From stable to destructive: Creeping fault segments can join earthquake rupture due to dynamic weakening

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Abstract

A fault showing rate-strengthening behavior at low slip rates - comparable to the tectonic plate motion - cannot nucleate a frictional instability and thus considered to be aseismic conventionally [e.g., Blanpied et al., 1991]. On the other hand, recent high-velocity friction experiments have revealed that almost all materials undergo remarkable weakening when they are slid at high slip rates around 0.1 ~ 1 m/s, a typical range for coseismic slip. Therefore, if a rate-strengthening segment has a mature fault core, characterized by a well localized shear zone embedded in fine-grained fault gouge which has low permeability, such a segment could convey a rupture spontaneously although it is unable to nucleate a rupture. A rate-strengthening segment can creep, and a creeping segment, in turn, is thought to act as a barrier against rupture propagation. Indeed the creeping segment north of Parkfield region, for example, is known to fail during earthquakes in Parkfield. Here, a practical question in seismic hazard is, "Do creeping segments always act as barriers or not?"

We have conducted simulations of a sequence of earthquakes accounting for long-term tectonic loading, inertial effects during earthquakes, frictional heating and hydro-thermal effects [Noda and Lapusta, 2010]. A planar fault is governed by a rate- and state-dependent friction law [Dieterich, 1979; Ruina, 1983], and embedded in a linearly elastic infinite medium. The fault has 2 square patches (35 km x 35 km) aligned perpendicular to the overall slip direction. One of the patches is rate-weakening and permeable (and thus not susceptible to high velocity weakening due to thermal pressurization (TP)), while the other is rate-strengthening and susceptible to TP. We use physical properties measured experimentally by Tanikawa and Shimamoto [2009] for samples collected from bore holes which penetrate Chelungpu fault, Taiwan, a source fault of 1999 Chi-Chi earthquake. The values at 60 MPa effective pressure, an assumed ambient effective normal stress in the model, are used.

We obtain two types of events, model-spanning large earthquakes and smaller and more frequent ones which rupture only the rate-weakening patch, as shown by a previous study [Noda and Lapusta, 2010]. The long-time averaged coupling ratio is smaller in the rate-strengthening patch. However, it behaves differently in one interseismic period from another; it can be almost always locked between model-spanning events, start creeping hundreds of years before a model-spanning event, or keep creeping for a long time while the rate-weakening patch accommodates multiple smaller events. Importantly, those rich behaviors are observed in a single model. A rate-strengthening segment can be locked or creeping depending on the local shear stress, and can rupture to produce large coseismic slip if the high-velocity weakening is activated. Whether the weakening is activated is dictated by many factors such as the poroelastic properties, the width of the actively shearing layer, and the efficiency of dynamic stress transfer.

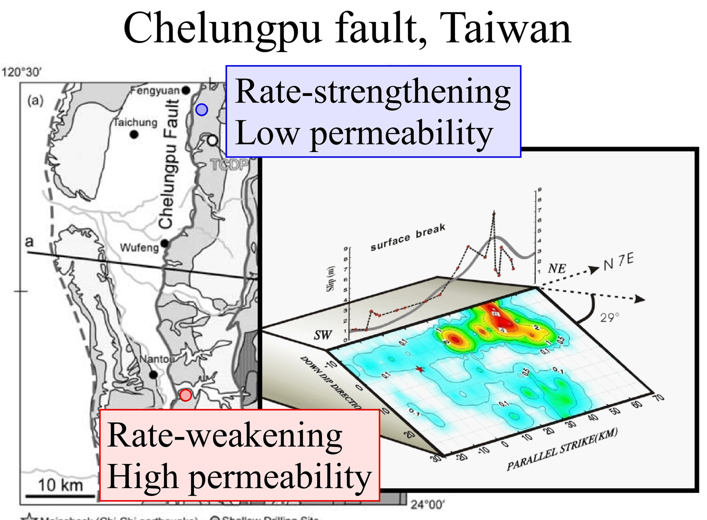
Our model suggests that current observations of creeping or seismically non-active segments do not guarantee impossibility of large coseismic slip there. Recent sophisticated geophysical observations for tens of years may only be capturing a snapshot of such a rich behavior, and searching longer records (e.g., geological records) for evidence of fault activities is important.

Introduction

Rupture propagation into creeping (or VS) faults

Velocity Strengthening

Chelungpu fault, Taiwan



Ma et al., 2000, Tanikawa and Shimamoto, 2009

Tohoku-oki, Japan (?)

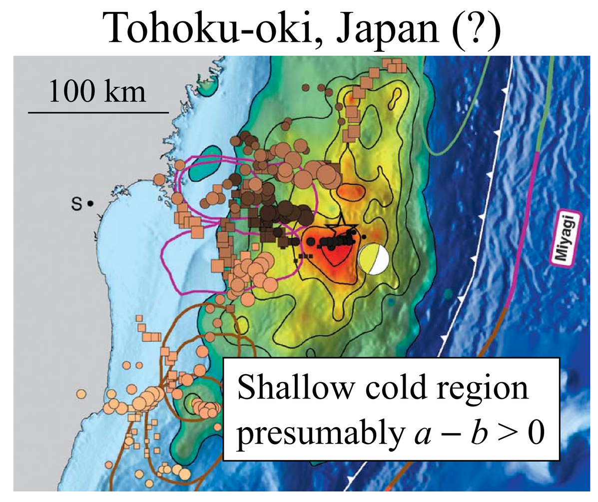


Figure from Simons et al., 2011

Parkfield, California

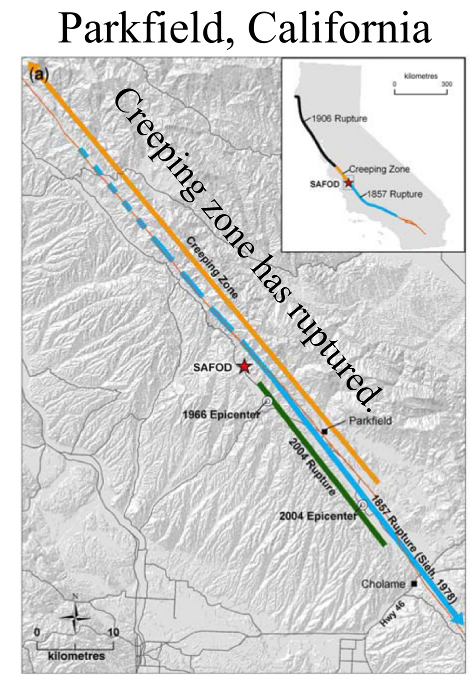


Figure from Ellsworth and Malin, 2011

There are several examples in which earthquake ruptures propagate into creeping or velocity-strengthening (VS) segments.

"Do creeping segments always act as barriers or not?"

Problem settings

Earthquake sequence simulation accounting for slow tectonic loading and coseismic inertial effect

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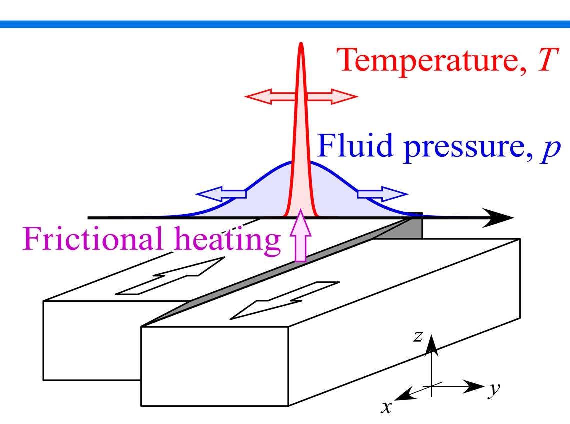
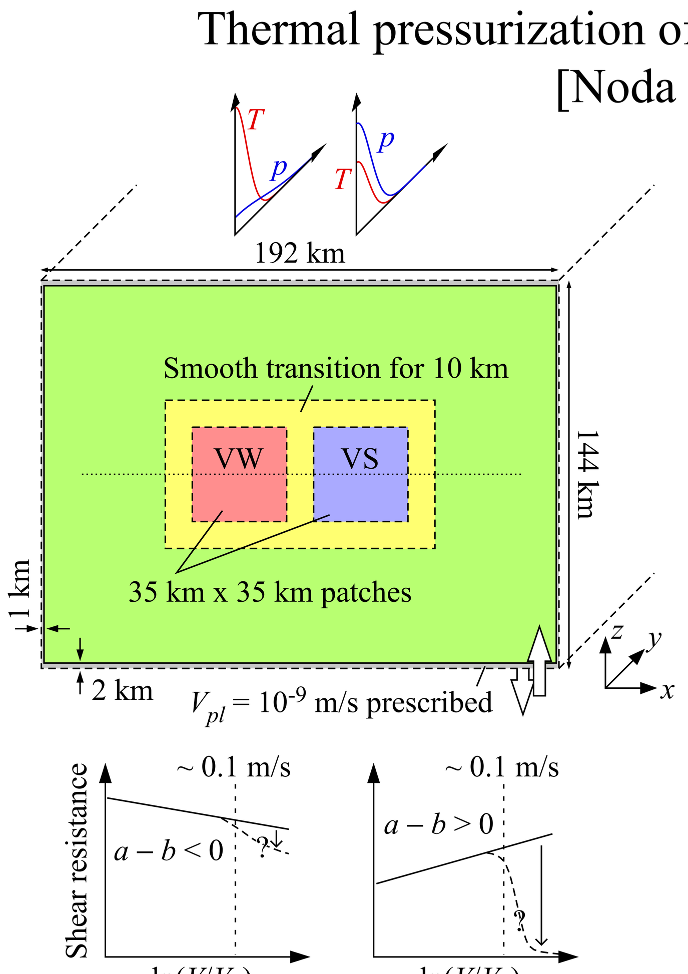
Thermal pressurization of pore fluid

[Noda and Lapusta, 2010]





Laboratory-measured physical properties for samples from boreholes penetrating Chelungpu fault [Tanikawa and Shimamoto, 2009]

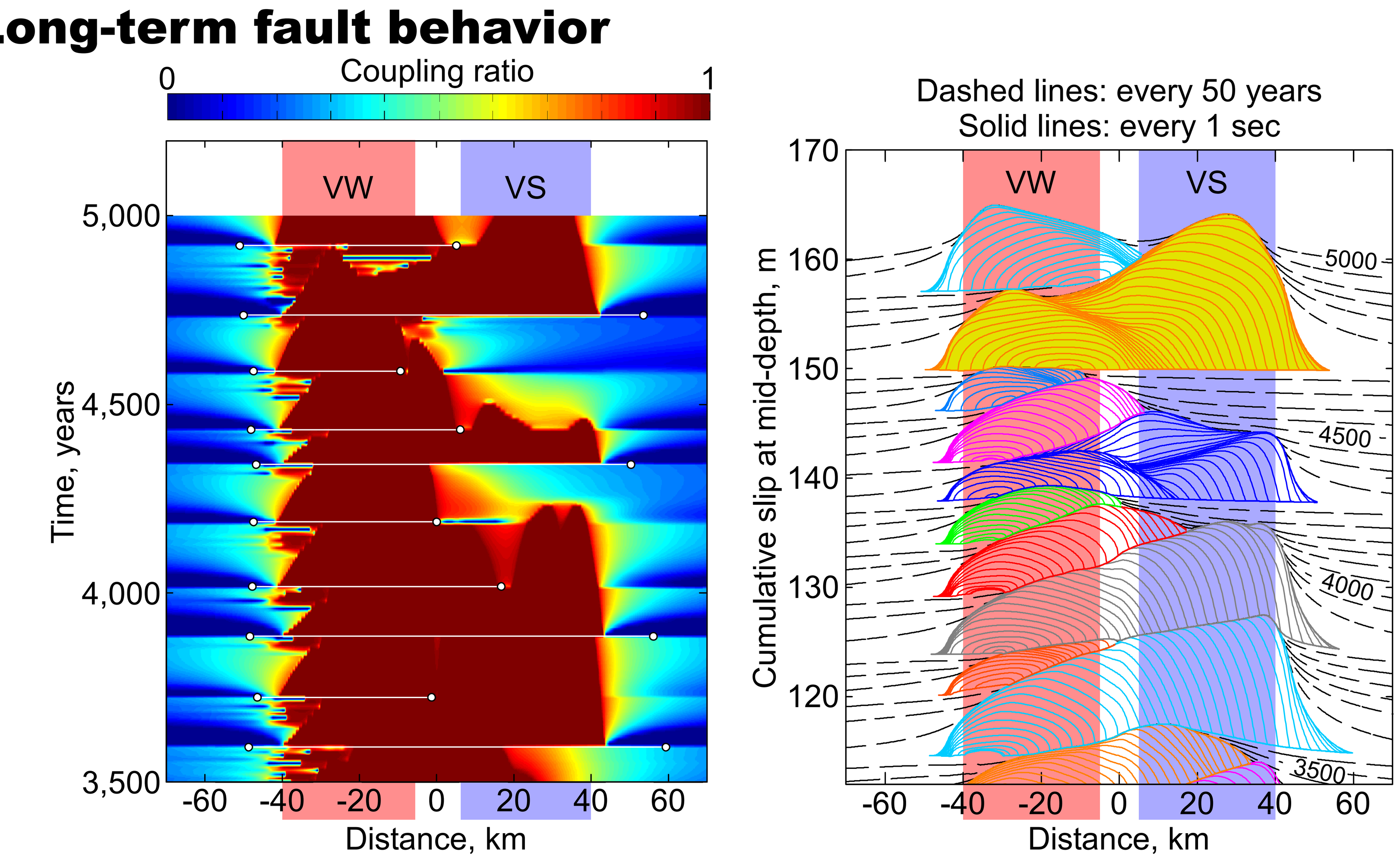
Elastodynamics		
S-wave speed	c_s	3000 m/s
Shear Modulus	μ	30 GPa
Poisson's ratio	ν	0.25
Frictional properties		
Reference slip rate	V_0	1 μm/s
Friction at a reference *	f_0	(VW) 0.7 (VS) 0.4
Rate-dependency *	$a-b$	(VW) −0.002 (VS) 0.004
Direct effect parameter **	a	0.0066
State-evolution distance	L	8 mm
Hydothermal properties		
Thermal diffusivity	α_{th}	10^{-6} m²/s
Hydraulic diffusivity *	α_{hy}	(VW) 3.5×10^{-2} m²/s (VS) 7.0×10^{-5} m²/s
Specific heat *	ρc	2 MPa/K
Unrained $\partial p/\partial T$ *	Λ	(VW) 0.036 MPa/K (VS) 0.069 MPa/K
Shear zone width	w	8 mm
Boundary condition		
Plate velocity	V_{pl}	10^{-9} m/s
Initial effective normal stress	σ_{e0}	60 MPa

* Tanikawa and Shimamoto [2009]. Hydraulic properties are at 60 MPa effective pressure.
** Tanikawa and Shimamoto, personal communication.

We treat the lab measurements as motivational rather than precise values, since they are based on samples from two boreholes at shallow depths (200-300 m).

Results

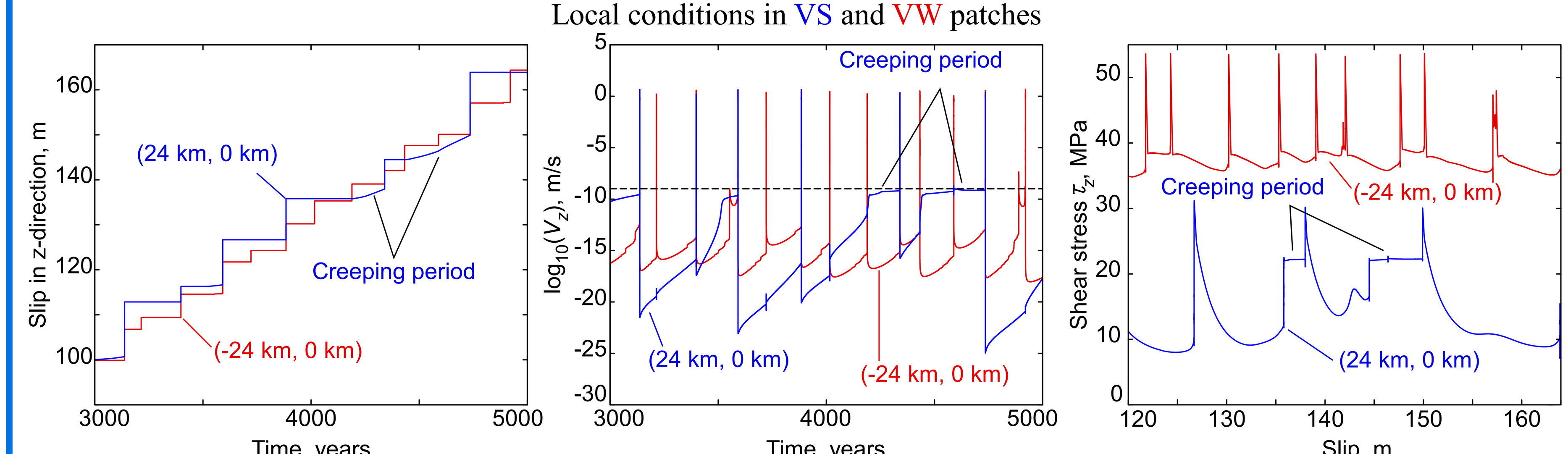
Long-term fault behavior



A VS segment susceptible to high-velocity weakening can ...
- be almost locked before a model-spanning event.
- start creeping hundreds of years prior to it.
- keep creeping while an adjacent VW segment host multiple events.

Importantly, those rich behaviors are realized in a single model.

Local conditions in VS and VW patches

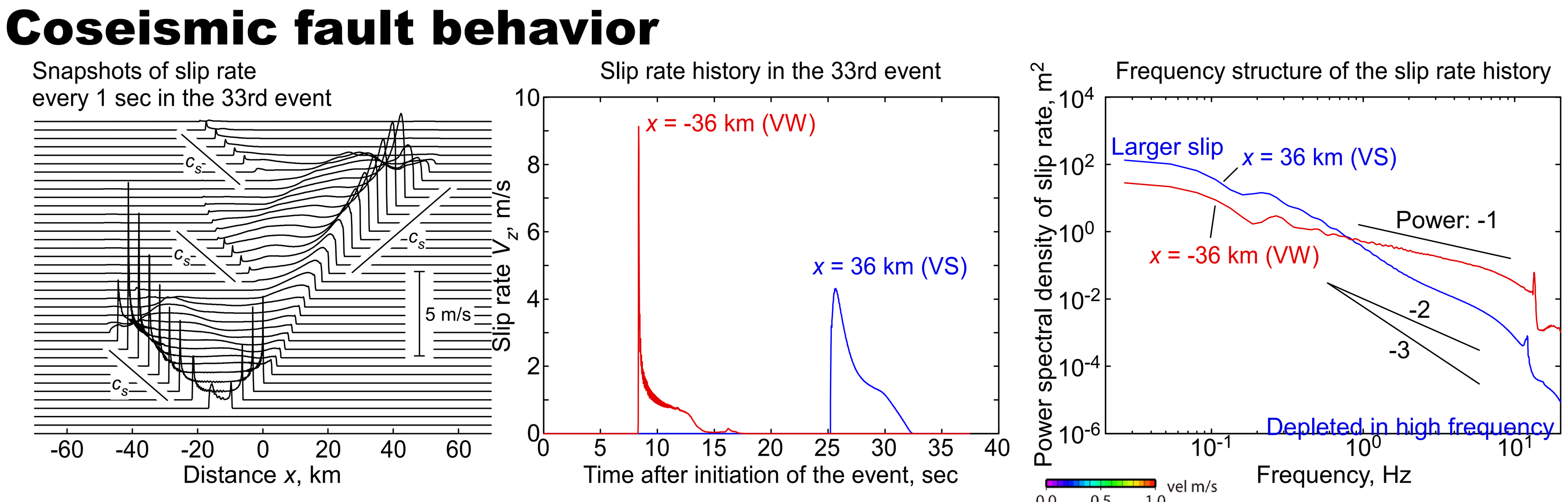


A creeping segment is a stressed segment with respect to the Low-velocity friction.

(Stress) < (Low-velocity friction) Locked (slip rate << plate rate)

(Stress) ~ (Low-velocity friction) Creeping (slip rate ~ plate rate)

Coseismic fault behavior



In the 26th rupture,

(1) Rapid propagation of a rupture front into the VW patch while the other front is almost arrested.

(2) The front into VS patch accelerates which does not have a sharp peak at the rupture front.

(3) Secondary ruptures, although they are minor, propagates into VW. They are nucleated by a large coseismic slip in VS.

The source-time function in VS is larger component at low frequency < 1 Hz, but more depleted in high frequency > 1 Hz than in VW.

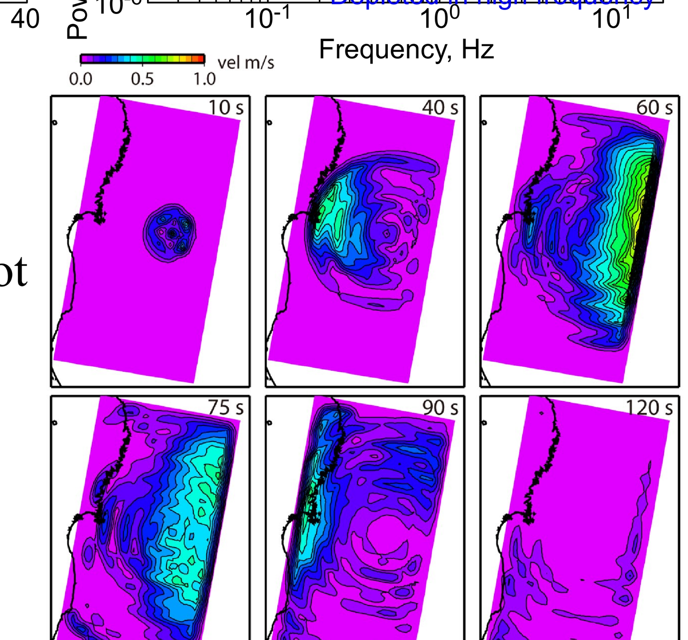


Figure from Ide et al., 2011, Tohoku-Oki earthquake

Qualitatively consistent with ChiChi earthquake and Tohoku-oki earthquake!

Discussion and conclusions

- **Observation of fault creep does not preclude the segment from having large coseismic slip in the next large earthquake.**
- **The fact that a segment produced large coseismic slip does not directly constrain creeping/locking of it before the event.**
- **Whether high-velocity weakening is activated or not is dictated by many factors.**

  Not only the distribution of the physical properties, but also the distribution of pre-stress and the location of nucleation (efficiency of dynamic stress transfer) matter. To fully understanding this system, more parameter study is required. Accurate enough constraint from observational and experimental studies may be challenging to constraint the characteristics of the next large earthquake.
- **"Accumulation of slip deficit" does not work in this system.**

  Long-term slip distribution must be, of course, uniform in this system. However, tens of years of geodetic observation may be just a snapshot in a long history, while the interseismic slip rate probably vary with time during an interseismic period. A velocity-strengthening segment may start creeping when it is loaded enough and ready to rupture.
- **An access to longer record is very important to constrain what has happened and can occur.**

  Geological record (e.g., heat detection [Sakaguchi et al., 2011]) or paleo-seismological studies on a currently creeping segment (e.g., North of Parkfield along San Andreas fault).

This study was accepted for publication in Nature.

Noda and Lapusta, Creeping fault segments can turn from stable to destructive due to dynamic weakening, Nature, doi: 10.1038/nature11703