Geophysicists reveal new insights into the 'earthquake machine'

December 6 2005

The San Andreas Fault Observatory at Depth (SAFOD)—the first underground observatory to provide physical samples and real-time seismological data from deep inside an active fault zone—is yielding surprising new clues about the origin of earthquakes. SAFOD scientists from around the world will discuss these new findings on Dec. 6 at the annual meeting of the American Geophysical Union (AGU) at Moscone Center West in San Francisco.

SAFOD is a major research component of EarthScope, a National Science Foundation-funded program being carried out in collaboration with the U.S. Geological Survey (USGS) to investigate the forces that shape the North American continent and the physical processes controlling earthquakes and volcanic eruptions.

The SAFOD project is located near the tiny Central California town of Parkfield on the notorious San Andreas Fault—an 800-mile-long earthquake-prone rift that runs between the Pacific and North American tectonic plates. Drilling of the three-mile-long SAFOD borehole began in June 2004 on the Pacific plate just west of the fault. In August 2005, project leaders achieved their goal of drilling through the active fault zone into the North American plate, reaching a depth of 10,081 feet (1.91 miles). When completed in 2007, the observatory will be equipped with dozens of underground seismological instruments installed in a segment of the fault where small earthquakes are born.

"We passed an important milestone in August when we finally drilled through an active section of the San Andreas Fault at depth," said Mark Zoback, the Benjamin M. Page Professor in Earth Sciences at Stanford University. "Although the instrumentation won't be fully in place for another year-and-a-half, SAFOD is already giving us unprecedented access to the fault."

Zoback and USGS geophysicists William Ellsworth and Steve Hickman are co-principal investigators of SAFOD. They are among a dozen SAFOD scientists from the United States, Germany and Japan who will participate in two oral sessions at AGU.

Nonvolcanic tremors

One of the more intriguing discoveries in seismology in recent years involves the relationship between earthquakes and nonvolcanic tremors—low-frequency seismic signals that emanate deep underground in areas where tectonic plates meet. Earthquakes generate distinct surface signals known as compressional and shear waves (P and S waves) that usually last no more than 30 seconds. But nonvolcanic tremors—which can originate more than 20 miles below the surface and last up to 20 minutes—seem to occur weeks or months in advance of actual earthquake events, offering scientists a promising new tool for earthquake prediction.

From 2000 to 2003, before SAFOD drilling began, researchers from the University of California-Berkeley recorded 110 nonvolcanic tremor events along the San Andreas Fault near Parkfield. Their data showed a remarkable correlation between the frequency of tremor events and the subsequent earthquakes. The scientists discovered that an increase or decrease in the number of tremor events over a certain period of time would usually be matched by a similar increase or decrease in the number of microearthquakes (magnitude 2.1 or smaller) several weeks later, suggesting a possible causal relationship.

"This discovery opens an important new window into the workings of the San Andreas Fault that will undoubtedly become a major research focus in coming years," Ellsworth said. In May 2005, he and his USGS co-workers recorded two nonvolcanic tremors using a seismic geophone array that was deployed in the SAFOD borehole to a depth of about 1.5 miles.

"Bill and his colleagues made beautiful recordings of these tremors," Zoback added. "We would like to know why these tremors are generated, and whether they will one day allow us to forecast episodic slips along the fault."

SAFOD researchers also have begun collecting visual images of ground deformation from a laser strainmeter that was cemented in the borehole last summer. The strainmeter, which measures tectonic stresses, is outfitted with a fiber-optic cable that stretches from a depth of 2,835 feet all the way to the surface.

"Although pre-drilling site characterization studies predicted a relatively simple fault zone, the geology actually encountered during drilling was more complex," Hickman said, noting that the SAFOD borehole passed through a 1.2-kilometer-long composite of sandstones, shales and other rocks as it crossed the fault zone into the North American plate.

2004 Parkfield quake

On Sept. 28, 2004, a magnitude 6.0 earthquake struck near Parkfield. While this moderate-sized temblor caused little damage, it was of particular interest to seismologists worldwide, because six quakes of similar magnitude had occurred at regular intervals between 1857 and 1966. Based on the geological record, scientists had predicted the next 6.0 quake would occur by 1993, but their forecast was off by 11 years.

SAFOD researchers were able to obtain some seismic data during the 2004 quake, thanks to a seismometer and tiltmeter that were installed deep inside a SAFOD pilot hole that had been drilled near the fault in 2002.

Immediately after the 2004 earthquake, scientists from the University of Southern California and the University of California-Los Angeles deployed an array of 45 seismometers along the San Andreas Fault near Parkfield to record aftershocks. The researchers also recorded seismic waves from a series of underground detonations to obtain a detailed image of the fault. The results, which will be presented at AGU, indicate that damaged rock began forming mineral seals—a process known as fault healing—soon after the 6.0 earthquake occurred.

"We've found a broad region of damaged rock with reduced seismic [ground-shaking] velocity," Ellsworth said. "There is an ongoing debate over whether these low-velocity zones are surficial or integral structures within the fault. The SAFOD data show that the damage zones must exist at great depth—at least two miles to perhaps five miles below the surface."

Heat-Flow Paradox

In addition to seismological data, SAFOD researchers have been collecting the first rock, gas and fluid samples from inside an earthquake-generating fault zone. Scientists are using these samples to solve one of the great mysteries about the San Andreas Fault—the so-called Heat-Flow Paradox.

According to geophysicists, large amounts of frictional heat should be produced within the fault zone as the Pacific and North American plates constantly grind against one another. "The same thing happens when you rub your hands together quickly," Zoback explained.

But after 40 years of trying, scientists who study the fault have been unable to detect the amount of thermal energy that's predicted by the laws of physics. One explanation for the missing heat is that water accumulates under high pressure deep inside the fault. When an earthquake occurs, the pressurized water acts like a lubricant and prevents the two plates from rubbing together.

During one AGU presentation, Colin Williams of the USGS will describe the remarkable similarity between the temperatures in the pilot hole and in the SAFOD main hole located more than half-a-mile to the east. Williams and his colleagues collected heat data from a depth of about 1.4 miles at both sites. It turned out that the temperature in the pilot hole was 198.5 F, while the SAFOD main hole, which is much closer to the fault, was 199.9 F. This slight difference—less than 1 degree—suggests that little heat is being generated within the fault.

"Little is known about the role and origin of fluid and gases associated with the San Andreas Fault Zone," said Thomas Wiersberg, a geochemist from Potsdam, Germany. "To gain information on fluids and gases at depth, we performed real-time mud gas monitoring during drilling of the SAFOD pilot hole and main hole."

At the AGU meeting, Wiersberg will explain how he and his colleagues discovered surprisingly large amounts of hydrogen and radon gas in the vicinity of the SAFOD fault zone.

"Where do these gases come from?" Zoback asked. "They were found at temperatures and depths too extreme to have been produced from biological activity. Hydrogen could also be generated when rocks break and shear during earthquakes."

SAFOD scientists plan to start recovering much larger samples of gases, fluids and rocks from the active fault zone in 2007. "The activities carried out in the first two phases of SAFOD have laid the ground work for years of exciting research in earthquake physics, fault-rock geology, rock mechanics and the role of fluids and gases in faulting and earthquake generation," Hickman said.

Source: Stanford University