What Makes the San Andreas Tick?

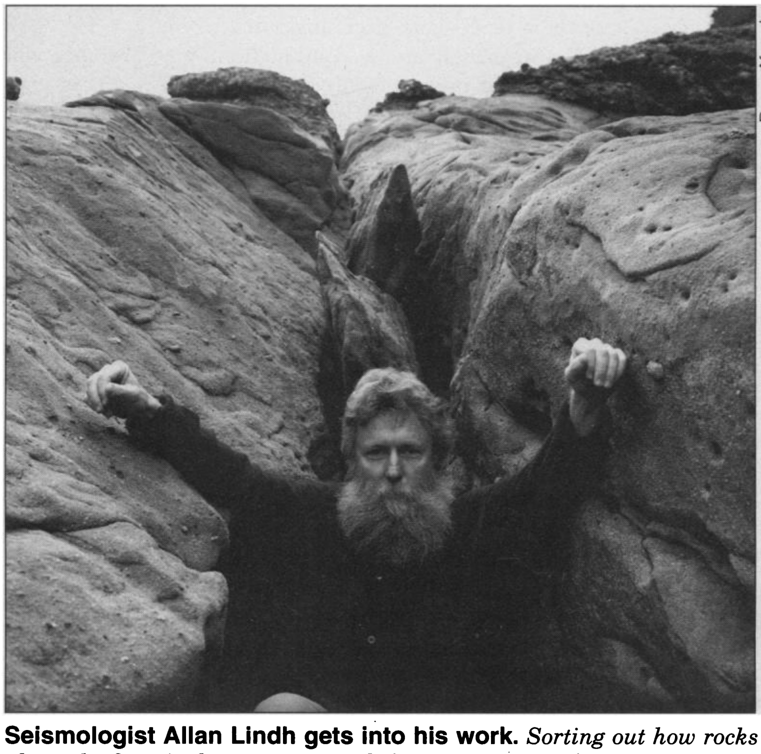
For Allan Lindh, the fault's smallest crackles and mightiest booms all echo the nature of the rocks along the way

THE SAN ANDREAS, SLICING 1000 KILOMETERS through California, is a fault of many faces. For 180 kilometers along its midsection, it is a harmless curiosity that pops off a minor tremor almost every week. Along the 30 kilometers of fault directly to the southeast, called the Parkfield segment, the San Andreas is a little less benign, breaking every few decades in a moderate quake that topples chimneys and shatters ill-guarded china. South of Parkfield the fault turns savage. That segment last broke in the great magnitude 8.3 earthquake of 1857, though it has been eerily quiet ever since.

That San Andreas earthquakes run the gamut from insignificant to catastrophic has long puzzled scientists. Seismologist Allan Lindh of the U.S. Geological Survey (USGS) in Menlo Park thinks the answer lies in the variety of rock types along the fault. Some rocks, he argues, produce a weak fault that slips often in minor earthquakes as plate motions drive the opposing sides of the fault past each other. Other rocks strengthen the fault, letting it store up dangerous amounts of strain before finally rupturing. If Lindh is right—and, despite a dearth of detailed evidence, many of his colleagues think he may be—the varied behavior of the world's most famous fault might, with any luck, be better predicted.

The basic idea may sound familiar to some of Lindh's older colleagues. Thirty years ago, some seismologists suggested that the size of the quakes along the San Andreas might depend on how much friction the rock along the fault could generate. Where low-friction rock allowed the fault to slip easily, frequent, minor quakes could be expected; where the friction was high, the fault would be stronger and lock up until the strain became great enough to break it, leading to larger earthquakes. The theory seemed to have a serious problem, however: Laboratory studies soon showed that friction between rocks actually doesn't vary much from one kind of rock to another. But discussions over the years with his friends in seismology, geology, and rock mechanics convinced Lindh that the rock-earthquake link should be rescued.

Ever the big thinker and synthesizer, Lindh credits others with most of the elements of his model. Geologist Richard Sibson of the University of Otago in New Zealand, who has inspected the heart of many a fault now laid bare by erosion, contributed a key idea—that fault strength is not related to frictional properties alone, but also to differences in how deeply the sides of a fault can lock together. Below a certain depth, rising temperatures can weaken rock. In one strength-robbing process, the rock changes from something that can fracture like porcelain and generate an earthquake to something that deforms quietly, like putty. Because the temperature—and hence the depth—at which different rock types lose their strength varies, Sibson pointed out, rock type might control the depth to which a fault can stay locked. And the deeper and larger the area of locked fault, the stronger the fault as a whole. That would mean less frequent—but more catastrophic—slip on the fault.



Seismologist Allan Lindh gets into his work. *Sorting out how rocks along the San Andreas can control the pattern of earthquakes will take deeper probing of the fault than this.*

Lindh applied that idea to the San Andreas using the rocks seen at the surface and some assumptions about how they would behave at the depths where earthquakes occur. In the harmless midsection of the fault, where the two sides of the fault smoothly creep by each other most of the time, the rock on one side is typically mélange, says Lindh—a jumble of rock fragments. Mélange should lose its strength quickly with increasing depth, becoming ductile. No wonder, says Lindh, that along this section the San Andreas only locks over meager spots that produce quakes smaller than magnitude 5. Those spots are probably the few inclusions of rock that are strong enough to lock the fault, he suggests.

To the south, in the Parkfield section, the rocks change to a patchwork of mélange, granite, and basalt. In Lindh's model, this rock's greater resistance to the effects of temperature explains why the fault seems to lock more tightly. Near Parkfield, a patch of fault 25 kilometers long is locked to a depth of about 10 kilometers, according to surveys of crustal deformation there. When it slips by a half-meter or so, as it did in 1966, the result is a modest-sized earthquake.

The extreme case comes still farther south, in the Carrizo segment, one of several sections of the San Andreas that broke in the great 1857 quake. The rock there, some of the most iron-rich and dense anywhere along the fault, is just the sort that could remain strong and brittle to great depths, says Lindh. That could explain how the fault resisted rupturing for the 300 years needed to build up the strain that was released in the great earthquake's 10 meters of slip. Though the depth of locking along this part of the fault is not known, Lindh figures it must extend to 20 kilometers or more—a conclusion reinforced by the micro-earthquakes that tend to mark the edges of locked patches elsewhere along the fault. Just north of Parkfield this microseismicity hovers between 4 and 7 kilometers; it deepens below the locked Parkfield segment, and toward Carrizo the micro-earthquakes deepen even more before disappearing.

This rough association of rock type, locking depth, and earthquake size intrigues some of Lindh's colleagues. "We would agree with most of this," says seismologist David Oppenheimer of the USGS in Menlo Park. But he, like other seismologists, is frustrated by Lindh's characteristically casual presentation of his idea. So far, Oppenheimer complains, there's been no paper—only a talk drawing on precious little data. "The problem with Al's theory is there's no paper trail we can cite. He's willing to stick his neck out; he likes to stimulate people to think about things. But it's not sufficient to get up in front of a meeting and just talk about it."

Maybe not. But other researchers are already gathering data that is starting to support the model. Seismologists Andrew Michael and Donna Eberhart-Phillips of the USGS in Menlo Park recently probed the structure of California faults using seismic waves crisscrossing the faults from a few hundred nearby earthquakes. As they reported in *Science* (9 August, p. 651), the variations in seismic wave velocity enabled them to trace the varying density of the rocks buried along the fault—something Lindh had only inferred from surface geology. According to the model, the densest rock (the kind most resistant to softening at depth) should go with the largest earthquakes. In their study of five earthquake sites, including Loma Prieta and Parkfield, Michael and Eberhart-Phillips found that the predicted correlation held up well, thus extending it to the kilometer scale at earthquake depths.

These results suggest that Lindh's model might be combined with seismic imaging and other techniques to pinpoint segments of the San Andreas where the rocks are capable of storing up great strain that is due for release. By identifying these most dangerous fault sections and even the parts of those sections most crucial in earthquake initiation, seismologists would gain a new way to focus their search for warning signs of an imminent quake.

Lindh is the first to concede that his idea will need some more testing before it can make much of a contribution to earthquake forecasting. "As we build better three-dimensional models and have more large earthquakes, these ideas will either hang in there or not," says Lindh. But he's not sweating it. Since he recently joined the ranks of the bureaucrats as seismology branch chief at Menlo Park, he jokes that "they can't fire me for having bad scientific ideas." ■ RICHARD A. KERR

Improvements Seen for RU-486 Abortions

Researchers are working to make the procedure safer but have split over the best way to achieve that goal

Geneva, Switzerland—PERHAPS IT'S a case of absence making the heart grow fonder. In the United States, where doctors have been unable to prescribe RU-486, the controversial French abortion drug has generally been treated, except by anti-abortion groups, as a cause célèbre with no known downsides. Indeed, in the 10 years since its development, RU-486 has been successfully used to induce abortions in 80,000 women, primarily in France. But while it has proved effective when used in association with a prostaglandin, some problems have cropped up.

Mostly these have been relatively minor, such as abdominal cramping, although one feminist group has recently released a report charging that the side effects are worse than they've been made out to be (see accompanying story on p. 199). But three cases of cardiovascular complications—one of them fatal—have been attributed to the RU-486-prostaglandin combination, further fueling opposition to its use by anti-abortion lobbyists. Now comes word, however, that some of the problems are on the way to being solved.

According to new research data obtained by the World Health Organization (WHO) in Switzerland and the drug's inventor, Etienne-Emile Baulieu, professor of biochemistry at the University of Paris Sud, progress has been made on ways to improve the drug regimen used to induce abortions. Still, WHO and Baulieu are far from agreement on where the research priorities should lie.

Jeremy Chertas

Looking to improve. *Etienne-Emile Baulieu wants safer prostaglandins.*

WHO has been concentrating—with apparent success—on lowering the RU-486 dose. Organization officials have released to *Science* the results of a large clinical trial showing that the dose of RU-486 can be reduced by at least two-thirds without a fall-off in efficacy. But Baulieu says those efforts may be misplaced. Sulprostone, the prostaglandin used in the majority of French RU-486 abortions, is the primary cause, he says, of the chief problem associated with RU-486 use—the abdominal cramps that occur in about 80% of cases. And sulprostone may also be the culprit behind the more serious heart problems that have been reported. Consequently, Baulieu has been spending his energies trying to find a safer substitute—also with apparent success.

The WHO trial included a total of 1188 women who were given the drug in 11 centers in eight countries. At each center, the women were divided into three groups, one of which received 600 milligrams of RU-486, the current standard dose, while the other two received either 400 or 200 milligrams. All got the same dose of prostaglandin. The result? All three RU-486 doses proved equally effective, each producing complete abortions in about 95% ofthe women.

And it may be possible to reduce RU-486 doses even further. According to Paul Van Look who organized the trials at WHO's Human Reproduction Program, preliminary studies have already shown that, using RU-486 alone, doses as low as 150 milligram might be effective. WHO plans to carry out another multicenter trial to verify that observation, using RU-486 with a prostaglandin.

Meanwhile, Baulieu has been making headway in his search for safer prostaglandins. In April, he reported to the French Academy of Sciences results with an oral prostaglandin, misoprostol, widely marketed for the treatment of gastroduodenal ulcer. Given to 100 women, the RU-486-misoprostol combination produced complete abortion in 95 cases, severe pain in only two cases, and no other significant side effects. Larger studies are about to