# Comment on "Atmospheric $P_{CO_2}$ Perturbations Associated with the Central Atlantic Magmatic Province"

Michael R. Rampino[1,2]* and Ken Caldeira[3]

Schaller *et al.* (Research Article, 18 March 2011, p. 1404) proposed that carbon dioxide ($CO_2$) released by the Central Atlantic Magmatic Province eruptions over periods of about 20,000 years led to substantial increases of up to 2000 parts per million (ppm) in the concentration of atmospheric carbon dioxide ($P_{CO_2}$) near the Triassic-Jurassic boundary. Use of an atmosphere-ocean model coupled to a carbon-cycle model predicts $P_{CO_2}$ increases of less than 400 ppm from magmatic volatiles, with only a small climatic impact.

Schaller *et al.* (*1*) proposed that large amounts of $CO_2$ released by the Central Atlantic Magmatic Province (CAMP) ($2.6 \times 10^6$ km$^3$ of magma) eruptions contributed to substantial increases in atmospheric $CO_2$ near the Triassic-Jurassic boundary. With an estimated volcanic efflux of $1.4 \times 10^{10}$ kg of $CO_2$ per km$^3$ of basaltic magma (*2*), the total $CO_2$ release for the CAMP basalts is about $3.4 \times 10^{16}$ kg of $CO_2$. There are three lava flow events in the Newark and Hartford Basins (*1*), so that each of the three lava flows could represent an erupted volume about $0.8 \times 10^6$ km of magma releasing $1.1 \times 10^{16}$ kg $CO_2$. Schaller *et al.* (*1*) estimate that the release of this much $CO_2$ over a period of ~20 thousand years (ky) (the resolution of orbital precession) would directly increase atmospheric partial pressure of $CO_2$ ($P_{CO_2}$) by ~1400 parts per million (ppm) from a base of about 2000 ppm (using a conversion factor of $7.82 \times 10^{12}$ kg of $CO_2$ per ppm $CO_2$). This is less than a doubling of $P_{CO_2}$ and hence a global climatic warming estimated as less than ~3°C (*3*).

An eruption rate producing $0.8 \times 10^6$ km$^3$ of basaltic magma in only 20 ky would be much greater than the commonly inferred $10^5$- to $10^6$-year duration for flood basalt volcanism (*4*, *5*). However, if one scales up from the eruption of Laki in 1783, which produced 12 km$^3$ of basaltic lava over about 2 months (*2*) at a rate of $4 \times 10^3$ m$^3$ s$^{-1}$ (or $1.1 \times 10^7$ kg s$^{-1}$), then it would be possible to produce ~$10^6$ km$^3$ of lava in about 20 ky of semicontinuous eruption.

The time over which the magma is erupted affects the amount of $CO_2$ that stays in the atmosphere. We used an ocean-atmosphere box model coupled to a carbon-cycle model (*6*, *7*) to simulate increases in $P_{CO_2}$ resulting from the CAMP eruptions for two cases: an unrealistic instantaneous release, and release over a period of 20 ky (Fig. 1). Instantaneous release of $10^{16}$ kg of $CO_2$ results in an increase of $P_{CO_2}$ of about 1300 ppm over a high early Jurassic background of about 2000 ppm, similar to results of Schaller *et al.* (*1*). If the release is accomplished over a substantial time period, then one must take into account uptake of $CO_2$ by the oceans, and if long enough, interactions with the solid earth through rock weathering. When released over 20 ky, the increase results in a peak $P_{CO_2}$ value of only about 400 ppm over early Jurassic background (Fig. 1). Thus, magmatic $CO_2$ release alone, even for eruptions producing a million cubic kilometers in periods as short as 20 ky, is probably not sufficient to cause major climatic changes and mass extinction (Fig. 1).

Schaller *et al.* (*1*) estimated $P_{CO_2}$ up to 4000 to 5000 ppm after CAMP eruptions based on pedogenic carbonates. Palaeobotanical evidence suggests that $P_{CO_2}$ may have increased by a factor of four across the Triassic-Jurassic boundary (*8*), and palynological studies have been interpreted as indicating an atmospheric $P_{CO_2}$ at least 10 times present levels, with temperatures rising by about 10°C (*9*). If these estimates are correct, then an additional source of $CO_2$ from interactions between CAMP magma and country rock (*10*) or release of marine hydrate deposits (*11*) seems to be required to explain the evidence for very high early Jurassic $P_{CO_2}$ at the time of the CAMP eruptions.

[1]Department of Biology and Environmental Studies Program, New York University, 100 Washington Square East, New York NY 10003, USA. [2]NASA, Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA. [3]Department of Global Ecology, Carnegie Institution, 260 Panama Street, Stanford. CA 24305, USA.

*To whom correspondence should be addressed. E-mail: mrr1@nyu.edu

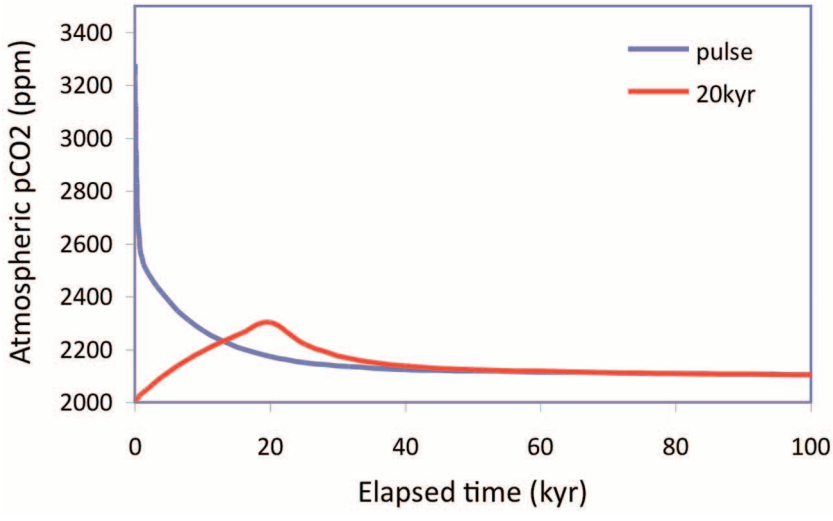


**Fig. 1.** Increase in atmospheric $P_{CO_2}$ caused by magmatic volatiles from CAMP eruption of $10^{16}$ kg of $CO_2$ added to the atmosphere instantaneously (blue line) and over 20 ky (red line).

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# Response to Comment on "Atmospheric $P_{CO_2}$ Perturbations Associated with the Central Atlantic Magmatic Province"

Morgan F. Schaller,[1]* James D. Wright,[1] Dennis V. Kent[1,2]

Rampino and Caldeira argue that the first pulse of the Central Atlantic Magmatic Province would increase the concentration of atmospheric carbon dioxide ($P_{CO_2}$) by only 400 parts per million if erupted over 20,000 years, whereas we observed a doubling within this interval. In the absence of any data to the contrary, we suggest that a more rapid (≤1000-year) eruption is sufficient to explain this observation without relying on thermogenic degassing.

Our observations from the Newark Basin indicate that the first pulse of the Triassic-Jurassic Central Atlantic Magmatic Province (CAMP), represented by the Orange Mountain Basalt, was emplaced within a precession cycle and resulted in a doubling of the atmospheric partial pressure of $CO_2$ ($P_{CO_2}$) above pre-eruptive background levels. A simple model with instantaneous degassing [<1 thousand years (ky), within the time scale of ocean overturning] of $2.5 \times 10^{17}$ moles of $CO_2$ (~$1.2 \times 10^{16}$ kg), roughly the efflux potential of the first volcanic pulse, gives a ~1400 parts per million (ppm) increase in $P_{CO_2}$ above the ~2000-ppm background level (*1*). This estimate is compatible with and (admittedly, barely) within the error of the doubling from ~2000 to 4400 ± 1200 ppm observed in the Newark Basin. Rampino and Caldeira (*2*) present a model whereby a 20-ky release of the same magnitude produces only a ~400-ppm atmospheric $P_{CO_2}$ increase, which they take as an indication that an additional source of $CO_2$ is necessary to explain the observed $P_{CO_2}$ increase. We do not dispute this point, but it begs qualification.

The cycle stratigraphic record from the Newark Basin provides a constraint on the maximum duration (<20 ky) of the first pulse of magmatism, but we are not aware of any data (e.g., weathering at the tops of individual lava flows or accumulation of sediments between flows) that preclude a much more rapid release. Therefore, these release-time constraints provide two useful end-member scenarios to explain the observed changes in $P_{CO_2}$: Either the $CO_2$ release was rapid and could be almost exclusively volcanogenic, or it was more protracted, which would require nearly 10 times as much $CO_2$ [e.g., see (*3*, *4*)] [$10^{17}$ moles atmospheric reservoir versus $10^{18}$ moles atmosphere-ocean reservoir (*5*–*8*)], opening the possibility that it may be thermogenic in origin.

Because thermogenic evolution of $CO_2$ from $CaCO_3$ sediments is an unlikely source [e.g., see (*9*)], the next largest reactive carbon pool in Earth's crust is organic, which implies that the extra $CO_2$ needed for a protracted release would be relatively depleted in $^{13}C$. However, the organic carbon $\delta^{13}C$ measurements from the Newark Basin (*1*) do not indicate a substantially larger $^{13}C$-depleted component in the overall atmospheric $P_{CO_2}$ increase, although there is a slight $\delta^{13}C$ decrease (~0.5 per mil) above each volcanic unit. We note that some marine sections record a potential light carbon-isotope excursion at about this time (*10*); however, the exact relationship of the marine $\delta^{13}C$ decrease to the CAMP eruptions remains unclear (e.g., see *11*). Moreover, our observation of comparable $P_{CO_2}$ and $\delta^{13}C$ changes after the second and third volcanic events would require a similar thermogenic input if the duration of each pulse was ~20 ky, which would represent a substantial repeated flux of thermogenic $CO_2$ to the atmosphere at discrete intervals.

Therefore, we are left to speculate on the precise source of the $CO_2$ pulse recorded in the Newark Basin, which is essentially an argument of release duration versus size. In the absence of any data to the contrary, we favor a rapid release that allows the majority of each perturbation to be volcanogenic but that does not preclude a metamorphic carbon source. The doubling of $P_{CO_2}$ observed after each volcanic unit in the Newark Basin is broadly consistent with other lower-resolution studies that indicate a tripling to quadrupling through the interval (*12*–*14*). The continued challenge to the modeling community is to devise a scenario that conforms to these observations.

[1]Earth and Planetary Sciences, Rutgers University, 610 Taylor Road Piscataway, NJ 08854, USA. [2]Lamont-Doherty Earth Observatory of Columbia University, 61 Route 9W, Palisades, NY 10964, USA.

*To whom correspondence should be addressed. E-mail: schaller@rci.rutgers.edu

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