Clay formation within brittle fault zones

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### Deformation Style

<table>
<thead>
<tr>
<th>Brittle</th>
<th>Ductile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frictional flow</td>
<td>Plastic flow</td>
</tr>
<tr>
<td>Non-cohesive</td>
<td>Primary cohesion</td>
</tr>
<tr>
<td>Secondary cohesion</td>
<td></td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Cataclasite series</td>
<td></td>
</tr>
<tr>
<td>Proto-cataclasite</td>
<td>Proto-phyllosilicate</td>
</tr>
<tr>
<td>Proto-mylonite</td>
<td>Mylonite</td>
</tr>
<tr>
<td>Biotite/mylonite</td>
<td>Ultraphyllosilicate</td>
</tr>
</tbody>
</table>

**Legend:**
- **Cemented HB:** Cemented breccia
- **Indurated HB:** Indurated breccia
- **Cemented proto-breccia:** Cemented proto-breccia
- **Indurated proto-breccia:** Indurated proto-breccia
- **Cemented ultrabreccia:** Cemented ultrabreccia
- **Indurated ultrabreccia:** Indurated ultrabreccia
- **Cemented gouge:** Pseudotachylite
- **Indurated gouge:** Pseudotachylite

*References:*
- Fossen, 2010
- Scholz, 1988
- Braathen et al., 2004
Anatomy of a fault: much effort in recent years to characterise geometrically and mechanically faults

Textural/fabric anisotropy

Compositional anisotropy

Dynamic character of faults vs. static characterisation - Transient evolution of properties!

Interaction of physical and chemical processes

Scale variance of fault properties

Choi et al., 2016
Clay authigenesis during fluid-assisted cataclasis

(a) Granular flow
  Rotation

(b) Cataclastic flow
  Micro-fracturing
  Frictional sliding

Fossen, 2010
Dynamic and complex system, continuously evolving in space and through time!!

Clays track and permit the developing texture and compositional changes of fault rocks and as such become valuable archives of the physical and chemical conditions at the time of initial faulting, but also of later slip events during reactivation!

- Complex clay assemblages in different types of brittle fault rocks!
  Expansive (!) oxidation of biotite as the mechanism for profound intergranular cracking that mechanically disaggregates the rock and abruptly increases its connected porosity and permeability.
  Once the disaggregation and hydrologic modification takes place, high pore-water velocities apparently facilitate the creation of additional pore-space through plagioclase dissolution-> until new clay authigenesis
Transient, that is, continuously evolving, property of faults: **PERMEABILITY**, leading to **FLUID INGRESS**

**EXAMPLE 1**

Key piece of information:

Fault zones can **transiently** be like open conduits and so facilitate important fluid ingress!

**Authigenesis and synkinematic **clay blastesis**!
Concept of heterogeneous and transient evolution of fault transmissivity

Bense et al., 2013
Bense et al., 2013
Permeability evolution with time in seismogenic faults

- Cyclic changes in
  - stress state
  - fluid pressure
  - permeability

Permeability “toggle switch”

→ EPISODIC FLUID FLOW

Flow transience in the seismogenic regime

- Fault-valve behaviour

Cox, 2010
Our knowledge of frictional sliding was improved dramatically by the work of Byerlee (1978; Byerlee’s Friction Law). This resulted from experimental data on frictional sliding in various environments, such as surface engineering, mining and shallow as well as intermediate to deep crustal conditions.

**Independent of rock type**
First-order compositional and textural control of clay/phyllosilicate rich fault rocks on fault strength

Byerlee, 1978
Why are some faults weak? That is, why did they ever form/slip? Issues with mechanical misorientation.

Collettini et al., 2009

Zuccale Fault, Elba Island, Italy
Collettini et al., 2009
Content and degree of physical interconnectivity of fine-grained, mechanically weak minerals such as phyllosilicates and clays is a key factor for the multiscalar intrinsic mechanic weakness of faults and brittle deformation features and for their pronounced hydrological anisotropy.

Collettini et al., 2009
Deteriorating tensile strength $T$ for a fossil weathered profile as a function of the intensity of weathering.
Take home messages:

- Clays are rich archives of the physical and chemical conditions at the time of faulting(s).

- They steer key petrophysical properties of brittle and brittle/ductile fault zones (examples of transmissivity and mechanical strength of faulted rock domains).

- Clay synkinematic authigenesis (and the effects thereof) has to be read in combination with the «time» dimension of a fault’s evolution: what we see at the outcrop is only the result of often a long-lasting and heterogeneous structural, textural, petrological and chemical evolution → Delicate balance between grain size comminution/grinding by cataclasis and synkinematic authigenesis.