Controls on seismic cycle deformation: modelling a rheological weak zone beneath a strike-slip fault

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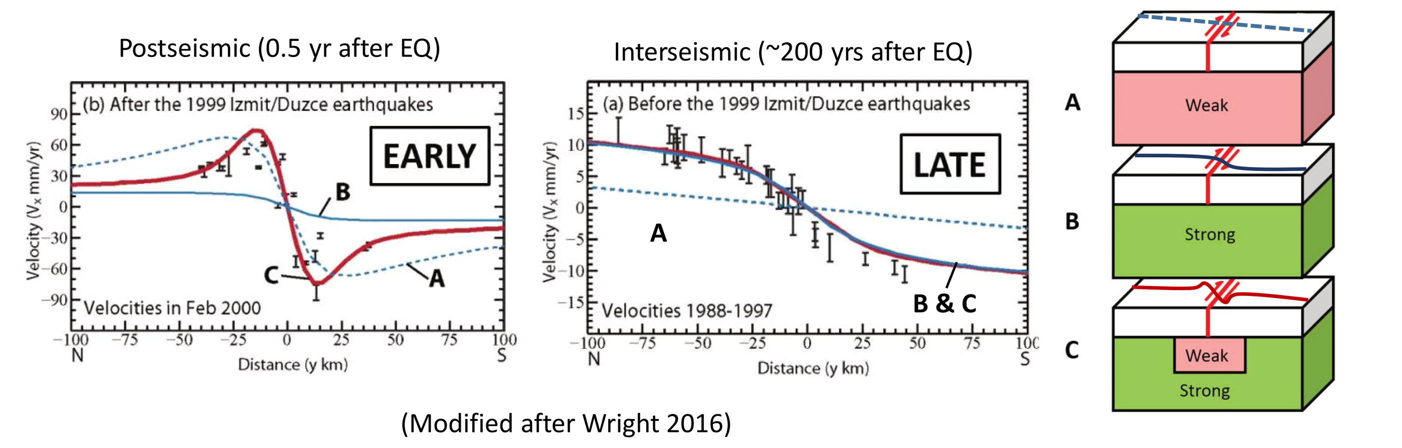
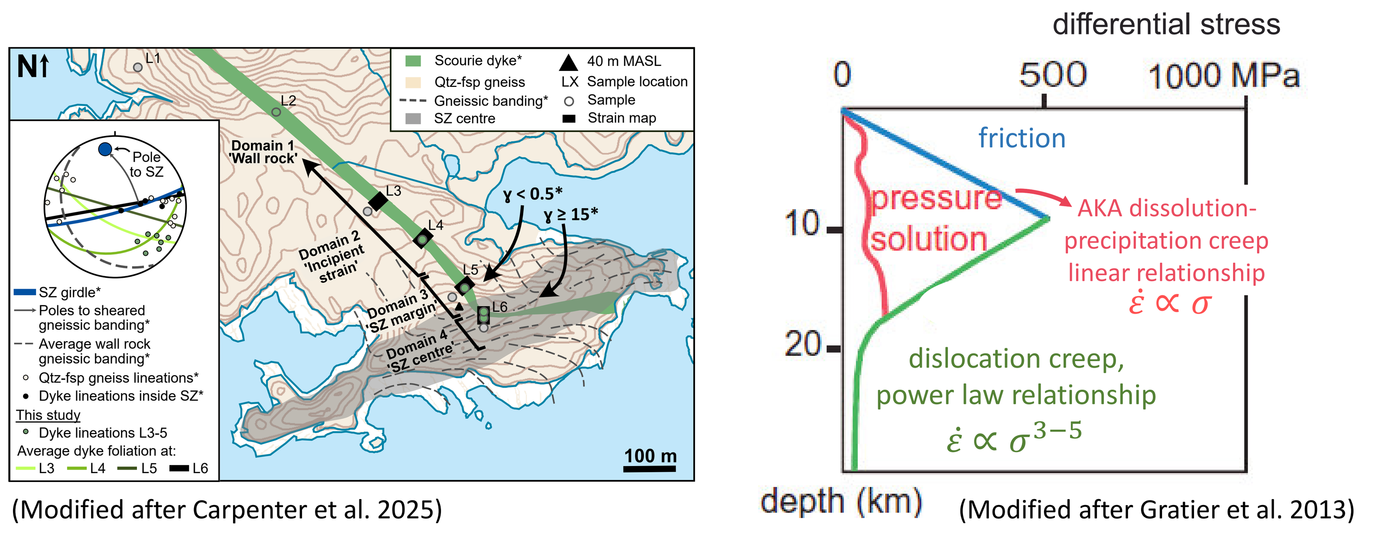
Background

To understand mid-crust deformation is vital to understand how strain is distributed in time and space, with implications for upper-crust deformation including seismic hazard. In particular, the reason for transient surface deformation observed prior to, and following, earthquakes is yet to be well constrained. A combination of frictional afterslip and spatially heterogeneous viscoelastic response of the mid-lower crust is proposed.



(Modified after Wright 2016)

A growing number of geological field studies of exhumed shear mid- to lower-crustal shear zones reveal viscous deformation in the dissolution-precipitation creep (DPC) regime, compared to the most historically observed dislocation creep (DislC) regime, and this signifies a significant rheological weakening.



(Modified after Carpenter et al. 2025) (Modified after Gratier et al. 2013)

Here, we illustrate how the distribution and availability of fluid in the mid-crust can determine material strength and create a hydrated 'weak zone'. Using SCycle modelling platform we investigate the influence of such a rheological weak zone on fault behaviour and the surface deformation response prior to, and following, earthquakes.

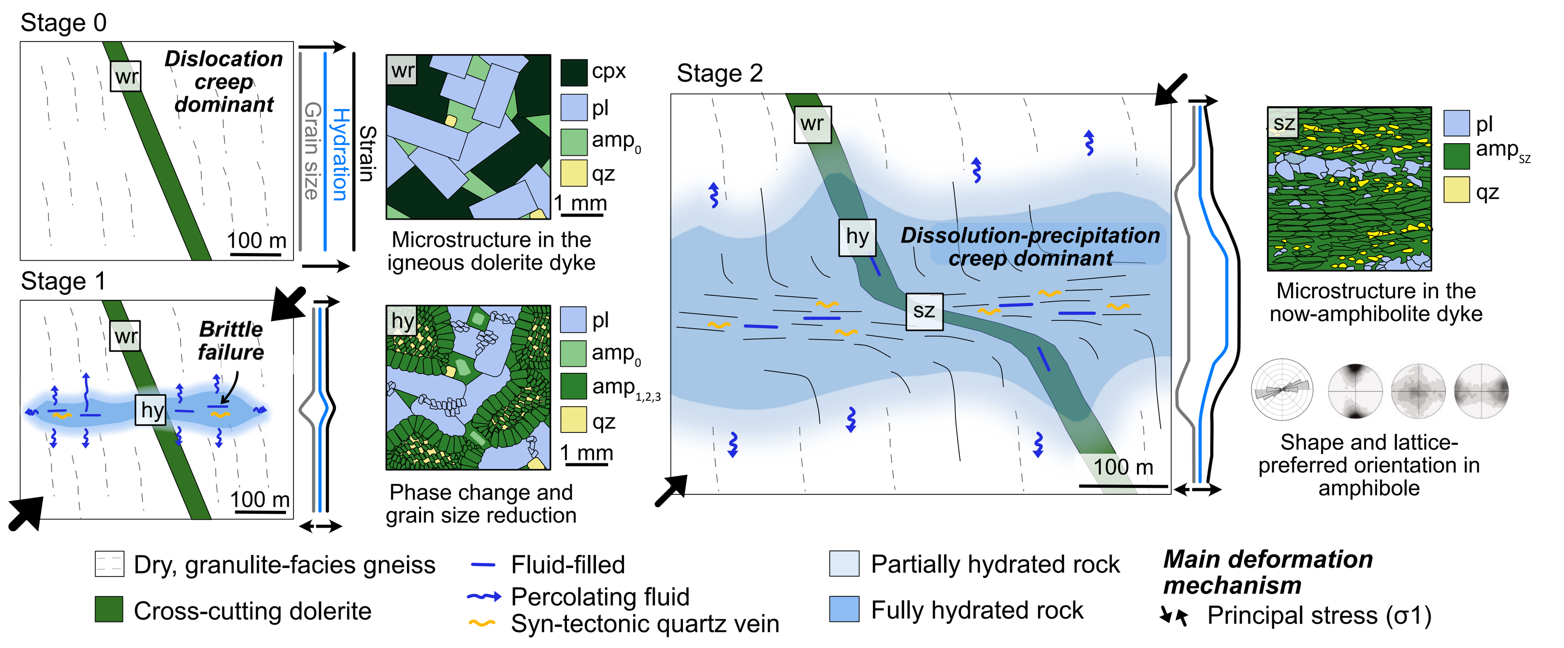
1. Conceptual model of mid-crustal shear zone from Lewisian Gneiss Complex, NW Scotland

Stage 0: Original anhydrous crust.

Stage 1: Brittle failure and local fluid ingress triggers weakening (phase and grain size change) and activation of dissolution-precipitation creep.

Stage 2: Repeated events enable progressive widening and maturity of the shear zone.

(Carpenter et al. 2025)



Hydration and deformation are correlated in space: hydrous reactions, quartz veins and high strain fabric.

Microstructures include: 1) asymmetrically truncated grains (dissolution), 2) preferentially grown chemically distinct rims (precipitation), 3) overall shape-preferred orientation and 4) lattice-preferred orientation only in amphibole.

2. Dissolution-precipitation creep means a much weaker rheology, where active

We fit a dissolution-precipitation creep flow law to rock deformation experiments carried out at mid-crustal conditions on a range of rock types.

Dislocation creep flow law (Ranalli 1997)

$$\dot{\varepsilon} = A\exp(-Q_c/RT)\,\sigma^n$$

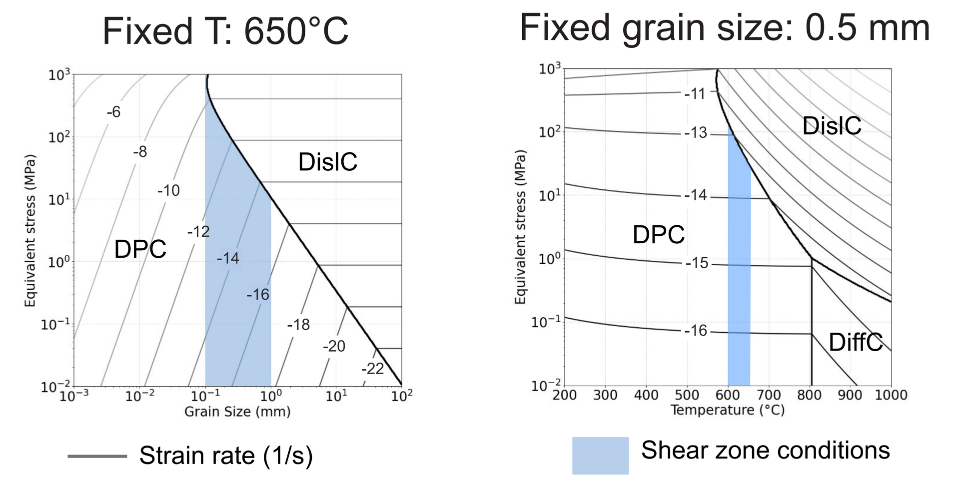
Power-law stress-strain rate relationship (n ≥ 3)
Grain size insensitive

Dissolution-precipitation creep flow law (Gratier et al. 2023)

$$\dot{\varepsilon} = A\,D\,w\,c\,V_s\left(e^{\frac{3V_s\sigma_d}{RT}} - 1\right)/d^3$$

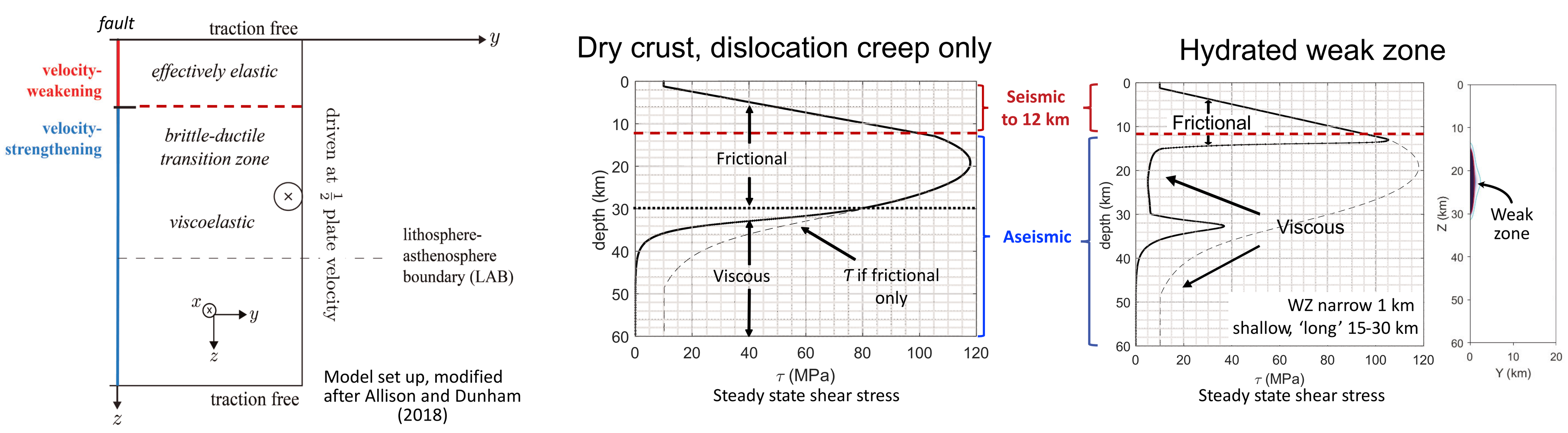
Close to linear stress-strain rate relationship
Grain size (*d*) sensitive, reaction or diffusion rate dependent

Deformation mechanism maps show dominant creep regime in stress-grain size or stress-temperature space. DPC, DislC and DiffC = dissolution-precipitation, dislocation or diffusion creep.



DPC is dominant at lower temperature, lower grain size conditions and is less sensitive to temperature.

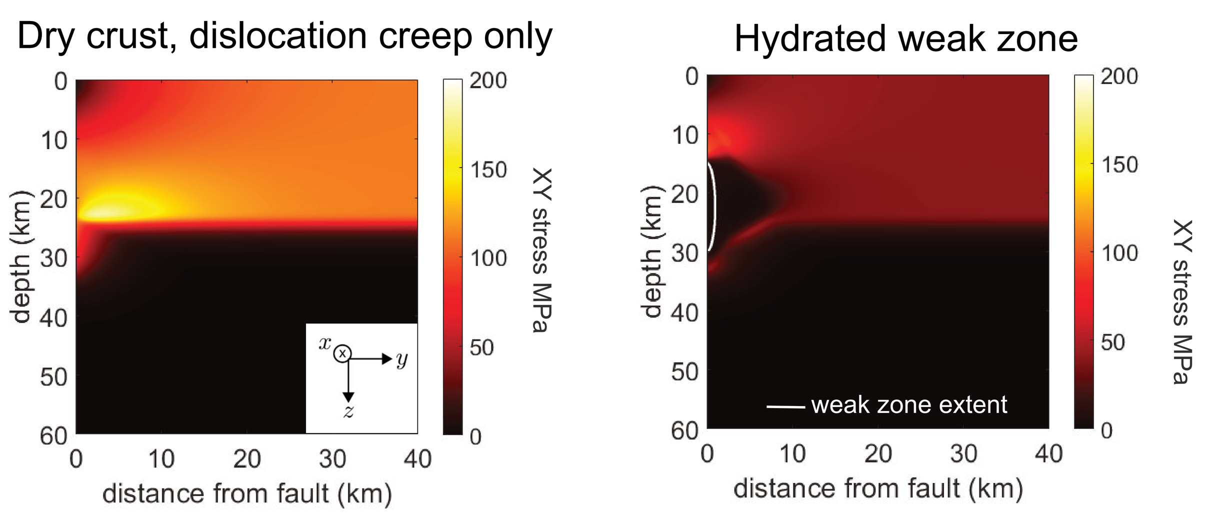
3. We use modelling platform SCycle to implement a hydrated 'weak zone' on a frictional-viscous crustal-scale fault



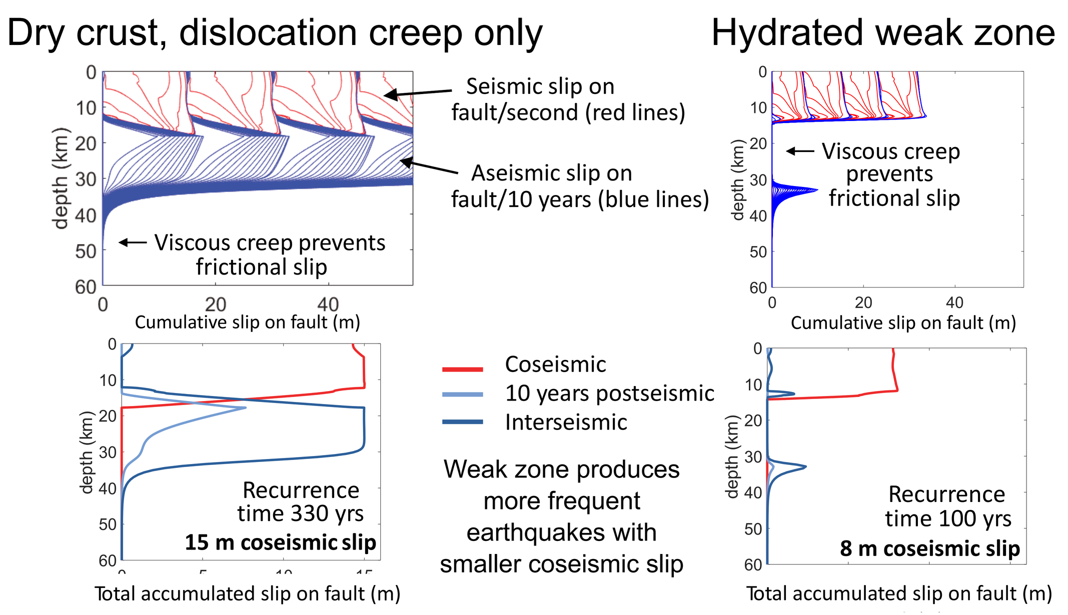
A reduction in shear stress on the fault occurs where weak zone prevents aseismic frictional slip and strain is instead accommodated by viscous creep.

- Parallelized finite difference code, 2D strike-slip fault
- Geotherm 25°C/km, plate velocity 3 cm/yr, feldspar rheology
- Steady-state spin up before earthquake cycles
- In weak zone both dissolution-precipitation creep and wet dislocation creep can be active

4. Weak zone reduces crustal stress, aseismic slip on the fault, and means smaller, more frequent earthquakes



Plots above show XY stress at steady state. Weak zone produces lower, more distributed stress in the crust.



Conclusions & Key Findings

- In nature, where fluid activates DPC it can facilitate significant rheological weakening and strain localisation. Additionaly, fluid can weaken rock prior to deformation, through phase change and/or grain-size reduction.
- A change from dislocation creep regime to DPC regime means stress-strain rate relationships change from power-law to linear Newtonian flow, and significant rheological weakening.
- Numerical modelling of an active fault shows that spatially heterogeneous material properties in the mid-lower crust influence the pattern of surface deformation in the fault's vicinity.
- A DPC weak zone prevents aseismic slip on the fault, and high surface velocities are more focussed around the fault when a weak zone is present.
- Smaller and more frequent earthquakes occur when a weak zone is present, particularly when the weak zone is shallow.

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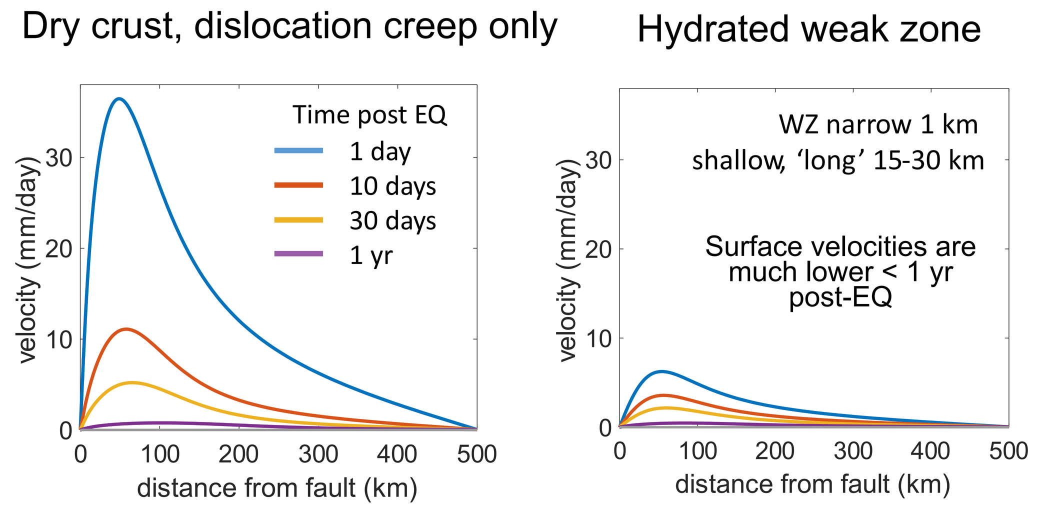
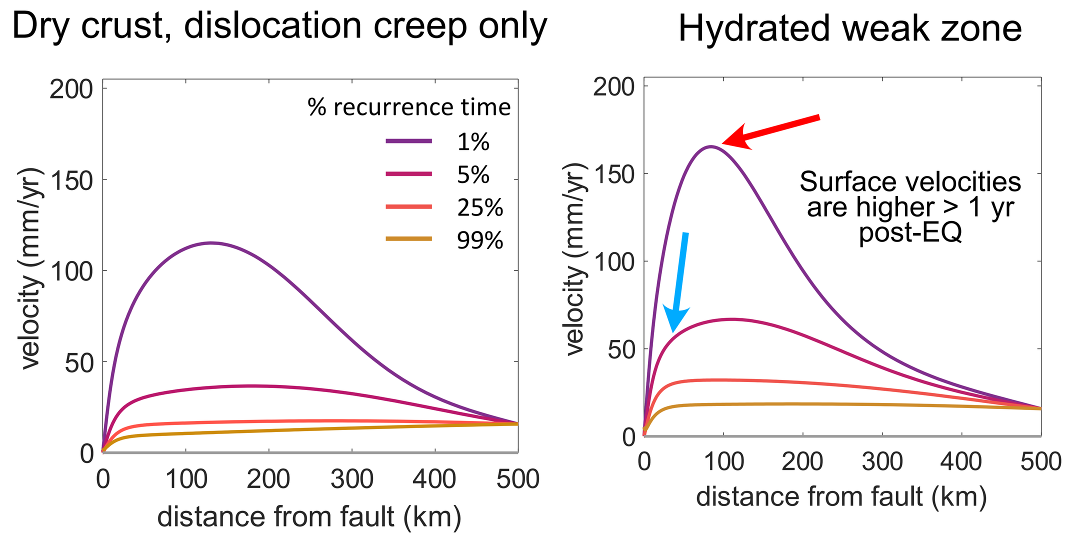
5. Weak zone influences short-term (postseismic) and long-term (interseismic) surface velocities differently

Short term surface velocities 1-365 days post EQ



With weak zone, surface velocities are lower in the short-term.

Long term surface velocities > 1 yr post EQ



With weak zone, long-term surface velocities are higher (red arrow), with more focussed strain close to the fault (blue arrow)

Different weak zone geometries (width, length, top depth) influence seismic cycle characteristics differently:

Weak zone geometry	Coseismic slip (m)	Recurrence interval (yrs)	Max. surface velocities after ≤ 30 days (mm/day)	Surface velocities @ 100 km, after ≥ 1 yr interseismic period (mm/yr)
None, dry	16	330	36	35
Shallow & narrow	↓↓	↓↓	↓↓	↑↑
Shallow & wide	↓↓	↓↓↓	↓	↑↑↑
Deep & narrow	↓	↓	little change	↑
Deep & wide	↓	↓	little change	↑

Top depth has a greater influence than weak zone width. Weak zone presence may allow faster loading of upper crust pre-EQ, and faster relaxation of the mid-crust > 1 yr post-EQ.

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