Frictional strength, stability, and healing properties of basalt faults for CO2 storage purposes

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Despite the numerous advantages of storing CO2 into basalts by dissolving carbon dioxide into water prior to its injection, the large amount of H2O required for this operation poses an increased risk of fluid overpressure into the fault/fracture networks, and renders the seismicity analysis pivotal to upscale this storage method to voluminous basaltic occurrences diffused worldwide.

To deepen our knowledge on the frictional strength, stability, and the healing properties of basalt-built faults, we carried out friction tests on basalts from Mt. Etna using the biaxial deformation machine, BRAVA, and the rotary-shear apparatus, SHIVA (HP-HT laboratory of INGV-Rome, Italy). Specimens were selected for their relative abundance of olivine and pyroxene crystals, i.e. the main sources of divalent cations in silicate rocks necessary to trap CO2 into basalts.

Experiments were performed both on synthetic powdered samples and bare surfaces, at room-dry and water drained-saturated conditions, at room temperature and pressure. Bare surfaces consisted in basalt slabs and hollowed cylinders, which were mounted on BRAVA and SHIVA apparatus, respectively. Samples were subjected to 5 to 30 MPa normal stress (σn) for powdered samples and in the range 5 to 10 MPa for bare surfaces.

At the investigated normal stresses, frictional sliding data obey Byerlee’s law for friction, with the friction coefficient µ = 0.59 – 0.78. Differences in µ mainly reflect sample variability, different experimental configurations, sample geometry, and, to a lesser extent, the boundary conditions (dry/wet). However, in detail, basalt slabs are generally characterized by the highest friction coefficient and hollow cylinders exhibit a slight increase in friction coefficient with increasing shear displacement, due to the progressive slip hardening resulting from gouge production during frictional sliding.

Velocity step increases were conducted on BRAVA after steady values of friction were attained (~ 6.5-7.5 mm for gouge and ~ 3 mm slip for bare surfaces) and consisted in velocity sequences from 0.1 to 300 µm s^-1, with ~ 500 µm displacement for each step. Rate-and-state friction experiments show opposite mechanical behavior between bare surfaces and synthetic fault gouge: while bare surfaces experience a transition from rate-weakening at low sliding velocity (V) to rate-
strengthening behavior at higher $V$ without any clear dependence on the applied $\sigma_n$, gouge revealed a negative trend of $(a-b)$ with shear velocity at $\sigma_n > 5$ MPa and a velocity-weakening behavior at $V \geq 30$ $\mu$m $s^{-1}$, regardless of experimental conditions. We ascribe this different behavior to shear delocalization owing to frictional wear production in bare surfaces, and to shear localization accompanied by grain size reduction along the Riedel R1 and boundary B shear zones in fault gouges, as also confirmed by microstructural analysis.

The velocity weakening behavior of fault gouge, coupled with the fast healing rates retrieved from slide-hold-slide experiments (500 $\mu$m displacement cumulated at $V = 10$ $\mu$m/s followed by hold times from 30 to 3000 s), define high strength zones that are potentially seismogenic. Conversely, velocity strengthening behavior of bare surfaces promotes aseismic creep at $V \geq 100$ $\mu$m $s^{-1}$, regardless of the faster restrengthening compared to fault gouge.