Introduction

Permeability is known to change during shear deformation. It has been widely observed that failure may occur stably (aseismically) at slow creep rates of long duration (order of 1–100 mm/yr) or unstably (seismically) at fast frictional sliding rates of short duration (order of 1 m/s). The stability of sliding is governed by the frictional properties of faults and can be described with rate-and-state friction laws. These studies provide potential insights into the rheological response of caprocks and unconventional reservoirs with regard to the mode and timing of induced earthquakes. However, it is still unclear whether different styles of permeability evolve from unstable fast sliding of seismic events versus slow-slip aseismic events. We integrate both experimental and computational methods to explore how fracture permeability changes in response to fracture/fault reactivation and investigate the roles of (1) mineralogy and (2) fracture roughness in conditioning response; together with (3) intrinsic controls of healing on the earthquake cycle and permeability evolution.

Frictional Stability and Permeability Evolution

Seismic displacement on faults is predicated on three principal requirements. First, the applied stress must exceed the strength to enable failure to occur. Second, the strength must reduce as failure occurs (velocity-weakening or strain-softening), enabling shear displacement to accelerate. These two requirements allow a sustained failure but do not define how fast the failure will radiate seismic energy. For the rupture to be seismic, the physical stiffness of the fault material must be larger than the geometric stiffness of the fault itself, enabling the dissipation of the stored strain energy in a runaway failure. This final necessary-and-sufficient requirement enables the indexing of potential modes of failure – aseismic versus seismic – to be recovered from straightforward friction-permeability experiments that concurrently measure the evolution of friction and permeability with shear displacement of laboratory faults and fractures. Thus measurements may characterize the response of both materials that control cross fault flows, via the fault core and that control along-fault flows in the fault damage zone. The focus here is on along-fault flows in the damage zone, that may transect caprocks, and promote fugitive flows for reservoirs and aquifers.

Mineralogical Controls on Friction and Permeability Evolution

Understanding the component response of individual fractures comprising the fault damage zone is the key constraint in constraining along-fault fugitive emissions. Deformation on such fractures may be velocity-weakening or-strengthening, with these styles of deformation potentially conditioning permeability evolution. The stability response is conditioned by the velocity-weakening/strengthening behaviour through the parameter \((a-b)\) for a finite step in shear velocity, \(V\), applied to a (laboratory) fault as, \((a-b) = \Delta \mu / \Delta \ln V\). Thus the \(\mu\) value defines the propensity for failure, while \((a-b)\) values define the mode of slip, as stable, aseismically (i.e. \(a-b>0\)), or unstable, seismically (\(a-b<0\)).

Thus, the anticipated seismic versus aseismic reactivation response may be probed by exploring the stability characteristics observed during shear, for the resulting magnitude of the instability parameter, \((a-b)\), and used to project the observed evolution of permeability as related to this propensity towards seismic or aseismic deformation. We conduct velocity stepping shear experiments on laboratory faults/fractures to explore this response. Shearing velocities are stepped-up then -down between 1 and 10 \(\mu m/s\). Figure 1a shows the results of one sample as an example of the net friction and permeability evolution with displacement. The calculated net fracture permeability monotonically decreases with displacement, consistent with previous observations. Local frictional change and permeability evolution in response to shear velocity change are shown in Figures 1b and 1c. The permeability change in each velocity step is normalized against the reference permeability in the state immediately before the velocity-step induced change. These responses are examined for a full range of compositional minerals of rocks binned into the groups of silicates, carbonates, and clays with a typical result for Green River Shale shown in Figure 1.
Outputs from the experiments are magnitudes of friction, stability (i.e. evolution of friction via \((a-b)\)) and change in permeability \(\Delta k\) resulting from the shear. Frictional parameters and transient permeability change in response to velocity change for a broad sequence of rocks are shown in Figure 2. As surface contact state, which determines the flow path, is reflected in the frictional strength and stability, we directly correlate the permeability change with friction (Figure 2). The permeability change \(\Delta k\) has a positive correlation with concurrently measured frictional strength \(\mu\) but a negative correlation with the corresponding frictional stability \((a-b)\). This intrinsic linkage of friction and permeability change is directly determined by the asperity contact state and the material properties (e.g., mechanical and swelling) that control the mechanical behaviors of fracture asperities. However, it is worth noting that the magnitude of permeability change in the natural samples is much larger than that of the artificial samples (shown as the solid black symbols in Figure 2)—this is due to the difference in the surface textures.

In summary, with known mineralogical compositions comprising the fracture, the frictional strength and stability of fractures can be estimated. Shear failure is less likely to occur for fractures with a higher content of tectosilicates. However, once failure initiates, the fracture is more likely to slip unstably. This process is opposite that for fractures with higher clay content—where the fracture is easier to reactivate and will slip stably. When an unstable fracture slides at an accelerating rate, the transient change in fracture permeability can be speculated—those richer in tectosilicates exhibit larger permeability enhancement.

**Upscaling Permeability Evolution for Fracture Roughness**

With permeability evolution and stability characteristics defined by rate-state response and linked via stability, the roles of roughness, asperity breakage and the generation of wear products may then be explored. Analog virtual fractures with calibrated roughness may be fabricated (Figure 3) to evaluate the role of shearing on the evolution of friction, stability and permeability, as an ensemble linked behaviour (Wang et al., 2020). In this, strain-weakening or -strengthening response is applied to the individual particle contacts. This enables the frictional (Figure 1, concurrent measurements of friction and permeability evolution on laboratory faults in Green River Shale. Insets show zoom-in of friction (inset left) and permeability (inset right) with shear offset for an upstep in shearing velocity.)
4(a)), stability and permeability evolution (Figure 4(b)) response to be followed when these “virtual” fractures are then sheared.

The evolution of shear strength interpreted as friction \(\tau/\sigma\) for rss1 through rss6 (RMS asperity heights ranging from 0.005cm to 0.05cm) is shown in Figure 4(a). The shear strength of the specimens generally builds until reaching peak strength, followed by a stress drop post-peak, sometimes comprising several successive stress drops. Specimens with rougher fractures exhibit a higher peak shear strength and larger threshold shear displacement to peak strength. All specimens show similar residual shear strength after failure.

The evolution of fracture permeability \(k/k_0\) for tests rss1 through rss6 is shown in Figure 4(b). Permeability decreases slightly with compaction during early shear. Permeability increases rapidly upon a threshold shear displacement and continues to increase until reaching a peak, after which plateau (rss1-rss3) is observed. Fracture in rss4 shows unstable permeability evolution after reaching the peak. Fractures with large RMS asperity heights (rss5 and rss6) exhibit permeability reduction after reaching peak values.

The ensemble of the responses for both mineralogy and geometric components are important in defining the overall response of in behavior, both seismic and aseismic, and the corresponding implications for the evolution of permeability for deformation in these two modes.

**Role of Healing and Sealing in Permeability Evolution**

As previously noted, the demarcation between seismic and aseismic response is defined by three conditions. That the fracture fails, that it wakes as it fails and that the geometric shear stiffness of the embedded fault is smaller than that of the physical fault material or interface. The latter enabling the stored strain energy to be unstably ejected – i.e. seismically. However, there is a fourth requirement for seismic response – and that is that the fault heals and strengthens after rupture – otherwise only a single rupture event can occur – all others being stable sliding. Thus the role of healing (strengthening) is important in defining the recurrence time of individual slip events (seismic or aseismic) with this
healing (strengthening) potentially influencing the mode of reactivation (seismic or aseismic) and thereby the style and magnitude of permeability evolution – reduction or enhancement – as noted earlier, is related to the style of deformation (Im et al., 2018).

The response during interseismic periods (repose) may be represented in experiments where the shear displacement is held, prior to reactivation in shear, as illustrated in Figure 5. Such “slide-hold-slide” experiments enable the evolution of healing (strengthening) to be followed – reactivation following a hold (Figure 5(a)) results in a gain in strength as a result of various processes of welding, cementation, pressure solution and others. During the hold, any initial gain in permeability engendered in the prior reactivation is reset as a power-law decline by sealing. Rates and magnitudes are broadly consistent with mechanisms involving interpenetration of compacting asperities driven by creep or pressure solution.

These responses are repeatable in multiple cycles of repose then reactivation. Similarly, the permeability response that results upon reactivation is typically conditioned by the duration of the prior repose – longer reposes result in greater healing and strengthening, and increased strengthening results in a greater increase in permeability that occurs with reactivation (Figure 6). Short duration reposes result in compactive reactivations (Figure 6①) and long-duration reposes in dilative reactivations (Figure 6②). The magnitude of the dilative reactivation scales broadly with repose time (Figure 6).

Conclusions

We have posited that the style of deformation, seismic versus aseismic, exerts systematic control on the mode and style of permeability evolution in faults and fractures. Frictional strength and stability may be used as appropriate indices to follow this relation and to define both mineralogical and geometric controls on behaviour – each linked to the stability characteristics of fractures and faults. These define not only the short-term response of fractures but also, by extension through healing, the long-term response. This linkage between both seismic and interseismic behaviours is mechanistically-based on the formalism of rate-state friction, defining the various characteristics of the complex first- and second-order deformation processes over a full range of timescales.

Acknowledgements

This work is a partial result of support by the US Department of Energy under grant DE-FE0023354 and by the EGS-Collab project. This support is gratefully acknowledged.

References

