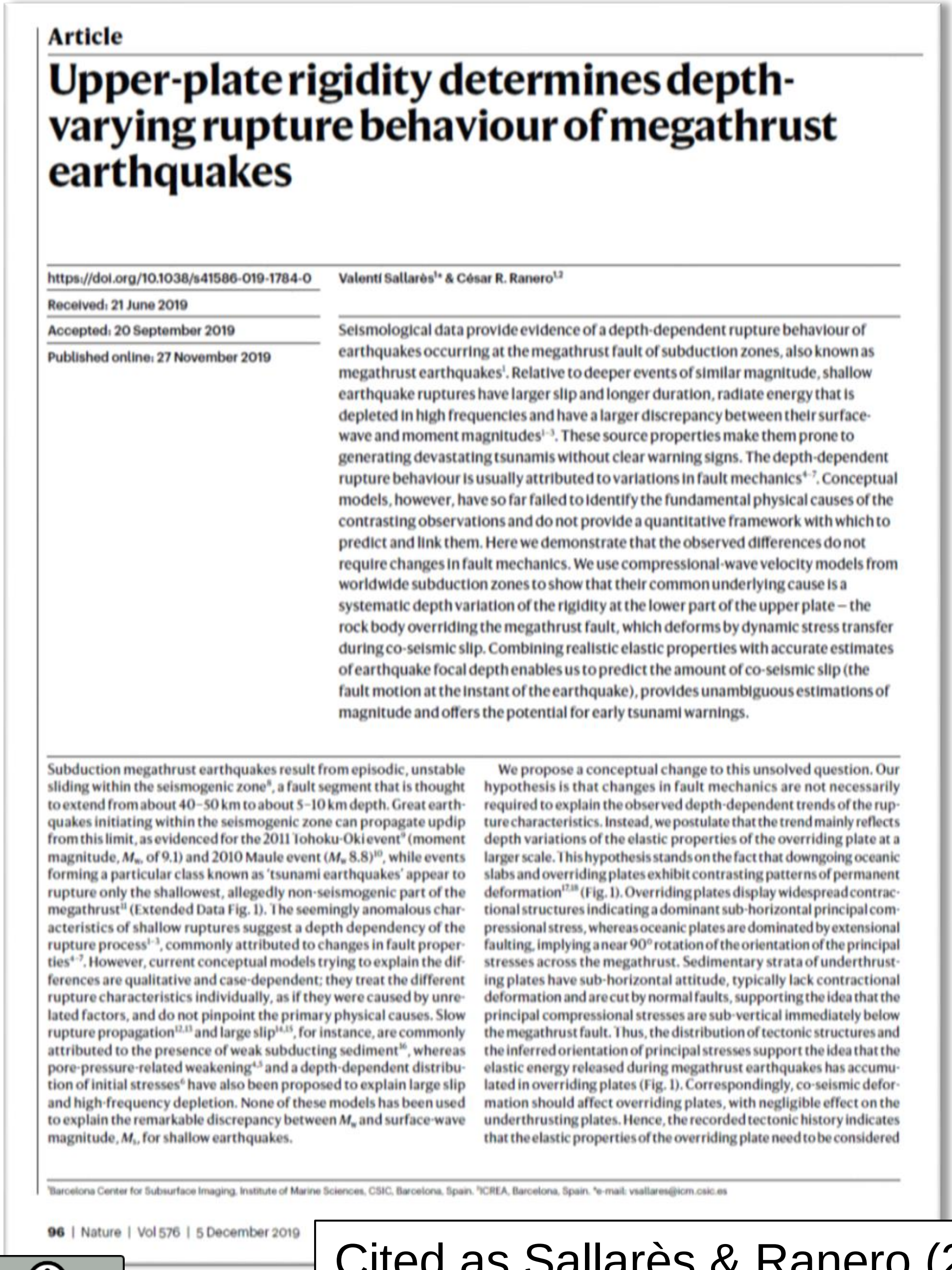
# Earthquake rupture properties and tsunamigenesis in the shallowest megathrust

**V. Sallarès,** C. R. Ranero, M. Prada, A. Calahorrano

Barcelona CSI
Center for Subsurface Imaging

ICM

CSIC



Article

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

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Valentí Sallarès[1*] & César R. Ranero[1,2]

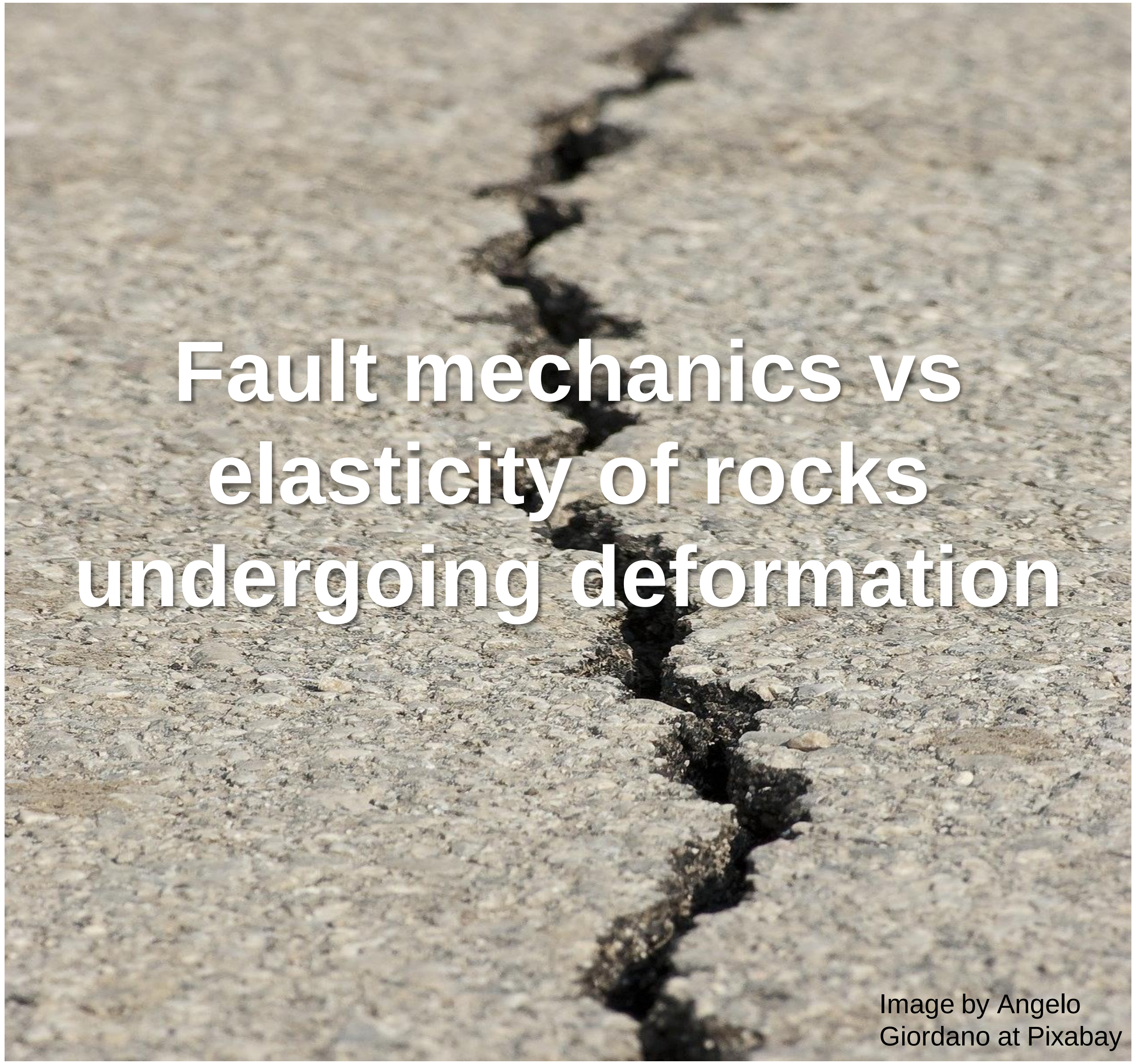
Seismological data provide evidence of a depth-dependent rupture behaviour of earthquakes occurring at the megathrust fault of subduction zones, also known as megathrust earthquakes[1]. Relative to deeper events of similar magnitude, shallow earthquake ruptures have larger slip and longer duration, radiate energy that is depleted in high frequencies and have a larger discrepancy between their surface-wave and moment magnitudes[1–3]. These source properties make them prone to generating devastating tsunamis without clear warning signs. The depth-dependent rupture behaviour is usually attributed to variations in fault mechanics[4–7]. Conceptual models, however, have so far failed to identify the fundamental physical causes of the contrasting observations and do not provide a quantitative framework with which to predict and link them. Here we demonstrate that the observed differences do not require changes in fault mechanics. We use compressional-wave velocity models from worldwide subduction zones to show that their common underlying cause is a systematic depth variation of the rigidity at the lower part of the upper plate – the rock body overriding the megathrust fault, which deforms by dynamic stress transfer during co-seismic slip. Combining realistic elastic properties with accurate estimates of earthquake focal depth enables us to predict the amount of co-seismic slip (the fault motion at the instant of the earthquake), provides unambiguous estimations of magnitude and offers the potential for early tsunami warnings.

Subduction megathrust earthquakes result from episodic, unstable sliding within the seismogenic zone[8], a fault segment that is thought to extend from about 40–50 km to about 5–10 km depth. Great earthquakes initiating within the seismogenic zone can propagate updip from this limit, as evidenced for the 2011 Tohoku-Oki event[9] (moment magnitude, $M_w$, of 9.1) and 2010 Maule event ($M_w$ 8.8)[10], while events forming a particular class known as 'tsunami earthquakes' appear to rupture only the shallowest, allegedly non-seismogenic part of the megathrust[11] (Extended Data Fig. 1). The seemingly anomalous characteristics of shallow ruptures suggest a depth dependency of the rupture process[1–3], commonly attributed to changes in fault properties[4–7]. However, current conceptual models trying to explain the differences are qualitative and case-dependent; they treat the different rupture characteristics individually, as if they were caused by unrelated factors, and do not pinpoint the primary physical causes. Slow rupture propagation[12,13] and large slip[14,15], for instance, are commonly attributed to the presence of weak subducting sediment[16], whereas pore-pressure-related weakening[4,5] and a depth-dependent distribution of initial stresses[6] have also been proposed to explain large slip and high-frequency depletion. None of these models has been used to explain the remarkable discrepancy between $M_w$ and surface-wave magnitude, $M_s$, for shallow earthquakes.

We propose a conceptual change to this unsolved question. Our hypothesis is that changes in fault mechanics are not necessarily required to explain the observed depth-dependent trends of the rupture characteristics. Instead, we postulate that the trend mainly reflects depth variations of the elastic properties of the overriding plate at a larger scale. This hypothesis stands on the fact that downgoing oceanic slabs and overriding plates exhibit contrasting patterns of permanent deformation[17,18] (Fig. 1). Overriding plates display widespread contractional structures indicating a dominant sub-horizontal principal compressional stress, whereas oceanic plates are dominated by extensional faulting, implying a near 90° rotation of the orientation of the principal stresses across the megathrust. Sedimentary strata of underthrusting plates have sub-horizontal attitude, typically lack contractional deformation and are cut by normal faults, supporting the idea that the principal compressional stresses are sub-vertical immediately below the megathrust fault. 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 overriding plates (Fig. 1). Correspondingly, co-seismic deformation should affect overriding plates, with negligible effect on the underthrusting plates. Hence, the recorded tectonic history indicates that the elastic properties of the overriding plate need to be considered

[1]Barcelona Center for Subsurface Imaging, Institute of Marine Sciences, CSIC, Barcelona, Spain. [2]ICREA, Barcelona, Spain. *e-mail: vsallares@icm.csic.es

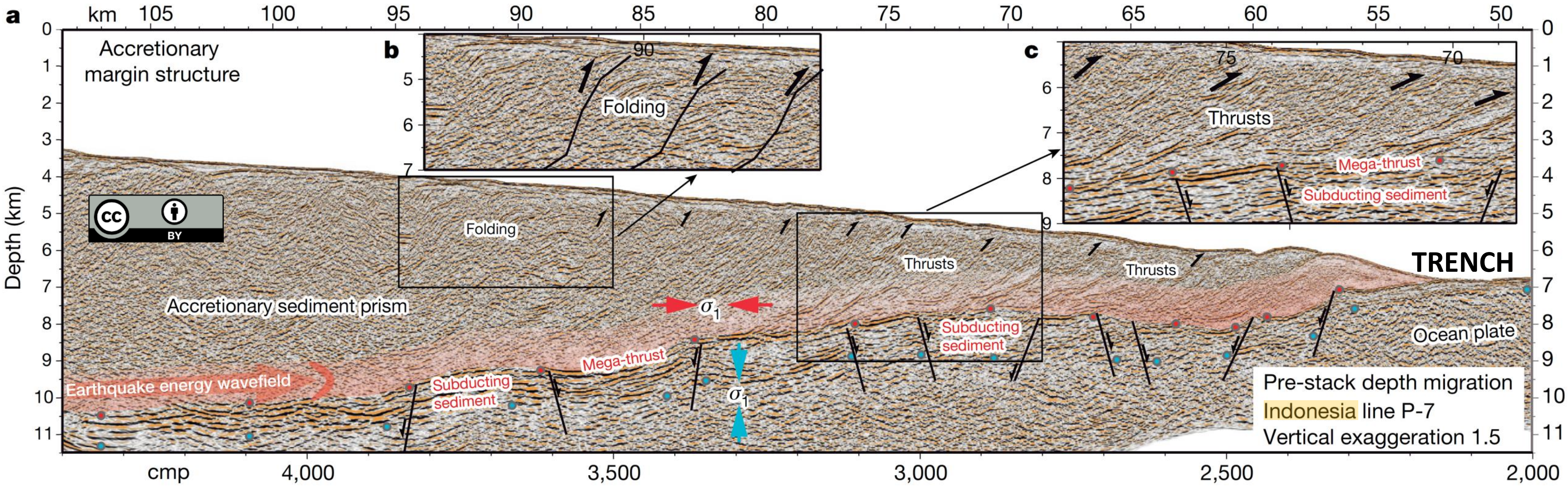





Cited as Sallarès & Ranero (2019) from here on

# Geophysical data (Multichannel Reflection Seismics, MCS)

Sallarès & Ranero (2019)

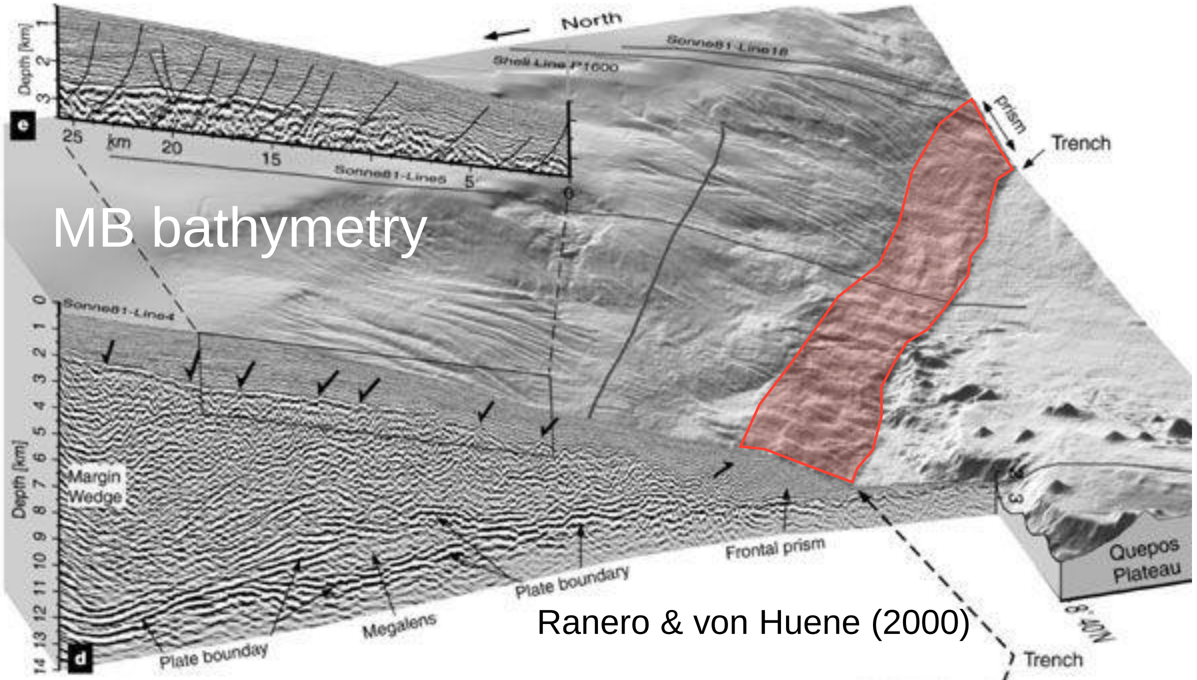



Upper and lower plate have contrasting patterns of permanent deformation

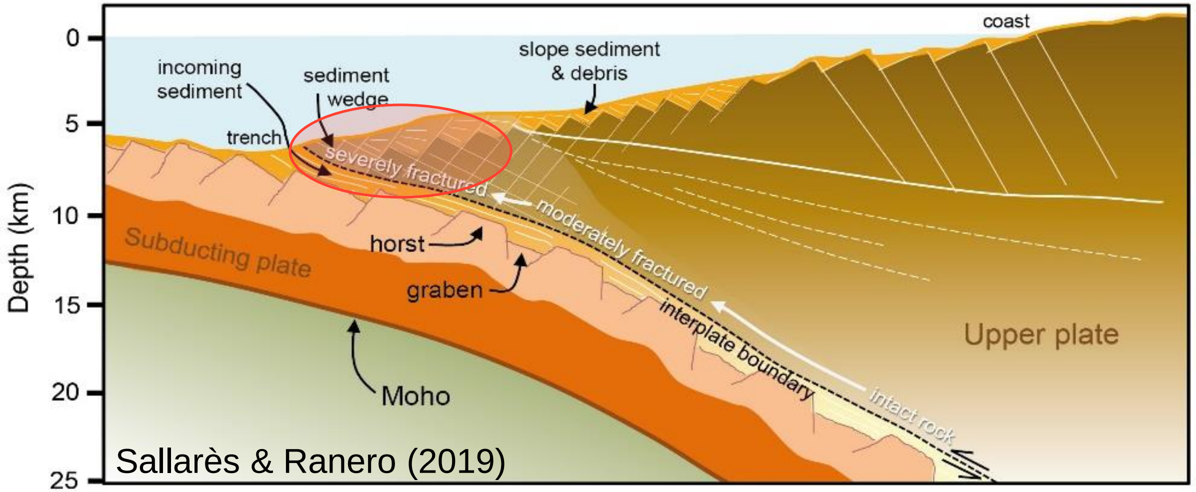
~90º rotation of the main stresses

Upper plate deformation, faulting and hence fracturing increase trench-ward

# Other geophysical data

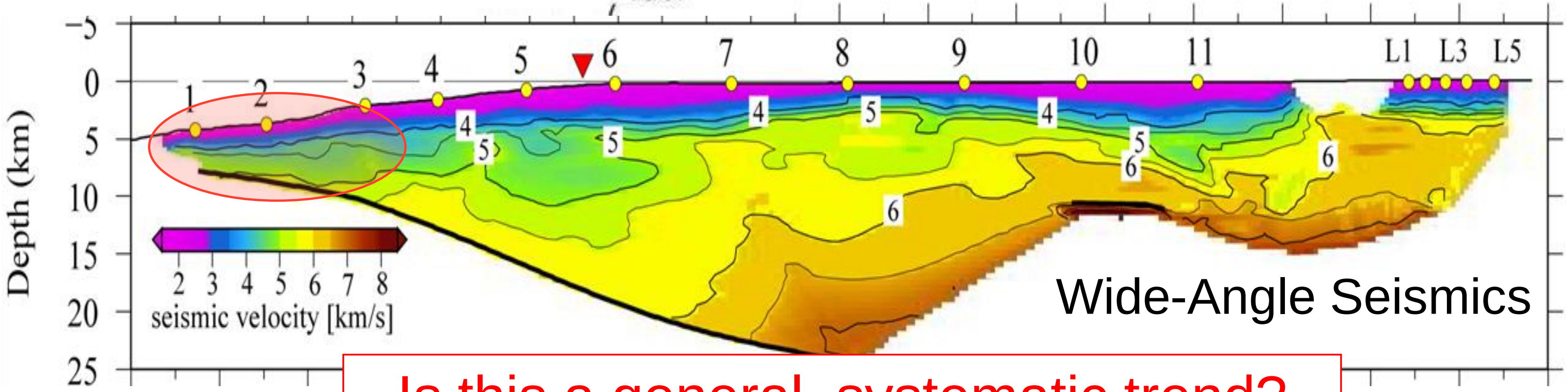



Ranero & von Huene (2000)



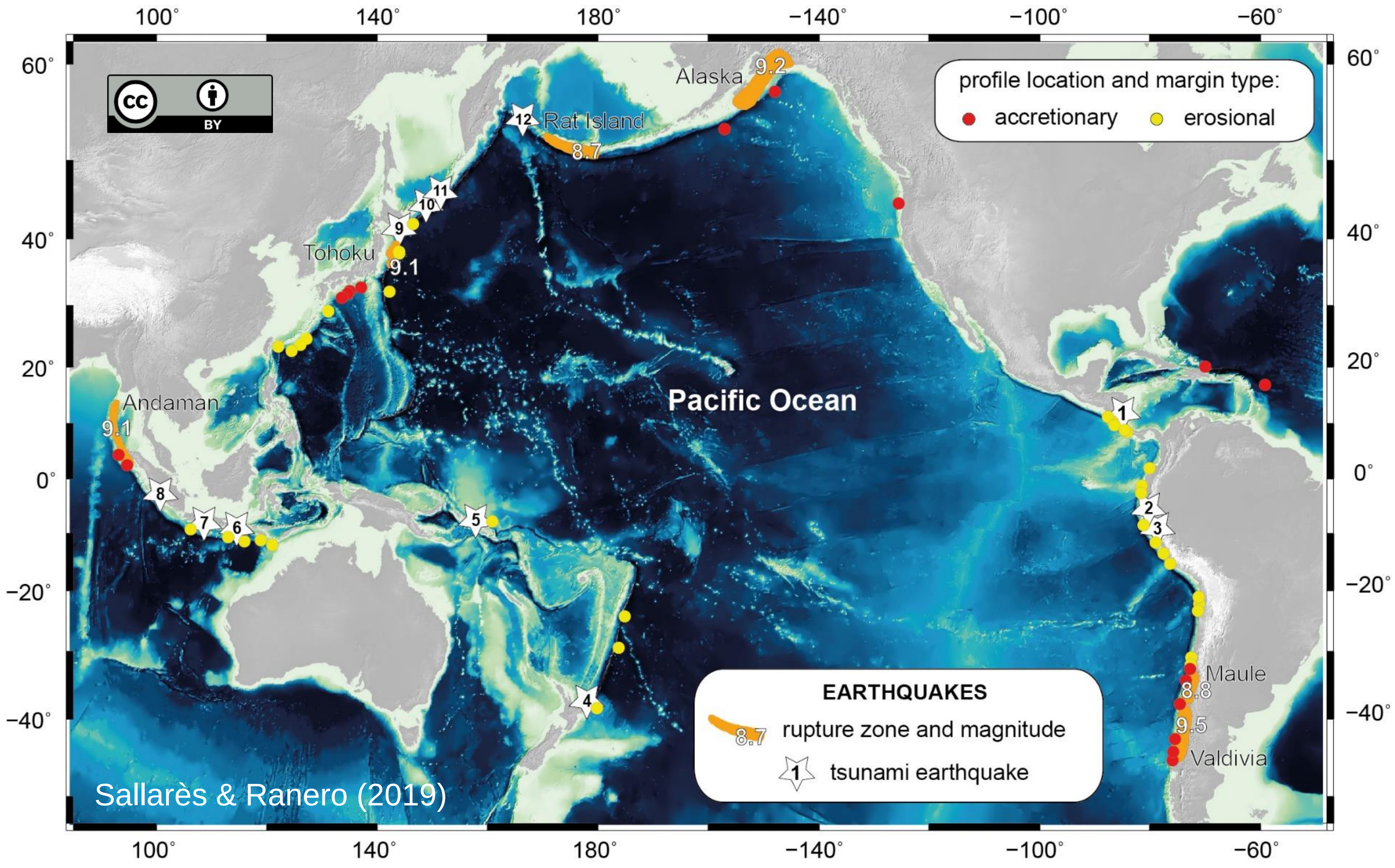

Sallarès & Ranero (2019)

Numerous evidences from worldwide margins and different geophysical data indicates fracturing increasing trench-ward



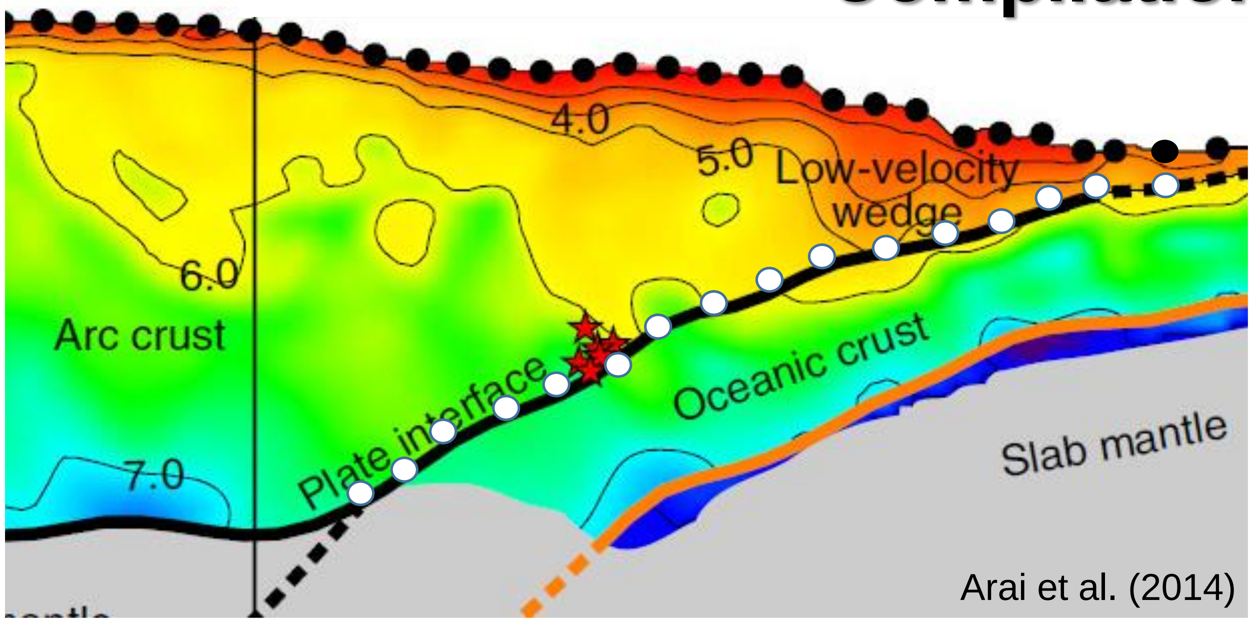

Is this a general, systematic trend?

Sallares et al (2013)



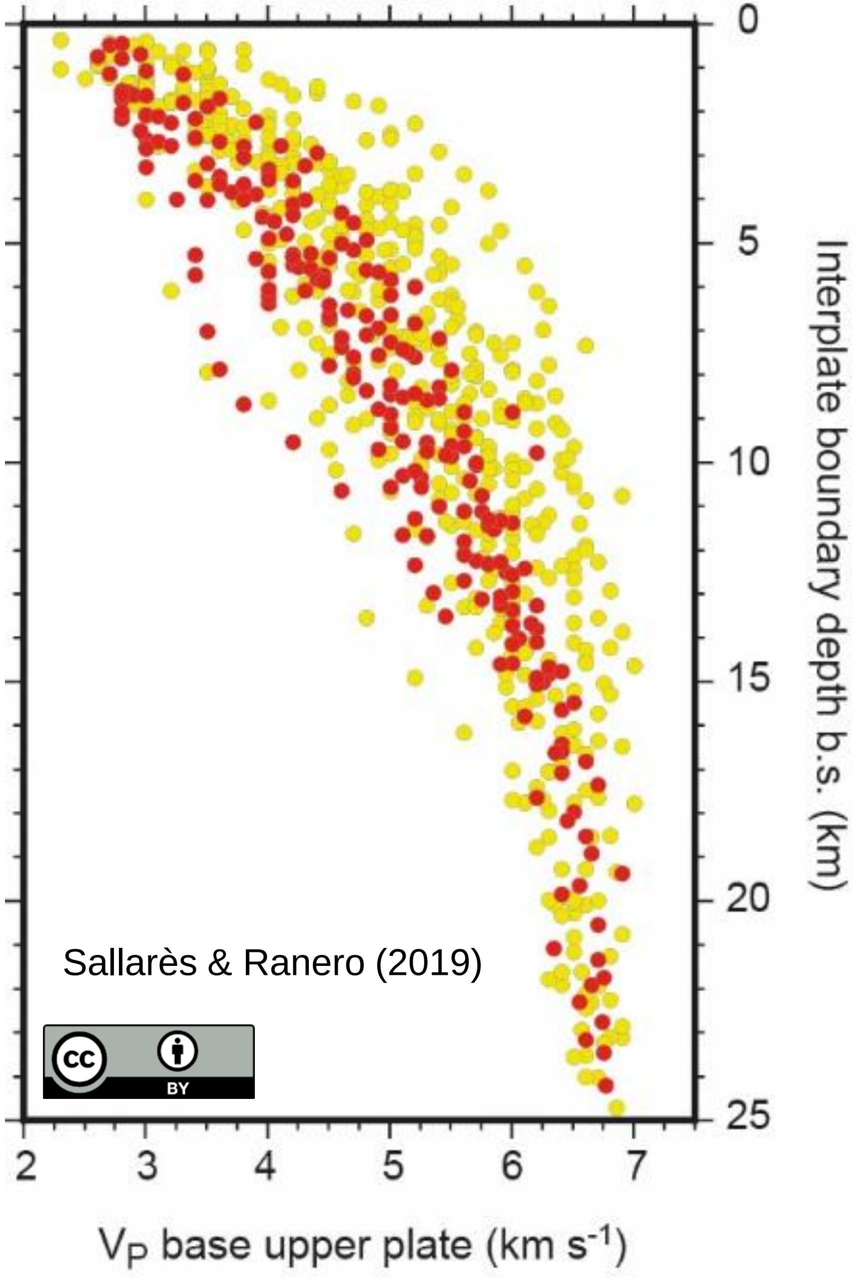

Compilation of 48 WAS $V_P$ models at Circum-Pacific and Indian ocean subduction zones (31 in erosional margins, 17 in accretionary margins)

# Compilation




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

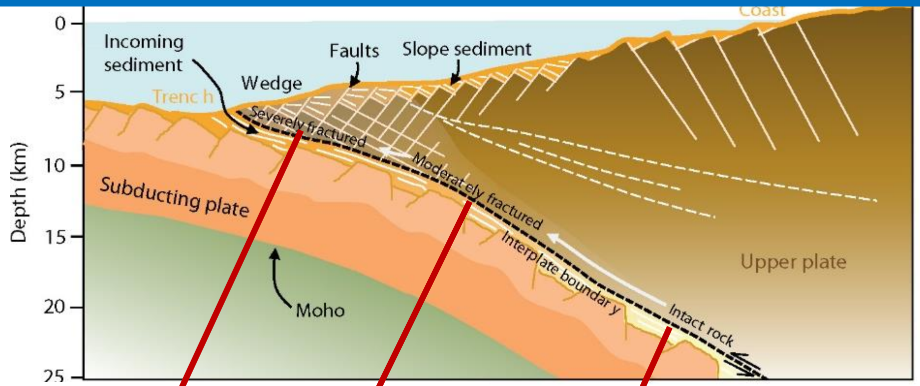


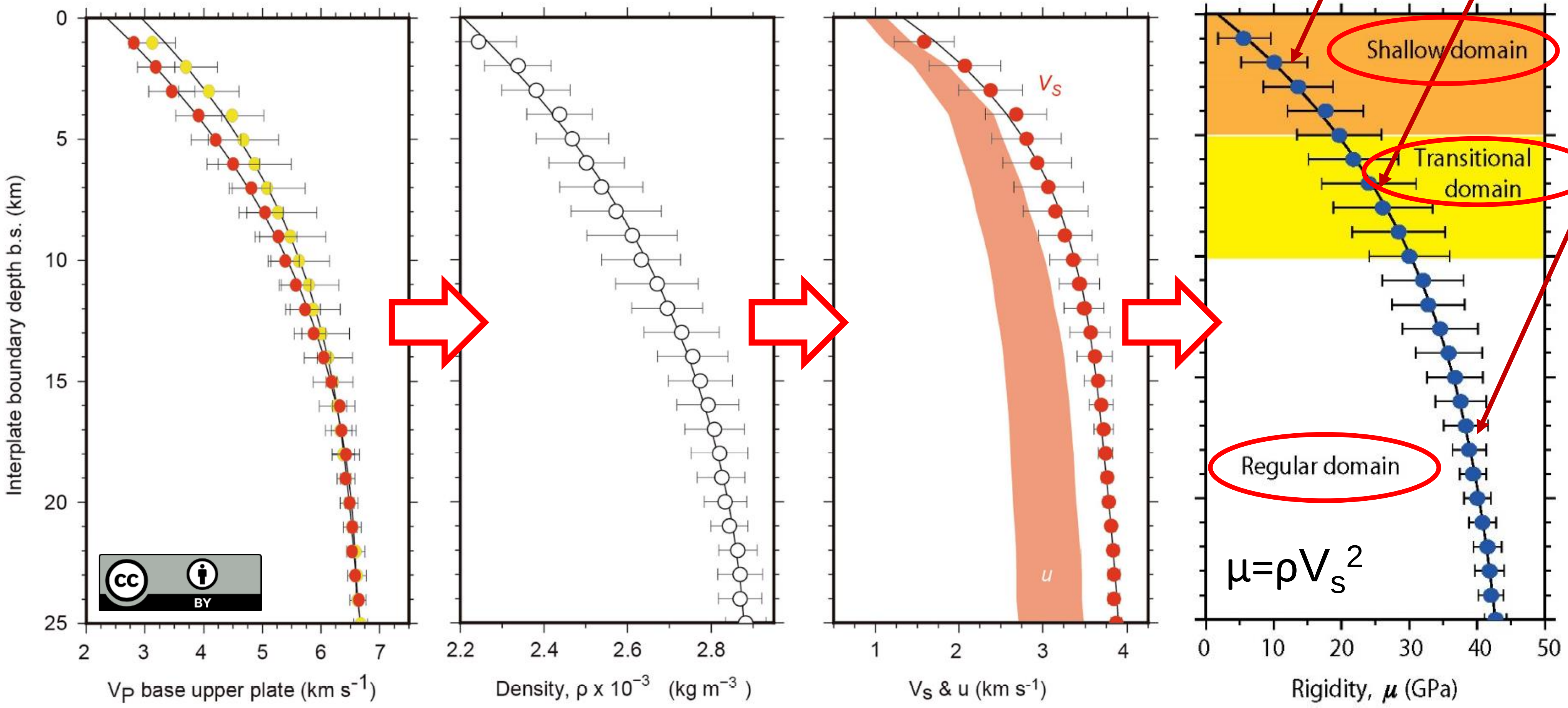
# Upper-plate elastic parameters

We estimate ρ(Vp), Vs(Vp) from Brocher (2005)

Then rigidity μ(ρ, Vs)

u is rupture speed

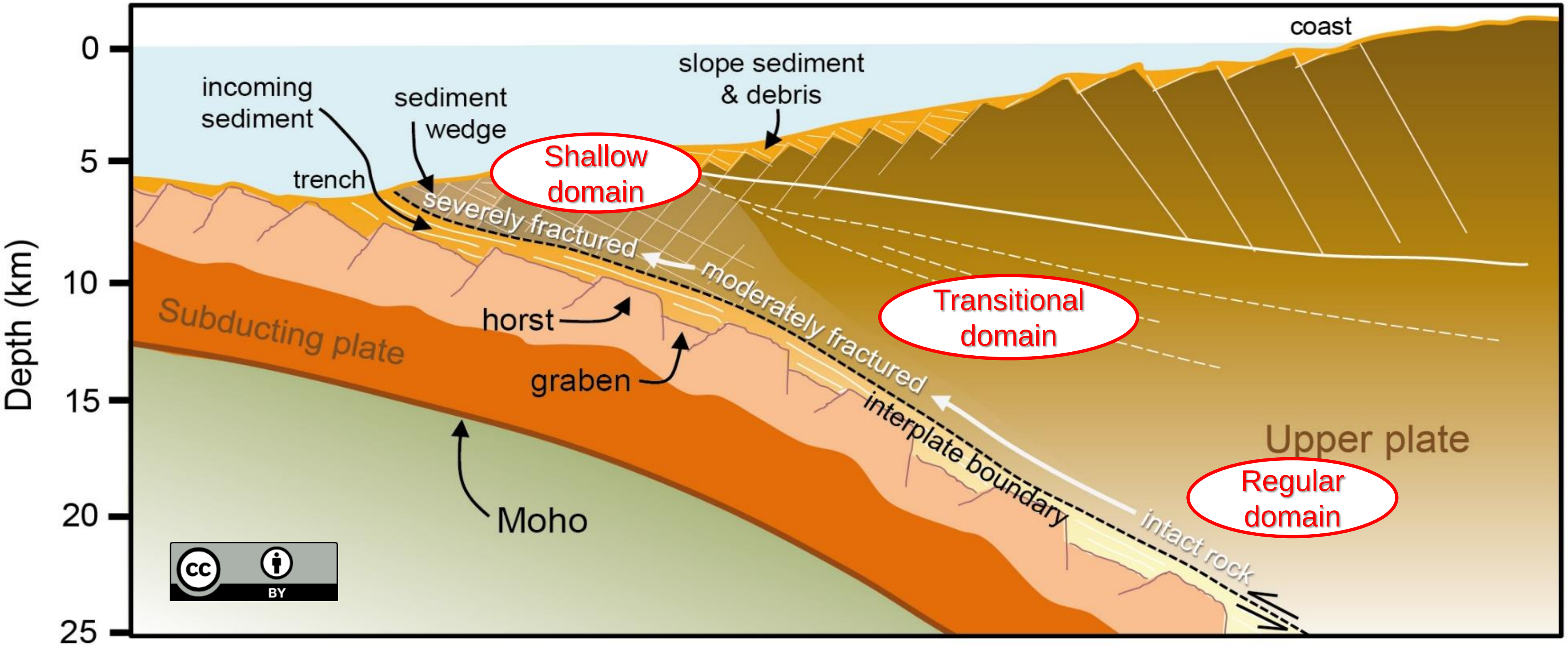



$\mu = \rho V_s^2$

Sallarès & Ranero (2019)

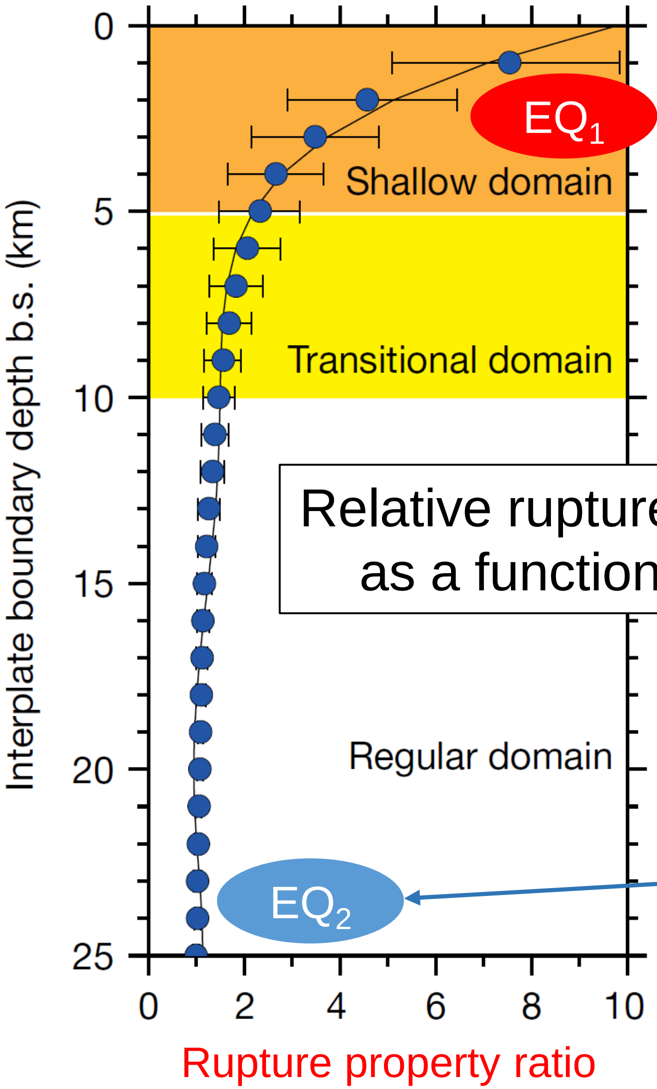
# The physical model




Sallarès & Ranero (2019)

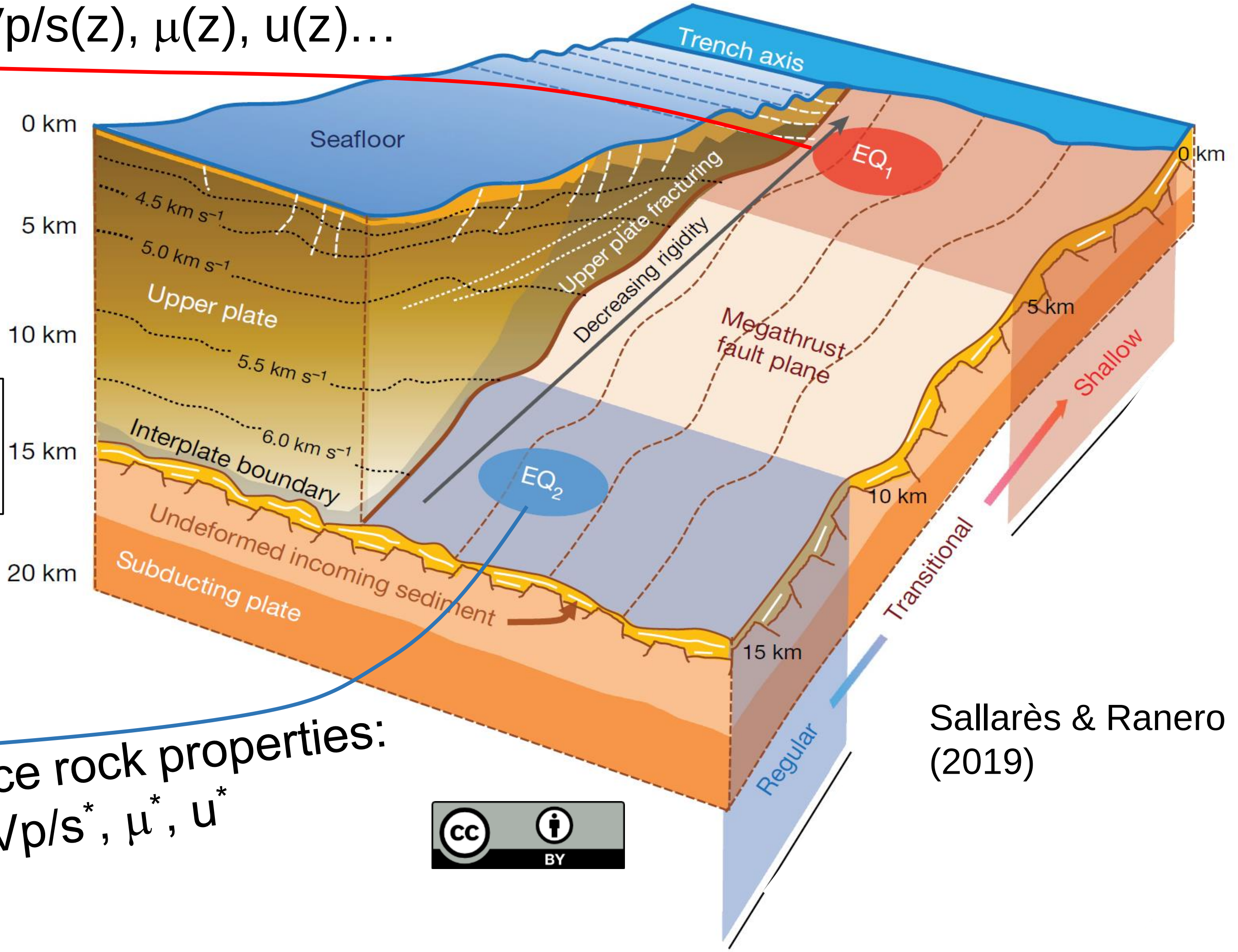
The base of the upper plate above the seismogenic zone is increasingly fractured towards the trench, mainly reflecting compaction due to lithostatic burden. The resulting depth-dependent rigidity explains differences between shallow and regular EQs.

# Relative rupture properties as a function of depth




Relative rupture properties as a function of depth

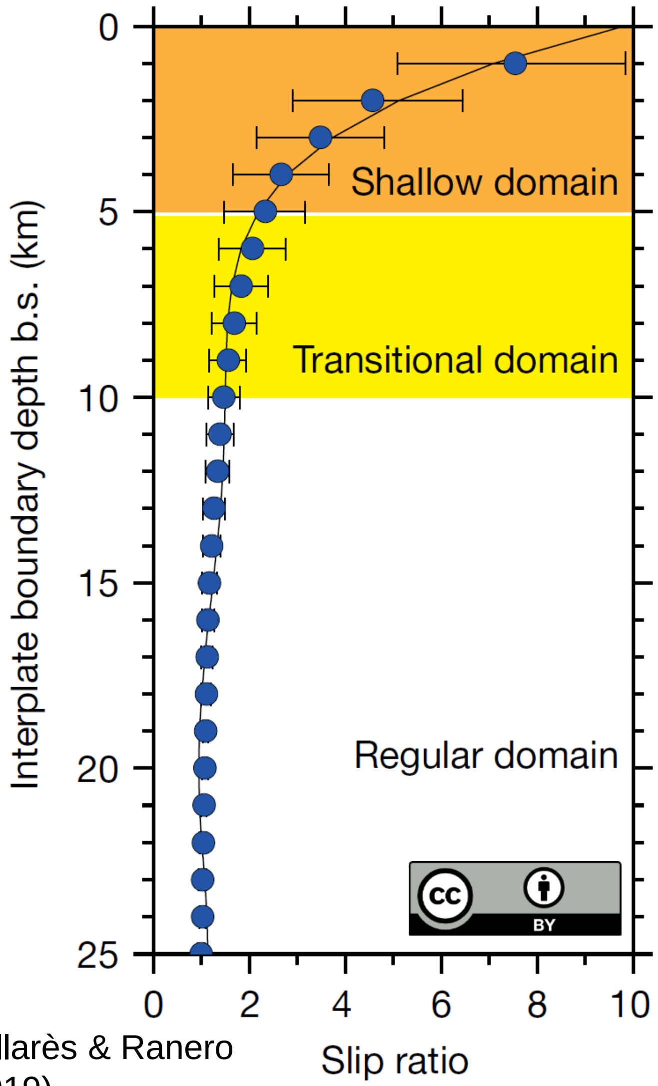
Rock roperties as a function of depth: Vp/s(z), μ(z), u(z)…




Reference rock properties: $Vp/s^*$, $\mu^*$, $u^*$

Sallarès & Ranero (2019)

# 1) Co-seismic slip

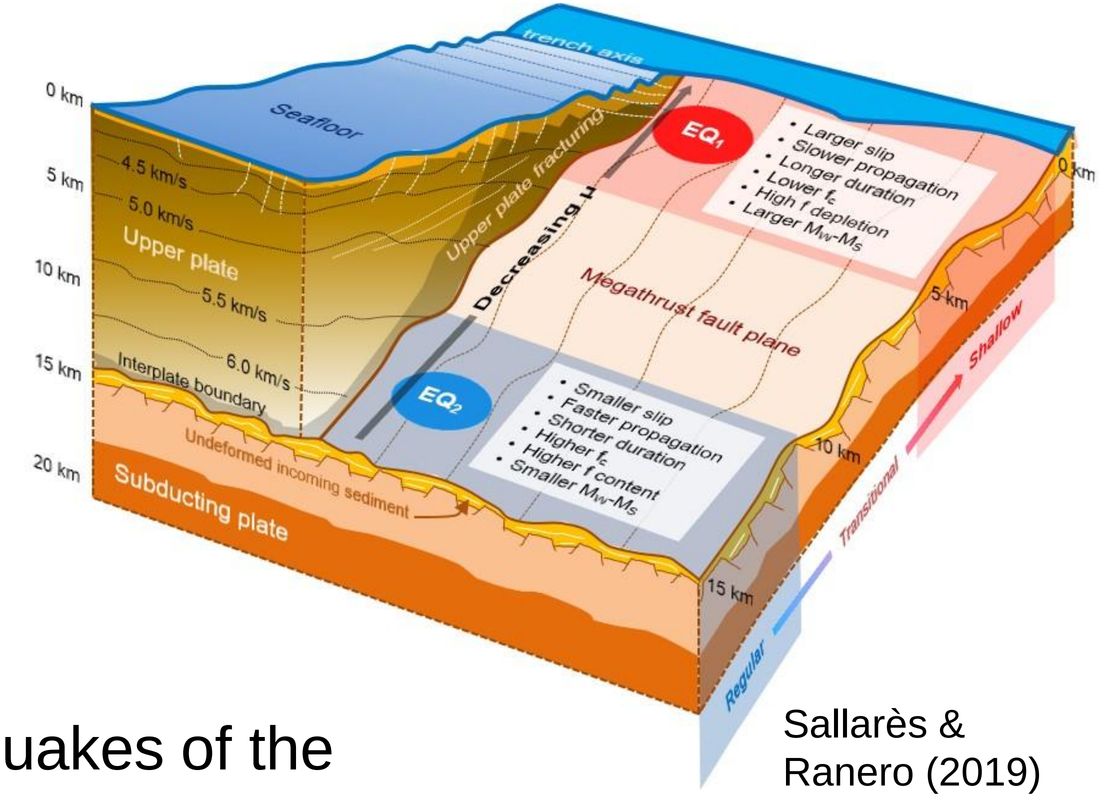



Sallarès & Ranero (2019)

$$M_0 = \int_S \mu D \mathrm{d}\mathbf{s} \approx \bar{\mu}\bar{D}S$$

$M_0$ Seismic moment
μ rigidity
D (δ) Slip
S rupture area

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

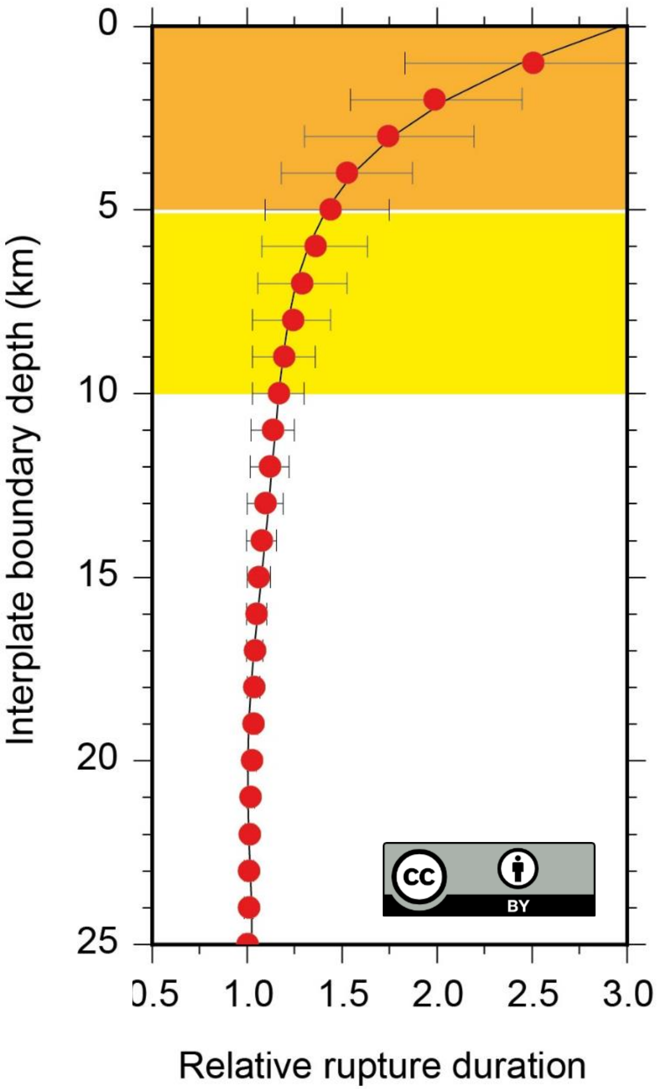



Sallarès & Ranero (2019)

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 $D_d$**

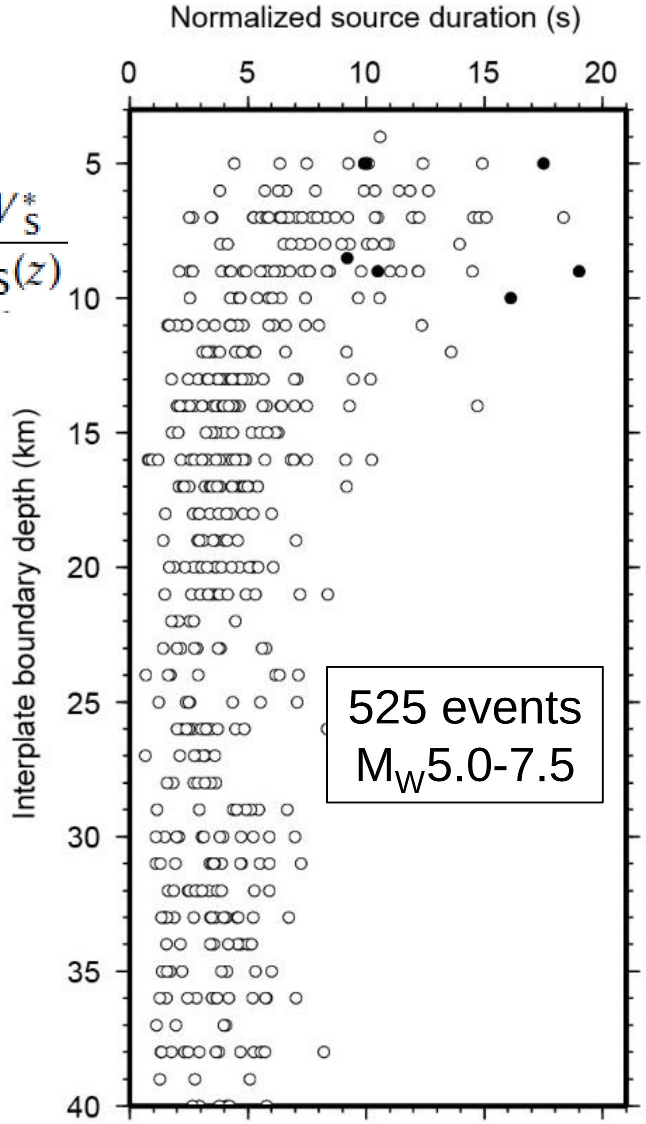
# 2) Earthquake duration



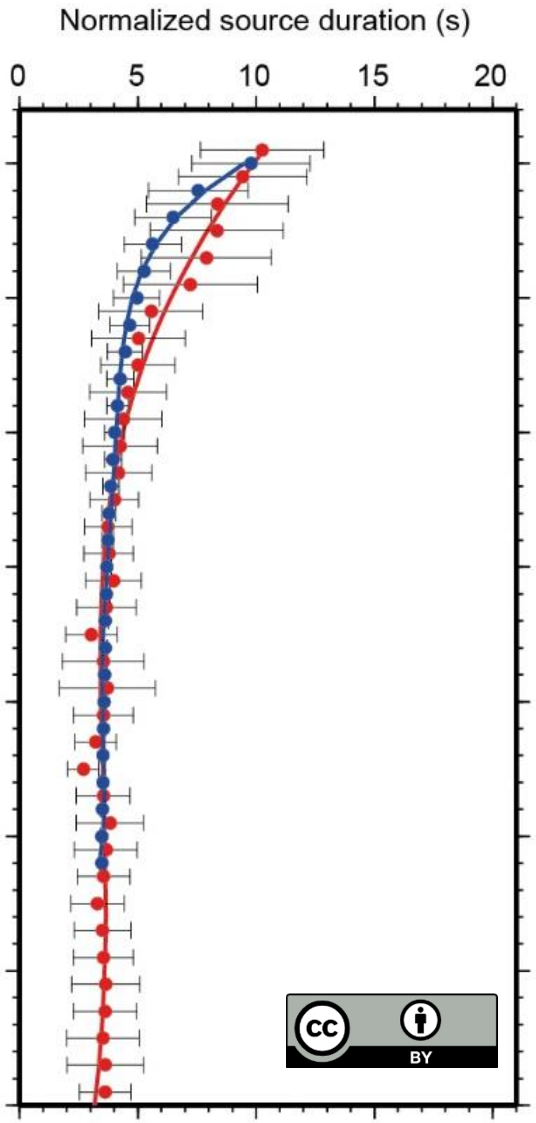

$$T_R(z) = \frac{T(z)}{T^*} = \frac{u^*}{u(z)} = \frac{V_S^*}{V_S(z)}$$

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

Sallarès & Ranero (2019)




Bilek and Lay (2002)

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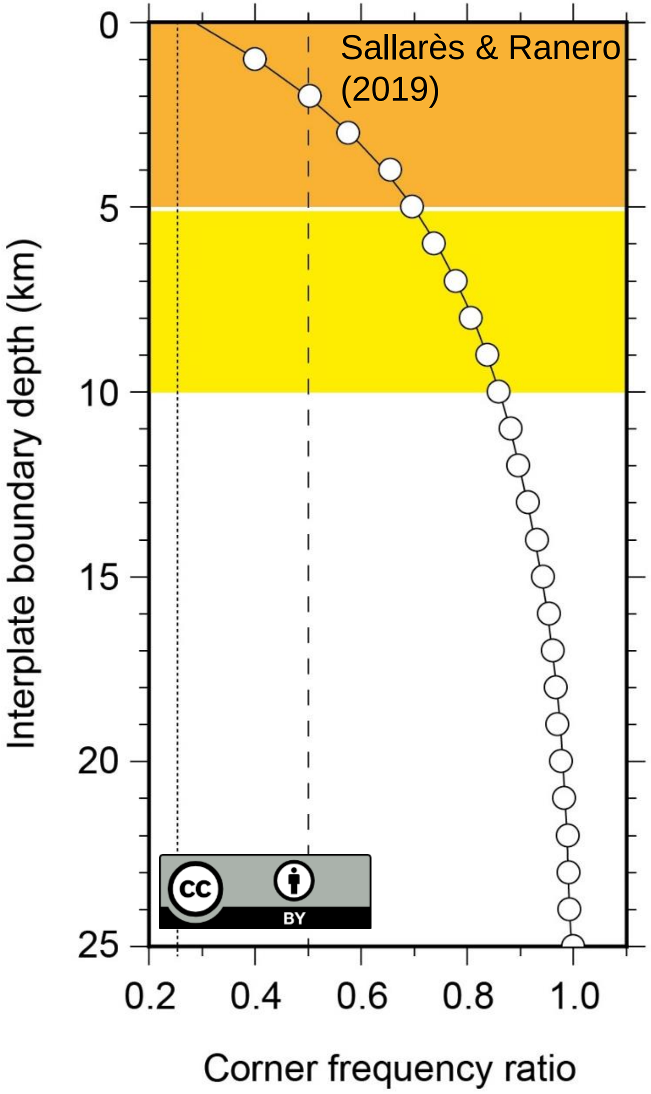
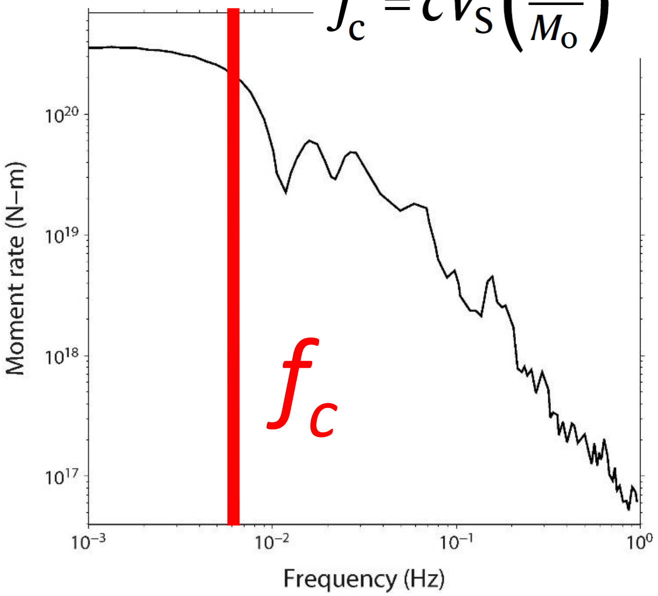
# 3) High frequency depletion (subdued seismic shaking)





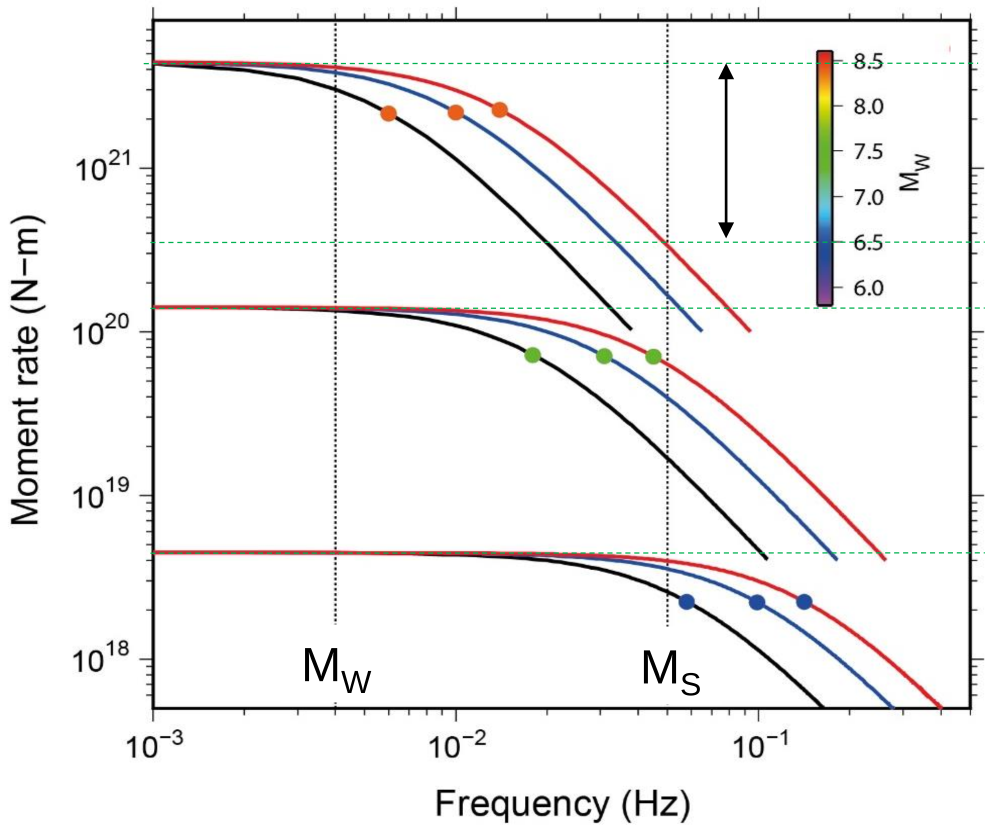

$$f_c = c V_S \left(\frac{\Delta\sigma}{M_0}\right)^{\frac{1}{3}}$$




**$f_s$ should be up to 1-2 octaves lower than $f_d$ due to the Vs decay**

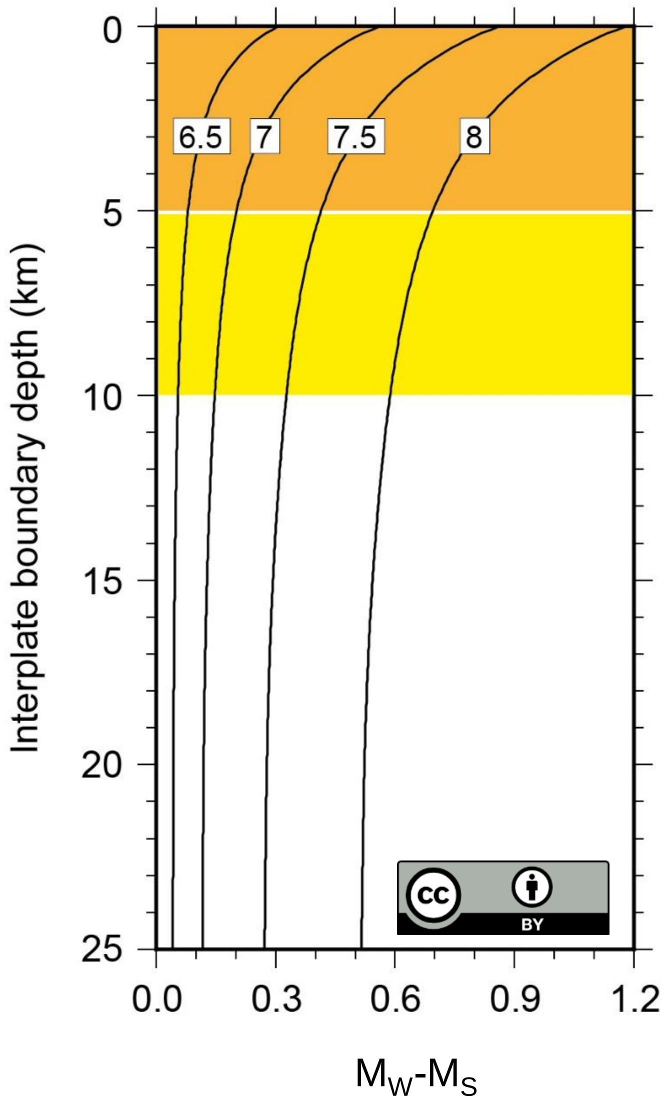
$$f_R(z) = \frac{f_c(z)}{f_c^*} = \frac{V_S(z)}{V_S^*} = T_R(z)^{-1}$$

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




Sallarès & Ranero (2019)

# 4) $M_W$-$M_S$ discrepancy




Sallarès & Ranero (2019)

| Tsunami Earthquakes | | | | | | |
|---|---|---|---|---|---|---|
| 2 | 9 | 1992 | 7.0 | 7.6 | Nicaragua | 77 |
| 20 | 11 | 1960 | 6.75 | 7.6 | Peru | 78 |
| 21 | 2 | 1996 | - | 7.5 | Peru | 79 |
| 25 | 3 | 1947 | 7.2 | 7.1 | Hikurangi | 80 |
| 3 | 1 | 2010 | - | 7.1 | Solomon | 81 |
| 2 | 6 | 1994 | 7.2 | 7.6 | Java | 82 |
| 17 | 7 | 2006 | 7.2 | 7.8 | Java | 83 |
| 25 | 10 | 2010 | 7.1 | 7.8 | Mentawai | 11 |
| 15 | 6 | 1896 | 7.2 | 8.0 | Sanriku | 84 |
| 10 | 6 | 1975 | 7.0 | 7.5 | Kurile | 78 |
| 20 | 10 | 1963 | 7.2 | 7.8 | Kurile | 78 |
| 1 | 4 | 1946 | 7.4 | 8.2 | Aleutian | 85 |

Average $M_W$-$M_S$ for tsunami EQs is 0.65

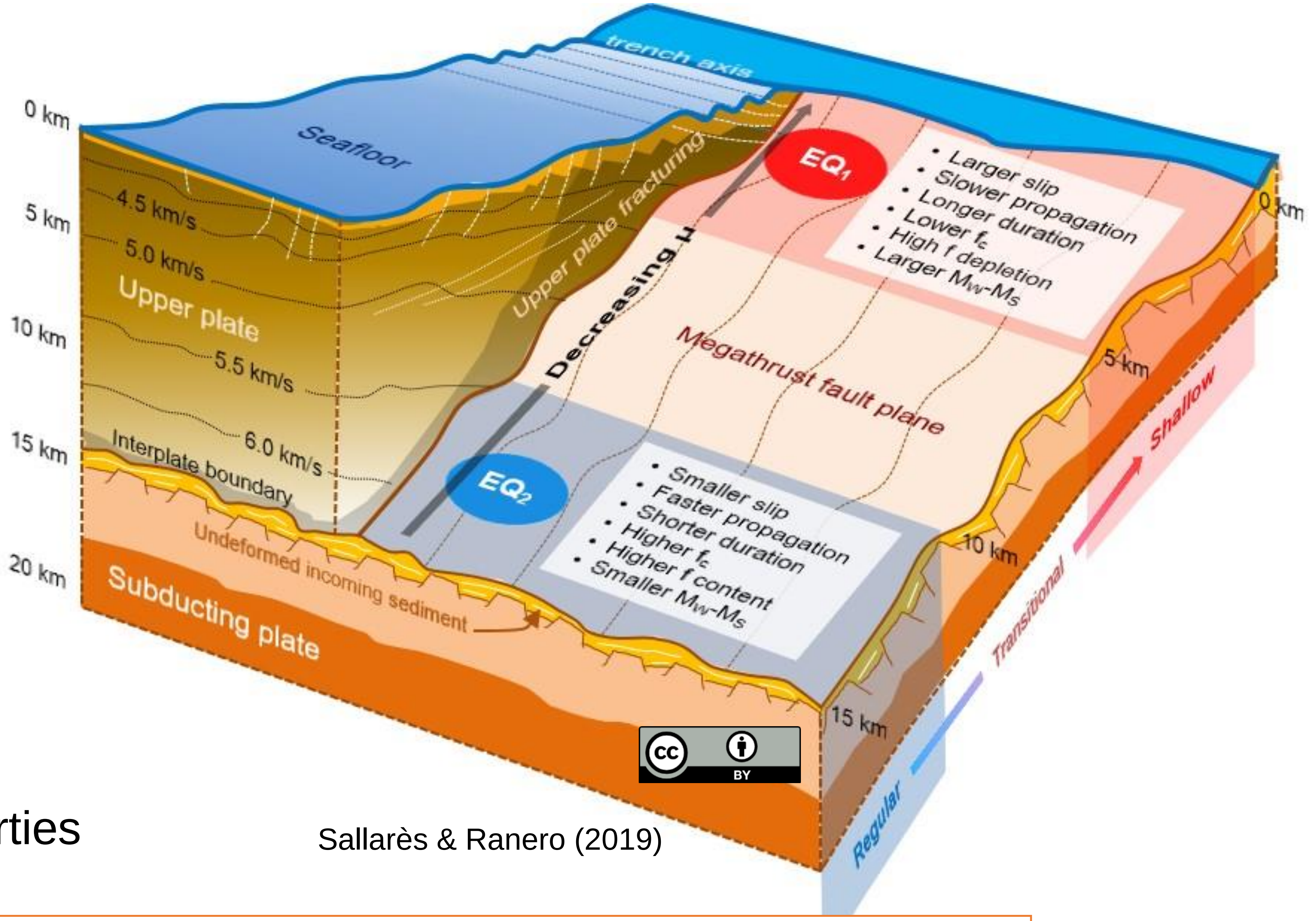
For a $M_W$7.5 earthquake, discrepancy due to $M_0$ alone is of 0.2-0.3

**However, $V_S$ variation with depth can account for a difference of up to 0.7-0.8**

# 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)

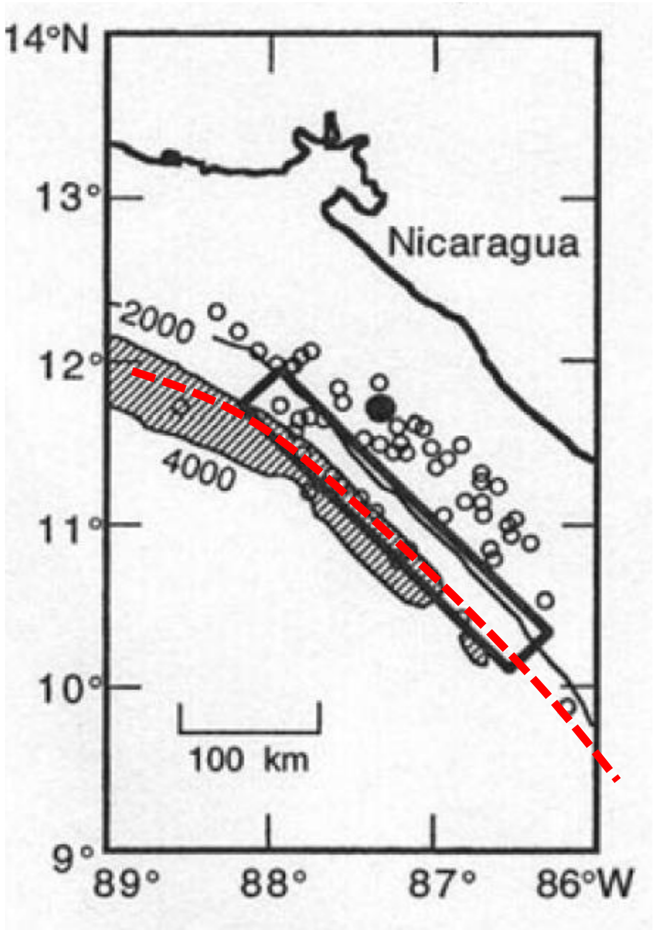
Long duration (>100 s), slow propagation

Triggered a large tsunami (up to 10m high)

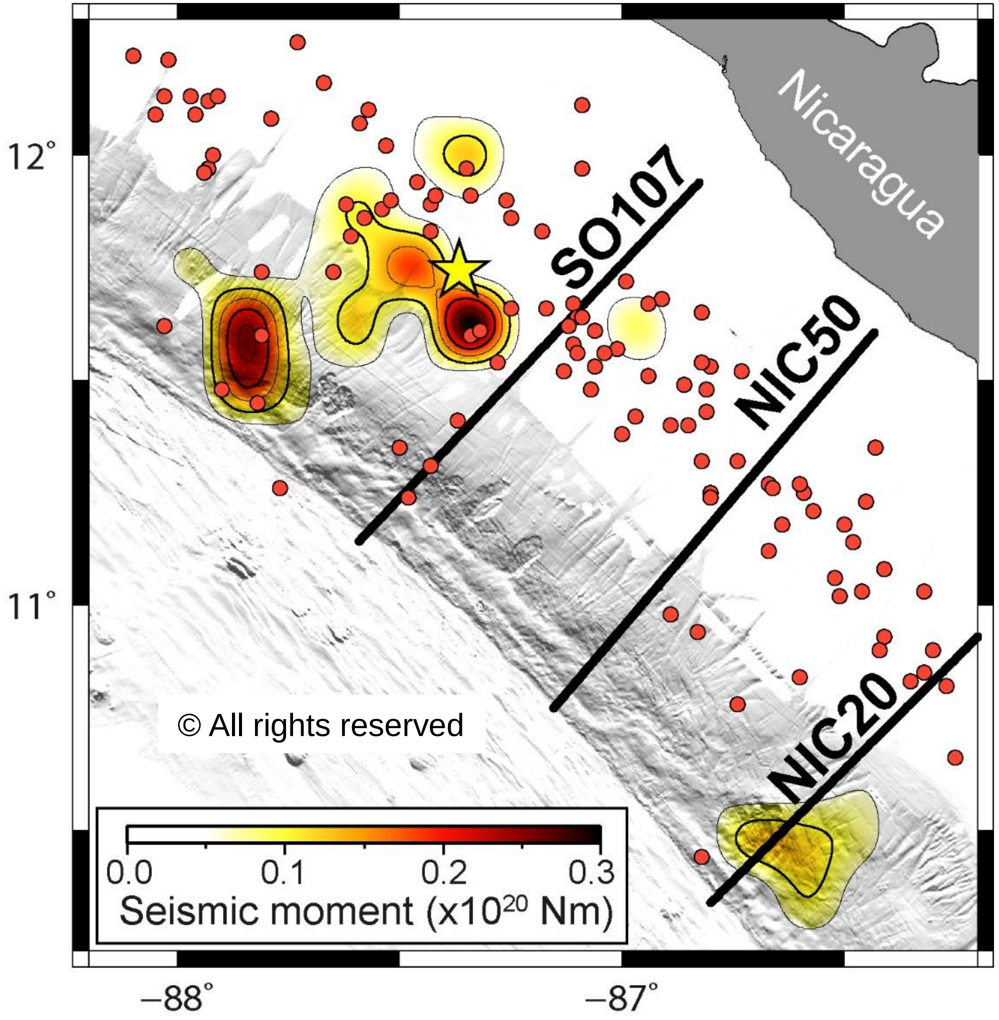
Nucleated at ~20 km depth

Large moment release near the trench

Kanamori & Kikuchi (1993)

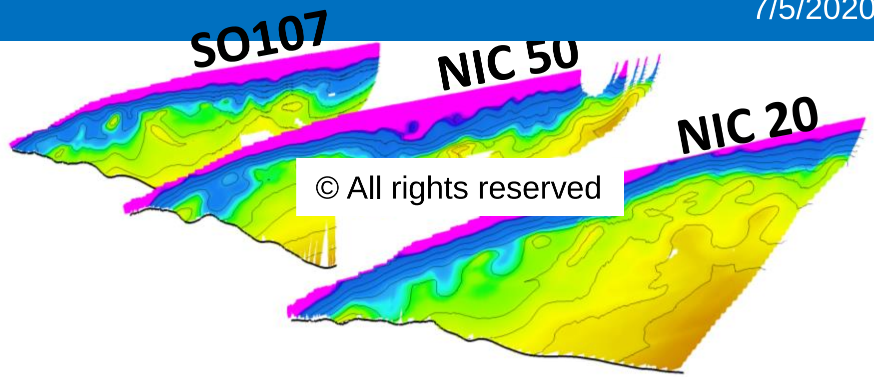



Moment release from Ihmlé (1996)

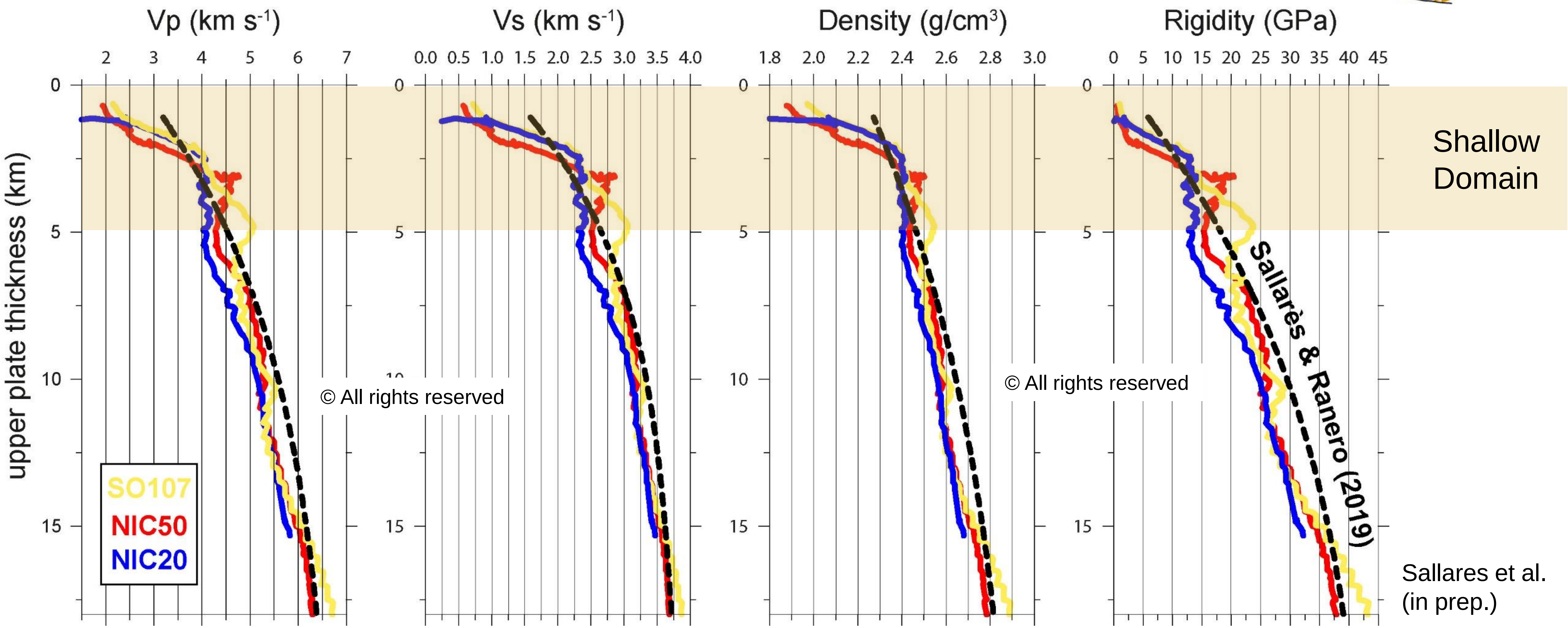


# Depth-varying elastic properties

Brocher's (2005) Vp-Vs & Vp-ρ empirical relationships



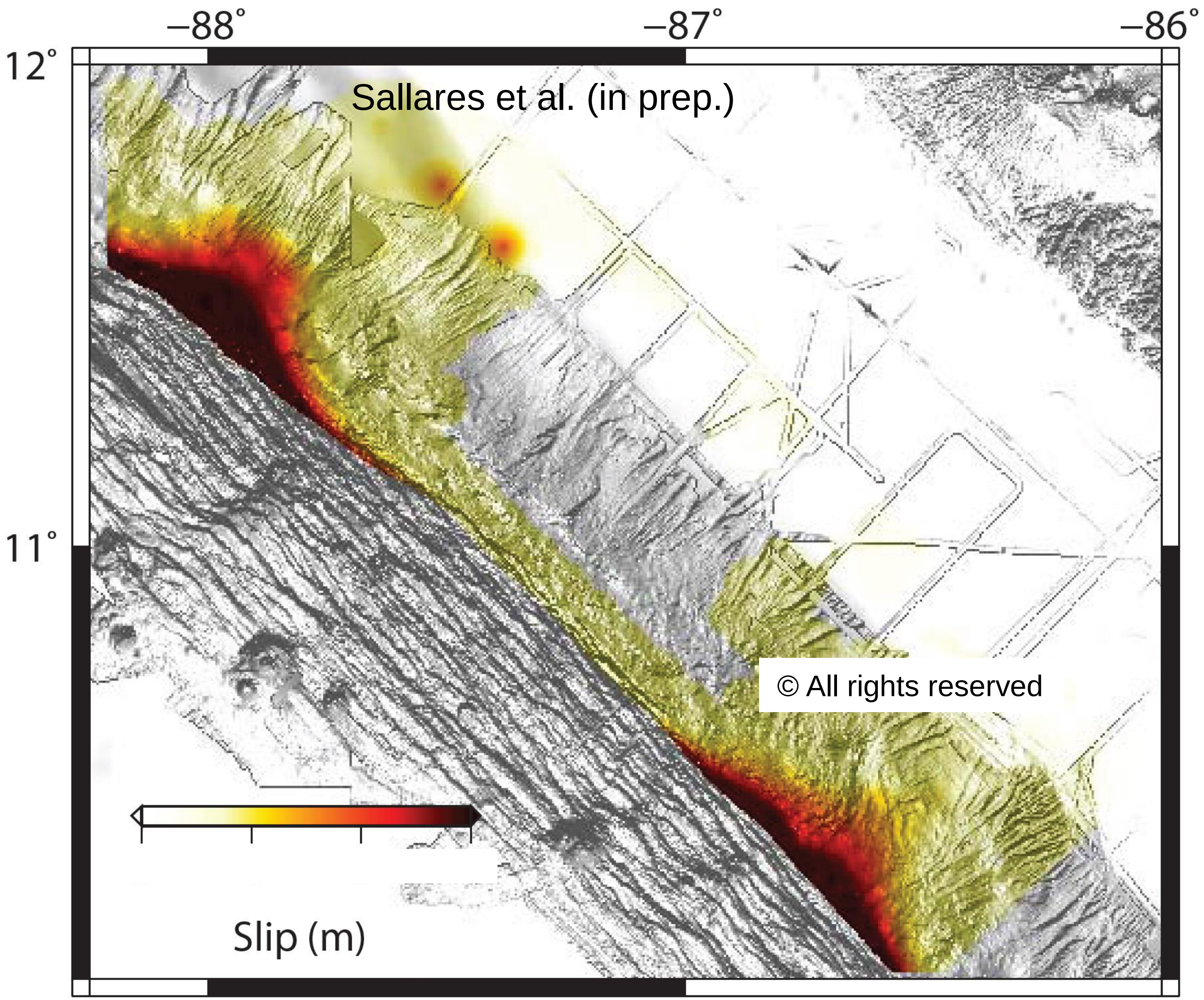





Sallares et al. (in prep.)

# Rupture characteristics: Slip




$$M_0 = \int_S \mu D \mathrm{d}s \approx \bar{\mu}\bar{D}S$$

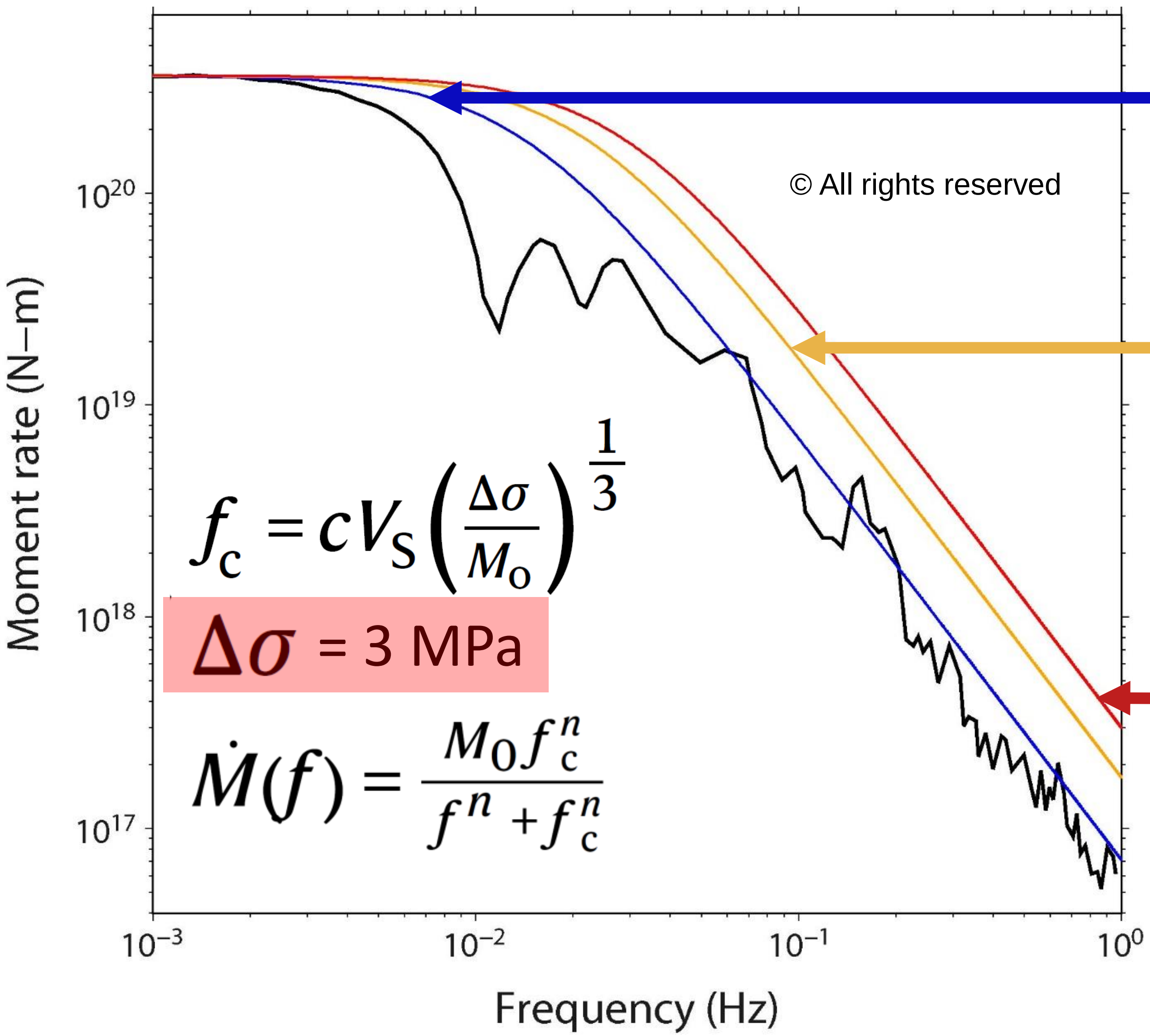
**$M_0$** Moment (Ihmlé, 1996)
**μ** Shear modulus (our models)
**D** Slip
**S** rupture area (subfaults of 10x10 km)

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 μ)

# Rupture characteristics: $f_c$ & high frequency depletion

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




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

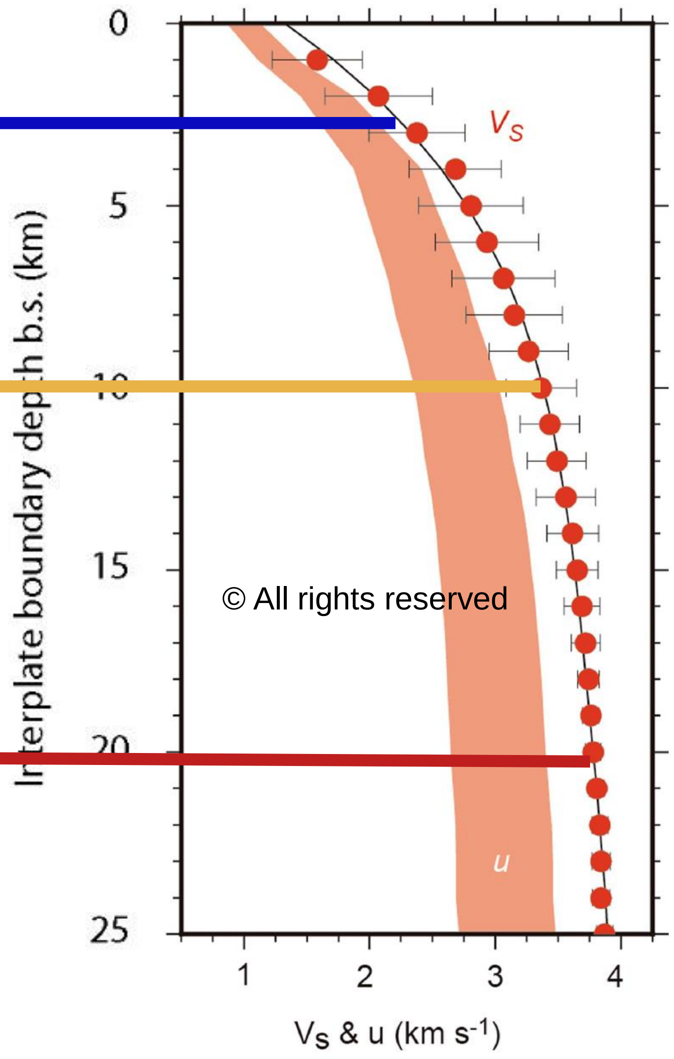
$\Delta\sigma$ = 3 MPa

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

Vs(2.5 km)

Vs(10 km)

Vs(20 km)




Sallares et al. (in prep.)