

## Geology

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*Geology* 1997;25;955-956

doi: 10.1130/0091-7613(1997)025<0955:TNFMBA>2.3.CO;2

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#### Notes



# OPINION

## The need for mass balance and feedback in the geochemical carbon cycle

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### INTRODUCTION

On a multimillion-year time scale, the level of atmospheric carbon dioxide, and consequently the atmospheric greenhouse effect, is affected largely by the geochemical, or long-term, carbon cycle. This cycle (for a review, see Holland, 1978; Berner, 1991) involves the exchange of carbon dioxide between rocks, on the one hand, and the surficial reservoir, consisting of the combined atmosphere, oceans, biosphere, plus soils, on the other. Carbon dioxide is exchanged with the surficial system via weathering of silicates and organic matter on the continents, the burial of carbonates (derived from silicate weathering) and organic matter in sediments, and the thermal breakdown of carbonates and organic matter at depth.

It has been suggested (Edmond et al., 1995; see also Edmond and Huh, 1997; Bickle, 1996) that in the geochemical carbon cycle there is no necessity for a close balance between atmospheric inputs and outputs of  $\text{CO}_2$ , and therefore no need for a strongly coupled feedback to stabilize  $\text{CO}_2$  level in the atmosphere. On the basis of their study of the chemistry of major rivers, Edmond et al. (1995) concluded that climate has little effect on global weathering rate and criticized the idea that long-term stabilization of  $\text{CO}_2$  and climate comes about by increased chemical weathering rate that accompanies global greenhouse warming. In place of a climate-weathering feedback, Edmond et al. (1995) and Bickle (1996) assumed that increases in global degassing are eventually matched by increases in  $\text{CO}_2$  uptake via enhanced weathering accompanying mountain uplift. We show here that in this case, atmospheric  $\text{CO}_2$  would vary untenably as a result of large imbalances in the carbon cycle.

### CARBON MASS BALANCE

The combined surficial atmosphere-ocean-biosphere-soil reservoir (about  $3 \times 10^{18}$  mol C) is small compared to that of the rock reservoir (about  $5000 \times 10^{18}$  mol carbonate C plus  $1300 \times 10^{18}$  mol of organic C; Berner et al., 1983). Appreciable carbon cannot be stored in the surficial system. The atmosphere cannot have stored too much  $\text{CO}_2$ , or greenhouse warming would have become excessive in the past and higher life would have perished. The oceans cannot have stored large amounts of dissolved carbon because (1) the existence of marine limestones over geologic time precludes the storage of high concentrations of dissolved  $\text{CO}_2$ , and therefore high acidity, in seawater, and (2) accumulation of high concentrations of dissolved  $\text{HCO}_3^-$  in the oceans, derived from continental weathering, would lead to supersaturation with carbonate minerals and the removal of the carbon to the sediments via precipitation, with or without biological mediation. The biosphere is limited in size by the carrying capacity of the land and sea.

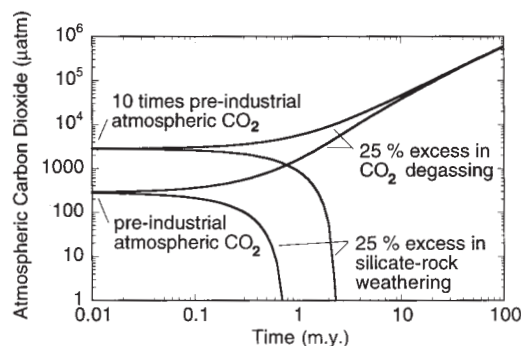
Integrated over millions of years, the fluxes of  $\text{CO}_2$  via degassing and silicate weathering, along with organic matter weathering and burial, are very large compared to the mass of carbon at the surface of the Earth. If appreciable carbon cannot be stored in the surficial system, there must be a close balance over millions of years between the total input and output fluxes from the rock reservoirs (Holland, 1978). Simple calculations show that this balance must be very close; the consequences of a 25% imbalance on atmospheric  $\text{CO}_2$  is shown in Figure 1. This calculation assumes: (1) the

approximate present-day uptake of  $\text{CO}_2$  by Ca and Mg silicate weathering is about  $8 \times 10^{18}$  mol C per million years; (2)  $\text{CO}_2$  gas solubility equilibrium and sediment calcium carbonate dissolution and/or precipitation to equilibrium are maintained in a simple one box ocean; (3) there is no other operative feedback mechanism to remove excess  $\text{CO}_2$ ; and (4) the organic carbon subcycle is balanced for the purposes of discussion. As shown by the figure, if degassing were to differ from weathering by only 25%, after millions of years levels of  $\text{CO}_2$  would become excessively high or low, inimitable to life, and far out of line with estimates of paleo- $\text{CO}_2$  over Phanerozoic time using a variety of techniques (for a recent compilation, see Berner, 1997). These calculations indicate that any appreciable imbalance between  $\text{CO}_2$  input to and outputs from the surficial system over millions of years (e.g., Edmond et al., 1995; Bickle, 1996) is untenable.

### NEGATIVE FEEDBACK

In order to maintain a close balance between atmospheric  $\text{CO}_2$  inputs and outputs, it is necessary that some sort of rapidly acting restorative mechanism be operative. Somehow, a rise in atmospheric  $\text{CO}_2$  must put into play a counteractive process or processes that would work against this rise. A number of mechanisms could accomplish the countereffect, but true negative feedback processes must functionally depend on the level of atmospheric  $\text{CO}_2$ . Processes independent of atmospheric  $\text{CO}_2$  would not be expected to prevent excessive fluctuations in atmospheric  $\text{CO}_2$ . For example, an increase in volcanic degassing would not be expected to be perfectly balanced, to a sufficient degree and within a sufficiently short period, by enhanced weathering due to mountain uplift to prevent excessive variations in  $\text{CO}_2$ .

The most commonly accepted process for providing rapid negative feedback, which also exhibits explicit functional dependence on atmospheric  $\text{CO}_2$ , is the response of silicate weathering to changes in climate (e.g., Walker et al., 1981; Berner et al., 1983). The key to this feedback is the atmospheric greenhouse effect. Simply stated, the idea is that high global temperatures and especially greater rainfall on continents, caused by higher  $\text{CO}_2$ , should bring about enhanced  $\text{CO}_2$  removal via faster silicate weathering.



**Figure 1.** Effect on atmospheric  $\text{CO}_2$  of 25% imbalance in  $\text{CO}_2$  degassing and silicate-rock weathering starting from two initial atmospheric  $\text{CO}_2$  contents (280  $\mu\text{atm}$  and 2800  $\mu\text{atm}$ ), assuming balanced organic carbon subcycle. Excess in  $\text{CO}_2$  degassing of 25% would increase atmospheric  $\text{CO}_2$  beyond reasonable Phanerozoic bounds within 10 m.y., and 25% excess in silicate-rock weathering would deplete nearly all atmospheric  $\text{CO}_2$  within a few million years. Excess of 2.5% would have same effect in 10 times as much time. This indicates that total  $\text{CO}_2$  inputs and output to and from the atmosphere have been closely balanced throughout Phanerozoic.

Atmospheric general circulation models indicate that enhanced atmospheric CO<sub>2</sub> content leads to warmer temperatures, increased precipitation, and increased runoff (e.g., Manabe and Stouffer, 1993). Studies of silicate weathering where other factors such as lithology are held constant (e.g., White and Blum, 1995) show that warmer temperatures, greater precipitation, and greater runoff lead to increased silicate rock weathering. Chemical calculations show that enhanced silicate rock weathering leads to diminished atmospheric CO<sub>2</sub> content. Together, these relations produce a negative feedback that stabilizes atmospheric CO<sub>2</sub>. With this feedback, possibly combined with others, atmospheric CO<sub>2</sub> content adjusts until a climate is produced in which CO<sub>2</sub> consumed in silicate weathering and organic matter burial balances the CO<sub>2</sub> supplied from organic matter weathering plus degassing from volcanism, metamorphism, and diagenesis.

Edmond et al. (1995) stated that nonclimatic factors, principally relief, but also lithology, explain most of the observed variance in chemical weathering between river basins. This contrasts with many other studies (e.g., Jenny, 1941; Loughnan, 1969; White and Blum, 1995; Amiotte Suchet and Probst, 1995; see also Berner and Berner, 1997) that show that climate, especially rainfall, is important in silicate weathering. Even if Edmond et al. (1995) are correct, it would be erroneous to conclude that any particular river basin of constant relief and lithology (or the continents as a whole) would not undergo increased weathering as a result of greater rainfall and higher temperatures due to global greenhouse warming.

Factors that enhance the ease by which silicate rocks are weathered ("weatherability"), such as mountain uplift or the evolution of land plants, might cool climate but do not simply bring about change in the long-term global silicate rock weathering rate. In this case, CO<sub>2</sub> would be removed from the atmosphere until the global reduction in weathering, due to a cooler and drier climate, was balanced by the increase in weathering due to increased weatherability. The time to reach the new steady state should be less than a million years (Sundquist, 1991). Thus, on a million-year time scale, chemical weathering rates are controlled by the rate of CO<sub>2</sub> supply to the surficial system.

## CONCLUSIONS

1. Inputs and outputs of carbon to and from the surficial system, consisting of the oceans, atmosphere, soils, and biosphere, are closely balanced over million-year time scales.

2. A negative feedback that is functionally related to atmospheric CO<sub>2</sub> content is required to maintain this close balance.

3. The response of silicate weathering to changes in climate is sufficient to provide this negative feedback.

4. Long-term global weathering rates are controlled by the rate of CO<sub>2</sub> supply to the surficial system (and imbalances in the organic carbon cycle).

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