Technical Report to Southern California Earthquake Center:

Piñon Flat Observatory: Continuous Monitoring of Crustal Deformation

Report for SCEC Award — 18133

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Project Overview

A. Abstract

Crustal deformation measurements at Pinon Flat Observatory (PFO), and at other longbase strainmeter (LSM) sites not supported by SCEC, have provided data on otherwise unobservable deformation changes and the fault processes that produce them. With the ending of funded LSM operation in 2018, we can conclude that, in the strike-slip setting found in most of Southern California, departures from steady strain accumulation during the interseismic peiod are few and far between. At PFO we have observed repeated rapid aseismic strain following moderate local earthquakes in 2001, 2005, and 2013 in the Anza area, as well as after the 1992 Joshua Tree, 1999 Hector Mine, and 2010 El-Mayor/Cucapah earthquakes, though not after the 1987 Superstition Hills or 1992 Landers earthquakes: a total of six occurrences over 45 years of operation. At other sites close to the San Andreas fault, we have likewise observed rapid aseismic slip a few times per decade, though in those locations modeling suggests that the signals are caused by shallow creep.

B. SCEC Annual Science Highlights

Stress and Deformation Over Time (SDOT), Tectonic Geodesy

C. Exemplary Figure

Figure ?? of Technical Report. Caption

Data from late 2008 to summer 2020, for the three LSM's at PFO. The EW and NWSE are fully anchored, the NS strainmeter is anchored only at one end. The long-term strain trends are compatible with other geodetic measurements. Shaded regions mark times of observed and possible strain fluctuations, some with obvious causes and others not.

D. SCEC Science Priorities

P1.e P2.a P3.e

E. Intellectual Merit

This project continued the operation of the three longbase laser strainmeters (LSM's) and one fully-anchored long fluid tiltmeter (LFT) at PFO.

F. Broader Impacts

This effort provides (I) paradigmatic datasets of strain and tilt used for training researchers in this field, or for new areas of research; (II) information on the design and construction of long-base and other sensors for future replication or improvement; and (III) a readily accessible field site that can be used as a training ground for undergraduate and graduate students in a variety of solid-earth studies.

G. Project Publications

See Technical Report.

Technical Report

1. Introduction

From 1992 through 2018, the Southern California Earthquake Center supported operations at Piñon Flat Observatory (PFO), a more consistent source of funding than any other agency. This funding allowed us to:

A. Produce high-quality strain data, over three decades, from longbase laser strainmeters (LSM's), which have a noise level, for periods from seismic to yearly, lower than other measurement systems.

B. Create other long time series, sometimes yielding unexpected results; for example, water-well monitoring at PFO (**Figure 4**) provided data on how seismic waves can change permeability (Elkhoury *et al.* 2006).

C. Make PFO available as a facility where researchers can easily test equipment or make short-term deployments, most recently of a number of dense seismometer arrays.

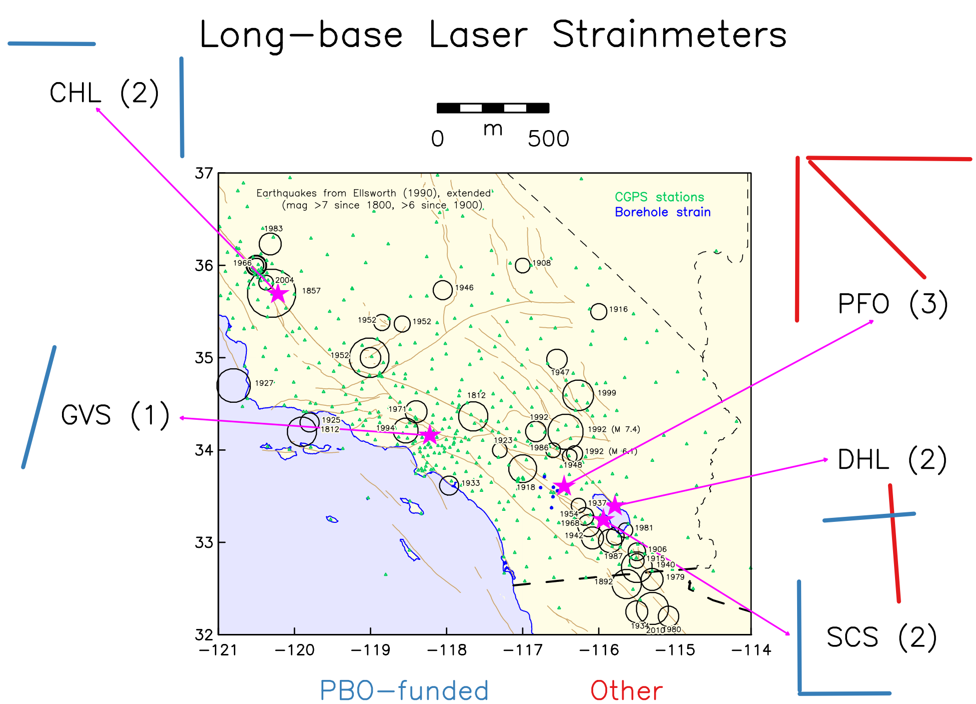

Figure 1. The center map shows the LSM's that were installed in California, together with major faults and the larger earthquakes of the region. The actual layouts of the LSM's are shown around this map at a larger scale (given at the top); in all cases, North is at the top. The LSM's are colored to show if they were constructed or supported by the PBO (blue), or not (red). The Yucca Mountain strainmeter, which ran from 2002-2007, is not shown.

PFO was the longest-operating of a number of LSM observatories in California (**Figure 1**), most of them installed as part of the Plate Boundary Observatory (PBO) project. As of the end of operational funding on September 30, 2018, these systems had, collectively, acquired 237 instrument-years of data, with the longest-running instrument, the NS LSM at PFO, having operated for over 47 years. **Figure 2** plots the complete LSM dataset at PFO, showing the very considerable improvements in instrument quality that have been made over the years, as well as data continuity broken only by the July 1994 brushfire which came through the observatory and damaged all the LSM vacuum pipes.

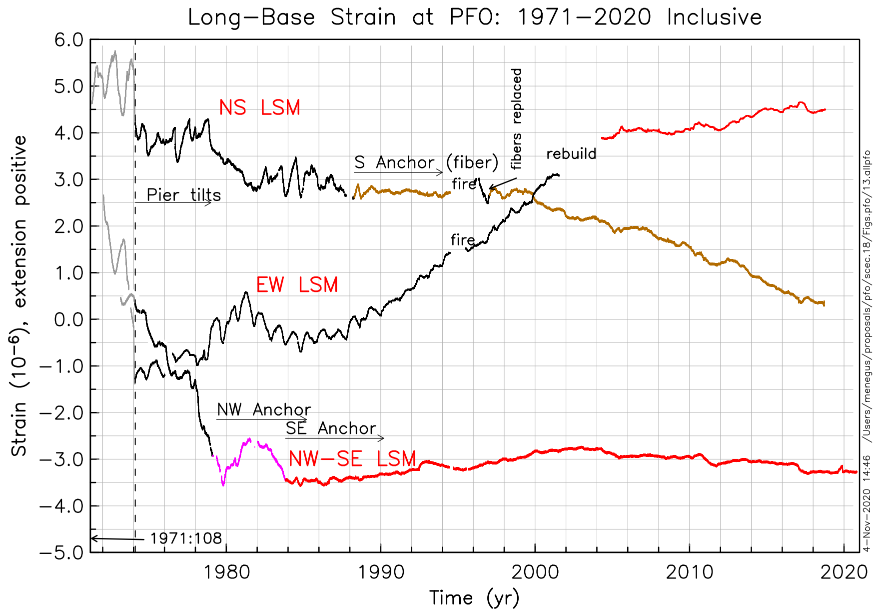

Figure 2. All laser strainmeter data from PFO, color-coded by the quality of the end-monument anchoring. The gray parts of the lines are for times when there was no correction for end-monument motion; adding tiltmeters to measure rotation of the instrument piers (black) made the data less variable, but further improvement was clearly possible. The next step was to an "optical anchor" to monitor surface motion relative to depth: when added to both ends of the NWSE LSM (red line) this improved the quality of the instrument to the excellent level it has kept since. Anchoring (using optical fibers) was added to one end of the NS LSM (brown line) and also improved its performance, as did the rebuild of the EW LSM in 2002-2004, which included putting optical fiber anchors at both ends. **Figure 3** shows an expanded view of the recent data from all three LSM's.

2. Closing Activities

1. Strainmeter operation: the strainmeters continued in operation somewhat past the originally planned end date, with the NS LSM ending on 2018:265, 47 years and 158 days from the start of data collection; the EW LSM ended on 2018:291, after 46 years and 275 days; the NW LSM has been kept in operation, at the time of writing having collected 47 years and 249 days of data.

2. Strainmeter upgrade: the workload involved in keeping the other two PFO LSM's running, and decommissioning and storing parts from the PBO systems, meant that no progress was or has been made on the proposed upgrades and rebuilds of the NW LSM; it has been kept in operation with labor donated by Frank Wyatt as a retiree, along with some salary support and payment of the power bills from other projects, notably the fiber strainmeter projects of Dr. Mark Zumberge.

3. An unanticipated task was imposed by PBO management for the final year, namely the preparation of a review paper covering the PBO laser strainmeters. This consumed time originally planned to be given to data organization. The review paper was submitted to a journal for publication; reviewers noted that the restriction to PBO systems made the paper significantly incomplete, and it was returned for revision (to include the PFO and Yucca Mountain installations) and resubmittal. Unanticipated administrative obligations meant that Agnew was unable to pursue this, but it is in progress, along with other papers analyzing the LSM data.

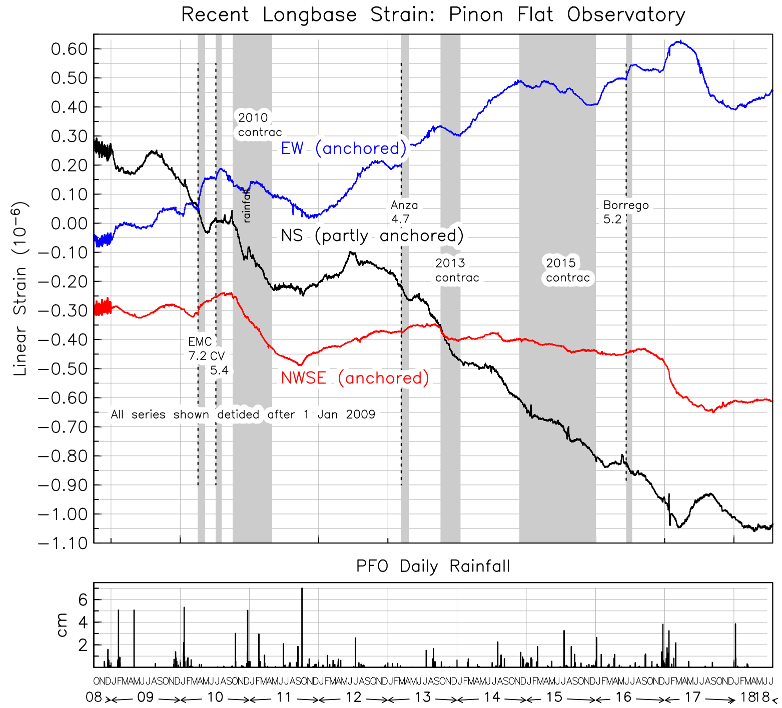

Figure 3. Data from late 2008 to the present, for the three LSM's at PFO. The EW and NWSE are fully anchored, the NS strainmeter is anchored only at one end. The long-term strain trends are compatible with other geodetic measurements. Shaded regions mark times of observed and possible strain fluctuations, some with obvious causes and others not.

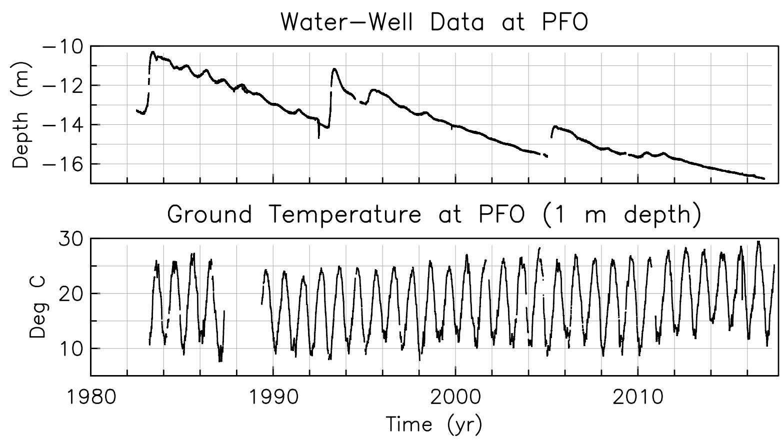

Figure 4: Two environmental series from PFO. There are four water wells monitored (none pumped), which all show this pattern of long-term dropping of the water table with occasional recharge. This well had been used to study changes in permeability. Ground temperature at a depth of 1 m show an offset between data from the 1980's and that after 1990 because of relocation of the sensor, and a warming trend after 1990.

Publications

Hillers, G., M. Campillo, F. Brenguier, L. Moreau, D. C. Agnew, and Y. Ben-Zion (2019). Seismic velocity change patterns along the San Jacinto fault zone following the 2010 M7.2 El Mayor-Cucapah and M5.4 Collins Valley earthquakes, *J. Geophys. Res. Solid Earth*, **124**, 7171-7192, doi:10.1029/2018JB017143