Take Your Choice: Ice Ages, Quakes, or Impacts

If you are looking for a coherent, tidily packaged program, do not bother with the meetings of the American Geophysics Union. Its name suggests at least certain constraints, but in practice there are almost none. This past December's meeting was typical: it included anything natural and nonliving within the gravitational influence of the sun. For good measure the marine biology of the American Society of Limnology and Oceanography was thrown in as well. Here are some selections.

A Combination of Impact and Volcano Is Dismissed

The claim read well in abstract form. Quartz grains shocked by the high pressures of an asteroid or comet impact were found lying just beneath the immense lava flows of the Deccan Traps of India. Linking the impact to subsequent volcanic outpourings and the more or less simultaneous death of the dinosaurs 66 million years ago seemed to be straightforward.

The talk itself, given at December's American Geophysical Union meeting, did not go so well. In an afternoon volcanology session, geochemist Asish Basu of the University of Rochester reported that he and his colleagues, Sankar Chatterjee of Texas Tech University and Dhiraj Rudra of the Indian Statistical Institute in Calcutta, had found grains in a sand layer at the base of the Deccan lavas that have all the characteristics of quartz shocked at the high pressures of an asteroid or comet impact.

Citing the criteria laid out in a paper by Richard Grieve of the Canadian Geological Survey and in other papers, Basu showed slides of magnified grains having what he described as the classic lamellae of shocked quartz—straight, continuous, and closely spaced. There also were the multiple sets of intersecting lamellae required for positive identification of true shock features. And the various sets of intersecting lamellae were oriented with respect to the quartz crystal structure just the way shock features are.

Response to the talk was one-sided, to say the least. The ending that morning of a session on the record of terrestrial impacts ensured a generous representation in the audience of experts in cratering and shocked minerals. After Basu fielded a couple of questions from those dubious about one point or another, Grieve, whose name had been invoked by Basu more than once, stood to say that "Not one of these photomicrographs indicate shock metamorphism" and that the relation between lamellae orientation and crystal structure was a poor one. Basu countered that hydrothermal alteration of the grains had occurred, altering their appearance somewhat. Grieve reiterated his disbelief.

Last up was Neville Carter of Texas A&M University. He is the shocked mineral expert who has been debating with Grieve and others the significance of claimed single sets of lamellae and other mineral features found in 66-million-year-old sediments and in volcanic ash. Carter sees evidence of high shock pressures, high enough that a volcanic eruption could impersonate an impact. Critics see evidence of chemical alteration and sample contamination by grains affected by rock deformation, that is, tectonics, but they see no signs of impact (*Science*, 11 November 1988, p. 865).

Carter said that he had looked at samples collected from the same sand layer that Basu sampled. "These are truly tectonic deformation features," he said. "They're classic tectonic lamellae." Basu responded that the two sets of samples could not be identical, but the discussion period was over. In the opinion of this audience, at least, Basu will have to find better evidence if he wants to link impacts, volcanoes, and extinctions.

Taking the Pulse of the San Andreas Fault

The ninth of January was the 132nd anniversary of the great southern California earthquake of 1857. The latest research shows that, on average, at least part of the section of the San Andreas fault that broke then should break again this year.

But the same research suggests that the fault's average behavior could be misleading. A newly refined dating of the past ten San Andreas ruptures adjacent to Los Angeles reveals a previously unrecognized clustering of large earthquakes in bunches of two or three. If this pattern were to hold, Los Angeles would wait at least another 80 years for another jolt from there. But the San Andreas is not that easy to get around.

The new view of the San Andreas's behavior comes from the continuing work of geologist Kerry Sieh of the California Institute of Technology in cooperation with radiocarbon dating specialist Minze Stuiver of the University of Washington and statistician David Brillinger of the University of California at Berkeley. As Sieh explained at the American Geophysical Union meeting, he has for some years been digging trenches across the fault to expose the geologic record of fault movement. If the right spot is picked, such as where Pallet Creek crosses the fault near Palmdale 55 kilometers northeast of Los Angeles, a nearly continuous record of repetitive sediment deposition and disruption by earthquake fault motion can be found. With luck, organic matter such as peat will have been laid down after each earthquake, allowing the dating of the event using the carbon-14 technique.

The problem has been that both the conventional carbon-14 technique and the new accelerator mass spectrometric analysis have errors of about 50 to 100 years, which roughly equals the intervals between large earthquakes on the San Andreas. For more precise dating, Sieh took his peat samples to Stuiver. His radiocarbon analyses have a standard error of 12 to 20 years. There are several reasons for Stuiver's improved precision. His carbon-14 decay counters can accommodate larger samples. They are buried underground and shielded with lead bricks. He counts decays for weeks rather than a fraction of a day. And in recent years he has determined more precisely how the production of carbon-14 in Earth's upper atmosphere has varied with time and thus how radiocarbon ages have differed from true ages.

The more precise dating of large earthquakes at Pallet Creek is both reassuring and revealing. Nine out of ten of the new dates for past events fall in the ranges previously determined, and the average interval decreased only from 145 to 132 years. But the sharper picture of quake timing shows that few of the intervals were average. The ten events were clustered in four groups of two or three events each. Of the six estimated intervals between earthquakes within clusters, only one, which was 134 years long, exceeded 63 years in length. The intervals between clusters lasted 200, 246, and 332 years.

A straightforward calculation yields a probability of 22% (confidence interval 7% to 51%) for another earthquake at Pallett Creek during the next 30 years. But to judge from the clustering, the group speculates, "it is more likely" that the present 132-year interval will be a long, intercluster interval, none of which has been shorter than about 200 years. That would clearly reduce the calculated 22% probability. The most recent estimate of that probability by the U.S. Geological Survey was 30% (*Science*, 22 July 1988, p. 413).

From study of the new data at Pallett Creek and at other sites along the fault, seismologists are looking southward more and more. "From these data," said Sieh, "it looks like our next [large] earthquake will be on the Coachella Valley segment," the second segment southeast from Pallett Creek's Mojave segment. The Coachella Valley segment has not broken since about 1688 even though the average interval there appears to be 220 years. That would place the next "Big One" in a sparsely populated area southeast of Palm Springs and more than 90 kilometers from the Los Angeles basin, but still as close as 50 kilometers to the San Bernardino area.

Although these latest results suggest where to look for the next big one, they are not encouraging about fault behavior and its predictability. "This is the most complete data set of its kind in the world," says Sieh, "and unfortunately it doesn't lend itself to a simple model." A simple model with considerable appeal is the characteristic earthquake model. It seems to work well for the short segment of the San Andreas near Parkfield, where the same section of fault slips about the same amount in earthquakes of the same magnitude at regular intervals of about 22 years (*Science*, 8 January 1988, p. 145). But there is nothing so regular about the quakes at Pallett Creek. The last three had fault slippage of about 6 meters each, but the intervals preceding them ranged from 44 to 332 years. "We may be back to the unpredictable model," noted Sieh.

The cause of this less than ideal behavior may be the company that Pallet Creek's Mojave segment keeps. As suggested by recent fault modeling by John Rundle of Sandia National Laboratories, the behavior of one fault segment may depend strongly on the behavior of its neighbors. If the Coachella Valley segment broke, passing stress northward, for example, the adjacent San Bernardino Mountains segment might break sooner than it would otherwise, extending the rupture past San Bernardino. The kind of clustering seen in the Pallett Creek record only appears in Rundle's model if such strong interaction between segments is allowed. The implication is that seismologists and geologists may have to learn a great deal about the entire southern San Andreas to pinpoint the time and place of the next big one.

New Way to Switch Earth Between Hot and Cold

A diminished carbon dioxide greenhouse seems to have been one immediate cause for the most recent ice age (*Science*, 29 July 1988, p. 532), but why was atmospheric carbon dioxide depleted then? Researchers have for some time assumed that the ocean had to be behind such changes, because it is the only large link in the cycling of carbon that can adjust rapidly enough (*Science*, 9 March 1984, p. 1053).

There is now new evidence that the oceanic change could have originated as an internal chemical redistribution rather than as a change in the elements flowing in and out of the ocean. Edward Boyle of the Massachusetts Institute of Technology reported at December's American Geophysical Union meeting that he has accumulated a record from the North Atlantic and North Pacific that allows him to keep track of where in the ocean dissolved carbon dioxide was over geologic time.

Columbia University

Racks of sediment cores *hold clues to the ice ages.*

Boyle's technique is somewhat indirect. He measures the element cadmium in the microfossils of bottom-dwelling forams. Because cadmium and phosphorous have similar chemical behaviors, cadmium content reflects the concentration of phosphorous, an essential nutrient, in seawater at the time the foram was alive and at the depth that it lived. Phosphorous, in turn, reflects the amount of dissolved carbon dioxide in that water because phosphorous and carbon in plants and animals tend to travel together as the debris of marine life drifts down from the surface, oxidizing, dissolving, and enriching the water as it goes.

Using the cadmium technique, Boyle found that during the peak of the last glacial period, about 18,000 years ago, the concentration of cadmium and thus carbon dioxide was lower in waters of intermediate depth (shallower than 2500 meters) and higher in deep waters than it is now. Somehow, carbon dioxide that is now stored at intermediate depths was then ending up in deep water. On the basis of stable carbon isotopic studies, it had been concluded that additions of phosphorous to the surface ocean at that time had stimulated biological production there and thus increased the delivery of carbon dioxide to deep water. Alternatively, northern Pacific surface waters might have sunk to form bottom water, which it does not now do (*Science*, 28 June 1985, p. 1519). Neither mechanism is now considered likely, and a half dozen different ones have been suggested. Some involve changes in ocean circulation that alter the way water sinks to deep and intermediate depths. Others depend on increasing the rate at which biological production reaches the deep sea.

Whatever the immediate cause, the effect of redistributing oceanic carbon dioxide to deep waters would be far-reaching. In a scenario proposed by Boyle, the preglacial ocean enters a mode of circulation and biological production that transfers carbon dioxide from intermediate to deep waters. That makes bottom waters more chemically corrosive, which accelerates the dissolution of calcium carbonate sediments. This shifts the balance among the forms of dissolved carbon dioxide, increasing the capacity of all seawater to absorb carbon dioxide from the atmosphere. Within a few thousand years, atmospheric carbon dioxide decreases, the greenhouse effect is diminished, Earth chills, and an ice age begins. Within a few thousand more years, the supply of dissolved calcium carbonate from rivers and its rate of deposition on the sea floor come back into equilibrium so that atmospheric carbon dioxide equilibrates at a new, lower level.

This scenario avoids some problems associated with earlier versions that included some of the same components. It has a lag of a few thousand years between the redistribution within the ocean and the carbon dioxide decrease, as is observed in stable carbon isotope data from the ocean and gas analyses of glacial ice. Decaying organic matter does not consume all the oxygen in intermediate waters during glacial periods, contrary to observations, as it might in other scenarios.

Testing this scenario will involve further dating of more geographically diverse sediments using the carbon-14 accelerator mass spectrometer technique. That may also reveal how the effects of Earth's rhythmic orbital variations, which are generally credited with controlling the 100,000-year pace of glacial cycles, can push the oceans from one state to another. ■ RICHARD A. KERR