

The role of climate in silicate weathering

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The major factors affecting the rate of chemical weathering of silicate minerals include lithology, topography (relief), permeability, climate (precipitation, temperature and vegetation) and aspect (e.g. Jenny, 1941). Recently it has been suggested (e.g., Edmond and Huh, 1997; Gaillardet *et al.*, 1997) that climate, especially temperature, is not an important factor in weathering, and that relief and lithology dominate. It has even been suggested by some workers that lower temperatures enhance chemical weathering. It is the purpose of this paper to show that: (1) even if lithology and/or relief dominate, a positive response of silicate weathering globally to CO₂-induced (greenhouse) changes in climate is the most reasonable process so far advanced for stabilizing atmospheric CO₂, (2) this positive response can be demonstrated if other weathering factors are held roughly constant and (3) some of the evidence cited against the importance of climate has been based on data where other factors, particularly the presence of minor calcium carbonate, obscure the climatic signal.

Weathering and the long term carbon cycle

It has been demonstrated (e.g. Berner and Caldeira, 1997) that the atmospheric input of CO₂ from global degassing must be matched closely, on a million year time scale, by CO₂ removal via silicate weathering. Otherwise, atmospheric CO₂ would rise or drop on geological time scales to levels inimical to the continuity of life. If degassing rate were constant, any acceleration in the weathering rate in one region must soon (<1 my) be accompanied by a compensating deceleration elsewhere in order to conserve atmospheric + oceanic + biospheric carbon. Likewise, any changes in the CO₂ degassing rate must be matched by a similar change in CO₂ removal by silicate weathering. The only well documented process for accomplishing this compensation, which is functionally dependent upon atmospheric CO₂ levels, is a change in the weathering rate via the

greenhouse-climate-weathering negative feedback. Specifically, if CO₂ is removed by accelerated weathering in a newly-formed mountainous region, the lowering of atmospheric CO₂ level should lead to global cooling and lowered continental rainfall, which should in turn lead to compensating decelerated weathering outside of the mountain belt. In this case the overall global weathering rate would remain constant and equal to degassing rate, and the mountain uplift would lead to a new, but lower, steady state CO₂ value.

One cannot call upon other processes such as degassing or the weathering of organic matter, which do not respond to changes in atmospheric CO₂ level, to accomplish the necessary carbon mass balance and rapid negative feedback that must accompany changes in silicate weathering rate. Also, accelerated weathering accompanying global cooling, due to lower CO₂, constitutes positive feedback and would lead in a few million years to a runaway ice house and the cessation of photosynthesis. The corollary to this, slower weathering at higher temperatures, would lead to a runaway greenhouse. The climate-weathering-greenhouse negative feedback is needed to stabilize CO₂, and therefore climate.

Field studies of silicate weathering and climate

The effects of increasing temperature and precipitation on accelerated weathering have long been accepted in the soil literature. The classic work of Jenny (1941) demonstrates positive correlations between both temperature and precipitation and clay content of several continental U.S. soils developed individually on specific rock types. Studies of weathering on the island of Hawaii clearly illustrate the important role of rainfall, for constant basaltic lithology and relief, in accelerating the rate of silicate weathering. A recent study by Dorn and Brady further demonstrates a strong temperature dependence of Hawaiian basalt weath-

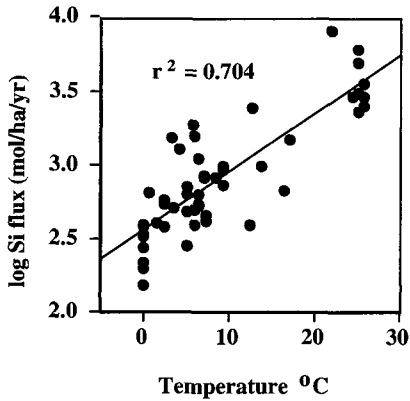


FIG. 1. The correlation between temperature and annual Si fluxes from a global distribution of small watersheds underlain by granitoid rocks.

ering. The early work of Biscaye on Atlantic Ocean sediments demonstrates a correlation of kaolinite abundance, as a measure of intense continental weathering, with lower latitudes where greater weathering would be expected due to greater rainfall and warmer temperatures. Also, extensive studies by Nahon and co-workers have shown a strong correlation of kaolinite formation with warm and wet climates. The statement that tropical weathering leads to the formation of a thick layer of kaolinitic clay that inhibits further weathering is not applicable to rugged terrain where landsliding is common.

When examining factors affecting weathering rate, it is necessary to isolate the variable under study and to hold all others constant as much as possible. This often cannot be done in comparing chemistries of rivers where identification of climate-induced effects are hidden by differences in relief, and especially lithology, and in large rivers where there are wide spatial ranges in temperature and precipitation. An exception is White and Blum (1995) where data on rates of weathering in small watersheds of uniform granodioritic lithology and well-constrained climates have been presented. An updated summary (Fig. 1) shows a strong influence of temperature on Si fluxes, the major element most indicative of silicate weathering. (Data for Na show a similar trend). Precipitation explains an additional portion of the variability in Si fluxes, with wetter watersheds tending to fall above the linear trend and dry watersheds below. Silicate weathering rates increase as a function of both increasing temperature and precipitation, with warm, wet watersheds having the highest weathering rates (White and Blum, 1995). This is completely consistent with the idea of

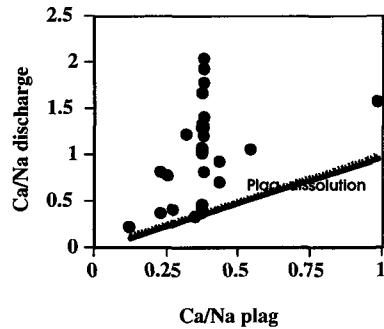


FIG. 2. Excess Ca/Na ratios in annual discharge from watersheds underlain by plutonic granitoid rocks.

negative feedback between increasing atmospheric CO_2 and accelerated silicate weathering.

A major problem in the interpretation of river water data is that traces of calcium carbonate in a silicate terrain give misleading weathering rates for Ca and Mg silicate minerals. Carbonates are much more reactive than silicates. Weathering fluxes from recently glaciated regions (<15 ky) that drain dominantly crystalline granitoid rocks bear chemical signatures from reaction with very small amounts of carbonate rocks contained within each area (eg. Blum *et al.*, 1998; White *et al.*, this volume and additional work by Anderson, Tranter and others). Trace amounts of disseminated calcite are ubiquitous within granitoid rocks, forming during late stage magmatic cooling and/or secondary stage hydrothermal reactions. As shown in Fig. 2, even though most of the Ca and Na in granitoids are contained in plagioclase feldspar, the Ca/Na ratio in discharge fluxes from small singularly granitoid watersheds can greatly exceed the respective feldspar stoichiometries. The extent of this Ca excess, attributed to disseminated calcite, varies depending on the age and the extent of past physical and chemical weathering in the watershed. Variations in the extent of calcite weathering, even in the well-constrained watersheds summarized by White and Blum (1995), explains why, in contrast to Si and Na, they observed no climate correlation for fluxes of Ca and alkalinity. The lack of similar correlations for total cation fluxes, commonly dominated by Ca in large river systems, is therefore not surprising based on the rapidity and variability in calcite weathering. The use of cation and/or alkalinity data to refute the idea that climate has an impact on global silicate weathering rates needs to consider this carbonate problem.