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# Biogeochemical weathering in sedimentary chronosequences of the Rhône and Oberaar Glaciers (Swiss Alps): Rates and mechanisms of biotite weathering

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ABSTRACT

We analysed the composition of phyllosilicate minerals in sediments deposited by the Rhône and Oberaar glaciers (Swiss Alps), in order to identify processes and rates of biogeochemical weathering in relation to glacial erosion. The investigated sediments are part of chronosequences consisting of (A) suspended, "fresh" sediment in melt water; (B) terminal moraines from the Little Ice Age (LIA; approximately 1560–1850); and (C) tills of the Younger Dryas interval (YD; approximately 11'500y BP). Secondary weathering products associated with the suspended sediment have not been observed; we therefore exclude intermittent subglacial storage and weathering of this material and assume that the suspended sediment is directly derived from mechanically abraded bedrock. This implies that biogeochemical weathering processes started once the glacially-derived sediment was deposited in the proglacial area. The combination of a developing vegetation cover, the generally high permeability allowing the percolation of precipitation, and the chemical reactivity related to the dominance of fine-grained material (<63 µm) drives the weathering process and the initial Umbrepts present in LIA profiles undergo podzolisation and lead to the formation of Humods observed in YD profiles. Systematic XRD analyses of these chronosequences show a progressive decrease in biotite contents and a concomitant increase in pedogenically formed vermiculite with increasing sediment age. Biotite contents decrease by 25–50% in the upper 30 cm of the moraines after 145–275 yr in the proglacial environment.

Biotite weathering rates are calculated using the difference in the biotite content between unweathered and weathered glacial sediments within the investigated profiles. The reactive mineral surface area is estimated geometrically, both with regards to the total relative surface ($WR_T$) as well as to the relative edge surface ($WR_E$). $WR_T$ Biotite weathering rates are estimated as $10^{-13}$–$10^{-15}$ $mol_{biotite}$ $m^{-2}{}_{biotite}$ $s^{-1}$. $WR_E$ Biotite weathering rates are on the order of $10^{-13}$–$10^{-14}$ $mol_{biotite}$ $m^{-2}{}_{biotite}$ $s^{-1}$. Biotite weathering rates obtained by this study are in the order of one magnitude higher in comparison to other published field-based weathering rates. Using biotite as an indicator, we therefore suggest that glacially-derived material in the area of the Oberaar and Rhône glaciers is generally subjected to enhanced biogeochemical weathering, starting immediately after deposition in the proglacial zone and subsequently continuing for thousands of years after glacier retreat.



## 1. Introduction

Glaciers are important agents of physical erosion and glacial abrasion may produce a high proportion of fine-grained sediment (<63 µm; e.g., Kirkbride, 1995). The high surface-to-mass ratio and the presence of strained minerals in this fraction condition this material for subsequent biogeochemical weathering. This process begins immediately after erosion within the subglacial environment of temperate glaciers (e.g., Tranter et al., 1993, 2002a,b; Gurnell et al., 1994; Sharp et al., 1995; Anderson, 2007; Anderson et al., 1997, 2000; Fairchild et al., 1999; Hosein et al., 2004), and continues once the sediment is transferred beyond the glacier margins and accumulated in proglacial deposits such as in moraines, where biogeochemical weathering may be intensified after glacier retreat (e.g., Anderson et al., 2000; Egli et al., 2001a,b, 2003; Jin et al., 2008).

Biogeochemical weathering processes in glacial environments may have a direct impact on the global carbon cycle through the sequestration of atmospheric $CO_2$ during silicate weathering, and may also have an indirect impact through the mobilisation of biolimiting nutrients (cf. phosphorus, iron, potassium, calcium),

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which mediate primary productivity rates and therefore influence the photosynthetic uptake of atmospheric $CO_2$ (Sharp et al., 1995; Föllmi, 1995; Föllmi et al., 2009; Hallet et al., 1996; Hodson et al., 2004). The study of biogeochemical weathering processes in glacial environments may, therefore, contribute to a more complete understanding of changes in the carbon cycle on glacial-interglacial timescales (e.g., Claridge and Campbell, 1984; Birkeland et al., 1987; Lidmar-Bergström et al., 1999; Righi et al., 1999; Egli et al., 2001a; Munhoven, 2002).

In glacial environments, the weathering of biotite and its transformation into vermiculite is an important source of biophile potassium and a useful indicator of the efficiency of biogeochemical weathering processes (Drever and Hurcomb, 1986; Anderson et al., 1997). We studied this alteration process in glacial deposits in the forefields of the Rhône and Oberaar glaciers, located in the Swiss Alps (Fig. 1; Arn, 2002; Arn et al., 2003; Hosein, 2002; Hosein et al., 2004; Föllmi et al., 2009). These areas experience similar climatic and weather conditions, which are presently resulting in considerable glacier retreat and loss in ice volume in both areas. Both areas share a common deglaciation history during the latest Pleistocene and the Holocene. Hormes et al. (2001) showed evidence for eight phases of glacial retreat and reduced glacier extent during the Holocene in the area of the Unteraar glacier, which is adjacent to the Oberaar glacier. The first phase of glacier retreat occurred between 9910 and 9550 cal yr BP based on $^{14}$C-dated wood. In this contribution, the term "PYD" is used as an age indication for glacial sediments dating back to this first post-YD phase of glacier retreat.

The areas are both contained within crystalline rocks of the Aar Massif (Fig. 1; Stalder, 1964; Abrecht, 1994). The lithologies of both catchment areas are geochemically quite homogeneous and comparable (Fig. 1; Table 1), except for the presence of a zone of highly deformed Variscan basement gneiss and schist in the Oberaar area (Oberhänsli et al., 1988).

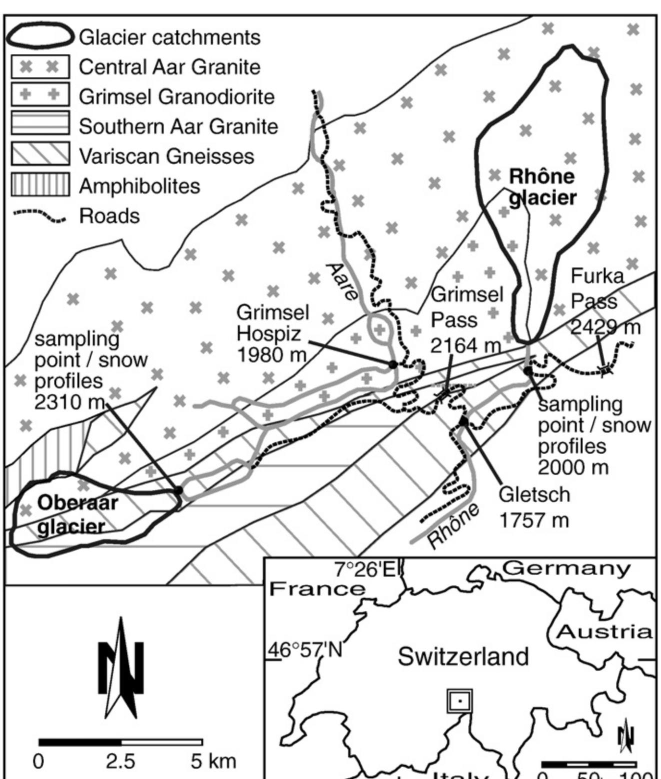


**Fig. 1.** Simplified geological map of the Aar Massif including the present-day catchments of the Oberaar and Rhône glaciers. Modified after Oberhänsli et al. (1988).

**Table 1**
Different parameters of the two catchments.

| | Oberaar | | | Rhône | | |
|---|---|---|---|---|---|---|
| Geographical position | 46° 32′ N 8° 14′ E | | | 46° 35′ N 8° 23′ E | | |
| Surface of catchment | 11.2 km$^2$ | | | 23 km$^2$ | | |
| Altitude | 2310–3631 m (a.s.l.) | | | 1750–3630 m (a.s.l.) | | |
| Glacier cover today (%) | 57% | | | 73% | | |
| Annual mean temperature* | −1 °C§ | | | +1.2 °C§ | | |
| Annual mean precipitation* | 2100 mm | | | 2200 mm | | |
| Geology of catchments: | Today | LIA | YD | Today | LIA | YD |
| Central Aar Granite | 38% | 38% | 25% | 90% | 82–86% | 40% |
| Grimsel Granodiorite | 7% | 7% | 12% | 10% | 8–9% | 20% |
| Variscan Gneisses | 42% | 42% | 38% | | 10–5% | 20% |
| Ultramafic Inclusions | 1% | 1% | 1% | | | |
| Southern Aar Granite | 12% | 12% | 24% | | | |
| Mesozoic metasediments | | | | | 20% | |

*Schwab et al. (2001).
§Within proglacial area, 2300 m at Oberaar, 1757 m at Rhône.
For geology see also Fig. 1.

The biotite weathering rates we established are high in comparison to published field-based data from a variety of climatic regimes (e.g., Swoboda-Colberg and Drever, 1993; Nagy, 1995; Murphy et al., 1998). They are, however, lower than the biotite weathering rates calculated for different conditions in laboratory experiments (e.g., Velbel, 1993a; Turpault and Trotignon, 1994; Nagy, 1995; Kalinowski and Schweda, 1996).

## 2. Sampling sites and methods

### 2.1. Sampling sites

The Oberaar catchment lies at approximately 2300 m above sea level (m.a.s.l.) and the forefield of the Rhône glacier is at approximately 1750 m.a.s.l. In the proximal forefields of the Rhône and Oberaar glaciers pioneer plants have colonised sediments that recently became ice-free. Scattered alpine meadows and peat bogs appear in more distal parts of the proglacial area (Ammann, 1977). Additionally, alder bushes are present in the Rhône forefield.

Soil profiles were dug and sampled in both catchment areas. In the Oberaar catchment, two profiles ($O_{145A}$ and $O_{145B}$; Fig. 2) were dug into the crest of a moraine ridge, which was deposited during the maximum glacial extent of the Little Ice Age (LIA) in 1860 (Ammann, 1977). A further profile ($O_{PYD}$; Fig. 2) was dug into a patchy till cover beyond the extent of the LIA moraines. This till is interpreted to have been deposited during the initial phase of glacial retreat following the Younger Dryas (YD; 11′500 BP; Christian Schlüchter, University of Berne, personal communication). In the Rhône glacier forefield, two LIA profiles were dug into the crests of moraine ridges dating from the beginning of the 18th century ($R_{275A}$, and $R_{275B}$; Fig. 2). A further profile was obtained from the terminal moraine dating from 1856 ($R_{150A}$; Fig. 2; Zumbühl, 1988). A PYD profile was dug into a patchy till cover in a scoured morphology beyond the limits of the LIA deposits ($R_{PYD}$; Fig. 2). This sediment became exposed during the initial phase of glacier retreat following the YD (cf. also Fitze, 1982).

### 2.2. Soil profiles

The LIA profiles are predominantly comprised of sand- to silt-sized grains with minor amounts of clay. The PYD profiles are not significantly enriched in clays. The general grain-size distributions imply good permeability, allowing precipitation to percolate through the sediments. The profiles are described in Table 2, where soil horizons and soil types are assigned according to USDA and AFES classifications (1998).