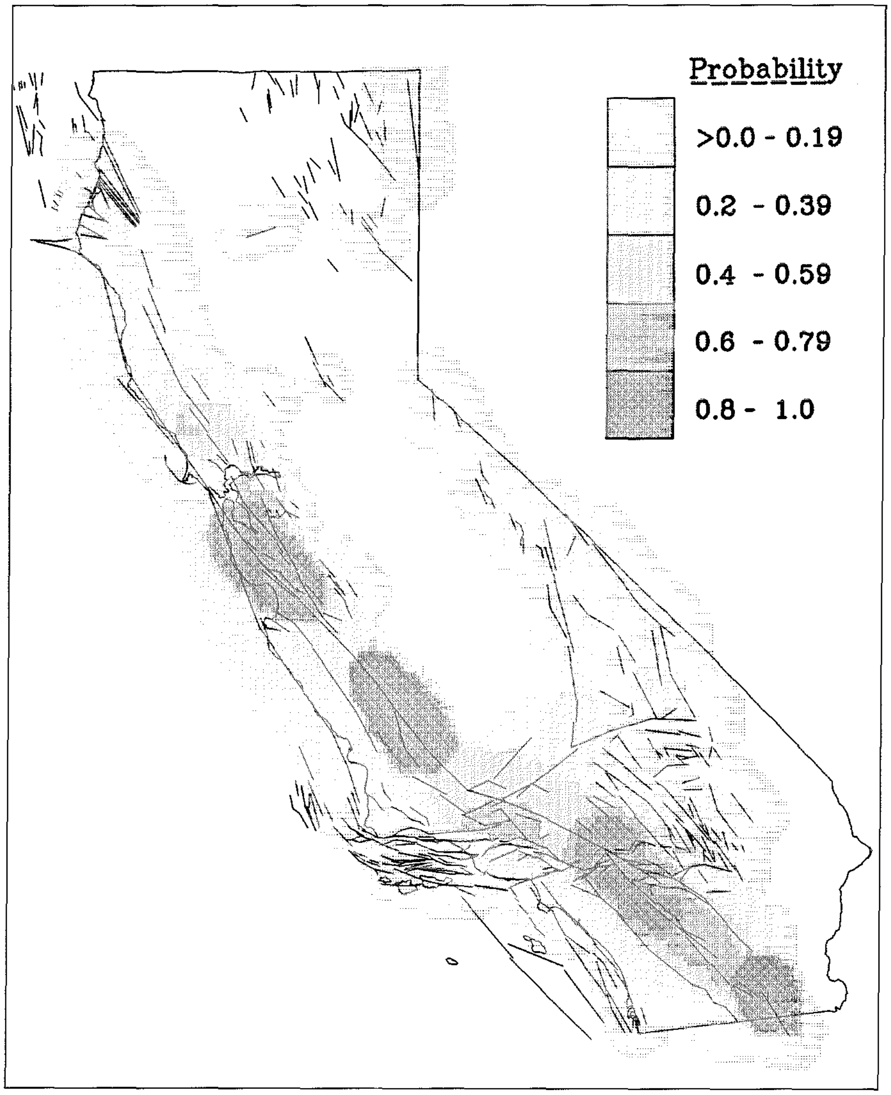
Research in Progress

Guessing a Hazard



This map shows the probability that any given area in California will suffer damage from an earthquake within the next 50 years.

THE RECENT SPATE of California earthquakes has led to renewed calls by communities around the state for reliable earthquake hazard estimates. While seismologists are still unable to predict individual quakes, they have long recognized that certain areas are more at risk than others. But until Steven G. Wesnousky, a former Caltech research fellow in geophysics, got involved, these risk estimates had a serious flaw — they were almost all based solely on the historic record of earthquakes, a record that is at best only a couple of hundred years old.

Wesnousky, who's now at the Tennessee Earthquake Information Center at Memphis State University, has conducted a detailed study of the geologic record of Quaternary Period faulting. By collating a massive amount of data bearing upon the location and magnitude of prehistoric earthquakes — at least those that have occurred during the last 100,000 years or so — he has produced the first geologically based earthquake hazard maps of the state of California.

In constructing these maps, Wesnousky had to determine both the magnitude and the rate of occurrence of earthquakes that rocked the state in the distant past. Earthquakes occur along faults, and studies of modern earthquakes reveal that larger earthquakes produce longer fault ruptures. The relationship between earthquake magnitude and rupture length is an empirical one, but observations of recent earthquakes have allowed seismologists to state that a rupture of length X is generally produced by a quake of magnitude Y. So by collecting information on fault length, Wesnousky is able to determine quake magnitude.

Wesnousky obtains estimates of the rate of occurrence of prehistoric earthquakes using data derived from two different methods — a direct method and an indirect one. In the direct method researchers examine sediments that are ruptured by a fault. When the ages of those sediments are known, investigators can often determine when prehistoric earthquakes have occurred.

The indirect method involves looking for rock formations on either side of a fault that were once adjacent but have become split and separated by a succession of quakes over the eons. By determining how old the formations are and how much separation there has been, the "slip rate" of the fault can be computed. The slip rate provides a measure of the average rate of strain accumulation on the fault, and from this it's possible to calculate how frequently earthquakes, which release this strain, occur.

Using this sort of information, Wesnousky constructed a series of California maps detailing different aspects of earthquake hazard. One shows the number of faults in a given area that might be expected to produce earthquakes causing peak ground accelerations of greater than one-tenth the force of gravity ($0.1g$). This is the level at which older structures and some modern structures not engineered to withstand earthquake shaking are susceptible to significant damage. Another map shows how frequently, on average, severe shaking can be expected. Still another series of maps shows the locations where the severe shaking is most likely to occur in California during any random 50-year period.

In the map pictured here, all this data has been combined with information on recent quakes. This map shows the estimated probability that mapped on-shore faults will produce ground accelerations of greater than $0.1g$ during the *next* 50 years. Writes Wesnousky in a paper soon to be published in the *Journal of Geophysical Research*, "[This figure] conveys information in a format that may prove useful for decisions regarding the siting of hazard mitigation procedures and the deployment of seismic instrumentation."

Not surprisingly, Wesnousky's maps indicate that the communities most at risk from a major earthquake lie along certain sections of the San Andreas fault. The San Andreas, which extends almost the entire length of the state, accommodates most of the slip as the Pacific plate moves northward relative to the North American plate. The San Jacinto fault, which traverses communities in the San Bernardino area and continues southward to the Mexican border, can also be expected to be the site of a large temblor in the not-too-distant future.

Although two of the most highly populated areas in the state — the Los Angeles and Ventura basins — are *not* traversed by faults the size of the San Andreas or the San Jacinto, they are shot through with a myriad of lesser faults. These faults are subject to only moderate slip rates, but there are so many of them in these regions that the hazard there is relatively high.

While Wesnousky's map highlights areas of high hazard, other areas of high hazard may yet remain unrecognized. On the map, an area can appear to be a low-risk area for two reasons: Either the risk really is low, or there simply haven't been enough geological data collected there to determine the true risk.

But this lack of data can be remedied. Says Wesnousky, "I think the primary result of this work is that it provides a framework for taking an active approach toward assessing seismic hazard. Rather than waiting till an earthquake occurs to modify our understanding of seismic hazard, we can look for faults and the features associated with them and gather information about slip rates and prehistoric earthquakes. I think research agencies should make a conscious effort to acquire those data. A lot of the data that I brought to bear on this problem came together in a rather hodge-podge way, from many investigators working in their separate little areas. It's worked quite well, but I think there's a chance here for a more rigorous approach." □ — *RF*

Tracking Stellar Reactions

THE UNIVERSE CONTAINS roughly equal amounts of carbon and oxygen. All life on our planet relies on this fact, but the carbon/oxygen ratio is also of vital importance to every star in the sky. If a star has too much carbon, an immediate supernova explosion is likely; if there's enough oxygen, on the other hand, the star can progress through several stages of evolution before its inevitable death as a supernova.

A team of physicists at the Kellogg Radiation Laboratory led by Bradley Filippone, assistant professor of physics, is trying to understand how it is that nature has made comparable amounts of carbon and oxygen. Included in the team are Kai Chang and Leon Mitchell, research fellows in physics, graduate student Rick Kremer, former undergraduates Kenneth Hahn and Aaron Roodman, Hugh Evans, visiting associate in physics, and Charles A. Barnes, professor of physics. They have been attacking the problem with Caltech's newest accelerator, nicknamed the Yellow Submarine.

At the heart of the problem are two nuclear reactions that take place in the interior of stars. In the first reaction,

$$3\alpha \rightarrow {}^{12}C$$

the nuclei of three helium atoms

(alpha particles) fuse to form one carbon-12 nucleus. This is called the triple-alpha process, and it is the principal source of carbon in the universe. In the second reaction,

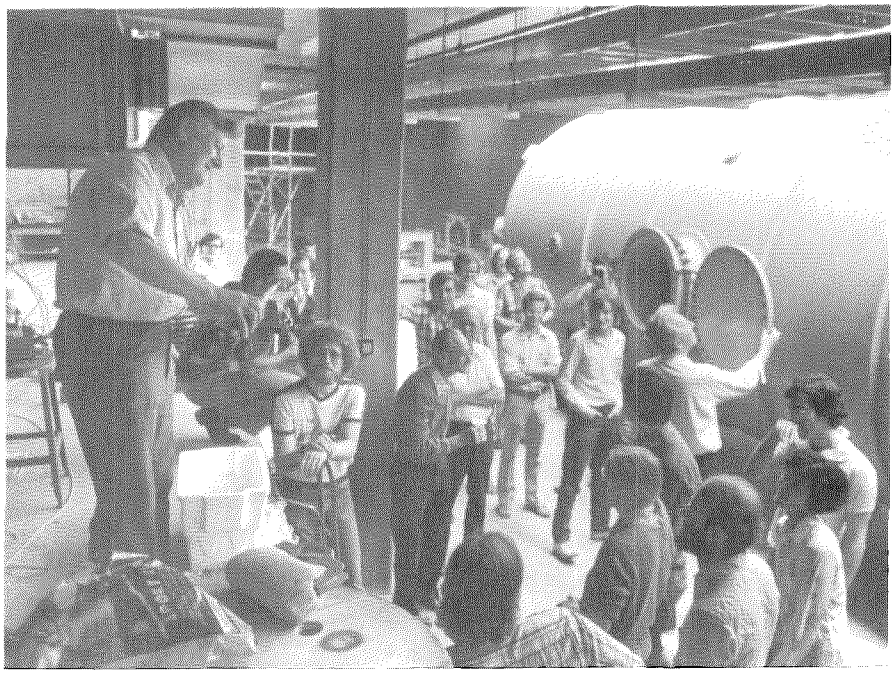
$$^{12}C + \alpha \rightarrow {}^{16}O + \gamma$$

the carbon produced in the triple-alpha process fuses with another alpha particle to form an oxygen-16 nucleus with the emission of a gamma ray.

If the first reaction goes at a much faster rate than the second, there will be an accumulation of carbon in the star, and carbon nuclei will begin fusing with each other. These carbon-burning reactions lead to a whole host of products: ^{23}Na plus a proton, ^{20}Ne plus an alpha particle, and ^{23}Mg plus a neutron, for example. These reactions produce huge amounts of energy, enough to cause a violent carbon-detonation supernova, which would leave no remnant of the star whatsoever. If, on the other hand, the second reaction proceeds faster than the first, then there will be an overabundance of oxygen. This condition, too, would eventually lead to a supernova after further evolution of the star, but in this case the explosion would leave a neutron star or a black hole as a remnant and would, in addition, produce a very different mix of elements in the explosion's ejecta.

It's only when the rate of production of oxygen is at least as fast as the rate of production of carbon that a fairly massive star can remain more or less stable. In this case, carbon nuclei still fuse with one another, producing quantities of energy, but the star is able to respond to the increased temperature by increasing in size. This decreases the pressure, cooling off the star and dampening the carbon fusion reactions. A star in this sort of cycle is said to be undergoing quasi-static carbon burning.

To determine whether the two reactions will be in balance, it's important to have precise data on the yields of the reactions as a function of energy and density. If the general shape of such a yield curve is smooth, as in the triple-alpha reaction, the curve's details can be worked out by making just a few measurements at critical points along the curve. But if the shape of the yield curve is complex, as in the reaction of ^{12}C with an alpha particle, a great many more measurements need to be taken for accurate determinations of the reaction's yield. This reaction is dominated by a number of "resonances" — sharp peaks whose locations on the energy scale are known, but whose exact shapes can only be determined by experiment.



In this 1981 photo, Charles A. Barnes toasts the arrival of the "Yellow Submarine," Caltech's newest tandem accelerator.

Working with Peggy Dyer, now of the Los Alamos National Laboratory, Barnes in 1974 determined the shapes of two of these resonances, which peak at 2.4 MeV and -0.045 MeV. But the most astrophysically interesting region of the curve is at about 0.3 MeV — this is where most of a star's heat production takes place. The oxygen yield in this region is dominated by two resonances at negative energies: the one at -0.045 MeV and another at -0.245 MeV.

"You can't get to these resonances even in principle because they're at negative alpha-particle kinetic energies," says Barnes. "But though the resonances themselves are physically inaccessible, nevertheless their effects on the oxygen yield are very real — their tails manifest themselves in the region of positive energies. The 'scents' of these resonances are present at higher energies, and even though it isn't a big effect, if you work hard enough you can 'smell' them, and they do all the things that positive energy resonances do."

One must, however, work very hard indeed. The problem is that the yield curve has an extremely steep slope in the region below 2.4 MeV. This means that as the energies get lower, the yields decrease very rapidly, causing problems in detection. In 1974 Dyer and Barnes were able to determine yields down to 1.4 MeV, but the rate of oxygen production in the region of interest near 0.3 MeV is about 100 million times less.

This job became somewhat easier in 1981 with the delivery of Caltech's newest tandem accelerator — the Pelletron, more commonly called the Yellow Submarine. Designed by Barnes along with engineers from the National Electrostatic Corporation, which built it, the Yellow Submarine has allowed Barnes and his colleagues to extend their measurements down to 0.95 MeV, where the yields are only about 1 percent of what they are at 1.4 MeV.

In these experiments, a beam of ^{12}C ions is accelerated and aimed at a two-inch cylinder filled with helium atoms. Within the cylinder a tiny proportion — maybe one in 100 quadrillion (10^{17}) — of the entering ^{12}C nuclei will fuse with helium nuclei to form ^{16}O, producing a gamma ray in the process. The ^{16}O nuclei streak out of the cylinder with the unreacted ^{12}C, but because of the Law of the Conservation of Momentum, the heavier oxygen nuclei travel 25 percent more slowly than the lighter carbon.

The researchers take advantage of this slower speed in their efforts to separate and detect each fusion event. Immediately after the beam leaves the target cylinder, it passes through a velocity filter that discards most of the faster-moving ^{12}C atoms. This changes the proportion of oxygen from one in 100 quadrillion atoms to a relatively rich one in 100 million. The beam then passes through a large magnet, which performs a further separation based on mass, and then to a counter that measures the charge of each remaining atom. Finally, the exact time of detection (which can be determined with an accuracy of just a few nanoseconds) is correlated with the time of detection of the gamma ray produced at the instant of fusion. If all of these quantities have the right values, the event is presumed to reflect the actual production of a nucleus of oxygen.

In this way the researchers have extended their measurements down to 0.95 MeV. But, Barnes says, "How much further we could go is really an endless question. We could probably get down to 0.90 with an enormous effort, dropping about another factor of 10 in yield." The problem is that even at 0.95 MeV, they are only detecting a few fusion events per day. Although it seems feasible to get the background noise in the detector system down to about 1 count per day, the lower the actual oxygen yield gets, the longer the experiment must be run to achieve a statistically significant number of counts above that background. As Barnes points out, "At some point you're not talking about an experiment that lasts the time it takes a graduate student to get a PhD; you're talking about an experiment that lasts an entire human lifetime — a length of time we cannot afford to spend on a single experiment."

However, the Kellogg team believes that if they can verify their results down to 0.95 MeV, the scent of the negative-energy resonances will be strong enough to reconstruct their shapes quite accurately. In turn, this will give the theorists the data they need to understand how nature has made the concentrations of carbon and oxygen observed in the universe.

Reflecting on the many years he has spent studying stellar helium burning, Barnes remarks, "Isn't it marvelous that nature has contrived to make comparable amounts of carbon and oxygen so we can live? On the other hand, if that were not true, we wouldn't be here to ask the question, 'Isn't it marvelous?'" □ — *RF*