Validation of subduction ground-motion simulations in New Zealand

Michael Dupuis

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Objectives

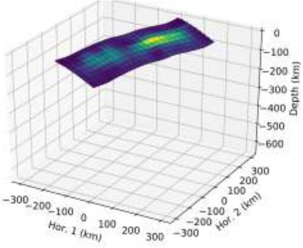
- Develop new subduction-specific ground-motion simulation models/parameters and validate using observed NZ data (this presentation)
  - Small magnitudes ($M_w < 5$) treated as point-source
  - Moderate magnitudes ($M_w > 5$) given finite-fault representation
- Extend new models to large magnitude Hikurangi rupture scenario simulations with James (next presentation)

Methodology

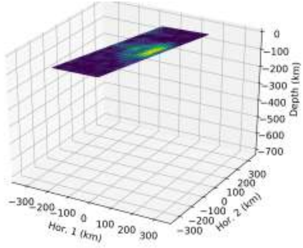
Examined features of crustal, interface, and slab models within:

- SRCMOD catalogue of rupture models (with low-slip subfault trimming)
- Empirical ground-motion models
- Studies of past earthquakes, particularly those which have done ground-motion simulation

2010 M_w8.8 Maule:



2011 M_w9.0 Tohoku:



Observed NZ-specific ground-motion data

- Only using high-quality records
- Tectonic classifications by manual review of focal mechanisms
- Requiring 3 records per event/station
- Considering earthquakes from both the Hikurangi and Puysegur subduction zones

Subduction simulation models

Parameter	Crustal	Interface	Slab
Stress drop	50 bar	?	?
Rupture velocity	$0.8V_S$	?	?
*Anelastic att.	Isotropic	?	?
M_w-area scaling	Leonard	?	?
CoV_{slip}	75%	?	?
Hypocentre	0.5 (mid-depth)	?	?
kappa	0.045		
c_1	1.45		
HF c_0	2.0		
risetime	0.5 s		
*HF Q_s	Q_s=a+bV_s, a=41, b=34		
Q_p	Q_p=2Q_s		

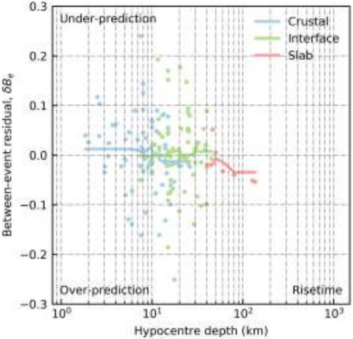
Brune stress drop

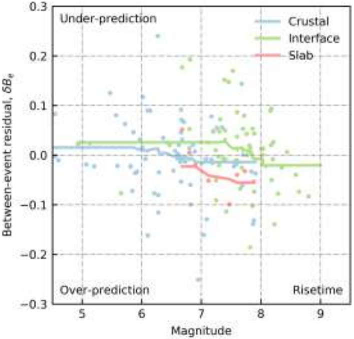
- Slab ruptures: high stress drop and significant depth dependence [Chhangte et al., 2021, García et al., 2004, Takeo et al., 1993, Asano et al., 2003]
- Equivalent point source GMM [Hassani and Atkinson, 2021]: 40 bar at 25 km and 79 bar at 55 km for interface, 85 bar at 40 km and 390 bar at 90 km for slab earthquakes in Japan.

Seem to indicate large stress drop and depth dependence for slab and small stress drop with minor depth dependence for interface

Brune stress drop (using risetime as proxy)

Risetime provided for each model in SRCMOD catalogue (inversely proportional to stress drop), computed residuals against $\tau_A = \alpha_T \times 1.6 \times 10^{-9} \times {M_o}^{1/3}$





Over-predict slab risetimes, ∴ under-predict stress drop
Under-predict interface risetimes, ∴ over-predict stress drop

Subduction simulation models

Parameter	Crustal	Interface	Slab
Stress drop	50 bar	15+CD	50+2CD
Rupture velocity	$0.8V_S$	?	?
*Anelastic att.	Isotropic	?	?
M_w-area scaling	Leonard	?	?
CoV_{slip}	75%	?	?
Hypocentre	0.5 (mid-depth)	?	?
kappa	0.045		
c_1	1.45		
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Q_p	$Q_p=2Q_s$		

Rupture velocity

- High rupture velocities for slab earthquakes [Chhangte et al., 2021, García et al., 2004, Takeo et al., 1993]
- Large magnitude interface simulations use background rupture models with low rupture velocity, but I didn't find consistent observations for moderate magnitude ruptures.
- SRCMOD did not provide compelling support for adjustment to either interface or slab.
- Currently leaving interface as $0.8V_S$ and increasing slab to $0.95V_S$ on the basis of it being greater than $0.8V_S$ (consistent with literature) and performing well in the simulations. Is this value OK, or too high?

Subduction simulation models

Parameter	Crustal	Interface	Slab
Stress drop	50 bar	15+CD	50+2CD
Rupture velocity	$0.8V_S$	$0.8V_S$	$0.95V_S$
*Anelastic att.	Isotropic	?	?
M_w-area scaling	Leonard	?	?
CoV_{slip}	75%	?	?
Hypocentre	0.5 (mid-depth)	?	?
kappa	0.045		
c_1	1.45		
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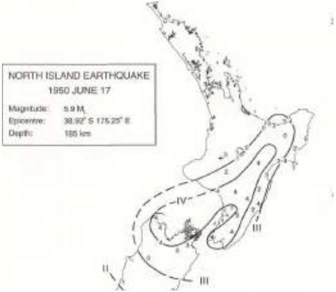
Q_p	Q_p=2Q_s		

Anisotropic anelastic attenuation

- Motivation:
  - Separate treatment of backarc/forearc sites in empirical GMMs
  - Isoseismal maps with characteristic contours anchored by subduction geometry
- Arc effects are already included in LF simulation, 3 options for HF component:
  - 3D HF simulation
  - Ray-tracing approach
  - Our proposed heuristic model using notion of a 'shadow site'



Anelastic attenuation—Proposed anisotropic model

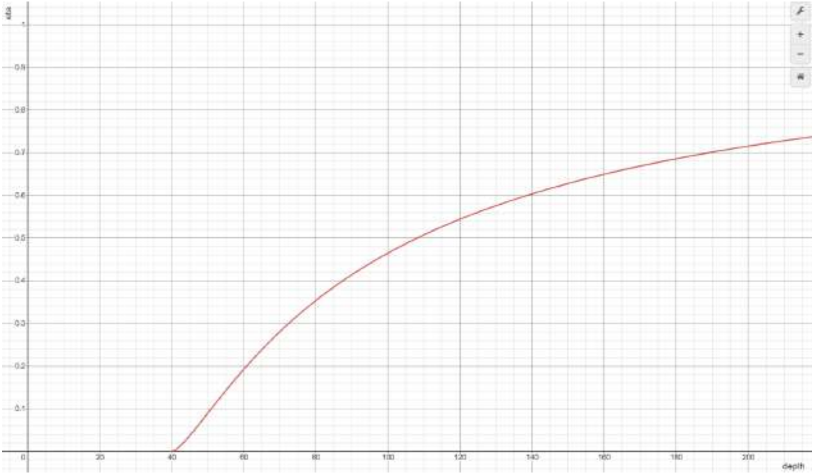
$$Q_{backarc} = \alpha^{\eta} Q$$

where:

- α is a term for anisotropic attenuation
- η is a depth term which scales the effect based on source depth
- The approach does not adjust Q in the forearc region.
- I am using the terms forearc/backarc, but I am referring to position relative to axis of strongest shaking

Anisotropic anelastic attenuation model—Depth term

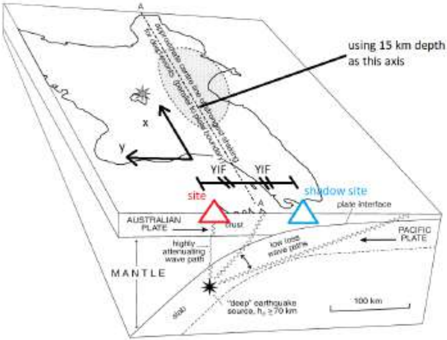
$$Q_{backarc} = \alpha^{\eta} Q, \text{ where } \eta = \begin{cases} 0, & \text{for } CD \leq 40 \\ \left(\frac{CD-40}{CD}\right)^{3/2}, & \text{for } 40 \leq CD \end{cases}$$

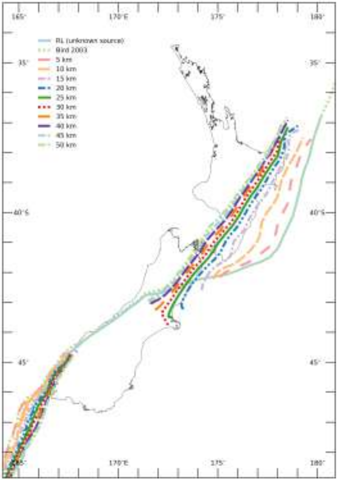


Anisotropic anelastic attenuation model—Anisotropy term

$$\alpha = \frac{Rrup_{site}}{Rrup_{shadowsite}}$$

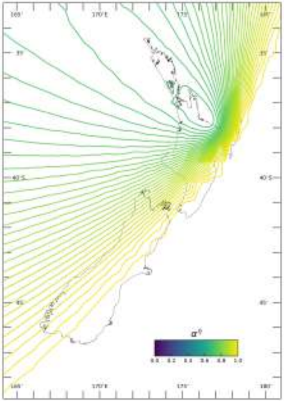
$$\alpha = \left[\frac{\Delta x^2 + CD^2 + \Delta y^2}{\Delta x^2 + CD^2 + (\Delta y + 2\Delta y_{IF})^2}\right]^{1/2}$$



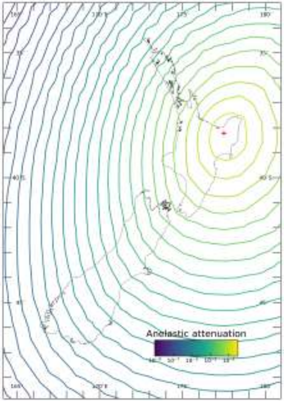


Motu River earthquake (1984)—M_L6.4, 73km

Adjustment factor



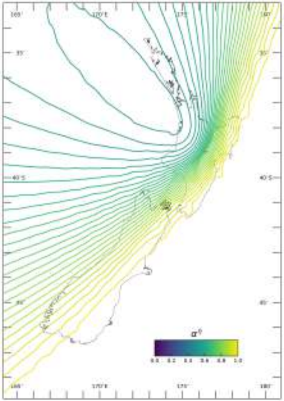
Anelastic attenuation



Historical intensity reports

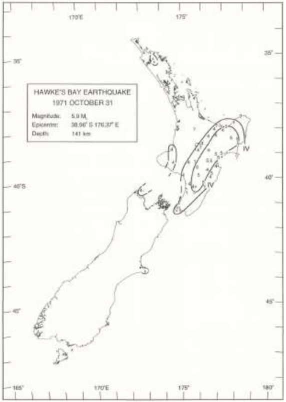
Hawke's Bay earthquake (1971)—M_L5.9, 141km

Adjustment factor



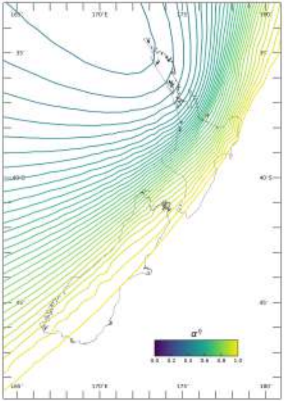
Anelastic attenuation

Historical intensity reports

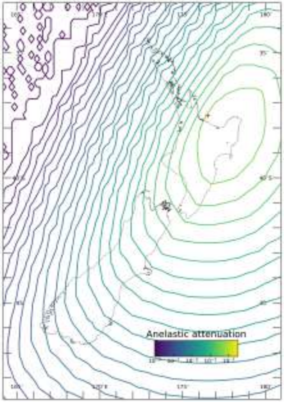


Bay of Plenty earthquake (1914)—M_w7.2, 300km

Adjustment factor



Anelastic attenuation



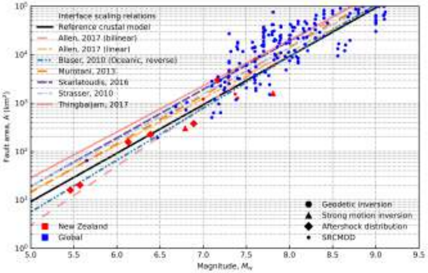
Historical intensity reports

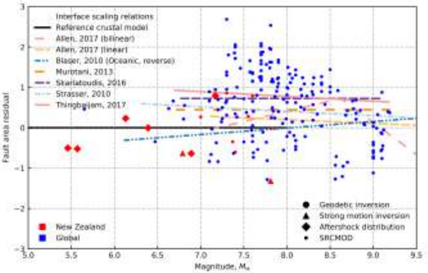
Subduction simulation models

Parameter	Crustal	Interface	Slab
Stress drop	50 bar	15+CD	50+2CD
Rupture velocity	$0.8V_S$	$0.8V_S$	$0.95V_S$
*Anelastic att.	Isotropic	Anisotropic	Anisotropic
M_w-area scaling	Leonard	?	?
CoV_{slip}	75%	?	?
Hypocentre	0.5 (mid-depth)	?	?
kappa	0.045		
c_1	1.45		
HF c_0	2.0		
risetime	0.5 s		
*HF Q_s	Q_s=a+bV_s, a=41, b=34		
Q_p	$Q_p=2Q_s$		

Magnitude-area scaling relation—Interface earthquakes

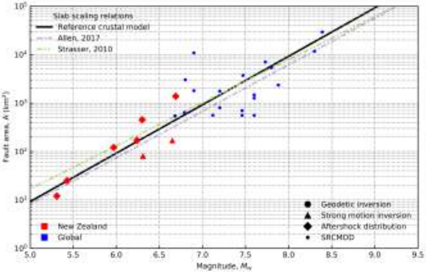
- Propose to use **Skarlatoudis, 2016** based on good fit to NZ data and wide magnitude domain
- Plan to test out all models, but sense is we are unlikely to find compelling case for any one model.
- Any insights on preferred model?

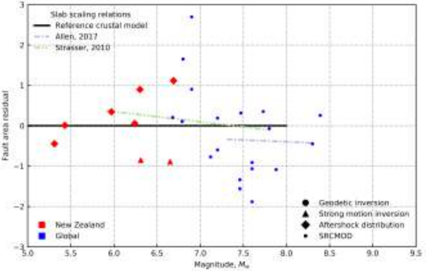




Magnitude-area scaling relation—Slab earthquakes

- Propose to use **Allen, 2017** which appears to fit global and NZ slab data well
- Plan to test out all models, but sense is we are unlikely to find compelling case for any one model.
- Any insights on preferred model?





Subduction simulation models

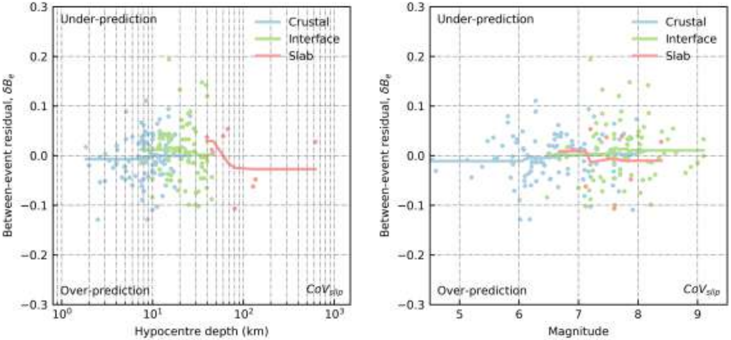
Parameter	Crustal	Interface	Slab
Stress drop	50 bar	15+CD	50+2CD
Rupture velocity	$0.8V_S$	$0.8V_S$	$0.95V_S$
*Anelastic att.	Isotropic	Anisotropic	Anisotropic
M_w-area scaling	Leonard	Skarlatoudis	Allen
CoV_{slip}	75%	?	?
Hypocentre	0.5 (mid-depth)	?	?
kappa	0.045		
c_1	1.45		
HF c_0	2.0		
risetime	0.5 s		
*HF Q_s	Q_s=a+bV_s, a=41, b=34		
Q_p	$Q_p=2Q_s$		

Coefficient of variation of slip

- Little in literature for slab events
- Studies of large magnitude interface events report large variation in slip between asperities and background rupture with trend towards large slip at trench
- Unclear how these macro-trends in slip relate to CoV_{slip} which is more related to small-scale variation between subfaults.
- Also unclear how the macro-trends for large magnitudes generalize to moderate magnitudes
- Do asperity models (e.g., Frankel and Wirth, or Pitarka et al. GP + Ikikura recipe), require a different CoV_{slip}? Asperity model for slab events?

Coefficient of variation of slip

CoV_{slip} was computed for SRCMOD models (after low-slip subfault trimming) and residuals were computed using crustal-based predictions of 75%



Differences between tectonic types are very slight — perhaps slight under-prediction for interface. Effect of CoV_{slip} on GM prediction is negligible at moderate magnitudes.

Subduction simulation models

Parameter	Crustal	Interface	Slab
Stress drop	50 bar	15+CD	50+2CD
Rupture velocity	$0.8V_S$	$0.8V_S$	$0.95V_S$
*Anelastic att.	Isotropic	Anisotropic	Anisotropic
M_w-area scaling	Leonard	Skarlatoudis	Allen
CoV_{slip}	75%	85%	75%
Hypocentre	0.5 (mid-depth)	?	?
kappa	0.045		
c_1	1.45		
HF c_0	2.0		
risetime	0.5 s		
*HF Q_s	Q_s=a+bV_s, a=41, b=34		
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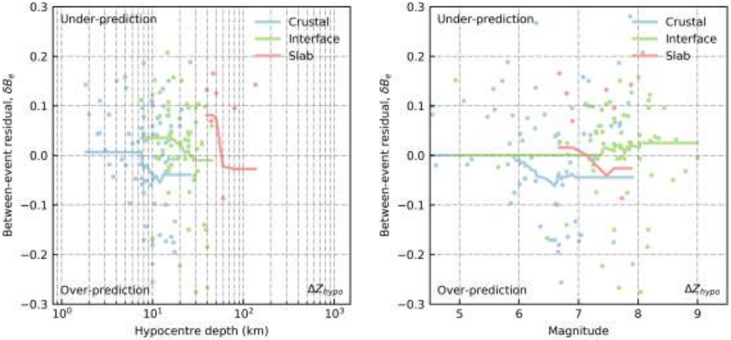
Hypocentre location

- Currently positioning hypocentre (location of rupture initiation) as coincident with centroid (0.5) for small/moderate magnitude crustal events without an event-specific finite fault.
- For megathrust events, my impression is that rupture tends to initiate in the deeper asperity regions
- As with CoV slip, its unclear how well this observation extends to moderate magnitudes where the effect on GMs becomes negligible; previous studies have noted that hypocentres are preferentially located in areas of large slip [Mai et al., 2005]
- For moderate magnitudes, hypocentre depth is not a particularly important parameter, therefore simplistic approach is reasonable

Hypocentre location

Computed hypocentre location relative to fault area in trimmed SRCMOD models, where 0 is top of fault, 1 is bottom of fault, and 0.5 is mid-depth. Residuals were computed relative to the crustal-based model of 0.5 (mid-depth)



Appears to be slight under-prediction of hypocentre depth for interface across domain indicating deeper rupture initiation

Subduction simulation models

Parameter	Crustal	Interface	Slab
Stress drop	50 bar	15+CD	50+2CD
Rupture velocity	$0.8V_S$	$0.8V_S$	$0.95V_S$
*Anelastic att.	Isotropic	Anisotropic	Anisotropic
M_w-area scaling	Leonard	Skarlatoudis	Allen
CoV_{slip}	75%	85%	75%
Hypocentre	0.5 (mid-depth)	0.6 (deeper)	0.5
kappa	0.045		
c_1	1.45		
HF c_0	2.0		
risetime	0.5 s		
*HF Q_s	Q_s=a+bV_s, a=41, b=34		
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Q_p	$Q_p=2Q_s$		

How well do the new models perform?

Validation simulation runs

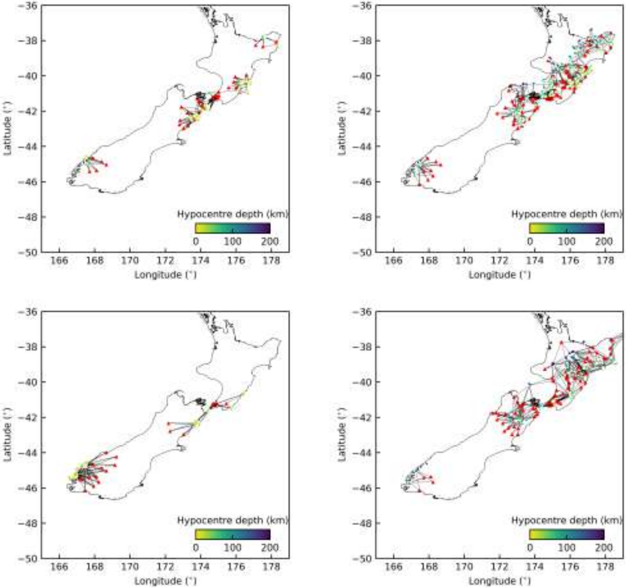
- GP Hybrid broadband approach
- 400 m grid; 1 Hz Transition frequency (exploratory work)
  - Will use 100 m grid; 0.25 Hz Transition frequency for production runs
- $V_{S30} = 500 m/s$
- 3D VM: version 2.06 (Squashed tapered)
- 1D VM: Cant1D-midQ_OneRay.1d

Validation data set

Interface | Slab

$M_w < 5$

$M_w > 5$

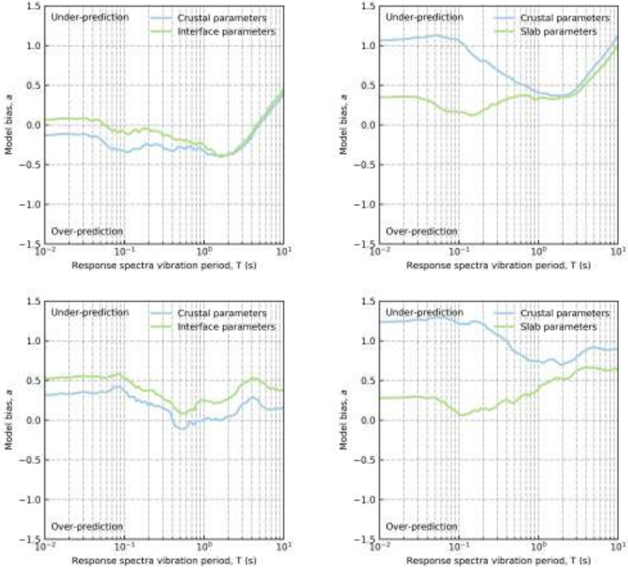


Prediction bias, a, for all events and sites

Interface | Slab

$M_w < 5$

$M_w > 5$

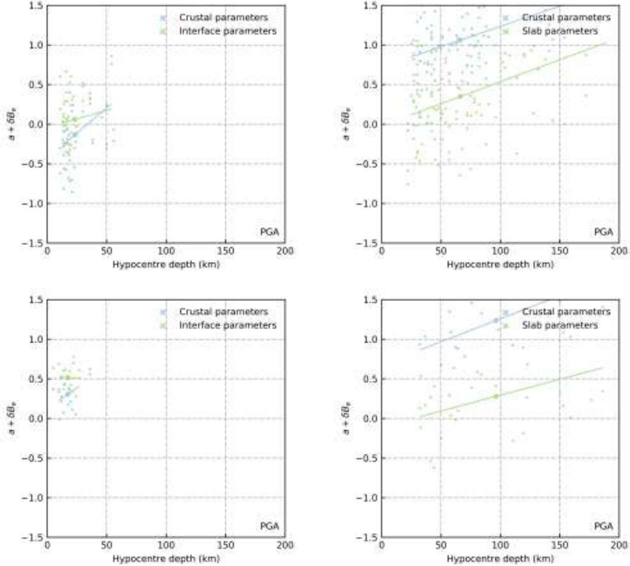


Depth dependence of δB_e: $\delta B_e'(Depth) = \Delta\delta B_e / \Delta CD$

Interface — Slab

$M_w < 5$

$M_w > 5$

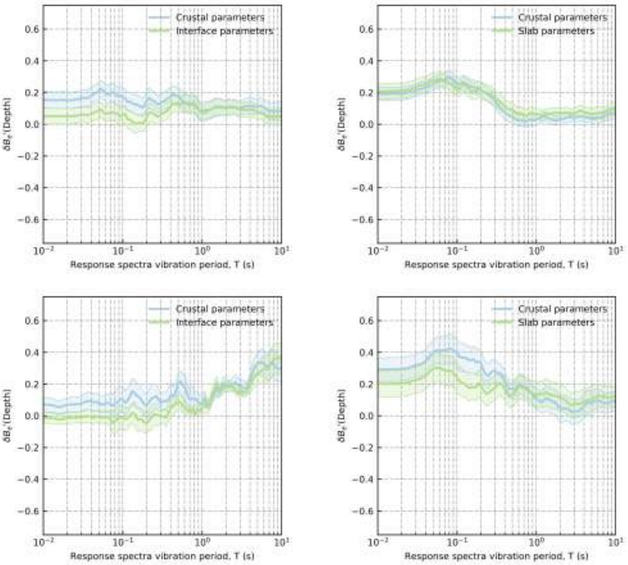


Depth dependence of δB_e: $\delta B_e'(Depth) = \Delta\delta B_e / \Delta CD$

Interface | Slab

$M_w < 5$

$M_w > 5$

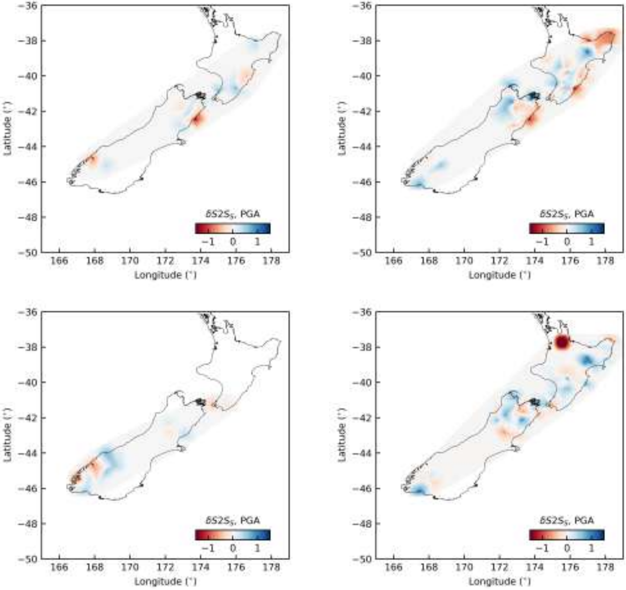


Distribution of $\delta S2S_s$—Crustal sim. parameters

Interface | Slab

$M_w < 5$

$M_w > 5$

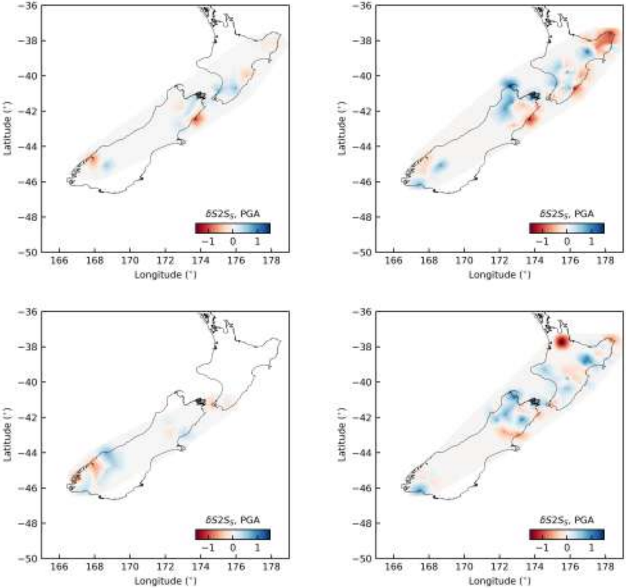


Distribution of $\delta S2S_s$—Subduction sim. parameters

Interface | Slab

$M_w < 5$

$M_w > 5$

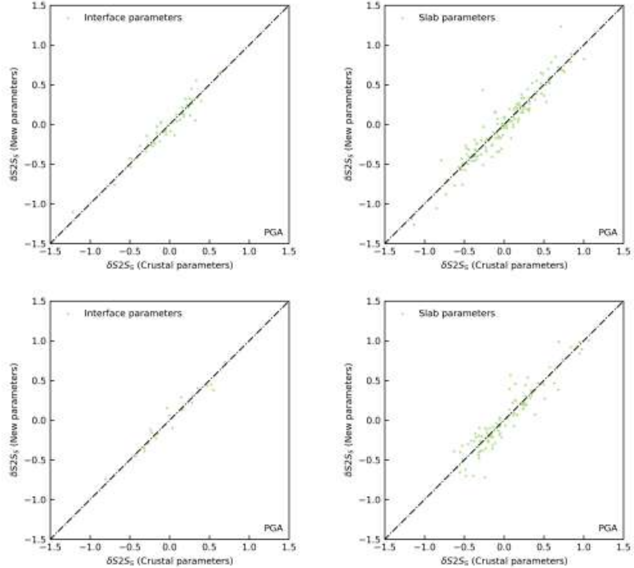


Correlation of $\delta S2S_s$

Interface | Slab

$M_w < 5$

$M_w > 5$



Thoughts?

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