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HUMAN EVOLUTION

How a Fickle Climate Made Us Human

Researchers are drilling for clues to how dramatic changes in African rainfall and vegetation shaped our species

Humans, like children, are the products of their environment. The famous anatomist Raymond Dart recognized that back in 1925, when he described the first hominin skull found in Africa. The evolution of this "Man-Ape," he wrote, markedly differed from that of earlier apes. While apes lolled about in "luxuriant" tropical forests that posed relatively few survival challenges, the "Man-Ape" had to compete for scarce food and water with saber-tooth tigers and other dangerous beasts of the arid savanna—and ended up sapient. "For the production of man a different apprenticeship was needed to sharpen the wits and quicken the higher manifestations of intellect—a more open veldt country," Dart wrote.

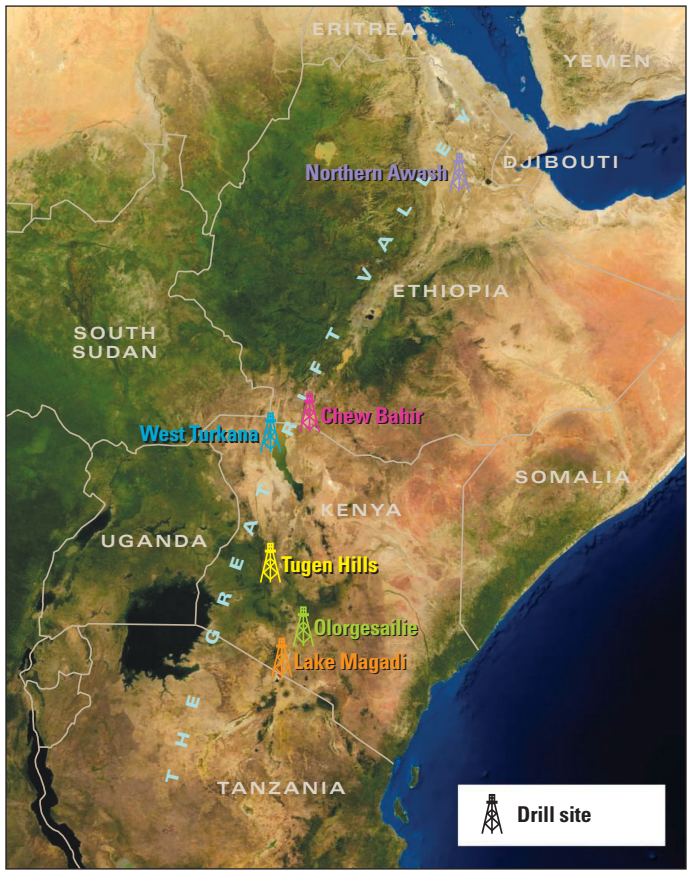
This "savanna hypothesis" suggested that as a drier climate caused grasslands to spread, our ancestors moved out of the trees and began walking upright in order to spot predators and prey in the waist-high stems. That freed their hands to use tools and spurred the development of big brains.

Today, no serious paleoanthropologist believes that particular evolutionary tale. But Dart's hypothesis was the first of many to propose that shifts in climate and environment made humans who we are. The idea has become practically received wisdom even though there has been little direct evidence to support or falsify it. True, researchers have extracted precise records of past climate from seafloor sediments and ice cores. And they have noticed that fossils and environmental clues on land also suggest that some climate shifts coincide with changes in human ancestors.

But correlation is not causation, and only "a circumstantial case" has been made for climate as the engine driving human evolution, says paleooceanographer Peter deMenocal of Columbia University's Lamont-Doherty Earth Observatory in Palisades, New York. Even correlation can be elusive: Syncing fossil discoveries with offshore climate records thousands of kilometers away has proven challenging. Most stories of how environmental change shaped our evolution have been "mainly fantasies of the past," says paleoanthropologist Andrew Hill of Yale University. "They are not proven."

That is beginning to change, however, as researchers deploy new tools to reconstruct climate and environment right where ancient hominins—the ancestors of humans but not other apes—once lived. This summer, for instance, a truck with a drilling rig has worked its way up the Rift Valley of Kenya, extracting sediment cores from dried-out lakebeds next to key fossil sites. Specialists are already analyzing a core drilled last year at Olorgesailie in Kenya (see story, p. 476).

CREDIT: ANDREW HILL/YALE UNIVERSITY



Wellsprings of data. Researchers are drilling deep into Africa's Great Rift Valley to get detailed climate data.

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Such detailed, localized work may put some theories to rest and breathe new life into others, including a revived version of the savanna hypothesis. "For the first time, we'll be able to frame the question as: 'How did hominins respond to the environment they lived in' rather than as responses to global or Northern Hemisphere events," says geologist Craig Feibel of Rutgers University in New Brunswick, New Jersey.

Grass roots

If the past is a foreign country, as historians say, then the prehistoric landscape is an alien world. Using a host of climate indicators, geologists have uncovered evidence of dramatic events that changed the planet in the past 7 million years, showing that the African landscape has evolved as dramatically as the anatomy of hominins. In the words of Dart, our ancestors' "eyes saw, their ears heard, and their hands handled," terrain far different from today's.

About 4 million years ago, for example, the Turkana Basin in Kenya—home to seven hominin species, including our direct ancestor *Homo erectus*—was covered by a vast inland sea, three times bigger than the lake there today. At the continent's northern edge, the Mediterranean Sea dried up between 5 million and 6 million years ago, decreasing the circulation of moisture over Africa and Europe, according to a 2010 National Research Council report. This may have amplified a cooling and drying trend that had already started in Africa 6 million to 8 million years ago, according to oxygen isotopes from marine and ice cores.

That long-term drying trend, which began at about the time when the human and chimp lineages diverged, tempted some researchers in the 1990s to propose a revised savanna hypothesis: Drier, cooler climates thinned the forests of Africa, perhaps driving hominins out of the woods to scurry upright across open grasslands between patches of trees in search of food.

Then, new fossil discoveries challenged that idea. Paleoanthropologists found three very early, upright hominins that, according to clues left in the fossil sites, apparently lived in the woods between 7 million and 4 million years ago: *Ardipithecus ramidus* from Aramis, Ethiopia; *Orrorin tugenensis* from the Tugen Hills of Kenya; and *Sahelanthropus tchadensis* from Chad. For example, researchers found fossils of *Ar. ramidus* with fossilized wood and seeds, and near fossils of woodland monkeys, parrots, and snails. With hominins walking in the woods, the savanna hypothesis bit the dust.

Now, however, a half-dozen geologists are resurrecting the importance of grasslands in human evolution once again. This time, however, the theory has to do with how human ancestors used the savannas for food, not hunting and rambling.

The renewed savanna hypothesis has its roots in evidence that as African climate dried out 6 million to 8 million years ago, the makeup of plant communities was also shifting, says geochemist Thure Cerling of the University of Utah in Salt Lake City. That's because the amount of carbon dioxide in the atmosphere began to decline 10 million years ago, giving a boost to plants that use the more efficient C_4 photosynthetic pathway; most of those plants are grasses and sedges, whereas woodland plants such as trees and shrubs usually rely on the older C_3 pathway. Grasses and other C_4 plants went from carrying out 1% of the photosynthesis in the tropics 10 million years ago to 50% today.

As went plants, so went the animals that grazed on them: By 6 million years ago, C_4 grasses had replaced C_3 plants as the most significant component in the diet of African grazers, Cerling says, according to studies of carbon isotopes in the tooth enamel of horses, elephants, antelopes, and other animals.

This suggests that hominins were born when grasses were on the rise. In fact, Cerling and his colleagues think that the first hominins had more grass in their environment than initially proposed—40% to 60% of the vegetation at nine *Ar. ramidus* fossil sites was C_4 plants, Cerling suggests (*Science*, 28 May 2010, p. 1105).

Recent data now show that later hominins responded to the rise of grasses by broadening their diets. Species that arose more than 4 million years ago, including *Ar. ramidus* and the oldest australopithecine, *Australopithecus anamensis,* subsisted on an apelike diet of at least 90% leaves and fruits from C_3 plants, Cerling and his colleagues reported in June in the *Proceedings of the National Academy of Sciences.* By 3.5 million years ago, a descendant of *Au. anamensis*—*Au. afarensis*, whose most famous member is the skeleton named Lucy—apparently adapted to the widespread grasslands by also munching on many C_4 plants, according to Cerling's analysis of carbon isotopes in the tooth enamel of seven hominin species. *Au. afarensis*—a leading candidate for the ancestor of *Homo*—and another hominin, *Kenyanthropus platyops*, still ate mostly C_3 woodland plants, but about 22% of their diet was also made up of these C_4 plants, making them the hominins with the most varied menu. Their meals included grasses and sedges such as water chestnuts and papyrus and perhaps animals that fed on those plants.

This appetite for grasses apparently left its mark on *Australo-*

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Where the hominins roamed? New data suggest that grassland environments were important in hominin evolution.

pithecus anatomy: Most members of the genus had much larger molars and premolars than earlier hominins. Such big choppers would last longer than small ones when chewing on gritty grasses and abrasive sedges.

Given that grasses were abundant in all hominin habitats for so long, "the savanna hypothesis is alive and well," Cerling says. The grasslands may have had other evolutionary impacts, too, although the revived savanna hypothesis is so new that paleoanthropologists are just beginning to consider it. They note that the earliest hominins walked upright, but with a variety of odd gaits; the savanna may have favored adaptations for more effective walking and running, such as an arched foot and nonopposable big toe, that led to the typical human gait (*Science*, 11 February 2011, p. 750). "Cerling's data are causing us to refocus on the link between environment and adaptation," says paleoanthropologist Carol Ward of the University of Missouri, Columbia. "But we still have more questions than answers."

Cerling's savanna hypothesis "is not Dart's savanna hypothesis," says Richard Potts, a paleoanthropologist at the Smithsonian Institution in Washington, D.C. That's partly because geologist Cerling uses a broader definition of "savanna" than many paleoanthropologists. But it's also because the hominin most

Out of the Kenyan Mud, an Ancient Climate Record

MINNEAPOLIS, MINNESOTA—When Richard Potts, Anna Behrensmeyer, Alan Deino, and Richard Bernhart Owen get together, it's usually at camp at Olorgesailie in Kenya's Great Rift Valley. The paleoscientists labor for hours in the hot sun, chipping away at exposed rock outcrops to develop a timeline for artifacts and other relics of the human ancestors who once lived nearby. But on a cold spring day earlier this year, they gathered with a dozen other researchers in a small lab at the University of Minnesota to analyze something quite different: 190 meters of mud, sand, and gravel cored last year, from what they hoped was once a lakebed 20 kilometers from their outcrops.

The team had never tried to drill a core before and hadn't even known for sure that a lake ever covered the area. But as the researchers kicked off their "core sampling party," they hoped that the mud would resolve into thousands of distinctive layers, each representing a different climate regime, ultimately reaching back 500,000 years. The goal: to test ideas about the role of climate variability in human evolution, by getting a continuous record of climate indicators from a place where hominins lived and died (see story p. 474). The project "has high potential to reconstruct the long-term history of environmental change," says team member Vanessa Gelorini, a paleoecologist at Ghent University in Belgium.

Although everyone eagerly anticipated what might be hidden in the 139 half-meter- to 3-meter-long cylinders of sediment, the group was anxious. The work required difficult on-the-spot decisions and taking hundreds of samples—chores best accomplished by everyone working together at the same place at the same time, says Potts, the Smithsonian Institution National Museum of Natural History (NMNH) paleoanthropologist who has led the Olorgesailie project since 1986 and raised $450,000 in private funding for the drilling and party. But cores don't come with labels, and everyone had questions. Do we have a truly continuous record? How far back does it go? Can we date the layers? In other words, will this investment give us the data we seek?

Digging for climate proxies

At the field site, Olorgesailie, researchers have been digging out artifacts and fossils since Louis and Mary Leakey first explored it in the 1940s. Since 1986, geologists have tried to extract clues to ancient climates from the outcrops (*Science* 23 March 1990, p. 1407). But the outcrops are not a continuous record of the past: They represent the period from 1.2 million to 500,000 years ago and then pick up again from 320,000 years ago to the present. Rock formed during the gap has eroded away.

Yet during those missing millennia, humans moved from a culture limited to stone axes to the so-called Middle Stone Age, marked by new tool innovations and perhaps more sophisticated social interactions. Potts proposed more than a decade ago that an increase in the variability of the climate during that time shaped human evolution by ratcheting up hominins' genetic and phenotypic plasticity, so that they could survive in a broad range of conditions. Those changes prepared our ancestors to eventually spread worldwide.

But Potts's theory couldn't be tested without a climate record from the missing years. Where might it be preserved? One possibility was the Koora Valley 20 kilometers to the south, which was connected by a shallow depression to the Olorgesailie site. Potts and his NMNH colleague Behrensmeyer speculated that sediments eroded away at Olorgesailie had washed into the channel and down to the basin. If there had been a lake there, the researchers would be in luck. Lake bottoms typically accumulate sediments year after year, and, hidden from the sun and weather, those

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specialized for the grasslands was not on the line leading to *Homo*. The "Nutcracker Man," *Paranthropus boisei,* used its giant molars to crunch on a diet of 75% C_4 grasses and sedges, according to recent isotopic studies—and it died out about 1.2 million years ago, Lamont-Doherty's deMenocal notes. They "weren't the successful ones."

Burst of speciation

Over the years, other hypotheses connecting human evolution to climate have also come and gone. For example, in the 1980s, Yale's Elisabeth Vrba suggested that dramatic shifts toward a cooler, drier climate in the East African Rift Valley between 2.7 million and 2.5 million years ago sparked bursts of rapid extinction and speciation in grazers like antelopes, as well as in hominins. But this turnover-pulse hypothesis—so named because pulses of climate change were thought to spark big turnovers in species—faded after later studies showed that the shift in species happened more gradually. Still, the idea's not dead yet: Arizona State University, Tempe, paleoanthropologist Kaye Reed has spotted another burst of speciation about 3 million years ago at Hadar, Ethiopia. There, 10 new species, including camels and hoofed grazers, appear just before *H. habilis* replaced *Au. afarensis.*

Although Vrba thought that drying had sparked rapid speciation, other researchers have noticed that new species of hominins seem to appear during wet, humid periods. For example, studies of lake sediments in 10 East African rift basins suggested that the overall cooling and drying trend of the past 8 million years was interrupted by at least three humid periods when deep lakes filled, which tie in with the birth of new hominins. So did cool, dry climates or wet, humid ones shape the evolution of hominins?

Potts has a different answer: It was all these changes, fluctuating wildly, that produced humans.

Creatures of change

Potts proposed 16 years ago that the key adaptation of the human lineage, manifested in everything from big brains to culture, is adaptability: Individuals who could survive in wet woods as well as dry grasslands fared better than those specialized for one or the other. He argues that the dramatic fluctuations of the ancient African climate shaped human nature, allowing our species to eventually thrive in all sorts of environments worldwide.

Deep-sea cores suggest that "the first appearance of every major genus in our evolutionary history, the origin of every major stone technology, happens to fall in long periods of high climate variability," Potts says. He ticks off in rapid fire the innovations of such periods: the birth of *Australopithecus, H. habilis, H. erectus, Paranthropus*, and *H. sapiens*, plus the invention of the first stone tools 2.6 million years ago, the creation of more advanced Acheulean tool kits 1.8 million years ago, and the first Middle Stone Age technologies 300,000 years ago. Each event is correlated with a period of high climate variability, such as wet and dry cycles, Potts says. For example, the span between 2.5 million and 2.7 million years, which Vrba noted had such turnover in species, cycled between extremely wet and extremely dry times.

But the evidence for those fluctuations comes from predictions

Assembly line. In a week, Richard Potts, Anna Behrensmeyer, and their colleagues studied all the core's sections.

CREDIT: JENNIFER CLARK

sediments are often well-preserved. "We didn't know for sure that there was going to be a lake," Behrensmeyer recalls. "If it were just a pile of pumice or volcanic ash, it wouldn't have preserved the environmental signals."

To test the idea, Potts secured funding from several private foundations. A local drilling company spent September 2012 digging out two cores on the Koora Valley and shipped them here to the National Lacustrine Core Facility (LacCore), a lake core processing and storage lab supported by the U.S. National Science Foundation.

Guest of honor

At the core party, technicians begin slicing each 4-centimeter-wide core section lengthwise down the middle, enabling researchers to mine the sediment for a plethora of indicators of ancient climate. For example, different types of plants fractionate the two isotopes of carbon, C-12 and C-13, differently. So analyses of plant waxes extracted from the sediments can indicate whether dry-adapted grasses or moisture-loving vegetation thrived. Bits of calcium carbonate, found in some soils, contain isotopes of oxygen (O-16 and O-18) that can reveal the temperature at which the carbonate formed. Certain clays indicate aridity.

Each material provides a proxy for what the environment was like during the formation of a sediment layer. Individually, however, the proxies and layers "are like blind men feeling the elephant," Potts says. Only by combining them can researchers assemble a cohesive picture. And that depends on accurately dating the sediments. At this point, the team isn't even sure that the core stretches to the sought-after 500,000 year time point. Dating is Deino's job, and that's why at this party he is the guest of honor. If he can find volcanic material, he can use radiometric dating to determine when it formed, and so provide a chronology for the cores, pegging the ups and downs of each climatic indicator to actual dates.

A beefy, taciturn geochronologist at the Berkeley Geochronology Center in California, Deino commands a dedicated computer terminal and one of the few stools in the lab—almost everyone else has to stand. He also gets first dibs on one-half of each sliced core. (The other halves are archived virtually untouched.) The cutaways reveal a panoply of colors and textures, ranging from midnight black to sunrise yellow, from fine clay grains to small pebbles. In some sections the layered striations are so narrow that they are barely discernible by the naked eye. >>

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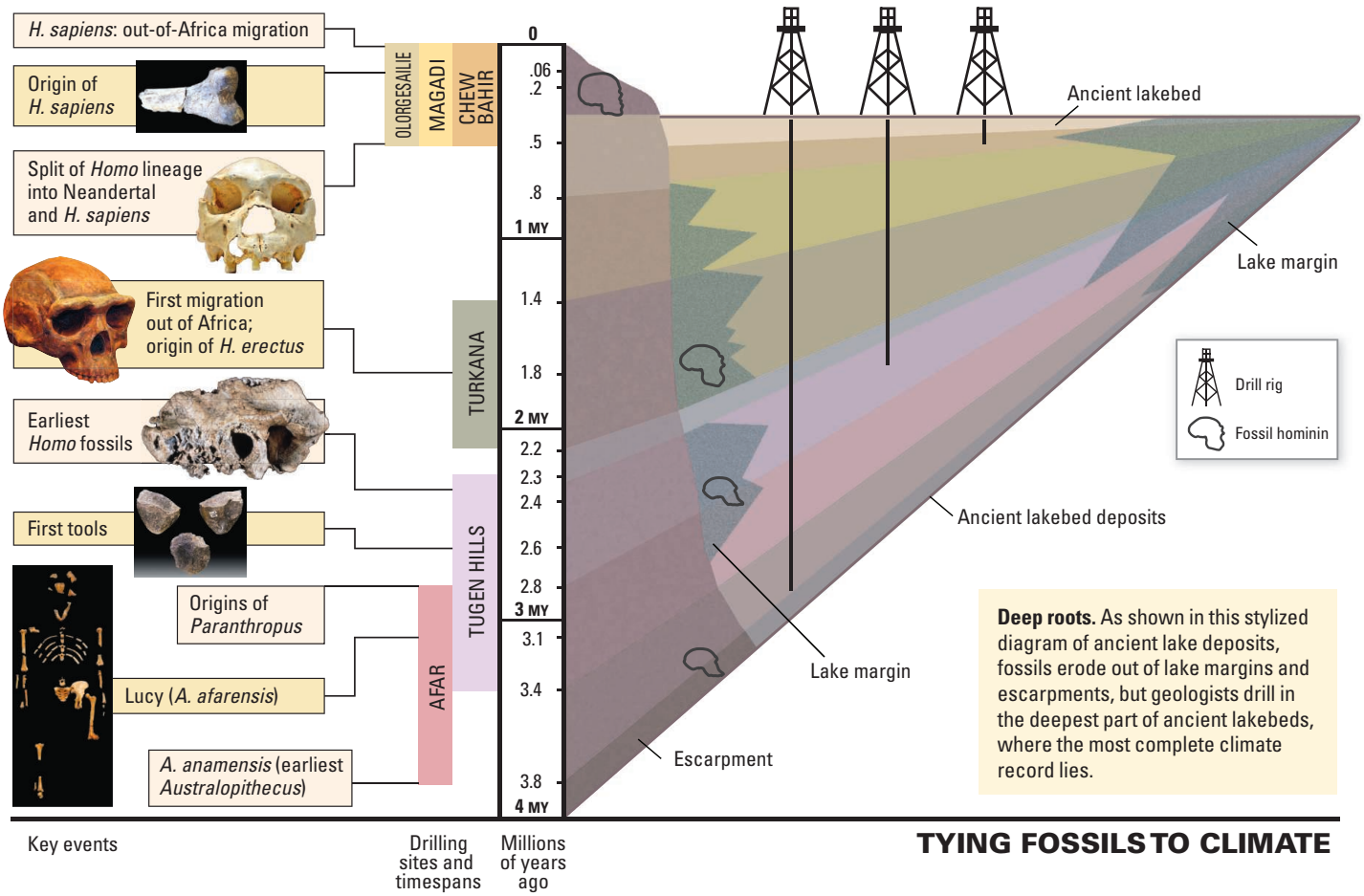

Deep roots. As shown in this stylized diagram of ancient lake deposits, fossils erode out of lake margins and escarpments, but geologists drill in the deepest part of ancient lakebeds, where the most complete climate record lies.

TYING FOSSILS TO CLIMATE

Core up close. Digital images of split cores reveal details of the many layers, aiding the search for key environmental proxies.

Deino also receives color scans of each core, which he enlarges to search for dark areas that signal volcanic rock and ash. In one section known as 3A 4Q1, he pokes around with a metal spatula, exposing small, angular pieces of pumice. The angularity signals that these fragments are fresh from an eruption, rather than being deposited sometime after formation. They prompt a rare smile from Deino. He's taken dozens of samples, but none as promising as this one. "It's yelling 'Date me, date me,' " he says, digging out a chunk several centimeters long and scooping it into a bag.

Hours earlier, LacCore curator Anders Noren had urged the researchers to sample very conservatively, preserving as much core as possible for the future. But Deino takes as much as he wants, no questions asked, sometimes up to 300 grams at a time.

When Deino said he has " 'lots to look at,' I breathed a huge sigh of relief," says team member Peter deMenocal, a geochemist at Columbia University's Lamont-Doherty Earth Observatory in Palisades, New York. Back at his lab, Deino will start by dating the best 10 samples that span the core from top to bottom, giving him a rough estimate of the overall sedimentation rate. Then he'll date more samples to boost the resolution. All other analyses will be pegged to the resulting chronology. "Al, all eyes are on you," deMenocal tells Deino.

Lake, or no lake?

Well, not all eyes. There's also the question of whether the sediment actually came from a lake, and so is likely to provide a continuous record. An initial look at the cores in the field suggested it had, but now came the real test.

Behrensmeyer and Owen, who has come all the way from Hong Kong Baptist University, hover over each core section to describe the texture, color, and layering. Such baseline data will help others know where to look for the climatic indicators they study.

Behrensmeyer studies enlarged photographs of the core for irregularities such as animal burrows or pieces of pumice, then pulls a dental pick from her hip pouch to tap the soil at those spots. Where the core seems to change character, René Dommain, a paleoecologist from the University of Greifswald in Germany, dissolves a tiny speck onto a slide and examines it with a petrographic microscope, whose polarizing filters help reveal the min-

CREDITS: (PHOTOS TOP) J. FLEAGLE/STONY BROOK UNIVERSITY; JOSÉ-MANUEL BENITO/WIKIMEDIA COMMONS; THOMAS ROCHE/WIKIMEDIA COMMONS; A. HILL/YALE UNIVERSITY; DIDIER DESCOUENS/WIKIMEDIA COMMONS; WIKIMEDIA COMMONS; (BOTTOM) LACCORE

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from climate models and from marine sediments collected far from fossil sites. On the African continent, many local factors may have modified climate, such as rain shadows created by mountains or differences in altitude. Some basins may have been buffered from climate change and served as refugia.

The few cases where fossils are paired with local climate data offer tantalizing hints of support for Potts's idea. For example, layers of ancient sediment from outcrops in the Tugen Hills in Kenya reveal signs of wet and dry cycles, according to work by Yale's Hill and geologist John Kingston of Emory University in Atlanta. They collected diatoms, siliceous blue-green algae that grow in fresh water but vanish from sediments when a lake dries up. These tiny tracers mark when ancient lakes were full or dry, and showed that the Baringo Basin repeatedly filled and emptied every 20,000 years between 2.58 million and 2.69 million years ago. This was a response to cyclical changes in the orientation of Earth's axis as it orbits around the sun, the Milankovitch cycles, which in Africa create alternating wet and dry conditions. These cycles are the "pacemakers of African climate," deMenocal says.

The repeated shifts had a "kaleidoscopic" effect on animals in the basin, breaking up communities as the lakes filled, then allowing new mixes of species to reassemble when the lakes shrank, says Hill, whose team noted these shifts in fossils. One species that was part of the mix was *Homo:* The oldest *Homo* fossil was found just above a layer with diatoms, dating to 2.5 million years ago, suggesting that our genus arose just after the wet and dry cycles intensified in the Baringo Basin (*Science*, 4 February 2011, p. 540).

To nail down such links, however, researchers need local evidence, for example that climate changes preceded bursts of speciation, as predicted by the turnover-pulse hypothesis. The climate record near fossil outcrops is often incomplete. However, fine-scale evidence of such changes can come from the sediments that piled up in the deepest part of ancient lakes, which trap chemical isotopes, pollen grains, charcoal, and other bits of detritus that offer telltale signs of past climates. "These lake sediments are like a metronome. They're accumulating all of the time," says paleolimnologist Andrew Cohen of the University of Arizona in Tucson. Adds Feibel: "Getting a lake record of environmental variability literally a few kilometers from the actual [hominin fossil] sites" can offer "an unprecedented perspective on when and how environmental fluctuations actually impacted these landscapes and habitats."

That's why this year, after 8 years of planning, an international team is drilling holes in six ancient lakebeds in Kenya and Ethiopia, says Cohen, who directs the $5 million Hominin Sites and Paleolakes Drilling Project. In June, the group drilled down 228 meters and extracted cores in the Baringo Basin, hoping to sync the local wet-dry cycles with records from deep-sea cores, and to see local changes as early as 3.4 million years ago. Farther north, in the Awash valley, cores will test whether dry climate preceded the turnover in grazers 3 million years ago. If the cores don't show that climate changes intensified, the turnover-pulse hypothesis would be falsified in that lake basin. Conversely, if signs of grasses are common, the data may strengthen the revised savanna hypothesis.

The same drill rig is also taking cores from the habitats of other ancient hominins, including the site where a 1.6 million-year-old skeleton of *H. erectus* was found in the Lake Turkana Basin. The team also will core two lake basins in Ethiopia and Kenya that cover the time span drilled at Olorgesailie—the past 500,000 years, when *H. sapiens* was born. "Each of these places will give us an interesting time slice through human evolution," Cohen says. The cores will enable researchers to "ask some of the most existential questions of our time," he says: "What it means to be human and what were the environmental constraints on why we are the way we are."

–ANN GIBBONS

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eral composition of the smeared sediment.

The smear slides reveal little sign of life in the core's youngest, uppermost layers. Then a slide taken at 37 meters down is littered with diatoms, tiny algae with distinctive siliceous shells that grow in specific environments. "We have a lake," Owen announces to the group; they erupt into a cheer. Potts and Behrensmeyer now know that their predictions are correct.

In subsequent slides, changes in the mix of diatoms reveal an ever-more saline environment as the sediments get older. At about 44 meters down, diatoms peter out, perhaps indicating that the lake was temporary or too saline for diatoms. Dommain also records sightings of fossilized fungal spores, bits of other algae, phytoliths, charcoal, and pollen, all of which can record environmental dynamics. The presence of one colonial alga, *Botryococcus*, for example, indicates a shallow lake. Charcoal speaks to fires: The bigger the piece, the closer the fire was to the lake. "All this [variability] tells you it's not a stable environment," Dommain says.

CREDIT: JENNIFER CLARK

Ready and waiting. At the LacCore lab in Minneapolis, 1.5-meter-long sections of core await processing.

When the weeklong party finally breaks up, there is still plenty of work left. Over the next 18 months, the guests plan to complete their initial analyses and tie what they find to what they know from the outcrops. Ultimately, they'll develop a catalog of how the climate indicators changed over time, then attempt to model how climate changes affected the local ecosystem and the hominins who lived there. "We will have lots of stories" to tell, predicts Naomi Levin, a paleoecologist at Johns Hopkins University in Baltimore, Maryland. "But to figure out the importance for human evolution will take a lot more time."

–ELIZABETH PENNISI

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