BOOK REVIEW

The Phanerozoic Carbon Cycle: CO_2 and O_2; by ROBERT A. BERNER, New York, Oxford University Press, 2004, 158 pages, $99.50.—A major focus of modern Earth science research has come to be upon the subject of this book by Robert Berner of Yale University. That much remains to be understood of the inner workings of the carbon cycle is made abundantly clear by the fact that, even 20 years after its discovery, the co-variation of the concentration of atmospheric CO_2 with the volume of continental ice through the series of intense glacial cycles of the late Pleistocene Epoch (~ last 2 million years) of Earth history remains unexplained. The focus of this book, however, is upon timescales much longer than the 100,000 year period that was characteristic of this orbitally induced cycle of glaciation and deglaciation. On the longer timescales of millions to hundreds of millions of years through the Phanerozoic Eon (0 – 540 Ma) to which Berner restricts his attention, his inference of the evolution of atmospheric CO_2 is based upon the assumption that the carbon cycle has operated in a quasi-equilibrium mode. The validity of this assumption has recently been demonstrated for the Cenozoic Era of Phanerozoic time (0 – 60 Ma) and for a portion of the Ediacaran period of the late Precambrian (540 – 550 Ma) by Rothman and others (2003). Berner's predictions of the evolution of CO_2 concentration over the entire Phanerozoic Eon, as represented by the GEOCARB III model (Berner and Kothavala, 2001) and more recently in the refined GEOCARBSULF model of the variation of both O_2 and CO_2 over this interval (Berner and Kothavala, 2001; Berner, 2006) have recently been subjected to further tests by employing appropriately simple models of surface climate to determine whether his predicted levels of CO_2, for specific epochs, for which paleo-temperature reconstructions are available, are compatible with these inferences (see for example, Hyde and others, 2006). These tests have led to the general conclusion that, for the Phanerozoic intervals tested, the Berner inferences based upon the steady-state assumption are reasonably well justified.

Given that such tests have yet to contradict the primary assumption that underpins his methodology, Berner's concise book on this important topic deserves our serious attention. This is especially true as the book does provide a clear account of this methodology as well as detailed discussion of the data he has employed and the cross-checks performed to test the predictions of his models against a range of independent constraints. Beginning by distinguishing between what he refers to as the "short term" and "long term" carbon cycles in Chapter 1, where the assumption of quasi-equilibrium that forms the basis of his methodology is stated, the book continues in 4 brief chapters to address the main inputs that are required to produce a Phanerozoic CO_2 reconstruction. The process of continental chemical weathering of calcium-magnesium silicates that controls the rate of draw-down of atmospheric CO_2 by the oceans on long timescales is addressed in Chapter 2; the processes involved in the burial on the ocean floor of organic matter and carbonate are discussed in Chapter 3, and finally the processes involved in the degassing of CO_2 and CH_4 from the Earth's interior into the atmosphere and oceans are discussed in Chapter 4. The 5th chapter of the book summarizes Berner's results for atmospheric CO_2 variations through the Phanerozoic by discussing the GEOCARB III model, a result that has been updated recently with the publication of GEOCARBSULF. The final chapter of the book presents an initial companion result for Phanerozoic O_2 based primarily upon the constraints available from the sulfur isotope system. The primary result for O_2 is the suggestion of a significant maximum in atmospheric O_2 concentration during the Carboniferous period which Berner suggests could have been responsible for the development of insect gigantism and enhanced forest burning and thus charcoal production.

The quasi-equilibrium methodology that the author has developed to perform such reconstructions is one that relies upon the representation of each of the processes that contributes to the addition (removal) of CO_2 to (from) the atmosphere in terms of a time-dependent strength that is inferred on the basis of related geological information. For example, the abundance of siliclastic rocks over the Phanerozoic, based upon the work of the Russian author Ronov, is employed to estimate the variation in the rate of continental erosion required in the prediction of the impact of CO_2 removal from the atmosphere through the action of weathering and marine carbonate sedimentation. Berner represents the action of the many such factors involved in his reconstruction by assigning time dependent factors "f(t)" to each of them. His method then consists of assuming an initial CO_2 concentration at the beginning of Phanerozoic time ($\sim$ 542 Ma, the beginning of the Cambrian epoch) and running the model forward to the present. He then varies the initial CO_2 concentration until he "hits" the present day (pre-industrial) target of 280 ppmv. The primary feature of the final model is that the CO_2 concentration should have been very nearly equal to modern during the Carboniferous period but considerably higher before and somewhat higher after, before falling to the modern level. That his result for the critical Carboniferous interval must be very nearly correct was shown some years ago through the use of a climate model to predict the extent of the glaciation of the super-continent of Pangaea that is well known to have occurred in that interval of time (Hyde and others, 1999).

Berner's results for the Phanerozoic Eon are especially important in highlighting what appears to be the fundamental difference between this period and the Neoproterozoic Era that preceded it. During the latter interval evidence has been presented recently that the carbon cycle was manifestly non-steady state at this time (Rothman and others, 2003). It must therefore be seen as extremely prescient that Berner has elected to apply his equilibrium based methodology only from the onset of the so-called "Cambrian explosion of life" and not to the earlier interval. Since the Neoproterozoic is known to have been a time during which extremely severe glaciations occurred, the Sturtian and Marinoan events, rather radical conjectures have been forthcoming (the "Snowball Earth" hypothesis) to explain the events of this period. This hypothesis is one in which it is envisioned that the entire surface of the planet was glaciated, with the continents covered by thick ice-sheets and the oceans by a thick veneer of sea-ice. Escape is imagined to have occurred through the continuing action of one of Berner's mechanisms, namely volcanic outgassing of CO_2. In this view, Neoproterozoic glaciations are imagined to occur as a consequence of aberrant behavior of the physical climate system. It may well be, however, that the dramatic Neoproterozoic $\delta^{13}C$ fluctuations that the snowball hypothesis is intended to explain are due to non-steady state behavior of the carbon cycle itself. Understanding such behavior will require the development of a much more elaborate model than that which Berner has employed in his interesting attack on the Phanerozoic Eon. The last million years of the Pleistocene Epoch may be similarly complex, with an appropriate dynamic model of the carbon cycle being required to finally explain the enigma posed by the co-variation of continental ice-volume and atmospheric CO_2 concentration.

In summary, Professor Berner's book is an important addition to the burgeoning literature on all aspects of Earth's carbon cycle.

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