Still, evolutionary biologist Nick Barton at the University of Edinburgh in the United Kingdom warns that the study hasn't quite sewn up the case for this model of speciation. He points out that the amount of gene flow the team found is quite small and says he's not surprised that it wasn't enough to swamp selection: "Four to five migrants per generation … that's very weak relative to selection." Smith acknowledges that because he doesn't know the little greenbul's population sizes, it's hard to prove just how significant the one to 10 migrants are. His team is now censusing the birds to find out.

While its implications for evolutionary theory are under debate, the study, if it holds up, might also have implications for the fight to save the world's biodiversity. If gene flow isn't a barrier to new species formation, then the ecotone is a likely source of new diversity, argues Smith. Species spawned in the ecotone might use forest resources in new ways that would be advantageous in the rainforest proper. Moreover, because migration between ecotone and rainforest is so common, over millions of years many of these new species might have moved back from their ecotone cradle to the rainforest. Thus, the patchy ecotone may generate species that find long-term homes in the adjacent rainforest, says Smith: "Maybe the rainforest is a sink for new species, rather than an area where new species are generated."

Yet conservationists have tended to neglect ecotones, because they are typically much less diverse and also less pristine than the central rainforest. The Australian ecotone between dry forest and rainforest, for example, is sometimes considered "not pure" and therefore difficult to protect, says Endler. In Cameroon, the transition zone—which at some points is over 965 kilometers wide—is currently being devastated by cattle grazing, burning, and wood cutting, according to Smith. In the 6 years of the study, the team lost three sites to fire. In addition, Exxon and Shell oil companies are planning to build a huge pipeline from the oil fields in Chad to the Atlantic Ocean. In an attempt to protect the rainforest, the line is to run right through the Cameroon ecotone. While Smith says the pipeline itself probably won't harm the ecotone much, he is concerned about the increased access of people to the area. "If we are to protect biodiversity, we should also protect the processes that generate it," he says. "The study suggests we need to look at what's happening at the periphery as well. … I'm hoping this paper might be a wake-up call."

–Martin Enserink

Martin Enserink is a science writer in Amsterdam, the Netherlands.

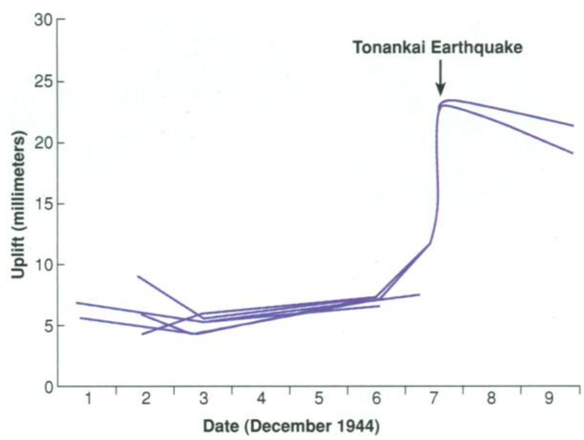
MEETING BRIEFS

Geophysicists Ponder Ancient Chills and Elusive Quakes

BALTIMORE—The spring meeting of the American Geophysical Union (AGU) here late last month attracted the usual assortment of presentations on climate and space science (*Science*, 13 June, p. 1648), but there was also much discussion of seismology, a subject usually more popular at the fall meeting in earthquake country in San Francisco. Here is a selection from each area: a series of reports that focuses new attention on "silent" earthquakes and a climate modeling study that takes the middle ground in a dispute over ice age cooling.

Listening to Silent Earthquakes

Seismologists have developed increasingly sophisticated means of watching and waiting, but they have yet to find a sure warning sign that a fault is about to rupture in an earthquake. At AGU, researchers had no magic solution to this problem, but they did offer persuasive new evidence of a potentially helpful phenomenon to which they had previously turned a deaf ear: so-called slow or "silent" earthquakes. These are fault movements so slow—taking days instead of seconds as in ordinary earthquakes—that they produce no seismic waves and hence can't be picked up by the listening ears of seismometers.



A silent quake speaks. Surveyors saw the land rising days before the great 1944 Tonankai earthquake.

SOURCE: EARTHQUAKE PREDICTION, BY KIGOO MOGI, ACADEMIC PRESS, 1985.

Silent earthquakes had seemed little more than rare curiosities, but as a flurry of presentations at the meeting showed, reanalysis of old records and use of additional instruments are revealing many more of these slow groanings of the crust. The new data also suggest that these slow movements can provide a window into the secret life of faults. A silent quake may defuse a fault that has been building toward failure—or transfer stress to part of the fault already near failure and trigger a normal earthquake. Detecting a silent precursor might thus give a few days' warning before a quake strikes. "There's enough evidence of slow and silent earthquakes to make them credible," says seismologist Paul Segall of Stanford University. "The grand prize in all this would be seeing something occurring before earthquakes" and so allow quake prediction.

No one has captured that prize yet, but a new analysis of data collected southwest of Tokyo just before the magnitude-8.1 Tonankai earthquake of 1944 suggests that a silent quake presaged that killer. Geophysicists Alan Linde and Selwyn Sacks of the Carnegie Institution of Washington's Department of Terrestrial Magnetism reexamined data collected by Japanese seismologist A. Imamura of the University of Tokyo. Fearing a great quake, Imamura had requested a survey to gauge the slow flexing of the land southwest of Tokyo. On the night of 6 December 1944, the surveyors were surprised to note that one end of an 800-meter survey line was 3 millimeters higher than it had been 3 days before. They resurveyed the next morning, only to find an additional 4-millimeter difference. Either their surveying was badly awry, or the southeast end of the line was rising extraordinarily fast. They got their answer that afternoon when the great quake struck.

At the meeting, Linde and Sacks reported that the survey data fit a silent quake that triggered the devastating quake from below. They found that the sharp rise of the land implied about 2 meters of silent slip along a deep, 60-by-50-kilometer patch of the fault during the few days before the earthquake. Such slip, equivalent to a magnitude-7.5 quake, would have loaded stress on the upper part of the fault, apparently bringing it to the point of failure.

It's not clear how often silent quakes presage normal ones or whether Japan's next great quake will issue a silent warning. To find out, the Japanese monitoring network is today listening for such silent precursors using two types of instruments. Strainmeters buried in drill holes record the flexing of the crust, while Global Positioning System (GPS) receivers on the surface determine their location to millimeter accuracy by comparing radio signals from U.S. military satellites overhead (*Science*, 5 April 1996, p. 27).

Whether or not silent earthquakes turn out to be useful warning signs, several other talks showed that these slow movements aren't as rare as they once seemed. Geophysicist Malcolm Johnston of the U.S. Geological Survey in Menlo Park, California, and colleagues reported that a slow earthquake struck the San Andreas fault 150 kilometers south of San Francisco in April of 1996, when a 6-kilometer-square patch of the fault slipped a few centimeters over the course of 2 days. If the same slip had taken a few seconds, as in a normal small quake, it would have delivered a magnitude-4.9 jolt to the residents of nearby San Juan Bautista; instead, they felt nothing and even nearby seismometers failed to note it. Johnston's team, however, had installed strainmeters in nearby drill holes, and two of these recorded slow crustal deformation as the silent quake relieved stress on that patch of fault.

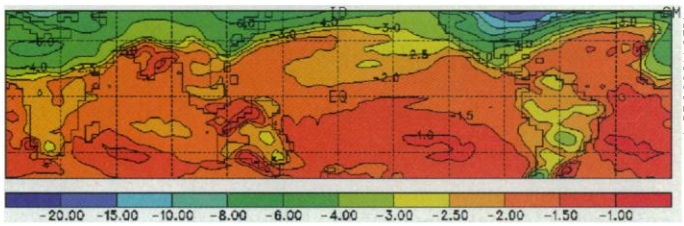
Across the Pacific, a GPS network detected a slow earthquake in May 1996, according to Takeshi Sagiya of the Geographical Survey Institute in Tsukuba, Japan. In the course of a week, about a dozen sites on the Boso Peninsula southeast of Tokyo moved as much as 15 millimeters to the south-southeast. With such limited data, Sagiya can't say which fault ruptured, but he suspects that it was a deeply buried fault, and estimates that the quake had a magnitude of 6.3.

In many instances, these silent earthquakes are good news, apparently releasing strain that would otherwise erupt in a damaging quake. The San Juan Bautista event, which may have been triggered by a smaller, normal quake, harmlessly released strain on the San Andreas. A similar silent quake just to the south in 1992 did the same, as Linde and colleagues reported in the 5 September 1996 issue of *Nature*. Some of the strain loaded on the Sierra Madre fault just northeast of Los Angeles by the 1994 Northridge earthquake also was apparently dissipated in a silent earthquake, according to a presentation by geophysicist Michael Heflin and his colleagues at the Jet Propulsion Laboratory (JPL) in Pasadena, California. The GPS receiver at JPL—which sits right on the Sierra Madre—measured 35 millimeters of horizontal motion, apparently reflecting silent strain relief that reduced the risk of a second earthquake. If such harmless strain release is common, notes Heflin, it could significantly reduce the hazard projected for areas such as San Juan Bautista, which are constantly strained as the Pacific and North American plates grind past each other.

For now, no one can be sure why some silent earthquakes harmlessly release strain and others trigger great quakes. But to catch more clues to how both noisy and silent earthquakes work, researchers will be listening ever more closely to Earth's most subtle whispers.

Moderating a Tropical Debate

Everyone knows that Earth was deeply chilled 20,000 years ago at the height of the last ice age, but how much did the tropics cool? For years, that question has divided researchers into two extreme camps, one seeing a much bigger drop than the other, with seemingly no middle ground between them. The gulf between these views may not be closing, but now at least it may be better understood.



Cool results. A new model suggests that ice age cooling in the tropics varied regionally, from less than 1°C (red) to more than 4°C (green).

The estimates of modest cooling came from oceanographers tracking the fluctuating abundance of microfossils in marine sediments. They inferred only a 2°C average cooling across the tropics, implying that the climate system then was dramatically different from today's and somehow kept more heat trapped in lower latitudes. But paleoclimatologists consulting a range of mostly terrestrial records—pollen in lake muds, isotopes in corals, and noble gases in ground water, for example—estimated perhaps a 5°C tropical cooling (*Science*, 4 October 1996, p. 35).

At the AGU meeting, climate modeler Anthony Broccoli of the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey, suggested that both groups' estimates may be reasonably accurate—but that neither is seeing the whole picture. His new computer modeling of ice age climate suggests that the cooling varied more from one region to another than indicated by previous models. This variation, Broccoli says, may explain much of the disparity in the data. Terrestrial temperature records are scattered so thinly that they could be missing areas of moderate cooling, he says, and even the more complete marine microfossil record probably has its blind spots. Completely reconciling the numbers is still going to be difficult, he says, but the model results could account for a few degrees of difference.

Broccoli came to these conclusions after adding two key improvements. Most earlier simulations simply adopted oceanographers' estimates of glacial sea-surface temperatures, but in the new model the surface ocean temperature can vary in response to changes elsewhere in the climate system. Moreover, the resolution of the model is about twice as good.

When this model was run under glacial conditions, such as increased ice coverage and reduced greenhouse gases, the tropics on average cooled only about 2°C, about as much as the oceanographers would have it. But the cooling was not uniform. For example, the model's Northern Hemisphere cooled more than the Southern Hemisphere due to the far larger area of ice in the north, an effect that extended into the northern tropics, where most of the best known terrestrial records are.

In general, Broccoli found that the model's tropical land cooled about 1 degree more than the ocean. He says part of this is due to the 100-meter sea-level drop during the ice age, which in effect raised the land 100 meters. Because temperature drops with increasing altitude above sea level, the land cooled slightly. Also, land has less moisture available to moderate temperature swings and so would be expected to show more cooling during an ice age. All this suggests that regional variation was typical of the glacial climate system—and that researchers should "be careful extrapolating from a few sites to the entire tropics," says Broccoli.

That message got a varied reception. Thomas Guilderson of the Lawrence Livermore National Laboratory in Livermore, California, who has inferred a 5° cooling from Caribbean coral isotopes, sees increasing evidence for a large tropical cooling, but admits that it may have varied regionally, conceding that it may have been only 3°C in places.

Paleoceanographer William Ruddiman of the University of Virginia, who was involved in the 1976 microfossil study that first proposed a moderate cooling, sees more hope for a reconciliation. Rather than requiring a glacial climate system radically different from today's, he can imagine "an accumulation of several really uninteresting 1° problems" of the sort Broccoli is finding that would account for much of the gap between the estimates. If so, there may be middle ground between land and sea after all.

–**Richard A. Kerr**