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Stable and Unstable Shear in Altered Downgoing Slabs: Predicted Strain Localization in Magnesian Carbonates and Wadati-Benioff Seismicity

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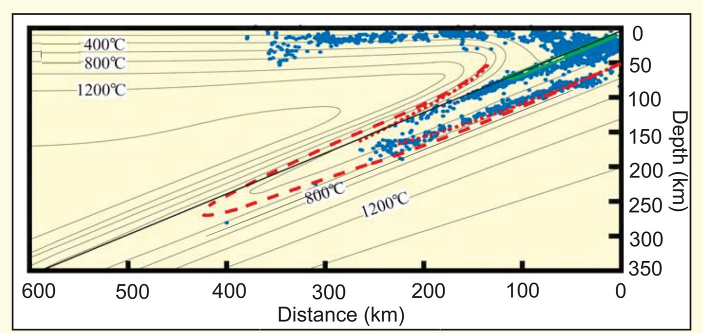
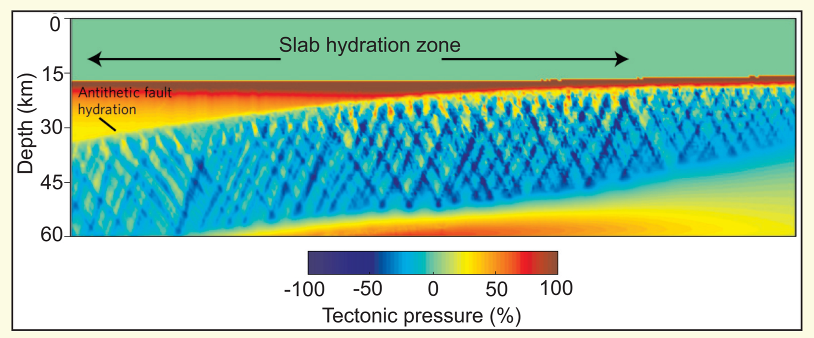
Introduction

Seismicity of subduction zones at upper-mantle depths is commonly explained by dehydration reactions of serpentine and hydrous silicates and reductions in effective pressure. However, the conditions of Wadati-Benioff zone seismicity do not strictly correspond to temperatures and depths of serpentine dehydration, and there is no independent evidence that sea water penetrates the lithosphere to form serpentine at depths >30km below the sea floor. Altered lithosphere may contain magnesian carbonates in addition to hydrous silicates, both at the top of plates, where CO_2 of sea water reacts with mantle rocks and at the base of plates where CO_2 is introduced by mantle plumes.

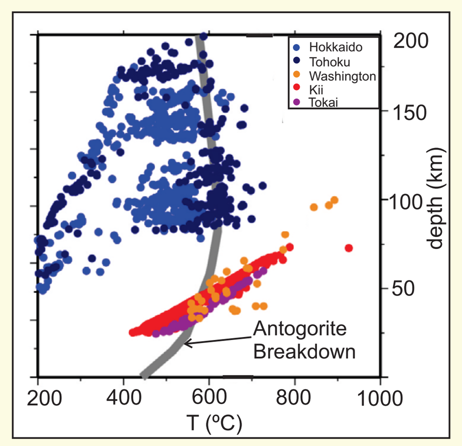
Adapting the thermal softening model of Kelemen and Hirth (2007), we model the strain localization and shear heating within magnesite horizons embedded within an olivine host using flow laws determined experimentally for dislocation creep and diffusion creep of the carbonate layer and olivine host (Hirth and Kohlstedt, 2003; Holyoke et al., 2014). Strain rates predicted within carbonate-rich layers of downgoing slabs are much higher than those of the surrounding olivine at all conditions. However, shearing may be either stable or unstable depending on the relative rates of shear heating and conductive heat loss from the shear zone. Localized strain rates reach a steady state when shear heating and heat flow are balanced, while unstable strain rates are calculated where shear heating exceeds heat flow. Modeled strain rates accelerate to $10^{+1}\,s^{-1}$, as temperatures reach melting conditions, and stresses drop, corresponding to a seismic event. Applications of this model to the double Benioff zones of the NE Japan trench predict unstable seismic shear for both upper and lower seismic zones to subduction depths of ~300 km. For cold downgoing slabs, such as the Tonga subduction system, unstable seismic shear is predicted for carbonate horizons of altered downgoing slabs to depths exceeding 400 km.



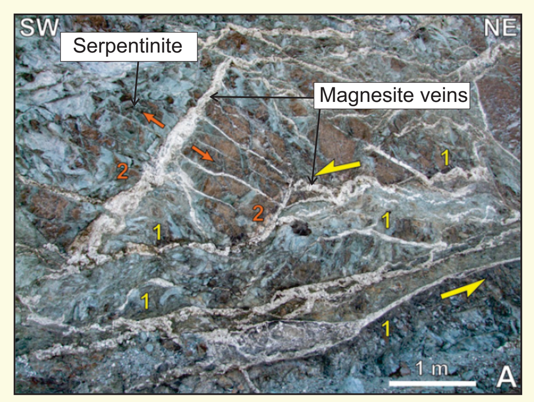
Double Benioff zone are commonly explained by serpentine dehydration embrittlement. Earthquake locations and thermal modeling of Yamasaki & Seno (2003).



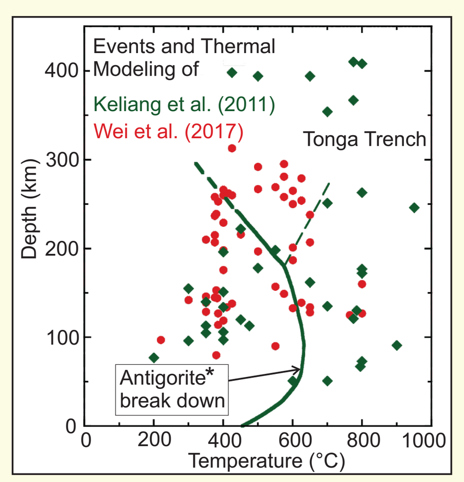
Serpentine alteration of upper regions of bending lithosphere is well explained by brittle deformation and sea water penetration (after Faccenda et al., 2009).



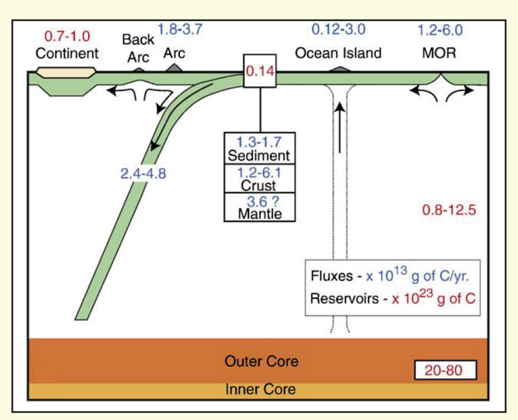
However, seismicity in downgoing slabs is not rigorously associated with conditions of serpentine dehydration (after Abers et al., 2013).



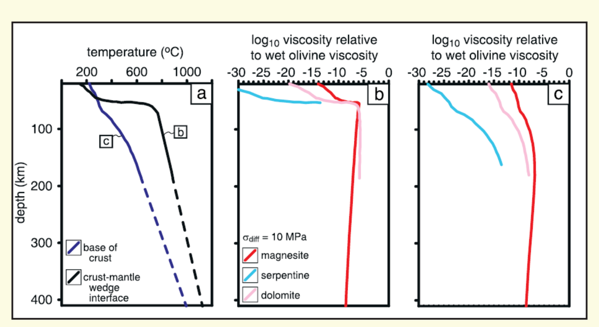
Shallow altered lithosphere in ophiolites. (Quesnel et al., 2013)



*(from Hacker et al., 2003)



Estimated global flux of carbon in the mantle. Potential carbonates in upper and lower regions of slab. (Dasgupta and Hirschmann, 2010)



Effective viscosities of serpentine, magnesite, and dolomite are all lower than viscosity of olivine (Holyoke et al., 2014).

Methods

Assuming downgoing slabs contain carbonate horizons as reported by Quesnel et al., (2013), we adapt the model of Kelemen and Hirth (2007) to evaluate strain localization and plastic shear instabilities.

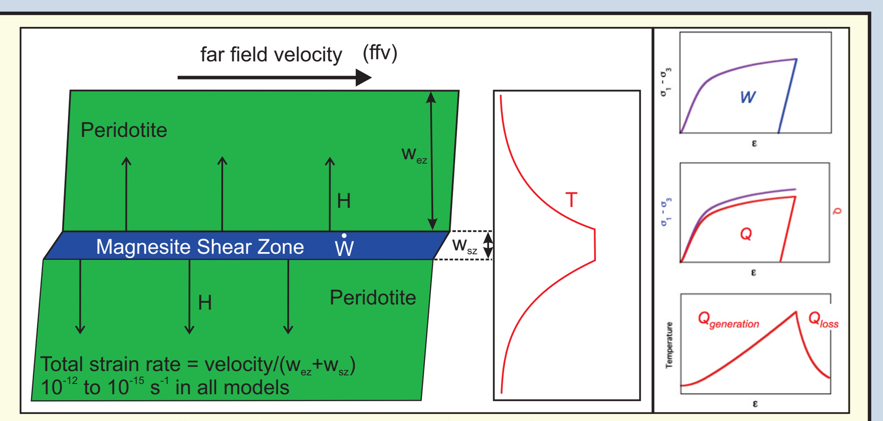
The work done W in the shear zone is modeled in one dimension:

$$W = \int_V \sigma_{ij}\, \varepsilon_{ij}\, dV$$

and W is dissipated as heat Q.

Shear heating and diffusional loss control changes in temperature of the shear-zone, by

$$dT/dt = -\kappa[d^2T/dx^2] + \sigma\, \dot{\varepsilon}_{viscous}/(C_p\, \rho)$$



Schematic illustration of numerical model with pre-existing magnesite shear zone that accommodates localized viscous deformation. H is heat flow and $\dot{W}$ is rate of work in the shear zone. (adapted after Kelemen & Hirth, 2007)

Olivine flow laws (Hirth & Kohlstedt, 2003)

Dislocation creep	$\dot{\varepsilon}_{dislo} = 10^{5}\sigma^{3.5}e^{-530,000/RT}$
Diffusion creep	$\dot{\varepsilon}_{diff} = 10^{9}\sigma\, d^{-3}e^{-375,000/RT}$
Grain boundary sliding	$\dot{\varepsilon}_{gbs} = 6500\,\sigma^{3.5}d^{-2}e^{-400,000/RT}$
Low T Plasticity	$\dot{\varepsilon}_{LTP} = 5.7\times10^{11}[1-\sigma/(8.5\times10^{3})]^{2}e^{-540,000/RT}$

Magnesite flow laws (Holyoke et al., 2014)

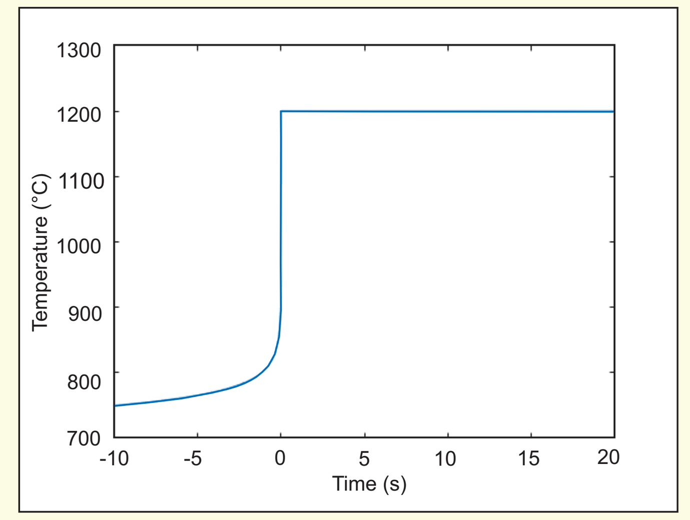
Dislocation creep	$\dot{\varepsilon}_{dislo} = 3.81\times10^{8}\sigma^{3}e^{-410,000/RT}$
Diffusion creep	$\dot{\varepsilon}_{diff} = 9.75\times10^{4}\sigma^{1.1}d^{-3}e^{-209,000/RT}$

Results

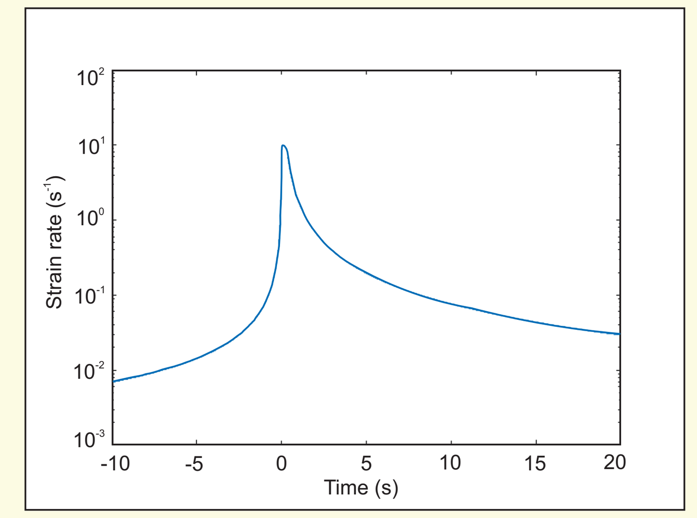
Unstable Localized Shear T_i = 500°C, $(\sigma_1-\sigma_3)_i$ = 10MPa, w_{sz}= 0.2m, w_{ez}= 1000m, d =1000μm, ffv = 0.1myr^{-1}

Positive feedback of mechanical dissipation to heat and temperature dependent strain rate

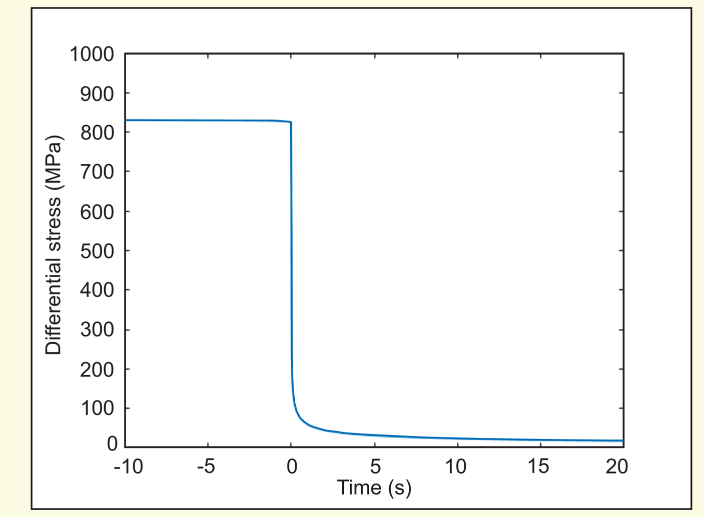
Model run for a 30s time interval centered on thermal runaway in carbonate shear zone



Temperature versus time

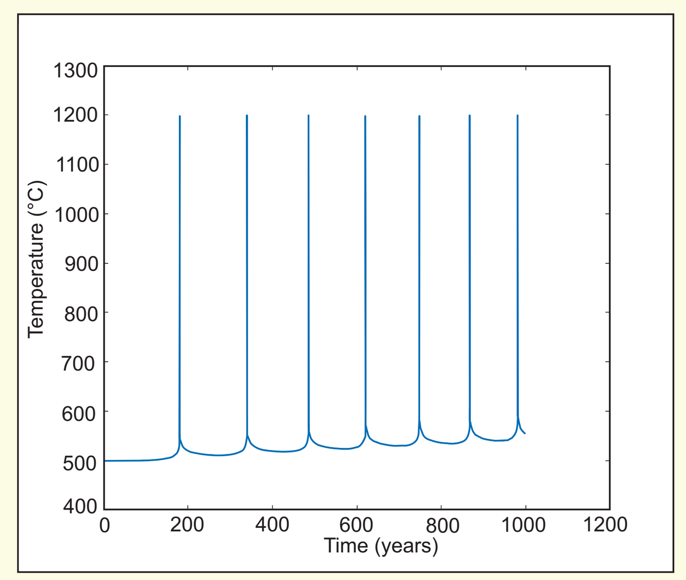


Strain rate versus time

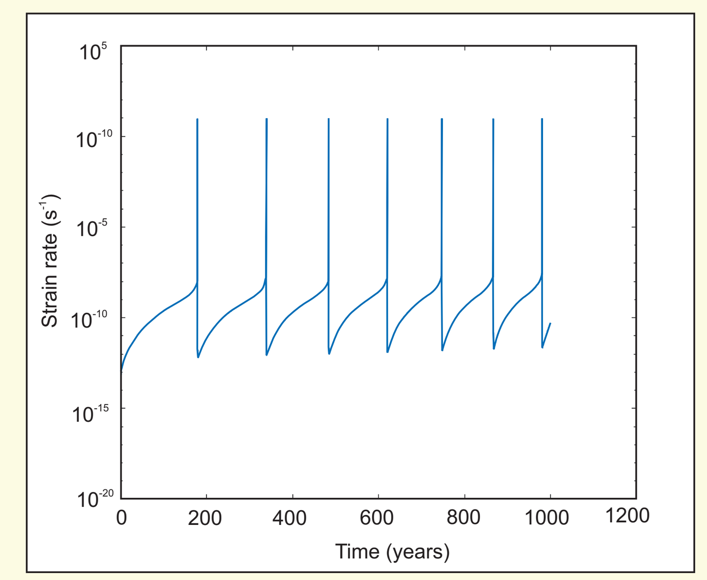


Differential stress versus time

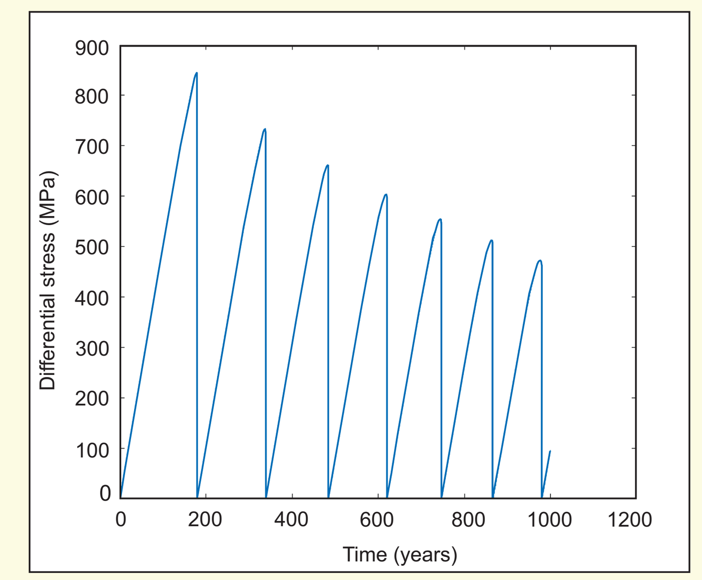
Model run for 1000 years showing periodic instability due to thermal runaway in carbonate shear zone



Temperature versus time



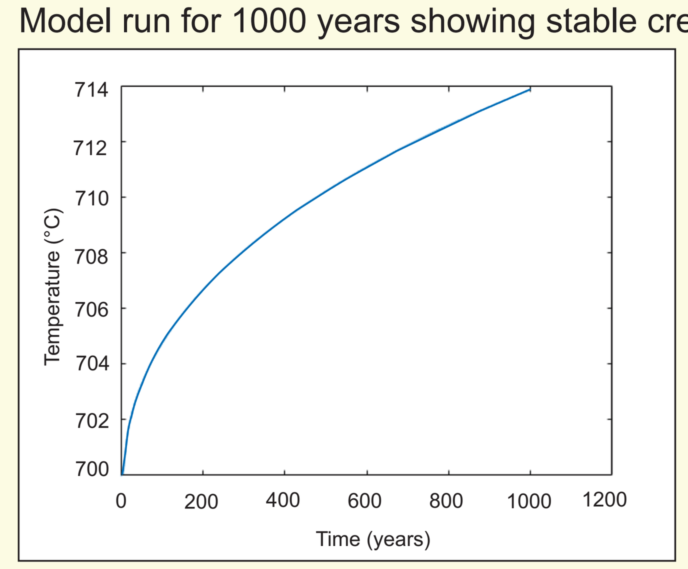
Strain rate versus time



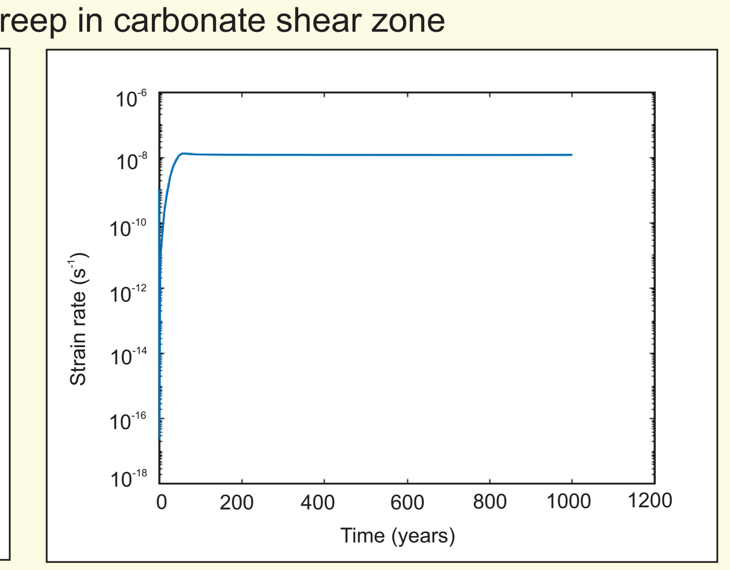
Differential stress versus time

Stable Localized Shear T_i = 700°C, $(\sigma_1-\sigma_3)_i$ = 10MPa, w_{sz}= 0.2m, w_{ez}= 1000m, d =1000μm, ffv = 0.1myr^{-1}

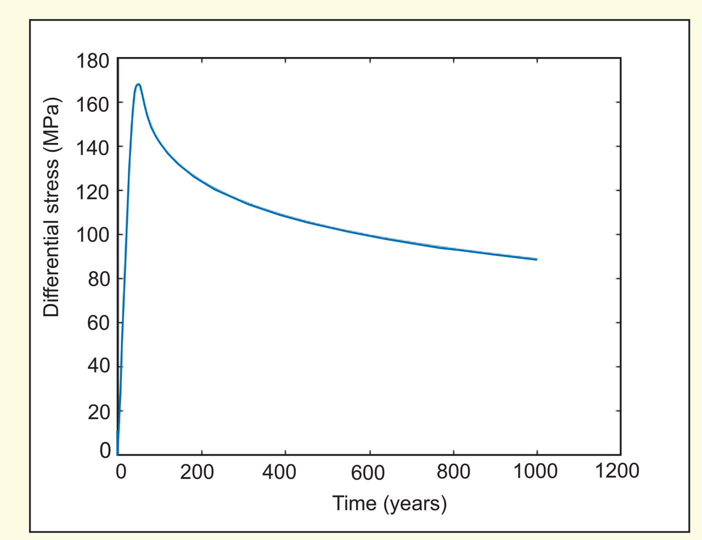
Model run for 1000 years showing stable creep in carbonate shear zone



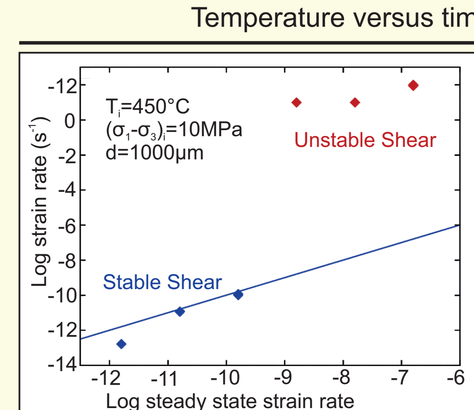
Temperature versus time

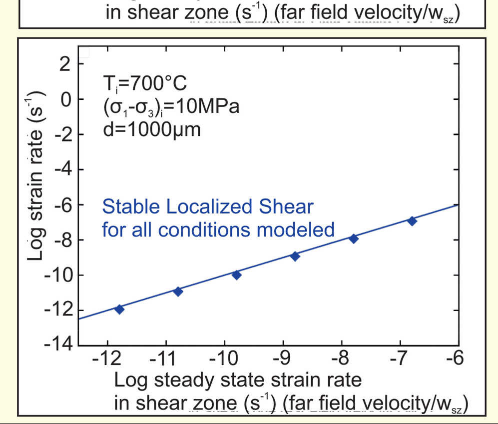


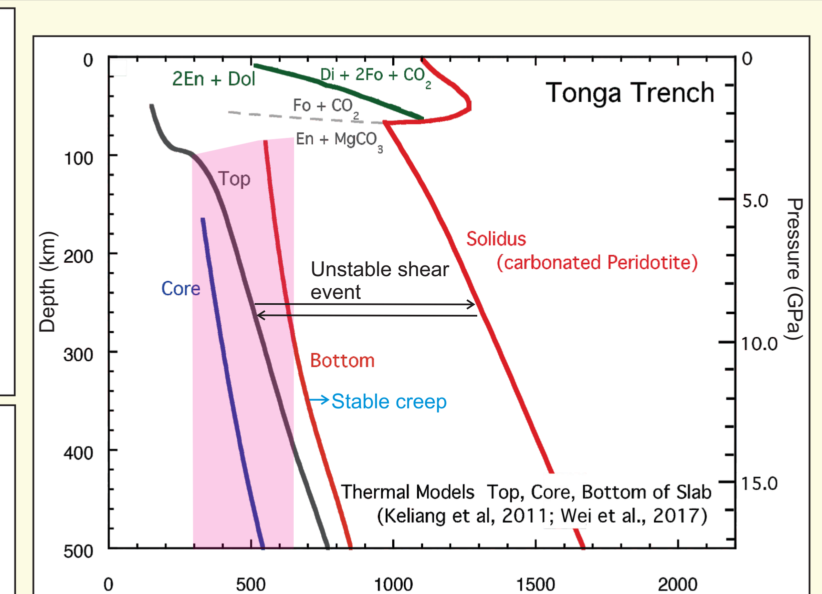
Strain rate versus time

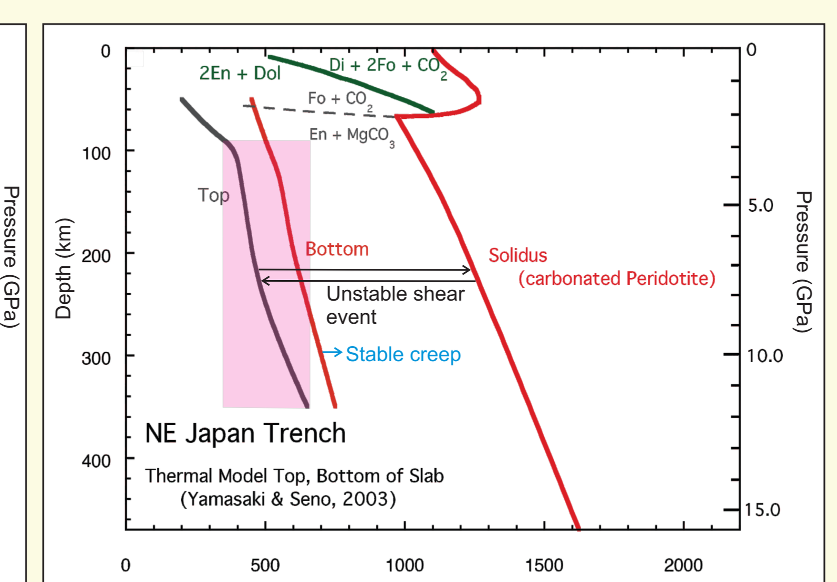


Differential stress versus time



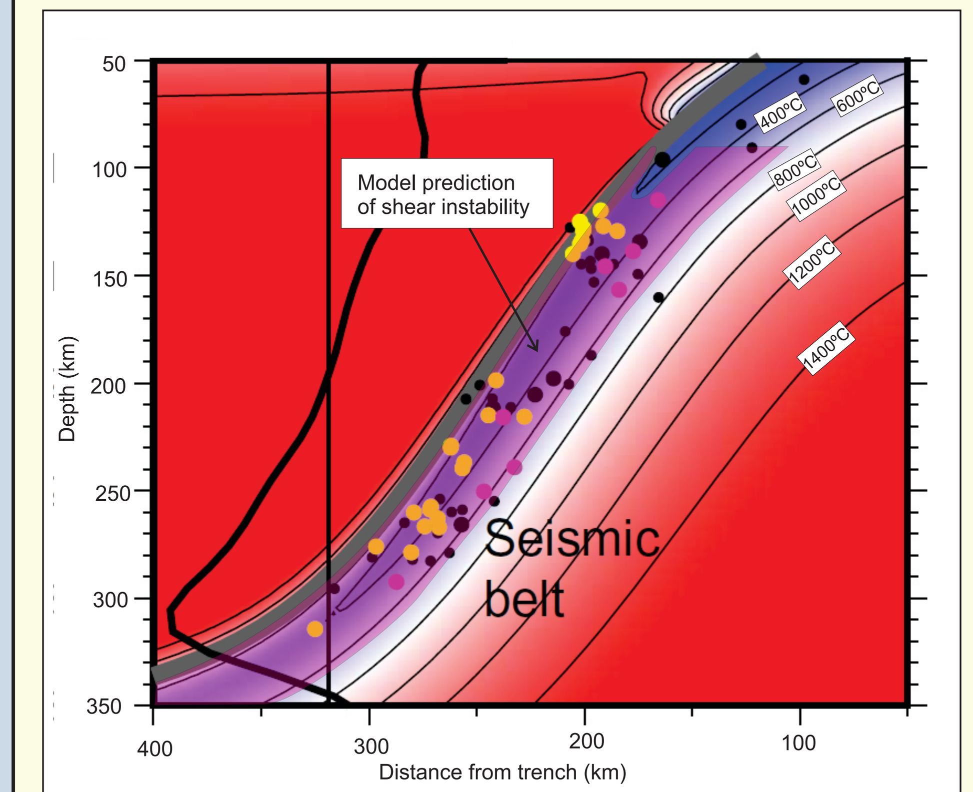




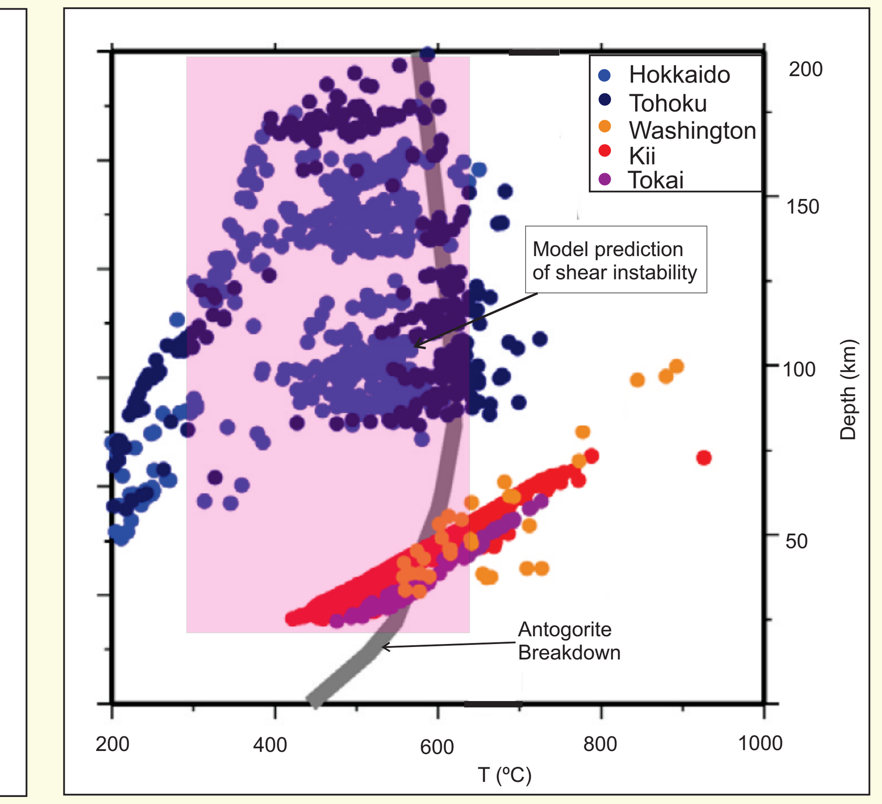


The shaded region in pink indicates conditions favorable for unstable shear events. Arrows (to right) indicate shear heating, leading to increased strain rate, unstable stress drop, and ultimately melting at solidus at lower temperatures, and steady-state strain localization at higher temperatures. Arrows (to left) show post-seismic temperature drop. Solidus of carbonated peridotite after Kelemen & Manning (2015).

Discussion

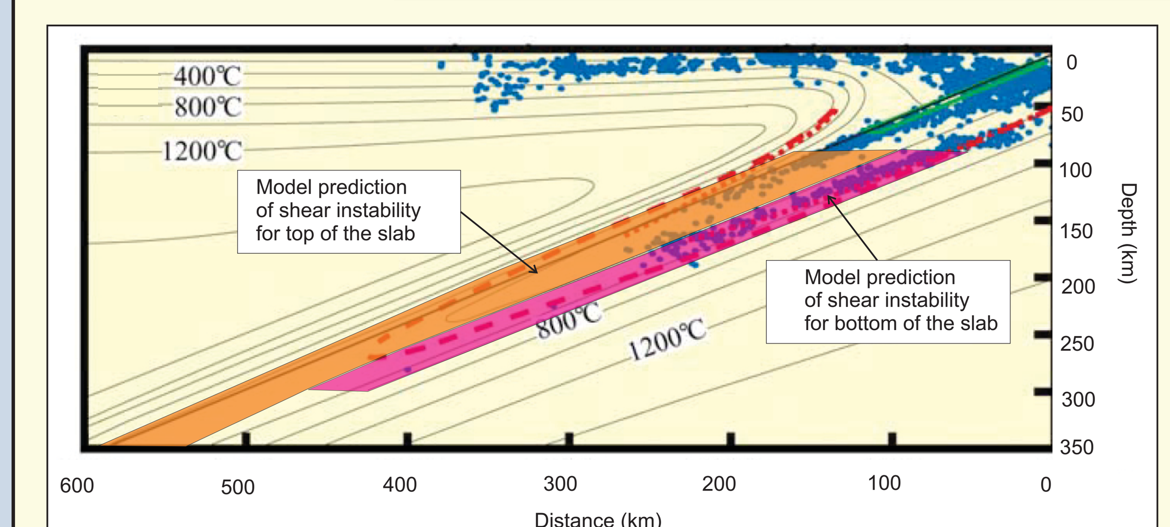


Model predictions of unstable carbonate shear (shaded pink) correspond to wide range of seismicity of Tonga subduction system. Based on depth determinations and modeled temperatures after Wei et al. (2017).



Model predictions of unstable carbonate shear (shaded pink) correspond to wide range of seismicity in hot and cold subduction systems. Earthquake distributions and conditions after Abers et al. (2013).

	Temperature (°C)	Subducting slab			Stable (S) / Unstable (U) for three grain sizes		
		Top (km)	Core (km)	Bottom (km)	d = (2 μm)	d = (50 μm)	d = (1000 μm)
Tonga Trench	200	90			U	S	U
	300	100	90-200		S	U	U
	350	100	150-200		S	U	U
	400	100-200	200-400		S	U	U
	450	200-250	400-450		S	S	U
	500	250-300	450-500		S	S	U
	550	300-350	500-550	90-150	S	S	U
	600	350-400	550-600	150-200	S	S	U
	650	400-450	550-590	200-300	S	S	U
	700	400-450	590-620	300-350	S	S	S
	750	400-450	620-660	350-400	S	S	S



Model predictions of unstable carbonate shear (shaded orange and pink) correspond well with upper and lower zones of seismicity of NE Japan trench. Earthquake distributions and temperature model of Yamasaki & Seno (2003).

	Temperature (°C)	Subducting Slab		Stable (S) / Unstable (U) for two grain sizes	
		Top (km)	Bottom (km)	d = (50 μm)	d = (1000 μm)
North-East Japan Trench	350	90-100		U	U
	400	100-150		U	U
	425	150-200		U	U
	450	150-200		S	U
	500	200-250	90	S	U
	550	250-300	100-200	S	U
	600	250-300	200-250	S	U
	650	300-350	250-300	S	U
	700	350	300-350	S	S
	750	350	300-350	S	S

Conclusions

(1) Unstable shear events can be triggered in carbonate horizons of altered subducting slabs due to localized shear heating.

(2) In cold, thick subducting slabs, shear instabilities in carbonates may explain earthquakes at conditions that do not favor brittle failure or dehydration embrittlement.

(3) Upper earthquakes of double-Benioff zones are readily explained by serpentine dehydration faulting, while unstable shear in carbonates may lead to earthquakes of both upper and lower double-Benioff zones.