Research News

Is the San Andreas Weak at Heart?

Scientists drilling a deep hole near the San Andreas fault are finding that it may be by far the weakest part of the crust, which would resolve a 15-year-long controversy

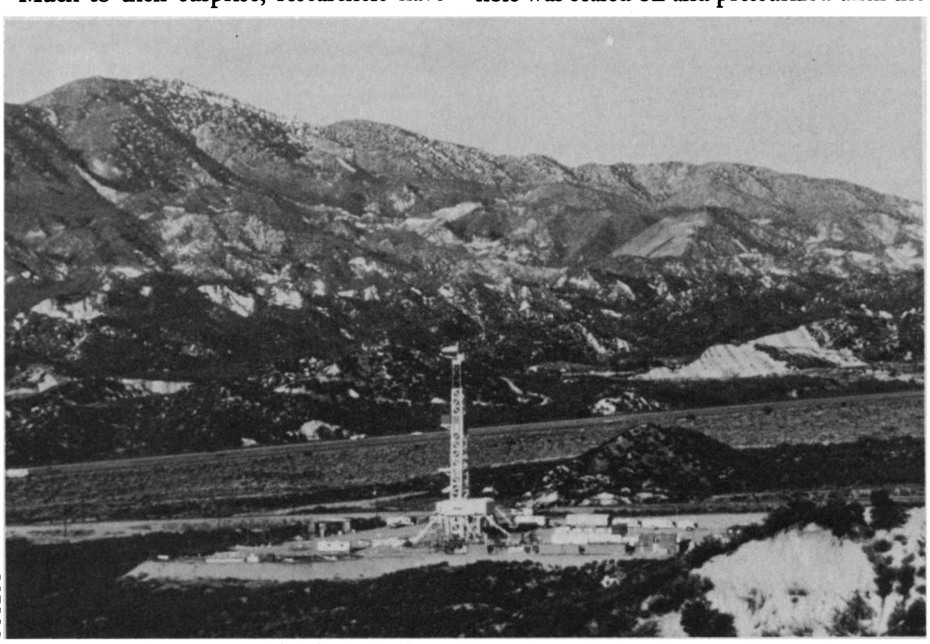
Cajon Pass, California

HARD by Interstate 15 just outside the Los Angeles basin, a 19-story oil drilling rig, one of the ten largest in the world, is hauling instruments up and down a hole that all concerned hope will never be a gusher. Three and one-half kilometers beyond the highway, the 7000-kilometer-wide North American plate abuts the 10,000-kilometer-wide Pacific plate to form the San Andreas fault, the objective of this deepest of U.S. scientific drill holes.

Although only 2 kilometers toward their 5-kilometer goal, the deep-drilling scientists sinking the Cajon Pass well may have already hit their first pay dirt. The primary goal of the Cajon Pass Project is to determine the amount of stress driving fault motion and how much resistance the rubbing of the two plates along the San Andreas offers to plate motion. The results should bear on how the forces driving plates operate, how earthquakes occur as plates stick and then slip by each other, and how to go about predicting earthquakes.

Much to their surprise, researchers have found that there seems to be little or no stress driving the two great plates past each other at Cajon Pass. Yet they do move, therefore the inference that the fault offers little resistance. The low stress observed at Cajon Pass does not prove that the whole fault is under low stress and is therefore weak, and these results may in fact change as the hole is deepened. But they have prompted Mark Zoback of Stanford University to reevaluate other stress indicators and measurements made farther from the fault. He is the chief scientist of the project and co-coordinator of the stress measurements with John Healy of the U.S. Geological Survey (USGS) in Menlo Park. The low stress at Cajon Pass "is something that we were surprised to see," Zoback says, "but we've been staring at [other indicators of low stress] for decades."

What has been the most striking about measurements in the Cajon Pass well is not so much the magnitude of the stress but its orientation. Two stress-measuring techniques are being used. In a technique called hydrofracturing, a 2-meter section of the hole was sealed off and pressurized until the rock broke. The orientation of fractures reveals the orientation of the stress field, and the pressure required reflects the magnitude of the stress. In the other technique, an acoustic imager precisely records the shape of the hole. The hole can become out of round because the stress tends to pop rock off the hole walls in the direction perpendicular to the greatest stress, giving the orientation of the stress field.



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Drilling for science near the San Andreas fault. *The 57-meter-high drilling rig at the Cajon Pass hole (see white trailer to left for scale) can lift 680,000 kilograms of drill pipe, enough to drill a 9-kilometer hole. The goal here is 5 kilometers, deep enough to measure the stress driving earthquakes on the San Andreas, which lies about 4 kilometers to the left.*

Although analysis of the hydrofracturing down to 2 kilometers has yet to produce a clear trend, some researchers believe that they have good reason to expect high stress. Sliding two blocks of rock past each other in the laboratory has shown that friction should be high between all kinds of rocks at that depth, and thus stresses driving crustal plates should be high as well. Stresses far from plate boundaries do seem to be as high as laboratory experiments suggested they would be. And drill hole measurements at depths shallower than 1 kilometer have indicated that stresses on the San Andreas increase with increasing depth and should reach 60 to 70 megapascals (600 to 700 bars) at the 5- to 15-kilometer depths where earthquakes break the fault.

However, there has been no sign in the Cajon Pass hole of the excess heat that slip on a high-stress, high-friction fault should generate. No sign had ever been seen of it in surface measurements of heat flow anywhere along the 1000 kilometers of fault, a pivotal observation supporting those who believe that the fault is a weak, low-friction surface requiring perhaps only 10 megapascals of stress to drive it. Such a fault would never generate much heat.

The advocates of high stress have argued in turn that the friction-generated heat was there deep on the fault but was wafted away by ground water before it reached the surface, although the hot water could not be found either. That argument now has considerable problems. The Cajon Pass hole has already passed through the zone where moving water would carry heat away from the fault, but none was seen, according to Arthur Lachenbruch of the USGS in Menlo Park.

This paradox involving multiple indicators of high fault stress and an apparent absence of stress-generated heat has been nagging researchers for 15 years, but Zoback thinks he sees a possible solution—crustal stress is high, but on the San Andreas it is oriented so that the component driving the plates past each other is low. The Cajon Pass well breakouts at 2 kilometers indicated that the stress tending to drive the plates past each other, the shear stress, is at a maximum in the north-south and east-west directions. The hydrofracturing confirmed this orientation. But the San Andreas here runs only 10° off a northwest-southeast direction, the direction in which shear stress is at a minimum. In fact, if anything, this stress orientation tends slightly to drive the San Andreas in the wrong direction.

After researchers get over their surprise, their next reaction is usually to think that the Cajon Pass well may be still too shallow to reflect the true stress on the fault. Zoback thinks not. "I would bet that we might see a little more northerly stress field down hole," he says, to give a driving force in the correct direction, but "I would be very surprised if we saw the stress field rotate by 65°," the amount needed to align high stresses on a strong San Andreas fault.

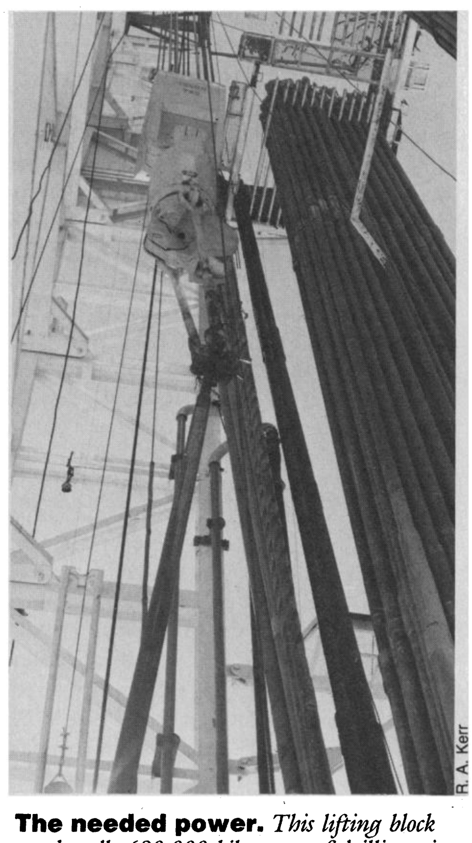
Zoback sees other support for the reliability of the Cajon results. Mary Lou Zoback of the USGS in Menlo Park and husband Mark have compiled over 1000 stress indicators of various sorts from across North America that Mark Zoback regards as reassuring with respect to the present depth of the well. "We have looked at a wide variety of data from North America," he says. "When we get below 100 meters, we generally see remarkable consistency."

He concedes that nearby faults splaying off the San Andreas make the the Cajon Pass area geologically complicated. Indeed, the stress orientation above 300 meters in the well seems to differ from that at 2 kilometers, he says, favoring instead the extension seen on faults at the surface rather than the compression expected from the way the two plates come together there. On the other hand, he notes, the deep stress is optimally oriented to drive the nearby Cleghorn fault, an east-west-trending San Andreas–like fault that moves in the direction opposite to that of the San Andreas.

Zoback also takes heart from the stress indicators in the Zoback and Zoback compilation that are near the San Andreas. These indicators include breakouts, hydrofracturing, and the orientation of fault slip during earthquakes. Even before drilling began, the Zobacks were on record that the stress in central California is oddly oriented. According to their compilation, the fault is not so near the minimum of shear stress as the results from the Cajon Pass well indicate, but the driving force on the fault would still be surprisingly low, surprising, that is, if a strong fault requiring a high driving force is assumed.

There is other new evidence that presumptions by some of a strong fault may be in error. Unbeknownst to the Zobacks, Van Mount and John Suppe of Princeton University had amassed stress orientations determined from breakouts in more than 100 oil and gas wells around California. The only conclusion from these well data, says Suppe, is that the San Andreas is weak. It lies within just 6° of the minimum in shear stress. That did not surprise Suppe, a geologist who has worked closely with oil companies in California for 25 years. The way the crust has been pushed up to form hills along the fault like the Kettleman Hills, the formation of which drove earthquakes like the recent one that hit Coalinga, was a clear sign that forces along the San Andreas are not optimally aligned to drive the fault, he says. Some of that force drives mountain building.

As enticing as such results may be, the San Andreas may be more complicated than they suggest. Lucile Jones of the USGS in Pasadena has recently determined stress orientations that diverge from Zoback's results and highlight Cajon Pass as a unique point on the fault. On the basis of her own set of 150 small earthquakes within 10 kilometers of the San Andreas, she found less shear stress on the San Andreas than some had assumed would be there but distinctly more than seen so far in the hole at Cajon Pass. In addition, "a very dramatic 15° change occurs right at Cajon Pass" in the stress orientation. It is the largest change that she found anywhere on the fault.


R. A. Kerr

The needed power. *This lifting block can handle 680,000 kilograms of drilling pipe, 2 kilometers of which is seen here stacked on the rig. This is part of the 1.6 million kilograms of equipment on the site that costs about $15,000 per day to operate, a good buy made possible by the depressed state of oil exploration.*

This is not the first time that the Cajon Pass section of the San Andreas has stood out as exceptional; it has long been a focus of attention. To the north the fault is geometrically simple and seismically quiet, whereas to the south numerous small earthquakes dot the anastomosing strands of the fault. The great rupture that raced 370 kilometers along the fault in 1857 stopped within a few kilometers of there for unknown reasons.

Jones thinks that the sudden drop in shear stress evident in her data might have acted as a barrier in 1857 to any further southeastward shearing of the fault. That stress drop may in turn be caused by the pulling away of the crustal block on the south side of the fault as it slips along the San Jacinto fault, a major splinter fault that leaves the San Andreas just 15 kilometers northwest of Cajon Pass.

If, as Zoback and Suppe now believe, the San Andreas is weak, there is still no new clue about what might have weakened it. Suggestions of how to make a fault permanently weak include lubricating it with a paste of rock that has been ground up by fault slippage and altered to clay by water. Such fault gouge would presumably have had plenty of opportunity to form during the hundreds of kilometers of slip on the San Andreas. Other ideas include weakening of stressed rock by water corrosion and the pushing apart of the faces of the fault by abnormally high water pressures.

So many of these suggestive observations are new to most researchers and enough indicators conflict with one another that there has as yet been no movement away from low- or high-stress positions espoused over the past 15 years. That is okay with Zoback. "The important thing is that all these ideas will be tested by deepening the Cajon Pass hole." That cannot come until the new fiscal year this fall when the consortium of universities drilling the hole for DOSECC (Deep Observation and Sampling of the Earth's Continental Crust, Inc.) expects to receive additional funding from the National Science Foundation. ■

RICHARD A. KERR