COMMENTARY

PALEONTOLOGY

Dinosaur diversity before the asteroid

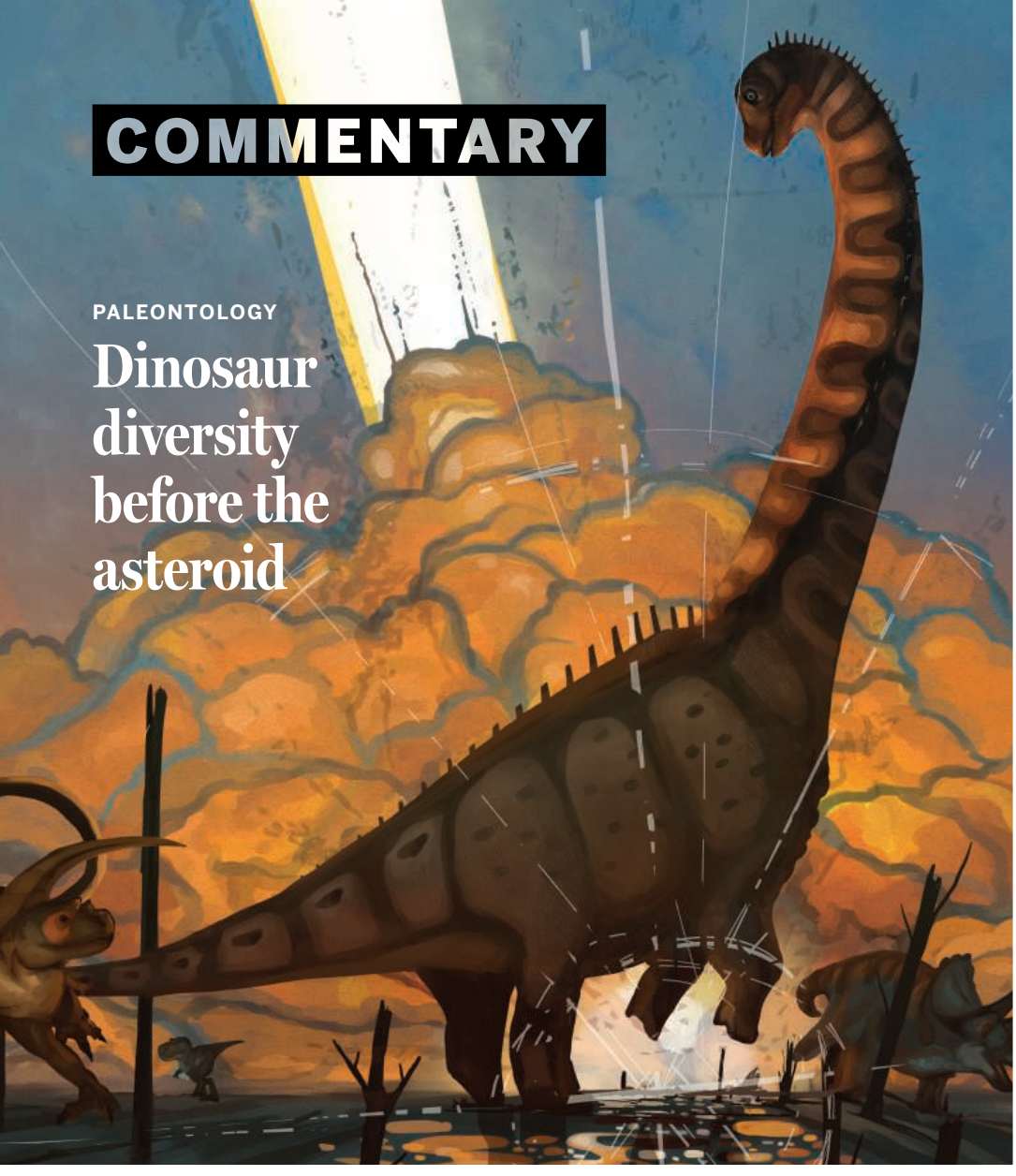


ILLUSTRATION: NATALIA JAGIELSKA

Evidence for low dinosaur diversity ahead of extinction event grows dimmer

Lindsay Zanno[1,2]

Few phenomena in Earth's history have been as widely popularized as the mass extinction of non-avian dinosaurs. Yet, the disappearance of such awe-inspiring animals has roused more than public fascination—it has spurred enduring scientific debate. Paleontologists largely agree that an asteroid dealt the final blow to non-avian dinosaurs, but their susceptibility to annihilation when the asteroid plummeted to Earth remains an open question. On page 400 of this issue, Flynn *et al.* (*1*) reveal that a well-known rock layer in northwestern New Mexico captures a rare glimpse into the last days of the dinosaurs. Their findings markedly increase the number of dinosaur species known to have roamed Earth ~400,000 years before the asteroid's impact, challenging the idea that weakened ecosystems played a role in their demise.

The extinction of non-avian dinosaurs 66 million years ago marked the end of the Maastrichtian, the final age of the Cretaceous Period. Controversy over this extinction event boils down to whether dinosaurs perished catastrophically at the time of the asteroid's impact (*2*–*5*) or whether they were already in decline and thus particularly vulnerable to the ensuing fallout (*6*–*9*). The answer to this dispute is highly relevant to humanity. Biodiversity on Earth is dropping at an alarming rate (*10*), and studies of living systems suggest that depauperate ecological networks are more liable to collapse (*11*). Yet, a view of life's fragility that is restricted to the present is myopic. Predicting the future of ecosystems requires data beyond what is directly observable on human timescales. It requires empirical insight derived from Earth's deep-time fossil archive.

The greatest challenge in estimating ecosystem stability before the asteroid's impact is the patchy nature of biodiversity data. Almost all fossil records from this time derive from a restricted area in northwestern North America—the Hell Creek Formation and nearby rocks of equivalent age (*12*). As a result, the biodiversity patterns observed in this region are used to inform conclusions on a global scale. Paleontologists regularly use statistical approaches to mitigate this type of geographic bias (*8, 13*), and these practices strengthen confidence in data analyses. However, no statistical approach can create real-world data where they do not yet exist.

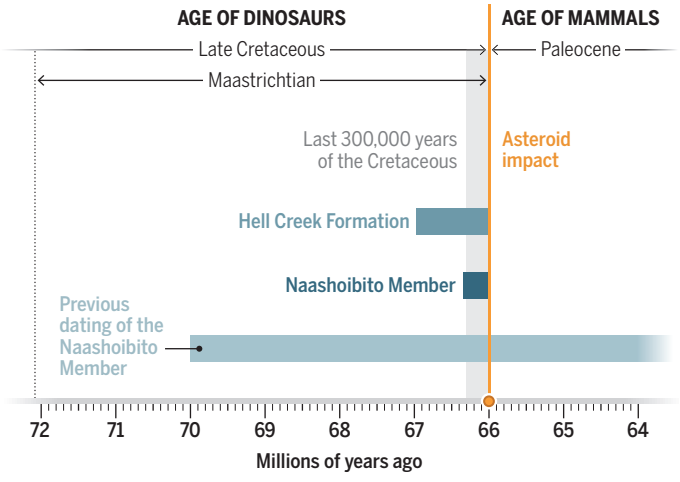
In the realm of paleontology, so-called "missing data" can take several forms. Species might have failed to enter the fossil record, they might have been preserved as fossils but not yet discovered, or they might have been discovered but lack essential context, such as precise estimates of geological age. Dinosaur species preserved in the Naashoibito Member of the Kirtland Formation in New Mexico fell within the latter category. Using radioisotopic dating and magnetostratigraphy of bounding strata, Flynn *et al.* demonstrate that extinct species specific to southwestern North America were contemporaneous with the iconic faunas of the Hell Creek Formation (see the figure). Their results indicate that dinosaurs were divided into ecologically distinct northern and southern biomes for the last 10 million years of the Cretaceous, thriving until the asteroid struck.

These revised estimates of dinosaur diversity during the Maastrichtian still do not match the bounty of the preceding Campanian Age—the apparent zenith of dinosaur diversification in North America (*14*). Nonetheless, current estimates of Maastrichtian biodiversity are still higher than those for most other Late Cretaceous ages (*6*). Future investigations may reveal that Maastrichtian ecosystems were a return to a healthy baseline after a Campanian anomaly.

Ultimately, several conditions must be met to determine whether or not a decline in biodiversity was a key factor in the extinction of non-avian dinosaurs. Most critically, there must be a genuine and global signal for or against decline. Obtaining this evidence requires largely contiguous data across space and time—a well-preserved, densely sampled record of Cretaceous ecosystems worldwide. The temporal realignment of the Naashoibito Member to the latest Maastrichtian by Flynn *et al.* brings us closer to that goal. The answer to the question also re-

Dating dinosaurs

Through radioisotopic dating, the Naashoibito Member of the Kirtland Formation in New Mexico was found to be contemporaneous to the Hell Creek Formation in Montana. The refinement increases the known diversity of non-avian dinosaurs before the impact of the asteroid that caused their extinction.



quires agreement on the metrics of evolutionary and ecological decline that matter—be they measures of functional diversity (*5*), morphological disparity (*15*), diversification rates (*6*, *9*), or species richness (*7*)—a consensus that has yet to be achieved. More generally, a claim that decline, by any measure, played a major role in the extinction of non-avian dinosaurs assumes that if a 10-km-diameter extraterrestrial body had careened into Earth at a different time, Earth's dominant megafauna would have survived. Such a scenario has yet to be rigorously explored.

The fossil record of life is incomplete, and reconstructing macroevolutionary trends such as extinction patterns will always require quantitative adjustments to counter bias. However, the ideal remedy for gaps and uncertainties is the refinement of metadata contextualizing known specimens and the hopeful discovery of new ones. By increasing data fidelity, Flynn *et al.* demonstrate that previous hypotheses of dinosaur decline before the asteroid's impact underappreciated their true taxonomic and ecological richness. Similar approaches could be applied to other fossil sites around the world (*3*, *4*). As paleontologists are known to lament, "we need more fossils"—or, as in this case, better-dated ones. □

REFERENCES AND NOTES

1. A. G. Flynn *et al.*, *Science* **390**, 400 (2025).
2. A. A. Chiarenza *et al.*, *Nat. Commun.* **10**, 1091 (2019).
3. Z. Csiki-Sava *et al.*, *Cretac. Res.* **57**, 662 (2016).
4. S. L. Brusatte, C. R. A. Candeiro, F. M. Simbras, *An. Acad. Bras. Cienc.* **89**, 1465 (2017).
5. D. W. Larson, C. M. Brown, D. C. Evans, *Curr. Biol.* **26**, 1325 (2016).
6. F. L. Condamine, G. Guinot, M. J. Benton, P. J. Currie, *Nat. Commun.* **12**, 3833 (2021).
7. F. Han *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2211234119 (2022).
8. P. M. Barrett, A. J. McGowan, V. Page, *Proc. Biol. Sci.* **276**, 2667 (2009).
9. M. Sakamoto, M. J. Benton, C. Venditti, *Proc. Natl. Acad. Sci. U.S.A.* **113**, 5036 (2021).
10. G. Ceballos *et al.*, *Sci. Adv.* **1**, e1400253 (2015).
11. B. C. Weeks, S. Naeem, J. R. Lasky, J. A. Tobias, *Ecol. Lett.* **25**, 697 (2022).
12. C. M. Brown, N. E. Campione, G. P. Wilson Mantilla, D. C. Evans, *Paleobiology* **48**, 210 (2022).
13. J. Alroy, *Palaeontology* **53**, 1211 (2010).
14. J. Ramezani, T. L. Beveridge, R. R. Rogers, D. A. Eberth, E. M. Roberts, *Sci. Rep.* **12**, 16026 (2022).
15. S. L. Brusatte, R. J. Butler, A. Prieto-Márquez, M. A. Norell, *Nat. Commun.* **3**, 804 (2012).

ACKNOWLEDGMENTS

The author acknowledges support from the National Science Foundation.

10.1126/science.aeb5725

[1]North Carolina Museum of Natural Sciences, Raleigh, NC, USA. [2]Department of Biological Sciences, North Carolina State University, Raleigh, NC, USA.
Email: lindsay.zanno@naturalsciences.org

GRAPHIC: A. MASTIN/*SCIENCE*

MATERIALS SCIENCE

Homogenizing two-dimensional crystals

An atom-thick layer of lanthanum orients semiconductor crystals in one direction

Dongyoung Kim[1] and **Kibum Kang**[1,2]

As semiconductor devices shrink to the nanometer regime, so too do the thickness of their components. Transition-metal dichalcogenides—a two-dimensional (2D) layer of transition-metal atoms sandwiched between 2D layers of chalcogen atoms (such as sulfur and selenium)—have emerged as the next-generation semiconductor material beyond silicon (*1*). Although their atomic-scale thickness is an intrinsic advantage, wafer-scale (size of an entire silicon wafer) integration of single-crystal transition-metal dichalcogenide (a lattice structure with an uninterrupted repeating pattern) has been a long-standing challenge. Synthesis often requires complex preconditioning of the substrate or highly constrained growth conditions, limiting reproducibility. On page 354 of this issue, Zou *et al.* (*2*) report that depositing an atomic layer of lanthanum on a sapphire substrate can template the growth of a single-crystalline transition-metal dichalcogenide. This versatile process of producing wafer-scale films with homogeneous orientation addresses the most critical requirements for industrial implementation.

At the core of semiconductor technology is a transistor that enables low-power operation of microprocessors by amplifying signals. Progress in transistor performance has traditionally been driven by two strategies: scaling down a device's dimensions and modifying the architecture of an integrated circuit (*3*). However, both paths are approaching the fundamental end point. For example, Moore's law predicts that the number of transistors on an integrated circuit will roughly double every 2 years, but this projection has slowed down because of the physical limits of a shrinking transistor. Alternatively, new semiconductor materials could make a major leap in future transistor performance.

A critical component of a transistor is the conducting path (channel) that connects source and drain electrodes. Atomically thin channels provide a stackable channel architecture, enabling high integration density (the number of electronic components per area on a chip) with robust electrostatic control and energy efficiency. Leading semiconductor manufacturers such as Samsung, Taiwan Semiconductor Manufacturing Company, Intel, and the Interuniversity Microelectronics Centre have presented 2D semiconductors in technology roadmaps, implying a general agreement that these materials represent the most credible pathway to extending Moore's law (*4*). Although deposition processes of traditional materials such as silicon, III–V compounds, dielectric materials, and metal thin films have been optimized, translating 2D semiconductors into manufacturable devices requires a fundamentally different approach. Channels must be a few atoms thick and crystalline to obtain sufficient electronic performance. This is challenging to achieve for 2D semiconductors, particularly transition-metal dichalcogenides, by using existing methods.