Earthquake rupture properties and tsunamigenesis in the shallowest megathrust

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Upper-plate rigidity determines depth-varying rupture behaviour of megathrust earthquakes

Subduction megathrust earthquakes result from episodic, unstable sliding within the subducting oceanic plate and the associated generation of seismic waves that can propagate upward from this interface, as evidenced for the 2011 Tohoku-Oki event (moment magnitude, Mw of 9.0). While events forming a particular class known as ‘‘twin earthquakes’’ appear to rupture only the shallowest, allegedly non-seismogenic part of the megathrust (Fig. 1). The seemingly analogous characteristics of shallow ruptures suggest a depth dependency of the rupture process,7 commonly attributed to changes in fault properties.8 However, current conceptual models trying to explain the different forces and shear strain across the interface, it must be noted that the relationship between the depth variations of the elastic properties of the overriding plate at a large scale. The hypothesis is based on the fact that down-dip seismic slip and strain energy decreases with the strain characterized by permanent deformation.9,10 Overriding plates display widespread contractional structures indicating a dominant sublithospheric principal compression stress, whereas oceanic plates are dominated by extensional faults, implying an increase in the orientation of the principal stresses across the megathrust. Sedimentary strata of subducting plates have sub-horizontal attitudes, typically lack contractional deformation and are not disrupted by normal faults, supporting the idea that the principal compressional stresses are sub-vertical immediately below the megathrust. Thus, the distribution of tectonic structures and the inferred orientation of principal stresses support the idea that the elastic energy released during megathrust earthquakes has accumulated in overlying plates (Fig. 1). Consequently, co-seismic deformation should affect overriding plates, with negligible effects on the subducting plates. Hence, the recorded fault history indicates that the elastic properties of the overriding plate need to be considered.

Sallarès & Ranero (2019) from here on.
Upper and lower plate have contrasting patterns of permanent deformation
~90° rotation of the main stresses
Upper plate deformation, faulting and hence fracturing increase trench-ward
Numerous evidences from worldwide margins and different geophysical data indicates fracturing increasing trench-ward.
Compilation of 48 WAS $V_P$ models at Circum-Pacific and Indian ocean subduction zones (31 in erosional margins, 17 in accretionary margins)
Only models that include Vp distribution and inter-plate geometry → digitize seafloor & inter-plate boundary depth + Vp above inter-plate boundary

Clear systematic, universal trend of $V_P$ increase with upper plate thickness regardless of crustal lithology and margin type
Upper-plate elastic parameters

We estimate $\rho(V_p)$, $V_s(V_p)$ from Brocher (2005)

Then rigidity $\mu(\rho, V_s)$

$\mu = \rho V_s^2$

$u$ is rupture speed

Sallarès & Ranero (2019)
The base of the upper plate above the seismogenic zone is increasingly fractured towards the trench, mainly reflecting compaction due to lithostatic burden. The resulting depth-dependent rigidity explains differences between shallow and regular EQs.
Relative rupture properties as a function of depth

Rock properties as a function of depth:
\( V_p/s(z), \mu(z), u(z) \)…

Relative rupture properties as a function of depth

Reference rock properties:
\( V_p/s^*, \mu^*, u^* \)

Sallarès & Ranero (2019)
1) Co-seismic slip

\[ M_0 = \int_S \mu D ds \approx \bar{\mu} \bar{D} S \]

- \( M_0 \): Seismic moment
- \( \mu \): Rigidity
- \( D (\delta) \): Slip
- \( S \): Rupture area

\[ D_R(z) = \frac{D(z)}{D^*} = \frac{\mu^*}{\mu(z)} \]

If we have two earthquakes of the same rupture surface, \( S \), and seismic moment, \( M_0 \) (so same \( M_W \)), one occurring at the regular domain and the other at the shallow domain, then

\( D_s \) should be up to 5-10 times larger than \( D_d \).
2) Earthquake duration

$T_R(z) = \frac{T(z)}{T^*} = \frac{u^*}{u(z)} = \frac{V_S^*}{V_S(z)}$

$T_s$ should be up to 2-3 times longer than $T_d$ because they propagate 2-3 times slower

Sallarès & Ranero (2019)
3) High frequency depletion (subdued seismic shaking)

\[ f_c = cV_s \left( \frac{\Delta a}{M_o} \right)^{\frac{1}{3}} \]

\[ M(f) = \frac{M_0 f_c^n}{f^n + f_c^n} \]

\[ f_R(z) = \frac{f_c(z)}{f_c} = \frac{V_S(z)}{V_s} = T_R(z)^{-1} \]

\( f_s \) should be up to 1-2 octaves lower than \( f_d \) due to the \( V_s \) decay

Sallarès & Ranero (2019)
4) M\(_W\)-M\(_S\) discrepancy

For a M\(_W\) 7.5 earthquake, discrepancy due to M\(_0\) alone is of 0.2-0.3

However, V\(_S\) variation with depth can account for a difference of up to 0.7-0.8

Average M\(_W\)-M\(_S\) for tsunami EQs is 0.65

Sellarès & Ranero (2019)
Conceptual model

Explains well global trends of characteristics and differences between shallow and deeper (regular) ruptures

Show that tsunami earthquakes are not ‘anomalous’ in terms of rupture properties

Sallarès & Ranero (2019)

DOES IT EXPLAIN RUPTURE OF INDIVIDUAL EVENTS?
The 1992 Nicaragua tsunami earthquake

$M_w$ 7.6-7.8; $M_s$ 7.0-7.2
Depleted on high frequencies (moderate shaking)
Long duration (>100 s), slow propagation
Triggered a large tsunami (up to 10m high)
Nucleated at ~20 km depth
Large moment release near the trench

Kanamori & Kikuchi (1993)
Depth-varying elastic properties

Brocher’s (2005) Vp-Vs & Vp-ρ empirical relationships
Rupture characteristics: Slip

\[ M_0 = \int_S \mu D dS \approx \mu \bar{D} S \]

\( M_0 \) Moment (Ihmlé, 1996)
\( \mu \) Shear modulus (our models)
\( D \) Slip
\( S \) rupture area (subfaults of 10x10 km)

Maximum slip of >10 m at the trench

**Consistent with tsunami modelling**, which requires larger near-trench co-seismic slip at trench than estimated from seismological data alone (constant \( \mu \))
Rupture characteristics: $f_c$ & high frequency depletion

Observed moment-rate from Ye et al (2013) *EPSL*

$$f_c = cV_S \left( \frac{\Delta \sigma}{M_0} \right)^{\frac{1}{3}}$$

$\Delta \sigma = 3 \text{ MPa}$

$$\dot{M}(f) = \frac{M_0 f_c^n}{f^n + f_c^n}$$