to space. In this scenario, no hypothetical missing reservoir is needed.

The crust hydration scheme has several implications for Mars' evolution. Global crust hydration may require a warm and wet climate to sustain liquid water. H released from the water-rock reactions itself could possibly sustain the warm climate because of its greenhouse effect in a dense carbon dioxide (CO_2) atmosphere (the Mars atmosphere is 96% CO_2) (*5*). Whereas H escape from water would lead to oxidation of the Mars surface (Mars is 0.2% O_2), crust hydration could possibly induce the accumulation of H in Mars' atmosphere (which would ultimately escape into space).

Crust hydration is common on Earth, but plate tectonics recycle the crust to the underlying mantle, and volcanism returns water to the hydrosphere. The absence of plate tectonics on Mars causes irreversible crust hydration. The traditional view holds that the difference in planetary sizes and the presence or absence of global magnetic fields led to the divergent fates of the two planets. The notion of crust hydration on Mars supports the importance of plate tectonics for the sustainability of liquid water on terrestrial planets.

The crust hydration scenario does not mean that atmospheric escape is not a major factor in Mars evolution. Surface oceans, which may be required for global crust hydration, need to be sustained by the greenhouse effect of a dense atmosphere, which is thought to have been chiefly lost through atmospheric escape processes. The D/H ratio recorded in an old (~4.1 billion years) martian meteorite suggests that substantial water loss predates the periods of geomorphologically recorded liquid water (*4*, *6*). The atmospheric escape rate could have been higher during this earlier period, when solar extreme ultraviolet radiation and solar wind were more intense. Future studies will need to quantify the contribution of crust hydration on water loss and how it changed throughout martian history. Nevertheless, Scheller *et al.*'s study highlights the importance of the aqueous alteration of crust as a potential driver of the climate change and the potential role of plate tectonics to control the sustainability of surface water, both of which are crucial for understanding planet evolution. ■

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PALEONTOLOGY

The impactful origin of neotropical rainforests

A mass extinction event led to vast diversity and structural complexity of neotropical rainforests

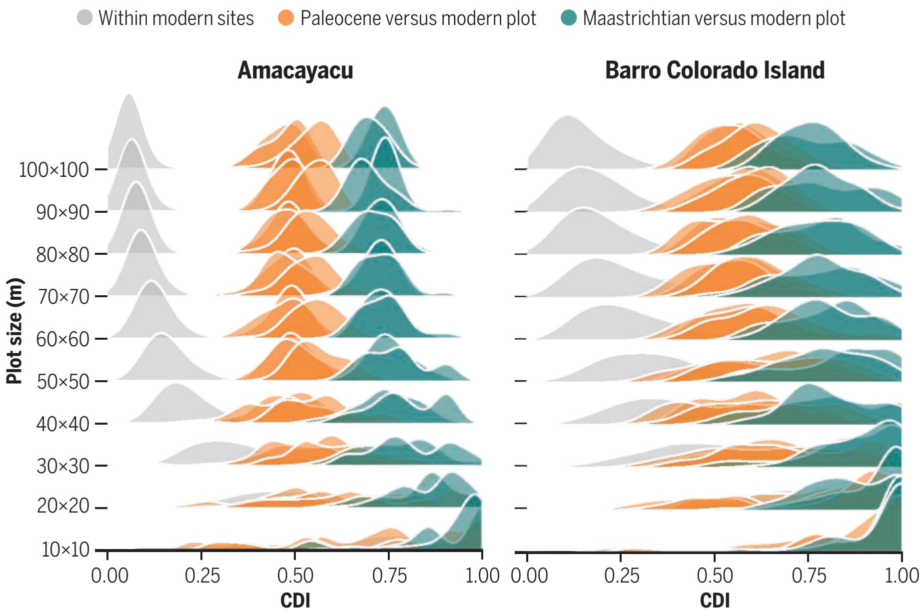
By **Bonnie F. Jacobs**[1] and **Ellen D. Currano**[2,3]

About 66 million years ago (Ma), at the boundary of the Cretaceous-Paleogene (K/Pg) period, a sudden mass extinction was triggered by the impact of a bolide, destroying an estimated three-quarters of Earth's plant and animal species. The long-term effects of this event varied across Earth, and little is known about the outcome in low-latitude regions of the world. On page 63 of this issue, Carvalho *et al.* (*1*) report analyses of fossil pollen and leaf data across the K/Pg boundary, ~1500 km south of the Chicxulub crater left behind by the impact. They assessed plant diversity and structure in the lowland tropics before and after the catastrophe, put their interpretations into the broader context of flowering plant (angiosperm) evolution, and answer one of the biggest questions in paleobotany: When and how did the diverse, angiosperm-dominated, stratified tropical forests of South America emerge?

Before about the mid–20th century, the low-latitude regions of the world were severely underexplored paleontologically, owing in part to perceived hindrances, including surface vegetative cover and the extreme weathering (and decomposition) of organic matter in soils of the wettest areas. In contrast to this were the obvious benefits of working in the mid-latitude temperate zones, where sediments were easy to see, excavate, and core into and known to produce fossils. A dearth of paleontologists in tropical countries exacerbated this relative neglect because developing nations were just beginning to train and hire their own scientists. Today, the situation is much improved, but to address big questions through paleontology, it takes time to collect and study samples,

Leaf comparison

Leaves from unbiased fossil census sites are compared with leaves from trees in 50 randomly selected areas of varying size within a 25-ha forest plot at Amacayacu (Colombia) and a 50-ha forest plot at Barro Colorado Island (BCI, Panama) (*1*). Dissimilarity at the family level is shown as density plots (Chao-Sørensen dissimilarity index, CDI). The Paleocene sites are more similar in family composition to the living forests of Barro Colorado Island (Panama) and Amacayacu (Colombia) than they are to the Cretaceous census sites.



GRAPHIC N. CARY/*SCIENCE* BASED ON M. R. CARVALHO *ET AL.* (*1*) and big gaps remain regarding the evolution of Earth's tropical biodiversity and its role in global climate dynamics through time.

Well-preserved leaves from the Cretaceous Guaduas and the mid-Paleocene (the earliest epoch of the Paleogene, 66 to 56 Ma) Cerrejón and Bogotá floras of Colombia and a compilation of pollen samples from 39 cores spanning the K/Pg boundary provided Carvalho *et al.* with hundreds of samples from which forest composition and structure could be determined (see the figure). A suite of methods was applied, including leaf vein density measures and determining the range of leaf carbon isotope values, both of which served as proxies of light variations. Leaf insect damage diversity and intensity were analyzed to assess ecosystem connectedness and stability. In addition, numerical analyses of >600 pollen samples through time provided a view of diversity, composition, and rates of change across the K/Pg boundary.

A fossil leaf from a 58 to 60 million years ago (Paleocene) tropical rainforest in Colombia was among the samples assessed by Carvalho *et al.* to determine forest composition and structure.

The well-supported findings of Carvalho *et al.* reveal that angiosperms were well on the way to becoming dominant and diverse members of forest communities by the latest Cretaceous—a previously accepted consensus (*2*, *3*). But it is now clear that in the tropics, as is true at higher latitudes, gymnosperms (cone-bearing plants, for example) and ferns were important members of forested communities before the K/Pg boundary. In addition, light availability in these forests, representing forest openness, was greater than in the early Paleogene. Across the boundary, diversity declined and became more dominated by angiosperms but did not exceed preboundary levels until about 60 Ma (an evolutionary recovery time of ~6 Ma). Although some angiosperm families found today in rich tropical forests were present in the latest Cretaceous (~69 Ma), they mingled with an (approximately equal) abundance of gymnosperms and ferns in a more open, nonstratified forest structure. It took a bolide smashing into Earth to reset these low-latitude ecosystems, putting them on a path to the rich, stratified tropical forests of today in the most productive terrestrial region of the world.

How do these findings differ from what is known elsewhere? The K/Pg extinction event demolished nonavian dinosaurs and killed off >75% of all species worldwide. What has become clearer more recently is that plant extinction and turnover varied, depending upon proximity to the impact location, the nature of the preimpact flora, and climatic conditions in the millennia afterward.

Until recently, K/Pg floras were reported primarily from the US western interior basins of North Dakota, Montana, Colorado, and New Mexico. Here, some 3000 km from the impact, loss in diversity of pollen and macrofossil taxa across the boundary is reported to range from 30 to >50%. Insect damage also reflects the strong imprint of the boundary event at this latitude. The telltale signs of high diversity, such as the presence of specialized leaf mines, decline across the boundary. Not far from these interior basins, and up against the newly emerging Rocky Mountain front, is the Denver Basin's Castle Rock site, which, in a wet, warm climate, preserves a highly diverse flora only about 1.6 Ma after the boundary event (*4*). This unusual flora was referred to as a rainforest, but its structure is unknown. Yet although floral diversity is high, insect damage diversity is among the lowest reported in the Paleocene. Combined high plant and insect damage diversity, as occurred in the latest Cretaceous, does not recur among the western US basins for some 10 Ma into the Paleocene (*5*). Thus, there is substantial heterogeneity among Paleocene plant localities even among the western US basins.

More than 8000 km from the impact crater, paleofloras from Patagonia document a very different pattern of change across the boundary. Latest Cretaceous pollen and spore assemblages from Patagonia indicate dominance by angiosperms, ferns, and gymnosperms, but, despite a large loss in overall diversity across the boundary, conifers extirpated elsewhere on Earth survived through to the earliest Paleocene (*6*). Patagonian macrofloras document a decline in specialized leaf miners across the boundary event but here took only 4 Ma (as opposed to 10 Ma) from which to recover (*5*, *7*). Similarly, major loss of leaf species (45%) across the boundary and the emergence of a different pattern of leaf shapes (*8*) reflect substantial ecosystem change. But palynological (pollen and spore) samples show change of little consequence at higher taxonomic levels. Thus, Patagonia, >8000 km from the impact crater, experienced less severe consequences of the impact than nearer sites to the north. As expected, palynological samples recently reported from New Zealand (*9*), ~12,000 km from the impact, show only moderate changes across the boundary. Gymnosperms declined about 10%, and although angiosperms increased to 60%, substantial dominance to 80% takes place later, in the Eocene (56 to 43 Ma).

The Carvalho *et al.* study and others show that a global catastrophe involving a mass extinction produces a different world, which recovers in a spatially and temporally heterogeneous way. At the K/Pg boundary, a bolide impact caused a mass extinction event, but the effects were heterogeneous—the consequences depended on proximity to the crater and local conditions such as climate. Today, the world is experiencing a sixth mass extinction event, but this time, there is no place on Earth far from the ultimate cause—humans. It seems that proximate perturbations are and will be substantial everywhere, even if they vary. ■

[1]Roy M. Huffington Department of Earth Sciences, Southern Methodist University, P.O. Box 750395, Dallas, TX 75275, USA. [2]Department of Botany, University of Wyoming, 1000 E. University Avenue, Laramie, WY 82071, USA. [3]Department of Geology and Geophysics, University of Wyoming, 1000 E. University Avenue, Laramie, WY 82071, USA. Email: bjacobs@mail.smu.edu

PHOTO: M. R. CARVALHO *ET AL.* (*1*)

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