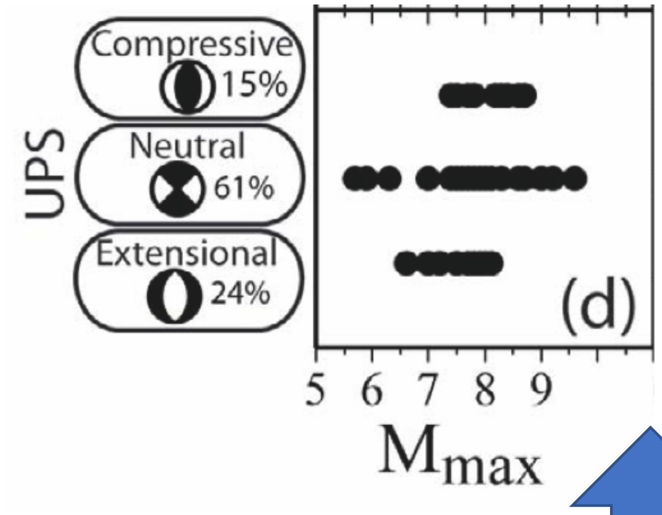
# Subduction zone seismo-dynamics:
# How mantle flow and geodynamic coupling may influence megathrust seismicity

Adam Beall [1.], Fabio Capitanio [2.], Ake Fagereng [1.], Ylona van Dinther [3.]
[1.] Cardiff University, UK [2.] Monash University, Australia [3.] Utrecht University, Netherlands

## *Global variations in margin-scale seismogenic behaviour*



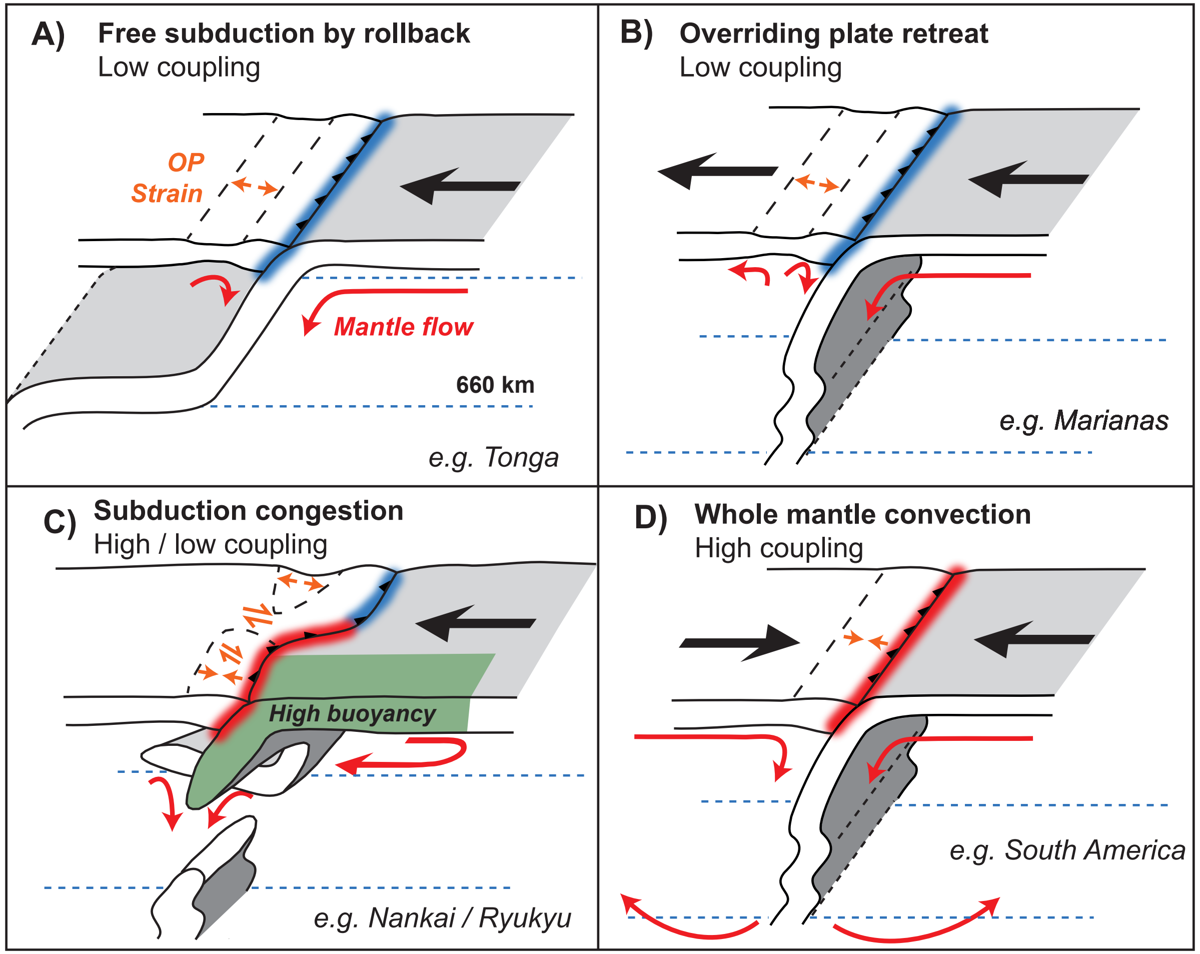

$M_w > 8$ hosted predominately by margins with back-arc shortening and especially strike-slip deformation (neutral)

Rarely by margins with back-arc extension

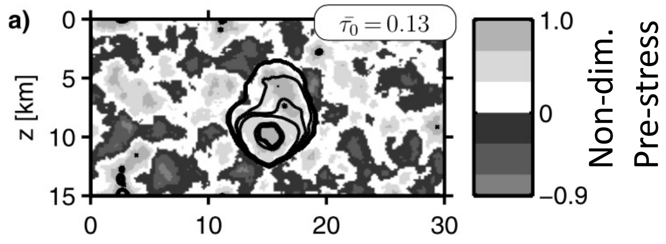
(Heuret et al. 2011)

## *Million year and margin scale geodynamics, idealised from models and geological/geophysical observation*

**Geodynamic Coupling Regimes**

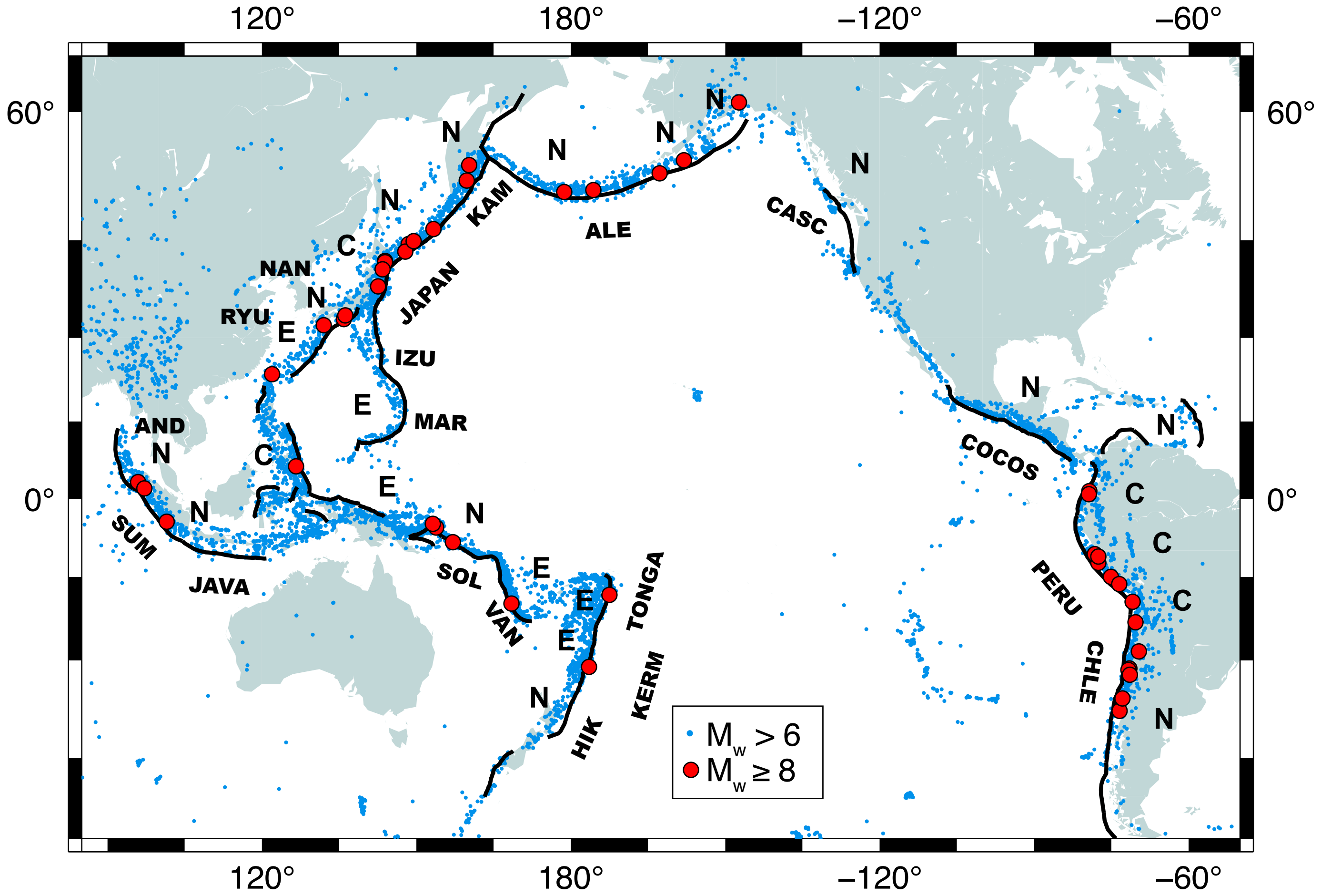



## *Role of regional stress on earthquake energetics and statistics in models and experiments*




Rupture arrest due to stress heterogeneity + low pre-stress (Ripperger et al. 2007)

# How may global variations in seismogenic behavior be influenced by mantle-scale dynamics?




Earthquakes 1900-2018, from USGS NEIC catalog and van Rijsingen (van Rijsingen et al. 2018 ).
C,E and N correspond to compressive, extensional and neutral (strike-slip) back-arc (Heuret et al. (2011)

The size of megathrust earthquakes has been associated with upper plate tectonic stress state (Uyeda and Kanamori, 1979; Heuret et al., 2011) where:

Back-arc extension ≈ few great earthquakes ($M_w$>8)

Back-arc shortening ≈ $M_w > 8$

Back-arc strike-slip ≈ $M_w > 8.5$

This association suggests a possible link between geodynamics and seismogenic behaviour. The dynamics or properties of individual margin segments do not clearly correlate with seismicity (Schellart and Rawlinson, 2011). *However, recent modelling indicates subduction dynamics involves complex 3-D processes influenced by global mantle flow.*

**We review the current understanding of how mantle-scale subduction dynamics influences the plate interface stress state at Myr and margin scales, and discuss implications for seismicity.**

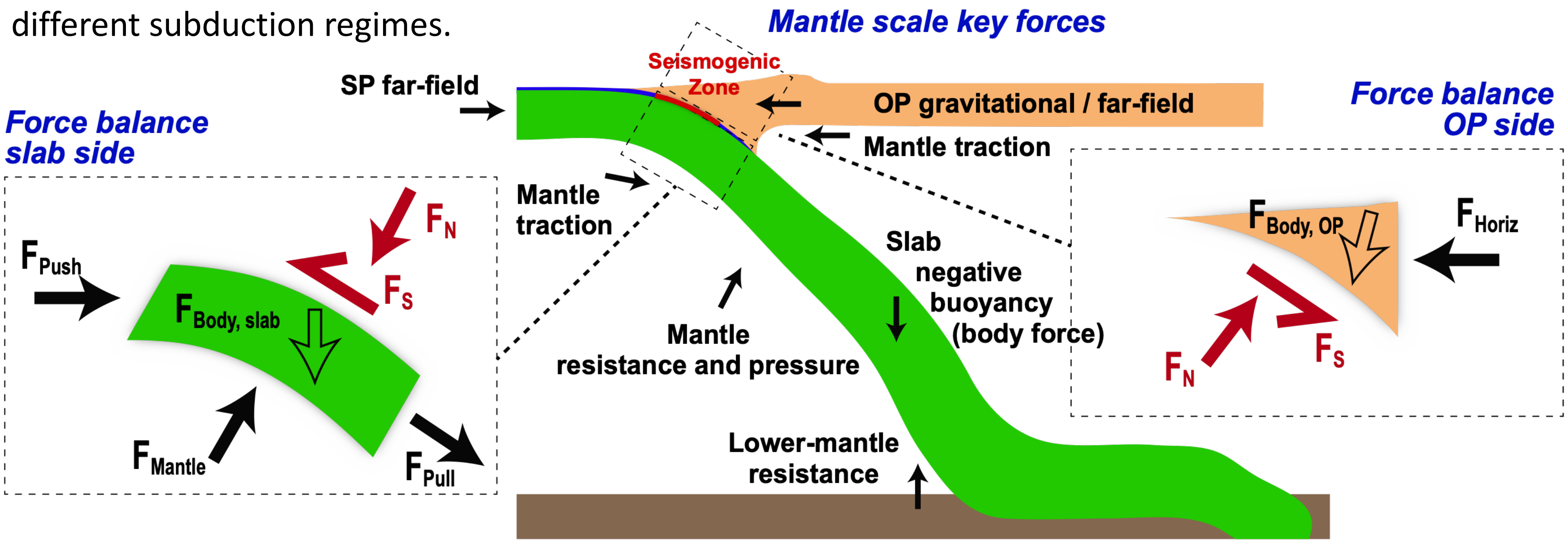
# Plate interface stress and geodynamic coupling

The plate interface stress state is rarely explicitly analysed in geodynamic models. However, it largely depends on how effectively forces are transmitted across the plate interface, referred to here as **geodynamic coupling**, which relates to how the forces driving subduction are balanced.

The key mantle-scale forces acting on the slab and plate interface are illustrated below.

This force balance fundamentally contrasts between different subduction regimes.

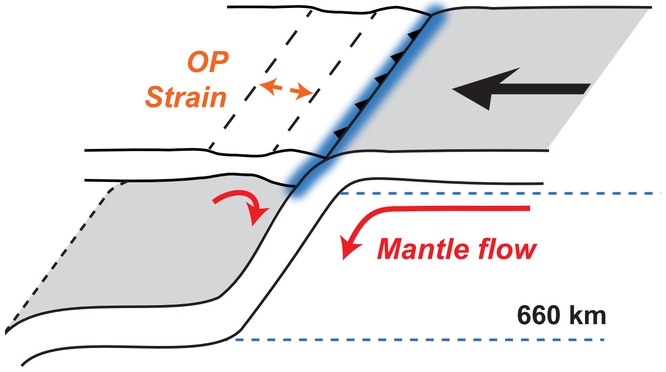
| High geodynamic Coupling ($F_N$ and $F_S$) | Low geodynamic Coupling ($F_N$ and $F_S$) |
| --- | --- |
| • High OP forcing / traction / topography<br>• Low mantle resistance (no rollback and short/torn slabs) | • Low OP forcing / traction / topography<br>• High mantle resistance (significant rollback and long slabs) |



# Geodynamic coupling regimes

We identify 4 subduction regimes associated with low or high geodynamic coupling

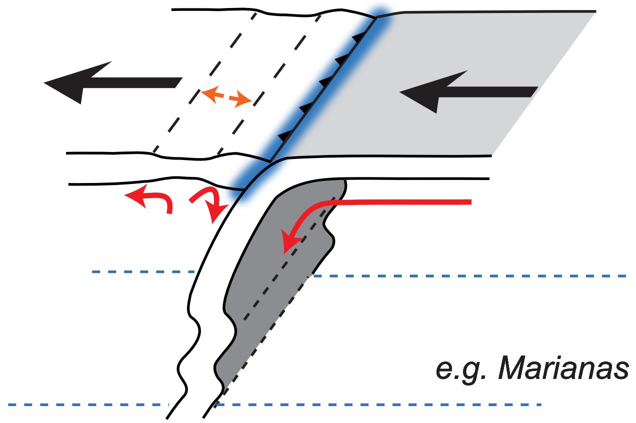
**A) Free subduction by rollback**
Low coupling




- Geodynamic coupling: **low**
- OP deformation: **back-arc extension**

- Subduction dominated by slab buoyancy and rollback, typically old sea-floor
- Slab rollback drives back-arc extension
- The slab stagnates at 660 km and mantle flow is asymmetric
- Examples: Tonga-Kermadec, Ryukyu ± Izu-Bonin
- Geodynamic models: Capitanio et al. (2007), Schellart et al. (2004)

**B) Overriding plate retreat**
Low coupling




- Geodynamic coupling: **low**
- OP deformation: **back-arc extension**

- OP is pulled away from the trench
- Convergent mantle flow towards the trench is low
- The slab can still penetrate the lower mantle and steepen
- Examples: Mariana ± Izu-Bonin
- Geodynamic models: Heuret et al. (2007), Holt et al. (2018)

# Geodynamic coupling regimes

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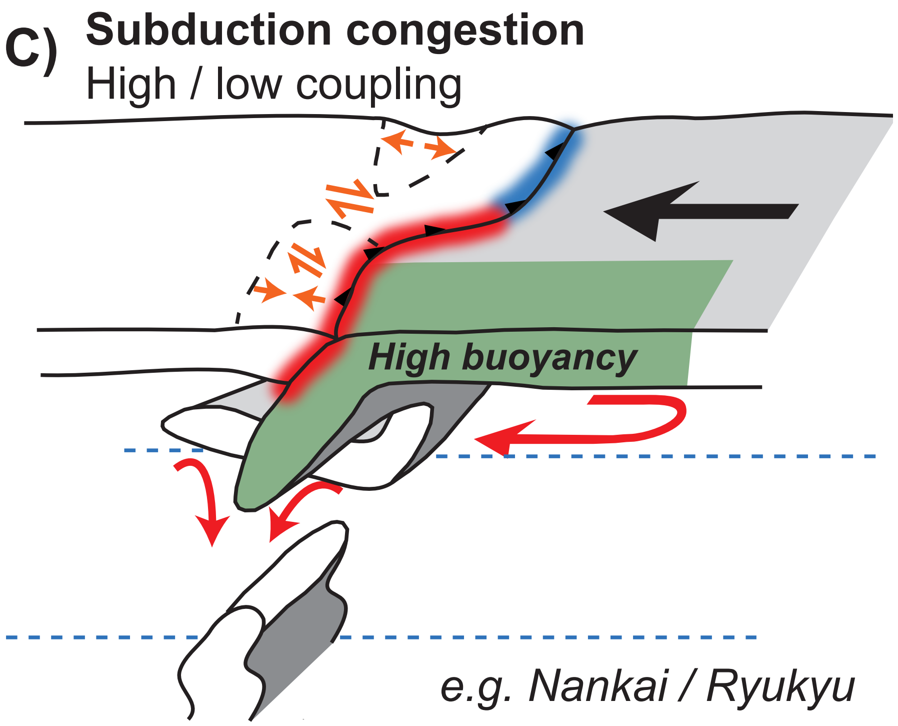


- Geodynamic coupling (*collision/rotated zone*): **high**
- OP deformation (*collision/rotated zone*): **fore-arc shortening** and **strike-slip deformation** (**'neutral' characterisation**)

- Geodynamic coupling (*escape zone*): **low**
- OP deformation (*escape zone*): **back-arc extension**

- Subduction affected by collision of a buoyant oceanic plate segment (sufficient to cause margin rotation or convergence slow-down)
- Margin segments with buoyant material and/or rotated margin segments experience trench advance or minimal rollback
- Margin segments away from buoyant material undergoe increased slab rollback (termed escape)

- Examples: Nankai/Ryukyu (high/low geodynamic coupling), Solomon Islands / Vanuatu (high/low), southern/northern Hikurangi (high/low), Hokkaido, Kamchatka, Cascadia, western Aleutian (oblique segment), Andaman (oblique segment), Sumatra
- Geodynamic models: Moresi et al. (2014), Magni et al. (2014)

# Geodynamic coupling regimes

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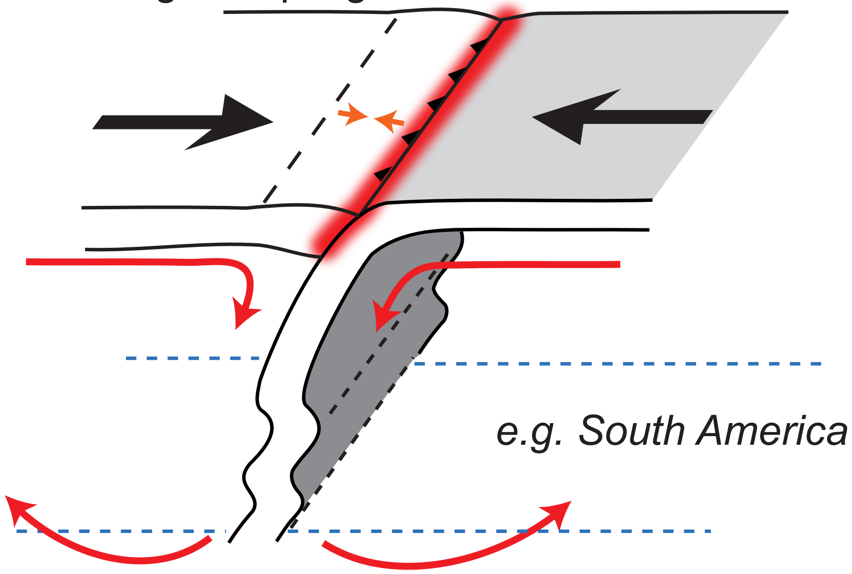
**D) Whole mantle convection**

High coupling




- Geodynamic coupling: **high**
- OP deformation: **back-arc shortening** (‘**<u>compression’ characterisation</u>**)

- Whole mantle convection drives plates together
- Upper-plate advance
- Slab penetrates the mantle for 20-50 Myrs, driving lower mantle flow
- Examples: South America ± central/northern Japan, Sumatra/Java
- Geodynamic models: Husson (2012), Faccenna et al. (2011), Schellart (2014)

# Preliminary Comparison of Geodynamic Regime and Seismicity

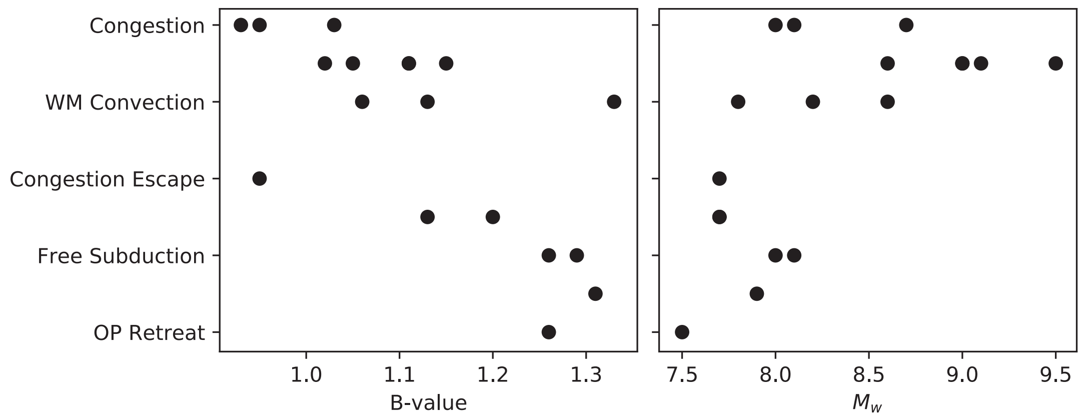
| ***Margin*** | ***B-value*** | ***$M_{max}$*** | ***Subduction Regime*** | ***Geodynamic Coupling*** | ***OP Regime** (Heuret et al. 2011)* | ***References (Geodynamics)*** |
|---|---|---|---|---|---|---|
| Chile | 1.02 | 9.5 | Congestion + Whole Mantle Convection | High | Neutral | Husson (2012), Russo et al. (2010) |
| NE Japan | 1.05 | 9.1 | Congestion + Whole Mantle Convection | High | Compression | Husson (2012), Kimura (1996) |
| Andaman | 1.11 | 9 | Congestion + Whole Mantle Convection | High | Neutral | Curray (2005) |
| Aleutian | 1.03 | 8.7 | Congestion | High | Neutral | Geist & Scholl (1994) |
| Kamchatka | 1.15 | 9 | Congestion + Whole Mantle Convection | High | Neutral | Geist & Scholl (1994) |
| Nankai | 0.95 | 8.1 | Congestion | High | Neutral | Raimbourg et al. (2017) |
| Solomon | 0.93 | 8 | Congestion | High | Neutral | Holm et al. (2016) |
| Sumatra | 1.11 | 8.6 | Congestion + Whole Mantle Convection | High | Neutral | Jacob et al. (2014), Pesicek et al. (2008) |
| Kuriles | 1.13 | 8.6 | Whole Mantle Convection | High | Neutral | Husson (2012) |
| Peru | 1.06 | 8.2 | Whole Mantle Convection | High | Compression | Husson (2012) |
| Vanuatu | 0.95 | 7.7 | Escape Rollback | Low | Extension | Schellart et al. (2006) |
| Hikurangi | 1.13 | 7.7 | Free Subduction Rollback | Low | Extension | Barnes et al. (1998); Strak & Schellart (2018) |
| Kermadec | 1.26 | 8.1 | Free Subduction Rollback | Low | Extension | Schellart et al. (2006) |
| Ryukyu | 1.2 | 7.7 | Free Subduction Rollback (+ Escape Rollback) | Low | Extension | Holt et al. (2018) |
| Tonga | 1.29 | 8 | Free Subduction Rollback | Low | Extension | Schellart et al. (2006) |
| Izu-Bonin | 1.31 | 7.9 | Free Subduction Rollback | Low | Extension | Hall et al. (2002) |
| Java | 1.33 | 7.8 | Whole Mantle Convection | High | Neutral | Husson (2012) |
| Marianas | 1.26 | 7.5 | Overriding Plate Retreat | Low | Extension | Holt et al. (2018) |

B-value - Nishikawa and Ide (2014), $M_{max}$ – USGS NEIC Catalog, OP Regime – Heuret et al. (2011)

The most seismogenic margins are commonly zones of subduction congestion (associated with OP transpression / neutral regime) and whole mantle convection.

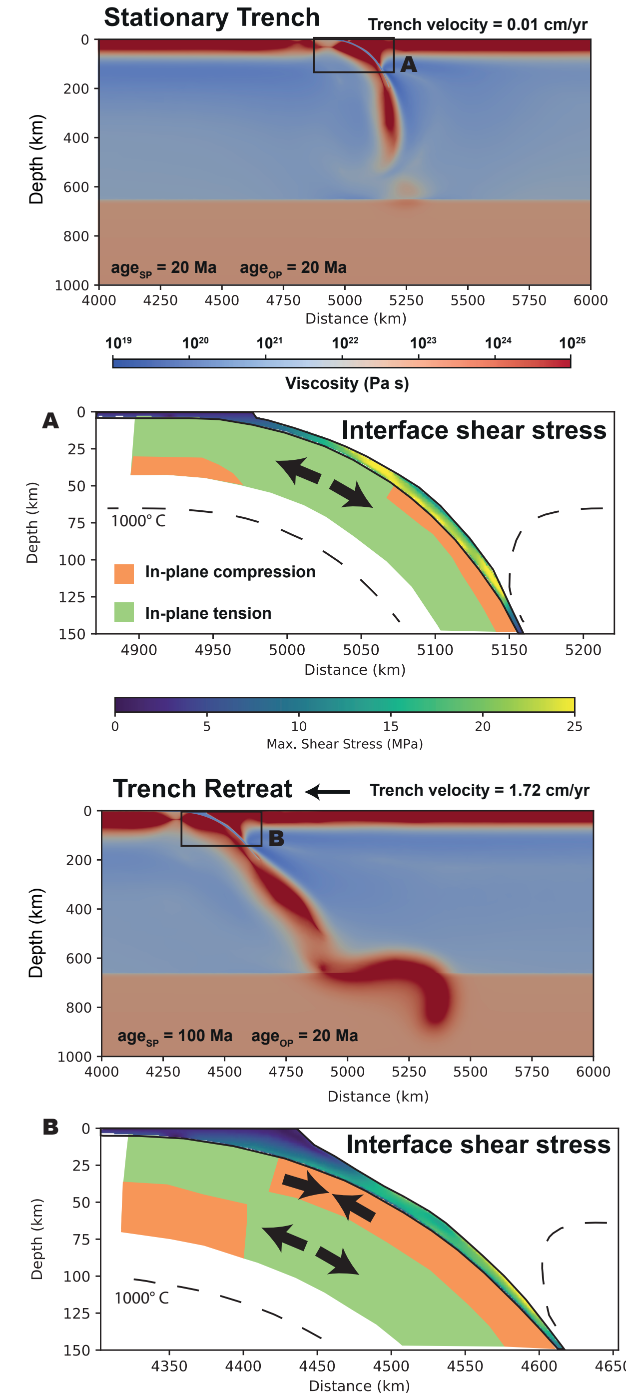
Margins hosting $M_w \geq 9$ appear to involve a combination of both geodynamic regimes.

These are preliminary characterisations, to be progressively tested with further plate interface stress constraint and understanding of regional geodynamics.



# Plate interface stress variation

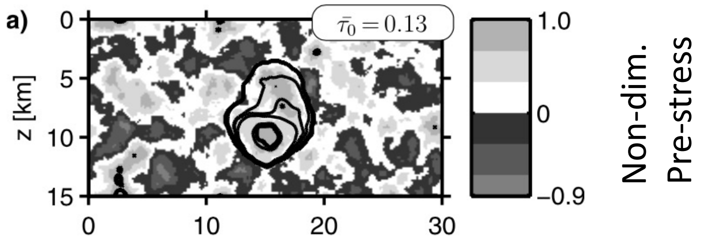
- Topography force balance indicates stress ranging from 10-50 MPa (Lamb 2003, Dielforder et al. 2020)
- Tectonic—earthquake cycle models also indicate stresses ranging from 10-50 MPa (van Dinther et al., 2013; Sobolev and Muldashev, 2017)
- Free subduction models indicate interface shear stress during slab rollback is 1.5-2x lower than when rollback is limited and slab break-off occurs (Beall et al., 2021).
- This stress contrast is sufficient to drive variation in earthquake rupture energetics (next slide) and is likely to be larger when 3-D congestion and whole mantle convection are considered.



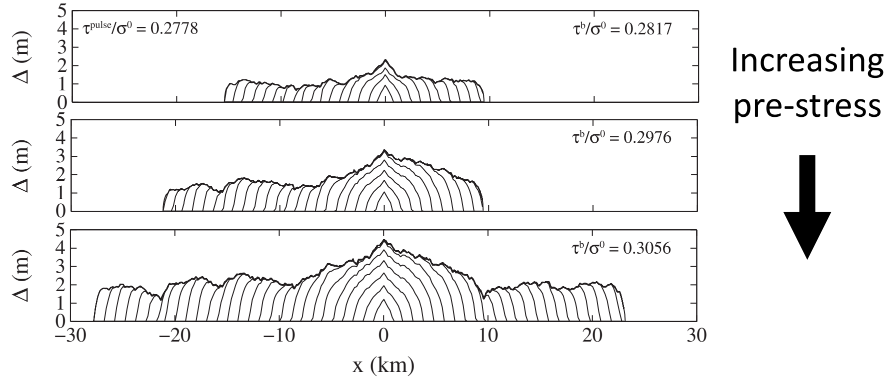

Beall et al. 2021

# Interface stress influencing seismic rupture

- How could long-term tectonic stress influence rupture dynamics? If the megathrust pre-stress follows the long-term shear stress, then a higher long-term stress may promote larger ruptures
- The propagation of a rupture through a heterogeneous stress field, rough fault or fault network greatly depends on prestress
- A 1.5x increase in pre-stress is enough to switch from a very low to high probability of whole fault rupture in the most heterogeneous rupture models of Ripperger et al. (2007) and Fang and Dunham (2007).
- The stress influence for 'smooth' faults, such as that hosting the 2011 Tohoku earthquake, is ambiguous, but may still involve earthquake nucleation on a deep asperity with high pre-stress




Rupture arrest on 2-D fault due to stress heterogeneity + low pre-stress (Ripperger et al. 2007)



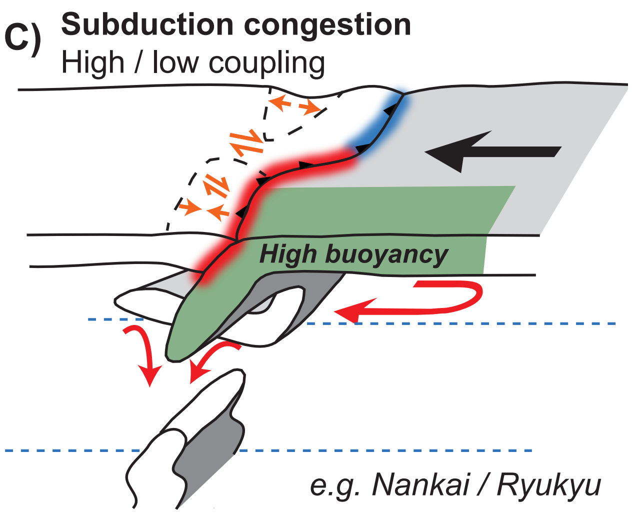

Fault slip vs position for 3 models with varying pre-stress (Fang and Dunham, 2007)

# Conclusions

- Geodynamic coupling depends on whole-mantle flow and interaction between margin segments, and even margins, over 10s Myrs – it cannot be predicted solely from margin segment data, cross-sections or without considering lower-mantle flow.

- There are distinct subduction regimes associated with the neutral and compression OP characterisations of Heuret et al. (2011) – '*subduction congestion*' and '*whole mantle convection*' respectively - both are associated with high geodynamic coupling

- The largest earthquakes commonly occur in regions of subduction congestion. How this geodynamic context influences seismogenesis should be further explored.



# Future integration of geodynamic and earthquake cycle modelling

- The modelling framework currently exists to:
  - Simulate how stress depends on 3-D whole mantle dynamics (e.g. Moresi et al. 2014), but the interface stress state needs to be explicitly constrained (e.g. Beall et al., 2021) and parameterized in smaller scale geodynamic models
  - Simulate rupture dynamics depending on pre-stress initial conditions (e.g. Fang and Dunham, 2007)
  - Couple or link geodynamics and earthquake rupture to understand the interplay between tectonic stress and seismicity (van Dinther et al., 2013; Herrendörfer et al., 2018; and van Zelst et al., 2019, resp.)
- Each of these methods covers different spatial-temporal scales, physics modelled and accuracy – ongoing integration (implicit and explicit) between all three is required
- Further constraint of how seismic coupling varies is also required, as well as an understanding of the relative influences of whole margin dynamics (this review) and megathrust-scale properties (sediment thickness, sea-floor roughness, etc.), to constrain how long-term and seismic coupling relate

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