

culations indicate that seafloor basalt weathering rates, near the pH of sea water, should be very insensitive to changes in atmospheric CO<sub>2</sub>, precluding this process as an important CO<sub>2</sub> feedback mechanism<sup>16</sup>. Hence, in the Raymo and Ruddiman model, atmospheric CO<sub>2</sub> could vary widely because the CO<sub>2</sub> concentration is not fixed by a set of feedbacks.

A more inclusive model for the evolution of atmospheric CO<sub>2</sub> should attempt to consider quantitatively all major processes affecting the carbon cycle, including the role of plant evolution as it affects weathering<sup>17</sup>, changes in the position of continents relative to climate zones<sup>18</sup>, the importance of marine versus terrestrial burial of organic matter<sup>19</sup>, the transfer of carbonate from the shelves to the deep sea<sup>20</sup>, the effect of uplift on weathering<sup>1</sup> and so on. These factors are already considered in a preliminary manner in an existing model<sup>7</sup>.

Raymo and Ruddiman have drawn attention to one potentially important factor in long-term climate change. Still, there is no need to propose a dichotomy between tectonic uplift and CO<sub>2</sub> degassing, because no one factor can explain atmospheric CO<sub>2</sub> changes over all time. Significant changes could well result from a simultaneous combination of any number of forcing factors.

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unweathered rock; uplift induced precipitation and runoff). Likewise, proxy records<sup>21,25-28</sup> indicate an increase in global chemical weathering rates over the past 100 Myr, a time of global cooling.

Both Volk and Caldeira *et al.* regard our challenge to the earlier view of chemical weathering as "conceptual" in nature, and Volk states that our views should be held up to the quantitative scrutiny that more detailed ("matter-conserving") models can provide. But their criticisms miss a key point implicit in our paper. Such models can only be used for verification if their key parameterizations and assumptions are sound. Matter-conserving numerical models supporting our view have been built<sup>22,29</sup>. We do not consider the fact that these models work to be "an essential test" of our hypothesis. Rather, a numerical model has been constructed which provides fewer conflicts with existing geological data (the true test).

A second key issue is the need for carbon fluxes sensitive to CO<sub>2</sub> levels and/or climate to provide a negative feedback that avoids a runaway 'ice-house' or 'greenhouse'. Instead of the temperature-weathering feedback, we point to the likelihood of carbon fluxes from other components of the global carbon cycle, such as the organic carbon subcycle<sup>1</sup>, basalt weathering<sup>22</sup>, or some place as yet unforeseen, playing such a role. Contrary to the specific criticisms of Volk and Caldeira *et al.*, small variations in the fraction of carbon buried as organic matter versus carbonate (from ~25 to ~20%) can provide enough CO<sub>2</sub> to balance a 40% increase in the chemical weathering of silicates, carbonates and organic-rich rocks. To oxidize this much carbon would require oxygen levels within ~10% of Berner's own

estimates of Eocene O<sub>2</sub> levels<sup>30</sup>. With the exception of a small downturn over the past 10 Myr, sulphur isotopes have been increasing for the past 100 Myr (refs 9, 10, 31) making this postulated oxygen consumption even less of a problem. To attribute the bulk carbonate δ<sup>13</sup>C data of Shackleton to changing photosynthetic fractionation factors would require a decrease much larger than suggested by data (>10‰ over 20 Myr, compared to 5-7‰ change observed over the past 100 Myr; refs 32, 33). And, contrary to the statement of Caldeira *et al.* we did reference previous attempts to model the organic carbon cycle (including refs 5, 7) and attributed our divergence of opinion to the use of different assumptions and data sets (see ref. 34 versus ref. 8).

The Walker and Berner carbon-cycle models revolutionized our thinking of long-term climate evolution and the global carbon cycle. However, mounting evidence suggests a world more complicated than this generation of models would imply. We are sure that our critics would agree that science advances by close scrutiny of both models and data. In this case, we believe sufficient modern (and palaeo) data exist to raise serious questions about the chemical weathering parameterization of the BLAG model (and similar models) of long-term climate change.

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RAYMO AND RUDDIMAN REPLY — The "dichotomy" we really present is between carbon cycle models assuming a positive dependence of silicate and carbonate weathering rates on atmospheric CO<sub>2</sub> and temperature<sup>2-5,7</sup> and those that do not<sup>1,21,22</sup>. In all BLAG-type models, including Berner's<sup>7</sup>, chemical weathering rates decrease as global temperatures fall (and vice versa). This is the result of a dimensionless feedback function included in these models. Viewed in isolation from other factors, this temperature-weathering feedback is of course correct. But we have suggested that an entirely different factor (tectonic uplift) is a more important control of chemical weathering in the real world. Modern river studies<sup>23,24</sup> support our view that chemical weathering is highly sensitive to uplift-related factors (exposure of folded, faulted, and largely

1. Raymo, M. E. & Ruddiman, W. F. *Nature* **359**, 117-122 (1992).
2. Walker, J. C. G., Hays, P. B. & Kasting, J. F. *J. geophys. Res.* **86**, 9976-9782 (1981).
3. Berner, R. A., Lasaga, A. C. & Garreis, R. M. *Am. J. Sci.* **283**, 641-683 (1983).
4. Garrels, R. M. & Lerman, A. *Am. J. Sci.* **284**, 989-1007 (1984).
5. Lasaga, A. C., Berner, R. A. & Garrels, R. M. in *The Carbon Cycle and Atmospheric CO<sub>2</sub>: Natural Variation Archean to Present* (eds Sundquist, E. T. & Broecker, W. S.) 397-410 (Am. Geophys. Un., Washington DC, 1985).
6. Kump, L. R. & Garreis, R. M. *Am. J. Sci.* **286**, 337-360 (1986).
7. Berner, R. A. *Am. J. Sci.* **291**, 339-376 (1991).
8. Shackleton, N. K. in *Marine Petroleum Source Rocks* (eds Brooks, J. & Fleet, A. J.) 423-434 (Geol. Soc. London, 1987).
9. Burdett, J. W., Arthur, M. A. & Richardson, M. *Earth planet. Sci. Lett.* **94**, 189-198 (1989).
10. Claypool, G. E., Holser, W. T., Kaplan, I. R., Sakai, H. & Zak, I. *Chem. Geol.* **28**, 199-260 (1980).
11. Arthur, M. A., Dean, W. A. & Claypool, G. F. *Nature* **315**, 216-218 (1985).
12. Kump, L. R. *Am. J. Sci.* **289**, 390-410 (1989).
13. Palmer, M. R. & Edmond, J. M. *Geochim. cosmochim. Acta* **56**, 2099-2111 (1992).
14. Broecker, W. S. & Peng, T. H. *Tracers in the Sea* (Eldigio, Palisades, New York, 1982).
15. Kastner, M. in *The Sea 7* (ed. Emiliani, C.) 915-980 (Wiley, New York, 1981).
16. Caldeira, K. *Am. J. Sci.* (in the press).

17. Volk, T. *Geology* **17**, 107-110 (1989).
18. Tardy, Y., Roger, N. K., Probst, J. D. *Am. J. Sci.* **289**, 455-483 (1989).
19. Kump, L. R. *Nature* **335**, 152-154 (1988).
20. Caldeira, K. *Nature* **357**, 578-591 (1992).
21. Raymo, M. E., Ruddiman, W. F. & Froelich, P. N. *Geology* **16**, 649-653 (1988).
22. François, L. M. & Walker, J. C. G. *Am. J. Sci.* **292**, 81-135 (1992).
23. Gibbs, R. J. *Science* **156**, 1734-1737 (1967).
24. Stallard, R. F. in *Physical and Chemical Weathering in Geochemical Cycles* (eds Lerman, A. & Meybeck, M.) 225-246 (Kluwer, Dordrecht, 1988).
25. Shemesh, A., Mortlock, R. A. & Froelich, P. N. *Paleoceanography* **4**, 221-234 (1989).
26. Richter, F. M., Rowley, D. B. & DePaolo, D. J. *Earth planet. Sci. Lett.* **109**, 11-23 (1992).
27. Hodell, D. A., Mead, G. A. & Mueller, P. A. *Chem. Geol. (Isotop. Geosci. Sec.)* **80**, 291-307 (1990).
28. Krishnaswami, S., Trivedi, J. R., Sarin, M. M., Ramesh, R. & Sharma, K. K. *Earth planet. Sci. Lett.* **109**, 243-253 (1992).
29. François, L. M., Walker, J. C. G. & Opdyke, B. AGU-IUGG Spec. Vol. (in the press).
30. Berner, R. & Canfield, D. *Am. J. Sci.* **289**, 333-361 (1989).
31. Lasaga, A. C. *Am. J. Sci.* **289**, 411-435 (1989).
32. Arthur, M. A., Dean, W. E. & Claypool, G. E. *Nature* **315**, 216-218 (1985).
33. Popp, B. N., Takigiku, R., Hayes, J. M., Louda, J. W. & Baker, E. W. *Am. J. Sci.* **289**, 436-454 (1989).
34. Lindh, T. B. thesis (Univ. Miami, 1983).