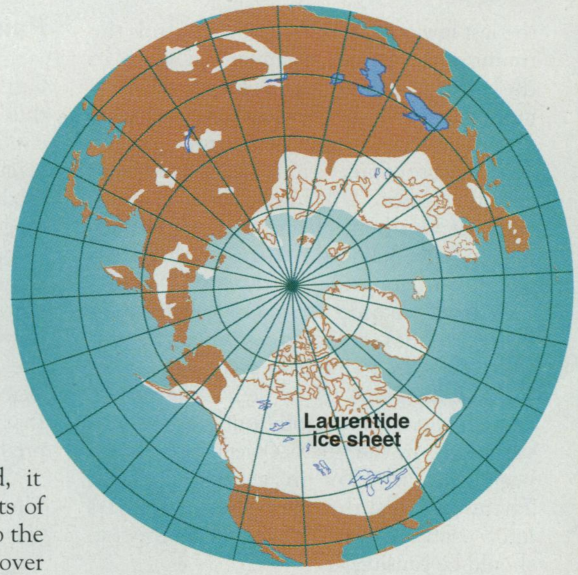
MEETING BRIEFS

Ice, Quakes, and a Wobble Shake San Francisco

The fall meeting of the American Geophysical Union (AGU) in San Francisco last month was bumped to the Moscone Center while the Civic Auditorium, its venue in past years, was being reinforced against earthquakes. And that may have been fitting, given the meeting's focus on sudden events in Earth history: the first moments of fault rupture, repeated outbursts of icebergs during the last ice age, and a shift in the seasons in the middle of this century.



Array of suspects. The biggest of the ice sheets ringing the North Atlantic, the Laurentide, was not to blame for cold snaps during the last ice age.

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Exonerating an Ice Sheet

The last ice age wasn't a calm, stable deep freeze. Every 7000 years or so, a bout of extreme cold racked the region around the North Atlantic, and armadas of icebergs surged into the ocean. A year ago, researchers puzzled by these "Heinrich events" thought they had identified the culprit: the great Laurentide ice sheet that covered North America. Pebbly debris shed by the icebergs far out at sea as they melted had been traced to the Laurentide, hinting that the ice sheet was driving the Heinrich events through an internal cycle of growth and collapse. Now, however, a closer look at the ice-rafted debris makes it clear that the Laurentide wasn't acting on its own.

At the AGU meeting, paleoceanographers Gerard Bond and Rusty Lotti of Columbia University's Lamont-Doherty Earth Observatory reported that the debris layers left by the Heinrich events contain traces of rock not only from North America but also from Iceland. If Iceland's tiny ice sheet was collapsing on exactly the same schedule as the Laurentide, Bond and Lotti say, the pacemaker of the Heinrich events could not have been the internal dynamics of the Laurentide ice: Separate glacial "clocks" controlling the cycles of such different ice sheets couldn't have remained synchronized. The master clock must have resided elsewhere.

The notion that the Laurentide ice sheet was to blame for Heinrich events gained support when Bond and his colleagues began studying the layers of debris deposited during five major Heinrich events between 14,000 and 70,000 years ago. The layers, visible in sediment cores from the ocean floor, are rich in light-colored carbonates, which could only have come from North America (*Science*, 24 December 1993, p. 1972). Heinrich events seemed to be a solo performance by the Laurentide ice sheet.

Because the Laurentide was the largest and thickest of the ice sheets ringing the North Atlantic, an explanation seemed to be at hand: The ice sheet periodically became too thick to survive. As the ice accumulated over millennia, glaciologists proposed, it would have trapped increasing amounts of heat from the Earth's interior, adding to the heat of friction generated as the ice slid over bedrock. Eventually the heat would have weakened the ice sheet's grasp on the land, and the ice would have surged outward. The resulting flotilla of icebergs could in turn have altered climate by capping warmth-carrying currents in the North Atlantic with a layer of cold meltwater.

But now Bond and Lotti have found trace amounts of dark, glassy rock in the ice-rafted debris, debris that must have been scraped from the volcanoes of Iceland. These traces of Icelandic icebergs show up at all four of the most recent major Heinrich events, coinciding with or even preceding the North American debris. And they also appear between the major events, at "mini-Heinrich" events Bond and Lotti have identified every 2000 to 3000 years.

Two ice sheets, one massive and the other tiny, oscillating together "cannot be explained as a result of an internal process analogous to surging," says Bond, "because that depends on the specific characteristics of each ice sheet." Glaciologist Douglas MacAyeal of the University of Chicago, who had argued that the Laurentide ice sheet could be the pacemaker of Heinrich events, now concedes the Laurentide could not have acted as climate's "lone gunman." Instead, he says, the new evidence implies that something external to both ice sheets was triggering their collapse.

What that external trigger might have been, Bond doesn't know. It might have been a third ice sheet—one whose internal cycle of growth and collapse was on an accelerated schedule. That way, the icebergs it discharged could have altered climate and indirectly triggered the collapse of the Iceland and Laurentide ice sheets hundreds of years later. Alternatively, the ultimate driver might have been in the ocean, where heat-carrying currents might have shifted on the needed 2000- to 3000-year schedule, touching off ice-sheet collapse. To study these possibilities, Bond wants to look for ice-rafted debris from other, less understood ice sheets, to see whether one of them might be to blame for ice-age shivers.

The Seasons of Global Change

"It just smelled wrong," says David Thomson of AT&T Bell Laboratories in Murray Hill, New Jersey, about earlier analyses of how Earth's surface temperatures have changed over the last few centuries. Thomson's experience analyzing the records of time-varying properties in everything from cellular phones to trans-Atlantic cables told him something was amiss with the long historical temperature records. What puzzled him wasn't the overall global warming revealed by the analyses, but the specific patterns it took, such as warming that was concentrated in winter and in the Northern Hemisphere. In a talk that left his listeners at the AGU meeting intrigued if not yet convinced, he reported that he had found the problem: the wobble, or precession, of the Earth's spin axis.

The toplike precession takes 26,000 years to complete each cycle, but even the vanishingly small part of one wobble that Earth has completed in the past few hundred years was enough to confound conventional methods of analyzing temperature records, Thomson says. When he took the wobble into account, some of the anomalies in the temperature record disappeared—but a disturbing new puzzle emerged. In the middle of this century, just when greenhouse-driven global warming may have begun to take hold, the timing of the seasons was disrupted. "Either something [natural] is happening that is very unusual," he says, "or we're the reason."

Thomson guessed that the Earth's precession might have affected climate records over the last few centuries because it controls the timing of the seasons. Summer and winter in the Northern Hemisphere occur when Earth's motion around the sun points the North Pole toward and away from the sun, respectively. And because of precession, 13,000 years from now the seasons will have swapped places, with the Northern Hemisphere winter falling in June, July, and August rather than December, January, and February.

When Thomson applied time series analysis techniques of his own devising to historical records, he found that precession's slow shift of the seasons is detectable, given enough years to smooth out year-to-year variations. In the first 300 years of a record beginning in 1659 in central England, Thomson found that winter set in 1.4 days later each century, just what precession should be causing.

Other researchers, however, have assumed that the timing of the seasons a century or more ago was identical to today's; to simplify analysis of the temperature records, they therefore removed seasonal variations. But the gap between the assumed seasonal cycle and the true seasons threw off their results, says Thomson, so that over the past century winters seemed to warm more than summers. All or most of that difference is an artifact, he says.

Climate researchers are withholding judgment while they grapple with the intricacies of time-series analysis. "I can't assess it yet. I just don't have my hands on a paper," says Jeffrey Park of Yale University. But he adds, "I think it's really interesting, quite important work."

He and others are equally intrigued by a second result of the new analysis, which shows up in the middle of this century. Until around 1945 or 1950 in the central England record, the seasons changed in time with precession, but then the rate of delay shot up. In the last 50 years the seasons in central England have been delayed 4.5 days, as much as in the previous 300 years. The same effect appears in some other long-term records from Europe and eastern North America, but not all. In the first part of the 150-year record of Northern Hemisphere temperature compiled by Philip Jones of the University of East Anglia and his colleagues, the seasons were delayed as expected from precession, Thomson says, and then around midcentury they headed the other way and began to get earlier rather than later.

Thomson thinks something strange is going on, and its coincidence with the accelerating accumulation of greenhouse gases in the atmosphere makes him suspicious. He smells another rat—but this one may be in the complex workings of the atmosphere itself.

Fair Warning From Quakes?

Earthquakes should start gradually. At least, that's what laboratory researchers and theorists have been telling their seismologist colleagues for the last 20 years. The laboratory models imply that, in real earthquakes, seismograph needles should start to quiver well before full-blown, building-shattering waves arrive. But most earthquakes have seemed to pop off unannounced. At the AGU meeting, however, seismologists William Ellsworth of the U.S. Geological Survey and Gregory Beroza of Stanford University announced that earthquakes are finally living up to the predictions.

"Earthquakes do not begin abruptly," said Ellsworth. "All the earthquakes we've looked at begin in a weak, hesitant fashion." That could be good news for researchers looking for clues about how to predict earthquakes days or weeks ahead. The slow starts identified by Ellsworth and Beroza precede the main shock by only a few seconds but could be heralded by subtle but potentially detectable changes on the fault days or weeks before it ruptures.

Like earthquakes themselves, this shift in the scientific landscape had a slow and hesitant start. That's because the first instants of an earthquake can be hard to study. If a seismograph is too far from the quake, subtleties get lost in background seismic noise. If it is too close, even the subtleties send the seismograph off scale unless it is a modern instrument capable of recording a wide range of intensities. Fortunately, three large recent earthquakes have struck smack in the middle of modern seismic networks: Loma Prieta in 1989, Landers in 1992, and Northridge in 1994. The records of each one revealed weak, hesitant beginnings, and Japanese seismologists have seen the same effect in some smaller quakes.

To determine whether slow starts are typical of all quakes, Ellsworth and Beroza amassed as many high-quality seismic records as they could find. Each of the 31 records analyzed so far, representing earthquakes with magnitudes ranging from a barely noticeable 2.6 to the 8.1 of the great Michoacan quake off Mexico in 1975, shows a hesitant start—slow, steady slip on the fault that either builds directly into the fast rupture of the main shock or subsides just before it.

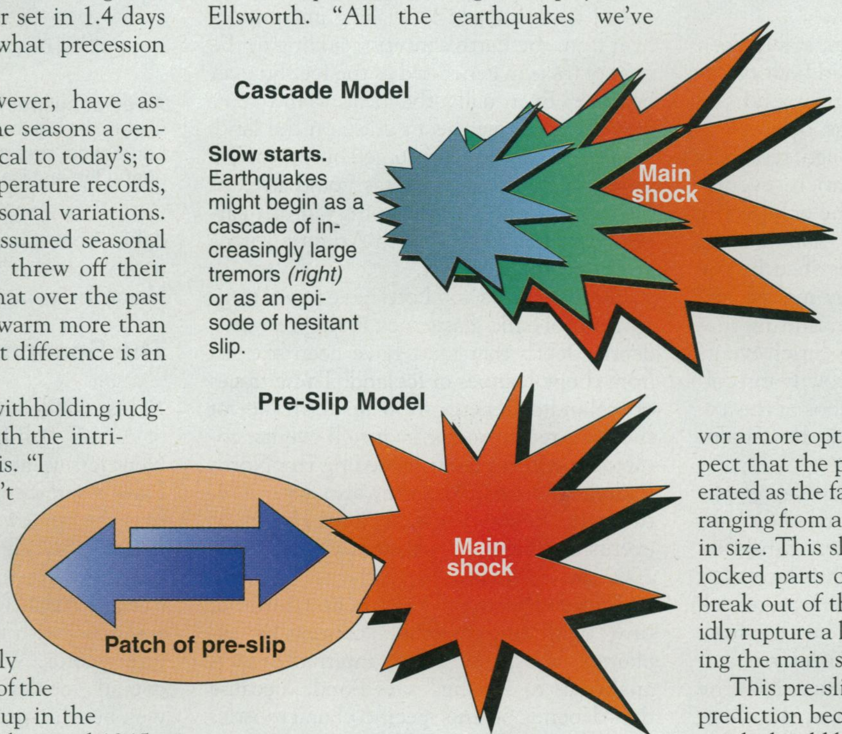
One possible explanation for these hesitant starts, Ellsworth and Beroza say, is that they are the earliest events in a cascade of quakes leading up to the main shock. That scenario, if it holds, would be bad news for quake prediction, because the first quakes in the cascade would be so small as to be indistinguishable from background seismicity. Quakes would be like chocolates in a box, says Ellsworth: "You would never know what you were going to get."

Ellsworth and Beroza favor a more optimistic explanation. They suspect that the precursor signals could be generated as the fault slips slowly within a patch ranging from a few meters to a few kilometers in size. This slow slippage stresses adjacent, locked parts of the fault until the slip can break out of the "nucleation zone" and rapidly rupture a large part of the fault, generating the main shock.

This pre-slip model would augur well for prediction because, according to theory, the patch should be preparing to rupture days or weeks in advance by slipping ever so slightly and deforming the rock around it. Sticking with his chocolate analogy, Ellsworth says that, if detectable, the signs of that preparation—changes in the shape of the Earth's surface or small tremors outlining a nucleation patch—would be like "the little design on top that tells you what's inside."

Ellsworth and Beroza aren't claiming the optimistic, pre-slip scenario is correct. But they found evidence against the competing cascade scenario in a study of foreshocks preceding the Landers quake. Instead of a sequence of triggered shocks, Douglas Dodge of Stanford, Ellsworth, and Beroza found a random sequence, which suggests that a slow slip was pushing the fault toward failure. If so, the foreshocks were a chocolate maker's mark on the Landers earthquake. Now the trick will be to read that mark before rather than after a quake.

–Richard A. Kerr



Slow starts. Earthquakes might begin as a cascade of increasingly large tremors *(right)* or as an episode of hesitant slip.

SOURCE: ELLSWORTH AND BEROZA ILLUSTRATION BY E. CARROLL