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Temperature and fluid activation of contact healing and fault lubrication in rate-and-state friction

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The frictional behavior of rocks under shear offers tremendous complexity depending among others on rock type, temperature, fluid content, and sliding velocity. A large body of laboratory experiments documents these effects, but a unifying theoretical framework linking these observations is still missing. Here, I present a constitutive law based on multiple temperature and fluid activated healing processes and a fluid lubrication phase to capture fault behavior in the brittle field in all conditions relevant to the seismic cycle. Distinct healing processes are activated at different temperatures, pore fluid pressures, and depths based on their respective activation enthalpy. A fluid phase is rapidly formed at the high temperatures facilitated by shear heating, allowing strong weakening at high slip velocity. The model explains the intricate change of frictional behavior of carbonate rocks at various temperatures, including simultaneous velocity-strengthening and temperature-weakening at temperatures lower than 70ºC, transitioning to simultaneous velocity-weakening and temperature-hardening at higher temperatures. With different parameters, the model explains the frictional properties of quartz and granitic rocks in hydrothermal conditions with velocity-strengthening behavior in nominally dry conditions, transitioning to velocity-weakening between 100ºC and 350ºC in wet conditions. Inclusion of a lubrication phase formed between the solidus and the liquidus of the host rocks explains the strong weakening at high slip velocity in a variety of rocks. The unified constitutive framework allows modeling of faults in varying temperature and pore pressure conditions, including for example injection of pore fluids in natural faults or shear heating of the host rocks.