Monitoring Stress-Induced Seismic Velocity Changes At SAFOD Using Crosswell Continuous Active-Source Seismic Monitoring (CASSM)

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Abstract

Monitoring of in-situ, stress-induced, seismic velocity change provides an increasingly important contribution to the study of the earthquake nucleation process. Continuous Active-Source Seismic Monitoring (CASSM) with borehole sources and sensors has proven to be a very effective tool to monitor seismic velocity and to identify its temporal variations at depth. Since June 2017, we have been operating a crosswell CASSM field experiment at the San Andreas Fault Observatory at Depth (SAFOD) where a previous CASSM experiment identified the two seismic velocity reductions approximately 10 and 2 hours before micro-earthquakes. The ultimate goal of our experiment is to continuously monitor tectonic stress for the San Andreas Fault near seismogenic depth. Our active-source experiment makes use of two boreholes drilled at the SAFOD project site. A piezoelectric source and a three-component accelerometer have been installed in the SAFOD pilot and main holes, respectively, at about 1 km depth. A seismic pulse is generated by the piezoelectric source four times per second, and waveforms are recorded with a 48 kHz sample rate, with recordings summed for 1 to 10 minutes to capture seismic velocity changes at a high-temporal resolution. Since deployment in June 2017, and as of July, 2019, local seismicity has not been above our current threshold of detection. However, we have identified a velocity reduction at the SAFOD site (0.5 microsecond change in crosswell travel time, measured in a coda window) possibly induced by dynamic stress changes from the distant 6 July 2019 M 7.1 Ridgecrest earthquake, California. We will characterize and report the co-seismic change and post-seismic recovery process for this remotely triggered velocity change. We will also report on the overall status of this unique CASSM experiment.

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Summary

Crosswell Continuous Active-Source Seismic Monitoring (CASSM)

- Crosswell CASSM makes use of fixed location sources and sensors in boreholes to continuously monitor seismic waveforms as they are temporally varied by changing geophysical conditions at depth.
- SAFOD (the San Andreas Fault Observatory at Depth) is a drilling project for directly investigating the physical and chemical processes occurring within the San Andreas Fault Zone at seismogenic depth, consisting of two boreholes called the pilot and main holes.
- These deep SAFOD pilot and main holes provide a rare opportunity to conduct a crosswell CASSM experiment at near seismogenic depth.

2017-2019 SAFOD CASSM Experiment

- Our SAFOD CASSM system consists of a specially designed piezoelectric source in the pilot hole and a borehole accelerometer in the main hole.
- Piezoelectric sources are very attractive because the source pulses constitute highly reproducible signals with a rapid duty cycle.
- We have been able to install the newly built CASSM system with the SAFOD pilot and main holes facilities in June 2017.
- The system has been operating normally under a very unusual borehole setting (extremely high temperature and very corrosive borehole fluid) for more than 30 months, which has never been achieved before.

Long-term Goal of the SAFOD CASSM Experiment

- Developing a tool to monitor the time-varying stress/strain field associated with earthquakes and other stress-dependent earth processes (e.g., aseismic slips) (Silver et al., 2007, BSSA).
- Using the stress sensitivity of seismic velocity, we strive to obtain the maximum precision in measurement of stress induced travel time changes and to obtain long term monitoring of these changes (Marchesini et al., 2017, Geophysics).

2017-2019 SAFOD CASSM Experiment

SAFOD Data Acquisition System

- We fired a pulse with a width of 1 ms four times per second and recorded 200-ms-long data with a sampling rate of 48,000 Hz.

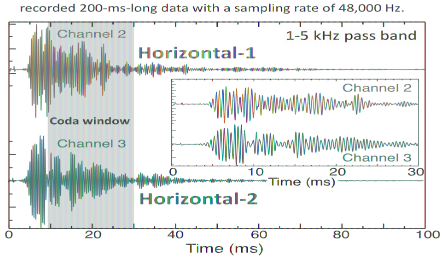

Fig. 4: Waveforms obtained in two horizontal components from our SAFOD experiment. Waveforms shown were obtained by stacking all recordings collected from June through November 2017. Inset shows the first 30 ms of the waveforms.

- Daily stacked waveforms have shown that our CASSM experiment has the precision and repeatability necessary to monitor changes in subsurface structures for over 2-year period.
- The waveforms were automatically stacked in groups of 100 shots, resulting in one record acquired every 27 s (two additional seconds were needed in storing the data).

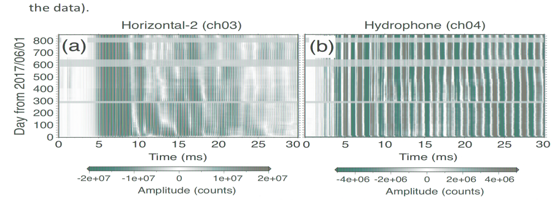

Fig. 5: Daily stacked waveforms in (a) one of the horizontal components (channel 3) and (b) hydrophone (channel 4). Amplitudes are plotted by the color code in the bottom of the figure. Gray areas indicate time windows in which waveforms were changed. It remains unclear the underlying mechanism of these changes.

Delay Time Estimation

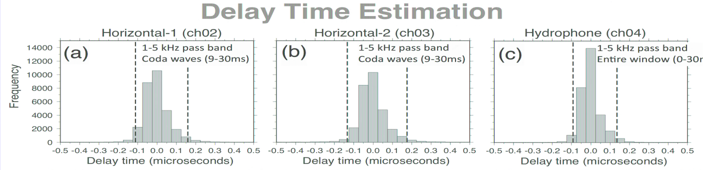

Fig. 6: Histogram of the measured delay times between two consecutive ~40 min records of (a) Horizontal-1 (ch02), (b) Horizontal-2 (ch03), and (c) Hydrophone (ch04). Dashed lines show the 95th percentile range.

- To address the experimental precision in measuring velocity change, we first measured delay times between consecutive recordings.
- The delay times measured here include both measurement errors and time-induced velocity perturbations. Thus they can be considered as the upper bound of the actual precision in the delay time estimate.

Crosswell Continuous Active-Source Seismic Monitoring (CASSM)

San Andreas Fault Observatory at Depth (SAFOD)

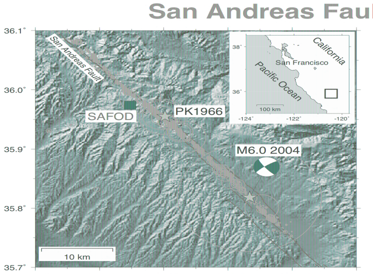

Fig. 1: Map of the Parkfield segment of the San Andreas Fault showing the SAFOD site (blue square). Also shown are seismicity (orange circles) from the Northern California Seismic System Earthquake Catalog (1984-2017). Two yellow stars are the epicenters of the 1966 and 2004 M 6 Parkfield earthquakes. Red lines are surface traces of faults from USGS. Inset map shows the location of our target area (black rectangle) in California.

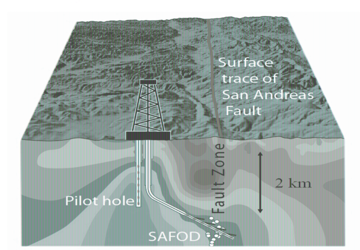

Fig. 2: Schematic cross-section view of the San Andreas Fault Zone at Parkfield, showing the SAFOD pilot and main drill holes. The colors in the subsurface show electrical resistivity of the rocks as determined from surface surveys. Red color indicates the lower resistivity rocks. Image from U.S. Geological Survey (https://earthquake.usgs.gov/research/parkfield/safod_pbo.php)

Crosswell CASSM System

- An 18-element piezoelectric source and a three-component accelerometer were deployed inside the pilot and main holes, respectively, at ~1 km depth.
- The instrumentation deployment was completed on June 15, 2017. Initial testing demonstrated that high-quality seismic waveforms would be acquired.
- A three-component accelerometer was clamped to the well casing to provide coupling and reduce relative motions between the source and receiver.

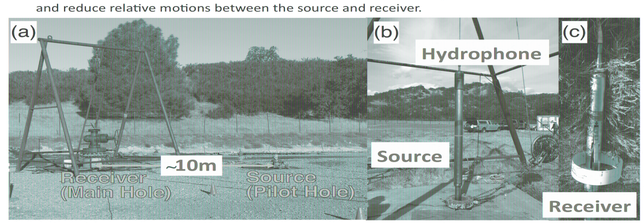

Fig. 3: Photographs showing (a) the SAFOD main and pilot hole well heads and (b) SAFOD piezoelectric source (PES) installed at the SAFOD pilot hole.

Time-Lapse Monitoring

Temporal Evolution of Delay Ti

- One of the challenges of active source borehole experiments is long-ter investigate longer temporal scale processes. We are currently working t

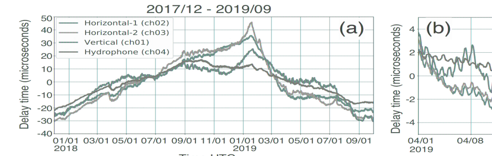

Fig. 7: Time history of delay time from three-component seismic and hydropho and (b) April-May 2019. (c) Power spectral density (PSD) estimate of delay time PSDs from different data sets.

Velocity Changes follow

Seismic Velocity Changed relat

- The 2019 M 7.1 Ridgecrest earthquake occurred ~270 km from the SAFOD site.

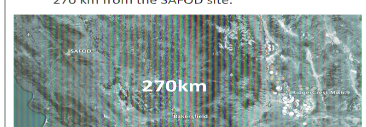

Fig. 8: Map view of the SAFOD site and the 2019 Ridgecrest earthquake sequence.

- Immediat the delay

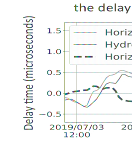

Fig. 9: Time histor is the "Horizontal-

Exploring Preseismic Ve

Preseismic Ve

- Niu et al. (2008, Nature) find two large excursions in the travel-time data t coincident with two local Parkfield earthquakes (M3 and M1 events) suffic produce large coseismic stress changes at SAFOD.

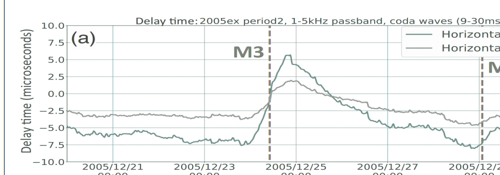

Fig. 10: Time history of (a) delay time and (b) amplitude ratio for Horizontal-1 (c of the piezoelectric source and three-component accelerometer at the SAFOD M

Acknowledgements

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