trate ulegyria, a cortical scarring that may have resulted from circulation problems in the womb.

A grim discovery prompted the new investigation. In early 2015, Wässle set out to identify victims whose remains ended up in Hallervorden's "Series H" collection, which included slices of Hans-Joachim's brain. In the process, he came upon a cardboard box containing about 100 brain sections. He confirmed that at least some were from euthanasia victims: Not all the Nazi-era slides were interred at Waldfriedhof after all. A search at the psychiatry institute also turned up more slides.

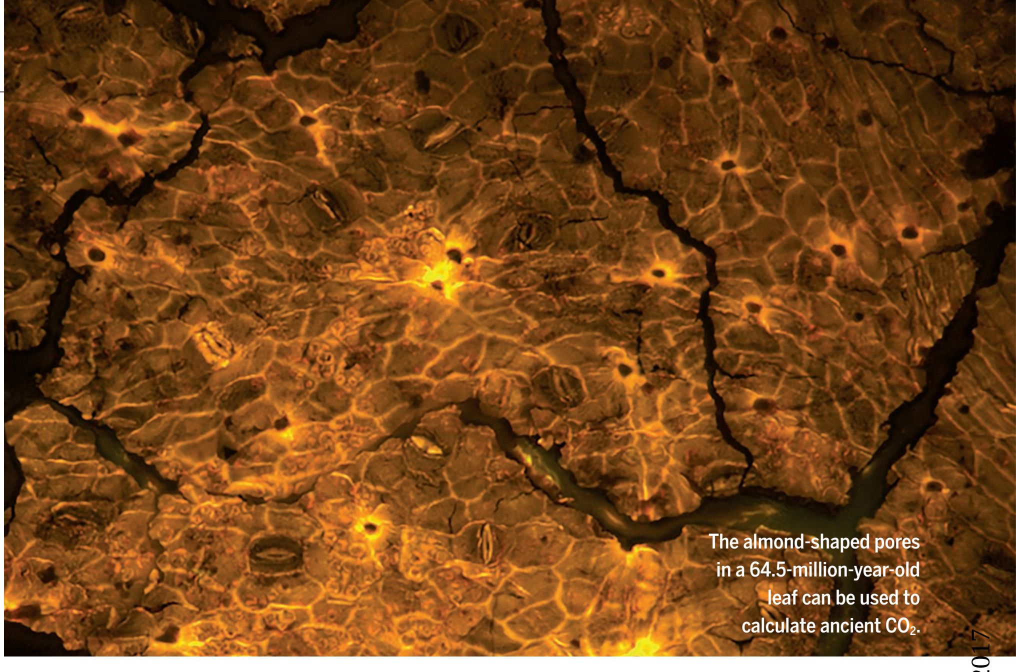
Over the next 3 years, the investigators will attempt to uncover any remaining specimens and link them to clinical records at hospitals and asylums, university archives, and KWG scientists' files, now scattered across a couple dozen institutions. Weindling says he and his colleagues hope to identify as many as 5000 victims. "Everybody knows that Nazi scientists were conducting unethical research," he says. "But what has never been done is a full-scale reconstruction of the extent to which it had taken place."

The historians also hope to gain a better understanding of how unethical science was allowed to flourish in Nazi Germany. The scientists involved "were not bizarre and perverse psychopaths," Roelcke says. "In the postwar period, they were very well integrated in German society. They were very good researchers of international standing. So what are the conditions under which these kinds of biomedical scientists are prepared to initiate or commit atrocities to further their research interests?"

Because Hallervorden and many other complicit scientists kept their positions after the war, Roelcke adds, probing MPG's role during the Nazi era was long taboo, and the reluctance persisted long after the first investigations. Roelcke encountered resistance several years ago, when he attempted to document that Ernst Rüdin, the Nazi-era director of KWG's Institute for Psychiatry in Munich, and the University of Heidelberg in Germany were involved in research on child euthanasia victims.

"This is not only about 'forgotten' specimens, but the apparent whitewashing of the [MPG's] darkest history and the failure to adequately respond to and to commemorate the tragic past," says Martin Keck, clinic director at the Max Planck Institute of Psychiatry. Roelcke sees the new investigation, and particularly Wässle's involvement, as an encouraging sign that MPG is ready to fully confront its past. ■

Megan Gannon is a journalist in Berlin.



The almond-shaped pores in a 64.5-million-year-old leaf can be used to calculate ancient CO_2.

PALEOCLIMATE

Fossil leaves bear witness to ancient carbon dioxide levels

Relics warn that climate may be more sensitive to atmospheric CO_2 than models predict

By **Eric Hand**

When it comes to carbon dioxide (CO_2) and climate, the past is prologue. Barring radical change to humanity's voracious consumption of fossil fuels, atmospheric CO_2 is bound to go up and up, driving global warming. But it won't be the first time that CO_2 has surged. In Earth's ancient atmosphere, scientists see the faint outlines of a CO_2 roller coaster, climbing and dipping across deep time in repeated bouts of climate change. "Each little slice in Earth's past is a replicated experiment," says Dana Royer, a paleoclimatologist at Wesleyan University in Middletown, Connecticut. "It helps us think about where we may be headed in the near future."

If only the past could be seen more clearly. Models of ancient atmospheres and tools for teasing out past CO_2 levels from fossils and rocks all have limitations. Now, scientists have developed a new method for wringing CO_2 estimates from fossilized leaves—one that can go deeper into the past, and with more certainty. "At the moment, it's very promising and it's probably the best tool that we've got," says David Beerling, a biogeochemist at the University of Sheffield in the United Kingdom who helped develop the so-called fossil leaf gas exchange technique. Already, it is solving ancient climate puzzles and delivering some unsettling news about the future.

Last month, at a meeting of the American Geophysical Union in San Francisco, California, another pioneer of the technique, plant physiologist Peter Franks of the University of Sydney in Australia, trained it on one of those puzzles: the time shortly after an asteroid impact killed off the dinosaurs 66 million years ago. Tropical forests were growing at temperate latitudes, yet earlier studies suggested CO_2 levels of about 350 parts per million (ppm)—less than levels today and seemingly too low to create a global hothouse. Based on a gas exchange analysis of fossil leaves in what was once a tropical forest at Castle Rock, near Denver, Franks and his colleagues now conclude that the atmosphere 1.5 million years after the impact contained CO_2 at about 650 ppm—a far more plausible level.

But in applications of the method to times between 100 million and 400 million years ago, Franks finds hints of a foreboding message. During documented episodes of global warmth, he says, the method reveals relatively low CO_2 values, nothing like the levels of 2000 ppm or more suggested by other proxies. If these downward revisions hold, Earth may be even more sensitive to injections of CO_2 than current models predict. "Temperatures are going

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to climb further for less carbon and we better be mindful of that," Franks says.

Geoscientists go to elaborate lengths to figure out Earth's past climate. For temperatures, they typically measure oxygen isotopes in carbonate rocks made up of the shells of tiny sea creatures that once lived near the sea surface. As temperatures drop, the animals tend to incorporate more of a heavier oxygen isotope into their shells—yielding a reliable measure of sea surface temperatures, which correlate well to atmospheric temperatures. "Those estimates are pretty good," Franks says. "CO_2 is the harder problem."

For the past 800,000 years, CO_2 levels can be measured more or less directly, in air bubbles trapped in ice cores retrieved from Antarctica or Greenland. But for earlier times, scientists look to models or proxies. Models reconstruct atmospheric CO_2 based on the geological processes that affect the long-term carbon cycle. Before humans came along, volcanoes were responsible for injecting most CO_2, whereas CO_2 was removed by the burial of organic matter—think coal beds—and the weathering of rocks and formation of limestone. By rewinding the motions of plate tectonics and tracking broad areas of volcanism, vegetation, and weathering, scientists such as the late Bob Berner of Yale University were able to chart rising and falling CO_2 over hundreds of millions of years. But their curves had huge margins of error.

Proxies, in contrast, ground estimates of ancient CO_2 in real observations. A handful of them have been used for the past 100 million years (see graphic, right). But for more ancient epochs, geoscientists rely on fossil soils (paleosols) or fossil leaves. Some paleosols contain nodules of precipitated calcium carbonate as well as bits of organic matter, from which atmospheric CO_2 levels can be worked out. But although they are sensitive recorders of higher CO_2 levels, paleosols do poorly below a few hundred ppm.

In the 1980s came the first method based on plant stomata—little openings that allow CO_2 into the leaf, where it is fixed into sugars through photosynthesis. Plants tend to have fewer stomata when CO_2 is plentiful, because water also escapes through these pores and plants must guard against losing too much. But the number of stomata in each species responds to rising or falling CO_2 in its own way. When fossil leaves belong to existing plant lineages like ginkgos, scientists can estimate ancient CO_2 levels based on studies of close contemporary relatives. But for extinct species, they have to take a best guess. And in contrast to paleosols, the stomatal technique is insensitive to high CO_2.

Franks and his colleagues set out to improve it. Their leaf gas exchange technique, outlined in a 2014 paper in *Geophysical Research Letters*, relies on two key inputs. One is a calculation of stomatal density—not only the number, but also the size and depth of the stomata in a fossil leaf—which indicates the rate at which gas could pass in or out of the plant. The other is an analysis of organic residue in the fossil, which contains carbon isotopes that track the ratio of CO_2 inside the leaf to that in the atmosphere. Together, those factors can be parlayed into a reading of the atmospheric CO_2 concentration.

Jennifer McElwain, a paleobotanist at University College Dublin and a longtime advocate for the basic stomatal method, was initially a critic of the arriviste. But she has since come around and is using it alongside older techniques. "It is going to be widely adopted and it is going to be a powerful method," she says.

If the gas exchange technique does end up supplanting the others, its lower-than-expected values for ancient CO_2 offer a sobering message for the future. Climate modelers talk about climate sensitivity—how much the world will warm for a doubling of CO_2 from preindustrial values of 280 ppm. (With Earth recently passing 400 ppm, it is well on its way.) Most of the models used in assembling the latest report of the Intergovernmental Panel on Climate Change, which forecasts climate change and its impacts, have sensitivities that cluster around 3°C.

But these estimates focus on "fast feedbacks"—effects that will quickly amplify small amounts of warming, such as the shrinkage of Arctic sea ice and the rise in atmospheric water vapor, itself a greenhouse gas. They ignore longer term feedbacks like the melting of land-based ice sheets and changes in vegetation, which most scientists say will contribute additional warming over decades or centuries. "They can't take into account these large-scale, deep-time processes—that's what we can glean from the geological history," Franks says.

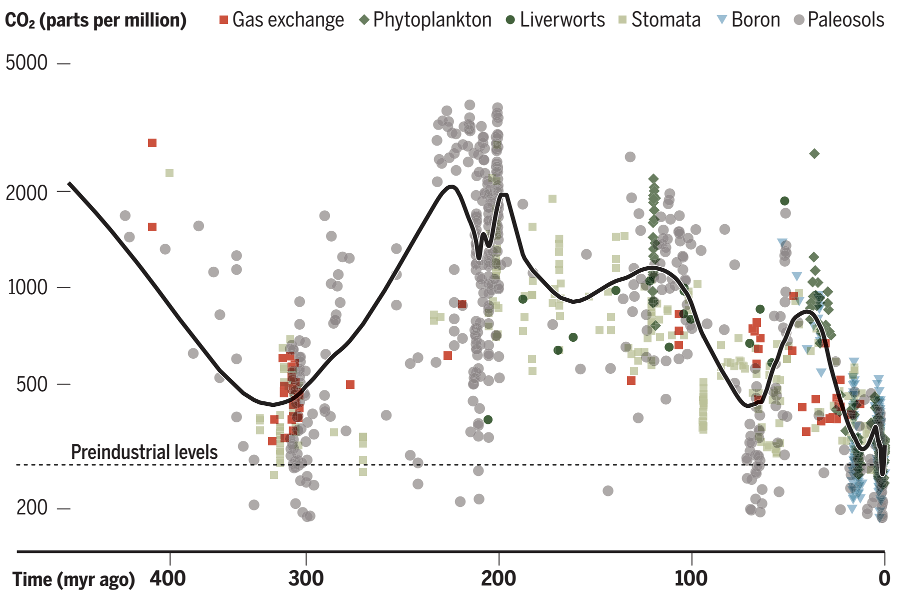
By revealing lower CO_2 levels during ancient warmings, he says, the gas exchange technique suggests a climate sensitivity closer to 4°C, not 3°C. It may take several generations for that rise to kick in, but history suggests that it is built into the climate system. "I do find it worrying," McElwain says. "Within 50–100 years the Earth's surface temperature could rise much higher than we currently anticipate."

Still, the technique is new, and its message is far from definitive. This March, at a workshop at Columbia University's Lamont-Doherty Earth Observatory in Palisades, New York, the CO_2 proxies will square off in a competition of sorts. Paleoclimatologists plan to weigh the different proxy techniques and come up with a consensus record of CO_2 over the past 66 million years.

Franks is confident that the gas exchange technique will fare well. "There's little argument that the uncertainty you get from this is improved," he says. "I'm not evangelizing for this model. I think it will take care of itself." ■

A roller coaster ride

Atmospheric carbon dioxide (CO_2) has swung dramatically in the distant past, according to indicators based on fossils (gas exchange, phytoplankton, liverworts, and stomata) and minerals (boron, paleosols). The ancient record suggests the recent jump from preindustrial levels (far right) could have an outsized effect on climate.



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