Broadband Observations of Plate Boundary Deformation in the San Francisco Bay Area

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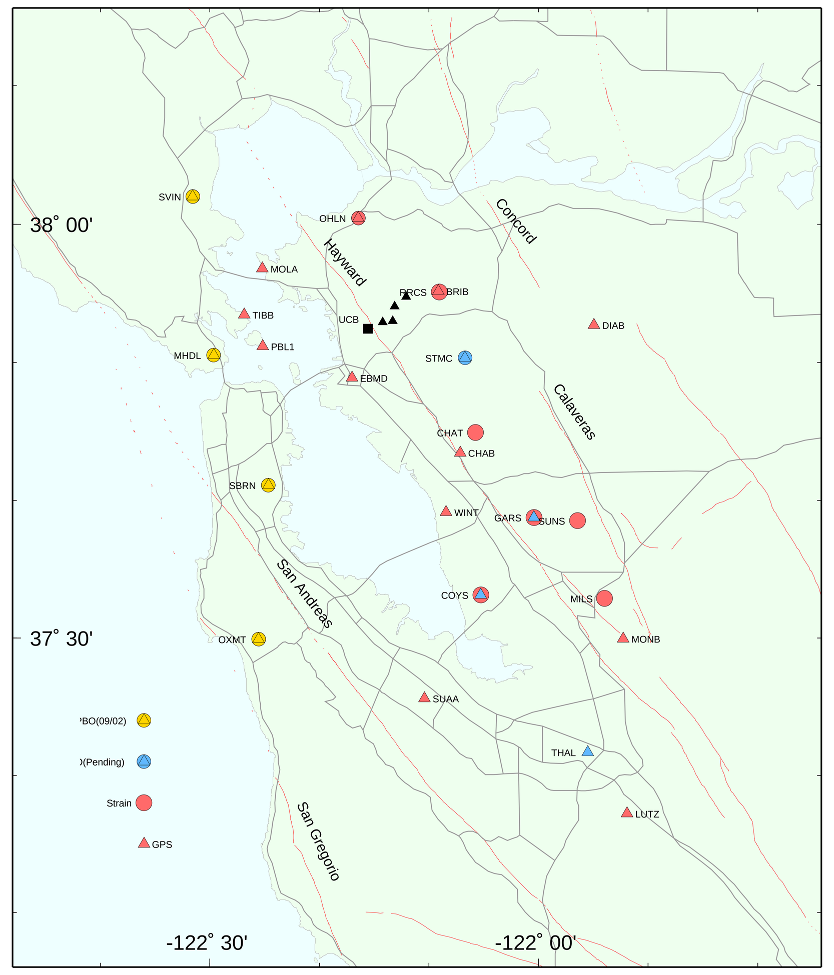
Abstract

The Integrated Instrumentation Program for Broadband Observations of Plate Boundary Deformation (‘‘Mini-PBO") is a joint project, partially funded by the EAR NSF/IF program with matching funds from the participating institutions and SCIGN, to develop an integrated pilot system of instrumentation for the study of plate boundary deformation in central California. Under the project, 9 GPS stations were installed last year near Parkfield, a subset of sites of which will soon collect and process data in real-time, and a 5-m X-band SAR downlink facility has been supported in San Diego to collect and archive InSAR data for integration with other geodetic data. We report on the installation of 5 borehole stations with GPS, tensor strainmeter, and 3-component seismometer instrumentation along the Hayward and San Andreas faults in the San Francisco Bay Area.

All 5 boreholes have been drilled and equipped with strainmeters and seismometers, and downhole pore pressure and tilt sensors, electronics, recording systems, and GPS systems have been or will soon be added. The GPS, strainmeter and seismometer data is telemetered over frame relay, while lower frequency data is telemetered using the GOES system. All data is available to the community through the NCEDC. The newly fabricated tensor strainmeters are reliably measuring tidal strain, and local and teleseismic earthquake deformation, and the inferred strain provides constraints on the depth of creep observed on the northern Hayward fault. The GPS antennas are mounted at the top of the borehole casings in an experimental approach to achieve stable compact monuments. While the time span has been too short to reliably assess long-term stability, the short-term repeatability in daily positions is similar to those obtained by more traditional monuments.



Location of existing (red), in preparation (yellow), and pending (blue) Mini-PBO sites in the San Francisco Bay area. Shown also (red) are currentlyoperating strainmeter (circles) and BARD (triangles) stations. Blue trianglesare other pending BARD stations. Black triangles are L1-system profile sitesnear the Hayward fault and the UC Berkeley campus.

A Mini-PBO Photo Gallery

USGS Water Resources Division rig used to drill the borehole at St. Vincents.

The 3-component seismometer package (Mark L22 velocity sensors) is readied for deployment at Marin Headlands.

Deployment of the tensor strainmeter at San Bruno.

Cores recovery was generally poor. Visual inspection by camera was a more reliable method to assess the competence of the rock.

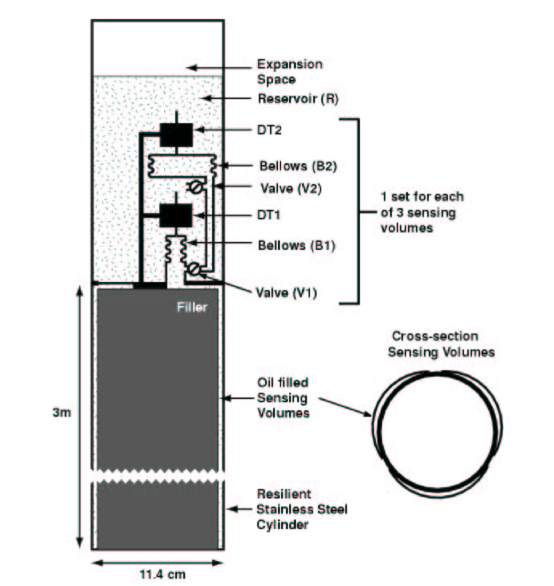
GPS antenna mounted on top of casing at OHLN. The final installation includes a SCIGN antenna dome and a steel protective shroud that envelopes the casing.

New GPS antenna mount design, using modified commercial flanges that enable high-precision self-center while allowing access to the top of the borehole for maintenance.

Overview

The Mini-PBO borehole installations augment existing instrumentation along theSan Andreas fault system in the San Francisco Bay area, including 5 borehole dilatometers along the Hayward fault, and more than 10 continuous GPS stations of the BARD network. During July 2001 to August 2002, five boreholes were drilled and equipped with tensor strainmeters and 3-component L22 (velocity) seismometers. The strainmeters are recently developed by CIW and use 3 sensing volumes placed in an annulus with 120 degree angular separation, which allows the 3-component horizontal strain tensor to be determined. One borehole station has also been equipped with a GPS receiver, Quanterra recording system, and downhole pore pressure sensor, and will eventully also include a tilt sensor. The other stations are in various stages of completion, primarily waiting for power and telemetry to be established. The GPS antennas at these stations are mounted at the top of the borehole casings in an experimental approach to achieve stable compact monuments.

The 30-second GPS, and 100-Hz strainmeter and seismometer data is acquired on Quanterra data loggers and continuously telemetered by frame relay to the BSL. Low frequency (600 second) data (including strainmeters, for redundancy) is telemetered using the GOES system to the USGS. All data is available to the community through the Northern California Earthquake Data Center (NCEDC) in SEED format, using procedures developed by the BSL and USGS to archive similar data from 139 sites of the USGS ultra-low-frequency (UL) geophysical network, including data from strainmeters, tiltmeters, creep meters, magnetometers, and water well levels.

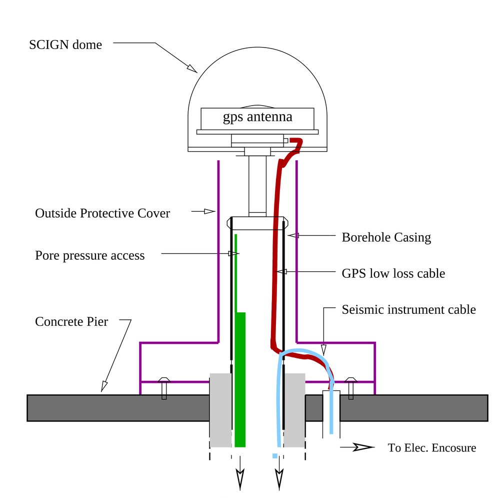


Tensor strainmeter diagram. These instruments are a modification of the Sacks-Evertson dilatometers that use a hydraulic sensing technique to achieve a volume strain sensitivity of 10**(-12) with constant frequency response from 0 to more than 10 Hz and a dynamic range of about 130 dB. The design incorporates a second bellows-DT-valve sub-system which provides extended dynamic range, complete preservation of baseline during required instrumental resets, and redundant sensing electronics.

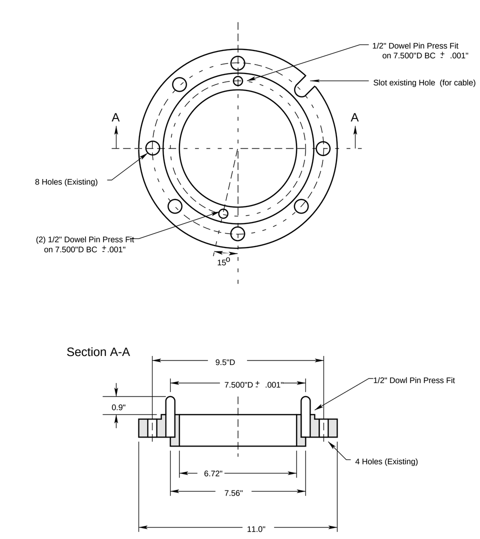
Installation

During this last year, the first Mini-PBO stations were installed. Boreholes were drilled by the USGS Water Resources Division crew at five sites. The drillers used a newly purchased rig (see photo gallery) that experienced numerous problems (hydraulics, stuck bits, etc.), which delayed the drilling considerably at several of the sites and significantly increased the costs of the project. Below are details from Ohlone Park in Hercules (OHLN); the drilling procedures and hole instrument configuration were similar at the other four sites

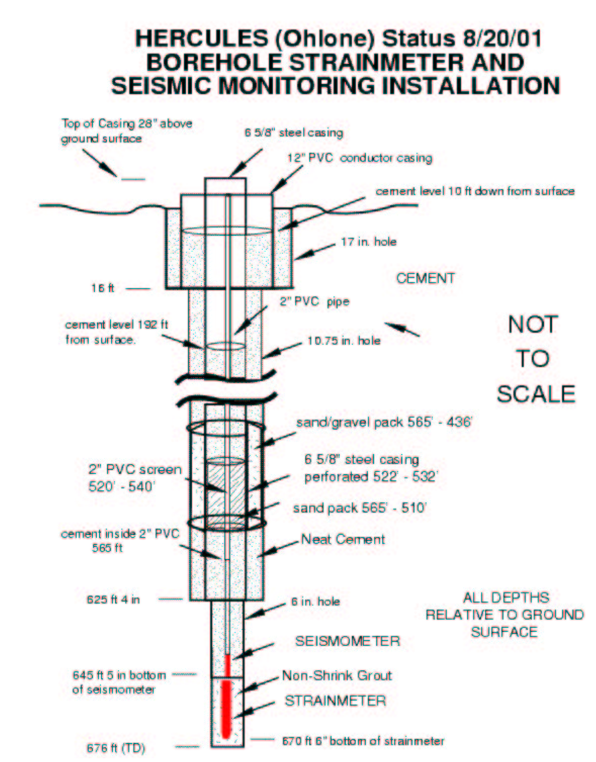
OHLN: Figure 2 shows the configuration of the borehole instrument installation at Ohlone Park. A 6.625" steel casing was cemented into a 10.75" hole to 625’4" depth to prevent the upper, most unconsolidated materials from collapsing into the hole. Below this depth a 6" uncased hole was drilled to 676’. Coring was attempted with moderate success below 540’ through poorly consolidated mudstone to about 570’, and increasingly competent sandstone below. Moderately good core was obtained from 655’ to 669’, so this region was selected for the strainmeter installation. The section of the hole below about 645’ was filled with a non-shrink grout into which the strainmeter was lowered, allowing the grout to completely fill the inner cavity of the strainmeter within the annulus formed by the sensing volumes to ensure good coupling to the surrounding rock. The 3-component seismometer package was then lowered to 645.5’, just above the strainmeter, on a 2" PVC pipe, and neat cement was used to fill the hole and PVC pipe to 565’. The pipe above this depth was left open for later installation of the pore pressure sensor in the 520-540’ region. To allow water to circulate into the pipe from the surrounding rock for the pore pressure measurements, the the steel casing was perforated, a sand/gravel pack was emplaced, and a PVC screen was used at this depth. The casing was then cemented inside to 192’, and outside to 16’ depth. A 12" PVC conductor casing was cemented on the outside from the surface to 16’ to stabilize the hole for drilling and to provide an environmental health seal for shallow groundwater flow. The annulus between the 12" conductor casing and the 6.625" steel casing was cemented from 16’ to 10’ depth and above was left decoupled from the upper surface to help minimize monument instability for the GPS antenna mounted on top of the steel casing.



Design of the GPS antenna mount on top of casing.



Bottom flange design of GPS antenna mount.



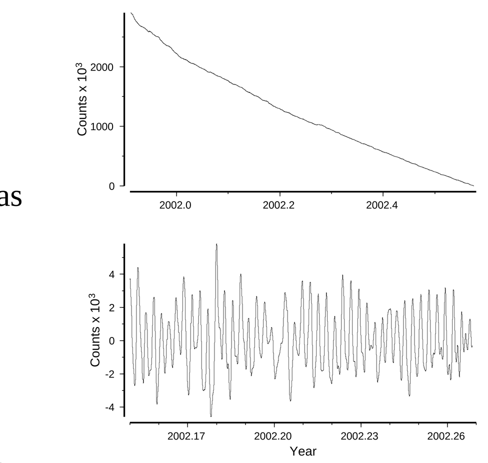
The Mini-PBO borehole configuration at Ohlone, showing the emplacement of the strainmeter and seismometer instruments downhole. The GPS receiver is mounted on the top. Figure courtesy B. Mueller (USGS).

The current GPS mount design consists of two 11-inch diameter stainless steel flanges. The lower slip-and-weld type flange is welded onto the top of the 6 5/8"-inch borehole casing providing a level surface for the second flange. The upper blind-type flange, to which the 1 1/4" stainless steel pipe used to connect to the SCIGN DC3 adaptor is attached, is bolted to the lower flange using four 3/4" by 3" stainless steel bolts. Two half-inch stainless steel dowels are press fit with high location precision (radius 7.500" +/-0.001") into the lower flange. Two matching holes are machined into the upper flange with a high location precision (radius 7.500" +/-0.001") and hole diameter precision (between +0.005" and -0. 000"). One of the dowels is offset to insure unique directional alignment.

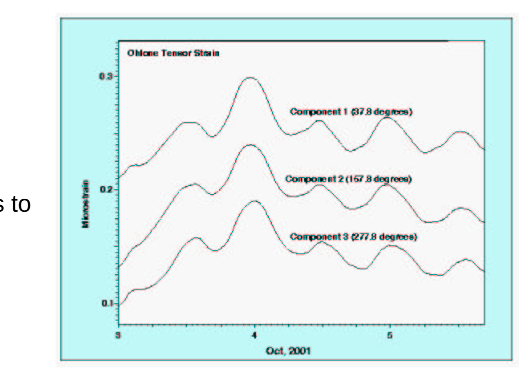
Results

We are in the initial stages of assessing the data quality of the Mini-PBO instrumentation. The newly designed tensor strainmeters appear to faithfully record strain signals over a broad frequency range. During the 12 months that the strainmeter at OHLN has been providing high-frequency data, the strain has been exponentially decaying. This large signal is most likely due to cement hardening effects and re-equilibration of stresses in the surrounding rock in response to the sudden appearance of the borehole. These effects can last for many years and are the principal reason that borehole strainmeters can not reliably measure strain at periods greater than a few months.

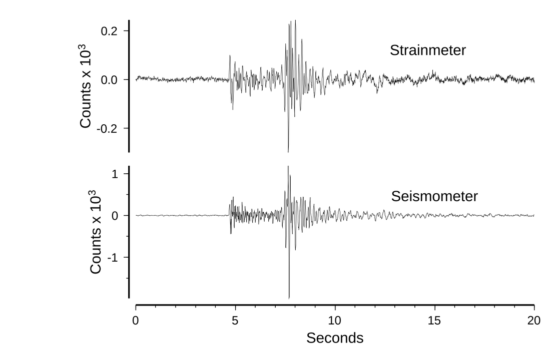
At periods around 1 day, tidally induced strains are the dominant strain signal, about 3 orders of magnitude smaller than the long-term decay signa. Since the response of the strainmeter volumes is difficult to estimate independently, theoretically predicted Earth tides are typically used to calibrate the strainmeters. At higher frequencies, strains due to seismic events are also evident. M=2 events near OHLN, for example, are well recorded on both the vertical velocity seismometer and strainmeter. Strains from this event are about an order of magnitude smaller than the tidal strains. We are beginning to examine the strain data for other types of transient behavior, such as episodic creep or slow earthquake displacements.



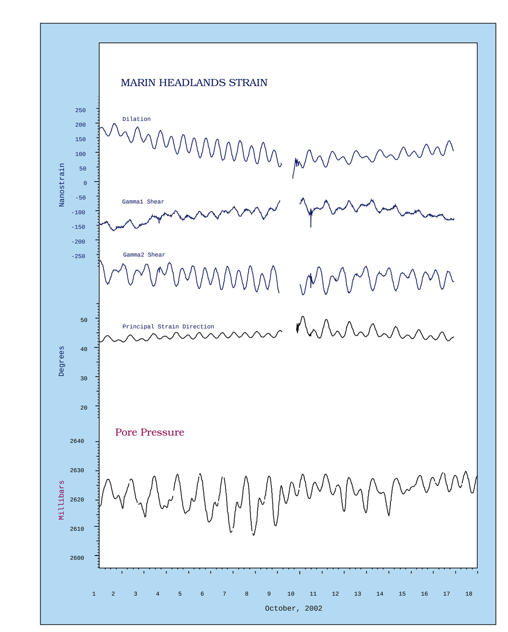
100-second strainmeter data measured by Component 1 at OHLN, in instrumental counts. Top, 9-month timeseries with instrumental offsets due to reservoir resetting removed. Bottom, 1-month timeseries bandpass filtered at 0.5-2 day to show tidal strain signals. Note the different vertical scales.



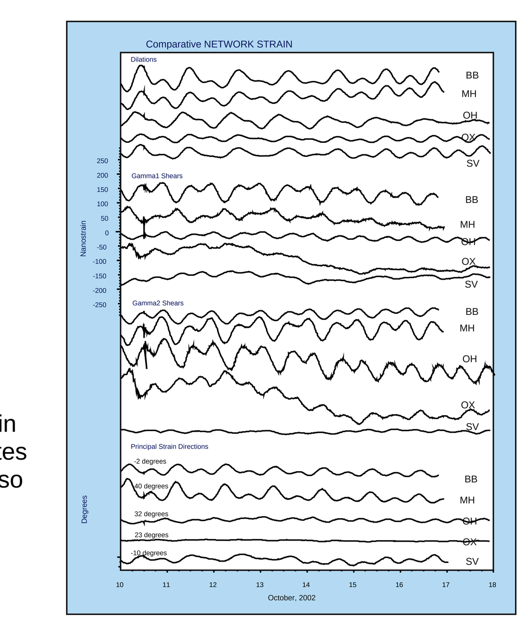
Three-component strainmeter data measured at OHLN, in microstrain. Tidal strain is used to calibrate the sensors, allowing instrument counts to be converted to microstrain. Figure courtesy M. Johnston (USGS).



100-Hz strainmeter and vertical component seismometer data measured at OHLN, in instrumental counts, showing response to an M=2.3 earthquake within 15 km of the station.



Comparative tensor strain and pore pressure from deep borehole on Marin Headlands. Together these data provide a way to investigate poroelastic behavior of crustal rocks near active faults. Figure courtesy of M. Johnston (USGS).



Comparative tensor strain components from five sites in the MiniPBO array. Also shown on October 10 is the M7.6 West Irian earthquake. Figure courtesy of M. Johnston (USGS).

Lessons for PBO

The Mini-PBO project provides some lessons for future installations planned under the Plate Boundary Observatory component of Earthscope:

• Site selection was tricky given the various criteria that need to be met to ensure high-quality measurements from the GPS seismometer, and strainmeter instruments. Most stringent is the need for competent, unfractured rock at 200 m depth for the strainmeters, which was not easily obtained in the geologically complex, highly urban Bay Area. Avoiding strain and seismic noises sources, such as trains, highways, water reservoirs, finding reasonable sky visibility for GPS, and satisfying other power, telemetry, and environmental concerns, such as endangered butterfly habitats also proved restrictive. Finding 200+ locations for boreholes will be daunting.

• Borehole drilling is a time-consuming, problematic process. Each hole drilled presented new challenges that generally required more time and money than originally envisioned: of the originally proposed 10 stations, only 5 could be completed with the available funding. Procedures to standardize, improve, and streamline the drilling process that might minimize the possibility of such problems should be considered with some care.