

# Chemical weathering beneath Alpine glaciers: rates and implications for CO<sub>2</sub> drawdown

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Alpine glaciers are warm-based, and their subglacial drainage system is believed to consist of two main components. Firstly, there is a distributed drainage system that is largely recharged with snowmelt. Secondly, there is a channelised drainage system, into which the distributed system drains, and that is also recharged with icemelt. The position of the snowline largely determines the transition between subglacial drainage largely occurring via the channelised system or the distributed system. Hence, as the snowline retreats each summer, the channelised drainage system expands towards the headwalls of the glaciated basin.

Different types of chemical weathering reactions dominate in each of the drainage systems. Chemical weathering reactions in the distributed drainage system consist largely of coupled sulphide oxidation and carbonate dissolution. Meltwaters pass slowly through this system and it is here that freshly comminuted glacial flour is believed to come into contact with meltwater for the first time. The freshly comminuted flour contains trace quantities of sulphides and carbonates, and oxidation/dissolution of these trace minerals dominates chemical weathering, since the reaction kinetics are more rapid than those of other minerals in the flour. Other chemical weathering reactions are more restricted because of the lack of an alternative proton source.

Chemical weathering reactions in the channelised drainage system are dominated by carbonation reactions. Suspended sediment in this drainage system is deficient in reactive sulphides. Hence chemical weathering is reliant upon the diffusion, and subsequent dissociation, of atmospheric CO<sub>2</sub> to supply protons. The high concentration of clay- to silt-sized suspended sediment (typically 1–2 g/L) promotes surface exchange reactions that increase the pH of the poorly buffered meltwaters and lowers the  $p_{\text{CO}_2}$  of the solution, promoting the influx of CO<sub>2</sub>. Transit times through the channelised system are low, and therefore the concentration of ions attributable to carbonation is low.

This simple model of subglacial chemical weathering easily explains the inverse association between the ionic strength and the discharge of glacial runoff on both seasonal and diurnal timescales. Low discharge is sustained by drainage from the distributed system. Hence, low discharge waters are relatively concentrated. High discharge is dominated by icemelt rapidly draining through the channelised system. Hence, high discharge waters are relatively dilute.

We present the results of 2 field seasons, 1989 and 1990, at Haut Glacier d'Arolla, Valais, Switzerland. Runoff was continuously monitored during May through September, and water samples were collected most days during June through August, both at times approximating to minimum discharge (10.00 hrs) and to maximum discharge (17.00 hrs). The samples were analysed for major cations, anions, pH and SiO<sub>2</sub>. Suspended sediment concentrations (SSC) were determined from samples collected every 2 hrs by a pump sampler during June through August.

The association between each major anion, cation, SiO<sub>2</sub> and SSC with discharge (Q) was determined. The association normally took the form of a log-log best fit regression equation. These equations were then used to predict hourly concentrations for the period May through September, when most runoff occurs, by using hourly mean values derived from the continuous discharge records. Fluxes were calculated for each hour by multiplying the discharge by the predicted concentrations. The fluxes were summed to give a minimum estimate of the mean annual chemical weathering rate.

The mean cationic weathering rate is 640–687 meq m<sup>-2</sup>a<sup>-1</sup>, whilst the solute and solid denudation rates are 45–51 and 2680–3520 tonnes km<sup>-2</sup>a<sup>-1</sup> respectively, assuming that the average density of crustal material is 2,800 kg m<sup>-3</sup>. The mean cationic weathering rate is higher than the continental average of 390 meq m<sup>-2</sup>a<sup>-1</sup>. This agrees with the results of other glacierised basins, that have been constructed from much smaller and restricted data sets. Hence, chemical weathering rates in the glacierised basins studied to date are higher than

the continental average.

The  $\text{HCO}_3^-$  found in bulk runoff may be derived from a number of sources, principally from atmospheric  $\text{CO}_2$  and carbonates. We partition the  $\text{HCO}_3^-$  found in bulk runoff into a) that derived from carbonate dissolution in the distributed system by assuming that each equivalent of  $\text{HCO}_3^-$  from carbonate dissolution is equated with an equivalent of  $\text{SO}_4^{2-}$  derived from sulphide oxidation; and b) the remaining  $\text{HCO}_3^-$  is divided in two, one half being derived from atmospheric  $\text{CO}_2$  and the other half from carbonate dissolution. In this way, we derive a minimum estimate of the atmospheric  $\text{CO}_2$  drawdown by meltwaters.

The  $\text{CO}_2$  drawdown is a linear function of discharge, and approximates  $1.2 \text{ gC m}^{-3}$ . We are aware that it is very dangerous to extrapolate from one small Alpine catchment to the global scale,

and we are well aware of the limitations of the following calculations. We present the following results as an illustration of the potential that meltwaters may have for  $\text{CO}_2$  drawdown, a potential that is presently not explored in the literature. It is believed that some  $4.5 \times 10^7 \text{ km}^3$  of meltwater was discharged to the oceans during the transition from the last deglaciation (18–6 kyr BP). We calculate that atmospheric  $\text{CO}_2$  may have been depleted by up to 12 ppm due to the increased meltwater runoff and chemical weathering, and that the total drawdown of  $\text{CO}_2$  during this period was equivalent to a removal of 27 ppm of present day  $\text{CO}_2$  levels. We conclude that  $\text{CO}_2$  drawdown by glacial meltwaters may help explain why atmospheric  $\text{CO}_2$  levels remained low during the last deglaciation, while mean global temperatures increased and ice volumes decreased.