Seismology in the Source: The San Andreas Fault Observatory at Depth

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Abstract: *The main drill hole of the San Andreas Fault Observatory at Depth successfully penetrated the fault in the summer of 2005, setting the stage for the deployment of a multi-component earthquake observatory within the core of this major plate boundary fault. Results obtained from instruments at the edge of the near field region provide a tantalizing glimpse of earthquake nucleation and propagation processes.*

1. Introduction

The San Andreas Fault Observatory at Depth (SAFOD) is a comprehensive project to establish a multi-stage geophysical observatory in the hypocentral zone of repeating M~2 earthquakes within the San Andreas Fault as part of the U.S. National Science Foundation's EarthScope Program. The goals of SAFOD are to exhume rock and fluid samples for extensive laboratory studies, to conduct a comprehensive suite of downhole measurements in order to study the physical and chemical conditions under which earthquakes occur, and to monitor changes in deformation, fluid pressure and seismicity directly within the fault zone during multiple earthquake recurrence cycles (Hickman, et al, 2004).

The main drilling target is a pair of M~2 earthquakes that have recurred multiple times over the past two decades (Figure 1). These target earthquakes are located at a depth of 3 km on the San Andreas Fault immediately to the northwest of the Parkfield segment (Waldhauser et al., 2004). Prior to the September 28, 2004 M 6.0 Parkfield earthquake, the target events occurred every 2-3 years, with the "S.F." event typically preceding the "L.A." event by a minutes to a few days. Clearly, these two sources interact. Following the 2004 Parkfield earthquake, the recurrence rate dramatically increased, with these repeating earthquake sources contributing events to the Parkfield aftershock sequence. The interval between the events has been steadily lengthening since, following Omori-like behavior. The close coupling between "S.F." and "L.A" has also been broken. Consequently, there is much to learn about earthquake interaction at SAFOD, in addition to earthquake nucleation and propagation.

2. Building the Observatory

Extending 4 km into the Earth along a diagonal path that crosses the divide between Salinian basement accreted to the Pacific Plate and Cretaceous sediments of North America, the main hole at the San Andreas Fault Observatory at Depth is designed to provide a portal into the inner workings of a major plate boundary fault. The successful drilling and casing of the main hole in the summer of 2005 to a total vertical depth of 3.1 km make it possible to conduct spatially extensive and long-duration observations of active tectonic processes within the actively deforming core of the San Andreas Fault. The observatory consists of retrievable seismic, deformation and fluid pressure sensors deployed inside the casing in both the main hole (maximum temperature 135 C) and the collocated pilot hole (1.1 km depth), and a fiber optic strainmeter installed behind casing in the main hole. By using retrievable systems deployed on either wire line or rigid tubing, each hole can be used for a wide range of scientific purposes, with instrumentation that takes maximum advantage of advances in sensor technology.

To meet the scientific and technical challenges of building the observatory, borehole instrumentation systems developed for use in the petroleum industry and by the academic community in other deep research boreholes have been deployed in the SAFOD pilot hole and main hole over the past year. These systems included 15Hz omni-directional and 4.5 Hz gimbaled seismometers, micro-electro-mechanical accelerometers, tiltmeters, sigma-delta digitizers, and a fiber optic interferometeric strainmeter. A 1200-m-long, 3-component 80-level clamped seismic array was also operated in the main hole for 2 weeks of recording in May of 2005 by Paulsson Geophysical Services, collecting continuous seismic data at a rate of 4000 samples/sec.

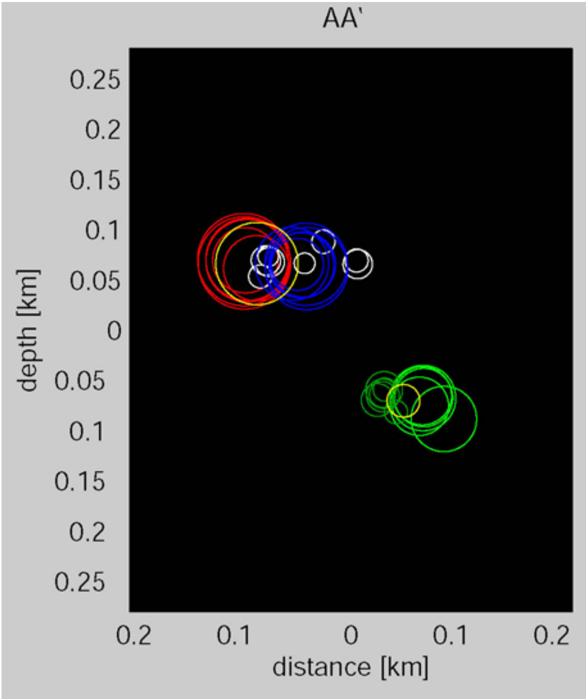

Figure 1 *Cross section in the plane of the San Andreas Fault showing repeating earthquakes of up to M2 in the drilling target, 1984-2005. The main trace of the San Andreas is associated with a northwestern event in red (San Francisco) and a southwestern event(Los Angeles) in blue; The green events are associated with a subsidiary trace of the San Andreas located 230 m closer to the SAFOD wellhead . Earthquakes are shown as circles centered on their hypocentroids with a diameter scaled by their moment for a 9 MPa stress drop (Imanishi et al., 2004). The S.F. and L.A. repeating earthquake sources are M 1.8 – 2.2. Hypocentroid locations courtesy of F. Waldhauser (after Waldhauser et al., 2004).*

3. Discussion

Some of the observational highlights include capturing one of the M 2 SAFOD target repeating earthquakes (Figure 1) in the near-field at a distance of 420 m, with accelerations of up to 200 cm/s and a static displacement of a few microns. Numerous other local events were observed over the summer by the tilt and seismic instruments in the pilot hole, some of which produced strain offsets of several nanostrain on the fiber optic strainmeter. We were fortunate to observe several episodes of non-volcanic tremor on the 80-level seismic array in May, 2005. These spatially unaliased recordings of the tremor wavefield reveal that the complex tremor time series is comprised of up-and down-going shear waves that produce a spatially stationary interference pattern over time scales of 10s of seconds.

4. Conclusion

The SAFOD observatory is now in operation. All data collected at SAFOD as part of the EarthScope project are open and freely available to all interested researchers. The Northern California Earthquake Data Center at U.C. Berkeley is the principal data repository for these SAFOD data. The more than 3 TB of 80-level array data are also available at the IRIS DMC as an assembled data collection.

5. Acknowledgement

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6. References

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