

Temperature dependence of silicate weathering in nature: How strong a negative feedback on long-term accumulation of atmospheric CO₂ and global greenhouse warming?

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ABSTRACT

Estimation of the temperature dependence of natural feldspar weathering in two catchments at different elevations yields an apparent Arrhenius activation energy of 18.4 kcal/mol (77.0 kJ/mol), much higher than most laboratory values. This finding supports recent suggestions that hydrolytic weathering of silicate minerals may consume carbonic acid and thereby remove atmospheric carbon dioxide more rapidly with increasing temperature than previously thought. This result provides a stronger negative feedback on long-term greenhouse warming than has been assumed in most models of global carbon cycling. The present estimate was determined from the ratio of feldspar weathering rates (determined by geochemical mass balance) in the southern Blue Ridge Mountains of North Carolina, United States. Temperature (a function of elevation) is the only factor that differs between the two catchments; parent rock type, aspect, hillslope hydrology, and vegetation type and successional stage are the same in both.

INTRODUCTION

Silicate-mineral weathering reactions are fundamental processes that determine the contributions of continental crustal weathering to global geochemical cycles. Silicate minerals weather by hydrolysis, thereby consuming naturally occurring acids, including carbonic acid. Because carbonic acid forms by the reaction of CO₂ with water, reactions that consume carbonic acid remove CO₂ from the atmosphere. Silicate weathering is responsible for over half (58%) of the carbonic acid consumption by continental weathering (Berner and Berner, 1987); weathering is therefore an important component of the global long-term carbon cycle and associated environmental consequences such as global ("greenhouse") warming. In spite of the importance of weathering in models of the long-term global carbon cycle, the response of silicate-mineral weathering rates to changes in Earth's surface temperature is not well known.

This paper reports the determination of the activation energy of feldspar weathering from natural systems.

GEOLOGIC BACKGROUND

Suites of catchments along elevation gradients have recently been studied to investigate the effect of elevation-dependent factors (temperature, soil thickness, vegetation) on silicate-mineral weathering rates (Drever and Zobrist, 1992). A similar approach is used here. Catchments 2 and 34 (C2 and C34) of the U.S. Department of Agriculture (Forest Service) Coweeta Hydrologic Laboratory were used in this study. Coweeta is located ~16 km southwest of Franklin, North Carolina, in the southern Appalachian Blue Ridge province. The geology, hydrology, topography, climate, and land-use history of the study area, summarized here, are described in detail elsewhere (Velbel, 1985a, 1985b, 1992; Swank and Crossley, 1988; Hatcher, 1979, 1980, 1988; Ciampone et al., 1992).

C2 and C34 range in elevation from 709 to 1004 m and from 866 to 1184 m, respectively. Both have been free of any intentional anthropogenic disturbance since 1924, and both have a south-facing aspect. Annual average rainfall is high (~2 m), and the two catch-

ments are similar in their topography (as measured by the relief ratio; Grantham and Velbel, 1988). All rock types and mineral assemblages of the catchments are those of the Tallulah Falls Formation (late Precambrian), a high-rank (amphibolite facies) metamorphic unit consisting principally of metasedimentary quartz-mica schists and mica-feldspar-quartz gneisses. Plagioclase feldspar (sodic andesine, An₃₂) is common in C2 and C34; its composition is areally very homogeneous. Both catchments lie along structural strike, such that both transect the same parts of the lithostratigraphic unit. Because parent rock type, aspect (south-facing), and vegetation type and successional stage are as similar as is possible for natural systems, temperature is the only factor that differs between the two catchments.

Weathering profiles in C2 and C34 consist of a thick (average thickness 6 m; range 0 to 20 m) mantle of soil and saprolite overlying a hydrologically impervious base of unweathered crystalline rock (Velbel, 1985a, 1985b). More resistant and remnant primary minerals and relatively insoluble weathering products retain much of the primary texture and preserve the volume of the parent material (Velbel, 1985a, 1990a). Despite the thick saprolites and mature soils, even the uppermost (oldest) soil horizons on the thickest (oldest) saprolites in the Blue Ridge landscape still contain weatherable primary minerals, including plagioclase feldspar (Velbel, 1992).

Hillslope hydrology at Coweeta is such that stream-water solute loads are depth-integrated samples representing weathering throughout the entire thickness of the profile. Interflow and overland flow (runoff) are not significant processes at Coweeta; precipitation infiltrates almost immediately, even on steep slopes (average 27°). Base and storm flows at Coweeta are sustained principally by water from subsurface soils and saprolites (Velbel, 1985b; Hewlett, 1961; Hewlett and Hibbert, 1963). This water continues to move downward through the saprolitic weathering profile until it reaches the hydrologically impervious unaltered bedrock. At this point the water is shunted laterally toward the stream (Velbel, 1985b).

TABLE 1. FELDSPAR WEATHERING RATES, AND TOPOGRAPHY AND TEMPERATURE DATA FOR COWEETA CATCHMENTS 2 AND 34

	Catchment 2	Catchment 34
Area (km ²)	0.12	0.33
Elevations (m):		
Top *	1004	1184
Bottom *	709	866
Mid-point	856	1025
Area-weighted mean [†]	849	1019
Catchment mean annual temperature at weighted-mean elevation (°C)	11.7	10.6
Plagioclase ₂ weathering rate [‡] (mol/m ² /yr)	5.67 × 10 ⁻²	5.00 × 10 ⁻²

* From Swank and Crossley (1988, Table 1.1).
[†] From 1:14,400 topographic map of Coweeta Hydrologic Laboratory.
[‡] From Taylor and Velbel (1991, Table 3).

METHODS

Weathering rates for individual minerals were determined by geochemical mass balance (Velbel, 1985a; Taylor and Velbel, 1991). The mass balance of a catchment is described by a system of simultaneous linear equations, relating the measured net fluxes to the (known) stoichiometries and (unknown) rates of weathering reactions for multiple minerals in the weathering profiles. The long-term average fluxes used to calculate weathering rates are based on weekly measurements and constitute one of the longest running catchment solute-flux records in North America (the period of record for the current study is 12 yr; Swank and Waide, 1988; Taylor and Velbel, 1991). Mineralogical and petrographic data determine stoichiometries of mineral weathering reactions, and uptake of mineral nutrients by the forest biota is explicitly included (Velbel, 1985a; Taylor and Velbel, 1991). The resulting system of equations is solved by conventional linear algebra to calculate the weathering rates of individual primary minerals (Velbel, 1985a; Taylor and Velbel, 1991). Natural weathering rates for plagioclase feldspars are determined primarily from solute mass balances for sodium. Sodium is not a major nutrient for terrestrial flora; consequently, calculations of natural weathering rates of plagioclase feldspars are not sensitive to uncertainties in botanical cycling rates (Taylor and Velbel, 1991). The weathering rates for plagioclase feldspar in C2 and C34 (Taylor and Velbel, 1991) are given in Table 1.

A similar decline in silicate-mineral weathering rates with increasing elevation (Table 1) has been observed in small catchments of the Swiss Alps (Drever and Zobrist, 1992). However, so many factors important to the weathering process (temperature, soil thickness, vegetation) vary along the large elevation gradient in the Alpine study (>2 km) that it is impossible to isolate the effects of any one factor (Drever and Zobrist, 1992). This study minimizes these limitations. Regolith character and vegetation exhibit much less variability than in Drever and Zobrist's (1992) study area (because of the much smaller range of elevation), leaving temperature alone as the dominant factor controlling differences in weathering rates.

In the absence of detailed data on long-term elevation and soil-temperature relations for the two study catchments, area-weighted mean annual temperatures were used as a first approximation in these calculations. Precipitation on the study catchments is essentially invariant with elevation (Swift et al., 1988, Fig. 3.1), so shallow levels of weathering profiles are affected by comparable leaching intensities. Thus, variable contributions to weathering budgets from the soils of different parts of the landscape are due to the tempera-

ture of each part. A catchment with a larger fraction of its area at lower elevations should be warmer than one at higher elevations and might therefore be expected to undergo more rapid weathering and contribute more to solute fluxes. The area-weighted mean elevations of C2 and C34 differ by ~170 m. Because of the similar elongate morphology of the two study catchments, the area-weighted mean elevation differs from the simple midpoint elevation by <8 m for each catchment (Table 1).

The part of the weathering that takes place at greater depths in the weathering profile does so under a thermal regime that makes smaller thermal excursions about the mean annual temperature than do shallower levels of the profile. Stream-water samples represent water that has been in contact with the entire thickness of the weathering profile (Velbel, 1985b). Stream-water temperatures in such systems tend to reflect the moderating influence of subsurface temperature; diurnal and seasonal thermal fluctuations are largely damped out at the depths (several metres) at which much of the mineral weathering takes place (Soil Survey Staff, 1975; Velbel, 1990b). Even in shallower soil horizons, mean annual temperature is a reasonable first approximation; both catchments used in this study face south: "South-facing slopes have smaller seasonal fluctuations from the annual mean than north-facing slopes" (Soil Survey Staff, 1975, p. 60). The mean annual temperature in the study area is 12.8 °C at 685 m elevation (Coweeta Climate Station 1; Swift et al., 1988). By using the mean atmospheric thermal lapse rate of 6.5 °C/km, the mean annual temperatures at the area-weighted mean elevations of C2 (849 m) and C34 (1019 m) are 11.7 and 10.6 °C, respectively (Table 1).

Differences in weathering rates between the two catchments studied here are not likely to be attributable to differences in catchment hydrology (including variations in rainfall and/or effective precipitation). Long-term average weathering rates at Coweeta are apparently independent of flow rate (Velbel, 1985a). Soil solutions from Coweeta catchment 27 (the only one for which all necessary data are available) are sufficiently far from equilibrium that the feldspar hydrolysis rate is independent of saturation state (Velbel, 1989), regardless of the specific formulation of the rate law (Walther and Wood, 1986; Burch et al., 1993). Fluid-rock contact times are sufficiently similar, and sufficiently short, so that solutions in both catchments are too far from equilibrium for differences in saturation state or flow rate to cause differences in reaction rates. Because the parent rock type is compositionally and texturally uniform from one catchment to the next, the stoichiometry and modal abundance (and consequent reactive surface area) of any given parent mineral can be assumed to be invariant. Thus, the ratio of weathering rates in two catchments with the same parent rock type equals the ratio of the rate constants.

The apparent Arrhenius activation energy (E_a) of the feldspar hydrolysis reaction in nature is determined here from the ratio of the feldspar weathering rates (as determined by mass balance) at the different (absolute) temperatures of the two catchments. Assuming that the preexponential term and activation energy are invariant over the range of temperatures being examined, Arrhenius expressions for the ratio of rate constants at two different temperatures (Velbel, 1990b; Brady, 1991) can be rearranged to solve for E_a .

RESULTS

From previously determined feldspar weathering rates (Taylor and Velbel, 1991) and the mean temperatures estimated here, the activation energy for feldspar hydrolysis is calculated to be 18.4 kcal/mol (77.0 kJ/mol). Most experimentally determined activation energies for sodic plagioclase or alkali feldspar dissolution (at near-neutral pHs) reported in the literature range from 7.1 to 13.5 kcal/mol

(29.7 to 56.5 kJ/mol; Pačes, 1983; Wood and Walther, 1983; Knauss and Wolery, 1986); values of 15.4 and 19.2 kcal/mol (64.4 and 80.3 kJ/mol) for albite and oligoclase, respectively, have recently been reported by Sverdrup (1990). The activation energy determined here from catchment weathering rates is thus higher than most published experimental values.

DISCUSSION

All experimental activation energies for plagioclase dissolution of <10 kcal/mol (<42 kJ/mol) have been derived from a single set of experimental data acquired at 100–200 °C (Lagache, 1965, 1976). Furthermore, the experiments on which the low activation energies are based all involve low-temperature (<200 °C) experiments in which silicate minerals dissolve at anomalously high rates (Walther and Wood, 1986). Many workers have shown that accelerated silicate-dissolution rates at low temperatures result from the enhanced reactivity of the surfaces of the crushed and ground minerals used in such experiments (see review by Velbel, 1986). Forcing an Arrhenius plot to pass through these artificially high rates at low temperatures lowers the slope of the Arrhenius plot, giving rise to artificially low activation energies. The activation energy in this study was determined from natural systems, which are not subject to these sample-preparation artifacts.

The activation energy calculated here is most likely a minimum value. Temperatures in the study catchments were estimated from a measured temperature (at known elevation) outside the catchments, known catchment elevations, and the mean atmospheric thermal lapse rate (in free atmosphere) of 6.5 °C/km. Actual thermal lapse rates for soil temperatures are likely to be lower. For instance, the average of local mean terrestrial lapse rates (measured at land surface) is slightly lower (5.9 °C/km; Meyer, 1992), and values as low as 3.3–3.9 °C/km have been observed for soil temperatures in the central Appalachians (Macfie, 1991). A lower lapse rate reduces the difference in estimated temperature between the two catchments. Because the rate terms (ratio of rate constants) are fixed from flux measurements, the use of a smaller temperature difference would yield a larger apparent Arrhenius activation energy than the value calculated here.

Most previous models of the global carbon cycle produce wide fluctuations of model Phanerozoic paleotemperatures and paleo-levels of atmospheric carbon dioxide, as a consequence of weak silicate weathering-mediated feedback between temperature and atmospheric CO₂; the weak feedback, in turn, results from the low temperature dependence of weathering rate used in the models (Brady, 1991). Two formulations of the temperature dependence of silicate weathering are in wide use. Walker et al. (1981) extrapolated from experimental feldspar-dissolution rates acquired at 100–200 °C (Lagache, 1965, 1976) to determine their weathering rate-temperature relation at Earth's surface temperatures; Berner et al. (1983) used ground-water data for bicarbonate concentration vs. temperature from carbonate aquifers as the basis for their temperature dependence. The temperature dependence so determined correlates with selected data (Meybeck, 1979) on the concentration of dissolved silica in rivers as a function of temperature (Walker et al., 1981; Berner and Barron, 1984). Berner's most recent model, GEOCARB II (Berner, 1993), which modifies GEOCARB I (Berner, 1990, 1991) and supersedes the model of Berner et al. (1983), uses a significantly higher activation energy (15 kcal/mol; 63 kJ/mol). However, most other recent modeling studies of the long-term carbon cycle invoke either the Walker et al. (1981) or Berner et al. (1983) temperature dependence. As noted by Brady (1991), these widely used weathering expressions all correspond to activation energies of <10 kcal/mol (<42 kJ/mol).

CONCLUSIONS

The less the weathering rate is accelerated by a given temperature increase, the less additional CO₂ is consumed by weathering; thus, lower activation energies produce model scenarios in which the CO₂ buildup and global mean temperature increase are greater than in scenarios invoking higher activation energies. The resulting weak temperature dependence produces unreasonably wide excursions in model CO₂ paleolevels, requiring modification of the temperature-dependence expression in the models (Berner, 1991). Recent studies have introduced an explicit expression for biotic influences on weathering, with a presumed strong temperature dependence, but, with the exception of GEOCARB II (Berner, 1993), the biotic term is introduced with little or no change in the expression for the temperature dependence of weathering itself.

Higher activation energies are more appropriate because most carbonic acid absorbed by continental weathering is consumed not by weathering of feldspars but by calcium and magnesium silicates (Berner and Berner, 1987), which are typically less abundant but more readily and quickly weathered than feldspars and which have significantly higher experimentally determined activation energies than do feldspars (Brady, 1991). Activation energies approaching 20 kcal/mol (84 kJ/mol) may significantly reduce model global mean temperatures and atmospheric CO₂ (Brady, 1991). The natural activation energy for feldspar weathering determined in this study is higher than most experimentally determined values for the same mineral. If natural activation energies of calcium and magnesium silicate weathering are similarly higher than experimental values, the weathering-mediated negative feedback between global temperature and atmospheric CO₂ may be even stronger than previous workers suggest.

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REFERENCES CITED

- Berner, E.K., and Berner, R.A., 1987, *The global water cycle: Geochemistry and environment*: Englewood Cliffs, New Jersey, Prentice-Hall, 397 p.
- Berner, R.A., 1990, Atmospheric carbon dioxide levels over Phanerozoic time: *Science*, v. 249, p. 1382–1386.
- Berner, R.A., 1991, A model of atmospheric CO₂ over Phanerozoic time: *American Journal of Science*, v. 291, p. 339–376.
- Berner, R.A., 1993, Paleozoic atmospheric CO₂: Importance of solar radiation and plant evolution: *Science*, v. 261, p. 68–70.
- Berner, R.A., and Barron, E.J., 1984, Factors affecting atmospheric CO₂ and temperature over the past 100 million years: *American Journal of Science*, v. 284, p. 1183–1192.
- Berner, R.A., Lasaga, A.C., and Garrels, R.M., 1983, The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years: *American Journal of Science*, v. 283, p. 641–683.
- Brady, P.V., 1991, The effect of silicate weathering on global temperature and atmospheric CO₂: *Journal of Geophysical Research*, v. 96, p. 18,101–18,106.
- Burch, T.E., Nagy, K.L., and Lasaga, A.C., 1993, Free energy dependence of albite dissolution kinetics at 80°C and pH 8.8: *Chemical Geology*, v. 105, p. 137–162.
- Ciamponi, M.A., McVey, D.E., Gerke, T.L., Briggs, W.D., Zhang, Y., Maynard, J.B., and Huff, W.D., 1992, Non-systematic weathering profile in the Blue Ridge Mountains, N.C.: Role of geochemical variables: *Geological Society of America Abstracts with Programs*, v. 24, no. 7, p. 214.
- Drever, J.I., and Zobrist, J., 1992, Chemical weathering of silicate rocks as a function of elevation in the southern Swiss Alps: *Geochimica et Cosmochimica Acta*, v. 56, p. 3209–3216.
- Grantham, J.H., and Velbel, M.A., 1988, Influence of climate and topogra-

- phy on rock fragment abundance in modern fluvial sands of the southern Blue Ridge Mountains, North Carolina: *Journal of Sedimentary Petrology*, v. 58, p. 219–227.
- Hatcher, R.D., Jr., 1979, The Coweeta Group and Coweeta syncline: Major features of the North Carolina–Georgia Blue Ridge: *Southeastern Geology*, v. 21, p. 17–29.
- Hatcher, R.D., Jr., 1980, Geologic map and mineral resources summary of the Prentiss quadrangle, North Carolina, including geologic map of Coweeta Laboratory: North Carolina Department of Natural Resources and Community Development, Geological Survey Section, GM-167-SW and MRS 167-SW, scale 1:14,000.
- Hatcher, R.D., 1988, Bedrock geology and regional setting of Coweeta Hydrologic Laboratory in the eastern Blue Ridge, in Swank, W.T., and Crossley, D.A., Jr., eds., *Forest hydrology and ecology at Coweeta*: New York, Springer-Verlag, p. 81–92.
- Hewlett, J.D., 1961, Soil moisture as a source of base flow from steep mountain watersheds: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station Paper 132, 11 p.
- Hewlett, J.D., and Hibbert, A.R., 1963, Moisture and energy conditions within a sloping soil mass during drainage: *Journal of Geophysical Research*, v. 68, p. 1080–1087.
- Knauss, K.G., and Wolery, T.J., 1986, Dependence of albite dissolution kinetics on pH and time at 25°C and 70°C: *Geochimica et Cosmochimica Acta*, v. 50, p. 2481–2497.
- Lagache, M., 1965, Contribution à l'étude de l'altération des feldspaths, dans l'eau, entre 100 et 200°C, sous diverses pressions de CO₂, et application à la synthèse des minéraux argileux: *Société Française de Minéralogie et de Cristallographie, Bulletin*, v. 88, p. 223–253.
- Lagache, M., 1976, New data on the kinetics of the dissolution of alkali feldspars at 200°C in CO₂ charged waters: *Geochimica et Cosmochimica Acta*, v. 40, p. 157–161.
- Macfie, T.G., 1991, Estimating mean daily soil temperatures using sparse regional long-term air temperature data to assess periods of biologically active reducing conditions [M.S. thesis]: Ithaca, New York, Cornell University, 222 p.
- Meybeck, M., 1979, Concentrations des eaux fluviales en éléments majeurs et apports en solution aux océans: *Revue Géologie Dynamique et Géographie Physique*, v. 21, p. 215–246.
- Meyer, H.W., 1992, Lapse rates and other variables applied to estimating paleoaltitudes from fossil floras: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 99, p. 71–99.
- Pačes, T., 1983, Rate constants of dissolution derived from the measurements of mass balance in hydrological catchments: *Geochimica et Cosmochimica Acta*, v. 47, p. 1855–1863.
- Soil Survey Staff, 1975, *Soil taxonomy—A basic system of soil classification for making and interpreting soil surveys*: U.S. Department of Agriculture, *Agricultural Handbook*, 753 p.
- Sverdrup, H., 1990, The kinetics of base cation release due to chemical weathering: Lund, Sweden, Lund University Press, 246 p.
- Swank, W.T., and Crossley, D.A., Jr., 1988, Introduction and site description, in Swank, W.T., and Crossley, D.A., Jr., eds., *Forest hydrology and ecology at Coweeta*: New York, Springer-Verlag, p. 3–16.
- Swank, W.T., and Waide, J.B., 1988, Characterization of baseline precipitation and stream chemistry and nutrient budgets for control watersheds, in Swank, W.T., and Crossley, D.A., Jr., eds., *Forest hydrology and ecology at Coweeta*: New York, Springer-Verlag, p. 57–79.
- Swift, L.W., Jr., Cunningham, G.B., and Douglass, J.E., 1988, *Climatology and hydrology*, in Swank, W.T., and Crossley, D.A., Jr., eds., *Forest hydrology and ecology at Coweeta*: New York, Springer-Verlag, p. 35–55.
- Taylor, A.B., and Velbel, M.A., 1991, Geochemical mass balance and weathering rates in forested watersheds of the southern Blue Ridge. II. Effects of botanical uptake terms: *Geoderma*, v. 51, p. 29–50.
- Velbel, M.A., 1985a, Geochemical mass balances and weathering rates in forested watersheds of the southern Blue Ridge: *American Journal of Science*, v. 285, p. 904–930.
- Velbel, M.A., 1985b, Hydrogeochemical constraints on mass balances in forested watersheds of the southern Appalachians, in Drever, J.I., ed., *The chemistry of weathering*: Dordrecht, Netherlands, D. Reidel, p. 231–247.
- Velbel, M.A., 1986, Influence of surface area, surface characteristics, and solution composition on feldspar weathering rates, in Davis, J.A., and Hayes, K.F., eds., *Geochemical processes at mineral surfaces*: American Chemical Society Symposium Series, No. 323, p. 615–634.
- Velbel, M.A., 1989, Effect of chemical affinity on feldspar hydrolysis rates in two natural weathering systems: *Chemical Geology*, v. 78, p. 245–253.
- Velbel, M.A., 1990a, Mechanisms of saprolytization, isovolumetric weathering, and pseudomorphous replacement during rock weathering—A review: *Chemical Geology*, v. 84, p. 17–18.
- Velbel, M.A., 1990b, Influence of temperature and mineral surface characteristics on feldspar weathering rates in natural and artificial systems: A first approximation: *Water Resources Research*, v. 26, p. 3049–3053.
- Velbel, M.A., 1992, Geochemical mass balances and weathering rates in forested watersheds of the southern Blue Ridge, III. Cation budgets and the weathering rate of amphibole: *American Journal of Science*, v. 292, p. 58–78.
- Walker, J.C.G., Hays, P.B., and Kasting, J.F., 1981, A negative feedback mechanism for the long-term stabilization of Earth's surface temperature: *Journal of Geophysical Research*, v. 86, p. 9776–9782.
- Walther, J.V., and Wood, B.J., 1986, Mineral-fluid reaction rates, in Walther, J.V., and Wood, B.J., eds., *Fluid-rock interactions during metamorphism*: Berlin, Springer-Verlag, p. 194–211.
- Wood, B.J., and Walther, J.V., 1983, Rates of hydrothermal reactions: *Science*, v. 222, p. 413–415.

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Reviewer's Comment

Important for determining local and global weathering rates.

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