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A description and instructions of laboratory setup mimicking subglacial rock crushing

Mimicking an environment in the laboratory always involves compromises, as one-to-one reproduction is rarely possible. Imitating the subglacial environment poses additional challenges, since the interplays between the physical processes of crushing (or abrasion), biogeochemical weathering and the microbial ecosystem are complex. The consequence is that, at present, there is no model that covers both physical glaciology and associated biogeochemical and microbial cycles. Laboratory experiments are needed to understand, constrain and quantify the biogeochemical processes. By contrast, the influence of parameters such as the basal shear stress, describing the stress at which the ice at the bed starts to deform, or the basal contact pressure, which impacts glacial abrasion (Bennett and Glasser, 2009), can be described in theoretical models.

The difficulty in setting up a laboratory experiment to mimic the subglacial environment also lies in its isolated character; the environment is characterized by cold temperatures, high pressure from the overlying ice mass, darkness and limited external organic matter and nutrient input. However, despite the harsh conditions, the subglacial environment hosts an active microbial ecosystem (e.g. Sharp et al., 1999; Skidmore et al., 2005). The abrasion of bedrock, which is to be simulated in the laboratory experiments, along with subglacial weathering processes, are essential for supplying the microbial ecosystem with nutrients, such as silicon, nitrogen, iron and phosphorus (e.g. Hodson, 2006; Meire et al., 2016; Wadham et al., 2016; Hawkings et al., 2017; Raiswell et al., 2018). A summary description of the release of nutrients and gases from crushed bedrock can be found in the deliverable “D2.1 – Rate of release of solutes and gases from reactivated crushed glacial flour”.

Table 1 lists the factors that influence conditions at the glacier bed and indicates whether and how these can be replicated in a laboratory setting. The laboratory setup described, and what is possible with it, refers to the use of a planetary ball mill (Figure 1), which has previously been used in glacial crushing studies (Telling et al., 2015; Macdonald et al., 2018; Gill Olivas et al., 2021, 2023; Hatton et al., 2021).

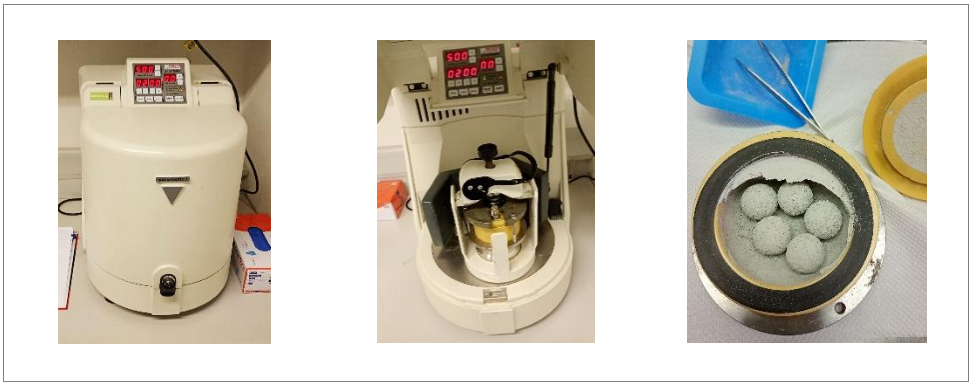

Figure 1: Photos of the Fritsch Planetary Mono Mill Pulverisette 6 (FRITSCH GmbH, Idar-Oberstein, Germany) used for glacial crushing experiments. From left to right: closed ball mill, open ball mill with the yellow grinding bowl, open grinding bowl after the crushing. Photos by Klara Köhler

What setting for the lab experiment to choose depends on the research question of the respective studies. If one wants to study the release of gases, it is recommended to work with dry sediment and a controlled headspace to be able to measure what is being released just from the sediment. To study the effects of crushing on the ability to release nutrients from the sediment into solution, both dry and wet crushing could be considered, depending on whether one wants to add a controlled amount of water after crushing or whether the focus lies on what goes directly into solution considering the pore water during the different crushing times.

In addition to deciding on the crushing setting, the type of sample must also be selected. Depending on the research question, different glacier sediment samples can be used. Samples with different mineralogy can be used to compare different glacier areas, and samples with different grain sizes such as glacial flour and basal debris. The use of glacial flour and basal debris, for example, makes it possible to either mimic the process of re-crushing, in which the already fine sediment is further crushed, or to investigate how much is released when the coarser debris is crushed until it reaches the grain size of the flour.

Further, it is recommended to complement the crushing and subsequent incubation or extraction experiments with the analysis of grain size and surface area of the samples before and after crushing to be able to link the released gases and nutrients to the change in properties of the sediment.

Table 1: List of conditions found in the subglacial environment and how these could be mimicked in a laboratory setup.

Subglacial environment	Laboratory setup
Crushing of the bedrock by high pressure and ice velocity Entrained debris in the basal ice layer acts as sandpaper grating over the bedrock, called abrasion. The abrasion is controlled by the contact pressure, which is determined by the thickness of the overlying ice mass, and the ice velocity. (Bennett and Glasser, 2009)	The ball mill cannot directly replicate the pressure present at the bed of the glacier. Nevertheless, short, high-intensity grinding (e.g. 500 rpm for up to 30 minutes) makes it possible to produce fine rock flour that resembles glacier flour and can then be used to study the properties of the fine particles.
Cold temperature The temperature at the glacier bed is around the melting point of the basal ice (pressure melting point, influenced by the thickness of the ice mass above; Bennett and Glasser, 2009). Sudden pressure releases (‘stick-slip movement’; Zoet et al., 2013) can lead to short-term high temperatures (up to 155 °C; Stone et al., 2023).	It is not possible to control the temperature inside the grinding bowl during crushing, as the friction of the sample generates heat and therefore a constant temperature cannot be maintained. However, it is possible to use the crushed sample afterwards in a temperature-controlled experiment, for example to investigate gas release or nutrient release from the sediment over time in a cold environment.
Oxic and anoxic conditions Weathering reactions such as sulphide oxidation ($4FeS_2 + 16CaCO_3 + 15O_2 + 14H_2O \leftrightarrow 16Ca^{2+} + 8SO_4^{2-} +$	It is possible to flush the headspace of the grinding bowl with N_2 or Argon (e.g. Telling et al., 2015; Macdonald et al., 2018; Gill Olivas et al., 2021) to create an oxygen depleted or anoxic atmosphere.

$16HCO_3^- + 4Fe(OH)_3$, here coupled to carbonate dissolution; Sharp and Tranter, 2017) and microbial oxidation can drive the glacial bed to (partly) anoxic conditions. (Tranter et al., 2002)	The grinding bowl can then be opened in a glove box filled with the same gas to ensure that the sample does not come into contact with oxygen.
Presence of meltwater film Subglacial abrasion and crushing of the bedrock only occur when the glacier slides over its bedrock and is not frozen to it. For this to happen, the temperature of the base ice must be just above its melting point so that a layer of meltwater can form. (Bennett and Glasser, 2009)	Crushing experiments were so far carried out on dried sediments (e.g. Telling et al., 2015; Macdonald et al., 2018; Gill Olivas et al., 2021). Dry crushing allows a better control and repeatability of the experiment, as water acts as lubricant and changes the grinding properties of the sample. Nevertheless, it is recommended to also test an experimental setup with wet crushing, either by adding a known amount of water to dried sediment samples or by using frozen sediment samples to better mimic actual subglacial grinding conditions.
Darkness	The insight of the closed grinding ball mill is dark, so that in longer term biogeochemical incubation studies, also including microbial activity, it would be possible to conduct the whole preparation, grinding and subsequent treatment procedure of the sample in the dark.
Long rock-water interaction time Until the sediment reaches the margin of the glacier and is discharged with the glacial runoff, the crushed bedrock faces long time rock-water interaction in the subglacial environment.	Studying of the long-term interactions between rock and water at the glacier bed can only be imitated to a limited extent in a laboratory setup. After 30 minutes (at 500 rpm), further grinding does not result in a smaller grain size (Macdonald et al., 2018), as well as the fact that no new material can be added during grinding, mean that only one grinding process can be carried out with the planetary ball mill at a time. Having a different setting that allows for slow grinding over a longer period of time could be tried, but it is still necessary to ensure that the force generated is sufficient to actually grind the sediment and not only stir it. One way to investigate the longer interaction times is through incubation experiments, in which the crushed sediment is incubated after crushing under conditions suitable for the research question (e.g. oxic or anoxic conditions, varying durations of incubation, re-crushing the sediment after incubation).

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