Integrated Instrumentation Program for Broadband Observations of Plate Boundary Deformation

1 Background

The Integrated Instrumentation Program for Broadband Observations of Plate Boundary deformation, commonly referred to as "Mini-PBO", is a joint project of the Department of Terrestrial Magnetism at Carnegie Institution of Washington (CIW), the Seismological Laboratory at Univ. of California, Berkeley (UCB), IGPP at Univ. of California, San Diego (UCSD), and the U.S. Geological Survey at Menlo Park. It augments existing infrastructure in central California, in order to form an integrated pilot system of instrumentation for the study plate boundary deformation, with special emphasis on its relation to earthquakes. This project is currently in its 3rd and last year of funding through the EAR NSF/IF program, with substantial matching contributions from the participating institutions and the Southern California Integrated Geodetic Network (SCIGN).

Because the time scales for plate boundary deformation range over at least 8 orders of magnitude, from seconds to decades, no single technique is adequate. We proposed an integrated approach that makes use of three complementary and mature geodetic technologies: continuous GPS (CGPS), borehole tensor strainmeters and interferometric synthetic aperture radar (InSAR), to provide a broadband characterization of surface deformation. In addition, ultrasensitive borehole seismometers will monitor microearthquake activity related to subsurface deformation. The transients that we seek to study have already been directly observed by all three geodetic techniques, including those transients that occur during and after large earthquakes, as well as fault-related strain transients not apparently associated with earthquakes, but which may nevertheless represent an important component of the plate-boundary deformation budget. CGPS networks and InSAR are well suited for studying spatial variations in secular (steady-state) deformation or large strain transients with periods longer than about a month, such as those following major earthquakes. Strainmeters, in contrast, are ideal for studying smaller transients with periods from minutes to a month or longer. The borehole seismometers provide the depth dimension to deformation. The integrated use of this instrumentation spans the entire plate boundary deformation spectrum.

The project has three components. One is focused on the San Francisco Bay Area, and augments existing instrumentation along the Hayward and San Andreas faults. The network originally proposed in the framework of an MRI proposal comprised 14 new borehole sites, each of them equipped with tensor strainmeters, borehole seismometers, and CGPS receivers, to complement 6 existing borehole strainmeter sites and 18 CGPS sites of the BARD (Bay Area Regional Deformation) network, which includes more than 50 stations in northern and central California. The cost of the initial proposal was \$2M (NSF) complemented by \$1.755M in matching funds from the participating institutions. This proposal was funded at a much reduced level (\$700,000) through the EAR/IF program, although the matching funds were maintained at the originally proposed level. This reduction in budget resulted in 1) the reduction from 14 to 10 borehole strainmeter sites (figure 1), 2) reduction from 14 to 7 CGPS sites in the San Francisco Bay Area, 3) the reduction from 10 to 6 CGPS sites in central California, and 4) the need to seek additional funding for the borehole seismometers. All data collected from this network will be made available to the community through the Northern California Earthquake Data Center (NCEDC).

The second component of this project is to link the BARD network in central and northern California to the SCIGN network in southern California. The distribution of these sites allows measurement of both near-field deformation from fault slip on the San Andreas and regional strain accumulation from far-field stations. The original MRI proposal was for 10 such CGPS sites, of which 7 were funded.

The third component involves the upgrade and operation of a 5-m X-band SAR downlink facility in San Diego to collect and archive radar imagery to make abundant InSAR data available for integration with the CGPS, strainmeter, and seismometer data, within the guidelines set by the European Space Agency. The ERS-1/2 SAR data, which extend from 1992 until present, offer the only means for monitoring plate boundary deformation at high spatial resolution over all of western North America. This data set is largely unexplored mainly because data distribution is restricted by ESA and working with the phase information requires a significant investment of a researchers time.

2 Accomplishments to Date

2.1 Component 1: Borehole Network in the San Francisco Bay Area

In particular, downhole pore pressure and tilt sensors were added to complement the strainmeters and to improve discrimination of real tectonic strain signals from atmospheric or hydrologic effects. During the summer of 2001, we were also able to secure $100,000 funding from Caltrans for the fabrication of borehole seismometers (L22: 3-component, 2-Hz velocity sensors). Figure 2 shows the final design of the standard mini-PBO borehole system as agreed upon and implemented.

The data from GPS, borehole strainmeters and seismometers are/will be acquired on Quanterra dataloggers and continuously telemetered over frame relay to U.C. Berkeley, while data from other low frequency sensors are initially telemetered using the GOES satellite system to the USGS. Sampling rates are 100 Hz for strainmeters and seismometers, 1 Hz atmospheric and 30 sec GPS through the Quanterra dataloggers and 600 sec for low frequency data (including strainmeters, for redundancy) over the GOES system.

In preparation for multiparameter data collection, archival, and distribution, UC Berkeley and the USGS have developed and implemented procedures to archive data from 139 sites of the "USGS ultra low-frequency" (UL) geophysical network, which includes strainmeters, creep meters, magnetometers, tiltmeters, and water well levels. These data are available in SEED format at the NCEDC (*http://quake.geo.berkeley.edu/ul/*) and set the stage for the archiving and distribution of data from the mini-PBO sites.

The increased number of high frequency, high dynamic range channels to be recorded from the borehole sensors necessitated that an appropriate number of channels be available from the Quanterra dataloggers, and hence resulted in an increase in the cost of those dataloggers.

The borehole design also includes GPS monumentation, as, wherever possible, we have resolved to mount the GPS receivers at the top of the borehole casings (Figure 3), in an experimental approach to achieve stable compact monuments. After careful review and testing of several current generation GPS receivers, we have decided to purchase Ashtech MicroZ receivers, which use about half the power of the Ashtech Z-12 receivers currently used in the BARD network. We are also designing an experimental GPS mount for the top of the borehole casings to create a stable, compact monument (Figure 4). The antennas, using standard SCIGN adapters and domes for protection, will be attached to the top of the 6-inch metal casing, which will be mechanically isolated from the upper few meters of the ground. The casing below this level will be cemented fully to the surrounding rock. Although this design takes advantage of the deep anchoring of the casing, we will need to assess in the future whether other effects, such as daily or annual thermal expansion of the upper few meters of the casing, limit the long-term stability of the monument.

Boreholes at four sites were drilled during the Summer and Fall of 2001. Two sites, at Ohlone Park (OHLN) in Hercules and San Bruno mountain (SBRN) near Brisbane, have been instrumented with newly fabricated (CIW) borehole strainmeters and seismometers. We are currently assessing whether the rock at depth is suitable for strainmeter installation at the boreholes in the Marin Headlands (MHDL) and at Ox Mountain (OXMT) near Half Moon Bay (Figure 1).

2.1.1 Site Selection and Permitting

We have identified over 10 sites in the Bay Area suitable for the integrated Mini-PBO network (Table 1). Selecting sites that met the criteria required for all the components proved to be time consuming. The primary criteria were location and geology. One of the goals of the network is to monitor slip at depth on the northern Hayward and peninsular San Andreas fault segments. We therefore tried to pick sites located 5-8 km away from the faults, where surface motions are most sensitive to slip at similar depths, particularly where earthquakes are often thought to nucleate. The rock where the strainmeter is installed ($\sim$200 m depth) must be hard and unfractured to measure strain correctly, so the geology at the sites was carefully investigated. We tried to pick sites where nearby outcrop gives an indication of the possible rock type at depth at the borehole location.

Other criteria also limited the possibilities. The sites ideally should be near power and telephone lines, and be as secure as possible. Ownership of the land should have long-term stability and not require significant expenditures to obtain the permit. The sites must be able to accommodate the drill rigs, pass environmental concerns such as disturbing endangered species (e.g., butterflies on San Bruno Mountain). Sky visibility should be acceptable for GPS; we tried to maintain clear visibility 15 degrees above the horizon, although we accepted some sites with only 25 degree cutoff in some directions. Strain and seismometer noise sources should be minimized; we rejected several sites due to their proximity to highways, railroad tracks, or large water reservoirs. Addressing all these concerns is challenging in the urban and geologically complex San Francisco Bay area.

We are planning to install two clusters of stations to improve the resolution and redundancy of the strainmeter observations. The northern cluster is focused on the northern Hayward fault and northern peninsular San Andreas fault. Instruments have been installed at two of these stations (Ohlone and San Bruno), and drilling has been completed at a third (Marin Headlands) and is in progress at a fourth (Ox Mountain). We have completed permitting three other possible stations in the northern cluster (Miller-Knox, St Mary's College, and Wildcat). We are also pursuing permits at Yerba Buena Island and Hamilton Field, both locations of former military bases that are in transition to civilian control, which has complicated and lengthened the permit approval process.

Permitting is in the early stage for three southern cluster stations (Rancho San Antonio, Castle Rock, and Almaden), all located at State or county parks. This cluster is designed to monitor the San Andreas fault just north of the section that ruptured in the 1989 Loma Prieta earthquake, which is a likely target for future rupture. We expect permitting, including environmental impact assessments, to be completed at these stations in the Spring of 2002.

We have pursued permits for more stations than will be possible to install at the current funding level both to ensure that enough sites will be available, given the vagaries of the permitting process, and to allow flexibility in target location of the monitoring. For example, excluding the southern cluster and including the northernmost stations (Wildcat and Hamilton Field) would provide better monitoring of the Hayward-Rodgers Creek fault step-over in San Pablo Bay, another geometrically complex faulting region where earthquake slip is likely to initiate or terminate.

2.1.2 Site Installation

Drilling at the first site (OHLN) at Ohlone Park in the city of Hercules began on June 19, 2001. A 6" hole was drilled to 640' and then coring started. The rock in upper portion of the hole was sandstone and poorly consolidated mudstone. Competent sandstone core was obtained from 655' to 669'. This region was selected for the tensor strainmeter (670.5') and seismometer (645.5') installations, completed on July 19. A 10" hole was reamed to 625' for the casing, which was perforated at 522-532' for the pore pressure instrument. Trenching for power and telemetry was completed in September, and continuous power was established in early October. The low-frequency datalogger was installed in September and the high-frequency Quanterra datalogger was installed in early October. We are currently completing the GPS monument and borehole cover, and expect continuous frame-relay telemetry by phone line to be established by November 6. Preliminary data measurements from this station are shown in the following section.

Drilling at the second site (SBRN) on San Bruno Mountain near Brisbane began in mid-July. After some delays due to a drill bit that could not be retrieved from the hole, the hole was drilled to 552' with good core obtained below 520'. The tensor strainmeter and seismometers were installed in early August at depths of 551.5' and 530.0', respectively. A 10" hole was reamed to 500' for the casing, which was perforated at 433-453' for the pore pressure instrument. We are currently working to establish continuous power and telemetry at the station, and install the GPS monument on the borehole casing.

Drilling at the Marin Headlands sites (MHDL), completed in mid-October, was hampered by slow and inconclusive coring, and artesianing of water from the well that required containment. Coring began at around 545', but encountered a hard greenstone rock with fractures and slickensides. No complete core sections were recovered. The hole has been cased to 278', cemented from 278-410' to prevent a chert layer from collapsing, and sand-filled below to protect the bottom section. In late October, we drilled through the cement layer, removed the sand, and examined the bottom section with a camera to determine if any sections of the greenstone rock are suitable for a strainmeter installation. Several promising sections were found on an initial, rapid inspection performed by a contractor. We plan to inspect these sections more carefully with a USGS camera when it returns from the field.

Drilling at Ox Mountain was completed in late October. This site is on a ridge, so we drilled as deeply as possible with the available equipment to minimize possible strain effects due to high topographic relief. We were able rapidly hammer drill the upper portions of the hole because the site did not have stringent water containment requirements. The site was drilled to 653' in hard granite, and cored below to 710'. The core went from a fine grained granite into a coarse grained granite, with some recemented cracks and fractures, that was not recovered intact. We plan to inspect the cored section with a camera to locate the best section for the strainmeter installation.

2.1.3 Data

We have been recording data from the Ohlone and San Bruno stations since early October. Low-frequency (600 second) strain data is currently being telemetered via the GOES satellite system to Menlo Park. Tidal strain variations are well recorded at the Brisbane station. Tidal variations are less well recorded at Ohlone due to large atmospheric pressure loading effects, perhaps due to the weaker rock at that site. An example of the low-frequency measurements from the tensor strainmeter at Ohlone are shown in Figure 5.

High-frequency (up to 100 Hz) strain and seismometer data are now being archived on the Quanterra datalogger at Ohlone, but can only be accessed by manual download until continuous telemetry is established. We are currently assessing the data quality and resolving issues related to wiring of the components and amplifiers. Preliminary results, however, show that strain is being measured at frequencies ranging from daily tidal variations, to 20 second surface waves from teleseismic events (Figure 6), and to 100 Hz body waves from local seismic events (Figure 7).

2.2 Component 2: CGPS in the Parkfield area

Seven CGPS sites were proposed in the framework of the UCSD subcontract, at $20,000 each ($70,000 from NSF and $70,000 from SCIGN cost sharing. Nine sites were actually constructed, with one contributed through USC and constructed by the US Geological Survey and additional funding from SCIGN for site preparation.

Seven continuous GPS sites are currently operational (6 constructed through mini-PBO and one by USGS) and two more are under construction (Figure 2). The sites are

Table 1: Mini-PBO Stations: Status (6 November 2001)

ID	Name	Lat. (N)	Lon. (W)	Status
OHLN	Ohlone Park	38 00.4	122 16.4	Strain., seismo., pore press. installed
SBRN	San Bruno Mt	37 41.1	122 24.7	Strain., seismo. installed
MHDL	Marin Headlands	37 50.5	122 29.6	Drilling completed, assessing rock
OXMT	Ox Mt	37 29.9	122 25.5	Drilling completed, assessing rock
KNOX	Miller-Knox Park	37 55.0	122 22.9	Permitted
STMC	St. Mary's College	37 50.4	122 06.6	Permitted
WLDC	Wildcat Mt	38 14.5	122 29.8	Permitted
HAMF	Hamilton Field	38 02.7	122 30.5	Permit under review
YERB	Yerba Buena Isl	37 48.6	122 21.6	Permit under review
RSAN	Rancho San Antonio	37 20.2	122 06.1	Permit under review
CSTR	Castle Rock	37 14.0	122 06.3	Permit under review
ALMD	Almaden	37 12.4	121 53.8	Site recon in progress

located in an array centered in the Parkfield area and span about 25 km on either side of the San Andreas Fault. Thus, the new array augments the considerable geophysical instrumentation already deployed in the area and contributes to the SAFOD component of Earthscope. The 24-hour data are currently downloaded by SCIGN and archived by SOPAC. These sites will eventually be upgraded to real-time streaming and analyzed in instantaneous positioning mode.

The budget summary for this task is as follows:

NSF/MRI funds	$70,000
SCIGN (USC/Keck) matching funds	$70,000
USGS (thru USC/Keck)	$15,000
SCIGN equipment	$160,000

2.3 Component 3: InSAR

Skeleton operations of a 5-m X-band SAR downlink facility in San Diego are in place. In addition, some funds are being used to develop an on-line SAR database for WInSAR users.

There have been several important ERS-2 developments over the past few months.

(i) The last of the gyroscopes on ERS-2 failed in late November 2000 which rendered the spacecraft useless for interferometry. Because of this we cancelled the purchase of a new antenna controller ($50,000 SIO Matching funds) and ran the station in an automatic mode with little or no quality control.

(ii) Funds for the controller were used to purchase a 1 Tbyte RAID storage to handle the entire WInSAR SAR archive as well as a selected portion of the 2 Tbytes of data collected at the ground station. This disk facility replaced a tape robot, which now served as an on-line backup. The transition of the SAR data to the new computer is nearly complete.

(iii) In June of 2001, ESA reprogrammed the ERS-2 satellite to improve its pointing accuracy. We ran an interferometry test on August 31, 2001 using data collected at the SIO ground station in July and August and the data quality are back to normal. Thus we will continue to operate the X-band facility until ERS-2 fails completely.

(iv) Since ESA has not provided direct-readout access to ENVISAT (November 2001 launch), the next opportunity for direct readout from a SAR satellite will be late 2003 when ALOS is launched. Utilization of the SIO ground station for ALOS acquisitions will require a major upgrade and a funding commitment from NSF. The current plan is to close the station when ERS-2 fails completely in perhaps early 2002.

3 Justification for Supplemental Funding

The original cost estimated for 10 multi-parameter borehole stations in the San Francisco Bay Area was on the order of $100,000 per station (more specifically $97,000, Table 2).

Table 2: Original budget estimates (in $)

	Unit cost	Sites	Total
Strainmeter fabrication	20,000	10	200,000
Drilling per site	28,000	10	280,000
Quanterra recorders	15,000	10	150,000
Drilling site prep	16,000	10	160,000
Pressure transducers and other aux. sensors	3,350	10	33,500
GPS receivers	14,000	7	98,000
GPS and telemetry instal.	2,400	7	18,000
DTM travel			30,375
Total non-personnel costs as funded through combination of NSF and matching (Task 1 only)			969,875

In fact, significant cost overruns were experienced in several areas: strainmeter fabrication, drilling costs, and datalogger and auxiliary sensors costs.

a) Strainmeter fabrication

The original design for the strainmeters incorporated sensing volumes which would be less expensive to incorporate into the assembled instrument. Initial research into availability of suitable roll-formed tubes indicated that we would be able to make these inexpensive sensing bodies for the strainmeters. Subsequently, after the proposal was funded, we found that we had been somewhat misled and that this option was not economically viable for the number of instruments required. Thus we have produced a sensing body of different design. It has been necessary to have the sensing bodies fabricated in a commercial shop. The resultant increase in costs have been minimized by ordering all the sensing bodies at one time but, primarily because the manufacture is labor intensive, the increase in cost per unit is about $7,000. Costs of other components have inflated somewhat since the budget was prepared, leading to about an additional $1,000 per instrument.

b) Drilling costs

The original drilling estimates were obtained using the average hole cost paid by the USGS over the last 10 years of drilling. Two problems were encountered with mini-PBO drilling in the urban San Francisco Bay area that greatly increased the cost of drilling. Firstly, the various cities and counties have all required us to contain and remove all drilling fluids from the sites. These fluids (sometimes clear water) have to be then transported to a distant toxic dump site. The more fundamental implication of this requirement is that all holes have now to be rotary drilled with drilling mud to minimize fluid volume and this slows the drilling rate by more than a factor of four over the rates obtained in crystalline rock with no fluid containment. The second problem derived from a new region wide requirement that cemented in casing have at least a 2" annulus of cement around the casing. This means that an 11" hole must be drilled to 600 feet to install a 6.6" casing. This greatly increases the drilling time and the volume of material to be removed. The consequence is that holes drilled in this region now cost on average more than $40,000 whereas 10 years ago the hole could be drilled for under $30,000.

In addition, assorted items for site preparation had not been included in the original budget estimates (including portable toilets, permitting, cables for pore pressure transducers, PVC pipe for seismometer, cement and cement pumper for casing cementing). Other items, such as enclosures DCP's and tiltmeters turned out to be more expensive than estimated (based on previous USGS experience). Miscellaneous $1,000 items amounted to an increase per site of site preparation costs related to drilling by $10,000 per site.

c) Datalogger and auxiliary sensor costs

The original budget called for a 6 channel recording system with minimal disk, memory and no Ethernet connections, to digitize and record 3 component analog strain and 3 component analog geophone signal. After further discussions with the relevant experts at the USGS, we determined that it was crucial for the quality of the program to also record pore-pressure downhole, and add an analog surface pressure meter that required 1Hz sampling rate. This required us to augment the number of channels available from the recording system from 6 to 8 and we settled on a standard configuration (Q4120) as used in the Berkeley Digital Seismic Network, which also includes Ethernet, 16 MB of memory (For the additional acquisition programs and telemetry memory) and a 4 GB disk for on-site recording providing the necessary back-up for telemetry.

Thus the actual costs can be summarized as follows (Table 3).

Table 3: Actual costs (in $) per site for these items:

Strainmeter fabrication	28,000
Drilling per site	40,000
Quanterra loggers	20,000
Drilling site prep. and enclosures	26,000
Pressure transducer, etc.	5,000
GPS receivers	11,500
GPS and telemetry installation	5,000
Travel	3,000
Total per site excluding borehole seismometers	138,500

In addition, Caltrans has provided $100,000 to UC Berkeley for the fabrication of downhole seismometer packages. In the end, with the current budget, we are able to construct and install 7 complete stations, instead of the 10 originally planned.

We are requesting an additional $140,000 from NSF, which will allow us to complete the purchase of equipment and install an 8th station. 10 strainmeters (and enclosures) have already been fabricated. However, two of those can be used by the USGS Volcano Program, freeing up funding for the drilling of 2+ holes. The freed-up funds take into account the manufacturing cost of the strainmeters and the fact that not all parts of the enclosures would be utilized by the Volcano Program. This transaction meets the approval of the co-PI's in this project, including those at CIW who fabricated the strainmeters.

Note that the actual expenditures up to now are distributed somewhat differently than presented in Table 3, so that the requested funding is actually needed to complete beyond the first 4 sites, and will be spent as follows:

Table 4: Funds needed (in $)

	Need	Have	Funds
Data loggers	8	6	40,000
Pressure transducers	8	5	15,000
GPS	8	7	11,000
Strainmeters and enclosures*	8	10	–86,000
Drill holes	8	4	160,000
Total			140,000

*Funds freed up by selling equipment to the Volcano Program.

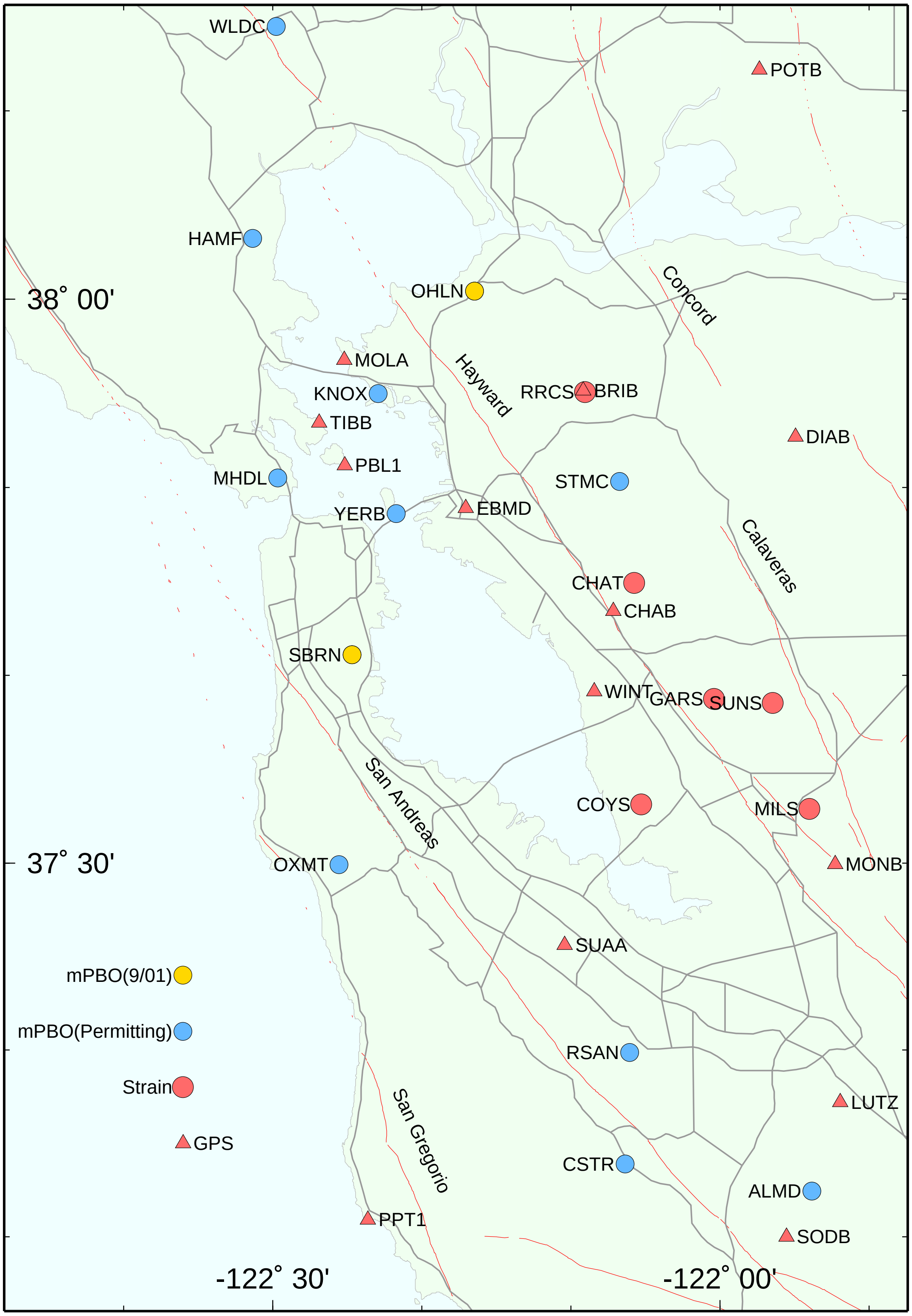

Figure 1: Location of existing (yellow) and planned (blue) Mini-PBO sites in the San Francisco Bay area. Shown also (red) are currently operating strainmeter (circles) and BARD (triangles) stations in the area.

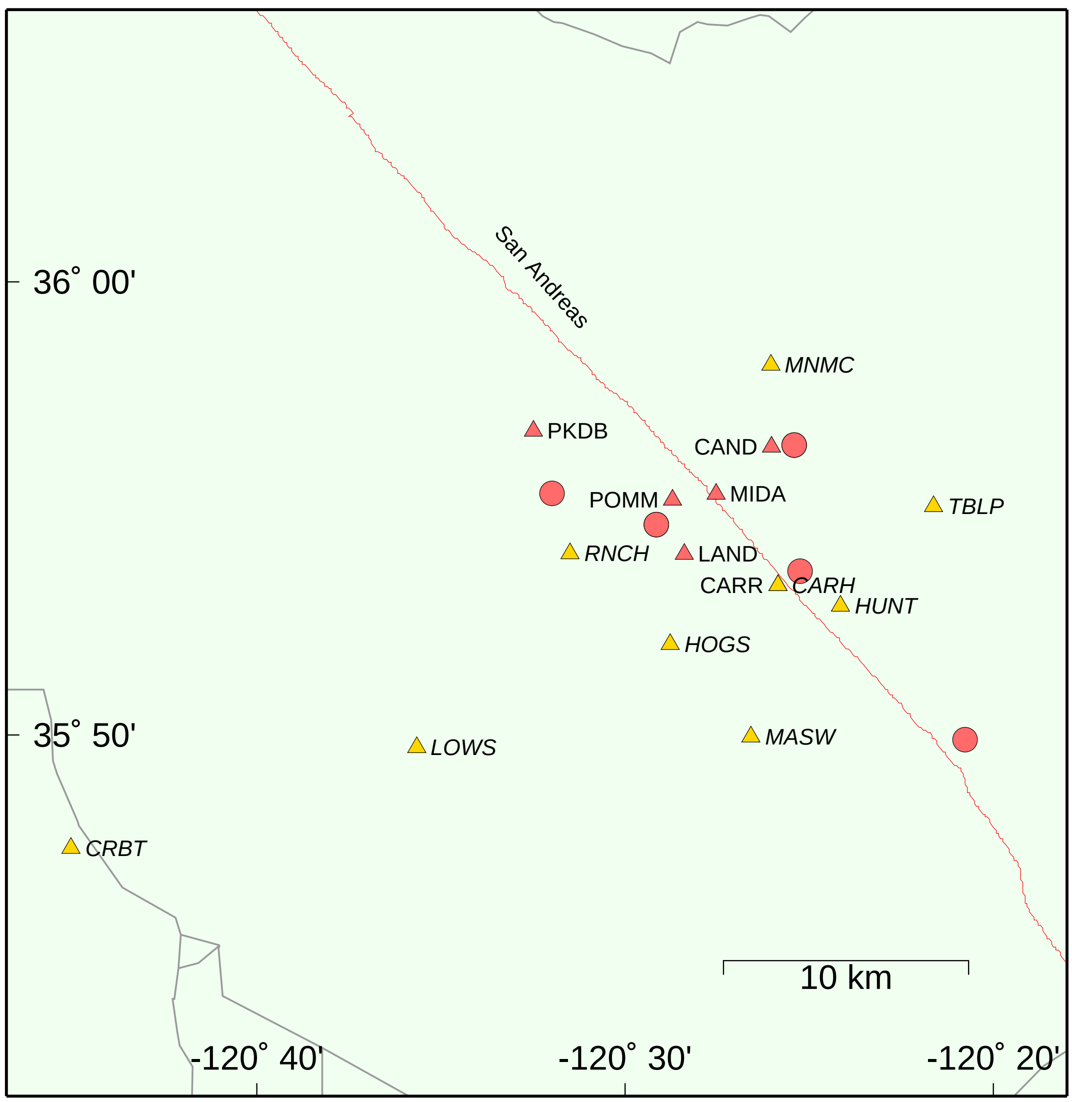

Figure 2: Location of the permanent GPS sites installed near Parkfield in the framework of this project (yellow triangles) along with other relevant instruments (red triangles:GPS; red circles: borehole strainmeters).

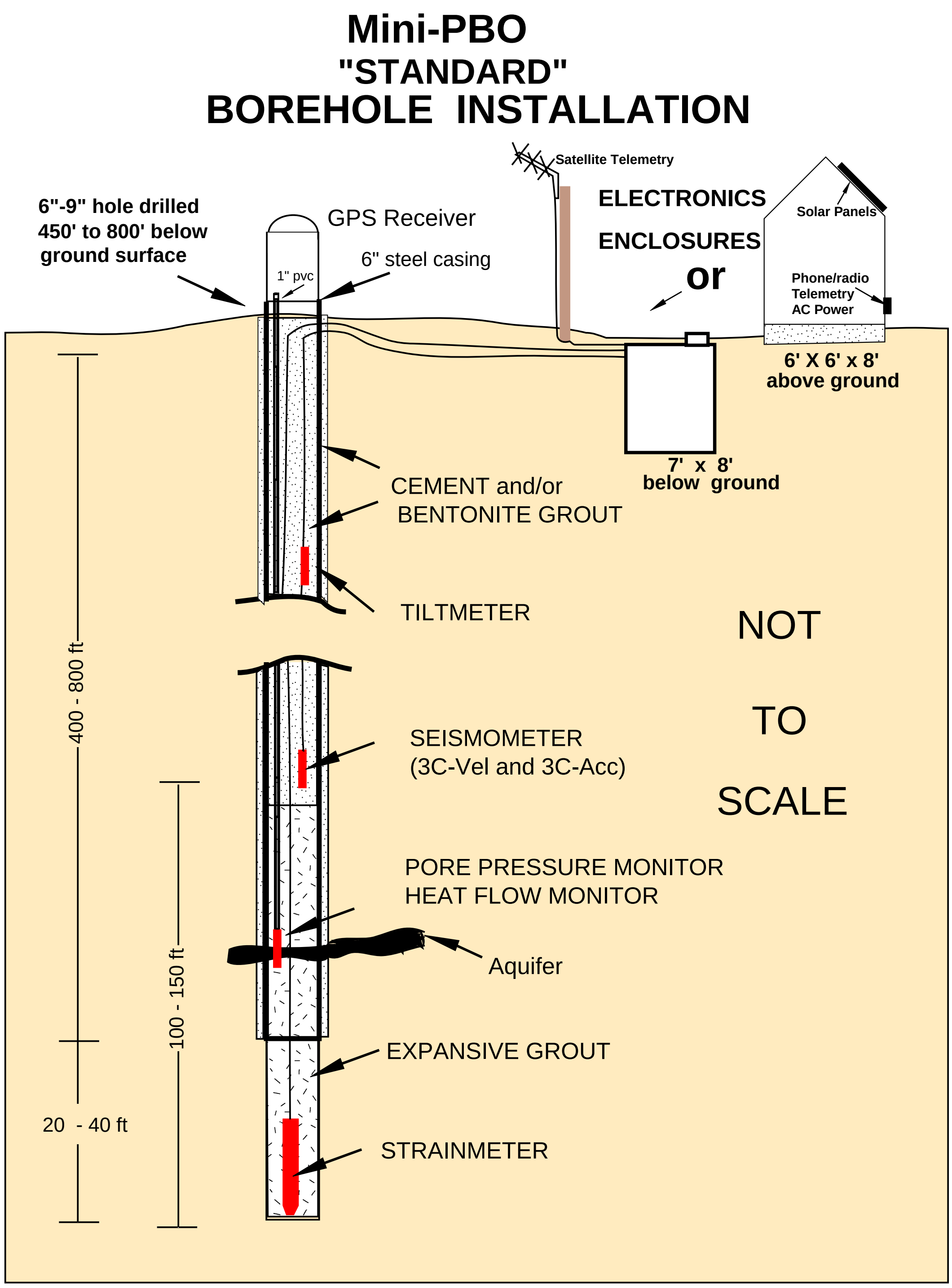

Figure 3: Design of the Mini-PBO borehole installation, showing the emplacement of the instruments downhole and the GPS receiver on the top.

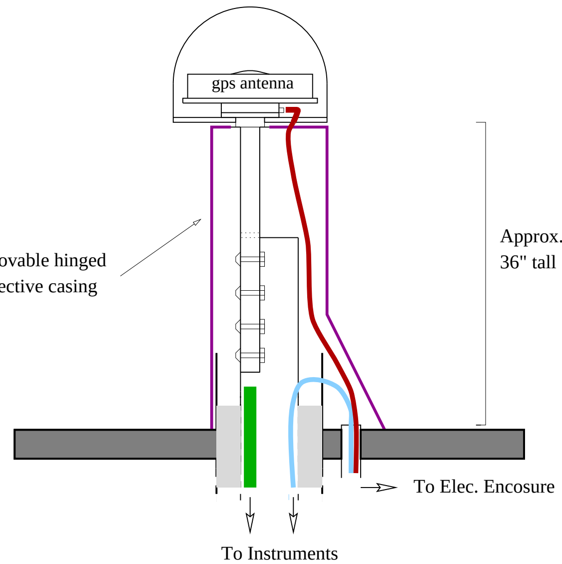

Figure 4: Design of the Mini-PBO GPS antenna mount on top of casing.

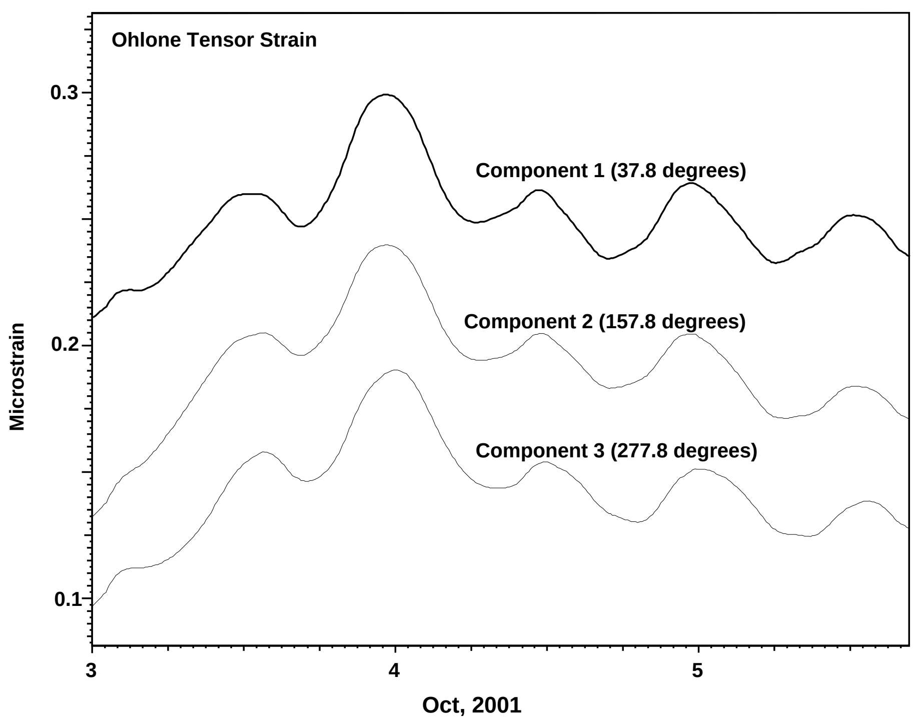

Figure 5: Low-frequency (600 second) tensor strain data from Ohlone showing earth tide variations.

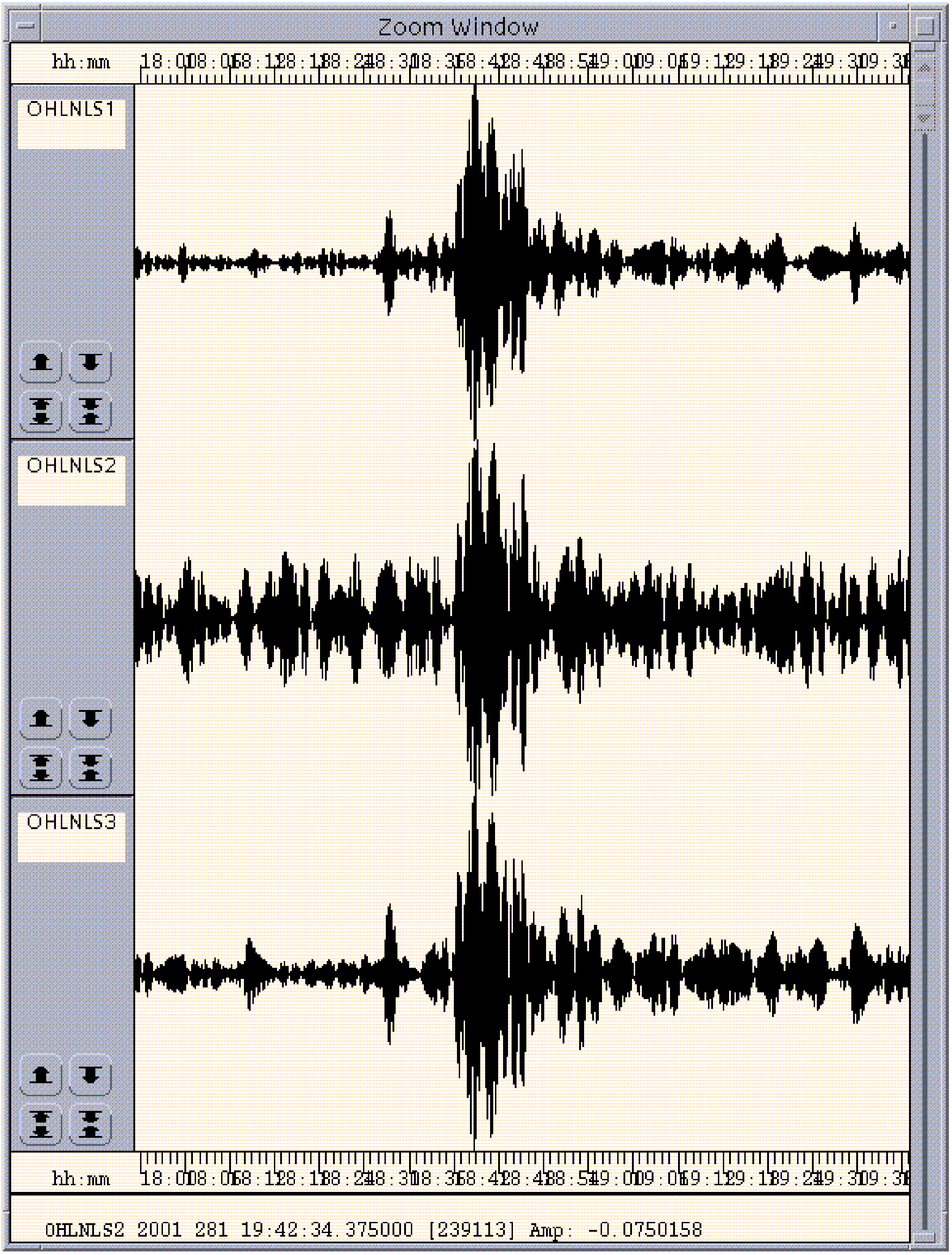

Figure 6: Bandpass filtered (17-23 second) tensor strainmeter observations at Ohlone showing surface wave displacements from an Ms = 6.3 earthquake in Alaska.

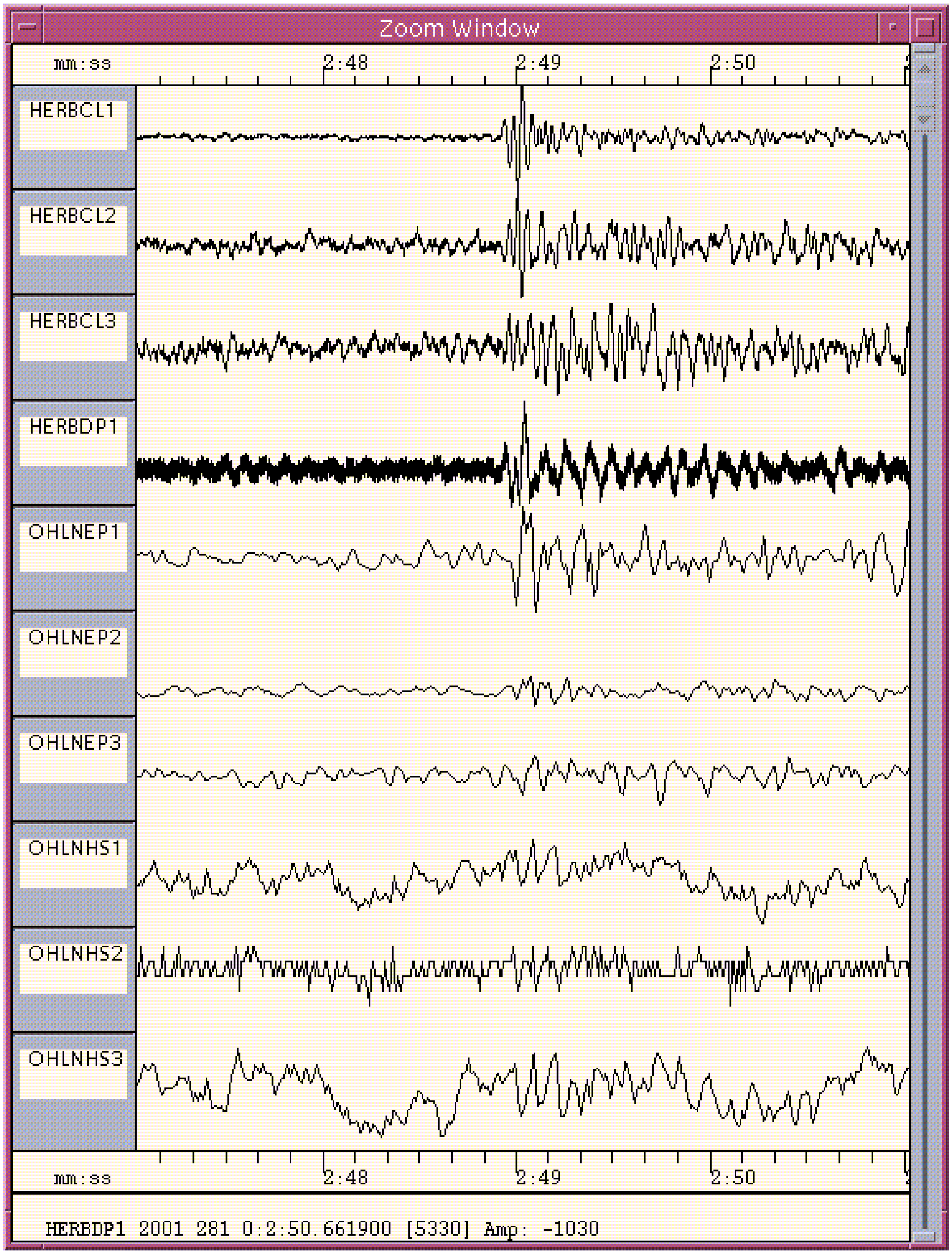

Figure 7: High-frequency (100-Hz) tensor strainmeter observations at Ohlone showing body waves from an M=1.3 earthquake located about 20 km. Top 4 traces are vertical and 2 horizontal accelerometer observations, and a vertical geophone observations from another borehole seismometer system (HERB) located about 1 km away. Traces 5-7 are the vertical and 2 horizontal 2-Hz geophone observations at Ohlone. Bottom 3 traces are the tensor strainmeter data at Ohlone, which show signals that are coherent with the geophones. Component 2 (OHLNHS2) may have an incorrect amplifier.