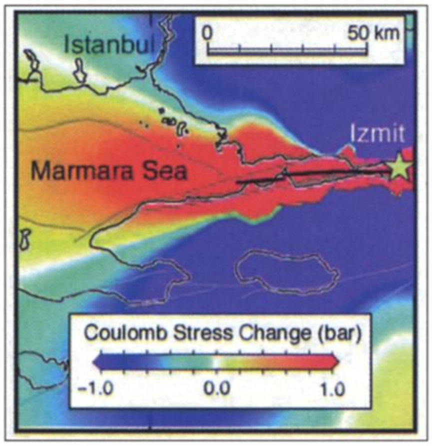
MEETING AMERICAN GEOPHYSICAL UNION

Quakes Large and Small, Burps Big and Old

SAN FRANCISCO—The fall meeting of the American Geophysical Union held here last month attracted 8200 earth scientists and a dizzying variety of topics, including the prospects for another large earthquake in Turkey, bursts of methane from the sea floor, and the use of microearthquakes in the study of fault behavior.

Istanbul's Next Shock

The metropolis of Istanbul, 13 million strong, is in the cross hairs of the next major Turkish earthquake, and seismologists are worried. They calculate that the magnitude 7.4 quake that struck 90 kilometers east of Istanbul last August near Izmit and killed 17,000 people has tightened the squeeze on the trigger for the next temblor. Since 1939, seven major earthquakes have marched along the North Anatolian fault toward Istanbul, rupturing one segment of the fault after another (*Science*, 27 August 1999, p. 1334). Using the new science of fault-to-fault communications, seismologists have found that the Izmit quake triggered the magnitude 7.2 earthquake that struck Düzce east of Izmit in November—and it also loaded the fault to the west of Izmit with additional stress. "There are large uncertainties," says seismologist Nafi Toksöz of the Massachusetts Institute of Technology (MIT), but "the likelihood of a magnitude 7 [quake] or larger has increased" just a few kilometers south of Istanbul.



Deadly fire. The Izmit earthquake shot high stresses (red) just south of Istanbul.

Researchers can talk about the prospects for the next Turkey earthquake because they have realized in recent years just how effectively quakes pass stress along faults. A quake releases stress on the section of fault it breaks but also transfers stress to adjacent sections. Once they know exactly where and how the fault broke in a quake, seismologists can calculate the location and magnitude of increased stress. At the meeting, seismologist Tom Parsons of the U.S. Geological Survey in Menlo Park, California, and his colleagues reported that according to their calculations, the Izmit quake increased the stress at the starting point of the Düzce quake by 1 to 2 bars. Because stress increases as small as 0.1 bar can sometimes trigger major quakes, the Düzce quake "is an induced quake if ever there was one," says geodecist Robert Reilinger of MIT.

What Izmit has wrought to the east, say researchers, it could wreak to the west. The North Anatolian fault splits west of Izmit into two strands that run beneath the Marmara Sea, which lies between the Black Sea to the north and the Aegean Sea to the south. The last major quake in the Marmara Sea was in 1894; six have struck there in the past 500 years. To judge by historical accounts, some struck the northern fault strand that passes within 15 kilometers of Istanbul on the north coast.

Parsons and his colleagues calculate that the Izmit quake increased stresses beneath the Marmara Sea by 1.5 to 5 bars. Making similar calculations, geodecist Geoffrey King of the Institute of Physics of the Globe of Paris, seismologist Aurelia Hubert-Ferrari of Princeton University, and their colleagues also reported at the meeting that Marmara Sea stress increased up to 5 bars. "We expect the next segment to rupture to the west [of Izmit] near Istanbul," says Hubert-Ferrari. "You can expect heavy damage in Istanbul, even a tsunami." Just how soon a Marmara Sea quake might strike depends on the poorly understood history of fault ruptures under the Marmara Sea, but Parsons and his colleagues estimate that a stress increase of merely 1 bar could increase the odds of a large quake by 20% to 50% in the next few decades. And recent history is not reassuring: In the sequence since 1939, no quake waited longer than 22 years and some came within a year of the one before.

This threat of another, possibly even more damaging, quake is being viewed with concern in Turkey. Toksöz says that the municipality of Istanbul was due to sign a contract last week for a first-ever evaluation of the likely effects of nearby quakes—none too soon given the tightening grip on the Marmara Sea trigger.

Gas Blast For the Dinosaurs?

A catastrophic meteorite crash wiped out the dinosaurs 65 million years ago, but they may have benefited from a gentler catastrophe 55 million years earlier. Rummaging in sediments laid down in the Cretaceous period, paleoceanographers have found signs of massive outpourings of methane gas from the sea floor that could have helped create the hottest climate of the past 150 million years. And there are hints of another methane burst 90 million years ago that may help account for a mass extinction in the ocean. These results join previous strong evidence of a methane burst 55 million years ago, which marked a major turning point in mammal evolution.

To track down methane bursts, paleoceanographers must dissect the sedimentary record finely enough to see each geologic moment, something they have begun to do only recently. For example, 55 million years ago, as the Paleocene epoch was slipping into the Eocene, the proportion of the rare isotope carbon-13 relative to carbon-12 dropped abruptly (*Science*, 19 November 1999, p. 1465). This isotopic shift was big—three parts per thousand—but it had gone unnoticed because the drop, most of which occurred over only a few thousand years, had slipped between widely spaced samples taken along sediment cores.

Such a large, abrupt shift points to a methane burp. Only the methane of methane hydrate—a combination of ice and methane formed by sub–sea-floor microbes—would have been poor enough in carbon-13 to drive such a shift; volcanoes could never have emitted enough carbon dioxide in such a short time. Apparently, a few thousand gigatons of methane escaped from the sea floor.

At the meeting, a group of paleoceanographers reported the discovery of another large, abrupt drop in the proportion of carbon-13, this one in 120-million-year-old marine sedimentary rock drilled in northern Italy. Bradley Opdyke of the Australian National University in Canberra and his colleagues described a 1.5-parts-per-thousand drop that took perhaps 20,000 years. Paleoceanographer Hugh Jenkyns of the University of Oxford has found the same isotopic

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change in the Pacific but with a magnitude of three parts per thousand. Most researchers see this drop as evidence of another burst of methane from sub–sea-floor methane hydrates. "I'm not 100% convinced myself" that some other mechanism won't turn up, says Jenkyns, "but it fits the facts." If there was a methane burst 120 million years ago, Opdyke has an explanation: the largest volcanic event of the past 160 million years. In his "hot LIPs" scenario, the volcanic eruption of large igneous provinces, or LIPs, onto the floor of the Pacific about 120 million years ago warmed midocean waters, breaking down methane hydrates and releasing their methane, which oxidized to carbon dioxide. Once in the atmosphere, the gas helped fuel a super–greenhouse warming.

The LIP-induced midocean warming would also have triggered an explosion of near-surface sea life, which would have used up the oxygen in the deep sea. Such anoxia would have ensured the preservation of organic matter in a layer of "black shales" that immediately overlies the isotopic drop. Two other such oceanic anoxia events mark the mid-Cretaceous, when soaring temperatures allowed the dinosaurs to expand into polar latitudes. One was at the transition from the Cenomanian epoch to the Turonian 90 million years ago, when another, smaller isotopic shift just preceded the anoxia and came in the midst of a major extinction event in the ocean.

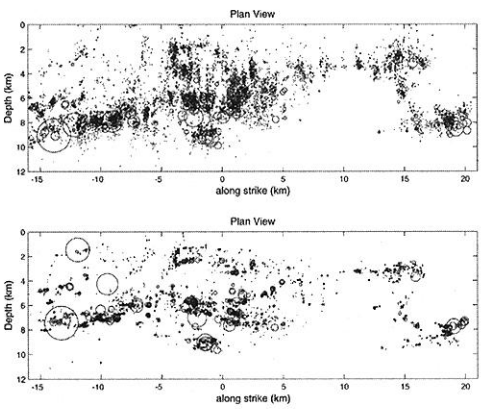
Confirming the role of sea-floor methane in these mid-Cretaceous anoxia events as well as their triggering mechanisms will require more work, says paleoceanographer James Zachos of the University of California, Santa Cruz, but "there should be more of these; it's a matter of looking more closely."

Fuzzy Faults Sharpened Up

Seismologists have long tried to get a picture of earthquake fault behavior by looking for patterns in the tiny quakes of magnitude 1 to 3, which constantly shiver along most active faults. Those microearthquakes have been hard to pinpoint, but now an improved technique is bringing the view into focus. Instead of fuzzy clouds of microearthquakes, researchers are seeing clusters of repeating quakes, mysterious streaks, and ominous holes that offer deeper understanding of how faults work. "It's like putting the corrective lens on the ailing Hubble Space Telescope and finally seeing what's out there," says seismologist William Ellsworth of the U.S. Geological Survey in Menlo Park, California. Through the new lens, seismologists seem to be witnessing the progressive failure of a fault that should lead to a long-predicted quake in Parkfield, California.

Seismologists locate quakes by triangulation. The distance between a seismograph and a quake can be calculated from the time it takes for the first seismic signal to arrive, and the quake's location can be determined by seeing where the distances from three or more seismographs converge. But until recently, even with dense networks of seismographs, the error margins were large—up to several hundred meters—for quakes of magnitude 1 and 2 that break patches of fault only 10 to 200 meters across.

Seismologists have now improved their accuracy by more than an order of magnitude by using a second type of information. They also examine seismic waveforms, the wiggly traces of seismograms ultimately produced by the ground motions of fault rupture. The closer two microearthquakes are on a fault, the more similar their waveforms. If they are similar enough, picking the time of one quake's arrival relative to the other's becomes far easier, allowing seismologists to locate quakes relative to each other with a precision of 10 meters or less. Although the technique is not new—it has been around for a couple of decades—only recently have seismologists' computers been powerful enough to apply it to thousands of microearthquakes on a fault. "It looks like a very, very promising technique and very important," says seismologist Yehuda Ben-Zion of the University of Southern California in Los Angeles.



New prescription. Reanalysis of conventionally located quakes *(top)* sharpens the view *(bottom).*

CREDIT: G. BEROZA AND D. SCHAFF/STANFORD UNIVERSITY

At the meeting, one speaker after another showed examples of how they could use the higher resolution techniques to snap a fault into focus. For example, groups headed by Ellsworth, Gregory Beroza of Stanford University, and Allan Rubin of Princeton University are studying the central San Andreas fault and two of its branches in northern California, the Calaveras and the Hayward. Quakes that used to seem scattered over large parts of these faults collapse into a few tiny areas covering only 1% to 5% of the fault. Some are tight clusters of similar quakes; others are identical ruptures that repeat time after time at the same spot.

Most surprisingly, many of the microearthquakes in some areas form streaks along the fault that run parallel to the fault motion and have been dubbed skid marks by one seismologist. Several kilometers long and about 100 meters high, they remain enigmatic, but they may indeed be skid marks of a sort, where slippage on the fault drags rock of a different composition against the opposing fault face. The rock could smear along the fault, causing it to stick there and break in microearthquakes.

The skid mark explanation won't work, however, for streaks that run across the direction of fault slip. On the San Andreas near the town of Parkfield in central California, two such inclined but roughly parallel streaks pass beneath Middle Mountain, where repeating magnitude 6 quakes have struck over the last 150 years—the most recent in 1966.

At Parkfield, streaks may be pointing to how a fault prepares to break. At the meeting, Ellsworth reported that a 1993 magnitude 4 quake that struck the same spot on the fault where three other magnitude 4 quakes have hit since 1934 clearly began on the lower of the two inclined streaks. It then ruptured upward toward the point where the 1966 Parkfield quake got started. At a depth of more than 12 kilometers, the lower streak may well mark where deep, hot rock cools enough to become brittle and break in earthquakes, says Ellsworth. Above it, the fault could be locked tight until a magnitude 6 Parkfield quake ruptures it.

Apparently, microearthquake-free holes between streaks or clusters mark fault patches that break in larger earthquakes. Ellsworth and his colleagues have found that coincidence not only at Parkfield but also in the case of the 1984 magnitude 6.2 Morgan Hill earthquake and the 1989 magnitude 6.9 Loma Prieta quake. "The streaks do seem to be telling us a lot about [fault] structural controls" on larger quakes, says Ellsworth. Holes in seismic activity may thus direct seismologists to the most dangerous parts of faults.

Researchers do not yet know what touches the big quakes off, however. At Parkfield, both streaks seem to have given rise to quakes that are "knocking on the door" without triggering the expected quake. Or as Ellsworth wonders, "what makes that '66 spot so hard to knock off?" Perhaps he'll get his answer as more faults get defuzzed.

–RICHARD A. KERR