Annual Project Summary

DEEP BOREHOLE TENSOR STRAIN MONITORING, SOUTHERN CALIFORNIA

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seismology, geodesy, borehole geophysics

1. Project Objectives and Approach

This project provides field observations necessary to enhance understanding of fault processes associated with earthquakes along the San Andreas and Sierra Madre faults. Continuous high precision and high resolution borehole tensor strain data provide an essential complement to long baseline interferometry studies, GPS studies, and seismic characterisation of faults.

The project continues a program of maintenance and analysis of deep borehole tensor strain instrumentation initiated at Pinon Flat in late 1983, and a further deployment in the San Gabriel mountains region (Coldbrook) in 1996. These instruments consist of a three component plane strain module operating at strain sensitivity of 10^{-10} and support data logging systems. They provide data sampling at 30 minute intervals for transmission via satellite to permanent archive. The instruments provided by this project have been unique in the program in that they provide continuous tensor strain data of quality and sensitivity not achievable by any other instrumentation. These data allow near real time assessment of strain rates and consequent earthquake risk, and measure fault processes associated with earthquake preparation and postseismic relaxation. Archived long term baseline data are openly available from *http://www.cat.csiro.au/dem/msg/straincal/straincal.html*. Data are also provided in near real time in the USGS Menlo Park computer system (***thecove:/home/mick/QUICKCHECK***). These data high resolution real time monitoring of short term strain phenomena.

The **immediate objectives** of the project are

- Maintenance of uphole system integrity at 2 Southern Californian sites, with repair or production of replacement uphole electronics as necessary.
- Manual preparation of raw instrument data for permanent archive.
- Analysis of continuous unique low frequency shear strain data (30 minute samples) and modelling studies based on the constraints of these data
- Near real time alert response to the earthquake studies community when necessary.
- Archive of processed data for access by the earthquake studies community, and provision of near-real time automatically processed data for inclusion in publicly accessible web pages linked to the USGS web datasets.

The project is carried out in parallel with maintenance of five further sites (San Juan Bautista, along the Hayward fault and near Parkfield) in Northern California.

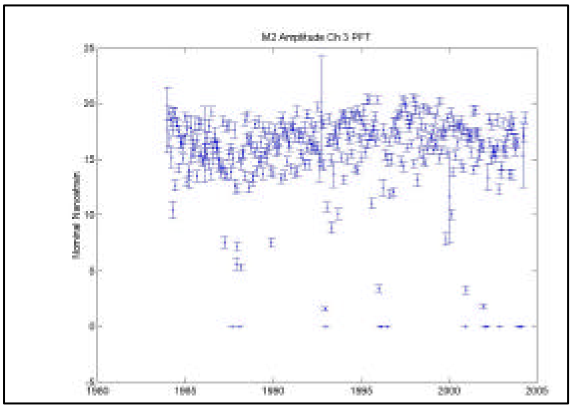
1 Investigations & Results

1.1 Pinon Flat Observatory -PFT

This is the oldest site measuring tensor strain in California, having been installed in 1983. As noted in previous reports, performance has been degrading since a series of lightning strikes on the site infrastructure. Channel 2 showed began to show degraded signal amplitude since early 1999. The internal gain compensation system ran out of dynamic range in mid-2000. In December 2000, an additional gain compensating circuit was installed on this channel. Normal operations were resumed, allowing the 19 year dataset baseline to be continued. However, since the electrical storm of September 2001 which disabled all PFO instruments, ongoing problems have been experienced at PFT.

Repairs were carried out in December 2001, May 2002, and December 2002. In October 2003, it was noted that gauge #1 auto-compensation system was activated indicating that the down hole preamplifier was beginning to fail. During the December, 2003 visit, extensive testing revealed that, contrary to expectations, borehole cable measurements indicated no additional electrical leakage. (The cable has reached its 20 year design lifetime/expected service life limit, so progressive deterioration was expected). The progressive gain degradation must then be the result of incipient failure of the FET preamplifiers. At this time, it is believed that sensors #1 and #2 are irrecoverable.

The performance of sensor #3 has been reviewed to determine its validity as a single component system.



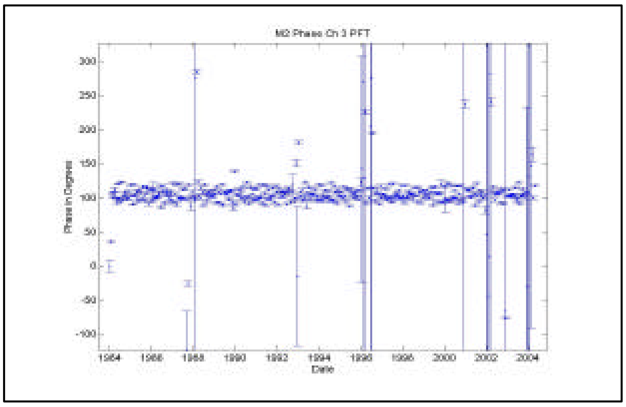


Figure 1: Tidal spectra for non overlapping 20 day periods of raw data for the lifetime of channel 3 of PFT strain meter. There has been no change of amplitude or phase on this channel during or after the failure of channel 1 and channel 2.

The data indicate that there has been no obvious effect of the failures of Channel 1 and 2 on the performance of channel 3. At next visit, additional attempts to recover the failed channels will tested, and if not effective, these channels will be permanently disabled to ensure optimal operation of channel 3 into the future. This gauge is approximately parallel to the NW/SE laser component.

The performance of channel three has recently begun to show degradation. The first symptoms of this are in the measured gains of the channel (routinely taken every three hours). Data for the last several years are shown in figure 2 (below) where the gain is compared with the observed uphole temperature. The black curve indicates the gain deviation from the expected value of approximately 1050. The gain has decreased approximately 4% over the past three years – this has no direct effect on the measurements until the gain compensation mechanism reaches its limits which will occur at approximately –950 on the scale shown. The change is abnormal.

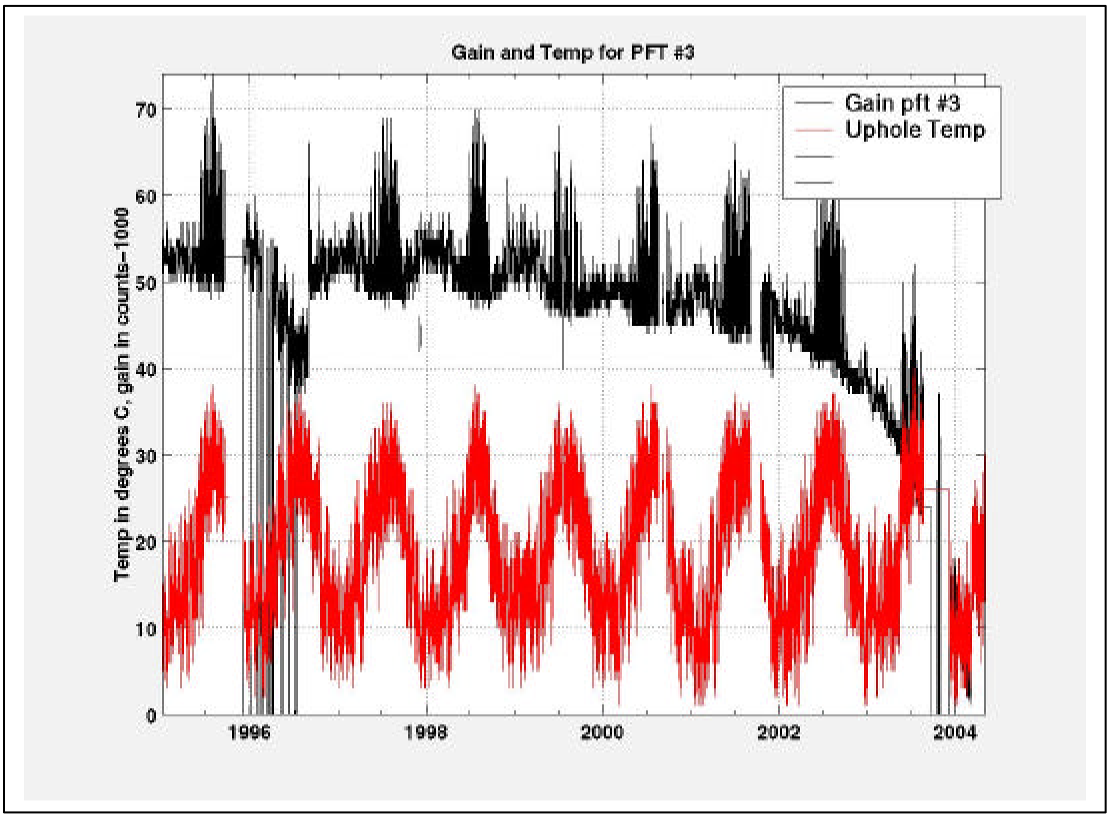


Figure 2. Gain change for channel 3 at PFT referenced to the normal value of 1050. the red plot is the three hourly temperature at the site.

A summary of long term performance for this site is shown in figure 3. The upper part of the figure shows the calculated strains (areal, gamma1 and gamma2) up to the time of the failure of channel 2. (From this time, it is not possible to provide a proper estimate of the three strains – current model instruments provide a redundant channel so that failure of particular components do not compromise performance.) The blue plot is a calculated strain for the north-west, south-east direction to allow direct comparison of borehole estimates and the only good (optically anchored) component of the laser strain meter (shown in green). This comparison indicates that, except for the steps associated with the Landers event in 1992 (where the static offset for the laser is not available), and a water loading event in 1993, the borehole measurement is of comparable stability long term to the laser strain meter. Note that the simplified response observed for one direction (here NW/SE) on either system does not imply that there are no deformations overall – the three strain components show long term structures as large as 1.5 microstrain over the period 1988 to 1992, yet the composite NW component shows nothing larger than 0.4 microstrain.

The lower part of the figure shows the individual gauges from 1986 to the present. This can be used to infer strain profiles since the failure of channel 2.

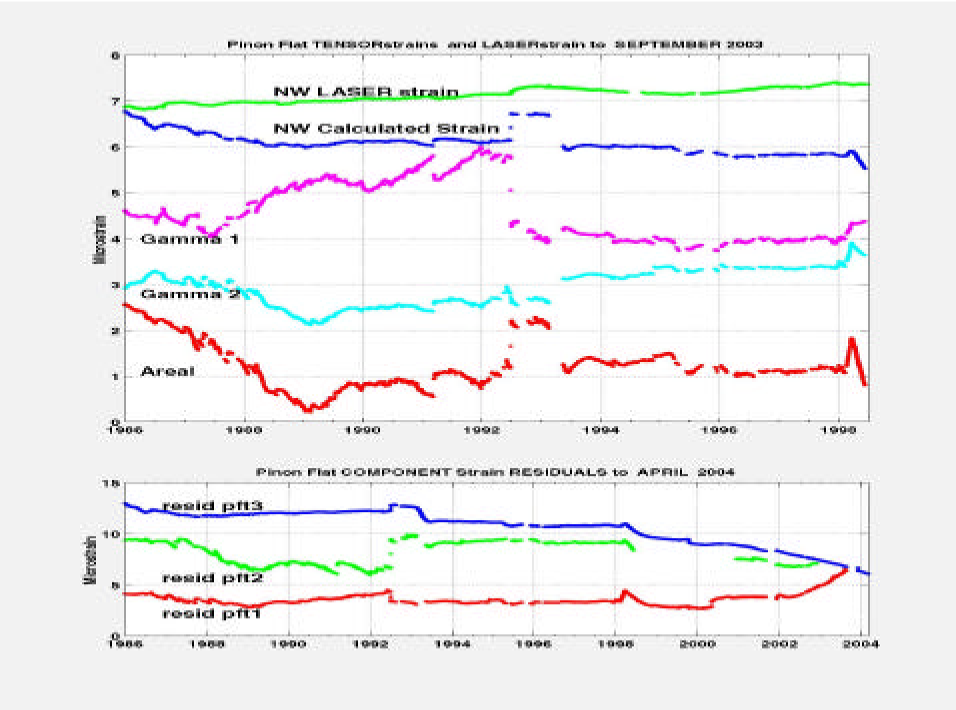


Figure 3. Pinon Flat strainmeter data. Lower panel shows each raw component since installation in 1986 to October 2003. Gauge #2 downhole failure in 1998, and successful uphole electronics compensation to recover this component in late 2000 are shown. Upper panel shows the computed strain components to point of gauge #2 failure in 1998. Step in 1992 is Landers offset, and in 1993 is due to water well loading(see Figure 4.) The Green trace is LASER strain NW/SE, and the Blue trace is GTS TENSOR strain estimate for the NW azimuth derived from the measured areal strain, gamma1 and gamma2.

Figure 4 (below) shows a comparison of rainfall, aquifer level in water well CIC, and NW LASER strain data. The anomaly in strain in early 1998 is correlated with an anomalous change in aquifer level, and may be associated with increased precipitation in that year. The enhanced response of the borehole system compared to the laser data to this water level change has not been observed in the previous lifetime of the instrument. It is not unlikely that the effects shown are associated with the early phase of the failure of channel 2, first suspected in December, 1997.

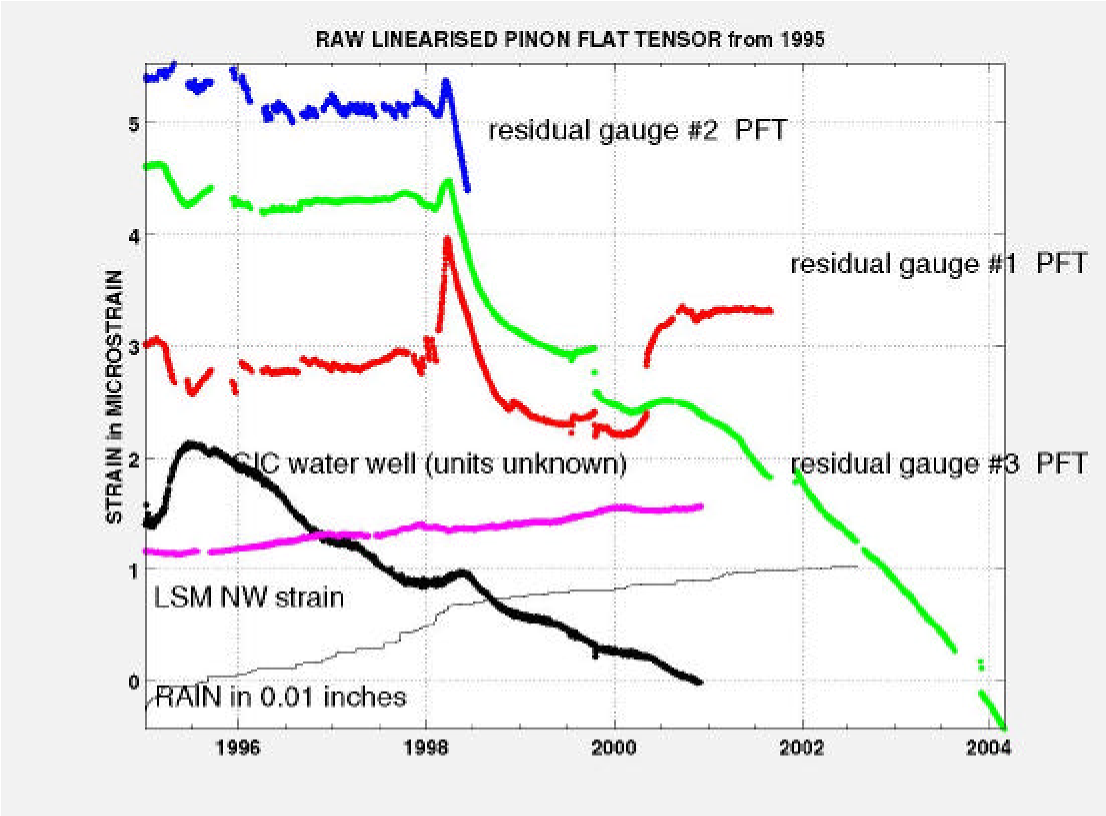


Figure 4 *Residual raw data from gauges #1 (red), #2 (blue), and #3 (green) are shown with CIC well data (black), LSM NW (magenta) and rainfall. All instruments are shown from 1995 onwards, and tensor channel data show exaggerated correlation with rainfall and well data at this site.*

1.2 San Gabriel Mountains - Coldbrook CLT.

The Coldrook site is situated in the San Gabriel mountains, and together with three USGS operated borehole dilatometers ***puba*** (20km NW), ***cnts*** (15 km SW) and ***bdts*** (15 km SE) forms a 4 instrument array in the region between the Sierre Madre and San Andreas faults.

The Coldbrook instrument was installed in late 1996, and borehole recovery processes evident in the data in the form of exponential signals have been removed.

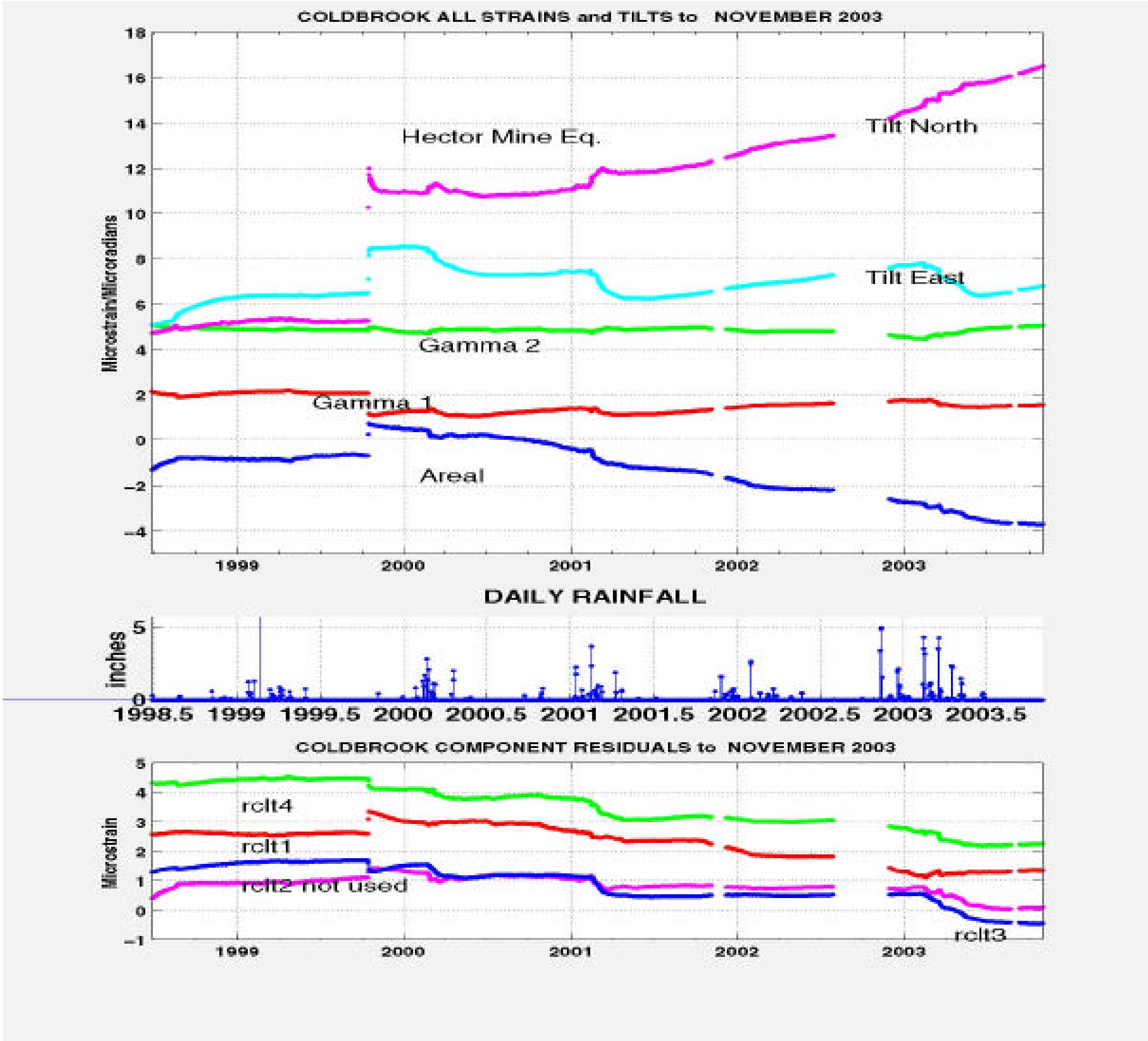
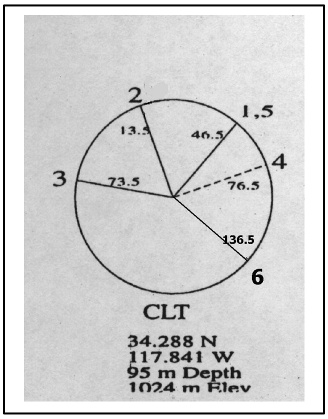


Figure 4. Strain and tilt observations for the CLT site. Three of the four channels are needed for strain determination.

The site is showing very little change in gamma2 through the whole record, yet significant fluctuation in both areal strain and gamma1. There is a change of strain rate approximately six months before the Hector Mine Earthquake which also shows in the tilt data. This is early in the site lifetime so should be treated with reserve. It is clear that all fluctuations on the strain components are accompanied by tilt fluctuations. The azimuthal orientation of the various instrument components is shown to the left. Channels 1 through 4 are strain, and 5 and 6 are tilt. The major driver of the strain and tilt variation at this site is on channel 2 and channel 6. The exponential grout curing and borehole strain recovery models removed from the data have now been reviewed and are now in final form in all archived data and may be obtained from



http://www.cat.csiro.au/dem/msg/straincal/oct2002models_str_tab.pdf

Small anomalous strain changes were observed on all of the strainmeters in the Sierra Madre array sites in late October 2001 (see Figure 5 below).

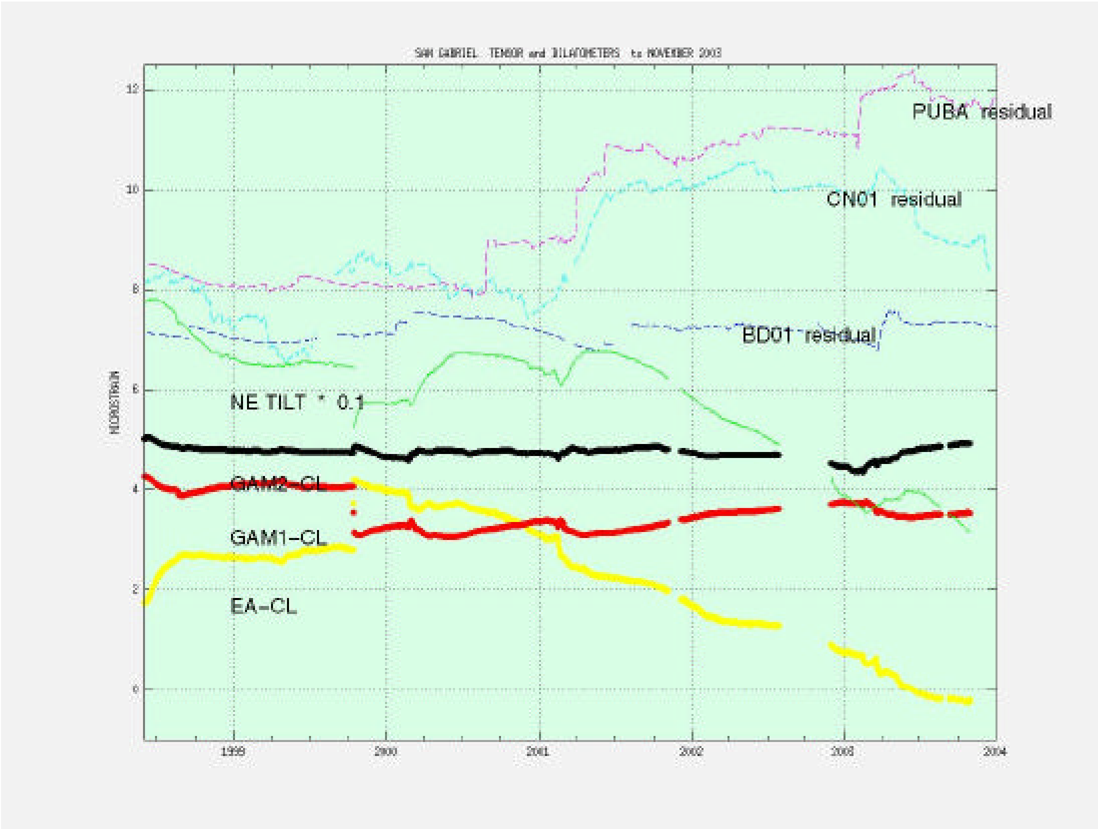


*Figure 5. Comparison of observed strain rates **puba**, **clt** and **cnt** since 1999.*

Currently , it is postulated that the **Punchbowl dilatometer (puba)** is at the end of its 25 year life and that **Big Dalton** and **Chantry** have steps of unknown cause (*Roeloffs, Hodgkinson Strainmeter Report to PBO Standing Committee and Unavco, 2004* pre-publication). It should be noted that **Coldbrook** is sited on an active landslip and approximately 170 feet below a fracture zone. The Chantry dilatometer is also located in an area of active surface slip, so coupling with rainfall is inevitable at both these sites. These installations give some insight into issues which should be identified in the borehole siting procedures where decisions have to be made before adequate data are available

2 Data Product Availability

Archived strain data from the Californian sites are stored in both raw component form, and as processed areal and shear strains. A regularly updated archive of data has been maintained in the USGS Menlo Park computer system since 1988. This data is stored in binary files with appended header information (USGS "*bottle*" format).

CSIRO home page for direct access to data from all borehole tensor strain instruments in open format is *http://www.cat.csiro.au/dem/msg/straincal/straincal.html* ***This page includes facilities for download of raw or processed data from our primary archive***.

Automatically processed near-real time data is always available in *thecove:/home/mick/QUICKCHECK* for users with access to USGS plotting software "*xqp*", and via the USGS crustal deformation web pages in graphical form.

Scientists requiring other access to the archived data should contact Dr. M.T. Gladwin (+617 3327 4562, email *mike.gladwin@csiro.au*).

3 Publications

Recent Publications

Gladwin,M.T. & Mee, M. On Boreholes and PBO Borehole Strain, *EOS.(Trans. Am. Geo. Un.)*, 2003

Gwyther,R.L , Gladwin,M.T, & Hart,R.H.G. &M.Mee Focussed Study of Aseismic Fault Processes, *Workshop Abstracts, Earthscope Workshop: Making and Breaking a Continent, October 2001. p 157-160, 2001*

Gwyther R.L., M.T. Gladwin, R.H. Hart & M.Mee Aseismic stress transfer between shallow and medium depths in transition zones of the San Andreas Fault.. *EOS. (Trans. Am. Geo. Un.)*, 2001.

Gwyther R.L., M.T. Gladwin, R.H. Hart & M.Mee Sharpening our Image of Fault Processes: what Borehole Tensor Strain Observations can add to Seismic and Geodetic Studies. *Seis. Res. Lett.* 70(1), 255, 2000.

Gladwin, M.T., R.L. Gwyther, R.H. Hart, & M.Mee Borehole Tensor Strainmeter Arrays to Enhance our Imaging of Crustal Processes *EOS. (Trans. Am. Geo. Un.)*,48(17), , 2000

Gwyther, R.L., C.H. Thurber, M.T.Gladwin &M. Mee Seismic and Aseismic Observations of the 12th August 1998 San Juan Bautista, California M 5.3 earthquake, *Proc. 3rd Conf. on Tectonic Problems of the San Andreas Fault*, 2000

Gwyther R.L., M.T. Gladwin, R.H. Hart & M.Mee Propagating Aseismic Fault Slip events at Parkfield: What they tell us about fault processes at depths of 1km to 5 km. *EOS. (Trans. Am. Geo. Un.)*,81(48), p F1125, 2000.

Gladwin, M.T., R.L. Gwyther, R.H. Hart, & M.Mee Are linear strain rates between major strain events characteristic of transition zone regions of the San Andreas Fault *EOS. (Trans. Am. Geo. Un.)*, 81(48), p F921, 2000

Gladwin,M.T., Gwyther,R.L., & Hart,R.H.G., Addition of Strain to Targeted GPS Clusters- New Issues for Large Scale Borehole Strainmeter Arrays, *Proc. 2nd Plate Boundary Observatory Workshop*,1.17a-1.17e, *2000*

Langbein, J., Gladwin, M.T., & Gwyther,R.L., Extension of the Parkfield deformation array,*Proc. 2nd Plate Boundary Observatory Workshop*,2.45-2.49,2000

Thurber,C., Gladwin,M.T., Rubin,A., & DeMets,D.C., Focussed Observation of the San Andreas/Calaveras Fault intersection in the region of San Juan Bautista, California, *Proc. 2nd Plate Boundary Observatory Workshop*,2.75-2.79, 2000

Roeloffs,E., Gladwin,M.T., & Hart,R.H.G., Strain monitoring at the bend in the Cascadia Subduction Zone, *Proc. 2nd Plate Boundary Observatory Workshop*,4.36-4.40 2000

Steidl,J., Gladwin,M.T., Gwyther,R.L., & Vernon, F., Fault Processes on the Anza section of the San Jacinto Fault, *Proc. 2nd Plate Boundary Observatory Workshop*,2.70-2.74, 2000

Agnew,D., Wyatt, F., & Gladwin, M.T., Strainmeter Calibration, *Proc. 2nd Plate Boundary Observatory Workshop*, I1-I5, 2000

Langbein, J., Roeloffs,E., Gladwin,M.T.,& Gwyther R.L., Creepmeters on the San Andreas Fault System between San Francisco Bay and Parkfield, *Proc. 2nd Plate Boundary Observatory Workshop*, 2.40-2.44, 2000

Selected Previous Journal Publications

Langbein, J., R.L. Gwyther, R.H.G.Hart and M.T. Gladwin Slip-rate increase at Parkfield in 1993 detected by high-precision EDM and borehole tensor strainmeters *Geophys. Res. Lett.* 26(16) pp 2529-2532, 1999

Gwyther R.L., M.T. Gladwin and R.H.G. Hart Anomalous Shear Strain at Parkfield During 1993-94 *Geophys. Res. Lett. V 23 (18)* p 2425-2428, 1996

Hart R.H.G., M.T. Gladwin, R.L. Gwyther, D.C. Agnew and F.K. Wyatt Tidal Calibration of Borehole strain meters: Removing the effects of small-scale inhomogeneity *J. Geophys. Res., V101(B11), p25553-25571*, 1996

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Wyatt, F.K, Agnew, D.C. and Gladwin M.T. Continuous Measurements of Crustal Deformation for the 1992 Landers Earthquake Sequence. *Bull. Seis. Soc. Am*, Vol 84, No 3, 768-779, 1994.

Gladwin, M. T., Breckenridge, K.S.,Gwyther, R. L. and Hart, R. Measurements of the Strain Field Associated with Episodic creep events at San Juan Bautista, California. *J. Geophys. Res.*,Vol 99 (B3), 4559-4565, 1994.

Gladwin, M.T., Gwyther, R.L., Hart, R.H.G. and Breckenridge K.(1993) Measurements of the strain field associated with episodic creep events on the San Andreas fault at San Juan Bautista, California (1994). *J. Geophys. Res.* Vol 99 (B3), 4559-4565.

Linde A.T., Gladwin M.T. and Johnston M.J.S. (1992) The Loma Prieta Earthquake, 1989 and Earth Strain Tidal Amplitudes: An Unsuccessful Search for Associated Changes. *Geophysical Res. Let.* Vol 19 No.3 pp 317-320.

Gwyther R.L., Gladwin M.T. and Hart R.H.G. (1992) A Shear Strain Anomaly Following the Loma Prieta Earthquake. *Nature* Vol 356 No.6365 pp 142-144.

Gladwin,M.T., Gwyther R.L., Higbie J.W. and Hart R.G.(1991) A Medium Term Precursor to the Loma Prieta Earthquake? *Geophys. Res. Let.* Vol 18 No.8 pp 1377-1380.

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Gladwin, M.T., Gwyther, R., Hart, R., Francis, M., and Johnston, M.J.S., Borehole Tensor Strain Measurements in California. *J. Geophys. Res*. 92. B8 pp7981-7988, 1987. .

Johnston, M. J. S., Linde, A.T., Gladwin, M.T., and Borcherdt, R.D. Fault Failure with Moderate Earthquakes. *Tectonophysics*. 144, 189-206, 1987. .

Gladwin, M. T. and Hart, R. Design Parameters for Borehole Strain Instrumentation. *Pageoph*.,123, 59-88, 1985. .

Gladwin, M. T., High Precision multi component borehole deformation monitoring. *Rev.Sci.Instrum.*, 55 , 2011-2016, 1984. .

Gladwin, M. T. and Wolfe, J. Linearity of Capacitance Displacement Transducers. *J.Sc.Instr*. 46, 1099-1100, 1975. .

Non-Technical Summary

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This project provides field observations of horizontal strain changes over timescales from minutes to years, which are critical to an understanding of fault processes associated with earthquakes along the San Andreas and San Gabriel / Sierre Madre fault systems. The project continues a program of maintenance and analysis of deep borehole tensor strain instrumentation initiated at Pinon Flat in late 1983, and a further deployment in the San Gabriel mountains region (Coldbrook) in 1996.

Continuous high precision and high resolution borehole tensor strain data provide a complement to long baseline interferometry studies (limited to sampling intervals of weeks), GPS studies, and seismic characterisation of faults. After 20 years of operation, the instrument at Pinon Flat has suffered irreversible damage to downhole components of gauges 1 and 2 following lightning strikes at the site. The remaining gauge 3 is performing to specification, though its gain has decreased during the past year. Internal compensation systems will allow this remaining gauge to be used as a single component system, which by chance is near parallel to the NW/SE component of the laser strain meter. The Coldbrook instrument is operating normally.

This project runs in parallel with a maintenance project covering six further instruments in Northern California.