doi.org/10.5194/egusphere-egu21-7436

Investigating the role of cohesion in the evolution of fault strength: an analog experiment

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vEGU21

30 April 2021

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Outline

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2. Description of the experiment
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4. Summary & outlook

Part 1: Scientific context

Shear strength: from theory to practice

- Classically (Coulomb):

$$\tau = \mu\sigma' + c$$

- In modern laboratory practice (RSF):

$$\mu = \mu_0 + \alpha \ln\left(1 + \frac{v}{v_o}\right) + \mathrm{b}\ln\left(\frac{v_o\theta}{\mathrm{D_c}}\right)$$

θ: parameter describing the state of the frictional interface

$$\mu = \frac{\tau}{\sigma'} \leftarrow c \text{ is absent!}$$

Does cohesion play a role in fault healing?

Field studies suggest that faults regain strength during the interseismic period; see Ben-Zion (2008) & Scholz (2019) for discussion in the context of seismicity.

Most laboratory studies assume $\mu = \frac{\tau}{\sigma'}$, therefore restrengthening is attributed to an increase of the friction coefficient.

Some laboratory studies have challenged that view, offering evidence of restrengthening due to cohesion (e.g.: Muhuri et al, 2003; Tenthorey & Cox, 2011; Weiss et al., 2016; van den Ende & Niemeijer, 2019).

Physicochemical processes could result in the development of cohesion

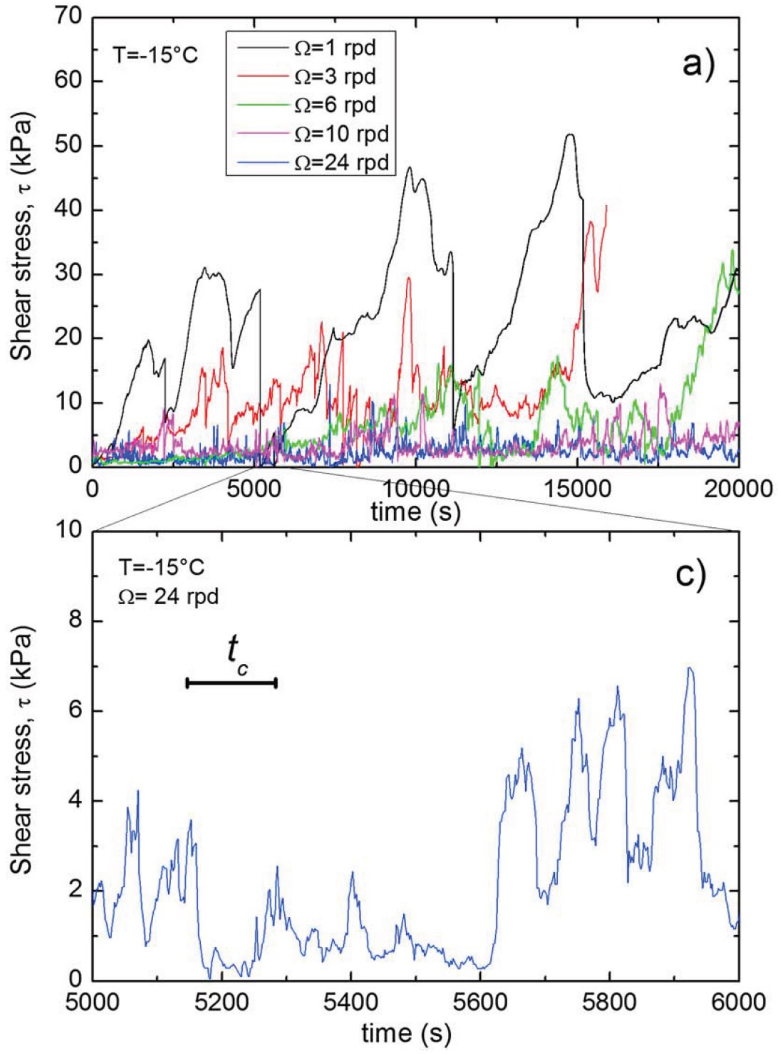
Time dependent processes, such as pressure solution, are known to operate under hydrothermal conditions in fault zones.

Indeed, Muhuri et al (2003) and Tenthorey & Cox (2011) experimented with sandstone under hydrothermal conditions. Van den Ende & Niemeijer (2019) used halite as an analog for quartz. Weiss et al. (2016) experimented with ice in an early version of the apparatus used here.

Does cohesion evolve as a function of sliding history?

Weiss et al. (2016) reported a mixture of slow and fast changes in shear strength of ice-ice faults sheared at a constant rate.

Does this behavior change when more complex loading histories are employed (e.g., velocity stepping & slide-hold-slide tests)?



Part 2: Description of the experiment

Key characteristics of our experiment

1. Nominally zero effective normal stress. Assuming a smooth, circular fault, its shear strength should be due to cohesion.

2. Co-existence of ice and water at the fault, at -10 oC ambient temperature. This generates a competition between frictional sliding along the fault and (re)freezing (=strengthening, healing).

3. The Couette geometry allows us to monitor the evolution of the experiment even at very large shear displacements.

Achieving all of the above conditions simultaneously is extremely difficult for classical rock mechanics experiments.

Brief description of the apparatus

(see photos & schematics in the following slides)

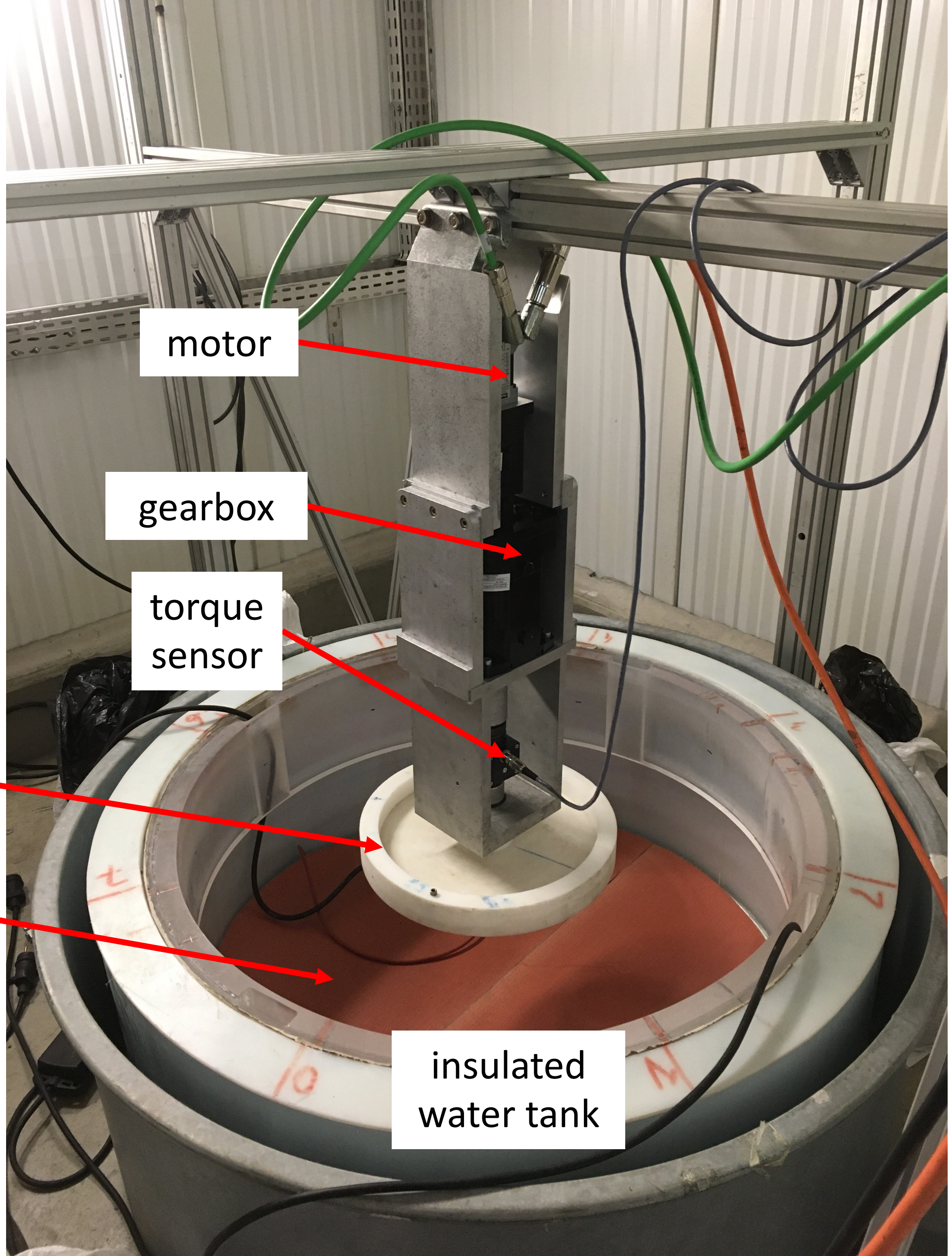
The apparatus is situated inside a cold room at -10 ^{o}C and consists of turntable that is partially submerged in a cylindrical water tank. A heat mat at the bottom of the water tank is used to regulate the rate that water freezes. We seed the nucleation of ice crystals and let the top 3 mm of water freeze, such that the texture of the resulting ice plate consists of randomly oriented grains (1 to 5 mm in size). Then, we apply a preselected speed pattern to the turntable and record torque and acoustic emission. The ice plate usually breaks approximately 1.5 cm away from the turntable, forming a roughly circular fault.

Details of the apparatus (see photos & schematics in the following slides)

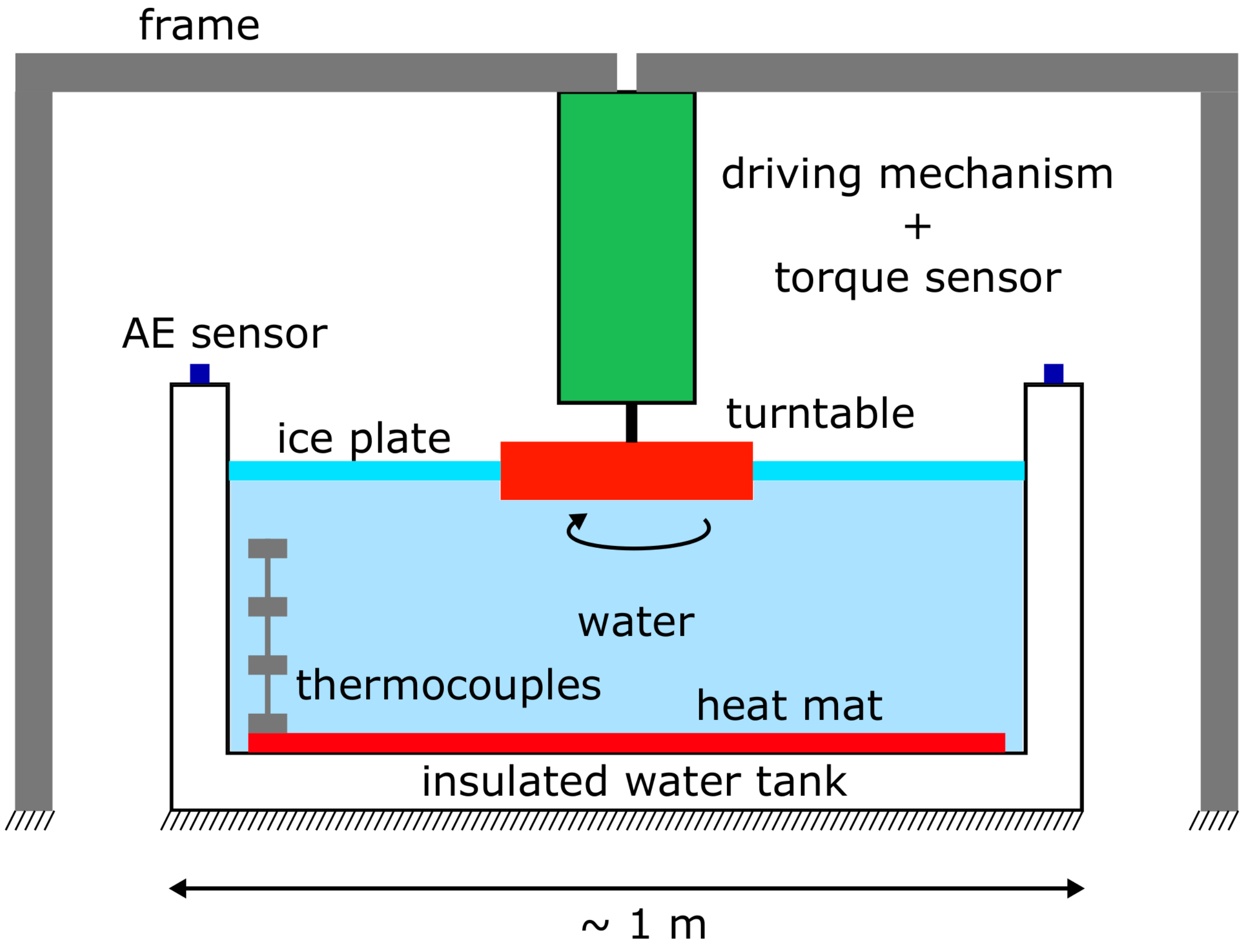
1. Torque data are recorded at rates up to 100 kHz.
2. Data from 6 acoustic emission sensors are recorded at 1 MHz.
3. Temperature readings taken at the top of the water tank and at various depths, at a rate of 1 Hz.

An earlier version of the apparatus was used by Weiss et al. (2016) and Lachaud et al. (2019).

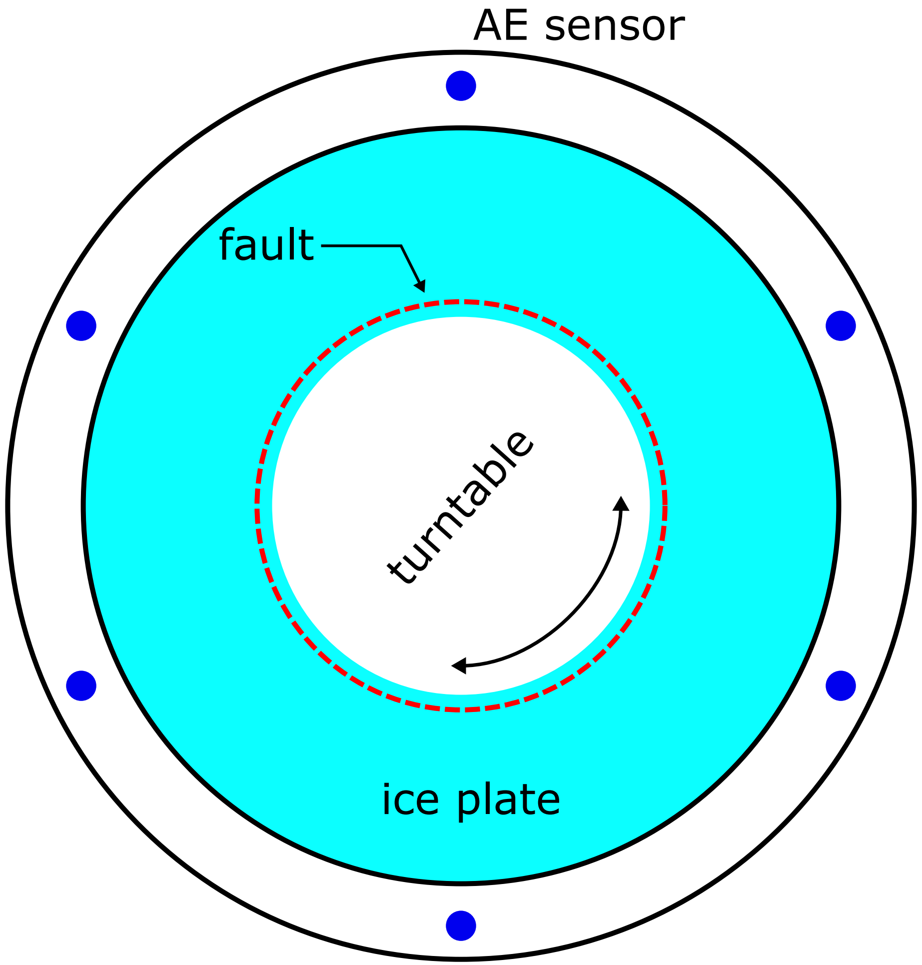
Photograph showing the apparatus inside the cold room (-10 ^{o}C), taken prior to filling the tank with water.



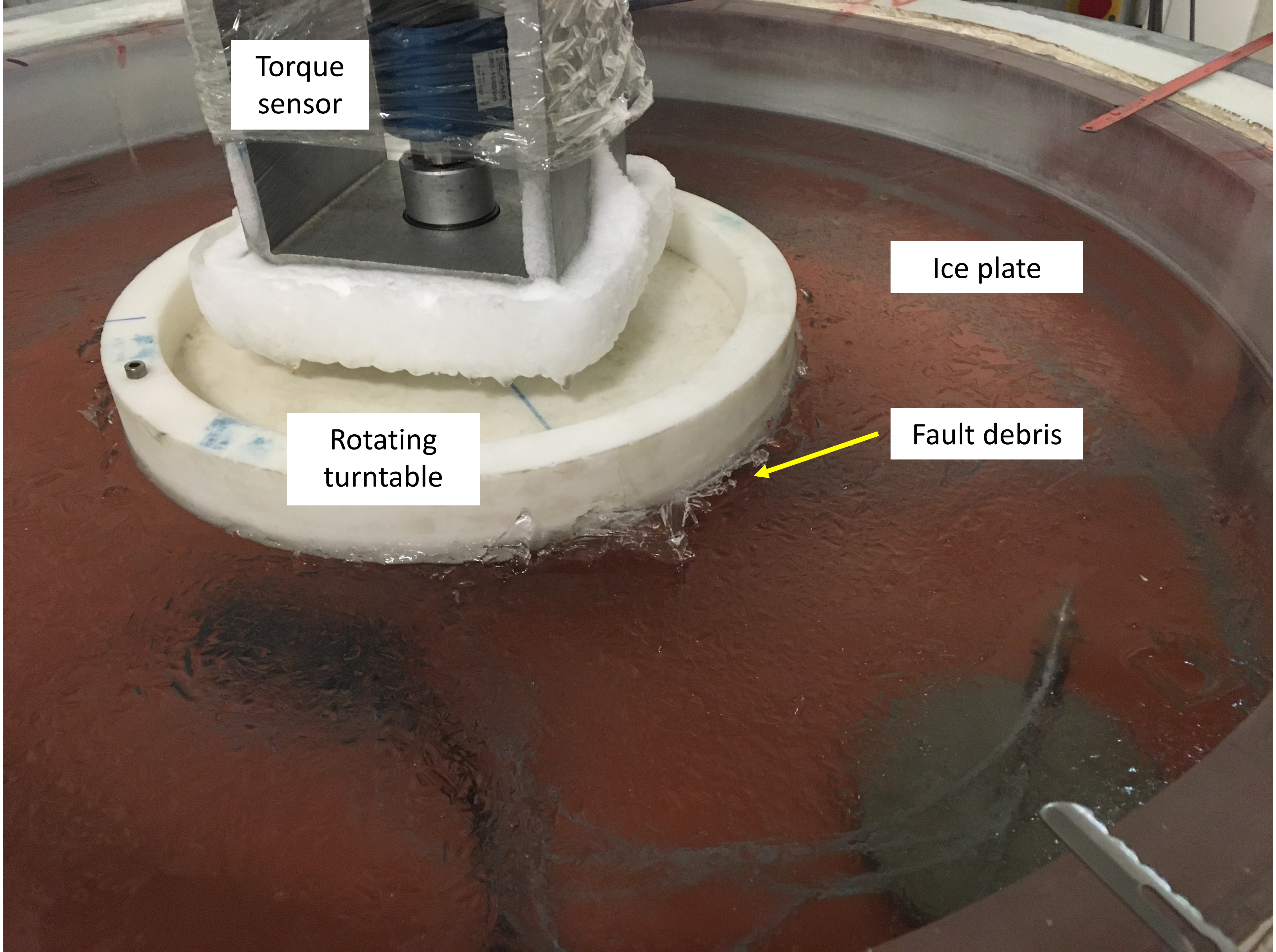
Side-view of the experiment



Top-down view



Room temperature: -10 °C


Torque sensor
Ice plate
Fault debris
Rotating turntable

Close-up photographs of a piece of an ice plate that was not sheared. Note the concave edge (bottom left photo) which was the boundary with the turntable. The ice plate is slightly thicker (i.e., stronger) at the boundaries with the turntable and the water tank walls. Therefore, the fault never forms along those interfaces but within the ice plate itself.

Part 3: First results

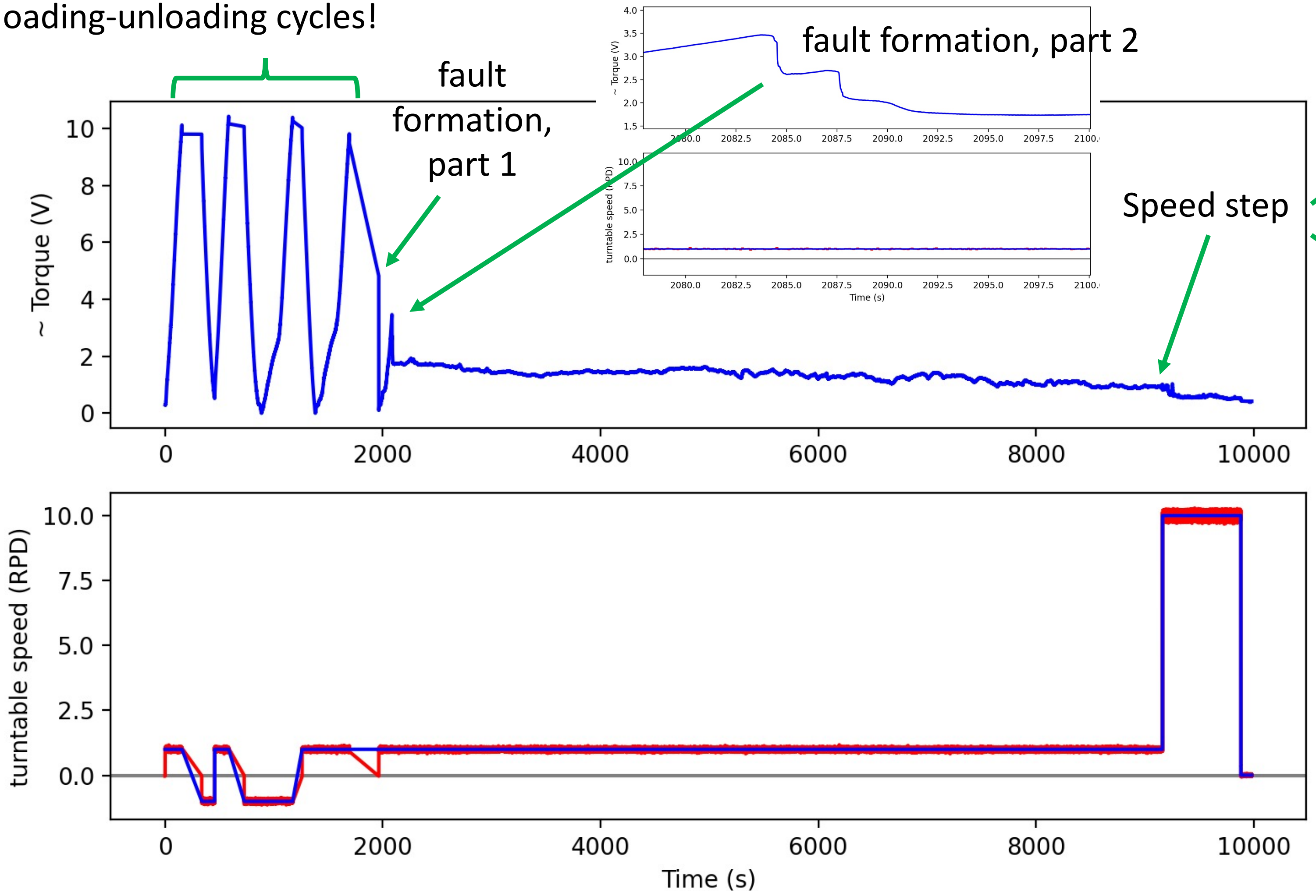
Torque evolution with increasing displacement

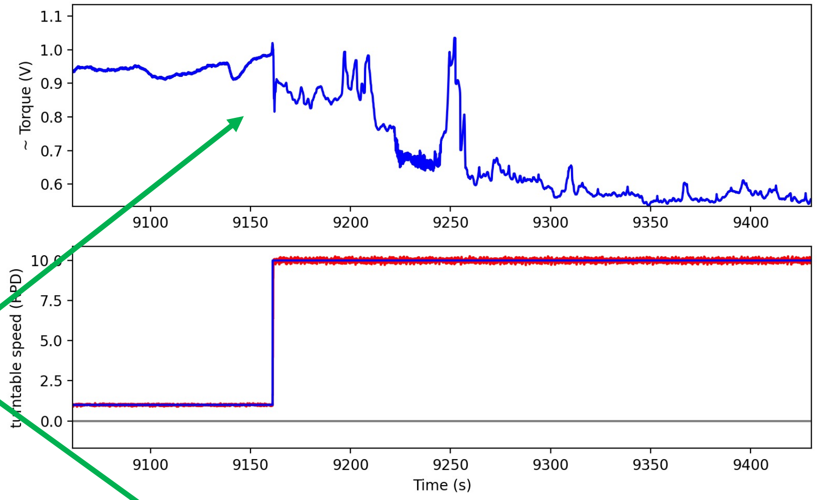
Ice appears to be too strong to fail, despite 4 loading-unloading cycles!

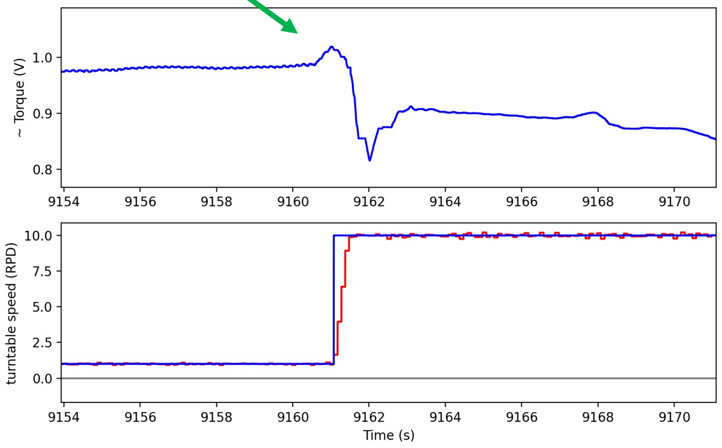
fault formation, part 1

fault formation, part 2

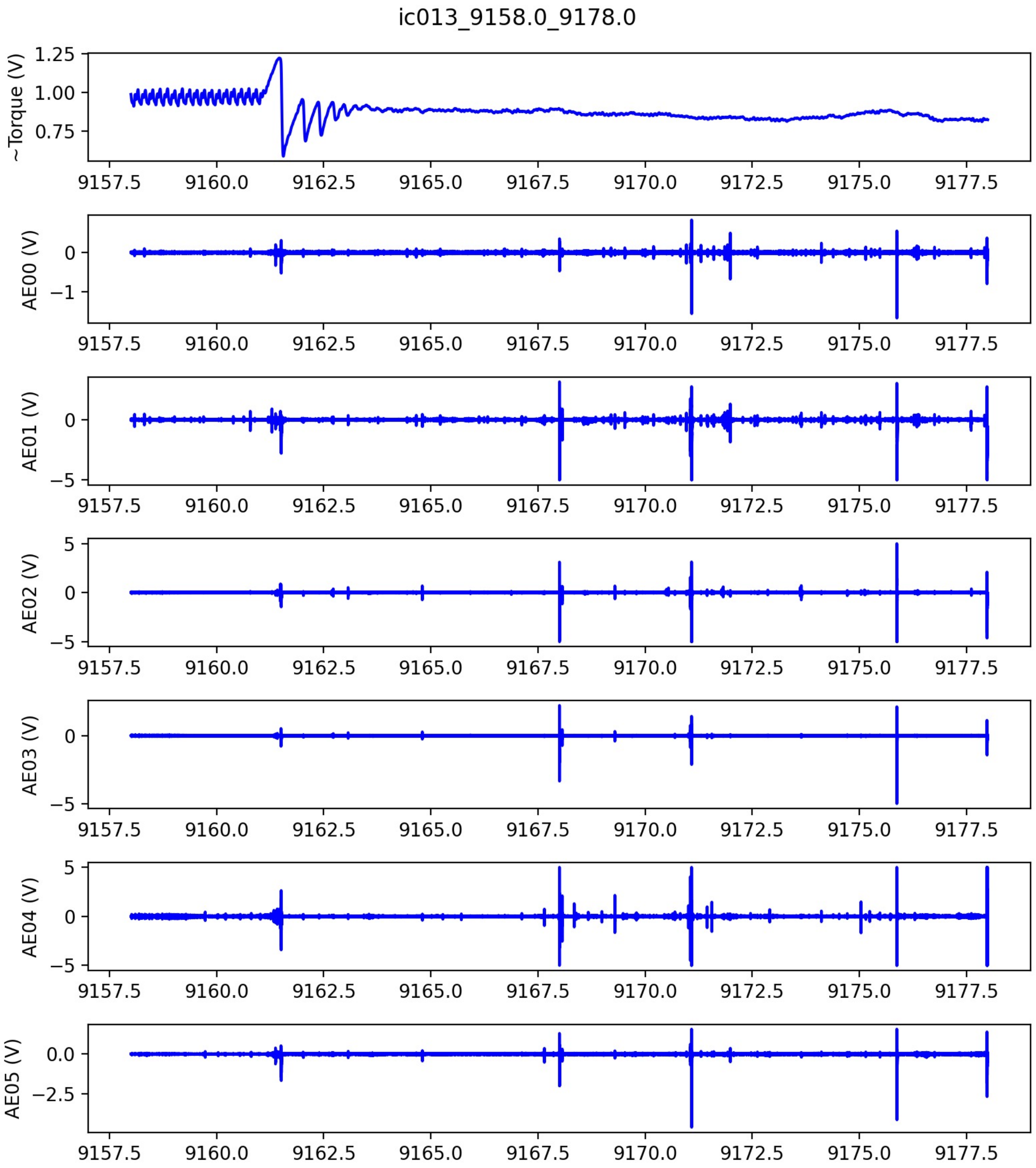
Speed step



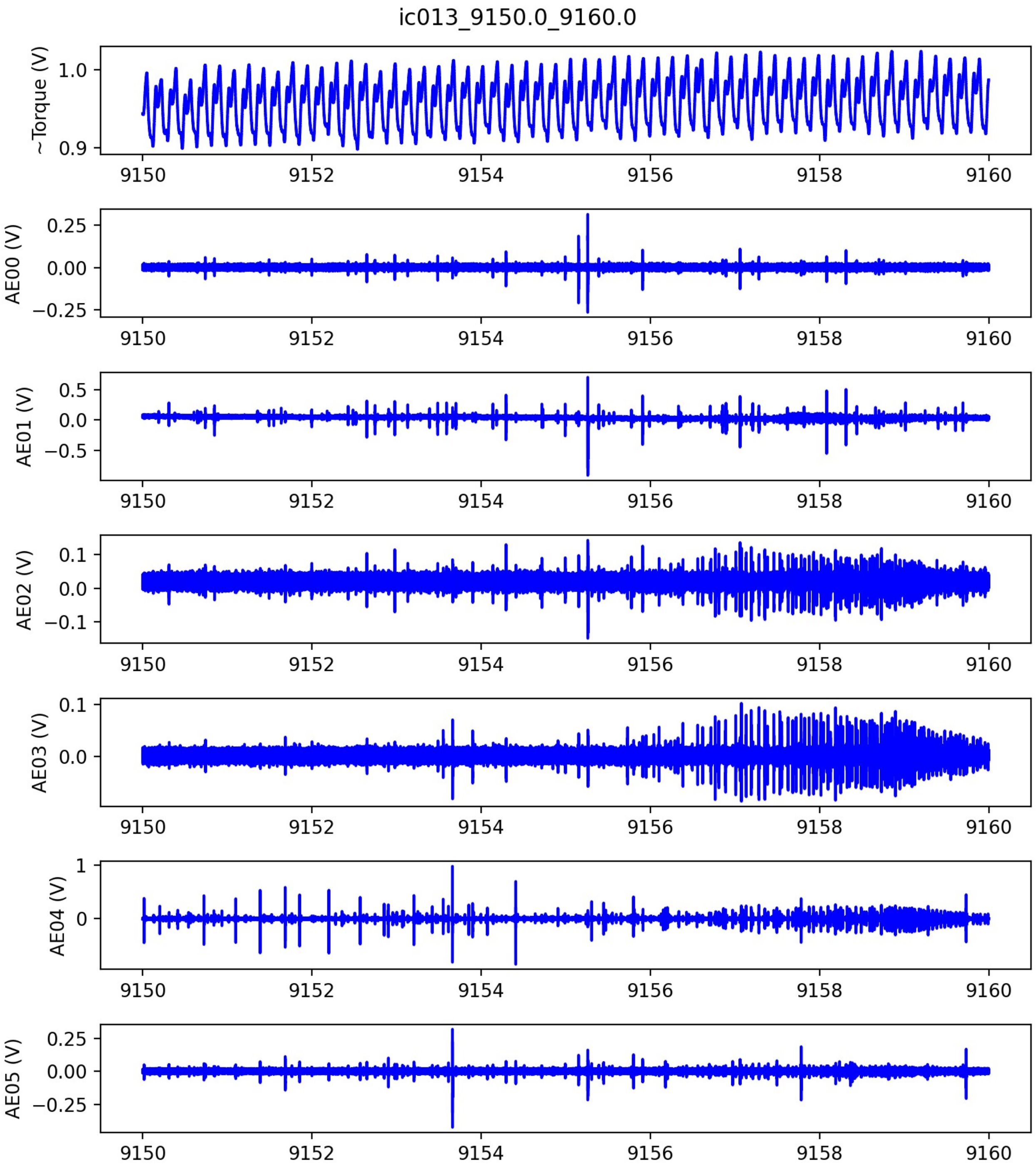




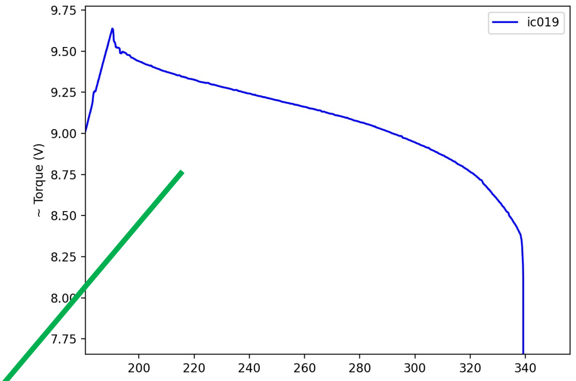
Torque and acoustic emission (AE) data from the previous experiment. Here we are looking at the speed step from 1 to 10 RPD. In this experiment the AE transducers were mounted directly onto the ice plate, near its outer edge. Note the mix of small and large events during steady-state sliding.



Another excerpt of torque and acoustic emission data. Note the group of quasi-periodic events recorded in channels 02, 03, and 04. The periodic signal in the torque time series is due to the operation of the motor at the lower end of its speed range.

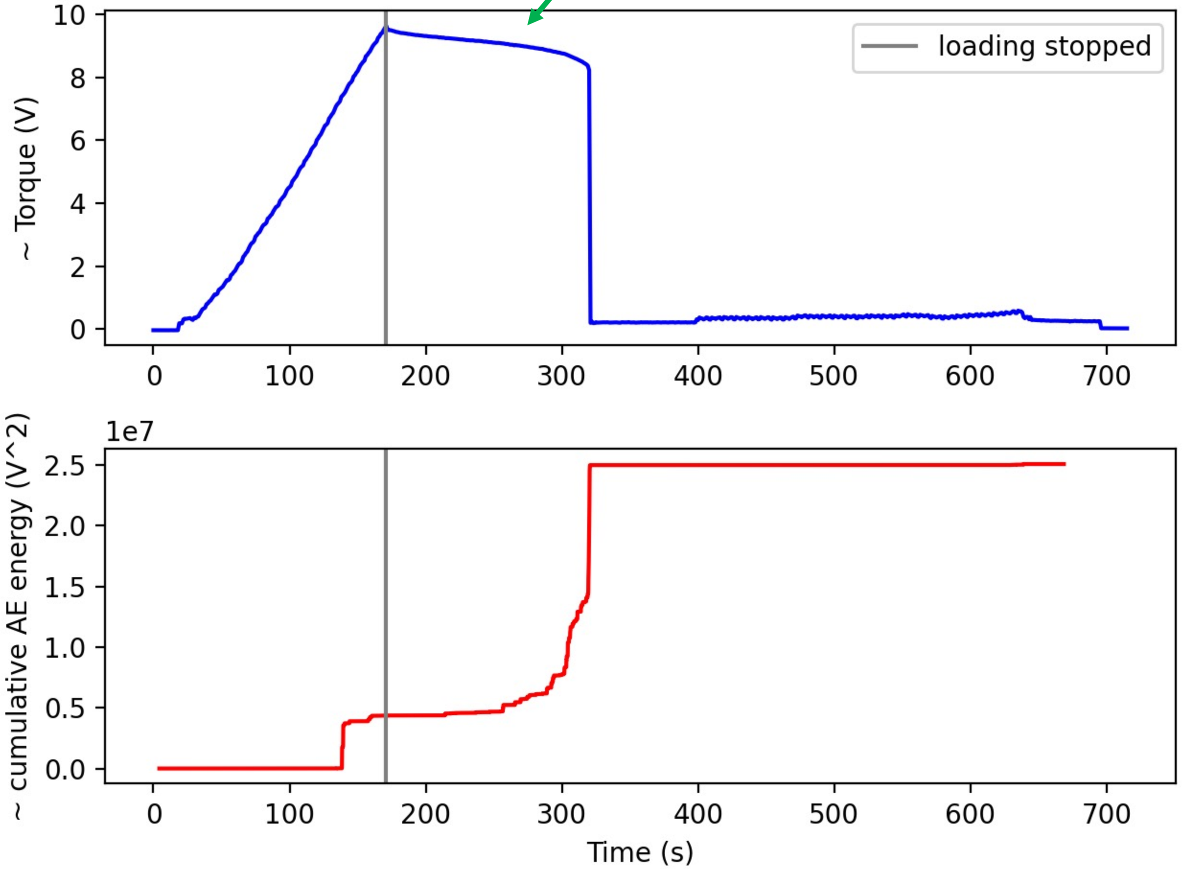


A stress relaxation experiment



In this experiment the sample was loaded until the output of the torque transducer reached approximately 9.5 V. At that point loading was stopped. A fault was formed after several seconds. Torque is shown in blue and the cumulative acoustic energy in red. Note the rapid increase of acoustic energy in the latter half of the stress relaxation window.

The data reveal the operation of time-dependent processes.



Part 4: Summary & outlook

1. We presented the upgraded version of a sliding experiment that aims to quantify the evolution of cohesion with increasing displacement.

2. The experiment is an analog for the hydrothermal conditions that prevail in shallow faults. Preliminary results indicate that the competition between frictional sliding and (re)freezing produces complex mechanical behavior and acoustic signature.

3. A series of slide-hold-slide test will be performed next, to determine healing rates under various loading conditions.

References

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