Ultralow frictional healing explains recurring slow slip events

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- **Frictional healing**: “… describes the ability of a fault to restrengthen and store elastic strain energy between events. . In the absence of a mechanism for restrengthening, a fault will fail only by aseismic creep. Frictional healing of an earthquake source region is particularly important because it plays a primary role in controlling rupture properties, including stress drop, recurrence interval, and potentially slip mode and amount.”
    - “Frictional healing describes the ability of a material to restrengthen frictionally over time and is a prerequisite for repeating stick-slip (seismic) failure of faults because it allows interseismic coupling and elastic strain accumulation”

Silently not able to heal

Faults on the Earth rupture over time but do not always produce earthquakes. Such aseismic, or slow slip, events are an important way to release stress. Shreedharan et al. determined the frictional healing properties of a slow slip portion of the Hikurangi fault in New Zealand. They found that the ability of the material to strengthen after failure was limited, unlike for earthquake-producing events. These observations could explain why these shallow, slow slip events happen frequently and at low stress.
—BG

Figure 1.

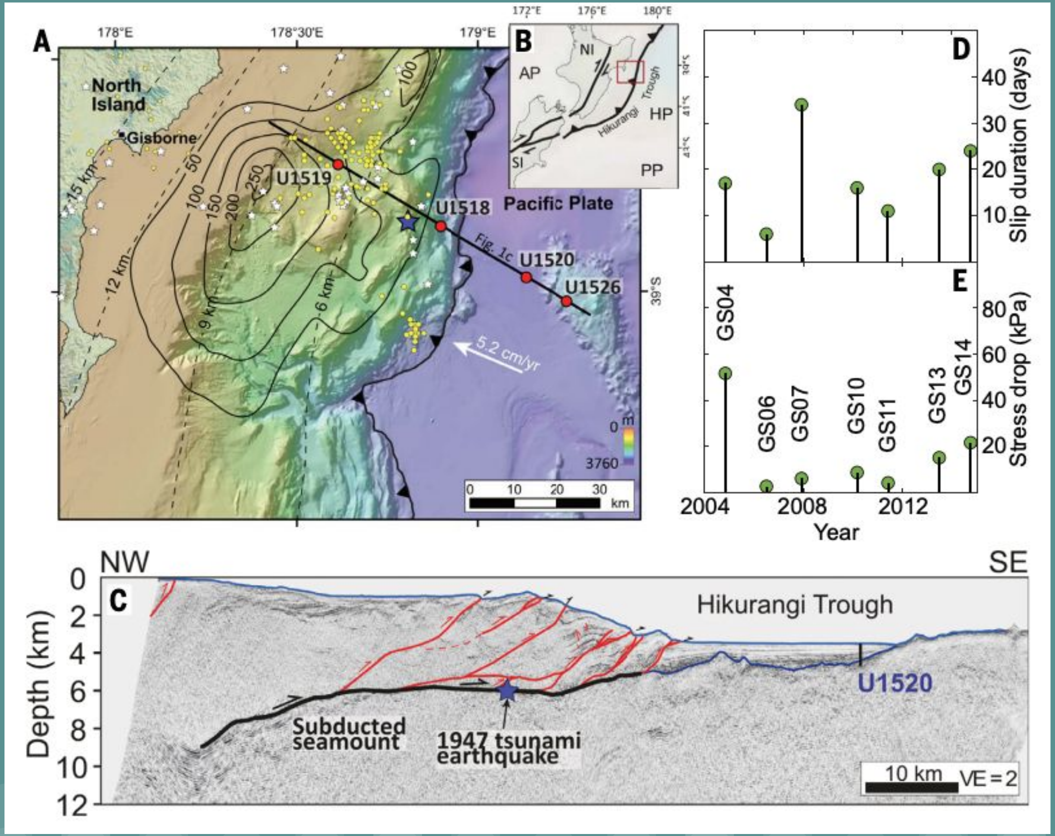

Fig. 1. Tectonic setting of the Gisborne area shallow slow slip events. **(A)** Bathymetric map of the northern Hikurangi margin showing the trench (bold black curve), depth to the plate interface (dashed contours), slip contours of the 2014 SSE in millimeters (black, as labeled), location of the 05CM-04 seismic line (black line), and locations of IODP expedition 375 drill sites (red circles) [modified from (12)]. Hypocenter of the 1947 tsunami earthquake (blue star), tremor activity (small yellow circles), and microseismicity (white stars) are also shown. **(B)** Regional tectonic map showing the Pacific plate subducting beneath the Australian plate, forming the northern Hikurangi margin. **(C)** Interpretation of the 05CM-04 seismic line [modified from (12)] showing the plate interface (bold black line), active upper-plate splay faults (red lines), and location and depth extent of IODP drill site U1520. The blue star at a depth of ~6 km represents the hypocenter of the 1947 tsunami earthquake. **(D)** Slip duration and **(E)** Spatiotemporally averaged stress drop of the quasiperiodic SSEs rupturing the Gisborne patch from 2002 to 2016 (table S2).

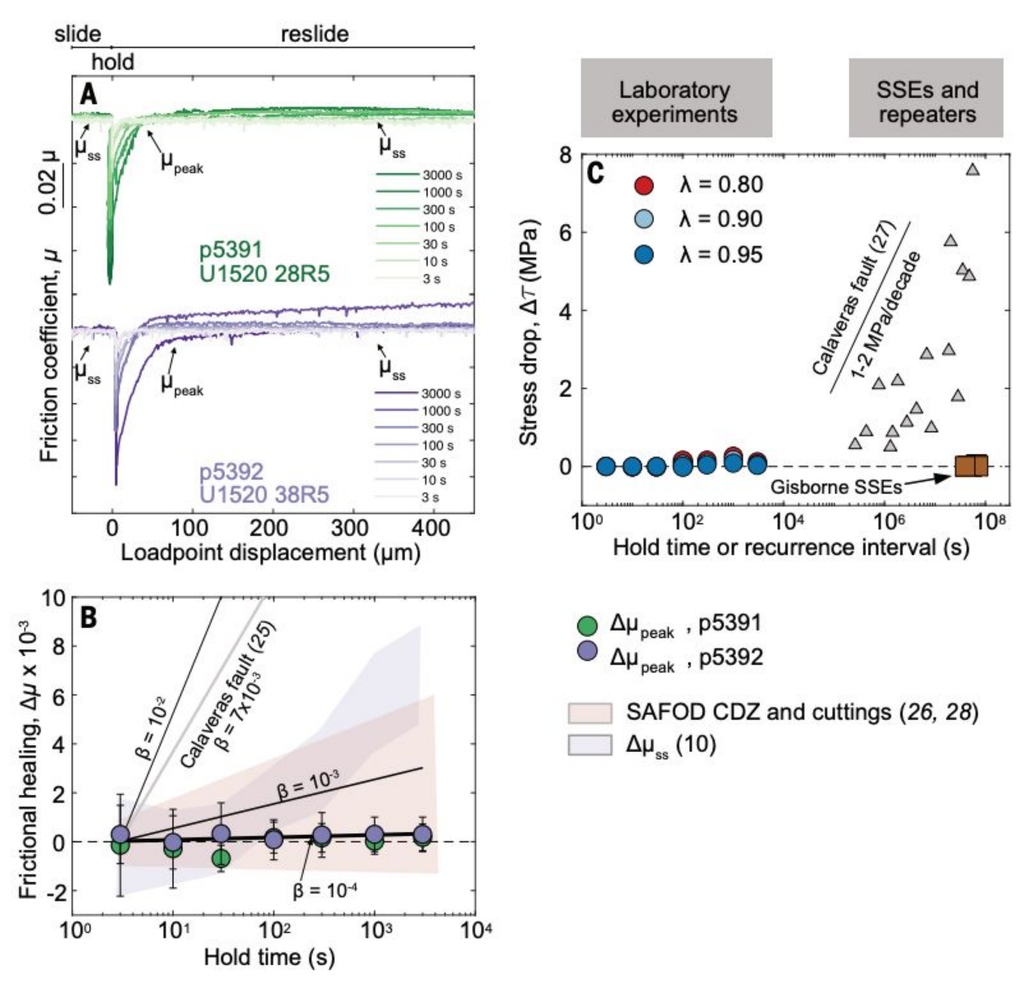

Fig. 2. Frictional healing constrained from laboratory experiments. **(A)** Overlay of multiple SHS protocols with different durations (3 to 3000 s) for two phyllosilicate-rich sediment samples from Site U1520. mss represents the pre- and posthold steady-state values of the friction coefficient, and mpeak represents the location of the (near-zero) peak friction upon reshear after a hold. **(B)** The change in friction (healing) between mpeak and mss shows little or no correlation with hold time. Error bars quantify electrical noise in the load cell and represent the limit of resolution of the friction drops. Fiducial lines show three different healing rates representing a range of values reported in prior studies (25), as well as values encompassed by the experiments reported here. Gray line represents the friction drops from SHS experiments conducted on samples from the Calaveras fault (25), where seismic repeaters have been observed. Pink area shows the range of values reported from SHS experiments conducted on smectite-rich San Andreas Fault Observatory at Depth (SAFOD) Central Deforming Zone (CDZ) cuttings (26, 28). Light blue region represents changes in steady-state friction coefficient from pre- to posthold reported by (10). **(C)** Changes in stress drop versus recurrence interval for the Gisborne SSEs and versus hold time for the experimental data. Stress drops for experimental data are calculated as the product of friction drop and effective stress for three different degrees of overpressure. Gray triangles represent stress drops estimated from the seismic source for Calaveras repeaters (27).

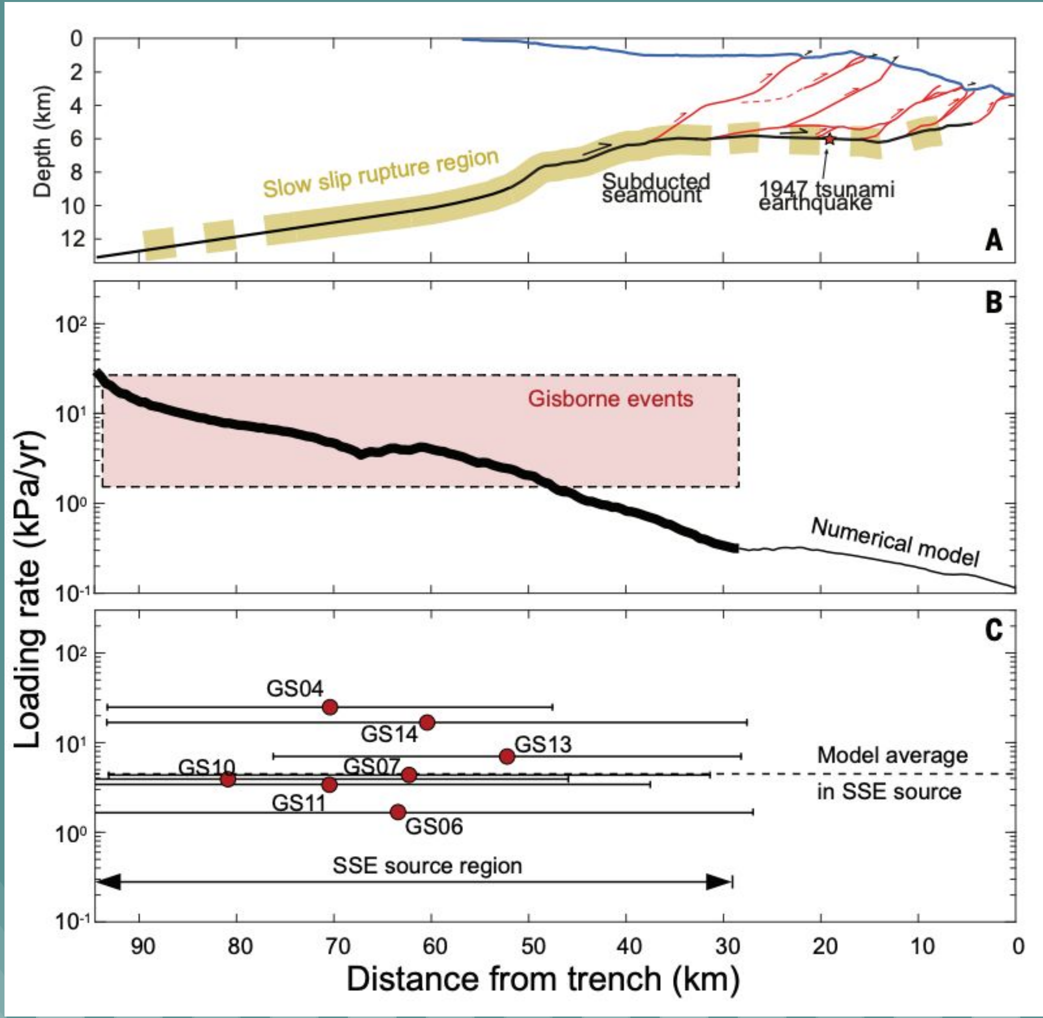

Figure 3

Fig. 3. Inter-SSE loading rates in the northern Hikurangi margin. **(A)** An illustration of the 05CM-04 line showing upper-plate splay faults (red curves), the hypocenter of the 1947 tsunami earthquake (red star), a subducting seamount, and the likely shallow SSE rupture region (thick yellow bars). **(B)** Annual tectonic loading rates (for convergence at 50 mm/year) along the 05CM-04 seismic transect, computed from 2D finite-element numerical model in Pylith (29). Loading rates increase from ~0.15 kPa/year near the trench to ~30 kPa/year at a depth of 15 km. **(C)** Tectonic loading rates constrained from the Gisborne SSEs as the ratio of average stress drops and interevent times. The black (~4.5 kPa/year) dashed line shows average loading rates from models.

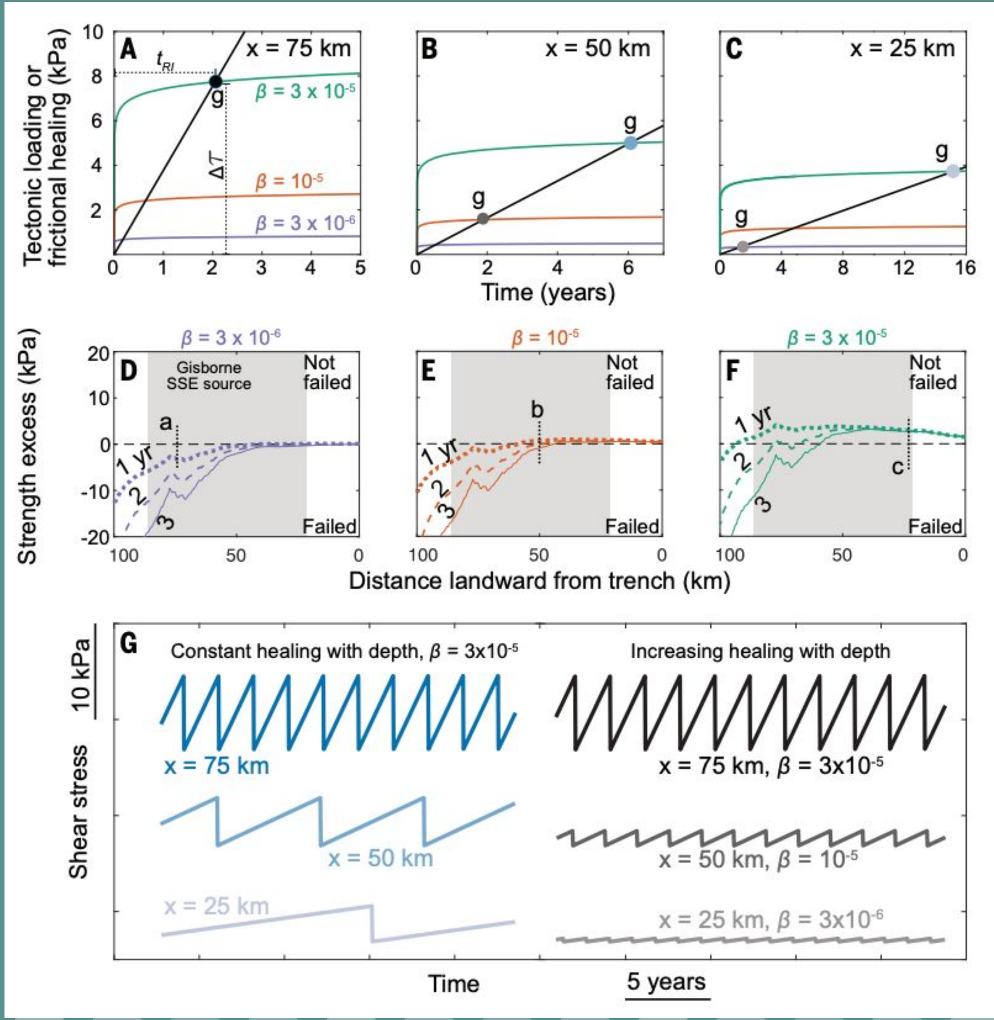

Figure 4

Fig. 4. A framework to quantify competition between tectonic loading and frictional healing. Tectonic loading as shown in Fig. 3 (black lines) and fault restrengthening (colored curves) as a function of time, for three different assumed healing rates (3 × 10–6 , purple; 1 × 10–5 , orange; and 3 × 10–5 , green) at **(A)** 75 km, **(B)** 50 km, and **(C)** 25 km from the trench. Strength excess as a function of distance from the trench, after 1 year (dotted curve), 2 years (dashed curve), and 3 years (solid curve) for healing rates of **(D)** 3 × 10–6 , **(E)** 1 × 10–5 , and **(F)** 3 × 10–5 [same color scheme as in panels (A) to (C)]. **(G)** Simplified models of recurrence and stress drop for two scenarios of depth-varying healing, showing shear-stress variations over time. Constant healing with depth (left, light to dark blue) results in small-stress-drop events with large recurrence intervals near the trench; increasing healing rate with depth (right, gray to black) results in very-small-stress-drop events (~1 kPa) every few weeks or months. Effective stress corresponds to l = 0.90 for all panels.

Supplementary

Figure S1

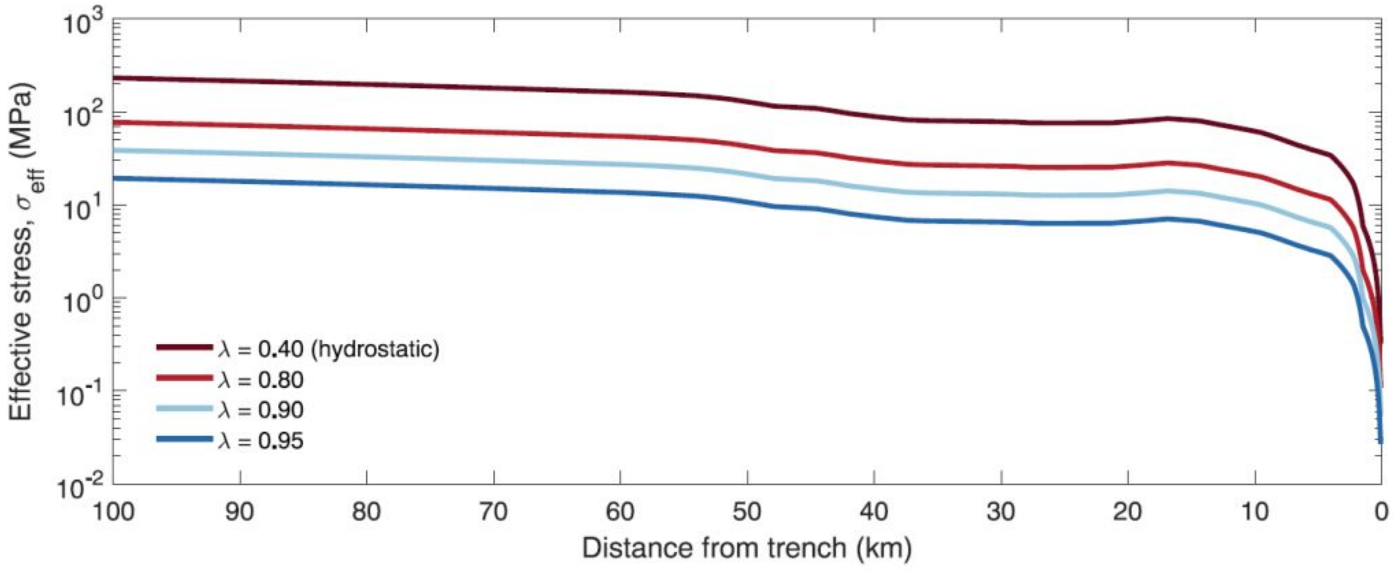

Fig. S1.

Effective stress profile for different pore pressure ratios.

Supplementary

Table S2

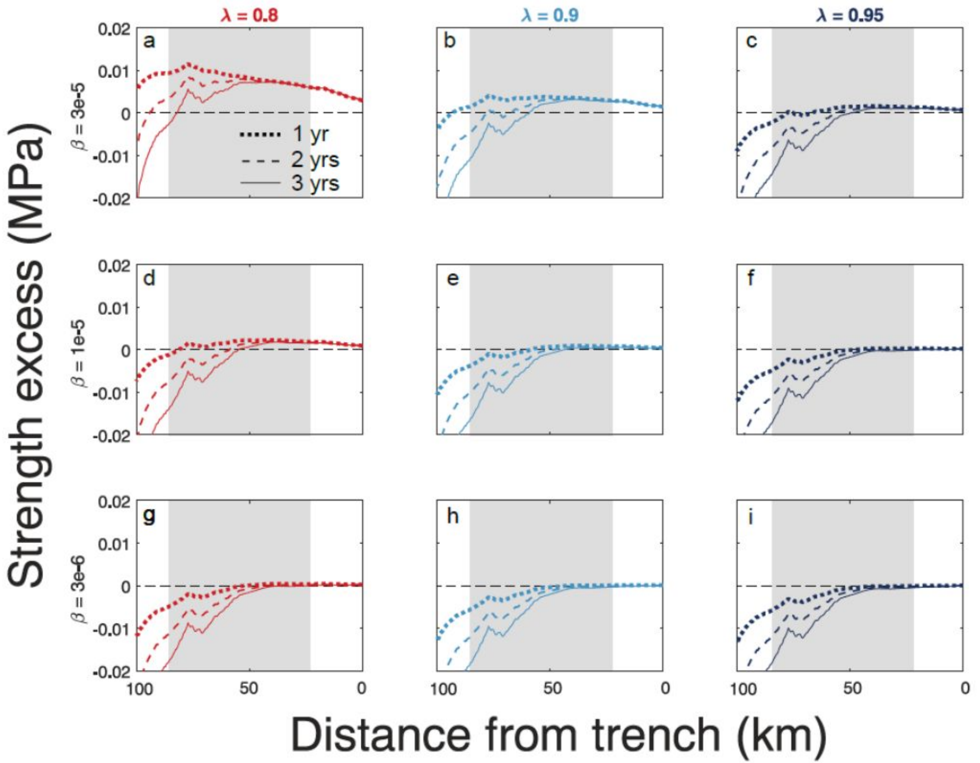

Fig. S2.

Measurements of strength excess for three healing rates (β = 3e-5, 1e-5 and 3e-6 /decade) and three degrees of overpressure (λ = 0.8, 0.9, 0.95) after one (dotted curves), two (dashed curves) and three (solid curves) years along the plate interface at the northern Hikurangi margin. Grey box shows likely source of Gisborne shallow SSEs.