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The gradual evolution of friction following a normal stress step reflects changes in contact strength, not contact area

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The rate-state friction equations represent the most widely used framework to describe friction evolution in rocks and in models of earthquakes. Despite their popularity, the notion of 'state' evolution of the frictional interface within this framework has been relatively poorly understood for fifty years. Empirically, the state of a frictional interface has been found to evolve with slip and/or time, and in response to abrupt changes in normal stress, but the microprocesses responsible for this evolution are unclear. Under physical conditions relevant to most shallow crustal earthquakes, frictional interfaces are in contact only at numerous smaller regions called asperities, and the real contact area is expected to be a rather modest fraction of the nominal contact area. Frictional resistance results from the shear strength of only these contacting asperities. It is commonly presumed that changes in state are due primarily to changes in this real contact area under the low temperature plasticity regime assumed to operate around these highly stressed contact points. An alternative explanation is that changes in state are due to changes in some measure of the strength of the real contact area, for example due to changes in chemical bond strength or their area-averaged density. In this study, using data from 5% to ~100% normal stress step experiments, we show that the transient evolution of frictional strength with slip following medium-to-large normal stress steps cannot be understood in terms of changes in real contact area alone. Instead, changes in area-averaged contact strength play a more important role in this evolution. We formulate a framework of evolution equations for contact area, area-averaged contact strength and state that encodes contrasts in area-averaged strength between old and new regions of interfacial contact as a rate-state parameter and show that slip rate reductions of Westerly granite samples following these normal stress steps can be used to estimate this strength contrast consistently across all step sizes. For our experiments, the new contact area created rapidly by the abrupt increase in normal stress is found to be only 10-20% of the strength of the old contacts at the pre-step steady state and eventually evolves back to its pre-step steady-state strength value with slip. These experiments might lay the foundation for replacing our empirical descriptions of state evolution with an understanding of operative

microprocesses that explicitly parametrizes the effect of changes in contact strength as well as contact area on frictional ‘state’ evolution.