from methane hydrate reservoirs, because CH_4 oxidizes in the atmosphere within 7–24 years to CO_2, which retains a very depleted carbon-isotope composition (typically −60‰, but as low as −110‰ $\delta^{13}C_{org}$)[4]. For example, unusually depleted carbon-isotope values for Early Triassic organic matter can be taken as indications of a methane-dissociation event[5]. An Early Triassic CO_2 greenhouse effect is shown by the very low stomatal index of fossil seed ferns[6], but pedogenic carbonate isotopic palaeobarometers indicate low atmospheric CO_2 levels in the Early Triassic[7]. The pedogenic–isotopic palaeobarometer was not designed for methanogenic isotopic compositions, which compromise this palaeobarometer during several greenhouse transients[6], and perhaps also at the Triassic–Jurassic boundary.

Gregory J. Retallack
Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403-1272, USA
e-mail: gregr@darkwing.uoregon.edu

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Tanner replies — Both Beerling and Retallack question our conclusion that atmospheric CO_2 levels remained relatively stable across the Triassic–Jurassic boundary, partly on the basis of insufficient stratigraphic resolution. However, the stratigraphy of the formations we studied is well known[1]. The Lower Jurassic McCoy Brook Formation of the Fundy basin overlies the North Mountain Basalt, which was extruded during the initial stages of volcanism in the Central Atlantic Magmatic Province (CAMP), and so this formation post-dates the main eruptive episode. Palaeosols in this formation occur within 10 m of the formation base; the age of these palaeosols is therefore constrained by the basalt to within several hundred thousand years of the Triassic–Jurassic boundary, which is located several metres below the basalt. Because the duration of the eruptions of CAMP volcanics, which occurred in several pulses, has been established as roughly 600,000 years[2], palaeosol formation in the McCoy Brook Formation is contemporaneous with the latter stages of the CAMP eruptions. These palaeosols may therefore be expected to record the cumulative effects of the eruptions.

Our palaeo-CO_2 values are calculated from the diffusion-reaction model, which requires measurements or assumptions for a variety of factors that control soil CO_2, not least the isotopic composition of plant-derived organic matter ($\delta^{13}C_{OM}$)[3,4]. Ideally, organic matter in the palaeosol that contains the carbonate is used to obtain this value because the $\delta^{13}C$ of C_3 plants is known to vary significantly in contemporaneous soils from differing climatic regimes[3]. Unfortunately, the McCoy Brook Formation, from which the Lower Jurassic carbonate samples were obtained, lacks well-preserved plant material.

The only record of $\delta^{13}C_{OM}$ across the Triassic–Jurassic boundary available at the time of our calculations provides data for locations in eastern Greenland and southern Sweden[5], but the negative $\delta^{13}C$ excursion at the boundary shown in the eastern Greenland data, represented primarily by a single data point, is not apparent in the southern Sweden data set. Moreover, the sediments that contain plant fossils at the eastern Greenland location accumulated under the influence of a significantly more humid climate than existed in the Fundy basin[1], a fact that renders isotope data from this location inapplicable to the interpretation of data derived from the semi-arid palaeosols.

For these reasons, we chose not to use these data, and instead assumed a single value for both the Late Triassic and Early Jurassic that is consistent with published measures of organic matter in Upper Triassic formations[3] that were deposited under climatic conditions similar to those of the studied formations. This potential source of inaccuracy may ultimately be resolved only by location and analysis of organic material in the McCoy Brook Formation.

The fossil stomatal evidence of Beerling and Retallack seems to indicate a several-fold increase in atmospheric pCO_2 across the Triassic–Jurassic boundary[5,6]. The use of stomatal indices for calculation of palaeo-CO_2 levels is based on experiments in which modern plants were grown at pCO_2 values of up to twice present levels[7], but calls for an extrapolation of the experimental pCO_2 values to the much higher palaeo-CO_2 values interpreted for the past. The use of these indices also requires the assumption that the floral response to these conditions was quantitatively the same 200 million years ago as it would be today. This approach may therefore also generate inaccuracies.

As mentioned by Beerling, data from the marine realm that indicate a significant negative carbon-isotope excursion at the Triassic–Jurassic boundary shed new light on the extinction problem[8], demonstrating an intense but short-lived perturbation of the global carbon cycle of a magnitude that is not consistent with volcanic outgassing. This is supported by a simple mass-balance calculation, on the basis of the largest estimate of the volume and volatile content of intrusions of the CAMP[9], showing that outgassing during the eruptions produced 5.6×10^{16} mol CO_2 in total, an amount that is equivalent to that in the modern atmosphere.

This volume is insufficient to drive the isotopic excursion of marine carbonates[8] and is unlikely to have affected the atmosphere of the early Mesozoic era, given the high pCO_2 of the Late Triassic[1]. Rapid release of seafloor methane hydrate, as suggested by Retallack, has been implicated in other extinction events, and this release may have been triggered by the effects of CAMP volcanism. Such a release, which is consistent with the magnitude of the isotopic excursion, need not have resulted in greatly increased atmospheric pCO_2 as suggested by Retallack, as evidence exists that much of the methane released by this process would be oxidized within the water column, resulting in a brief interval of ocean anoxia[10] and widespread extinction.

Our conclusion stands: the isotope compositions of pedogenic carbonates fail to indicate a substantial increase in atmospheric pCO_2 as a result of the CAMP eruptions. We are all in agreement that although existing methods of estimating palaeo-CO_2 are inexact, their validity is not mutually exclusive, and also that the cause of the end-Triassic extinction event is uncertain, with environmental degradation resulting from the CAMP volcanism probably being involved. Acquisition of new data by both methods from other locations should resolve this uncertainty; better time resolution will constrain the relationships between the abrupt marine extinctions[11], the possibly asynchronous floral turnover[12] and the duration of the CAMP eruptions, which may have lasted for several million years[13].

Lawrence H. Tanner
Department of Geography and Geosciences, Bloomsburg University, Bloomsburg, Pennsylvania 17815, USA
e-mail: lhtann@bloomu.edu

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