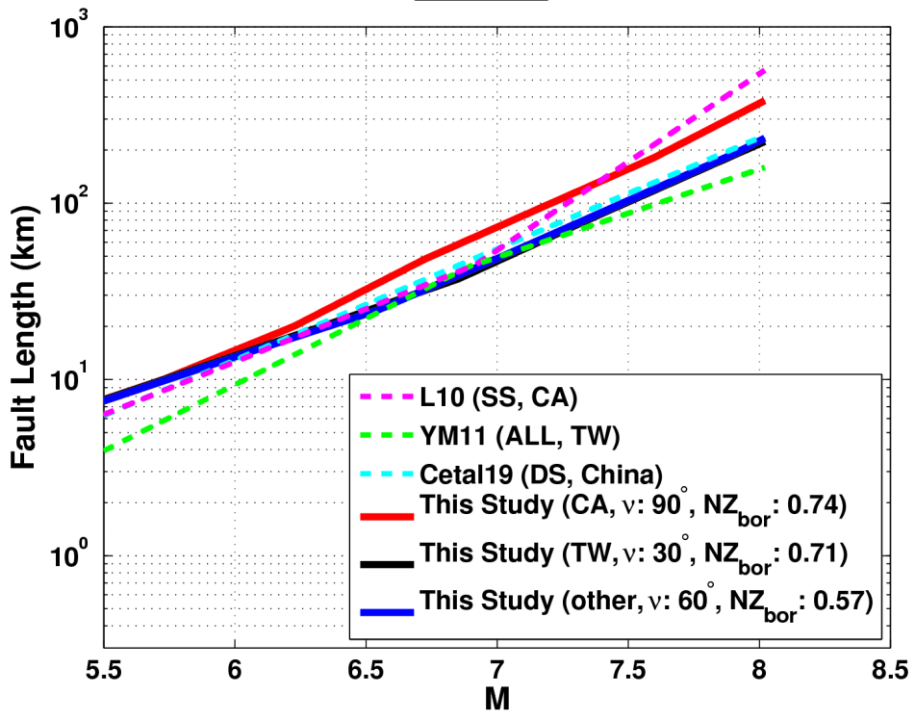
S4

$$\checkmark \log_{10}(Asp_e) = S4_{ASP}(M, v, NZ_{bor}, region)$$

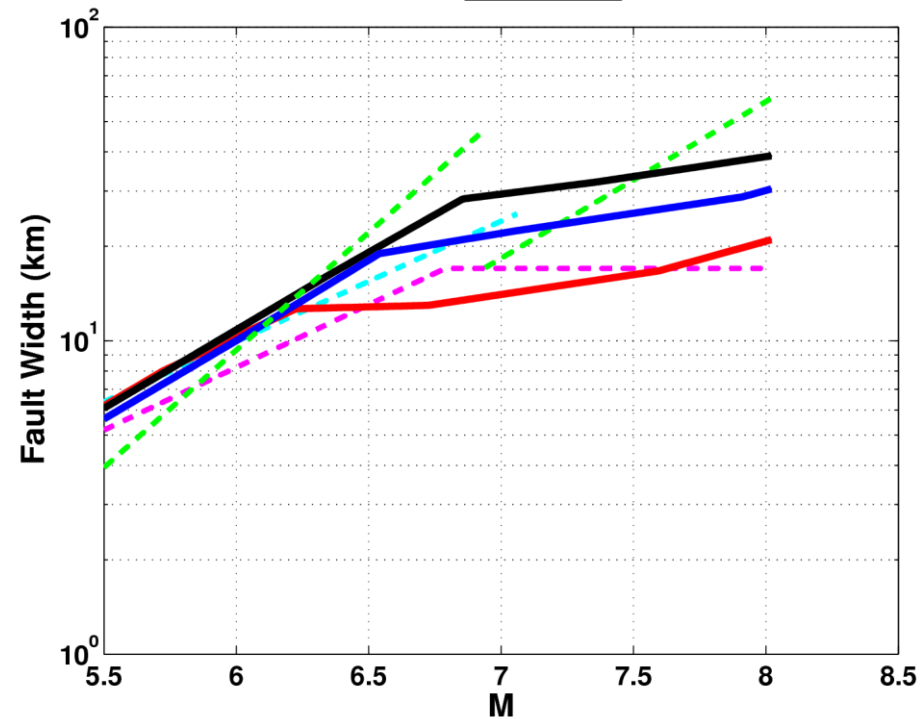
$$\checkmark \log_{10}(A_e) = S3_A(M, v, NZ_{bor})$$

Model Comparisons

M-L

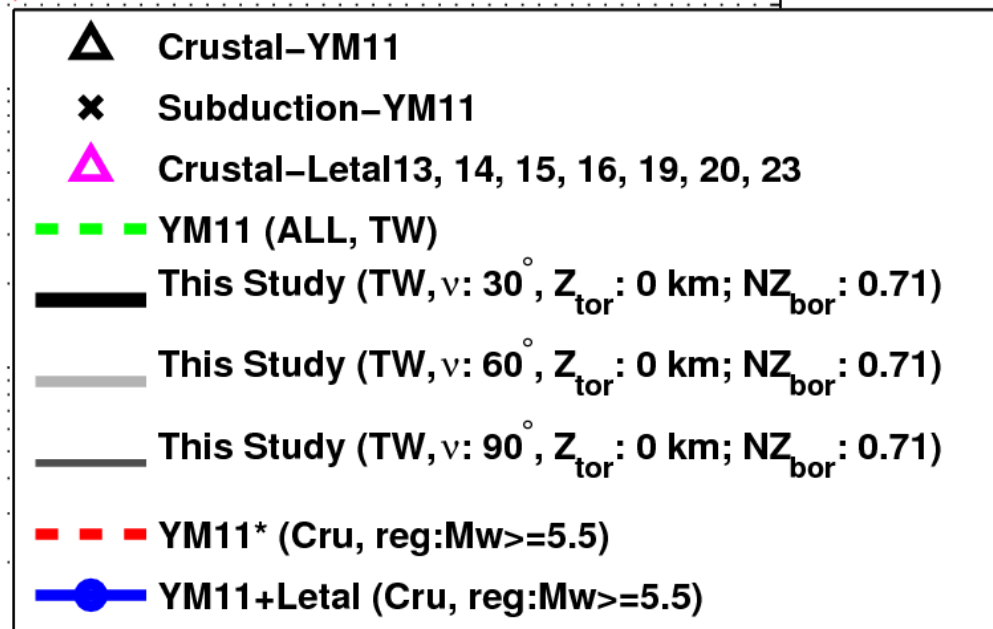
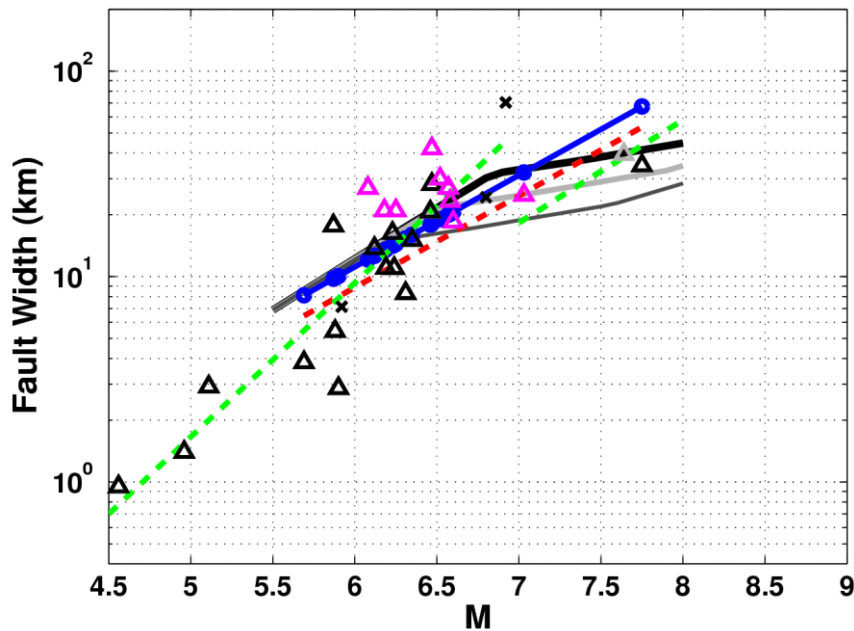


M-W



Model Comparisons

M-W



Short Summary

- The finalized regional source scaling relations for crustal earthquakes include the **width-limit**, **depth-dependent**, and **free-surface effects**.
- The proposed new scaling relations explained the previous finding that the style of faulting dependence could be captured by considering geometry-related parameters.

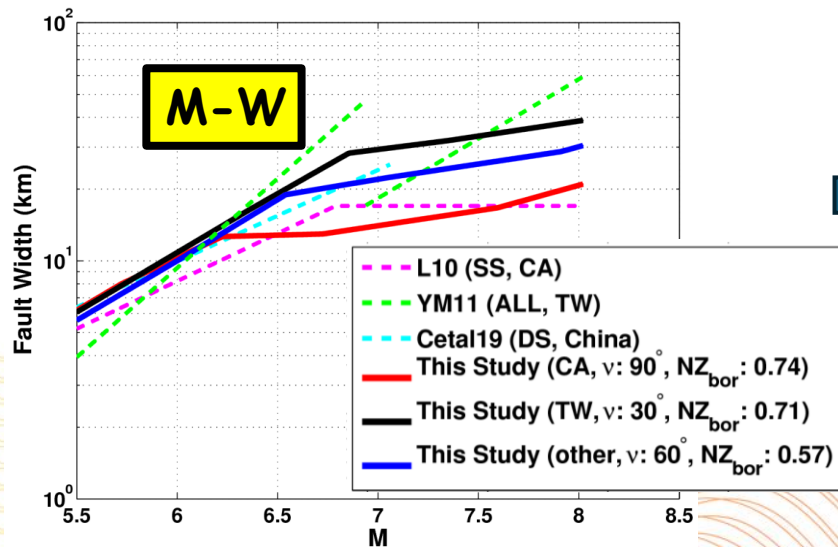
Extension for Fault-Based Analysis

✓ $\log_{10}(A_{sp_e}) = S4_{ASP}(M, v, NZ_{bor}, region)$

- Width-limit effect: M, W_{Flt}^{FZS} related M_{BP}
(RT(M) for large-M)
- Depth-Dependent and Free-surface effects: NZ_{bor}

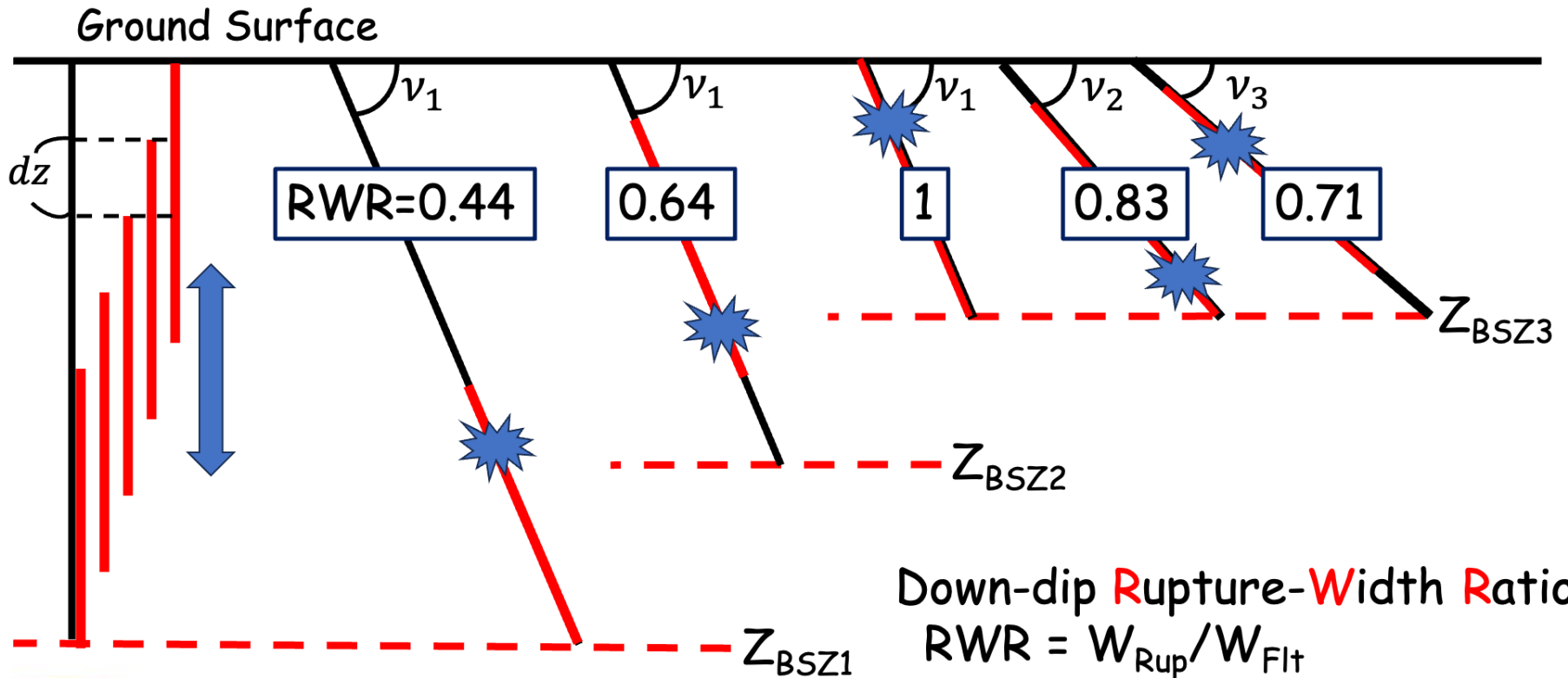
Regional scaling

Fault-based scaling



- Translate $M_{BP}(v)$ related to fault-zone-specific W_{Flt}
- Turn-off free-surface effect
- Applied regional average scaling for NZ_{bor}
- Turn-off RT(M)

Extension for Fault-Based Analysis



Extension for Fault-Based Analysis

➤ Aspect ratio scaling law

✓ $\log_{10}(Asp_e) = S4_{ASP}(M, \nu, NZ_{bor}, region)$ Turn off

➤ $S4_{ASP}(M, \nu, NZ_{bor}, region) = S3_{ASP}(M, \nu, NZ_{bor}) + RT(M)$ Use the regional mean NZ_{bor}^{MS}

➤ $S3_{ASP}(M, \nu, NZ_{bor}) = S2_{ASP}(M, \nu) + c_4 + c_5 NZ_{bor}$

➤ $S2_{ASP}(M, \nu) = \begin{cases} c_0, & M \leq M_{BP}(\nu). \\ c_0 + c_1(M - M_{BP}(\nu)), & M > M_{BP}(\nu) \end{cases}$ $M_{BP}(\nu) = c_2 + c_3 \nu$

➤ Area scaling law

Use before width-limit
(b_WL)

Modified to include W_{Flt}^{FZS}

✓ $\log_{10}(A_e) = S3_A(M, \nu, NZ_{bor})$

➤ $S3_A(M, \nu, NZ_{bor}) = S2_A(M, \nu) + d_3 + d_4 NZ_{bor}$ Use the regional mean NZ_{bor}^{MS} , w/o FS

➤ $S2_A(M, \nu) = S1_A(M) + \max[d_0(\max(M, M_{BP}) - M_{BPL}) + d_1, d_1];$
 $M_{BPL}(\nu) = M_{BP}(\nu) + d_2$

➤ $S1_A(M) = M - 4$

Use before width-limit (b_WL)

Extension for Fault-Based Analysis

Use before width-limit (b_WL)

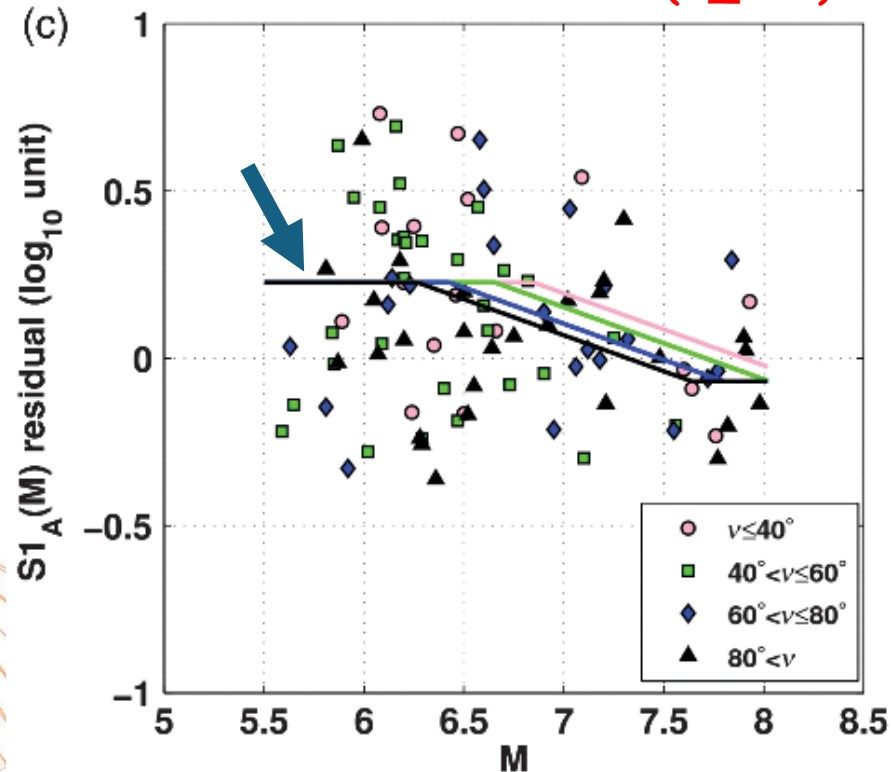
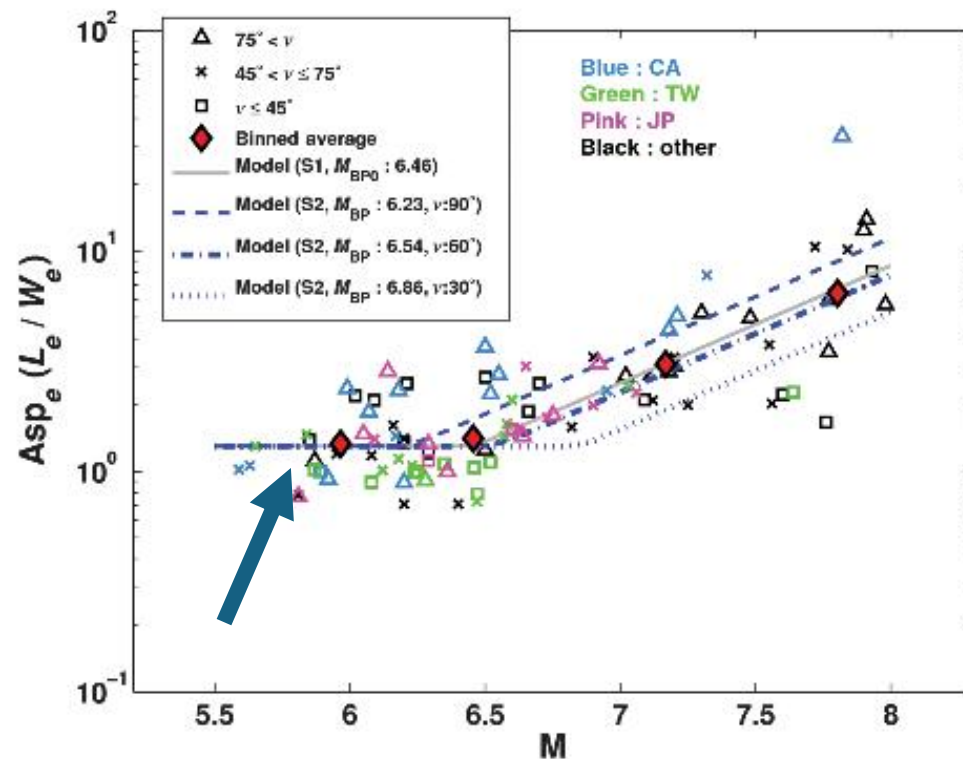
$$\triangleright S2_{ASP}(M, \nu) = \begin{cases} c_0, & M \leq M_{BP}(\nu). \\ c_0 + c_1(M - M_{BP}(\nu)), & M > M_{BP}(\nu) \end{cases} \quad M_{BP}(\nu) = c_2 + c_3\nu$$

$$\triangleright S2_A(M, \nu) = S1_A(M) + \max[d_0(\max(M, M_{BP}) - M_{BPL}) + d_1, d_1];$$

$$M_{BPL}(\nu) = M_{BP}(\nu) + d_2$$

$$\Rightarrow d_0 \times (-d_2) + d_1$$

Use before width-limit (b_WL)



Extension for Fault-Based Analysis

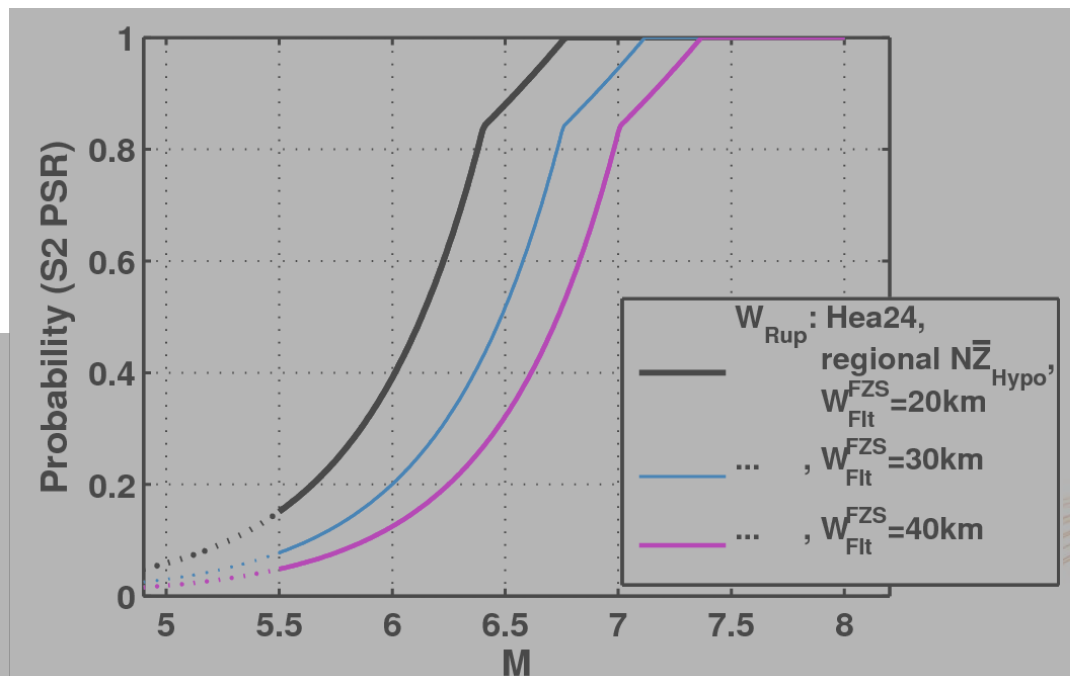
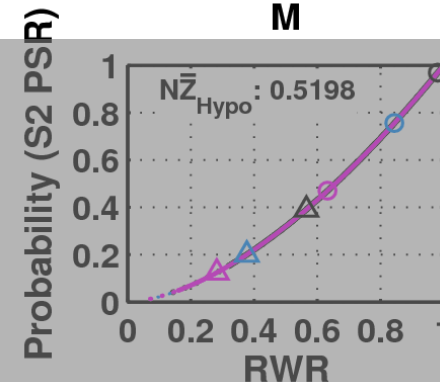
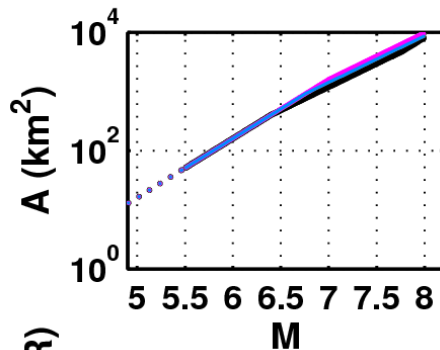
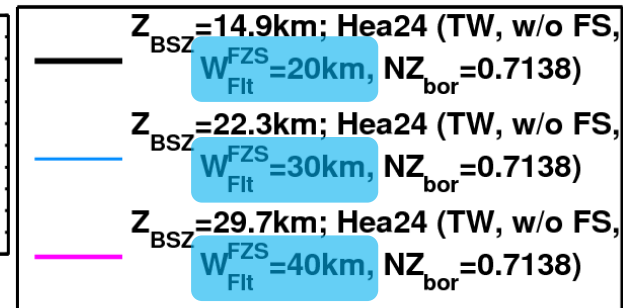
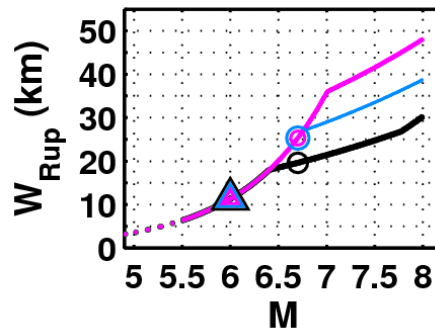
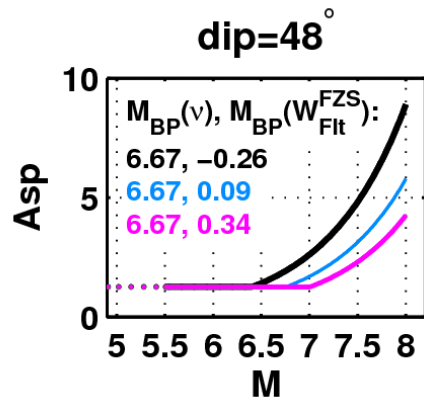
- $M_{BP}^{RWR=1} = M_{BP}(W_{Flt}^{FZS}) + M_{BP}(v)$
- $Asp^{b-WL} = 10^{\wedge}(c_0 + c_4 + c_5 \times NZ_{bor}^{MS})$
- $A^{b-WL} = 10^{\wedge}(M - 4 + (d_0 \times (-d_2) + d_1) + d_3^{w/o FS} + d_4^{w/o FS} \times NZ_{bor}^{MS})$
- $W_{Rup}^{b-WL} = \sqrt{A^{b-WL} / Asp^{b-WL}}$
- $(W_{Rup}^{b-WL})^2 = 10^{\wedge}([M - 4 + (d_0 \times (-d_2) + d_1) + d_3^{w/o FS} + d_4^{w/o FS} \times NZ_{bor}^{MS}] - [c_0 + c_4 + c_5 \times NZ_{bor}^{MS}])$

solve $M = M_{BP}^{RWR=1}$

- $M_{BP}^{RWR=1} = 2 \times \log_{10}(W_{Flt}^{FZS} \times 0.9) - (d_4^{w/o FS} - c_5) \times NZ_{bor}^{MS} + c_0 \times W_{Flt}^{FZS}$
- $c_0 \times W_{Flt}^{FZS} = 4 - (d_0 \times (-d_2) + d_1) - d_3^{w/o FS} + c_0 + c_4 = 4.2566$
- $M_{BP}(W_{Flt}^{FZS}) = M_{BP}^{RWR=1} - M_{BP}(v)$

Extension for Fault-Based Analysis

TW Z_{BSZ} scaling



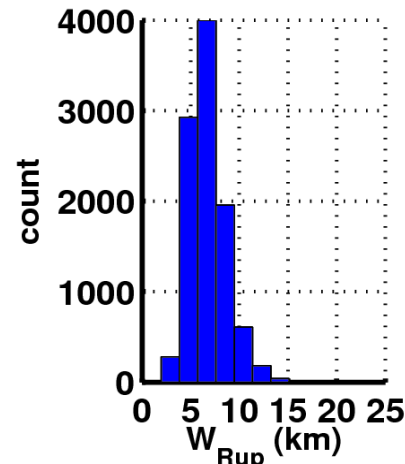
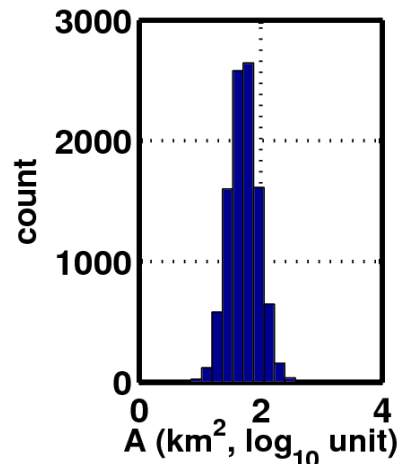
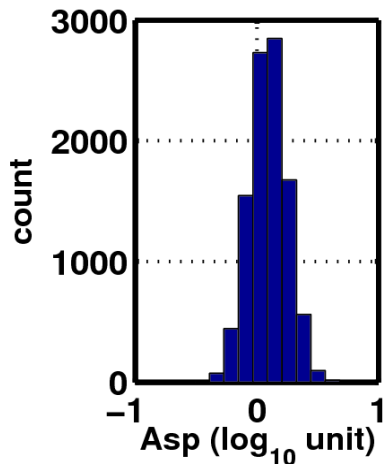
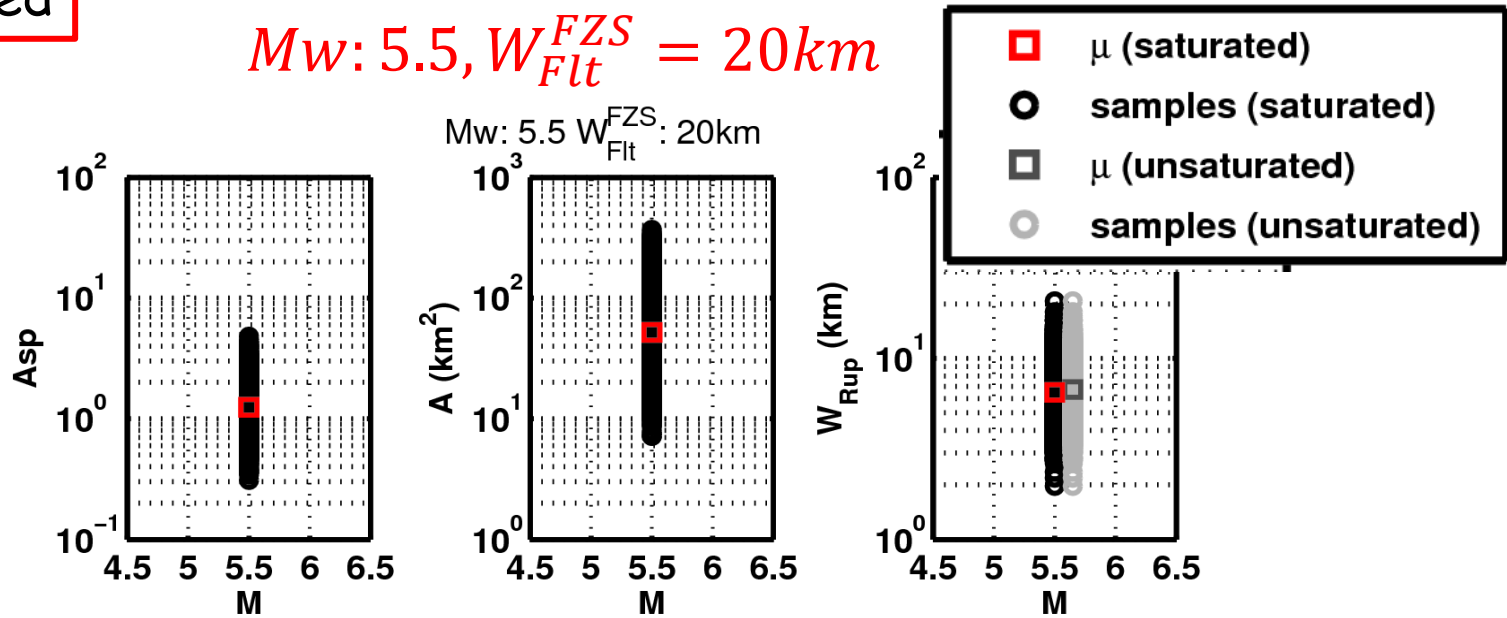
Extension for Fault-Based Analysis

- Probabilistic approach in application
 - ✓ Consider the aleatory variability (σ_{al}) for W_{Rup} .
 - ✓ Monte Carlo sampling for σ_{al}
 - Multivariate lognormal distribution
 - 10k simulation samples for log-residuals of both A and Asp (ε^A and ε^{Asp})
 - ✓ Saturated for W_{Rup} sampling at $W_{Fzt}^{FZS} \times 1.1$
 - ✓ Calculate mean and aleatory variability (2 times σ_{al}) range of W_{Rup}

Extension for Fault-Based Analysis

Saturated

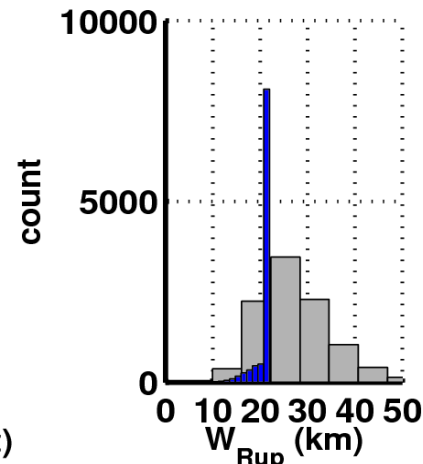
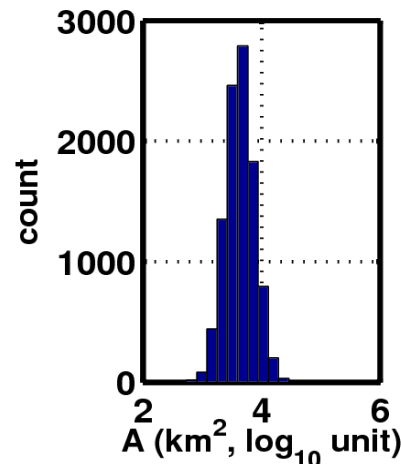
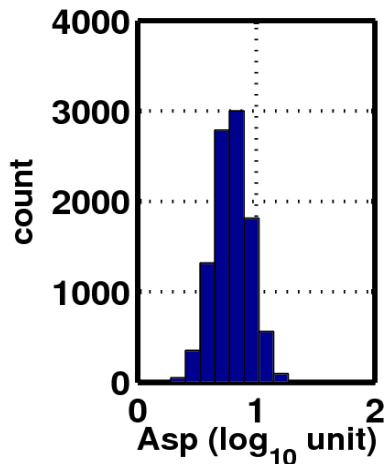
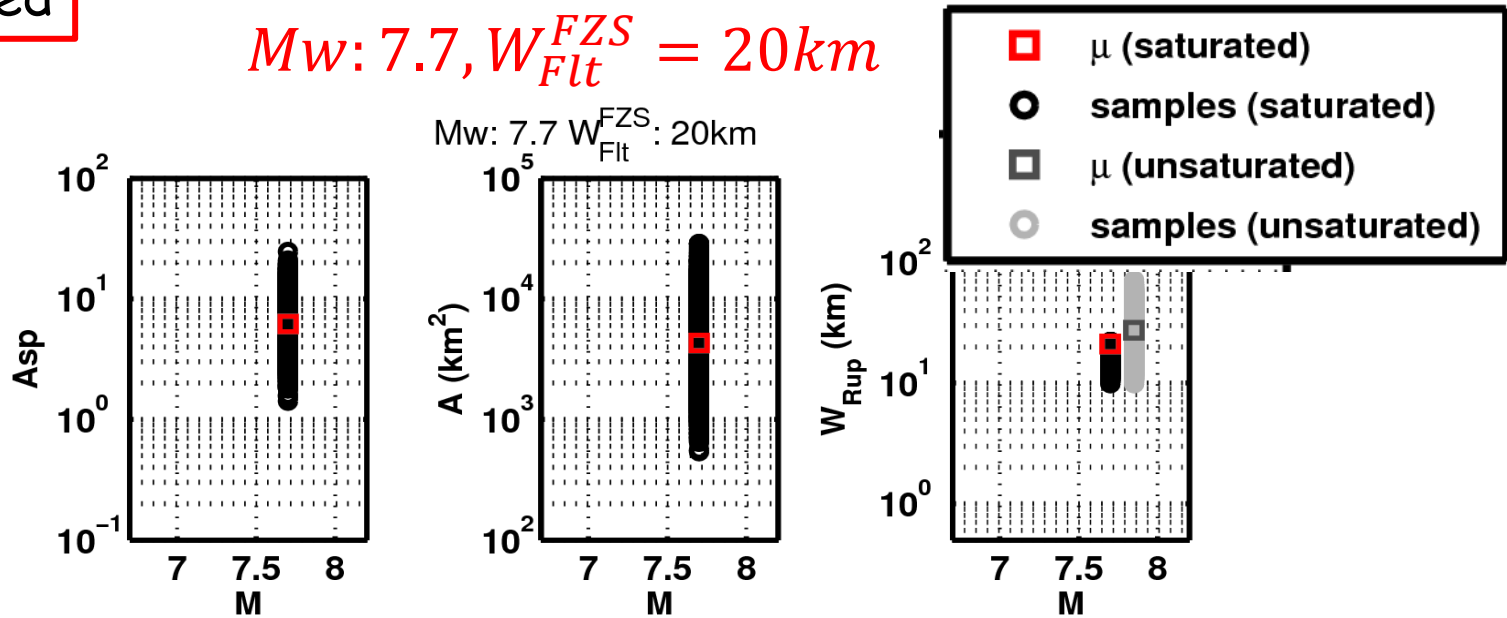
$M_w: 5.5, W_{Flt}^{FZS} = 20km$



Extension for Fault-Based Analysis

Saturated

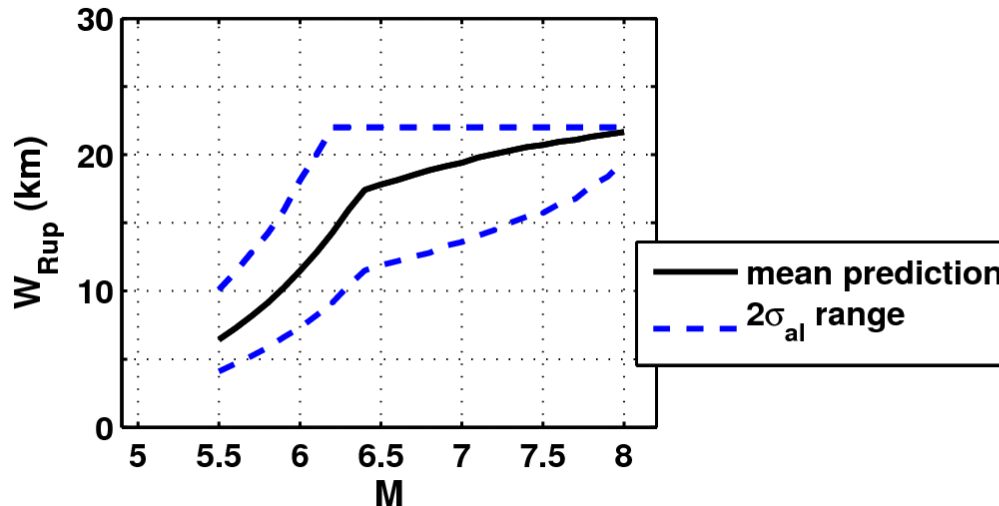
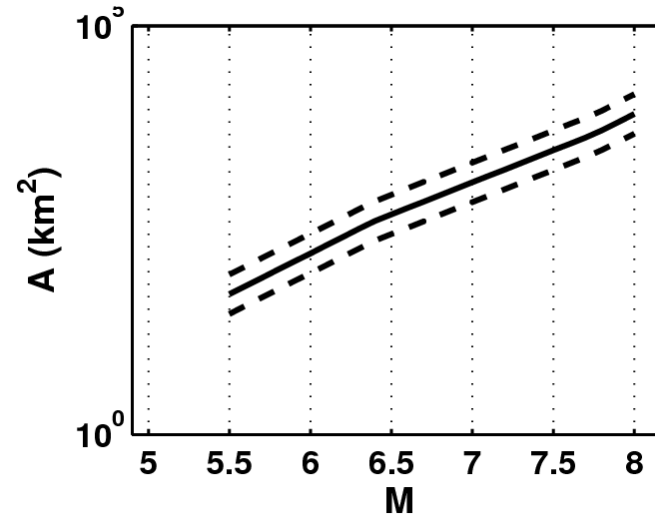
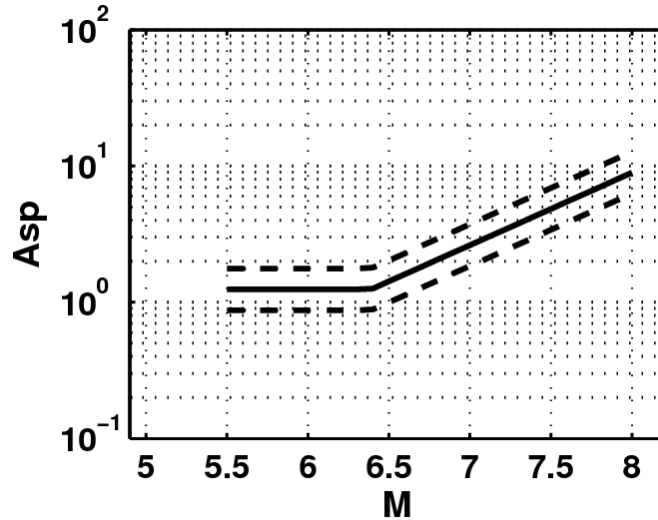
$M_w: 7.7, W_{Fzt}^{FZS} = 20\text{km}$



Extension for Fault-Based Analysis

Saturated

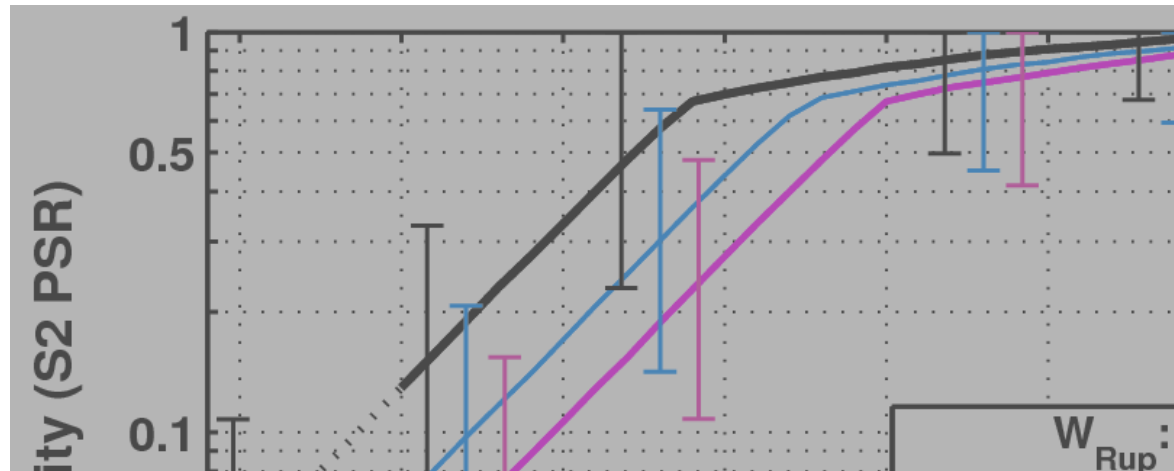
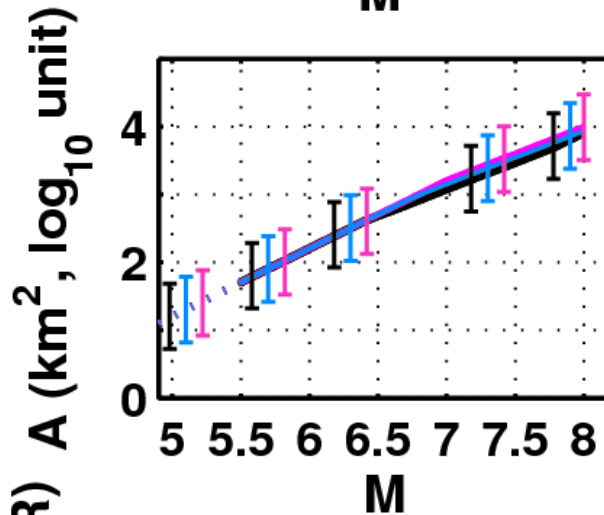
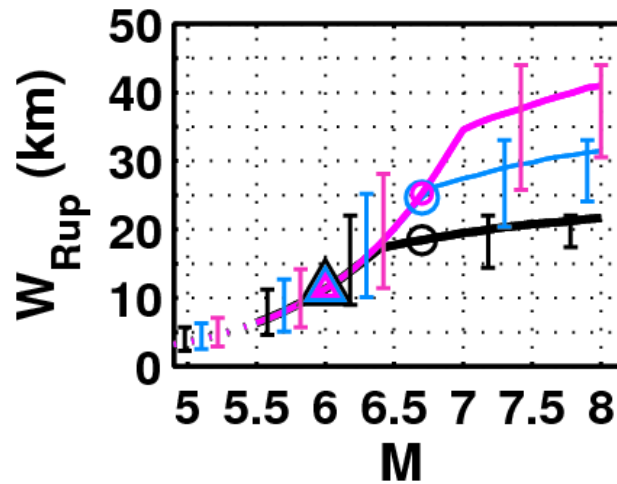
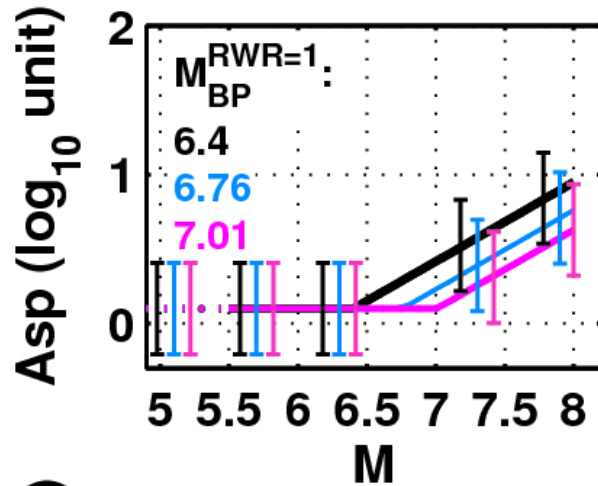
$$W_{Flt}^{FZS} = 20km$$



Extension for Fault-Based Analysis

TW Z_{BSZ} scaling

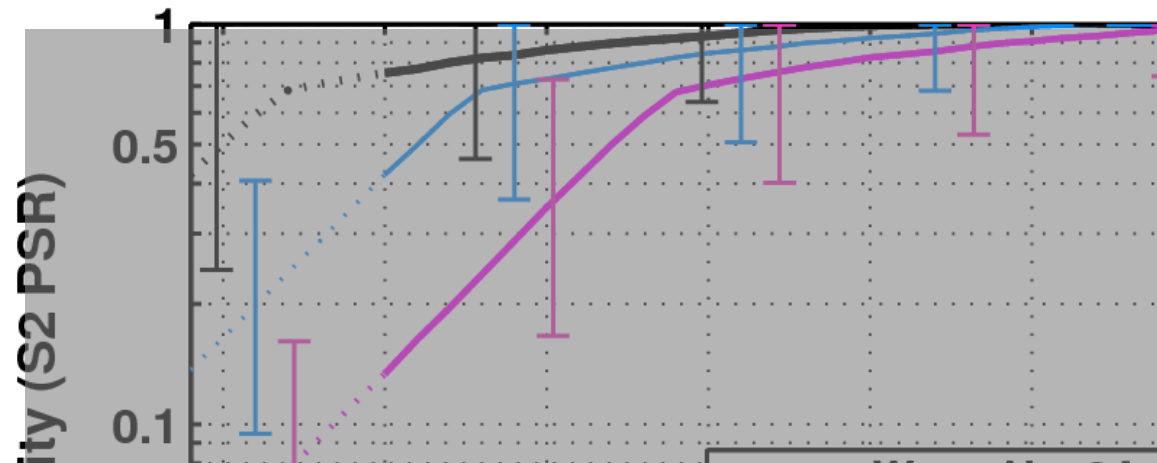
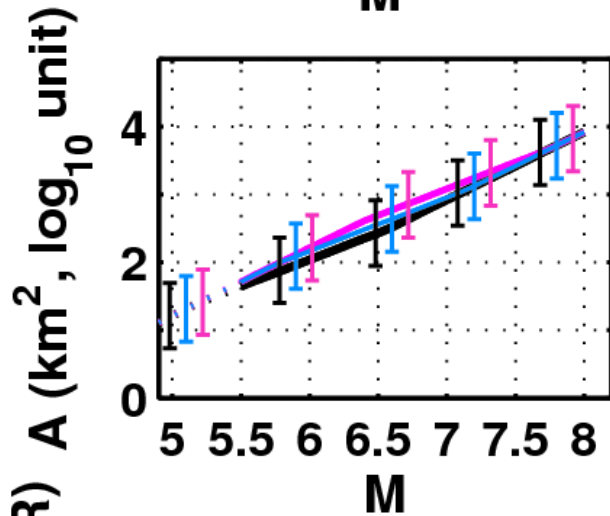
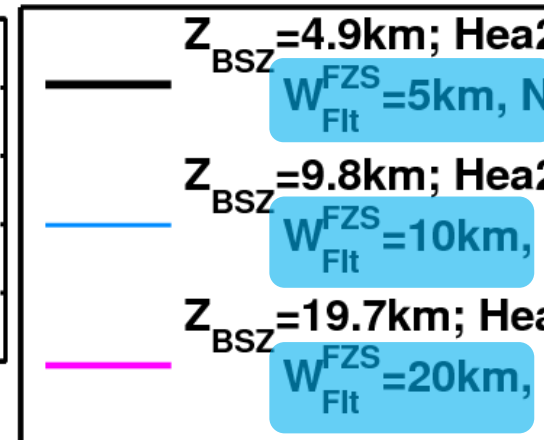
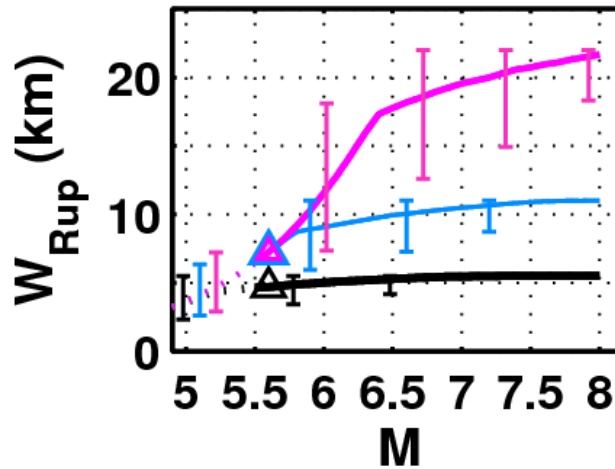
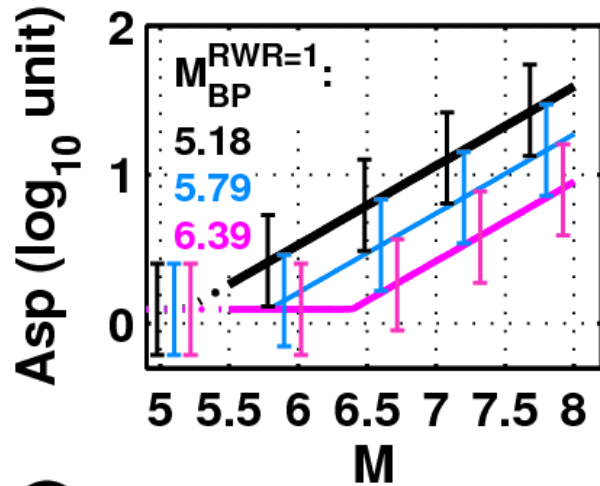
$\nu=48^\circ$



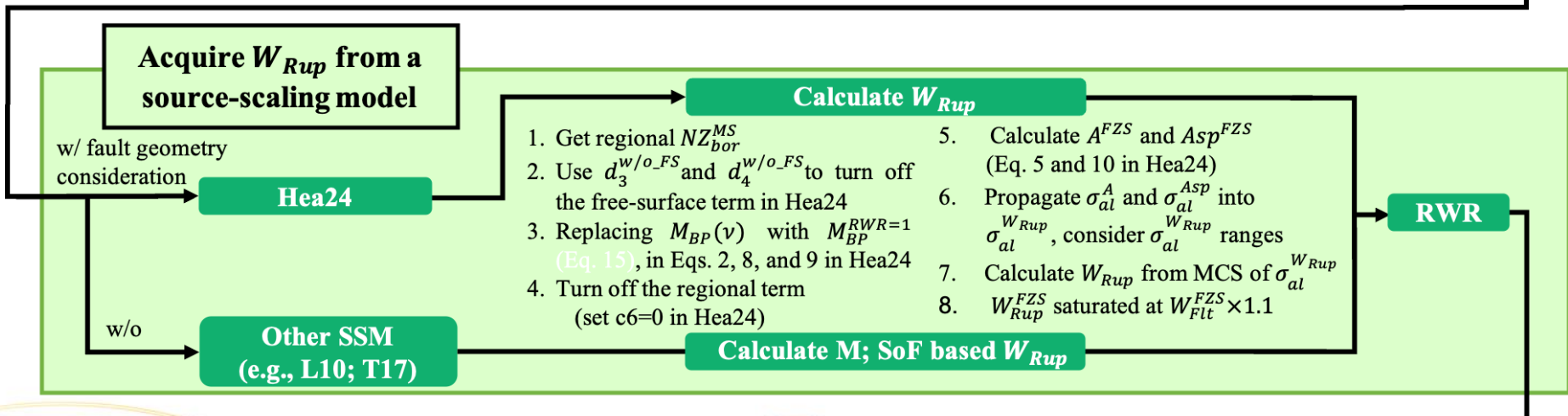
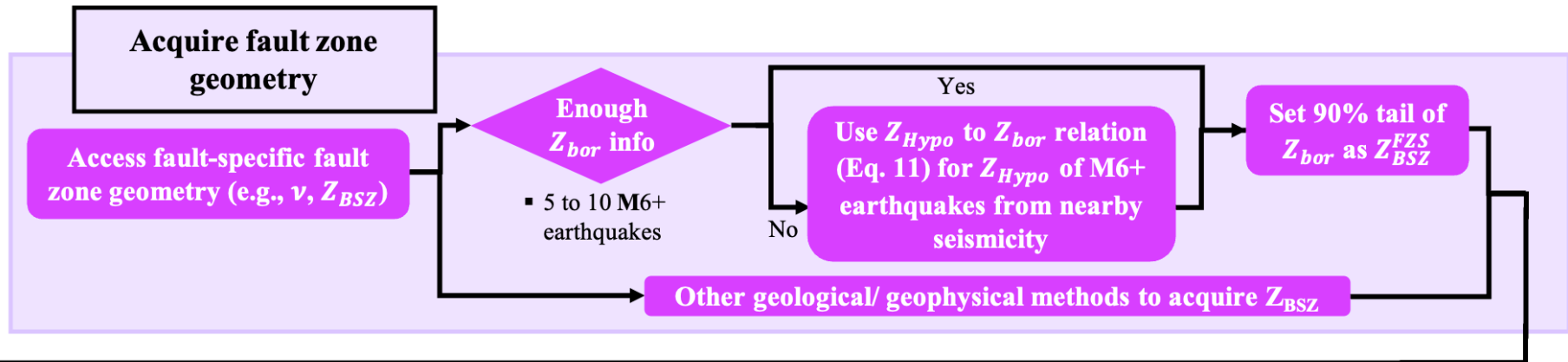
Extension for Fault-Based Analysis

CA Z_{BSZ} scaling

$\nu=80^\circ$



Extension for Fault-Based Analysis



Conclusions

- We shifted the source-scaling model, originally based on the width-limit effect and relying on regional scaling, to a fault-based, probabilistic approach by replacing the dip-angle-dependent MBP with one that uses fault-zone-specific fault width.
- The proposed procedure, based on Monte Carlo sampling, propagates the aleatory variability and the saturated mean in the original Hea24 scaling for rupture width in applications and is more suitable for fault-specific hazard analysis.

- **Leading source:**
 - **Huang J.Y.**, N. A. Abrahamson, C.H. Sung, and S.H. Chao, (2024), New empirical source scaling laws for crustal earthquakes incorporating the fault dip angle and seismogenic thickness effects, *Seismol. Res. Lett.*, 95(4), 2352-2367.
 - **Huang J.Y.**, and N. A. Abrahamson, A new empirical probability model for surface faulting utilizing rupture-width ratio for crustal earthquakes. (in preparation)
- <https://github.com/BobHuangNCREETW/GeometryRelatedSourceScalingRelation.git>

- Others

- Abrahamson N. A., W. J. Silva, and R. Kamai, (2014), Summary of the ASK14 ground motion relation for active crustal regions, *Earthq. Spectra*, 30(3), 1025-1055.
- Bruce J. N., (1970), Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, 75(26), 4997-5009.
- Cheng J., Y. Rong, H. Magistrale, G. Chen, and X. Xu, (2019), Earthquake rupture scaling relations for mainland China, *Seismol. Res. Lett.*, 91(1), 248-261.
- Cornell A. C., (1968), Engineering seismic risk analysis, *Bull. Seismol. Soc. Am.*, 58(5), 1583-1606.
- Grigull S., (2011), Insights into the Rheology of rocks under brittle-ductile deformation conditions from an exhumed shear array in the southern Alps, New Zealand, PhD. Thesis, Victoria University of Wellington.
- Hanks T. C., and H. Kanamori, (1979), A moment-magnitude scale, *J. Geophys. Res.*, 84, 2348-2350.

• Others

- Hanks T. C., and W. H. Bakun, (2002), A bilinear source-scaling model for M–log A observations of continental earthquakes, *Bull. Seismol. Soc. Am.*, 92(5), 1841-1846.
- **Huang J.Y.**, S.H. Chao, C.M. Lin, C.C. Chou, C.H. Loh, and C.L. Wu, (2024), Site-specific response spectra developed by considering near-fault motions derived on ground-motion simulation technique in Taiwan, *Earthq. Eng. Structr. D.*, 53(2), 968-991.
- Kaklamanos J., L. G. Baise, and D. M. Boore, (2011), Estimating unknown input parameters when implementing the NGA ground-motion prediction equations in engineering practice, *Earthq. Spectra*, 27(4), 1219-1235.
- Lee S. J., T. Y. Yeh, and Y. Y. Lin, (2016), Anomalously large ground motion in the 2016 ML 6.6 Meinong, Taiwan, earthquake: A synergy effect of source rupture and site amplification, *Seismol. Res. Lett.*, 87(6), 1319-1326.
- Lee S. J., H. H. Huang, J. B. H. Shyu, T. Y. Yeh, and T. C. Lin, (2014), Numerical earthquake model of the 31 October 2013 Ruisui, Taiwan, earthquake: Source rupture process and seismic wave propagation, *J. Asian Earth Sci.*, 96, 374-385.

• Others

- Lee S. J., T. C. Lin, T. Y. Liu, and T. P. Wong, (2019), Fault-to-fault jumping rupture of the 2018 Mw 6.4 Hualien earthquake in eastern Taiwan, *Seismol. Res. Lett.*, 90(1), 30-39.
- Lee S. J., T. Y. Liu, and T. C. Lin, (2023), The role of the west-dipping collision boundary fault in the Taiwan 2022 Chihshang earthquake sequence, *Sci. Rep.*, 13, 3552.
- Lee S. J., L. Mozziconacci, W. T. Liang, Y. J. Hsu, W. G. Huang, and B. S. Huang, (2013), Source complexity of the 4 March 2010 Jiashian, Taiwan, Earthquake determined by joint inversion of teleseismic and near field data, *J. Asian Earth Sci.*, 64, 14-26.
- Lee S. J., T. Y. Yeh, H. H. Huang, and C. H. Lin, (2015), Numerical earthquake models of the 2013 Nantou, Taiwan, earthquake series: Characteristics of source rupture processes, strong ground motions and their tectonic implication, *J. Asian Earth Sci.*, 111, 365-372.

- Others

- Lee S. J., T. P. Wong, T. Y. Liu, T. C. Lin, and C. T. Chen, (2020), Strong ground motion over a large area in northern Taiwan caused by the northward rupture directivity of the 2019 Hualien earthquake, *J. Asian Earth Sci.*, 192, 104095.
- Leonard M., (2010), Earthquake fault scaling: Self-consistent relating of rupture length, width, average displacement, and moment release, *Bull. Seismol. Soc. Am.*, 100(5A), 1971-1988.
- Mai P. M., and G. C. Beroza, (2000), Source scaling properties from finite-fault-rupture models, *Bull. Seismol. Soc. Am.*, 90(3), 604-615.
- Mai P. M., and K. K. S. Thingbaijam, (2014), SRCMOD: An online database of finite-fault rupture models, *Seismol. Res. Lett.*, 85(6), 1348-1357.
- Shaw B. E., (2009), Constant stress drop from small to great earthquakes in magnitude-area scaling, *Bull. Seismol. Soc. Am.*, 99(2A), 871-875.
- Shaw B. E., (2023), Magnitude and slip scaling relations for fault-based seismic hazard, *Bull. Seismol. Soc. Am.*, 113(3), 924-947.

- Others

- Somerville P., K. Irikura, R. Graves, S. Sawada, D. Wald, N. A. Abrahamson, Y. Iwasaki, T. Kagawa, N. Smith, and A. Kowada (1999). Characterizing crustal earthquake slip models for the prediction of strong ground motion, *Seismol. Res. Lett.*, 70(1), 59-80.
- Thingbaijan K. K. S., P. M. Mai, and K. Goda, (2017), New empirical earthquake source-scaling laws, *Bull. Seismol. Soc. Am.*, 107(5), 2225-2246.
- Thingbaijam K. K. S., and P. M. Mai, (2016), Evidence for truncated exponential probability distribution of earthquake slip, *Bull. Seismol. Soc. Am.* 106(4), 1802-1816.
- USGS (2023). Webpage of the search earthquake catalog, available at <https://earthquake.usgs.gov/earthquakes/>.
- Wells D. L., and K. J. Coppersmith, (1994), New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seismol. Soc. Am.*, 84(4), 974-1002.

- Others

- Yen Y.T., and K.F. Ma, (2011), Source-scaling relationship for M 4.6-8.9 earthquakes, specifically for earthquakes in the collision zone of Taiwan, Bull. Seismol. Soc. Am., 101(2), 464-481.
- Youngs R. R., W. J. Arabasz, R. Ernest Anderson, A. R. Ramelli, J. P. Ake, D. B. Slemmons, J. P. McCalpin, D. I. Doser, C. J. Fridrich, F. H. Swan, A. M. Rogers, J. C. Yount, L. W. Anderson, K. D. Smith, R. L. Bruhn, P. L. K. Knuepfer, R. B. Smith, C. M. dePolo, D. W. O'Leary, K. J. Coppersmith, S. K. Pezzopane, D. P. Schwartz, J. W. Whitney, S. S. Olig, and G. R. Toro, (2003), A methodology for probabilistic fault displacement hazard analysis (PFDHA), Earthq. Spectra, 19(1), 191-219.

Thanks for attention

Model Construction (Regional scaling)

➤ Aspect ratio scaling law

$$\checkmark \log_{10}(Asp_e) = S4_{ASP}(M, \nu, NZ_{bor}, region)$$

$$\text{➤ } S4_{ASP}(M, \nu, NZ_{bor}, region) = S3_{ASP}(M, \nu, NZ_{bor}) + RT(M)$$

$$\text{➤ } S3_{ASP}(M, \nu, NZ_{bor}) = S2_{ASP}(M, \nu) + c_4 + c_5 NZ_{bor}$$

$$\text{➤ } S2_{ASP}(M, \nu) = \begin{cases} c_0, & M \leq M_{BP}(\nu) \\ c_0 + c_1(M - M_{BP}(\nu)), & M > M_{BP}(\nu) \end{cases} \quad M_{BP}(\nu) = c_2 + c_3 \nu$$

➤ Area scaling law

$$\checkmark \log_{10}(A_e) = S3_A(M, \nu, NZ_{bor})$$

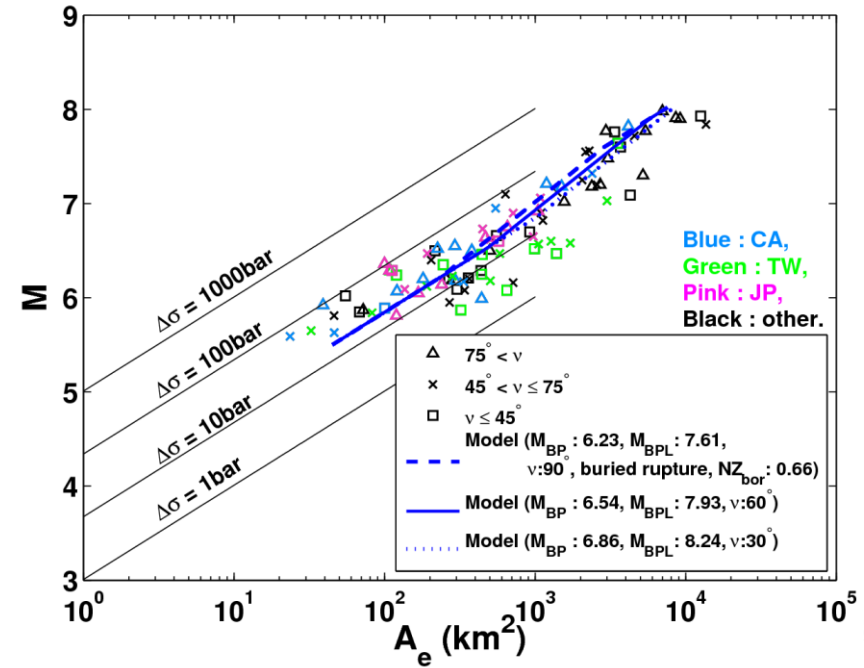
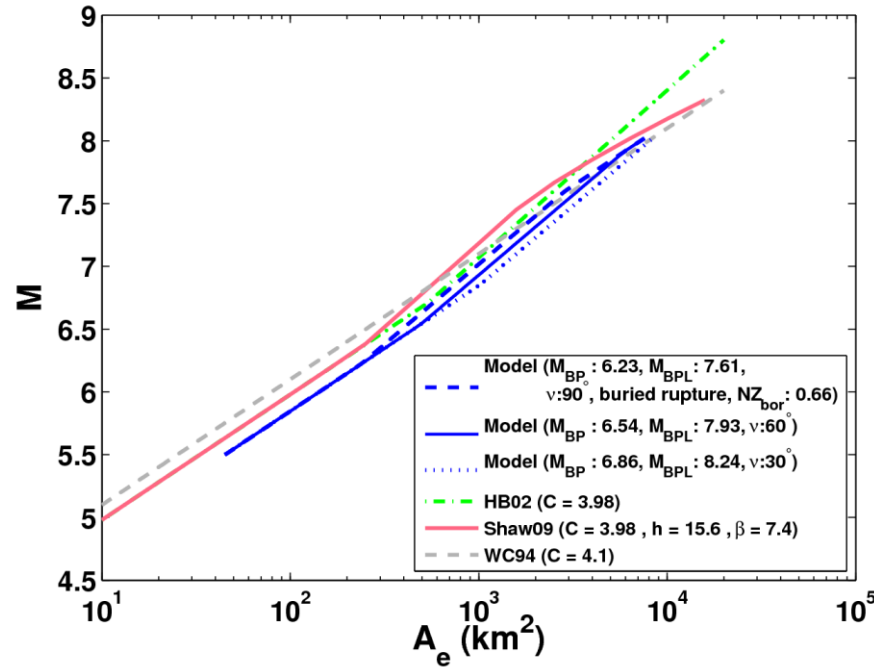
$$\text{➤ } S3_A(M, \nu, NZ_{bor}) = S2_A(M, \nu) + d_3 + d_4 NZ_{bor}$$

$$\text{➤ } S2_A(M, \nu) = S1_A(M) + \max[d_0(\max(M, M_{BP}) - M_{BPL}) + d_1, d_1];$$
$$M_{BPL}(\nu) = M_{BP}(\nu) + d_2$$

$$\text{➤ } S1_A(M) = M - 4$$

Model Comparisons

Area



- Typical source scaling Laws (models)
 - Fault area, length (surface-; subsurface-rupture), width, asperity size, slip (average; maximum),
 - M_w (M_0)-dependent
 - Style of faulting-dependent
 - Regional difference
 - Width-limit effect for crustal earthquakes
 - Fault-dip angle difference



✓ Regional scaling -> Fault-based scaling