This apparent excess could come from unwanted influence of the Brownian motion of the tethers that pull on the molecule, or it might indicate that more coordinates of the biomolecule in addition to the length are needed to describe the transition. Such an explanation would not be surprising, because the length coordinate is not expected to be perfectly correlated with the folding or misfolding reaction coordinate (see the figure). The protein system studied by Neupane *et al.*—a prion—also probably does not have a well-funneled energy landscape, given that its configurational diffusion is extremely slow. For rugged landscapes, theory suggests that the logarithms of the escape times nearly follow a normal Gaussian distribution. This distribution gives a wider range of transit times than the prediction for strictly one-dimensional diffusion (*5*).

Now that Neupane *et al.* have directly confirmed some of the most basic notions of energy landscape theory by observing transition paths, we can expect future refinements to give more structural details about the transitions. To access these details, one can simultaneously measure fluorescence and length (*6*). However, existing measurements of this sort must be extended in time range and stability to uncover the multidimensional aspects of folding transition paths. Even without such enhancements, combining the capabilities of protein engineering with transition path measurement will give direct access to the structural aspects of the transition path ensemble. These structural factors have been predicted by theory and simulation for many proteins (*2*). Leaving its days of controversy, biomolecular folding is now on its way to becoming one of the best-understood processes in biochemistry. ■

> ***"...biomolecular folding is now on its way to becoming one of the best-understood processes in biochemistry."***

REFERENCES

1. K. Neupane *et al.*, *Science* **352**, 239 (2016).
2. M. Oliveberg, P. G. Wolynes, *Q. Rev. Biophys.* **38**, 245 (2005).
3. H. S. Chung *et al.*, *Science* **335**, 981 (2012).
4. S. Chaudhury, D. E. Makarov, *J. Chem. Phys.* **133**, 034118 (2010).
5. J. D. Bryngelson, P. G. Wolynes, *J. Phys. Chem.* **93**, 6902 (1989).
6. S. Hohng *et al.*, *Science* **318**, 279 (2007).

10.1126/science.aaf6626

CLIMATE CHANGE

A heated mirror for future climate

Climatic changes 55.9 million years ago resemble those expected in the future

By **Richard B. Alley**

Climate has always changed naturally, and this is not good news when contemplating a human-forced future. The natural responses have been as large as, or larger than, those simulated by leading models for shorter time scales, with major biological and physical impacts. The possible effects of rapid carbon dioxide (CO_2) release may be clearest from the Paleocene-Eocene Thermal Maximum (PETM) about 55.9 million years ago, when a large, natural CO_2 release drove strong warming that caused amplifying feedbacks, dwarfing of large animals, ecosystem disruptions, soil degradation, water-cycle shifts, and other major changes (see the figure). The climatic changes during the PETM occurred over longer time scales than those of anthropogenic climate change. The impacts of the latter may thus be even more severe.

The source of the initial CO_2 release that drove the PETM remains debated (*1*). Increasing evidence points to a concentrated igneous outpouring during the opening of the North Atlantic, which intruded oil-bearing and otherwise carbon-rich rocks (*2*). The PETM was amplified and extended by sustained CO_2 release, probably at least in part because the warming released organic carbon stored in soils, seafloor sediments, or elsewhere (*1*).

Most estimates of the total CO_2 added to the atmosphere during the PETM are similar to, or somewhat lower than, the total CO_2 that would arise from burning all fossil-fuel resources estimated to exist on Earth—especially if, as suggested by the PETM and by current understanding, warming releases additional carbon from reservoirs such as tundra soils and seafloor hydrates (*1*). However, the initial CO_2 rise during the PETM took place over the course of a few millennia, about a factor of 10 slower than if humans burned the remaining fossil-fuel resources under a business-as-usual scenario (*3*). PETM CO_2 remained elevated for more than 150,000 years, confirming the long persistence expected for human-released CO_2 (*1*).

The strong PETM warming suggests that climate is highly sensitive to rising CO_2. This implies a higher climate sensitivity than the lower end adopted for somewhat shorter times by the Intergovernmental Panel on Climate Change (IPCC), and perhaps larger than the higher end (*4*). Thus, temperatures may rise more than currently projected.

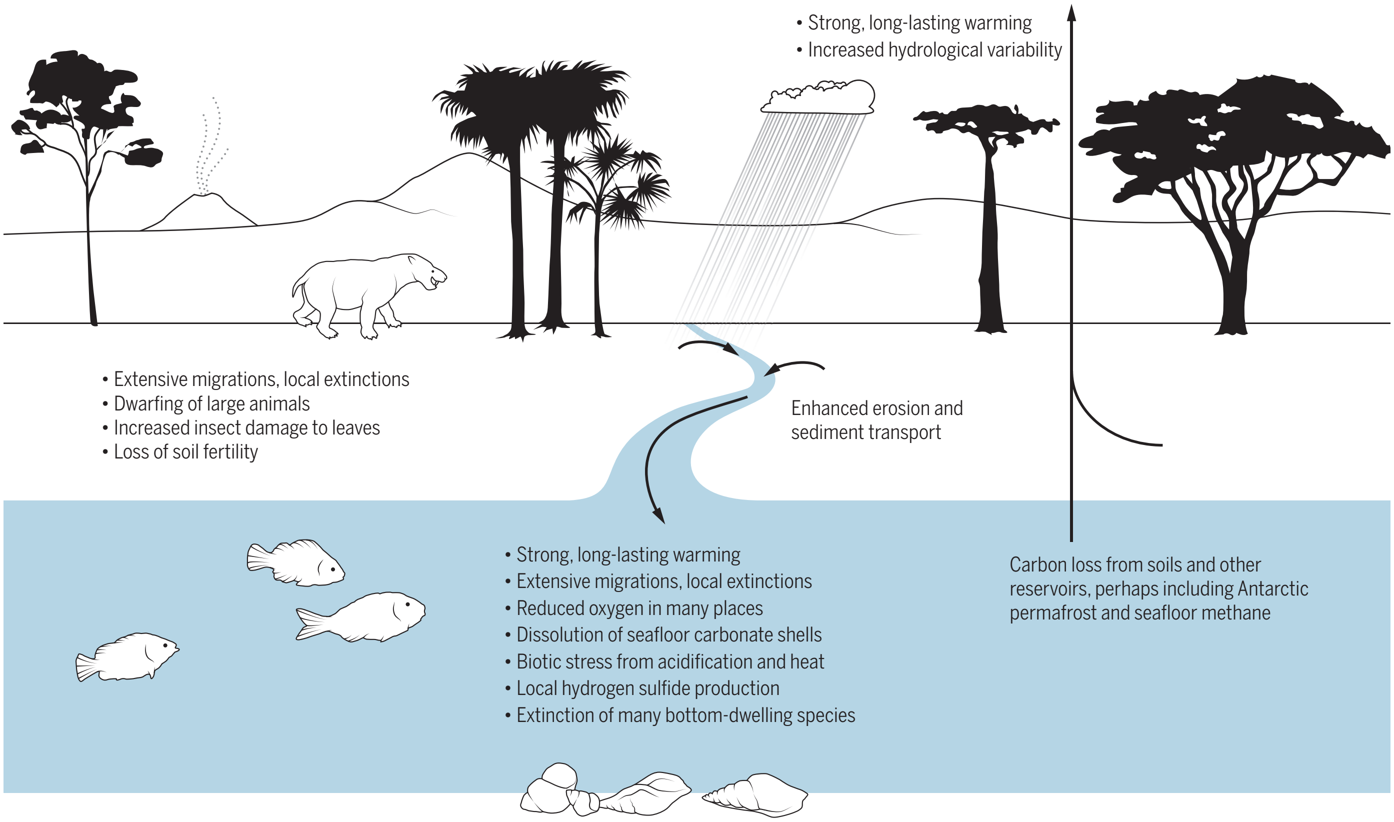
During the PETM, the rise in CO_2 and resulting climate shifts caused further changes propagating across the Earth system. On land, enhanced erosion and sediment transport to the sea (*5*, *6*) are consistent with the expected increase in hydrological variability from warming; larger or more intense storms separated by longer and drier intervals likely contributed to regional loss of vegetation, soil carbon, and soil fertility (*5*).

Over the course of the PETM, terrestrial species migrated long distances poleward or upward and crossed land bridges between continents. Some types became extinct, whereas others spread. Ecosystems during the event were notably different from those before or afterward. Wing and Currano have shown that of a sample of 91 common plant taxa known from fossils during a million-year-long interval starting 200,000 years before the PETM in Wyoming's Bighorn Basin, only 7 persisted before, during, and after the PETM. Another 12 experienced at least local extinction at the onset, 20 were confined to the event, 40 were locally absent during the event but present before and after, and 12 first appeared after the event (*5*).

PETM plant leaf fossils from the Bighorn Basin are almost twice as likely to show insect damage as the average from before and after; one PETM leaf shows 10 different types of damage. Possible reasons include increased insect feeding as higher CO_2 reduced nutritional value of plants, invasion by new insects, and disruption of established ecological balances (*7*). Heat and water stress and loss of soil fertility likely also challenged plants (*5*). Large mammals became notably dwarfed, perhaps because of heat stress or the lower nutritional value of their food (*8*).

In the ocean, the high CO_2 levels during the PETM raised acidity while ocean warming

Department of Geosciences and Earth and Environmental Systems Institute, Pennsylvania State University, University Park, PA, USA. E-mail: rba6@psu.edu



Clues to the future? About 55.9 million years ago, a rapid rise in greenhouse gas concentrations in the atmosphere had major impacts across the planet. Today, greenhouse gas concentrations are rising even faster than they did then.

increased stratification. Low-oxygen zones expanded and anoxic, H_2S-producing conditions developed at least seasonally in some places (*9*). Up to half of the bottom-dwelling foraminifera species became extinct, and some other types were lost elsewhere, with widespread migrations (*1*). Coral reefs were largely lost as functioning ecosystems, with the oceans instead hosting flatter, less complicated structures dominated by foraminifera (*10*). Limited data suggest additional major biological impacts, perhaps including partial or complete loss of many types of plankton in some coastal tropical oceans because of heat or other stresses (*6*).

Slower climate changes allow more time for biotic adaptation or migration. A slower pace of change also gives time for rising CO_2 to dissolve seafloor shells and break down land-surface rocks, thus supplying calcium and bicarbonate and reducing impacts of acidification on creatures with carbonate shells. Hence, the biological impacts of the PETM were likely less severe than those of human-caused emissions under a business-as-usual scenario.

The PETM stands out in paleoclimatic records, but several other somewhat similar although smaller events over the next few million years provide additional supporting evidence. In these events, features of Earth's orbit, perhaps aided by volcanic forcing, appear to have pushed the climate system past some threshold, triggering feedback loss of stored carbon that amplified the warming, as in the PETM (*11*).

The PETM poses major research challenges, but confidence is growing rapidly that studies targeted at key questions can greatly reduce the uncertainties. The sources and rate of rise of the atmospheric CO_2 concentration are still poorly known, but progress in using boron records and other techniques to estimate past CO_2 levels is more tightly constraining the total mass of CO_2 that was released (*12*). This result, together with knowledge of the timing and size of the shift in carbon isotopic compositions in terrestrial and marine settings, can provide a more accurate history of CO_2 sources (*13*). Collection of further high-resolution records, including those on land and in shallow marine settings with rapid deposition, could clarify these key issues. Records of ecosystem changes are still available from only a few locations, and many deposits of this age remain to be explored for physical or biological changes.

Narrowing the uncertainties about this important climate event and other similar features in the geologic record could provide additional valuable insights to inform decisions on our energy future. What is clear, however, is that the large release of CO_2 during the PETM transformed conditions on land and in the ocean in ways that affected the Earth system for more than 100,000 years and that might be considered catastrophic by many people today. The history of the PETM shows that our decisions will have large and long-lasting consequences. ■

REFERENCES AND NOTES

1. R. E. Zeebe, J. C. Zachos, *Phil. Trans. R. Soc. A* **371**, 20120006 (2013).
2. H. Svensen, S. Planke, F. Corfu, *J. Geol. Soc.* **167**, 433 (2010).
3. R. A. Zeebe, A. Ridgwell, J. C. Zachos, *Nat. Geosci.* 10.1038/ngeo2681 (2016).
4. PALAEOSENS Project Members, *Nature* **491**, 683 (2012).
5. S. L. Wing, E. D. Currano, *Am. J. Bot.* **100**, 1234 (2013).
6. T. Aze *et al.*, *Geology* **42**, 739 (2014).
7. E. D. Currano *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 1960 (2008).
8. R. Secord *et al.*, *Science* **335**, 959 (2012).
9. A. Sluijs *et al.*, *Clim. Past* **10**, 1421 (2014).
10. C. Scheibner, R. P. Speijer, *Earth-Sci. Rev.* **90**, 71 (2008).
11. D. J. Lunt *et al.*, *Nat. Geosci.* **4**, 775 (2011).
12. D. E. Penman, B. Honisch, R. E. Zeebe, E. Thomas, J. C. Zachos, *Paleoceanography* **29**, 357 (2014).
13. S. Kirtland Turner, A. Ridgwell, *Earth Planet. Sci. Lett.* **435**, 1 (2016).

ACKNOWLEDGMENTS

This Perspective grew out of a workshop on 11–12 January 2016 at Arizona State University, Tempe, AZ, on the PETM, organized by W. Broecker and D. Kent, aided by J. Severinghaus, J. Zachos, and R. Zeebe, with support from the Julie Ann Wrigley Global Institute of Sustainability at Arizona State University and from the Comer Family Foundation. Thanks also to K. Freeman, L. Kump, and T. Bralower for helpful insights.

10.1126/science.aaf4837

ILLUSTRATION: P. HUEY/*SCIENCE*

A heated mirror for future climate

Richard B. Alley

Science **352**, 151 (2016);
DOI: 10.1126/science.aaf4837

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005.