The LEAF ANNALS

Fossil foliage puts scientists on the scent of ancient air

By RICHARD MONASTERSKY

It is the breath of the planet. Volcanoes exhale it in flaming belches, while plants and eroding rocks quietly suck it out of the air, ultimately storing it underground.

Carbon dioxide flows into and out of the Earth so much that its atmospheric concentration hardly remains constant. Over millions of years, it varies whenever the planet's metabolism kicks into high gear or downshifts. Over much shorter time spans, carbon dioxide concentrations rise and fall in concert with modulations of ocean currents or vegetation patterns. On top of such natural cycles, humans have overlaid their own imprint by burning fossil fuels, pouring billions of tons of carbon dioxide into the air each year.

As a greenhouse gas, carbon dioxide helps set the planet's thermostat, so any change in its atmospheric abundance amounts to a twist of the temperature dial. Knowing how such gas variations tweaked the ancient climate can help earth scientists predict what lies in store for the next century as pollution drives carbon dioxide levels skyward. But to understand the past climate, researchers need to find a means of gauging how much carbon dioxide the air held long ago.

Though they would love to discover actual samples of the atmosphere from millions of years ago, scientists have little hope of finding anything that old because gases, unlike bone and wood, do not fossilize. The oldest air ever found comes from bubbles trapped in ancient ice, but these date back only 250,000 years — a brief tick in geologic time. The carbon dioxide exhaled by the human ancestor Lucy and her kindred australopithecines 3 million years ago has long since disappeared from the atmosphere, leaving only distant clues in its place. Air today, gone tomorrow.

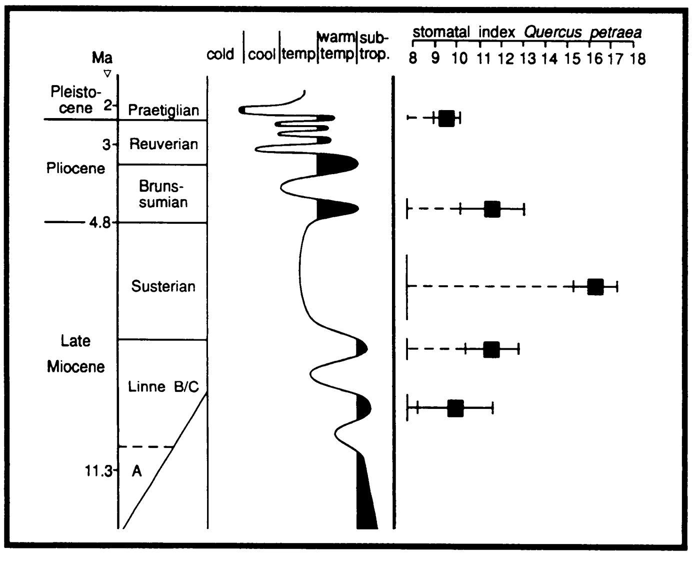
But a new technique offers hope for tracing carbon dioxide levels back in time. In the June 18 SCIENCE, paleobotanists report that fossil leaves can open a window for probing the ancient atmosphere.

"This is a pioneering attempt to get a handle on the relationship between carbon dioxide fluctuations in the atmosphere and climate change," says David L. Dilcher of the University of Florida in Gainesville. Dilcher collaborated on the leaf study with Henk Visscher, Johan Van Der Burgh, and Wolfram M. Kürschner of Utrecht University in the Netherlands.

Led by Visscher, the research team developed a technique for gauging ancient carbon dioxide levels by counting the number of pores on the underside of fossilized leaves. These holes, called stomata, serve as miniature mouths, providing openings through which gases can enter and leave a leaf.

Research on vegetation growing in special greenhouses has shown that the density of stomata depends on the atmospheric concentration of carbon dioxide, which plants use during photosynthesis. Trees and shrubs grown in air with extra carbon dioxide develop fewer stomata, presumably because they can obtain the needed carbon dioxide without as many pores. Cutting down on the density of stomata helps a plant because it minimizes the amount of moisture that can escape when the pores open.

Outside the greenhouse, plants exhibit the same relationship between carbon dioxide and stomata—a fact made clear in the years following the Industrial Revolution. Over the last two centuries, carbon dioxide concentrations in the atmosphere have climbed from 280 to 355 parts per million (ppm). During that same period, trees in European temperate forests have decreased their stomatal density by 40 percent, according to findings reported in 1987 by F.I. Woodward of the University of Cambridge in England. Woodward made his discovery by examining preserved plants from the last 200 years that are kept in special repositories called herbaria.



Van Der Burgh *et al.*/SCIENCE

***Partners in step:** The stomatal index of durmast oak fossils closely tracked the variations in climate of northern Europe. When temperatures warmed, the stomatal index dropped and vice versa. Numbers on left indicate millions of years before present.*

Visscher and his colleagues leafed their way even further back in the climate chronicles by studying

Dilcher

Flattened foliage: These leaf fossils, found in western Tennessee, belong to the laurel family and hail from the Eocene period, about 45 million years ago. The stomata of a leaf from the same family and time (above) show up as white holes amid the pink-stained epidermal cells. Each opening is surrounded by two bean-shaped cells that can close the pore.

fossilized plants dating back 2.5 million to 10 million years. The mummified leaves, found in northwestern Germany and the Netherlands, belong to the European species *Quercus petraea*, or durmast oak, which currently grows from the Mediterranean to southern Scandinavia. To compare leaf samples, the researchers calculated what they call the stomatal index—a value that depends on the number of stomata and the total number of epidermal cells in a particular patch of leaf.

Charting the changes through time, Visscher's group found that the index averaged 10 for the oldest leaves, rose to a high of 16 a few million years later, and then dropped back to 9.5 for leaves from 2.5 million years ago. Because a high index means less carbon dioxide in the air, the leaf record suggests that concentrations of the gas were relatively high 10 million years ago, declined around 7 million years ago, and later rose toward their previous values.

The paleobotanists compared this scenario with a climate tale told by fossilized pollen, fruit, and seeds found in the same region. These indicate that northern Germany 10 million years ago had a warm-temperate to subtropical climate similar to that of Georgia and Florida, says Dilcher. The region cooled over the next few million years, causing a temperate forest to replace its predecessor. But by 2.5 million years ago, temperatures had rebounded, and warm-temperate conditions returned.

Because carbon dioxide concentrations and temperature followed each other closely through this span, the researchers proposed that the gas shifts played a role in causing the climate changes.

To flesh out the story, they sought to determine how much carbon dioxide the atmosphere held. This involved a leap-frogging technique, starting in the present and then jumping into the past. The researchers used living and preserved plants to devise an equation relating the stomatal index to carbon dioxide concentrations for modern times. That equation served to translate stomatal indexes into gas concentrations for times in the distant past. This technique suggests that gas levels 10 million years ago averaged around 370 ppm, then dropped to 280 ppm during a cool spell, and later rose back to 370 ppm during a warmer time.

If correct, these findings carry some sobering implications. Carbon dioxide concentrations are now nearing the top of the range calculated from the fossil leaves. In the past, northern Germany has had a warm-temperate to subtropical climate when carbon dioxide concentrations reached such high levels. But at present the region maintains a temperate climate, which is characteristic of periods with less carbon dioxide. According to Visscher's group, this mismatch suggests that the climate has not yet responded to the rapid buildup of greenhouse gases since the Industrial Revolution.

"This is one more piece of evidence suggesting that, given the recent changes in carbon dioxide, we would expect to have a climate that reflects the kind of climate we reconstruct for the past, which was warmer than today," Dilcher says.

The researchers may have ventured too far out on a limb, however, by drawing such conclusions from fossil leaves, some fellow researchers contend.

Fakhri A. Bazzaz, a plant physiologist at Harvard University, says many factors aside from carbon dioxide influence stomatal density. Variations in humidity or light conditions, for instance, might spur plants to alter their leaf structure and number of pores.

Bazzaz cites another complicating factor. In his own experiments, he finds that individual species respond quite differently when growing in air enriched with carbon dioxide. Bazzaz says physiologists need to test a variety of species in different environments to see how each responds to various gas levels.

"Before this issue is laid to rest and this technique is extensively used to make inferences about the past climate, I would like to see more elaborate and detailed experimental studies done," Bazzaz contends.

Earth scientists, as well, question the reliability of stomatal studies, but the technique has attracted their attention because it could potentially fill an important gap in studies about the past atmosphere.

"If this would work, it would be very, very nice," says Thure Cerling, a geochemist at the University of Utah in Salt Lake City. Cerling has estimated atmospheric carbon dioxide concentrations for the past by examining the ratio of two carbon isotopes in ancient soils. But this technique has a large margin of error—about 400 ppm—so it works best for times in the distant past when carbon dioxide concentrations ranged in the thousands of parts per million. For more recent periods, when carbon dioxide levels resembled those of modern times, it can only offer broad hints.

John M. Hayes, a geochemist at Indiana University in Bloomington, is working on a process for gauging atmospheric carbon dioxide from isotopic information stored in sea sediments. While this approach can offer insight into why carbon dioxide concentrations vary, it is a roundabout means for calculating those concentrations, says Hayes. "The stomatal density is a more direct monitor of the atmosphere," he says.

While each method has its problems, researchers hope that a combination of the available approaches will eventually yield an accurate picture. Says Cerling, "We'd like to have a bunch of different techniques that are independent of each other, because I don't think we have the same confidence with any of them that we have when we can actually measure the air itself. If all of these techniques are telling the same story and they're completely independent of each other, then we can have a lot more confidence in that tale." □