Precursory changes in seismic velocity for the spectrum of earthquake failure modes

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Supplementary Material

Contains: Supplementary Figure 1, 2, 3, 4 and Supplementary Table 1

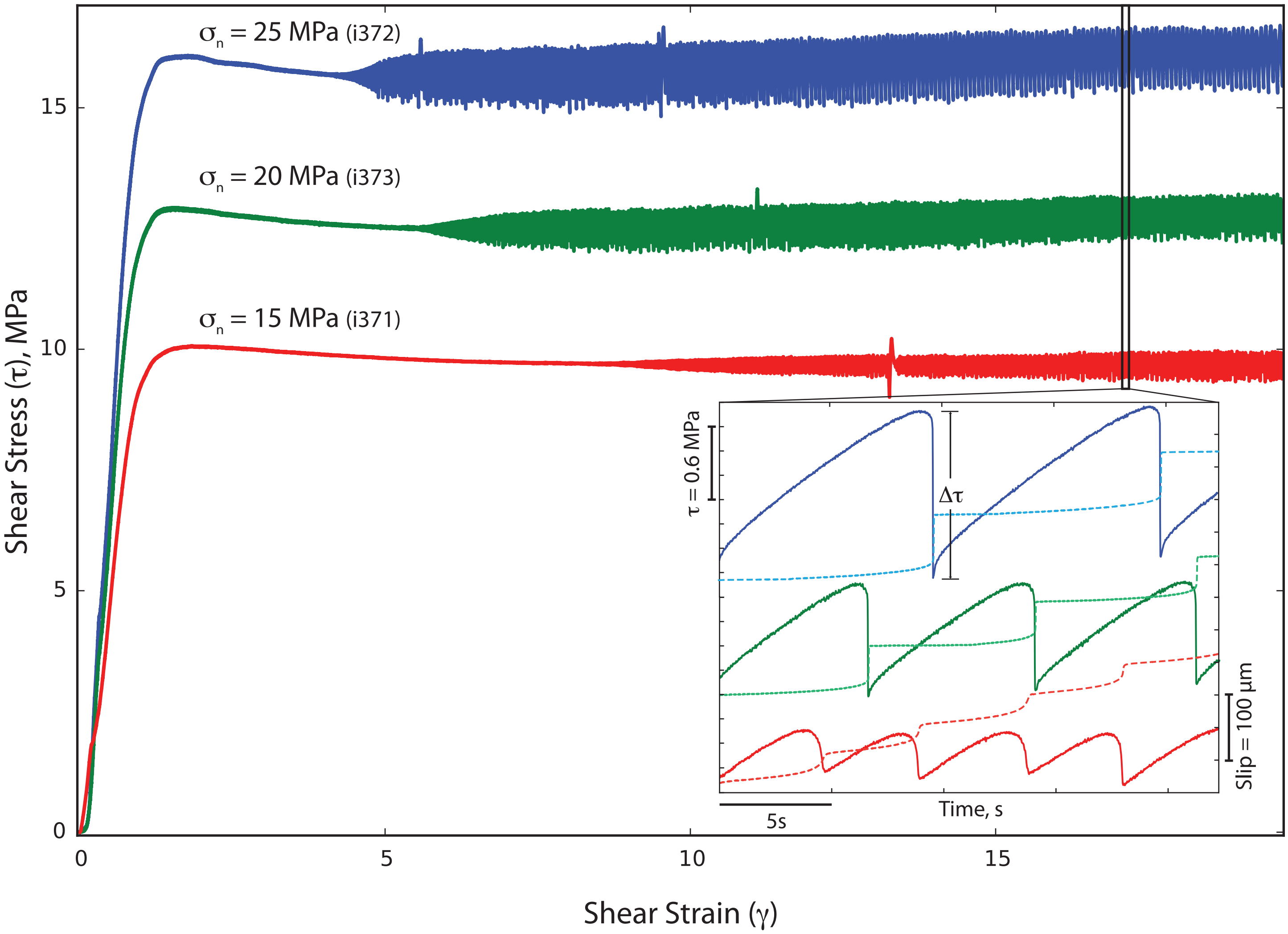

Figure Supplementary 1. Records of shear stress as a function of shear strain for representative experiments at three normal stresses, σn, and a constant shearing rate of 10μm/s. In each case, shear is initially stable and transitions to unstable stick-slip spontaneously. Lower right inset shows detail of slip events (solid line is stress) and the corresponding fault slip (dashed lines) across the transition from slow to fast stick-slip.

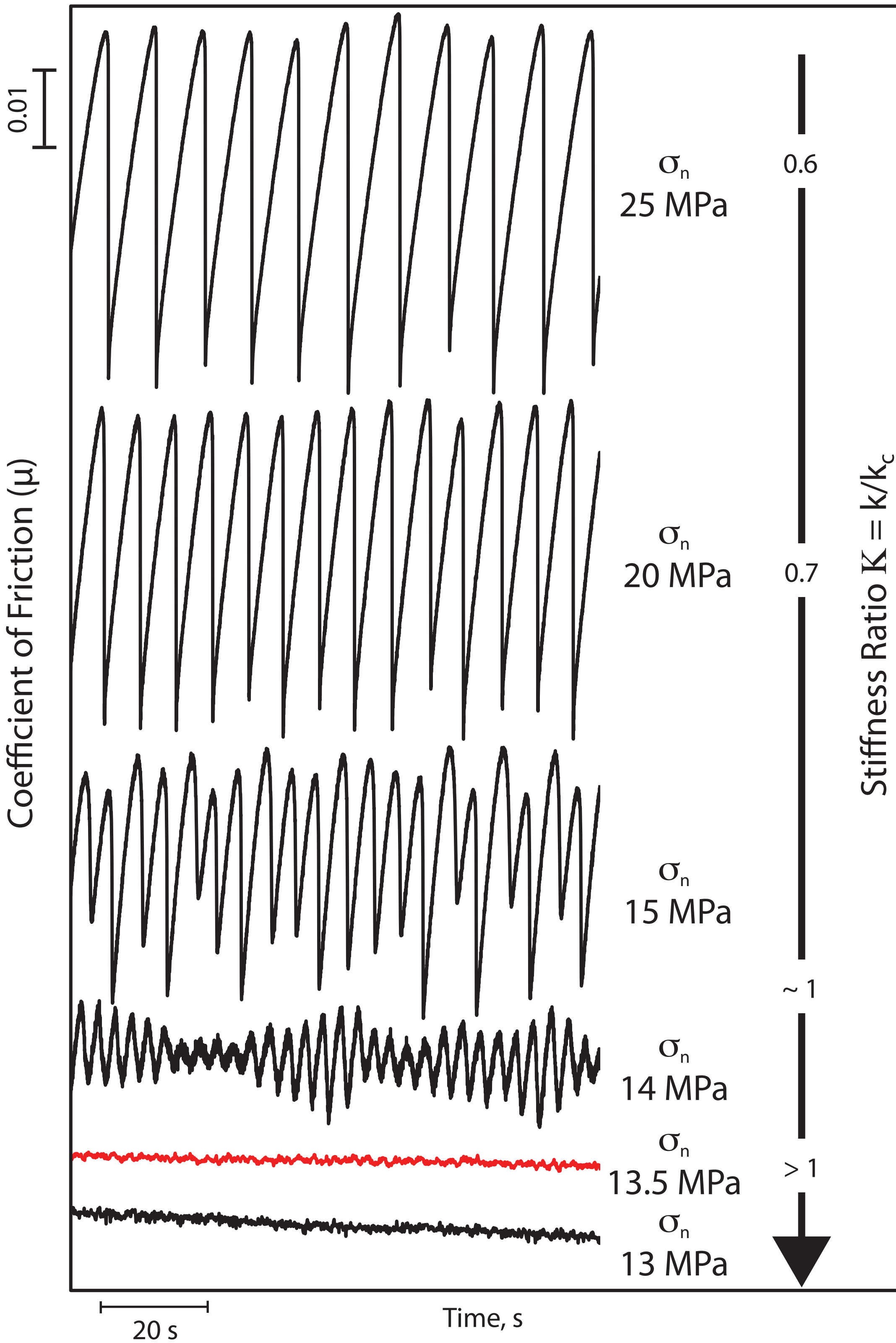

Figure Supplementary 2. Friction records for a series of experiments performed at different normal stresses to span the transition from fast stick-slip to stable sliding. As the stiffness ratio increases we document a net decrease in stress (friction) drop, an increase in stress drop duration and an increase in the frequency of the events. As the stability threshold is approached (i.e. K ~ 1) period doubling (σ_n = 15 MPa) and amplitude modulation of stress drop (σ_n = 14 MPa) arise, reflecting chaotic behavior. When K > 1 we observe stable shear. Note that the transition from fast stick-slip to steady sliding takes place in a very narrow range of normal stresses. All data are reported in terms of friction coefficient ($\mu = \tau/\sigma_n$) and have been offset for clarity.

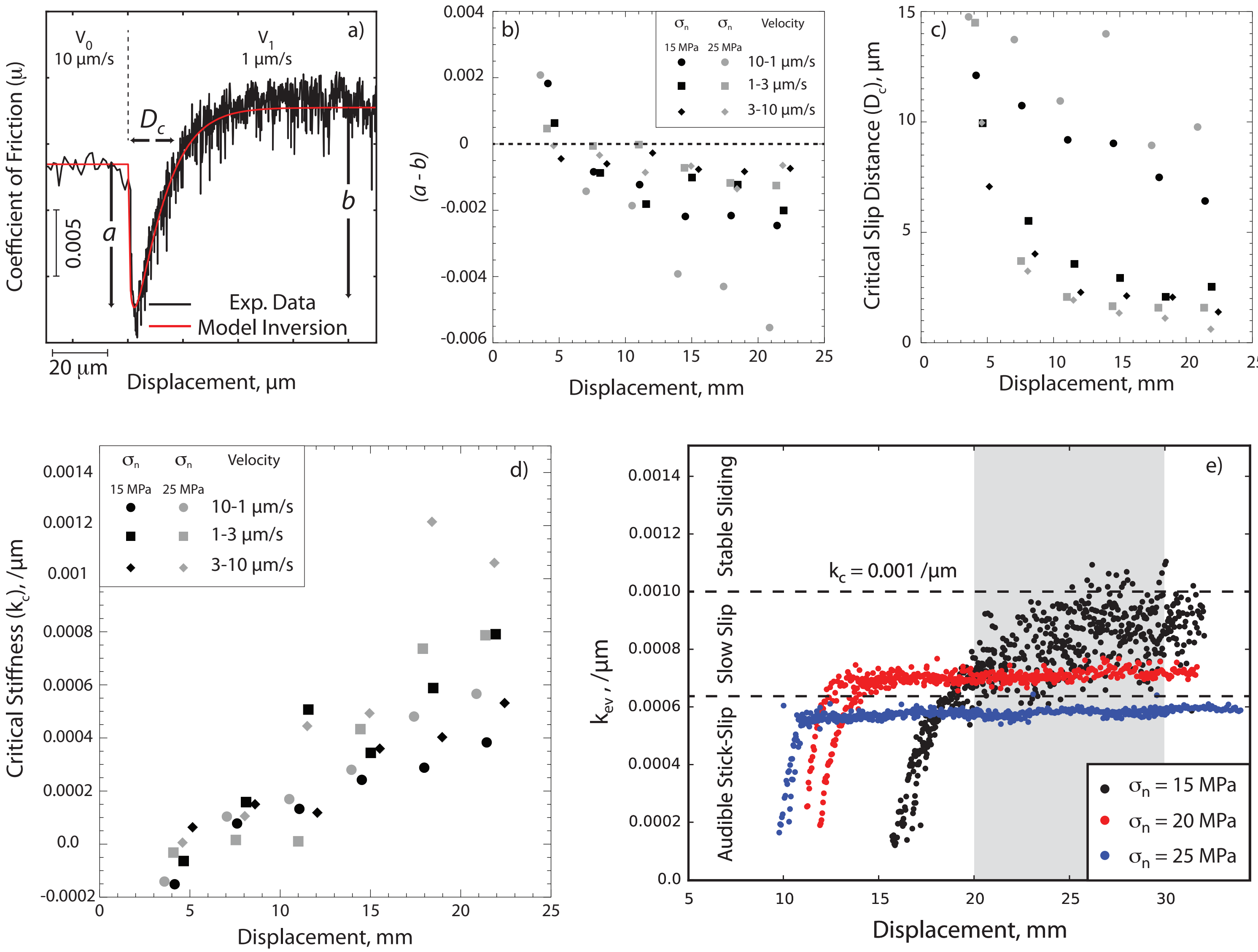

Figure Supplementary 3. Experimental data and modeling procedure used to obtain the rate- and state- friction parameters. (a) Representative data for a velocity step from 10 to 1 μm/s. The evolution of frictional strength is shown as a function of shear displacement (black). Results of the model inversion are shown in red superimposed on the raw data. (b) The friction rate parameter (a-b) shows a transition from velocity strengthening to velocity weakening as shear displacement increases. (c) The critical slip distance (Dc) decreases with increasing displacement. (d) The resulting critical rheologic stiffness, kc, increases as a function of displacement. (e) Evolution of the stiffness computed for each slip event (k) in three experiments (Table Supplementary 1) as a function of shear displacement. Grey box indicate the interval of the data we used in Figure 1a, b.

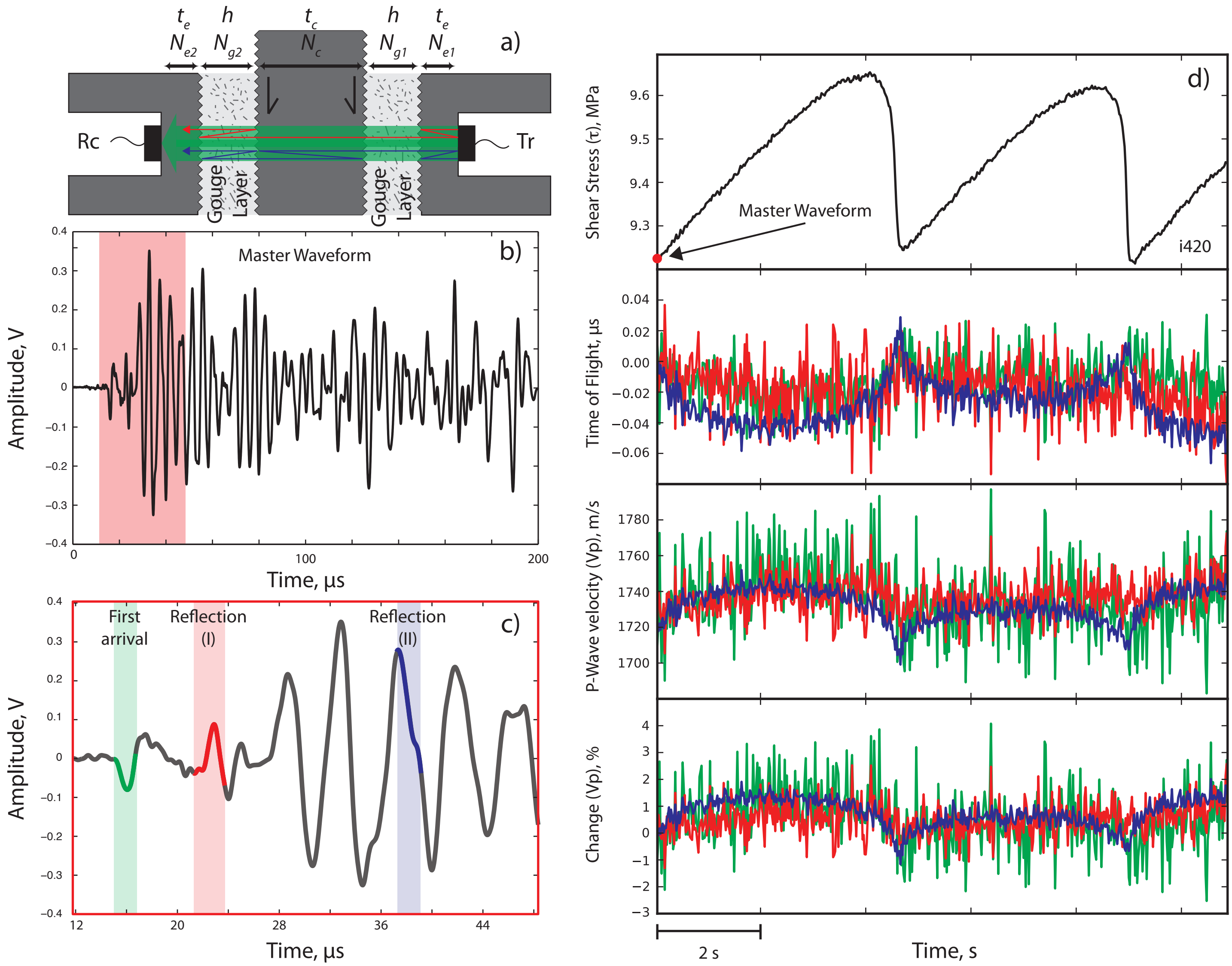

Figure Supplementary 4. (a) Schematic representation of the double direct shear configuration, showing the propagation model with elastic wave ray paths of the direct wave (green) and two reflected waveforms (red and blue). (b) Typical master waveform taken at the beginning of a slow slip event (red dot in panel d). (c) Zoom of the master waveform (red box in b) indicating the P-wave arrival and the P-wave coda. Two patterns corresponding to the reflections schemes indicated in (a) are shown. (d) Evolution of time of flight, P-wave velocity and change in P-wave velocity (%) for two slow slip events (upper panel), obtained from the cross-correlation of the P-wave arrival (green) and P-wave coda (red and blue).

Experiment Number	Normal Stress (MPa)	Velocity (μm/s)	Spring Constant (MPa/ μm)	RH (%)	Comments
i416	15	Run in 10 v.steps 1-3-10	NO	100	Velocity Steps
i433	25	Run in 10 v.steps 1-3-10	NO	100	Velocity Steps
i266	13	10	0.0296264	100	Stable Sliding
i268	13.5	10	0.0296264	100	Stable Sliding
i267	14	10	0.0296264	100	Slow-Slip
i371	15	10	0.0296264	100	Slow-Slip
i390	15	10	0.0296264	100	Slow-Slip
i420	15	10	0.0296264	100	Slow-Slip
i363	20	10	0.0296264	100	Intermediate
i373	20	10	0.0296264	100	Intermediate
i418	20	10	0.0296264	100	Intermediate
i372	25	10	0.0296264	100	Audible Stick-Slip
i391	25	10	0.0296264	100	Audible Stick-Slip
i415	25	10	0.0296264	100	Audible Stick-Slip
i417	25	10	0.0296264	100	Audible Stick-Slip
i433	25	10	0.0296264	100	Audible Stick-Slip

Table Supplementary 1. Summary of experiments and boundary conditions. All tests were conducted under 100% relative humidity (RH) to ensure experimental reproducibility.