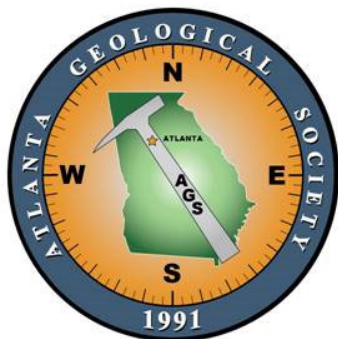




Atlanta Geological Society Newsletter

ODDS AND ENDS

Dear AGS Members,

I went on vacation but there'll be no informative geological travelogue this year. A cruise to the Yucatan is relaxing but not much to see geologically. I wondered about any residual anything from the Chicxulub impact crater that ended the Cretaceous and the dinosaurs. Nothing to see here except some sinkholes roughly in a ring. 65 million years later, almost all eroded away. The crater was 170 km wide and 20 km deep, fully two orders of magnitude larger than meteor Crater in Arizona. Amazing to read the history of those first minutes and hours. But now, just folks trying to earn that tourist dollar.

As we go into the fall, I see that we have about 65 members, plus some new student members. That's up a bit from last year which I account to the quality of our presentations, (Thanks Steve Stokowski), the steady reliability of our hospitality (Thanks John Salvino) and the great good fortune we have to keep meeting at Fernbank. Fall is also time to consider a greater involvement for the Society as we have our officer elections in our final meeting of the year in November. Additionally, it would be a time to consider if there are additional activities or features of the Society that you think might improve our organization. Give it some thought and please bring it up. Mention any ideas to any of the officers and we can discuss it during the meeting.

Hope to see you on Tuesday.

Ben Benthowski, President

October Meeting

Join us **Tuesday, October 29, 2019** at the Fernbank Museum of Natural History, 760 Clifton Road NE, Atlanta GA. The dinner starts at 6:30 pm, and the meeting will start at 7:00 p.m.

This month our presentation is **“Underground Space Resource of Granitic Plutons in Georgia”** presented by C.W. Myers. Please find more information about the presentation and Mr. Myers's bio on the next page.

Please come out, enjoy a bite to eat, the camaraderie, an interesting presentation and perhaps some discussion on the importance of accurate mineral characterization.

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Atlanta Geological Society October Speaker

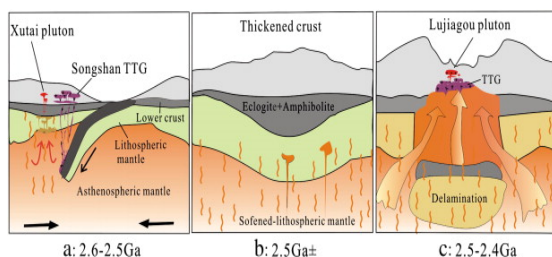
“Underground Space Resource of Granitic Plutons in Georgia”

Speaker C. W. Myers Bio:

Independent geologist and advocate for expanded use of underground space for siting 1) critical infrastructure, industrial and commercial facilities and 2) underground nuclear power plants. Worked 24 years at Los Alamos National Laboratory, including 12 years as head of the Earth and Environmental Sciences Division; also worked two years as a university assistant professor and two years as a petroleum geologist. Member of the International Society of Rock Mechanics Commission on Underground Nuclear Power Plants, Fellow in the Geological Society of America, and Member of the American Nuclear Society. BS 1966 and MS 1968, University of Georgia; Ph.D. 1973, University of California, Santa Cruz; and Post-Doctoral Fellowship 1973-1974, State University of New York, Stony Brook. Georgia native.

Abstract:

Granite plutons in the Piedmont region of Georgia are an underground space resource potentially suitable for constructing bedrock caverns to site special-purpose underground facilities (UGFs). Portions of rock masses in the interiors of some of these plutons might be suitable for excavation of large caverns, potentially at relatively low cost because of recent advances in underground excavation technology. Site characterization studies to evaluate these rock masses should cover not only geology and groundwater conditions, but focus on joint sets, discontinuities, and other geotechnical conditions important to determine the mechanical strength and permeability of the rock mass and options for cavern design. Domal and other high-relief pluton exposures have the advantage of direct surface-to-underground access to UGFs using tunnels or ramps rather than being dependent on shafts. Types of UGFs potentially suitable for siting in Georgia's granitic plutons include 1) critical infrastructure facilities requiring high levels of security against, for example, hurricanes, tornados, electromagnetic pulses, or attacks by terrorists; and 2) industrial or commercial facilities requiring low operating cost and an environment with constant temperature and humidity and/or low-vibration levels. Specific examples will be described.



How life blossomed after the dinosaurs died

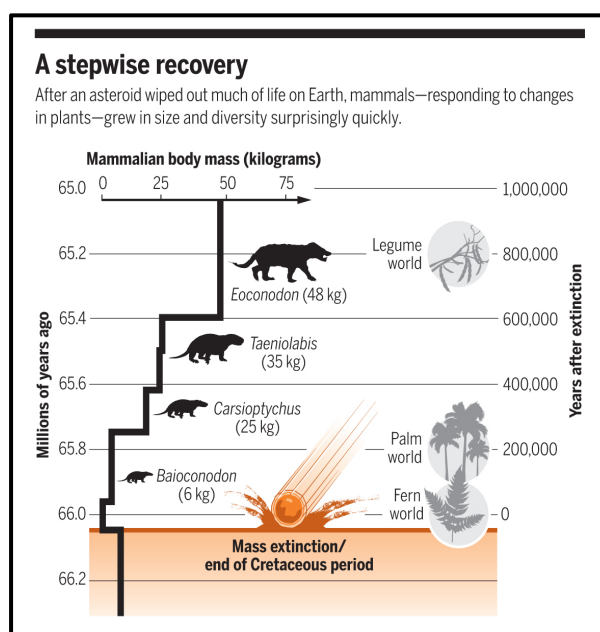
In 2014, when Ian Miller and Tyler Lyson first visited Corral Bluffs, a fossil site 100 kilometers south of the Denver Museum of Nature & Science where they work, Lyson was not impressed by the few vertebrate fossils he saw. But on a return trip later that year, he split open small boulders called concretions—and found dozens of skulls. Now, he, Miller, and their colleagues have combined the site's trove of plant and animal fossils with a detailed chronology of the rock layers to tell a momentous story: how life recovered from the asteroid impact that killed off the dinosaurs 66 million years ago.

Plants and animals came back much faster than thought, with plants spurring mammals to diversify, the team reports online in *Science* this week. “They get almost the whole picture, which is quite exciting,” says functional anatomist Amy Chew of Brown University. “This high-resolution integrated record really tells us what's going on.”

When the asteroid slammed into Earth, it wiped out 75% of living species, including any mammal much larger than a rat. Half the plant species died out. With the great dinosaurs gone, mammals expanded, and the new study traces that process in exquisite detail.

Most fossil sites from after the impact have gaps, but sediment accumulated nearly continuously for 1 million years on the flood plain that is now the Corral Bluffs site. So, the site preserves a full record of ancient life and the environment.

Such sites can be hard to date. But Miller, a paleobotanist, and his colleagues collected 37,000 grains of pollen and spores, which revealed a clear marker of the asteroid impact: a surge in the growth of ferns, which thrive in disturbed environments. The site also includes two layers of ash from nearby volcanoes. Volcanic ash includes radioactive minerals whose decay can be used as a precise geochronological clock, providing two-time markers. The known flips in Earth's magnetic poles, which some minerals in the layers had recorded, add detail to the chronology. “They have a very strong geochronological framework,” says David Fastovsky, a paleontologist at the University of Rhode Island in Kingston.



The record confirms the devastation wrought by the impact. Raccoon-size mammal species had swarmed the site before the catastrophe, but for 1000 years afterward just a few furry creatures no bigger than 600-gram rats roamed a ferny world where flowering plants, with their nutritious seeds and fruits, were scarce.

By 100,000 years later, twice as many mammal species roamed, and they were back to raccoon size. These critters foraged in the palm forests that replaced the ferns. “It's a world that's coming back from complete and utter devastation,” Miller says.

Over the next 200,000 years, what he calls the “palm period” gave way to the “pecan pie” period, when walnut like plants arose. New mammals evolved to take advantage of the nutritious seeds. Mammal diversity increased threefold, and the biggest of the new species reached 25 kilograms—beaver size.

How life blossomed after the dinosaurs died (Continued)

After about 700,000 years, legumes showed up; their fossil pea pods are North America's oldest discovered to date. Pea and bean species from the “protein bar period” provided protein-rich meals that further boosted mammalian size and diversity, Lyson says. Mammals topped 50 kilograms—a 100-fold increase over those that survived the asteroid. The forests, too, had recovered. “The biggest message is how fast the recovery was ... and how closely the vegetation and fauna are tied together,” says Vivi Vajda, a paleobiologist at the Swedish Museum of Natural History in Stockholm.

The team also classified 6000 leaves, counting how many species at each time interval had smooth or toothed edges. Smooth-edged species are more common in hot climates. The team concluded that the site underwent three warming periods. They estimate that the first, just after the impact, saw temperatures rise about 5°C, agreeing with earlier work. This period coincides with the massive volcanic eruptions of India's Deccan Traps, which could have warmed Earth by belching carbon dioxide (*Science*, 22 February, p. [862](#) and p. [866](#)).

“At each warming period you see a change in the plant community and subsequently, changes in the mammals,” says Lyson, who thinks temperature drove the stepwise recovery.

Vajda thinks no matter what happened to temperature and plant life, the loss of dinosaurs alone might have opened the door to bigger, more diverse mammals. But Jukka Jernvall, an evolutionary biologist at the University of Helsinki, says the team's analysis of ancient ecosystems shows just how the recovery unfolded. “We are starting to get the time and spatial resolution to reconstruct the environment and what happened in a way that can be linked to ecological processes.”

The record also holds a sobering message about the future, and how quickly ecosystems might recover from ongoing, human-driven extinctions. Even a recovery that geologists call “fast” took hundreds of thousands of years, and the world was never the same. “A very dramatic resetting of the ecosystem could be in our future,” Chew says.

Read more about this article at: <https://science.sciencemag.org/content/366/6464/409>

Stepping out of the dinosaurian shadow

We live in the Age of Mammals, yet warm-blooded beasts are still overshadowed by dinosaurs. Even when considering the last great shake-up to life's story, when an enormous asteroid triggered a mass extinction that decimated dinosaurs and gave mammals a shot at terrestrial expansion, we are often more focused on the terrible lizards lost than the furry creatures who set the stage for the Cenozoic. But a new NOVA documentary—“Rise of the Mammals”—seeks to change that and, in the process, offers viewers a window into paleontology beyond bone hunting.

Narrated in soothing tones by actor Keith David, the 1-hour program promises to tell how life surged back after the Cretaceous-Paleogene mass extinction. The catastrophe, we learn, did not just affect dinosaurs. Flying pterosaurs and seagoing mosasaurs disappeared, as did coil-shelled ammonites and huge clams called rudists, along with mass extinctions of birds, lizards, and mammals. But the mammal-versus-dinosaur competition is the film's primary focus, with images of tiny, shrew like insectivores living beneath the feet of dinosaurs providing the background for what follows.

The “Mesozoic mammals as underdogs” trope should be extinct by now. In the past several decades, paleontologists have recognized that mammals thrived during this era, evolving into an impressive array of forms. All were small, fair enough, but so are most of today's mammal species. To navigate a clear relationship of cause and effect, then, “Rise of the Mammals” emphasizes size. When did mammals start to get big?

Stepping out of the dinosaurian shadow (Continued)

An arid field site called Corral Bluffs near Colorado Springs, Colorado, is offered as the key place to answer this question. How this dot on the map was uncovered is told in a circuitous fashion. We are first introduced to Denver Museum of Nature & Science paleontologist Tyler Lyson and his quest to find fossil beds from the earliest days of the Paleocene, the epoch directly following the Cretaceous.

“Rise of the Mammals” leans heavily on the romance of fieldwork and *Indiana Jones* imagery here, even cribbing a famous sunset shot from *Raiders of the Lost Ark*. But the key to the story is not a new discovery by Lyson. It is a previous find that was already in the Denver collections.

Paleontology lore often focuses on first authors, field leaders, and museum curators to the exclusion of other workers who make the science possible. To the documentary's credit, the contribution of Denver museum volunteer Sharon Milito who made the first critical find at Corral Bluffs, picking up a hard concretion that preserved a Paleocene mammal palate inside is recognized and underscored by an interview with Milito herself. Lyson happened across this fossil in the Denver collections and, upon visiting the site with colleague Ian Miller, started finding dozens more well-preserved Paleocene fossils.

The film quickly shifts into detective mode. What species were found at the site? How old were they? What was their environment like? Instead of following the standard and often false story of how a single discovery changes everything, the program follows various threads to assemble a picture of life in the first million years of the Paleocene.

Although the legacy of storytelling from the “Bone Wars” era of epic fossil hunts is certainly there, the latter half of the film broadens in scope. “Rise of the Mammals” ends up being a short course in modern paleontology, following the story as it goes back and forth between museum and fossil outcrops. The changing face of paleontology is visible, too; the cast of scientists shown and interviewed is much more gender-balanced and diverse than many programs of the past few decades.

The Corral Bluffs fossils are phenomenal, and what they have to tell us about the Paleocene is just starting to drip out into the published record, but the ancient ecosystem is only one small part of a global story. Where the film shines—and offers something rare—are the moments when the process of science is allowed to unfold, revealing how experts assemble views of lost worlds. And if nothing else, it is helpful to pry the spotlight out of dinosaurian claws now and then.

Read more about this article at: <https://science.sciencemag.org/content/366/6464/430?intcmp=trendmd-sci>

Exceptional continental record of biotic recovery after the Cretaceous–Paleogene mass extinction

The Cretaceous–Paleogene (K–Pg) boundary marks Earth’s most recent mass extinction, when over 75% of species, including non-avian dinosaurs, went extinct. In the terrestrial realm, the mass extinction was followed by a radiation of modern clades, particularly placental mammals, crown birds, and angiosperms. The drivers and tempo of the K–Pg mass extinction (KPgE) have been hotly debated and the patterns of terrestrial recovery in the first million years after the KPgE remain poorly understood. The extinction of all large-bodied vertebrates undoubtedly impacted the post-KPgE taxonomic, ecologic, and body-mass diversification of various clades, but the lack of a well-studied fossil record has left the factors influencing ecosystem recovery unknown. Here we provide a detailed and temporally constrained terrestrial fossil record from this critical interval.

Exceptional continental record of biotic recovery after the Cretaceous–Paleogene mass extinction (Continued)

Fossils of terrestrial and freshwater organisms from the first million years after the KPgE are exceedingly rare worldwide, hindering our knowledge of post-KPgE taxonomic and ecological radiations. Thus far, the most fossiliferous sections from this time interval occur in the Williston, San Juan, Hanna, and Denver basins along the eastern margin of the Rocky Mountains in North America. In all of these study areas, discontinuous outcrops result in composite stratigraphic sections, plant fossil localities are geographically widely spaced, vertebrate-bearing horizons are sparse and separated by long temporal gaps, complete vertebrate fossils are exceptionally rare, and age control is variable. The Williston Basin has the most comprehensive fossil record with excellent age control, but the vertebrate specimens are fragmentary. The San Juan Basin preserves a well-studied early Paleocene vertebrate record but does not record the K–Pg boundary itself. Moreover, overlying Paleocene rocks only contain two vertebrate fossil-bearing horizons within the first one million years post-KPgE. The Hanna Basin K–Pg section is rich in fragmentary vertebrate fossils but has structurally complex strata and lacks a detailed chronostratigraphic framework (17). Finally, the Denver Basin has well-documented Cretaceous and Paleocene strata, a precisely dated K–Pg boundary, and abundant, geographically dispersed plant fossils, but, prior to this study, a sparse and fragmentary vertebrate fossil record.

Corral Bluffs Study Area, Denver Basin, Colorado, USA

We developed a new high-resolution stratigraphic framework in the Corral Bluffs study area, a single continuous (physically traceable) (~27 km²) outcrop from the Denver Basin that preserves the biotic recovery of a terrestrial ecosystem in the first million years post-KPgE (Fig. 1 and fig. S1). This stratigraphy is tied to the Geomagnetic Polarity Time Scale (GPTS 2012) using paleomagnetism and a CA-ID-TIMS U–Pb-dated volcanic ash. For comparison, ages using an alternative age model based on work in the Denver Basin are also provided in data files S1 to S14. The study area contains an exceptionally dense vertebrate (299 localities) and megafossil (65 localities) record with fossils occurring at more than 150 stratigraphic levels in the ~250 m thick sequence (Fig. 1). The extensive and nearly continuous outcrop belt spans the last ~100 thousand years (ka) of the Cretaceous and first ~1 Ma of the Paleocene. It includes four North American Land Mammal Age (NALMA) interval zones, four palynostratigraphic biozones, three magnetochron boundaries, two U–Pb radiometric dates, and the palynologically defined K–Pg boundary, yielding a locally derived, high-resolution chronostratigraphic framework (Fig. 1, figs. S2 to S5, and supplementary materials). Together, these data provide an unprecedented opportunity to assess the biotic recovery of a terrestrial ecosystem following the KPgE.

Vertebrate fossils in the Corral Bluffs succession are unusually complete for this time period, and are found in a range of depositional environments, and represent a diversity of taxa and body sizes (Figs. 1 and 2). Most are three-dimensionally preserved in hydroxyapatite concretions and are found in all observed facies, often as articulated skeletons or skulls with intact delicate structures such as middle ear and hyoid elements (Fig. 2). Among vertebrate specimens preserved in concretions, mammalian, turtle, and crocodilian crania (Fig. 2, A to T) and turtle shells (Fig. 2, U to X) are most common. Individual fossils range in size from ~3 mm² (isolated teeth) to larger forms such as 1.5 m-long, articulated crocodilian skeletons. Plant fossils also span the size spectrum across all observed facies, including microscopic palynomorphs as well as seeds, leaves, roots, branches, and in situ saplings, and large stumps and logs (Fig. 3).

We recognize sixteen mammalian taxa, eight of which are based on cranial remains, including the first occurrence of the late Puercan (Pu3) index taxon *Taeniolabis taoensis* (Fig. 2, K and L) from the Denver Basin. Cranial size and lower first molar area were used to estimate mammalian body mass – an important feature that impacts many aspects of the biology and ecology of mammals (Fig. 4). Given that there appears to be bias toward large vertebrates

Exceptional continental record of biotic recovery after the Cretaceous–Paleogene mass extinction (Continued)

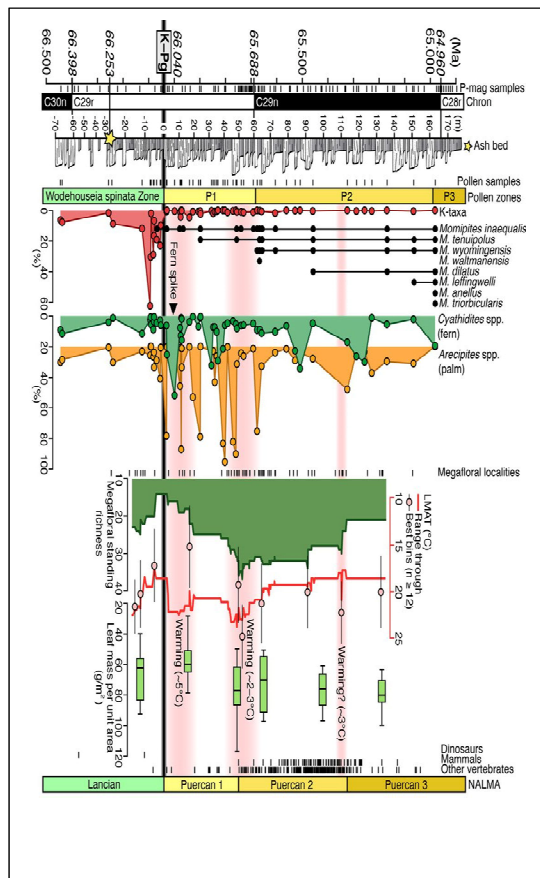


Fig. 1 Temporally calibrated stratigraphic, floral, and faunal data for the K–Pg interval in the Corral Bluffs study area (fig. S1).

Stratigraphy is tied to the Geomagnetic Polarity Time Scale (GPTS 2012) using paleomagnetism and a CA-ID-TIMS U–Pb-dated ash (italicized dates) (data file S1 and figs. S3 and S5). The composite lithostratigraphic log (figs. S2 to S5) is dominated by intercalated mudstone and sandstone, reflecting a variety of fluvial facies. Pollen zones (data file S3) are defined by diversification of *Momipites* spp. (fossil juglandaceous pollen) (Fig. 3I). The K–Pg boundary is demarcated by the decrease in abundance of Cretaceous pollen taxa (labeled as “K-taxa”) without recovery, and subsequent fern (*Cyathidites* spp.) spike (data file S2). Relative abundance (%) of fern (*Cyathidites* spp.) and palm (*Arecipites* spp.) (Fig. 3E) palynomorphs increased dramatically post-KPgE (data file S2); note palm pollen percentages are offset from scale by 20%. Standing richness of dicot morphospecies or megafossil standing richness is exclusive of species that occur at a single locality (data files S4 to S7). Leaf-estimated mean annual temperature (LMAT) calibrated with East Asian forests (data file S8 and fig. S6). Pink horizontal bars indicate hypothesized warming intervals. Estimated leaf mass per unit area (data files S9 and S10 and fig. S7); shown with box plots that represent the distribution of species-site pair means for each 30-m bin starting from the K–Pg boundary (supplementary materials). Boxplots are placed along the y-axis near each bin’s stratigraphic midpoint, repositioned for visibility. See data file S11 and supplementary materials for placement of NALMAs. Tick marks next to GPTS, pollen zones, megafossil standing richness, and NALMAs show stratigraphic placement of samples and fossil localities (supplementary materials).

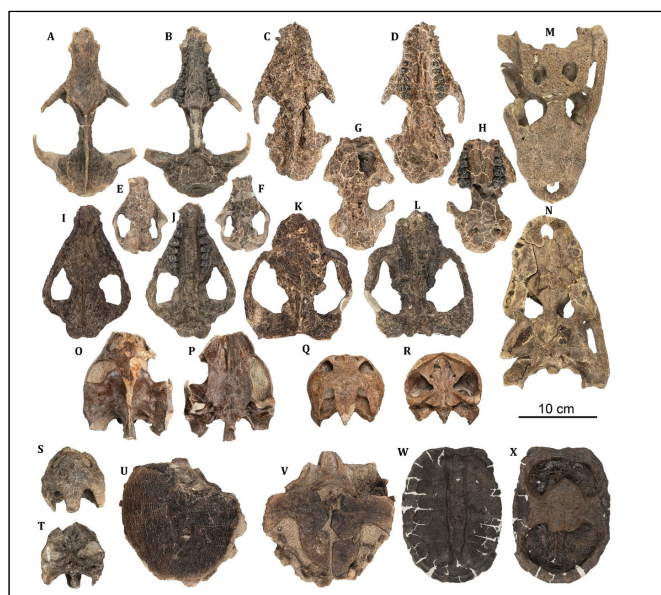


Fig. 2 Representative selection of vertebrate fossils.

(A to R) Crania in dorsal and ventral views of *Eoconodon coryphaeus* [(A) and (B); DMNH.EPV.130976], *Ectoconus ditrigonus* [(C) and (D); DMNH.EPV.130985], *Loxolophus* sp. [(E) and (F); DMNH.EPV.132501], juvenile *Ectoconus ditrigonus* [(G) and (H); DMNH.EPV.132515], *Carsioptychus coarctatus* [(I) and (J); DMNH.EPV.95283], *Taeniolabis taoensis* [(K) and (L); DMNH.EPV.95284], cf. *Navajosuchus* [(M) and (N); DMNH.EPV.48541], *Axestemys infernalis* [(O) and (P); DMNH.EPV.132514], *Palatobaena* sp. [(Q) and (R); DMNH.EPV.134081], and (S and T) *Cedrobaena putorius* (DMNH.EPV.130982). (U to X) Turtle shells in dorsal and ventral views of *Gilmoremys* sp. [(U) and (V); DMNH.EPV.95454] and *Hoplochelys* sp. [(W) and (X); DMNH.EPV.95453]. All crania and shells are scaled 1:2 compared to other specimens (10-cm scale bar).

Exceptional continental record of biotic recovery after the Cretaceous–Paleogene mass extinction (Continued)

in our dataset (supplementary materials and data file S11), we focused on maximum mammalian body mass. The largest bodied mammals disappear at the K–Pg boundary and returned to near pre-KPgE levels within 100 ka after the K–Pg boundary (Fig. 4). Subsequent shifts in maximum mammalian body mass occurred at the Pu1/Pu2 and near the Pu2/Pu3 transitions, ~300 and ~700 ka post-KPgE, respectively (Fig. 4). In addition, the pattern and abundance of vertebrates preserved in all paleoenvironments suggest that by ~700 ka post KPgE the largest mammals (25+ kg) were spatially partitioned across the landscape. We observe a strong pattern of association between taxa and facies (Fig. 4) indicating that baenid turtles (Fig. 2, Q to T) and *Taeniolabis taoensis* (Fig. 2, K and L) lived in or near river channel margins whereas chelydroid turtles (Fig. 2, W and X) and the large peripitychid mammals *Ectoconus ditrigonus* (Fig. 2, C, D, G, and H) and *Carsioptychus coarctatus* (Fig. 2, I and J) primarily occupied distal portions of the floodplain (Fig. 4).

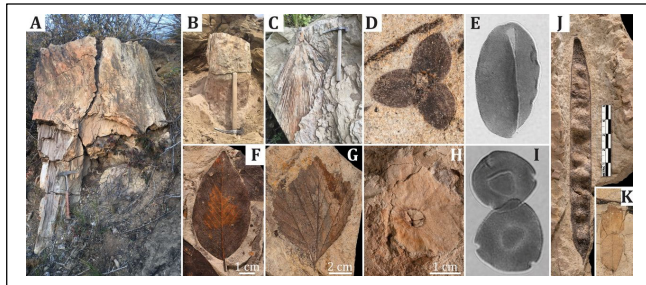


Fig. 3 Representative selection of plant fossils.

(A) In situ tree stump. (B to E) Palm fossils—in-situ stump (B), frond (C), flower (D; DMNH.EPI.45594), and *Arecipites* sp. pollen grain (E). (F and G) Most common smooth and toothed dicot morphospecies—(F) “*Rhamnus*” *goldiana* (DMNH.EPI.52262) and (G) *Platanites marginata* (DMNH.EPI.23281). (H and I) Walnut family flower and pollen—*Cyclocarya* sp. (DMNH.EPI.52272) and *Momipites tenuipolus* pollen grains preserved as a dyad (H). (J) Legume seedpod (DMNH.EPI.45540). (K) Legume leaflet (DMNH.EPI.45576). Rock hammer handle = 38 cm in (A) to (C); (D), flower is 5 mm wide; (E), pollen grain is 42 μ m long; (I), each pollen grain has a 20 μ m diameter; leaflet in (K) is scaled 2:1 compared to (J) (5-cm scale bar).

We recognize 233 plant morphospecies in our study area (supplementary materials). Despite lower sampling of Cretaceous strata (11 Cretaceous localities vs. 54 Paleocene localities), richness of dicotyledonous (dicot) leaf morphospecies from raw species counts at localities in the last ~100 ka of the Cretaceous (–18–0 m; 7 localities, 777 specimens, most speciose locality $n = 31$) and the first ~100 ka of the Paleocene (0–20 m; 6 localities, 1,019 specimens, most speciose locality $n = 13$) indicates that earliest Paleocene dicot diversity was less than half that of the latest Cretaceous (fig. S6). Additionally, 46% of Cretaceous dicot leaf morphospecies that occur at more than one site do not occur in any of our Paleocene localities. A comparable study with similar time bins from the Williston Basin estimated 57% extinction in dicot leaf morphospecies at the KPgE. Leaf mass per area (LMA), a proxy for carbon investment and ecological strategy in plants, decreased in both maximum and minimum values across the K–Pg boundary (Fig. 1 and fig. S7) consistent with a shift to faster growth strategies. Megafloral standing richness and LMA are lowest in the earliest Paleocene, but exceed pre-KPgE levels within ~300 ka (Fig. 1 and fig. S7).

Following the KPgE, many angiosperm clades diversified. The Corral Bluffs section preserves the oldest known occurrence of the Leguminosae, or bean family, as evidenced by fossil seedpods and leaflets dated to 65.35 Ma (Fig. 3, J and K). The oldest previously recognized legume is based on wood and leaflets from early Paleocene rocks of Argentina, whereas the earliest legume seedpods are not recognized until the late Paleocene (~58 Ma) of Colombia.

Exceptional continental record of biotic recovery after the Cretaceous–Paleogene mass extinction (Continued)

Our discovery supports (i) a nearly synchronous first appearance of legumes in North America and southern South America; (ii) a rapid diversification for the group in the earliest Paleocene; and (iii) their apparent origination in the Western Hemisphere.

Relative changes in leaf-estimated mean annual temperature (LMAT) (Fig. 1, fig. S6, and supplementary materials) from our section track paleotemperature proxies from sections elsewhere in the world. Corral Bluffs experienced a 4.6 °C cooling (22.1 ± 2.7 °C 1SE to 17.5 ± 3.4 °C 1SE) during the last ~100 ka of the Cretaceous, comparable to cooling estimates derived from LMAT and carbonate-clumped isotopes from the Williston Basin, and $\delta^{18}\text{O}$ of benthic foraminifera from the South Atlantic. For the first time, we corroborate a warm interval immediately post-K–Pg in a terrestrial section. Here we observe a 5.1 °C warming event (17.5 ± 3.4 °C 1SE to 22.6 ± 3.5 °C 1SE) occurred from the K–Pg boundary through the first ~60 ka of the Paleocene, similar to the ~5 °C in ~100 ka warming pulse inferred from $\delta^{18}\text{O}$ of phosphatic fish scales from the El Kef K–Pg section of Tunisia. A second ~150 ka interval (65.80–65.65 Ma) shows an initial warming of 2.2 °C (21.1 ± 3.3 °C 1SE to 23.3 ± 2.9 °C 1SE) over ~30 ka, sustained temperatures for ~50 ka, and then 3.0 °C cooling (22.7 ± 2.8 °C 1SE to 19.7 ± 3.1 °C 1SE) over ~70 ka at the top of magnetochron C29r. This event corresponds with the Danian C2 carbon isotopic excursion and inferred warming interval observed in marine and terrestrial strata. Sampling between these warming intervals is limited and an alternative hypothesis is a general warming trend from the K–Pg boundary to the magnetochron C29r/29n boundary. A third 2.9–3.2 °C warming pulse (18.0 ± 3.3 °C 1SE to 20.9 ± 3.0 °C 1SE) over ~10 ka is tentatively recognized ~700 ka post-KPgE.

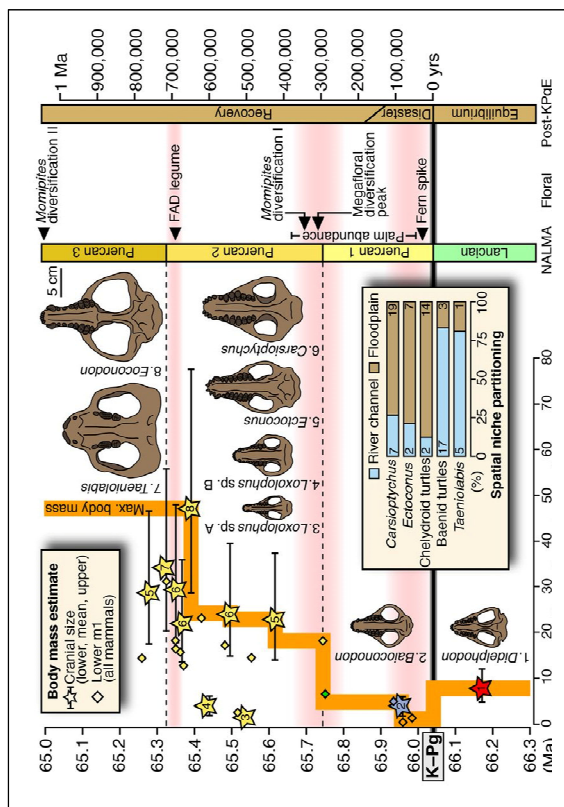


Fig. 4 Timeline of expansion of maximum body mass and niche space in earliest Paleocene mammals correlated with diversification and origination of key plant groups and warming intervals.

Post-KPgE “disaster” ecosystems occur for less than 100 ka, ecosystem “recovery” occurs between ~100–300 ka, and overall post-KPgE ecosystem equilibrium occurs within ~300 ka. Mammalian body mass estimated based on cranial and lower first molar dimensions of specimens recovered from Pu1–Pu3 intervals (data files S13 and S14 and figs. S8 and S9). Data from Corral Bluffs study area (yellow) except for Pu1 mammals, which come from adjacent outcrops in the Denver Basin (West Bijou (no fill; orange), South Table Mountain (blue), and Alexander Locality (green)) and *Didelphodon* from North Dakota (red) (data files S13 and S14 and supplementary materials). Not plotted is distribution of other large (10–100+ kg) vertebrates (e.g., turtles, crocodilians, dinosaurs) found throughout the section (Fig. 1). Pink, blurred horizontal bars represent hypothesized warming intervals interpreted from LMAT. Niche partitioning graph showing environmental distribution of vertebrate groups (data file S12): *Carsiiopteryx*, *Ectoconus*, and chelydroid turtles predominantly associated with floodplain and ponded water facies; baenid turtles and *Taeniolabis* predominantly in river channel complexes and proximal to medial crevasse splay facies. FAD = first appearance datum.

Exceptional continental record of biotic recovery after the Cretaceous–Paleogene mass extinction (Continued)

Paleotemperature and Ecosystem Recovery

The timing of these warming intervals corresponds with changes in plant richness and taxonomic composition and, likely due to additional food sources, coincident shifts in mammalian taxonomic composition, ecologic diversification, and expansion in the range of maximum mammalian body mass (Fig. 4). A mammalian taxonomic increase has been documented elsewhere in the Denver Basin, within the first 100 ka of the Paleocene, from nine species found in the earliest Pu1 faunas to 21 species found in later Pu1 faunas. Maximum mammalian body mass increased through this interval to near pre-KPgE levels, from the largest known Lancian mammal (~8 kg) to the largest known Pu1 mammal (~6 kg), coincident with the first post-KPgE warming episode (Fig. 4 and figs. S8 and S9). The Pu1/Pu2 transition occurred ~300 ka after the KPgE and was marked by the appearance of varied and large (20+ kg) peripitychid mammals. The appearance of larger-bodied peripitychid mammals, particularly the herbivorous, hard-object feeder *Carsiptychus coarctatus* (Fig. 2, I and J) (37, 38), marks a notable dietary niche specialization in the earliest Paleocene moving from the largely omnivorous/insectivorous diet found in Pu1 mammals to a more herbivorous diet found in some Pu2 mammals. This dietary shift is correlated with a three-fold increase in maximum mammalian body mass compared to Pu1 faunas (Figs. 1 and 4 and figs. S8 and S9). The Pu1/Pu2 transition was coincident with the onset of a high plateau in megafloral standing richness, an increase of LMA beyond pre-KPgE levels, a doubling of the diversity of *Momipites* spp. [fossil juglandaceous (walnut family) pollen (Fig. 3I)], and the second early Paleocene warming interval (Figs. 1 and 4). The diversification of Juglandaceae taxa with small, winged seeds to later taxa with larger wingless seeds is hypothesized to reflect a transition from wind to animal transport. This hypothesis is supported by the close correlation between diversification reflected in fossil juglandaceous pollen and the appearance of several large herbivorous peripitychid mammals whose specialized and enlarged premolars are thought to be for hard-object feeding. Finally, the appearance of legumes co-occurred with a tentatively recognized short warming pulse and shift in maximum mammalian body mass. Specifically, two large-bodied mammals appear within ~700 ka post-KPgE (Fig. 4) – the herbivorous multituberculate *Taeniolabis taoensis* (~34 kg) and the omnivorous triisodontid archaic ungulate *Eoconodon coryphaeus* (~47 kg) (Fig. 2, A and B). These data suggest that earliest Paleocene warming pulses may have played an important role in post-KPgE ecosystem recovery, perhaps by facilitating immigration and/or in situ co-evolution of flora and fauna.

The transition from an ecosystem characterized by a small-bodied mammalian fauna, post-“disaster” ferns, and low diversity plant communities to one exhibiting a larger-bodied mammalian fauna and more ecologically and taxonomically complex forests mirrors modern post-disaster ecological successions, but on a much longer timescale (typically 10^4 – 10^5 years for recoveries from global mass extinctions versus 10– 10^2 years for modern local-regional ecological recoveries). The overall and long-term recovery we observe has recently been described as an aspect of “Earth system succession”. This concept proposes that global ecological succession following mass extinctions is intrinsically paced by the interactions of the biosphere and geosphere, both of which may be knocked out of equilibrium. The low-diversity, small-bodied mammalian fauna and low-diversity forests dominated by ferns and palms, often indicative of ecological disequilibrium, suggest that a period of ecosystem disequilibrium lasted for up to ~100 ka post-KPgE in our research area. A period of ecosystem “recovery” followed ~100 – 300 ka post-KPgE when megafloral diversity steadily increased. At ~300 ka post-KPgE we see several additional signs of ecosystem “recovery”, including i) the increase and then plateau of megafloral standing richness; ii) LMA exceeding pre-KPgE levels; iii) diversification of Juglandaceae, a potentially energy-rich food source for mammals; and iv) the first significant taxonomic diversification, dietary specialization (e.g., increased herbivory), and increase in maximum body mass of mammals (Pu1/Pu2). Finally, spatial niche partitioning, appearance of several additional large (30+kg) mammals, and expansion of mammalian body mass disparity continues through ~700 ka at the Pu2/Pu3 boundary, all further indications of ecosystem “recovery.” These changes are correlated with the arrival of plant taxa (e.g., legumes) that would have offered mammals new calorie-dense food sources. Taken together, our record places time

Exceptional continental record of biotic recovery after the Cretaceous–Paleogene mass extinction (Continued)

estimates on the patterns of biotic recovery in Earth system succession and demonstrates that several aspects of ecosystem “recovery” occurred within ~300 ka post-KPgE (Fig. 3).

The pattern of warming pulses correlated with biotic change during the earliest Paleocene demonstrates a strong relationship between the biosphere and geosphere. The Deccan Traps of the Indian subcontinent represent repeated and voluminous volcanic eruptions ($>10^6$ km³ of magma) during the post-KPgE Earth system succession. These eruptions might have induced warming pulses via the release of greenhouse gases (e.g., CO₂). Recent work on the timing of these eruptions places ~70% of the total volume within the 300–400 ka window roughly coincident with the earliest Paleocene warming pulse(s) observed at Corral Bluffs and the temporally correlated shifts in biotic recovery (Figs. 1 and 4). Although not a feedback of the biosphere-geosphere system, Deccan eruptions likely influenced atmospheric chemistry, in turn shaping Earth system succession and post-KPgE ecosystem recovery (Fig. 4). Detailed records of post-mass extinction biotic recovery, such as the one presented here, will provide a critical framework for predicting ecosystem recovery following mass extinction events including the one we currently face.

Read more about this article at: <https://science.sciencemag.org/content/early/2019/10/23/science.aay2268?fbclid=IwAR2qYGNY8bRFYjgoOab1fEOMV7phSCr8GwBt46Cu0s7N84PGlsinXSzHyV8&intemp=trendmd-sci>

U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction

Two timelines for extinction

The Cretaceous-Paleogene extinction that wiped out the nonavian dinosaurs 66 million years ago was correlated with two extreme events: The Chicxulub impact occurred at roughly the same time that massive amounts of lava were erupting from the Deccan Traps (see the Perspective by Burgess). Sprain *et al.* used argon-argon dating of the volcanic ash from the Deccan Traps to argue that a steady eruption of the flood basalts mostly occurred after the Chicxulub impact. Schoene *et al.* used uranium-lead dating of zircons from ash beds and concluded that four large magmatic pulses occurred during the flood basalt eruption, the first of which preceded the Chicxulub impact. Whatever the correct ordering of events, better constraints on the timing and rates of the eruption will help elucidate how volcanic gas influenced climate.

Continental flood basalt provinces are characterized by eruption of >1 million km³ of basalt over a period of <1 million years, representing the largest volcanic events on Earth. Four of the five most severe Phanerozoic mass extinctions [~ 541 million years (Ma) ago to the present] coincided with emplacement of one of these provinces. Although the temporal link between flood basalts and extinctions is well established, the mechanisms by which eruptions drive extinction are poorly understood. Two models of environmental change from volcanic activity relate to eruptive volatile emissions. The first is volcanogenic CO₂ release, with associated global warming, ocean acidification, and carbon cycle disruption. The second is SO₂ injection into the stratosphere and its conversion to sulfate aerosols, causing global cooling, acid rain, and ecosystem poisoning. The predicted time scales of these perturbations contrast sharply. The emission of SO₂ from a single eruption would produce years of cooling, whereas accumulated greenhouse warming from CO₂ can be sustained for many thousands to tens of thousands of years. Testing the effects of this interplay on ecosystems thus requires precisely calibrated volcanic eruption rates that can be correlated to high-resolution climate proxy and biostratigraphic data.

We applied U-Pb zircon geochronology to construct a precise temporal record of eruption within the Deccan Traps volcanic province, India (Fig. 1). The province is temporally correlated to the K-Pg mass extinction, in which

U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction (Continued)

roughly three-fourths of life on Earth was eradicated, including non-avian dinosaurs. Previous attempts to constrain eruption rates were limited by poor stratigraphic coverage and/or high analytical uncertainties. We used U-Pb geochronology by isotope dilution–thermal ionization mass spectrometry (ID-TIMS), which provides analytical uncertainties ($\pm 2\sigma$) as low as 40,000 years (40 ka) for individual dated zircons. Our sampling covers the nine major Deccan formations in the Western Ghats, where the most voluminous (>90% total volume) and complete Deccan exposures are preserved (Fig. 1). We sampled both coarse-grained basalts and sedimentary beds between basalt flows that infrequently contain zircon-bearing volcanic ash (fig. S1). These beds, locally termed “redboles,” range from oxidized volcanoclastic material with visible lithic fragments and phenocrysts to paleosol-type horizons produced by in situ weathering of flow tops. Of 141 sampled redboles and coarse-grained basalts (Fig. 1 and figs. S1 and S2), 23 redboles and one basalt sample yielded sufficient zircon (≥ 5 crystals) to estimate an eruption age, including four distinct bole horizons and one basalt previously presented by Schoene *et al.* Pristine volcanic crystal morphology indicates minimal transportation or reworking of zircon in a sedimentary environment. Consequently, we inferred that this volcanoclastic, zircon-bearing material was incorporated into redboles as air fall tuff, consistent with some redboles containing a high-SiO₂ (nonbasaltic) component, and that these zircons provide a robust means for dating Deccan eruptive stratigraphy.

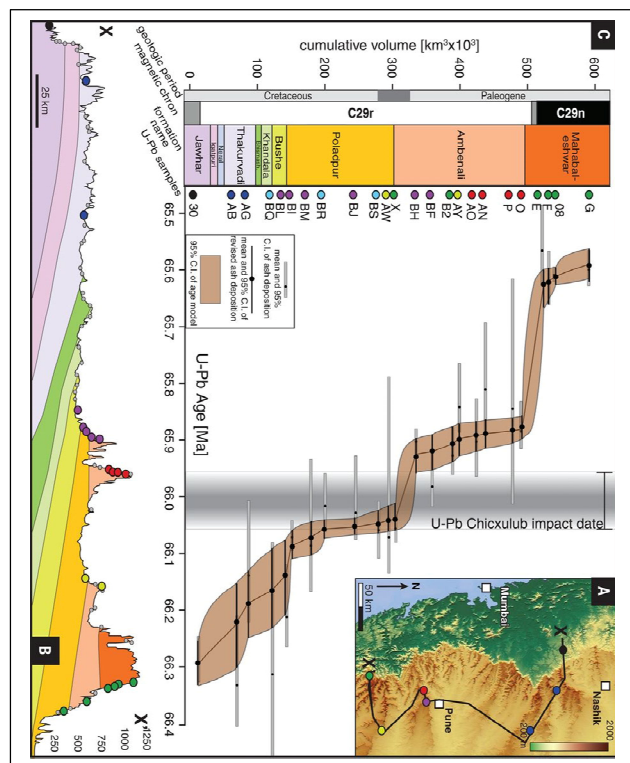


Fig. 1 Stratigraphy, sampling transects, and U-Pb age model for the Deccan Traps.

(A) Elevation map of study location in the Western Ghats, India. A black segmented line denotes cross section X-X' as shown in (B). Sampling transects are located by colored dots. (B) Geologic cross section through the field area, with sample locations indicated. Different basalt formations in the Deccan Traps are color-coded to the stratigraphic column in (C). Cross section is based on previous work, modified according to our geochronology. (C) Volumetric stratigraphic column and magnetic chrons of the major formations of the Deccan Traps. The plotted sample heights (“RB” sample prefix omitted) are based on the composite stratigraphic section compiled in fig. S2. The age model for the Deccan Traps, based on our U-Pb geochronology, is shown with 95% credible intervals. Horizontal gray bars indicate eruption ages derived from populations of zircon dates from each horizon; black horizontal bars show dates refined from the stratigraphic Bayesian model. The vertical gray-shaded bar shows an age for the Chicxulub impact.

To estimate the eruption date and associated uncertainty for each sample, we developed an approach using Bayesian statistics to account for the probability distribution of zircon dates and their analytical uncertainties (fig. S6). Although we considered alternative data interpretations, they do not affect the conclusions of this study. Twenty-one of 24 dated horizons are from five stratigraphic sections along prominent roads in the Western Ghats, providing complete coverage of the upper four Deccan formations (Fig. 1 and figs. S1 and S2). The remaining three samples

U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction (Continued)

span the lower five Deccan formations, where redboles are rare and less likely to contain zircon.

When compiled into a composite stratigraphic section (Fig. 1), almost all samples follow anticipated “younging-up” temporal order based on the independently defined regional stratigraphy (figs. S2 and S7). The exception is the Katraj Ghat south of Pune city, where two samples from what was mapped as upper Poladpur Formation are ~100 ka younger than samples near the Poladpur-Ambenali contact in other sections. To resolve this discrepancy, we placed the Poladpur-Ambenali contact in the Katraj Ghat section as ~100 m lower than previously mapped. This simple adjustment does not violate geochemical or geological observations in the stratigraphy, as the Poladpur-Ambenali contact is geochemically transitional in published datasets. Furthermore, our placement of the contact is consistent with geochemical studies of the nearby Sinhagad Fort section suggesting that the Poladpur Formation is relatively thin just south of Pune.

To further refine the composite stratigraphic age model, we used a Bayesian Markov chain Monte Carlo (MCMC) model in which stratigraphic superposition is imposed on U-Pb zircon dates (Fig. 1). The result is a deposition age estimate for each dated horizon, incorporating dates from all beds above and below each sample to produce an internally consistent age model (Fig. 1). The accuracy of refined age estimates depends solely on sample placement in proper stratigraphic order and is independent of samples’ exact stratigraphic heights.

To calculate volumetric eruption rates through the Deccan Traps, we adopted the volume model of Richards *et al.*, in which units of the Wai subgroup (i.e., the Poladpur, Ambenali, and Mahabaleshwar Formations) were interpreted as more voluminous than is apparent from their proportionate thickness in the Western Ghats. This assertion carries nontrivial uncertainties, but we believe it is justified given the correlation of these formations to basalt flows on the province’s periphery, including massive flows that traveled ~1000 km to India’s eastern shore. Although different volume models produce changes in the magnitude of calculated eruption rates, the timing of peak eruption rates is unaffected by either the volume model or the interpretation approach of the zircon data (figs. S8 and S9). Additional uncertainty relates to the unconstrained mass and age of Deccan basalt that is currently submerged and inaccessible off India’s western shore. We consider this uncertainty to be intractable because current volume models cannot account for this mass component of the province. Consequently, all eruption rates are likely minimum estimates, although we also cannot assess whether the offshore component erupted during the same time intervals as that of the Western Ghats.

We converted our age model into a probabilistic estimate of volumetric flux of basaltic lava using outputs from the MCMC algorithm (Fig. 2). Our results showed that the Deccan Traps erupted in four high-volume events, each lasting ≤ 100 ka, separated by periods of relative volcanic quiescence. The first event corresponded to the eruption of the lowermost seven formations from ~66.3 to 66.15 Ma ago; the second to the Poladpur Formation from ~66.1 to 66.0 Ma ago; the third to the Ambenali Formation from ~65.9 to 65.8 Ma ago; and the fourth and final to the uppermost Mahabaleshwar Formation, from ~65.6 to 65.5 Ma ago.

Our Deccan eruption model (Fig. 2) constrains the volcanic tempo with high resolution, providing a means to correlate eruption records with biostratigraphic and climate proxy data across the K-Pg extinction. Our model places the second pulse of Deccan volcanism (Poladpur Formation, 66.1 to 66.0 Ma) as slightly predating a published U-Pb zircon date for the K-Pg boundary (KPB), defined as the Ir anomaly and associated fallout from the Chicxulub impact, within the Denver Basin, Colorado. For consistency, we applied the Bayesian approach to that dataset to estimate a date of 66.016 ± 0.050 Ma ago for the KPB [95% credible interval, internal uncertainties only].

U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction (Continued)

Comparison of our data with recently published $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology from the Deccan Traps and the Chicxulub impact is currently not possible at the necessary level of precision given systematic bias between the two dating methods, primarily related to uncertainty in ages of $^{40}\text{Ar}/^{39}\text{Ar}$ fluence monitors and the values of the ^{40}K decay constant and physical constants. Assuming that the Chicxulub impact coincides exactly with the main phase of extinction, the MCMC model outputs from our Deccan data demonstrate a ~90% probability that the Poladpur Formation eruption pulse began tens of thousands of years before the K-Pg mass extinction event.

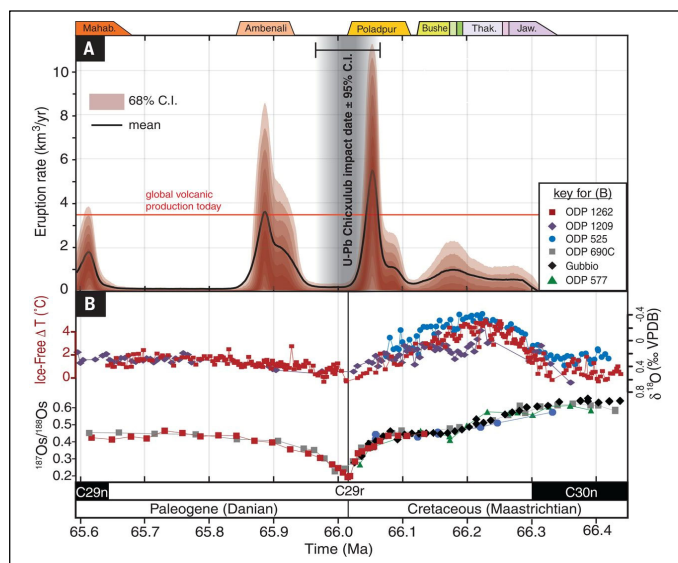


Fig. 2 Eruption rate model for the Deccan Traps, based on U-Pb geochronology.

(A) Results from the MCMC algorithm used to generate the age model in Fig. 1, converted to a probabilistic volumetric eruption rate for the Deccan Traps shown with contours up to 68% credible intervals. The U-Pb date for the Chicxulub impact is the same as in Fig. 1. Total global volcanic productivity (~3 to 4 km³/year) includes mid-ocean ridges and volcanic arcs. (B) Compilation of proxy records from ODP cores and outcrops. Upper data points are $\delta^{18}\text{O}$ of species-specific benthic foraminifera from ODP 525, ODP 1262, and ODP 1209; VPDB, Vienna PeeDee Belemnite standard. Temperature is calculated for benthic foraminifera *Nuttallides truempyi* in ODP 1262. Osmium isotopic records come from bulk carbonate from both ODP cores and outcrop. Age models are described in.

The K-Pg extinction preserves the only known mass extinction that coincides with both a large igneous province and a bolide impact. As such, several hypotheses have been forwarded in which the impact triggered or modulated volcanic eruptions. Although the most recent iteration of this hypothesis concedes initiation of Deccan eruptions several hundred thousand years before the impact, it proposes that impact-induced seismicity increased eruption rates in the Deccan Traps and at mid-ocean ridges through evacuation of preexisting magma chambers in the upper mantle and lower crust. It is unlikely that our Deccan eruptive history is consistent with this model, given the high probability that the Poladpur pulse began before the impact by tens of thousands of years, followed by an eruption hiatus of ≤ 100 ka after the impact.

Estimates for the entire volcanic flux on Earth today are 3 to 4 km³/year, indicating on average a doubling in global volcanic activity for ≤ 100 ka during each of the four high-volume Deccan eruptive events, but requiring periods of >5 to 10 times the global average. In fact, groups of flows within the Poladpur and Mahabaleshwar Formations, each potentially comprising $>50,000$ km³, lack secular evolution in paleomagnetic poles, suggesting eruption over decades to centuries. Such high eruption rates of >1000 km³/year are permitted by our U-Pb geochronology, requiring hiatuses of hundreds to thousands of years within our resolved pulses so as not to exceed total volume estimates. In addition to being consistent with brief but extreme eruption rates, our data demonstrate that the Deccan Traps erupted in pulses with durations of ~100 ka, providing insight into tempos of melt production and/or transport in the upper mantle and lower crust.

Our eruption rate model is a first step toward robustly evaluating the environmental impacts associated with

U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction (Continued)

Deccan volcanism. The most commonly cited contributors to environmental change associated with flood basalts are CO₂ (warming), SO₂ (cooling upon conversion to sulfate aerosols), and chemical weathering of fresh basaltic material (cooling via CO₂ drawdown). For single continental flood basalt flows that erupt over a few decades, volcanic SO₂ has been modeled to drive cooling of 5° to 10°C for the duration of the eruption, after which acid rain rapidly removes sulfur compounds from the atmosphere. For persistent cooling over many thousands of years, therefore, hiatuses of only several decades between eruptions are required.

In contrast to SO₂, the time scale of CO₂ removal from the ocean-atmosphere system is slow: ~1 ka, ~10 ka, and ~100 ka for mixing into the deep ocean, reaction with sediments, and removal by silicate weathering, respectively. As a result, although climate effects during an eruptive event may be dominated by cooling associated with elevated sulfate aerosols, accumulation of volcanic CO₂ emissions can lead to net warming on intermediate time scales between eruptive events. On time scales of hundreds of ka to >1 Ma, weathering of fresh basalt has been modeled to result in net CO₂ drawdown and cooling, especially if the basalt is at low latitudes, as were the Deccan Traps.

As an initial attempt to correlate our eruptive history with paleoenvironmental data, we used two proxy records across the K-Pg transition (Fig. 2B). Benthic foraminifera $\delta^{18}\text{O}$ compositions indicate ~2° to 4°C of deep ocean warming over ~150 ka, beginning at the C30n-C29r magnetic reversal (~66.3 Ma ago), followed by cooling over ~150 ka prior to the KPb. It has also been argued on the basis of $\delta^{18}\text{O}$ data from Elles, Tunisia, that renewed warming began tens of thousands of years before the KPb (fig. S11).

Initial warming at ~66.3 Ma ago and a coeval increase in carbonate dissolution have been interpreted as resulting from volcanogenic CO₂ buildup and consequent ocean acidification, which our geochronology shows to have occurred during the initial pulse of Deccan eruptions. Warming curtailed toward the end of the first pulse, and cooling began before and continued through the initiation of the Poladpur Formation eruptions (Fig. 2). The extrusion of the voluminous Poladpur Formation may have resulted in short periods of SO₂-driven cooling that could have continued to promote the overall cooling trend, but cooling for tens of thousands of years due to SO₂ emissions is difficult to sustain given the predicted short residence time of sulfate aerosol. Alternatively, an increase in surface area of exposed basalt associated with the Poladpur eruptions is possible given current Deccan stratigraphic area/volume models, resulting in enhanced basalt weathering, CO₂ drawdown, and continued global cooling during the tens of thousands of years before the extinction. If periods of cooling did result from sulfate aerosols during the Poladpur eruptions, the short intervals of temperature decrease could have slowed silicate weathering and associated CO₂ drawdown, thus permitting CO₂ buildup in the atmosphere that would be manifest between punctuated eruptions within the Poladpur Formation.

Testing whether basalt weathering was important leading up to the KPb is aided through study of the Os isotope system in marine carbonates because the ocean residence time of Os is short and basaltic $^{187}\text{Os}/^{188}\text{Os}$ is low [0.1] relative to late Mesozoic seawater [0.6]. Published Os isotopic data from marine carbonates show a marked decrease toward mantle values beginning at the onset of Deccan volcanism (Fig. 2B). A second downturn in $^{187}\text{Os}/^{188}\text{Os}$, beginning tens of thousands of years before the KPb, has been interpreted as a downward redistribution of extraterrestrial Os derived from the Chicxulub impactor. However, this decrease is synchronous with the Poladpur eruption pulse and is thus also consistent with increased weathering of a more extensive Deccan basalt pile.

Post-extinction and post-Chicxulub benthic foraminifera $\delta^{18}\text{O}$ and carbonate Os isotopic records do not covary with the Deccan eruption record. However, the Os record does not recover to the pre-Deccan $^{187}\text{Os}/^{188}\text{Os}$ value either,

U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction (Continued)

perhaps indicating that a steady state was reached between basalt production and weathering despite continued eruptions. Regardless, the starkly different responses of O and Os isotope records during the post-extinction recovery require models that explicitly incorporate the effects of continued Deccan eruptions, the Chicxulub impact, and biotic effects on the carbon cycle in a world with devastated ecosystems.

Although the initiation of a massive eruptive pulse shortly before the Chicxulub impact and mass extinction supports a Deccan contribution to ecosystem collapse, much remains to be discovered as to how flood basalt magmatism contributes to mass extinctions. U-Pb geochronology has shown that, similar to the K-Pg extinction, the end-Permian (~252 Ma ago) and end-Triassic (~201 Ma ago) mass extinctions occurred on short time scales (< tens of ka), hundreds of thousands of years after the onsets of the Siberian Traps and Central Atlantic Magmatic Province flood basalt provinces, respectively. The eruptions and associated intrusive magmatism are presumed to have driven rapid extinction despite this time lag and the absence of bolide impacts. This lag between the onset of magmatism and extinction may be a result of highly nonlinear rates of magmatism, as documented here for the Deccan Traps. Continuing to study other flood basalt provinces will clarify the importance of eruptive and intrusive tempo in driving ecosystem collapse and extinction. Such an understanding of biosphere sensitivity and the importance of threshold processes during climate change is as relevant today as for these catastrophic events in Earth history.

Read more about this article at: <https://science.sciencemag.org/content/363/6429/862?intcmp=trendmd-sci>

Machu Picchu was hit by strong earthquakes during construction

The Incan citadel of Machu Picchu in Peru is known for its marvelous stonework. But several structures at the site suffered through at least two earthquakes as they were being built, a new study suggests. Those temblors not only damaged walls, but also triggered a sudden change in construction techniques.

The study—an archaeological survey of three of Machu Picchu's most significant temples—reveals more than 140 examples of damage. These include large blocks of stone that have shifted or whose corners have been chipped. Some of this damage can be attributed to slumping rocks or soil beneath the temples. But the movement of many damaged blocks, including substantial gaps between some formerly interlocking blocks of stone, was likely driven by seismic shaking from at least two major quakes, the team concludes. That's because the type of damage seen on the corners of blocks embedded in the stone walls only occurs as they rhythmically clatter against each other during an earthquake, researchers report this month in the *Journal of Seismology*.

The quakes that rattled Machu Picchu likely occurred between 1438 and 1491 C.E., the period when the main parts of the city were developed and well before Europeans arrived in the area. A lack of written records or oral tradition make it difficult to narrow that window of time. Regardless of when those quakes occurred, construction thereafter shifted to a cheaper and easier scheme of merely stacking smaller blocks of rock (upper layer of stones, above right), not carving them so that they interlocked.

The Andes are no stranger to strong quakes. Besides a major subduction zone offshore, which can spawn megaquakes with magnitudes of 8 or greater, there are active faults inland as well as some that lie directly beneath Machu Picchu itself.

Read more about this article at: <https://www.sciencemag.org/news/2019/10/machu-picchu-was-hit-strong-earthquakes-during-construction>

Global impacts of thawing Arctic permafrost may be imminent

The Arctic permafrost, frozen soil that is chock full of carbon, is a ticking time bomb. When it thaws because of global warming, sometimes slumping into pits like on Herschel Island in Canada (above), scientists believe it is likely to release more carbon than it absorbs from new plant growth—adding to the atmosphere's burden and accelerating climate change. But studies in the Arctic have been so limited that no one could say when that time would come.

It's here now, according to research published today by a large team of scientists in *Nature Climate Change*. By pooling observations from more than 100 Arctic field sites, scientists from the Permafrost Carbon Network estimate that permafrost released an average of 1662 teragrams of carbon each winter from 2003 to 2017—double that of past estimates. Meanwhile, during the summer growing season, other surveys have found that the landscape absorbs only 1032 teragrams—leaving an average of more than 600 teragrams of carbon to escape to the atmosphere each year.

The study remains limited by the paucity of Arctic observations; the overall uncertainty of Arctic winter emissions, for example, is 813 teragrams, nearly half the total emissions. The study also found no rise in emissions since 2003. Still, researchers say, it's a sign that the permafrost feedback—which would see carbon emissions from permafrost lead to warming that would in turn thaw more permafrost—is already underway.

Read more about this article at: <https://www.sciencemag.org/news/2019/10/global-impacts-thawing-arctic-permafrost-may-be-imminent>

How the world's largest geode grew to half the size of a small bedroom

Most geodes—hollow, crystal-lined rocks—can fit in the palm of your hand. But the giant Pulpi Geode, which is about half the size of a small bedroom, fills part of an abandoned mine in southeastern Spain. Now, researchers have analyzed some of its crystals to figure out its age—and how this real-life Fortress of Solitude came to be so big.

The 11-cubic-meter geode—the largest in the world, the researchers say—was discovered in 1999, in a long-closed mine near its namesake town. Some of the crystals are several meters long and are so pure that they're transparent, despite their thickness.

Although the geode is embedded in rocks that are about 250 million years old, the crystals themselves are much younger than that. Radioactive dating of some of the oldest suggests they formed less than 5.6 million years ago but probably no more than 2 million years ago, the researchers report this week in *Geology*.

Although the cave is now dry, when the geode was growing, its cavity was filled with hot, mineral-rich water. The oldest layer of crystals, which include the mineral barite (barium sulfate), formed at temperatures of about 100°C. Subsequent layers, which include crystals of celestine (strontium sulfate), grew in waters somewhere around 70°C. The youngest crystals of gypsum (hydrated calcium sulfate) formed at temperatures of about 20°C at least 60,000 years ago—well before the coldest part of the last ice age.

Read more about this article at: <https://www.sciencemag.org/news/2019/10/how-world-s-largest-geode-grew-half-size-small-bedroom>

Underwater volcano belched explosive bubbles larger than a stadium

Two years ago, a barely submerged volcano in Alaska's Aleutian Islands released giant bubbles of gas, some of which were broader than the world's largest humanmade dome, the 310-meter-wide National Stadium in Singapore, researchers reported today in *Nature Geoscience*. Known as Bogoslof, the volcano vents only 100 meters below sea level, with remnants of past eruptions forming a steaming lagoon at the ocean's surface (above). Historically, at Bogoslof and other similar submarine volcanoes, passing ships have reported that before an explosive eruption, a giant, black dome emerges out of the ocean. But these exploding bubbles have remained poorly understood, as they make studying the volcanoes hazardous.

So, researchers spied on Bogoslof from afar, using low-frequency microphones in the ocean 59 kilometers to the south. The volcano erupted more than 70 times over 9 months. And a distinctive, seconds long grumble preceded each eruption, scientists found. The vibration matched the song that eruptive bubbles would sing as they stretched, over expanded, and collapsed, computer modeling shows.

The Bogoslof bubbles likely reached up to 440 meters in diameter and formed when lava hit seawater and chilled, creating a cap over the volcano's vent. A bubble of volcanic water vapor, carbon dioxide, and sulfur dioxide then pushed the cap outward, until the encapsulating film of volcanic rock and liquid water collapsed to produce an eruptive plume.

Read more about this article at: <https://www.sciencemag.org/news/2019/10/underwater-volcano-belched-explosive-bubbles-larger-stadium>

This lake on Mars was drying up 3.5 billion years ago

Mars was a very different place as a young planet. Liquid water dotted the Red Planet's landscape with lakes and rivers. But the planet's climate changed drastically in the past few billion years. Today, scientists see the remains of the planet's bodies of water in dried-up river channels and salts left in its rocks.

Now, new data from the Curiosity rover show that the planet's waters were evaporating about 3.5 billion years ago. Curiosity found pockets of concentrated salts in rocks about 3.3 – 3.7 billion years old in Mars' Gale Crater. This is evidence that a salty lake was evaporating from the surface around that time, scientists reported Monday in a new paper in *Nature Geoscience*.

Uncovering martian history

Curiosity is well suited to studying the evolution of Mars' environment because of its access to Gale Crater. The crater formed when a meteor hit Mars at least 3.5 billion years ago, leaving a 100-mile-wide hole in the ground. The crater still exposes layers of rock hundreds of yards deep. The deepest rocks are the oldest, and higher rocks make up younger, more recently formed layers. So, Curiosity can analyze the chemical compositions of rocks and, in the process, document Mars' history back at least 3.5 billion years. It's a unique opportunity to study how a planet's environment can change across billions of years.

Curiosity's latest work shows that rocks in Gale Crater between about 3.3 and 3.7 billion years in age had pockets of sulfur-containing salts called sulfates. Older rocks that Curiosity analyzed didn't have such concentrations of these salts. That leads scientists to believe this is evidence that a lake at Gale Crater was particularly salty around this time. The lake may have gotten saltier then because the waters were evaporating, leaving higher concentrations of salt behind. If true, it implies that Mars' climate was changing and becoming drier around 3.5 billion years ago.

This lake on Mars was drying up 3.5 billion years ago (Continued)

To William Rapin, a planetary scientist at Caltech and an author of the new study, the project is an exciting way to uncover Mars' history and understand more broadly how planets and their environments evolve over time.



Mars' Gale Crater once held a lake of liquid water.

“Our geology and our understanding of planets’ climates is very Earth-centric,” Rapin says. “Mars has had its own fate, potentially very different than the Earth.”

Read more about this article at: <https://astronomy.com/news/2019/10/this-lake-on-mars-was-drying-up-billions-of-years-ago>

Quakes reveal Mars has a unique interior

NASA's Mars InSight spacecraft landed on the Red Planet in November 2018. Scientists equipped the mission with a seismometer so they could learn how Mars releases seismic energy — that is, to get a feel for how the Red Planet rumbles. So far, InSight has recorded more than 100 seismic signals, and researchers are confident at least 21 of those are real marsquakes. But these quakes aren't exactly what they expected to hear, and the findings have sparked intense curiosity about what lies beneath the dusty surface of Mars.

Strange rumblings

InSight caught its first likely marsquake on April 6. The tiny quake, which occurred during a lull between a gust of wind and NASA moving the lander's robotic arm, looked a bit like quakes recorded on the Moon in terms of duration and size. But the signal was too small to reveal information about the planet's deep interior.

The way Mars vibrates can tell researchers a lot about what the planet's interior is made of and how it's structured. Prior to InSight, planetary scientists expected rumbling on Mars to look like the earthquakes and moonquakes we see in our home system. But it turns out that's not the case. “The signatures, the shape of the signals, is not really anything that we're familiar with from either the Earth or the Moon,” says InSight Principal Investigator Bruce Banerdt.

NASA recently released audio from two such events. The sound of these quakes indicate that Mars' structure may look like a combination of Earth and the Moon. So far, Mars seems to “ring” longer during a quake, more like the Moon, as opposed to Earth, where quakes appear and disappear much more quickly.

Quakes reveal Mars has a unique interior (Continued)

Into the unknown

InSight's initial mission will last one Mars year, or about two Earth years. During that time, it will collect plenty of quakes. "We're seeing sort of an average of a couple, maybe a couple events of some sort per week, lately," says Banerdt. Not all of them will turn out to be real marsquakes, but some are.

The seismometer *has* seen about the number of small events — magnitude 3.5 and below on the Richter scale — that scientists were prepared to detect. But there are few events above that magnitude, which is not what they expected.

But that expectation, Banerdt says, is based on what's been observed on Earth and the Moon. "We don't know yet whether [the lack of bigger events is] just the statistics, or whether it just means that Mars has a little bit different distribution of the way that it releases its seismic energy than the Earth and the Moon," he says.

Only time — and more marsquakes — will tell. And whether Mars turns out to act like we thought, or to defy expectations, the InSight team is excited. "Having Mars tell us something a little bit different, it means that there's some aspect of planetary behavior that has not yet been understood," says Banerdt. "And so that's really an exciting possibility that we're going to learn something fundamentally new about the way planets work in a physical sense."

Read more about this article at: <https://astronomy.com/news/2019/10/quakes-reveal-mars-has-a-unique-interior>

Plant hydraulics and agrichemical genomics

A challenge of continued efforts to increase crop yields to feed the expanding population is that humans are competing with crop plants for clean water. Treatment of wastewater is required not only for drinking, but also to water crops. For example, when wastewater is used on crops, some vegetables accumulate synthetic contaminants, including antibiotics and psychoactive drugs arising in part from personal care products and pharmaceuticals disposed in drains. Ensuring that crop plants grow efficiently even when clean water is in short supply is crucial to secure food production. On page 446 of this issue, Vaidya *et al.*, using prior knowledge of the structure of a family of plant proteins that play a key role in drought tolerance, introduce a new generation of synthetic compounds that may lead to reduced water use in agriculture.

Although animals and plants both need clean water, plants use water as a hydraulic system much like bones and muscles—that is, for strength in maintaining an erect structure, and for movement of root and shoot tissues in response to gravity and sunlight. Thus, one of the most important water-associated properties in plants is turgor pressure, the force of the plasma membrane against the thick cellulose cell wall. In plants, turgor pressure is high when the cells have high concentrations of osmolytes, such as K^+ ions. When osmolyte concentrations are low, the cells become flaccid. Because of the semi-rigid cell wall, turgor pressure in plants is a formidable force necessary for plant growth and development. A graphic example of this is the observation of tree roots disrupting pavement.

Although the hormone abscisic acid (ABA) affects water usage in all plant cells, there are two cell types in which it plays especially important roles. After fertilization of the ovule by pollen, ABA is responsible for regulating the water content of the developing embryos as they are desiccated naturally on their way to becoming dry seeds. This hormone plays an equally important role in regulating the water content of guard cells in leaves. Guard cells form pores (called stomata) in leaves, and these holes are the main pathway through which water is lost and carbon dioxide (used for photosynthesis) enters the plant. The state of inflation of guard cells, determined through turgor pressure, regulates the size of the pore that forms in the space between them. ABA and guard cells have thus been a major

Plant hydraulics and agrichemical genomics (Continued)

focus of basic and translational plant research for many decades.

Unlike animals, plants use proton gradients to regulate water pressure at the plasma membrane. A protein transporter that pumps protons (H^+) out of plant cells can generate much higher membrane potentials than are found in animals. This provides a huge driving force for the major osmolyte, K^+ , to become concentrated inside the cytoplasm via potassium channels. In touch-sensitive plants, such as *Mimosa pudica* and the Venus flytrap (*Dionaea muscipula*), the rapid movement of plant parts generated by touch is driven by an action potential that changes at the millisecond time scale and leads to rapid collapse of the membrane potential and loss of intracellular K^+ . This in turn leads to rapid loss of water and, consequently, loss of turgor. In guard cells, instead of rapid mechano-sensitivity-induced turgor changes, slower hormone-mediated turgor pressure changes occur, which result in opening or closing of the stomatal pore. Therefore, engineering ABA-like compounds that specifically alter guard cell function is a key aspect of current agricultural research to lower water loss via stomatal transpiration from plants.

In a series of landmark discoveries in 2009 arising from an analysis of *Arabidopsis thaliana* mutants together with in vitro reconstitution and x-ray crystallography, the critical early events in ABA perception were elucidated. These studies revealed that the ABA receptor family comprises small proteins that function in different cell types with different affinities for ABA and, together with ABA, form a ternary complex with a protein phosphatase. When ABA or its synthetic analogs bind to the receptor, a portion of the protein acts as a gate and swings down and blocks the active site of the phosphatase enzyme.

The study of Vaidya *et al.* combined chemical genomic screens and synthetic organic chemistry guided by protein crystal structures to identify a new generation of ABA receptor agonists that are active at lower concentrations in the two major phylogenetic categories of land plants: dicots (such as soybean) and monocots (such as wheat). Through a salt bridge to a specific lysine in the ABA receptor, the new compounds add a “lock” to the latch on the gate, keeping the phosphatase inhibited. This leads to an increase in the phosphorylation state of a specific protein kinase that initiates a signaling pathway that leads to drought tolerance.

The ABA receptor gene family has 14 members, each of which is expressed at different amounts in different plant tissues and has different affinities for ABA. Therefore, because of this functional redundancy, finding compounds that bind to each of the receptors with different specificities and affinity is an important but challenging goal for basic research purposes as well as for future applications in lowering water use in agriculture.

Even though most plants die when their water content drops below ~75%, all plant cells encode in their DNA the proteins that allow their cells to stay alive at 12% water content, because plants desiccate embryos to form seeds as a natural and carefully programmed part of their life cycle. However, staying alive and producing high yields of food even during periods of drought are two different outcomes. ABA receptor activation controls water dynamics in all cells of the plant, but the loss of water through transpiration via leaf guard cells during the noonday sun while carbon dioxide is taken up through these same pores creates a paradoxical competing situation of maximizing crop yields (by promoting photosynthesis) while minimizing water needs. Perhaps an armada of technologies that chemically and genetically alter the various ABA receptors throughout the plant can hasten a “blue” revolution in water use efficiency that could be as important for our future as the green revolution that arose from the scientific research of decades past.

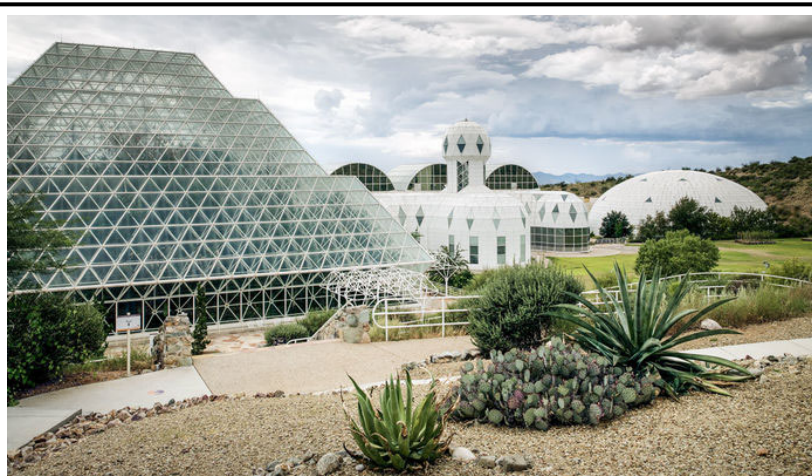
Read more about this article at: <https://science.sciencemag.org/content/366/6464/416>

Unprecedented drought in an artificial ecosystem may reveal how rainforests will cope with climate change

Earlier this month, the doors to the tropical rainforest, enclosed under a ziggurat of glass, were sealed shut. Christiane Werner turned a valve to release about \$12,000 worth of carbon dioxide (CO₂) spiked with carbon-13, an isotope that is normally scarce in the atmosphere. The luxuriant plants inside Biosphere 2, a 30-year-old set of greenhouses and artificial ecosystems in the Arizona desert, soaked up the isotopic tracer, enabling investigators to follow the flows of carbon through the healthy forest. Werner, an ecosystem physiologist at the University of Freiburg in Germany, and her team gathered these baseline data for the harsh test to come: the largest forest drought experiment ever monitored with isotopes. "It will be amazing to see the results," says Tamir Klein, a plant ecophysiology at the Weizmann Institute of Science in Rehovot, Israel, who is not involved.

On 7 October, the researchers shut off the sprinklers that irrigate the rainforest, beginning a 6-week drought. Next month, they will inject another pulse of isotopically enriched CO₂ into the densely instrumented ecosystem and apply other tracers. A forest's consumption of CO₂ slows during drought, but scientists haven't pinned down how thirsty rainforest plants—especially large trees—use and release their stored carbon. The answers are important for the global climate cycle, Klein says. Droughts, expected to become more severe as the climate warms, could turn tropical forests from sinks of greenhouse gases into sources that accelerate climate change.

Field experiments in the Amazon, in which plastic panels intercept rain to keep large swaths of forest dry, have sketched out how drought kills trees of different sizes. Smaller studies targeting individual plants with isotopic tracers have revealed some of the impacts on plant function. But the Biosphere 2 experiment will do both by applying tracers across an entire forest. "We have an ecosystem in a lab," Werner says.



The Biosphere 2 rainforest greenhouse, built in Arizona in the late 1980s, contains 90 plant species.

The \$150 million Biosphere 2 was built in the late 1980s as a kind of spaceship on Earth, in which humans would attempt to survive inside a sealed ecosystem. That mission flopped, but the University of Arizona now operates the facility for research, education, and tourism. It has hosted large ecology studies and an ongoing 3million experiment in landscape evolution. Biosphere 2's original funder, financier Edward Bass, helped support that earlier work, but much of the new experiment is funded by part of a €1.9 million grant Werner won from the European Research Council. About 50 researchers from 13 institutions are contributing equipment and expertise.

Unprecedented drought in an artificial ecosystem may reveal how rainforests will cope with climate change (Continued)

The focus is Biosphere 2's tropical forest, which includes some 90 plant species across an area the size of seven tennis courts. All summer, the team prepared by building canopy platforms where they could enclose dozens of leaves and stems in small chambers to capture their emissions. They drilled into tree trunks to insert probes, and dug observation pits to measure emissions from soil and roots. Four kilometers of tubing carry gases from the probes to a room full of instruments. "The scale of measurements on this drought is completely unparalleled," says co-leader Laura Meredith, a biogeochemist at the University of Arizona in Tucson and director of rainforest research at Biosphere 2.

By tracking the carbon-13, the researchers will learn how quickly carbon is taken up during photosynthesis and then moves through the forest. They will compare those rates before and during the drought across six tree species that differ in their drought resistance. And they will learn how the trees apportion stored carbon in their leaves, trunks, and roots. It's a "huge black box," and crucial for predicting how plants respond to stresses like drought, says plant physiologist William Anderegg of the University of Utah in Salt Lake City.

Another set of tracers will show in finer detail how particular metabolic pathways use carbon. During the past month, the researchers have supplied a solution of isotopically enriched pyruvate, a chemical building block used in many biological processes, to leaves, roots, and clumps of soil. One type of pyruvate tracer reveals how much carbon is given off during daytime respiration—a key part of the carbon cycle that needs to be better quantified, Werner says. Another pyruvate tracer, taken up into a different pathway, shows how much carbon the plants and soil microbes use to synthesize volatile organic compounds (VOCs). When plants are stressed, these chemicals make up a considerable fraction of their carbon emissions. They can warm the atmosphere or turn into aerosols that cool it, but their overall climatic effect is unknown. Plants use VOCs for many purposes, including as a homing signal for a vast web of soil fungi that provide water and nutrients to roots during drought. The researchers hope to quantify rates and amounts of VOCs exchanged between the microbes and plants and whether they change during drought.

At the end of the drought, the researchers will perform one last tracer experiment, irrigating the deep soil with water enriched in an isotope of hydrogen. They expect large trees to take up most of the water, and they hope to learn whether their deep root systems will leak some of the water into the shallow soil, helping smaller plants recover. Finally, the sprinklers will turn on and return the ecosystem to normal. When parched soil and fallen leaves are rewetted, microbes go into metabolic overdrive and churn out CO₂ and VOCs. Meredith and her colleagues will measure emissions and link them to patterns in microbial genes.

Ultimately, results from the drought test will improve the way global climate models account for vegetation. "You need these experiments to unlock the physiology and add it into the models," Anderegg says. "It gets us much more mechanistic and rigorous projections of how tropical trees and forests might respond to climate change." After the experiment wraps up, tourists will be let into the rainforest again. But the canopy platforms will remain for future research, and some of the carbon tracers will also stick around. "We can look for the signal for years to come," Meredith says.

Read more about this article at: <https://www.sciencemag.org/news/2019/10/putting-artificial-ecosystem-drought-could-reveal-how-rainforests-will-cope-climate>

Fernbank Events & Activities

Fernbank Forest Night Walk

Friday, November 1, 2019 6:30 PM

Join a Fernbank scientist on a guided tour of Fernbank Forest to experience the unique nocturnal world that awakens at dusk.

Adventures in Science

Saturday, November 2, 2019 10:00 AM

Join us as we investigate what it's like to be a scientist.

Fernbank After Dark: Cocktails & Culture

Friday, November 8, 2019 7:00 PM

Explore beverages, writing, dance and other cultural traditions through a variety of fun, hands-on activities and interactive demonstrations inspired by special exhibit, Traveling the Silk Road.

Latin Dance Night

Friday, November 15, 2019 8:00 PM

Spice things up with sassy Latin rhythms as you dance the night away to Salsa, Bachata, Cumbia and Merengue.

Things New and Strange: A Southerner's Journey Through the Smithsonian Collections

Sunday, November 17, 2019 4:30 PM

Free lecture and book signing by Dr. G. Wayne Clough, author of Things New and Strange: A Southerner's Journey through the Smithsonian Collections.

Past Meets Presence: Yoga Under the Dinosaurs

Thursday, November 21, 2019 7:00 PM

Join instructor Elizabeth Rowan for an evening of movement and meditation. Beginners welcome!

Sensory Morning

Saturday, December 7, 2019 9:00 AM

Join us for a series of special sensory events, designed for guests with sensory sensitivities, special needs or various physical abilities who might benefit from a less-crowded environment.

Noon Year's Eve

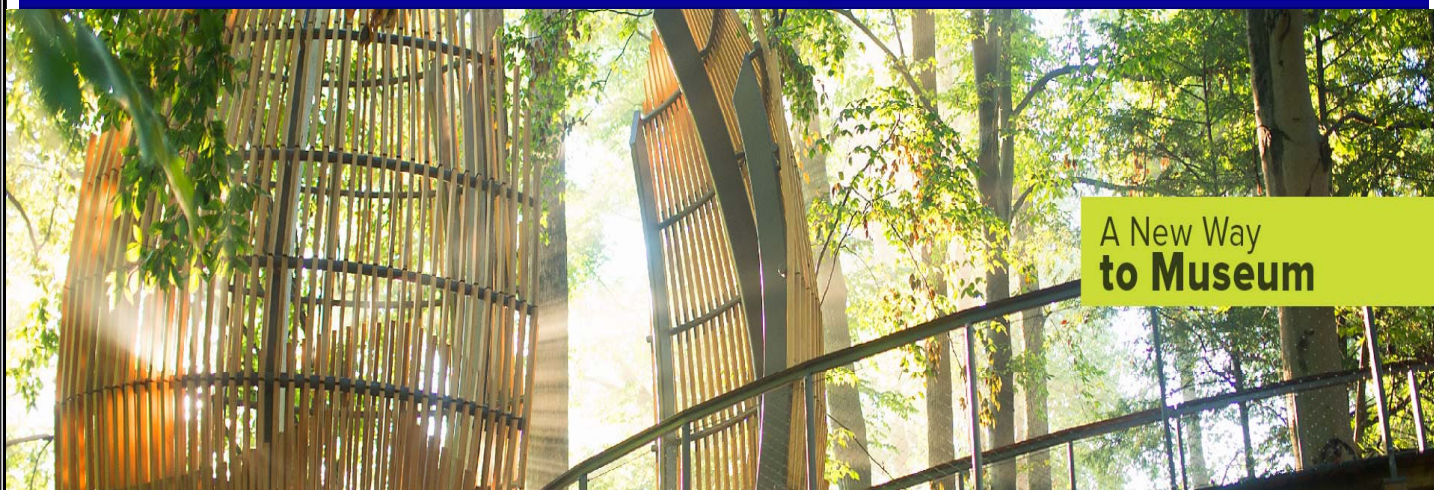
Tuesday, December 31, 2019 9:00 AM

Ring in the New Year a full twelve hours early with Atlanta's biggest party animals.



FERNBANK MUSEUM

of NATURAL HISTORY



A New Way
to Museum



A New Way to Museum

Take a walk on the wild side as you explore 75 acres of new outdoor nature adventures. WildWoods and Fernbank Forest combine to highlight the natural world through immersive trails, educational programming, hands-on exhibits and beautiful scenery.

New for Summer! Experience the wonders of nature on Fernbank's giant 4-story screen with Backyard Wilderness 2D, and enjoy hands-on nature adventures outside in WildWoods.



Apollo 11 First Steps Edition 2D

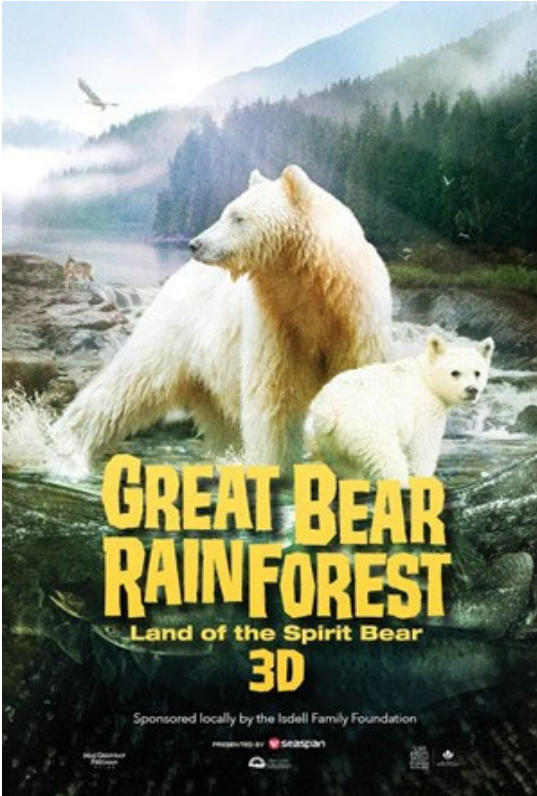
Showing May 31 through December 31, 2019

In this special giant-screen edition created exclusively for science centers and museum theaters of Todd Douglas Miller's critically acclaimed Apollo 11 documentary, the filmmakers reconstruct the exhilarating final moments of preparation, liftoff, landing and return of this historic mission—one of humanity's greatest achievements and the first to put men on the moon.



Fernbank Museum of Natural History
 (All programs require reservations, including free programs)

Now showing in the Fernbank IMAX movie theater:



Great Bear Rainforest 3D

Showing May 3 through October 31, 2019

Hidden from the outside world, the Great Bear Rainforest is one of the planet's most exquisite and secluded wildernesses. Found on Canada's rugged Pacific coast, it is the largest temperate coastal rainforest in the world and is home to indigenous First Nations peoples, who have provided stewardship of the forest for millennia. Embark on a remarkable journey into a land of grizzlies, coastal wolves, sea otters, and humpback whales—and discover the secret world of the Spirit Bear. Narrated by Ryan Reynolds.

Volcanoes: The Fires of Creation 3D

Showing September 13 through January 16, 2019

From the air we breathe to the water we drink, volcanoes have helped shape the Earth's landscape for billions of years. Between eruptions and cooling magma, over 500 volcanoes ignite the fires of creation on Earth today, continuing to form environmentally significant ecosystems and wildlife habitats on the planet. Journey around the globe from Hawaii to Ethiopia, Vanatu to Pompeii to explore the fascinating world of lava lakes, acid ponds and geysers. Dodge boulders and descend into hot lava with adventurer and photographer Carsten Peter.

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AGS 2019 - 2020 Meeting Dates

Listed below are the planned meeting dates for 2019 - 2020. Please mark your calendar and make plans to attend.

2019 - 2020 Meeting Schedule

November 26

December No Meeting

January 28

February 25

March 31

PG Study Group meetings

November 30

December No Meeting

January 25

February 29

March 28

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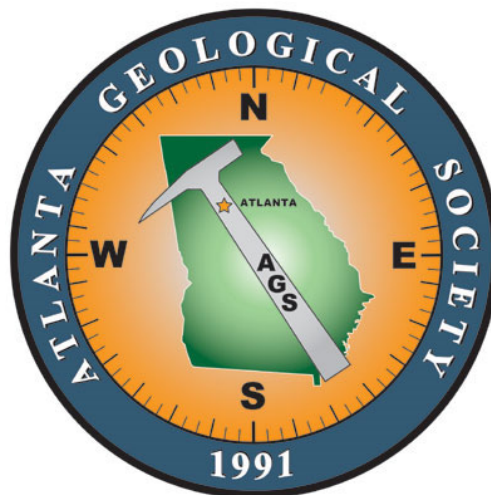
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STUDENT \$10 ☐

PROFESSIONAL MEMBERSHIP \$25 ☐

CORPORATE MEMBERSHIP \$100 ☐

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For further details, contact the AGS Treasurer:
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