

Frictional behavior of partially water-saturated phyllosilicate-bearing gouge of mixed composition

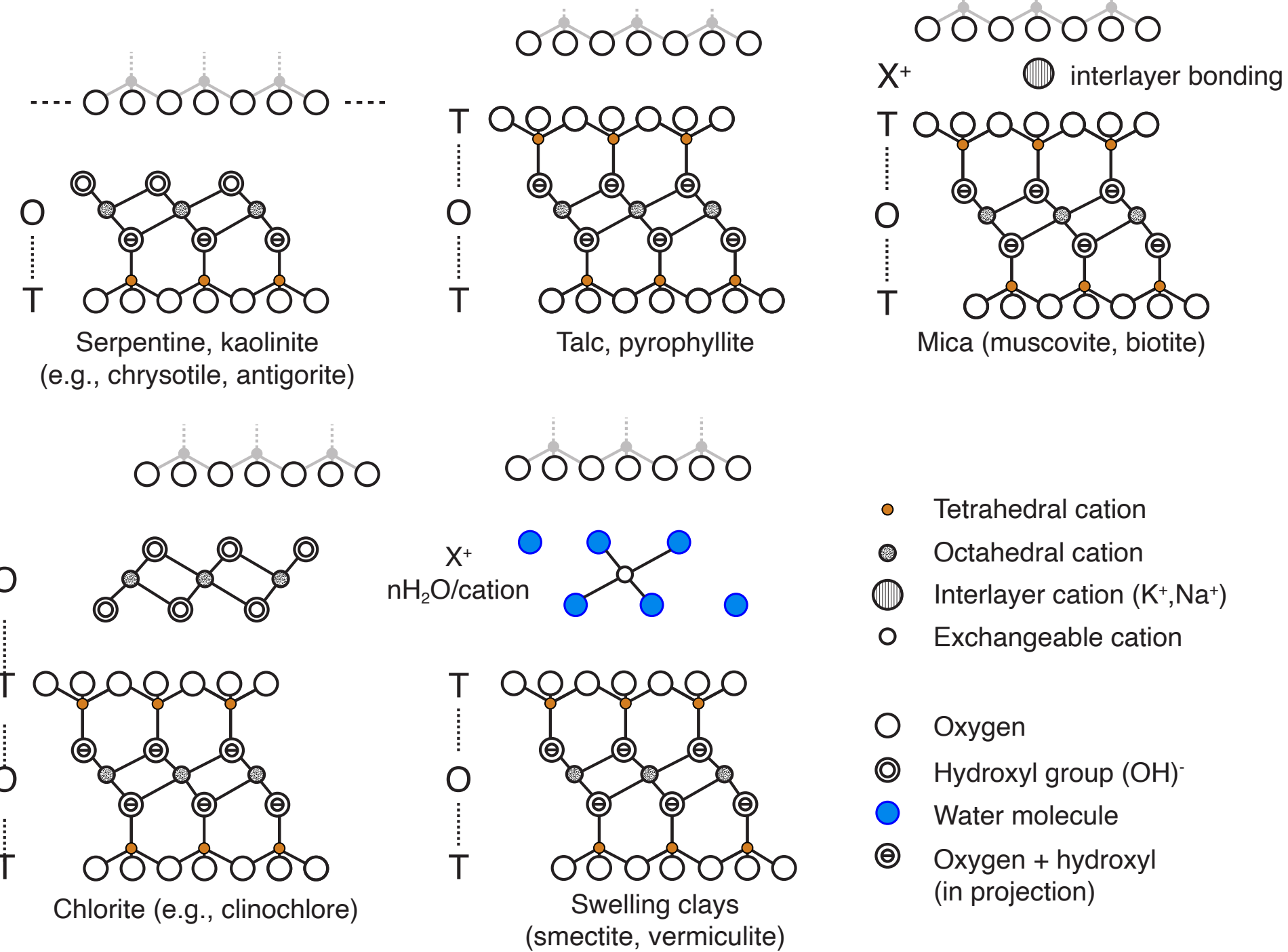
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Abstract

Phyllosilicates form an important group of silicate minerals characterized by a polymeric layered structure that results in unique hydro-mechanical properties. These sheet silicates exhibit distinct frictional behaviors in dry versus water-saturated states, implying substantial changes of fault strength with fluctuations of temperature and pore-fluid pressure. Given their prevalence in fault zones, the frictional behavior of phyllosilicates may exert important controls on the seismic cycle. Here, we present a constitutive law for the frictional behavior of partially water-saturated phyllosilicates of mixed composition under the hydrothermal and pressure conditions relevant to earthquake nucleation. The model explains the increase of the friction coefficient with effective normal stress of low-temperature, water-saturated phyllosilicates via osmotic pressurization at mineral surfaces around contact junctions. A mixing law provides in closed form the evolving frictional properties of heterogeneous phyllosilicate-bearing gouge accompanying temperature and fluid-pressure dependent dehydration reactions. The model describes the conditions for substantial weakening of phyllosilicate-rich fault zones associated with hydrothermal activity, with implications for natural and anthropogenic seismic hazards.

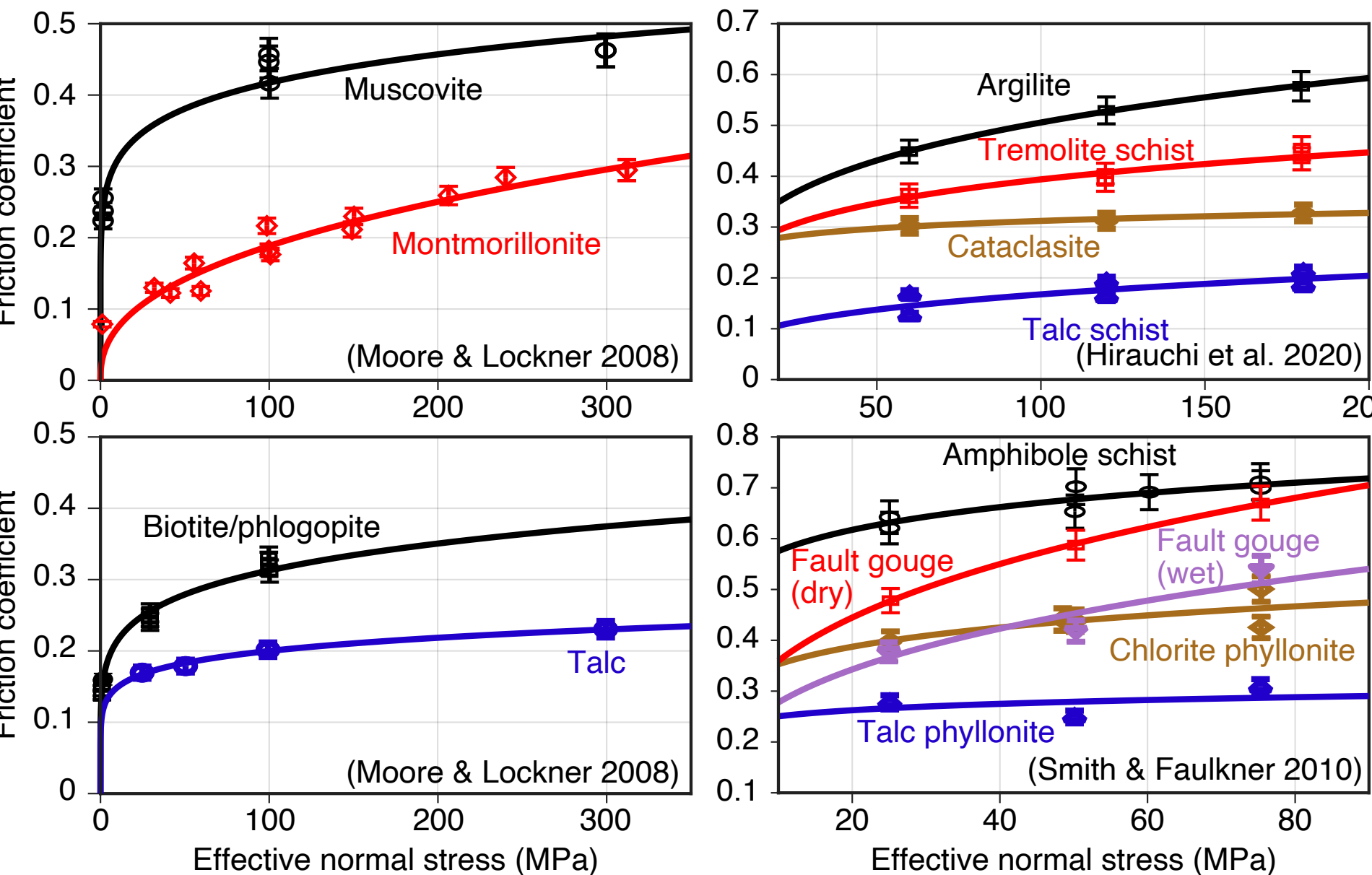
Phyllosilicate crystal structure

Classification of phyllosilicate groups based on crystal structure, modified from Brown (1982). The crystal structures extend in infinite horizontal sheets combining tetrahedral (T) and/or octahedral (O) layers. Brucite $\text{Mg}(\text{OH})_2$ and gibbsite $\text{Al}(\text{OH})_3$ (not shown) consist only of an octahedral layer.



Strength of water-saturated phyllosilicates

Characteristic dependence of the friction coefficient of water-saturated phyllosilicate-rich gouge on effective normal stress. We attribute the increase of the friction coefficient with effective normal stress to the formation of **osmotic pressure** in the interlayer space, particularly for expanding clays.



Effect of osmotic pressure on rock friction

The weak strength of water-saturated clay-rich rocks can be explained by the lubrication of contact junctions by a water film subject to osmotic pressure, reducing the real area of contact, as

$$A = \frac{\bar{\sigma}}{\chi_n} \left(\frac{d}{d_0} \right)^\alpha \left(\frac{\bar{\sigma}}{\sigma_0} \right)^{-\beta} \left(\frac{\Delta}{\Delta_0} \right)^{-\gamma}$$

the area of contact density simplifies to

$$A = \frac{\bar{\sigma}}{\chi_n} \left(\frac{d}{d_0} \right)^\alpha \left(\frac{\bar{\sigma}}{\sigma_0} \right)^{\gamma-\beta}$$

A yield strength can be defined as $\tau_y = \mathcal{A}\chi$. The constitutive law for frictional sliding follows a thermobaric activation

$$V = V_0 \left(\frac{\tau}{\tau_y} \right)^n \exp \left[-\frac{Q}{R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]$$

where the activation temperature depends on pressure

$$\frac{1}{T} = \frac{1}{T_0} - \frac{CR}{Q} \ln \frac{\bar{\sigma}}{\sigma_0}$$

Combining the above results, we obtain an explicit formulation for the friction coefficient

$$\mu = \mu_0 \left(\frac{d}{d_0} \right)^\alpha \left(\frac{\bar{\sigma}}{\sigma_0} \right)^{\gamma-\beta-\zeta/n} \left(\frac{V}{V_0} \right)^{\frac{1}{n}} \exp \left[\frac{Q}{nR} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]$$

water-saturated montmorillonite features a sufficiently large lubrication coefficient that the friction coefficient increases with effective normal stress.

Mixing law for rock friction

The mixture model is derived as follows. We assume that the mechanical behavior of each phase k in isolation follows the constitutive model above, as

$$V_k = V_0 \left(\frac{\tau}{\mu_k \bar{\sigma}} \right)^{n_k} \left(\frac{d}{d_0} \right)^{-\alpha_k n_k} \left(\frac{\bar{\sigma}}{\sigma_0} \right)^{(\beta_k - \gamma_k) n_k} \exp \left[-\frac{Q_k}{R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]$$

The total slip-rate of the gouge, encompassing all the different phases, is given by

$$V = \prod_k V_k^{\phi_k}$$

In general, the area of contact is modulated by the time-dependent plastic compaction of micro-asperities and slip-dependent rejuvenation of the contact population. The thermodynamics of the plastic deformation of micro-asperities is a function of mineralogy. We assume that the compaction strain-rate of each mineral phase in isolation follows

$$\dot{\epsilon}_k = f_0 \left(\frac{d}{d_0} \right)^{-p_k} \left(\frac{\bar{\sigma}}{\sigma_0} \right)^{q_k} \exp \left[-\frac{H_k}{R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]$$

The compaction rate for the mixture is the weighed sum of the strain-rates for each phase in logarithmic space. The resulting **aging-law end-member** for the evolution law of the mixture is given by

$$\frac{\dot{d}}{d} = \prod_k \dot{\epsilon}_k^{\phi_k} - \frac{\lambda V}{2h}$$

The corresponding **slip-law end-member** evolution law for the mixture is given by

$$\frac{\dot{d}}{d} = \frac{\lambda V}{2h} \ln \left\{ \lambda V \prod_k \dot{\epsilon}_k^{\phi_k} \right\}$$

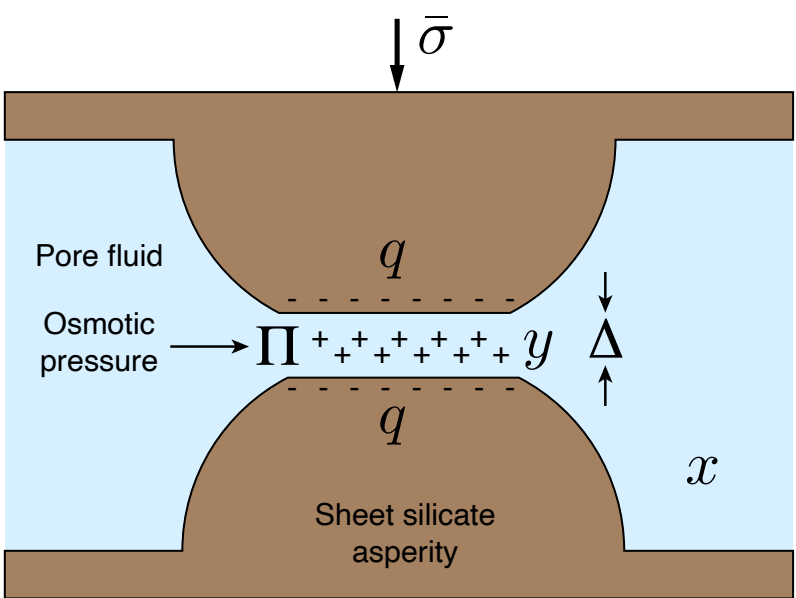
The constitutive laws and frictional properties of the mixture can be found in closed form. For the direct effect, the effective stress power-law exponent, effective compressibility factor, and effective activation energy for the mixture are given by

$$\bar{\alpha} = \frac{1}{\bar{n}} \sum_k n_k \phi_k \alpha_k \quad \bar{n} = \sum_k \phi_k n_k \quad \bar{p} = \sum_k \phi_k p_k$$
$$\bar{\beta} = \frac{1}{\bar{n}} \sum_k n_k \phi_k \beta_k \quad \bar{\zeta} = \sum_k \phi_k \zeta_k \quad \bar{q} = \sum_k \phi_k q_k$$
$$\bar{\gamma} = \frac{1}{\bar{n}} \sum_k n_k \phi_k \gamma_k \quad \bar{Q} = \sum_k \phi_k Q_k \quad \bar{H} = \sum_k \phi_k H_k$$

Furthermore, the reference frictional strength evolves as

$$\bar{\mu}_0 = \exp \left[\frac{1}{\bar{n}} \sum_k n_k \phi_k \ln \mu_k \right]$$

which can be used as a first-order approximation of the strength of mixtures at steady-state.



The evolutionary effects of frictional resistance emerge due to the collapse and rejuvenation of micro-asperities, which overall dimension evolves toward a steady state following the aging-law end-member evolution law

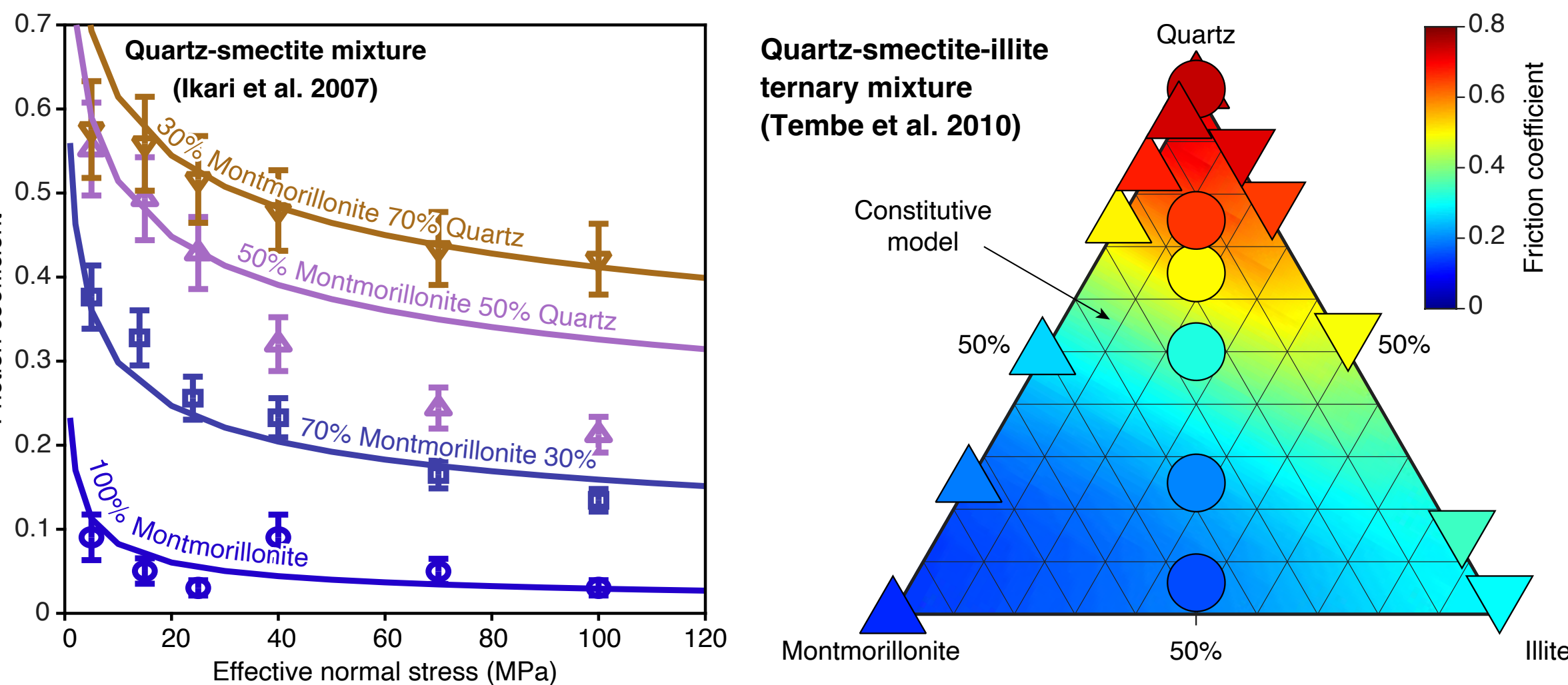
$$\frac{\dot{d}}{d} = f_0 \left(\frac{d}{d_0} \right)^{-p} \left(\frac{\bar{\sigma}}{\sigma_0} \right)^q \exp \left[-\frac{H}{R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right] - \frac{\lambda V}{2h}$$

In isokinetic and isothermal conditions with $V=V_0$ and $T=T_0$, the steady-state friction coefficient becomes simply a power-law of effective normal stress

$$\mu_{ss} = \mu_0 \left(\frac{\bar{\sigma}}{\sigma_0} \right)^{\frac{\alpha p}{p} + \gamma - \beta - \frac{\zeta}{n}}$$

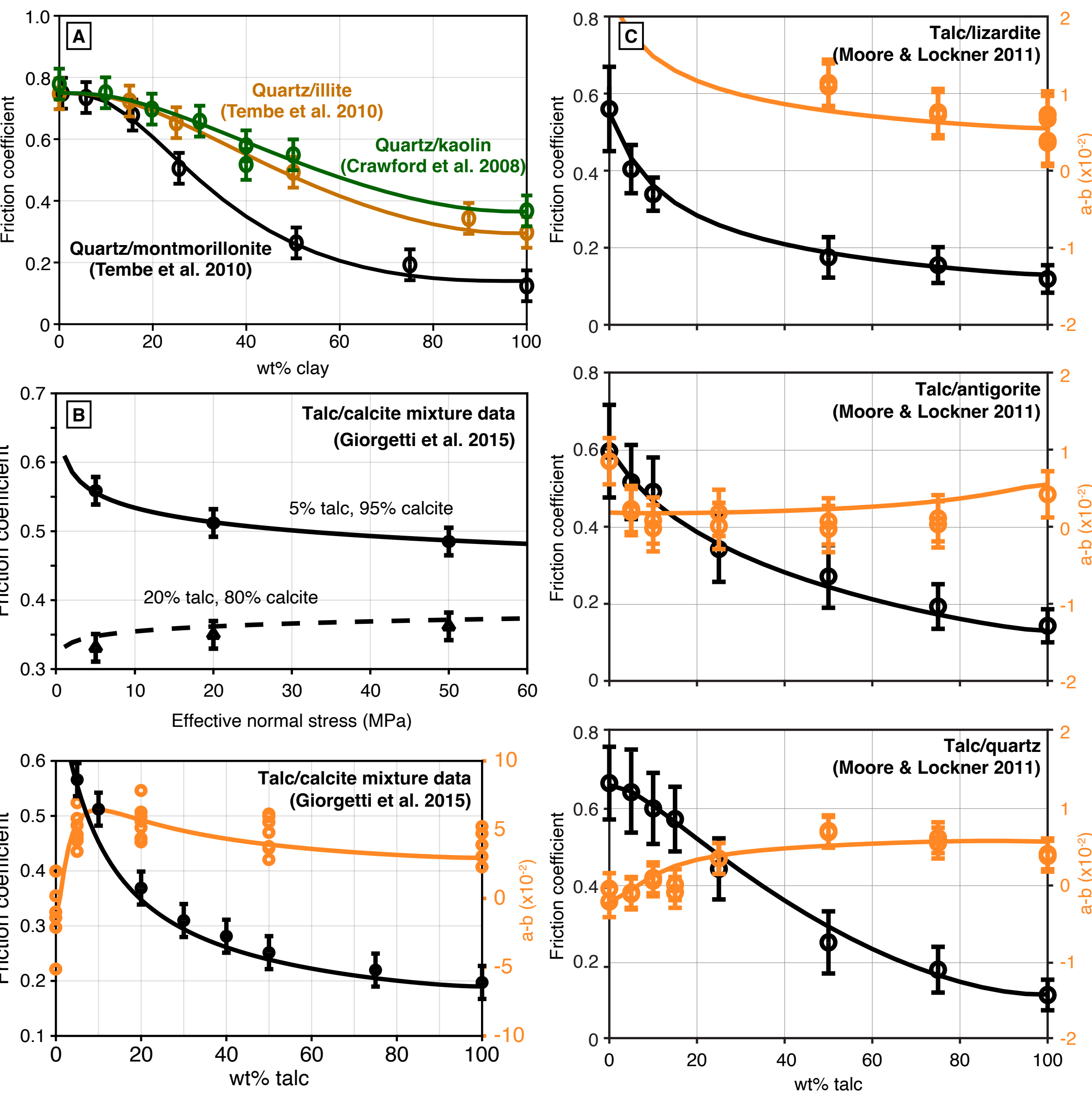
Strength of binary and ternary mixtures

We compare the model with experimental data on synthetic gouge based on phyllosilicate minerals mixed with other phases. The model explains the steady-state frictional resistance of a binary mixture of Ca-montmorillonite with quartz ranging from 100% to 30% montmorillonite by weight in fully water-saturated conditions (Ikari et al. 2007). We explain the strength of montmorillonite/illite/tertiary mixtures (Tembe et al. 2010). The model captures the weakening caused by smaller proportions of montmorillonite than illite.



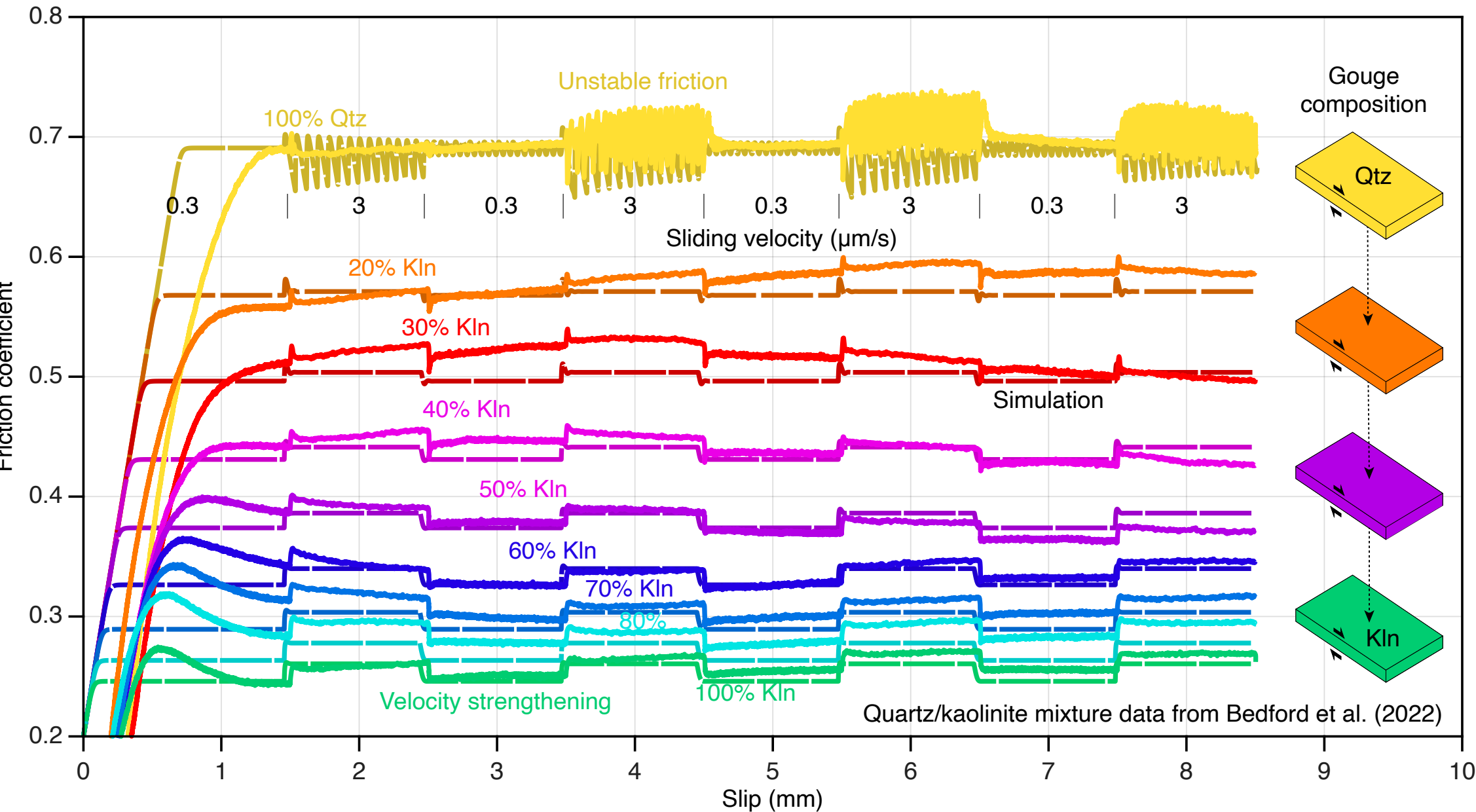
Frictional properties of mineral assemblages

The mixing model explains the co-evolution of frictional strength with the velocity dependence of the friction coefficient at steady-state as a function of mineral content for mixtures of quartz with illite or montmorillonite (Tembe et al. 2010), talc and calcite (Giorgetti et al. 2015), and mixtures of talc with lizardite, antigorite, or quartz (Moore & Lockner 2011).



Effect of composition on frictional stability

We describe the frictional stability of homogeneous mixtures of quartz (Qtz) and kaolinite (Kln) documented by Bedford et al. (2022). In the experimental setting, pure quartz is steady-state velocity-weakening and exhibits stick-slip instabilities under 40 MPa effective normal stress. Mixture with 20% of kaolinite forces a transition to velocity-strengthening and a reduction of strength. Pure kaolinite is features negligible transient effects and is much weaker. The model captures the salient aspects of the experimental results.



Effect of partial water saturation on clay friction

Frictional properties of partially water-saturated phyllosilicate-rich gouge as a function of pore-fluid pressure and temperature. The mixing law predicts the frictional behavior of oven-dry and partially water-saturated montmorillonite based on a phase diagram of montmorillonite dehydration and the properties of the dry and water-saturated end-members. The model captures the thermal activation of clay dehydration in terrigenous sediment from Costa Rica subduction zone. Fluctuations of partial water saturation of phyllosilicate-rich gouge induce changes of strength potentially surpassing those caused by the slip-rate and state dependency, thereby representing a mechanism for strong weakening of fault zones, depending on mineral composition and hydration state.

