Annual Project Summary

DEEP BOREHOLE TENSOR STRAIN MONITORING, NORTHERN CALIFORNIA

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seismology, geodesy, borehole geophysics

Project Objectives and Approach

This project provides field observations critical to an understanding of fault processes associated with earthquakes along the San Andreas and Hayward faults. Continuous high precision and high resolution borehole tensor strain data provide an essential complement to long baseline interferometry studies (limited to sampling intervals of weeks), GPS studies, and seismic characterisation of faults.

The project continues a program of maintenance and analysis of deep borehole tensor strain instrumentation initiated at San Juan Bautista in late 1983, expanded by three sites installed in the Parkfield area during December of 1986, by two sites deployed near the Hayward Fault in the San Francisco Bay region in 1992. These instruments consist of a three component plane strain module operating at a strain sensitivity of 10^{-10} and support data logging systems. As deployed to date they provide data sampling at 30 minute intervals for transmission via satellite for permanent archive purposes. The instruments provided by this project are unique in the program in that they provide

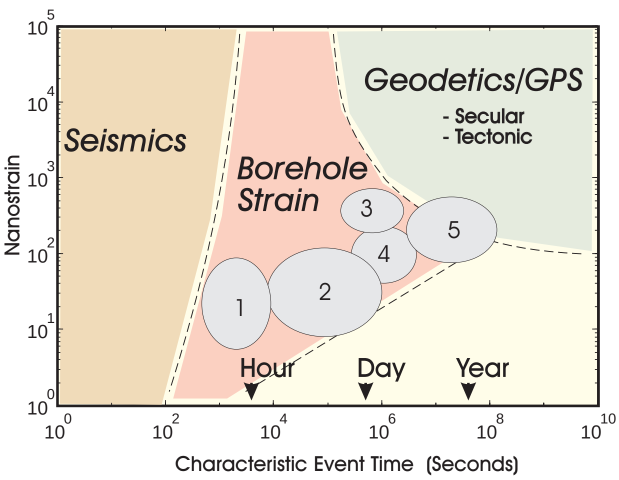

Figure 1. *Effective detection capabilities of seismic,borehole strain, and geodetic instrumentation. The vertical axis is in units of strain, whilst the horizontal axis covers the period band from 1 second to 10^{10} seconds (100 years). GPS instrumentation will lower the boundary of the geodetic domain, but not significantly. For precise monitoring of short term strain rate fluctuations, there is a clear necessity for borehole strain instruments with nanostrain resolution in the minutes - months time scales. Data observed over the past 14 years have included identifiable episodes in each of the domains numbered 1 to 5.*

continuous tensor strain data of high quality and sensitivity not achievable by any other instrumentation. These data form a critical complement to GPS and geodetic studies (see Figure 1) in assessing strain rates and consequent earthquake risk, as well as investigating fault processes associated with earthquake preparation and postseismic relaxation. Data are made available in near real time in the USGS Menlo Park computer system (thecove:/home/mick/BASEDATA). These data supplement long baseline survey data, and permit real time monitoring for short term strain phenomena.

The **immediate objectives** of the project are

- Maintenance of uphole system integrity at 6 Northern Californian sites, with repair or production of replacement uphole electronics if 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
- Regular reporting and real time alert response as part of the Parkfield Prediction experiment.
- Archive of processed data for access by the earthquake studies community, and provision of near-real time automatically processed data for inclusion in publically accessible web pages linked to the USGS web datasets.

The project is carried out in parallel with maintenance of two further sites (Pinon Flat and San Gabriel mountains) in Southern California.

Investigations & Results

San Juan Bautista:

A slow earthquake was observed on the SJT tensor strain instrument in August 1998 (see ***Figure 2)***. This slow event, with an equivalent magnitude of 4.9 was initiated by an earthquake with magnitude of 5.2 and typical aftershock sequence extending over 8 days. Our modelled coseismic failure region corresponds approximately with the zone of aftershocks, but extends some 2 km futher northwest along the fault. The slip region we model as causing the slow earthquake is immediately adjacent to, and directly above, the aftershock zone delineating the seismic failure surface. These combined strain and seismic observations provide direct evidence of the linkage between slow earthquakes and associated seismicity. Data from the SRL dilatometer for direct comparison were unobtainable, as the dilatometer irretrievable failed two months prior to this event.

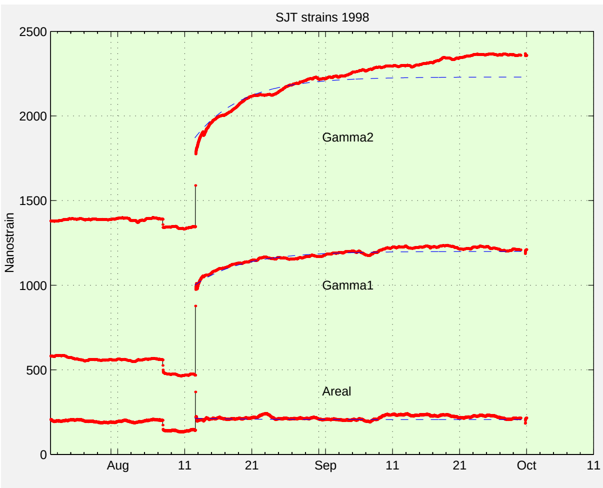

Figure 2. *Strain data observed at SJT during the August 1998 seismic & slow earthquake sequence.*

The modelled failure surfaces for this earthquake, as well as two previous slow earthquakes of comparable magnitude observed in December 1992, April 1996 and August 1998 are both separate and adjacent, and are shown in ***Figure 2(b).*** Principal aftershocks occurred at the lower extent of the failure region, and are shown in the figure as green circles. Accurately relocated historical micro-seismicity (*Rubin, et. al., 1999*) is also plotted on this figure, and shows a remarkable correspondence with the lower bounds of the slow earthquake failure zones. Together the three slow earthquakes have relieved a 25 km region of the fault surface to a depth of 5-6 km in the transition zone of the San Andreas Fault over the past 6 years. These results were reported at Fall 1999 AGU.

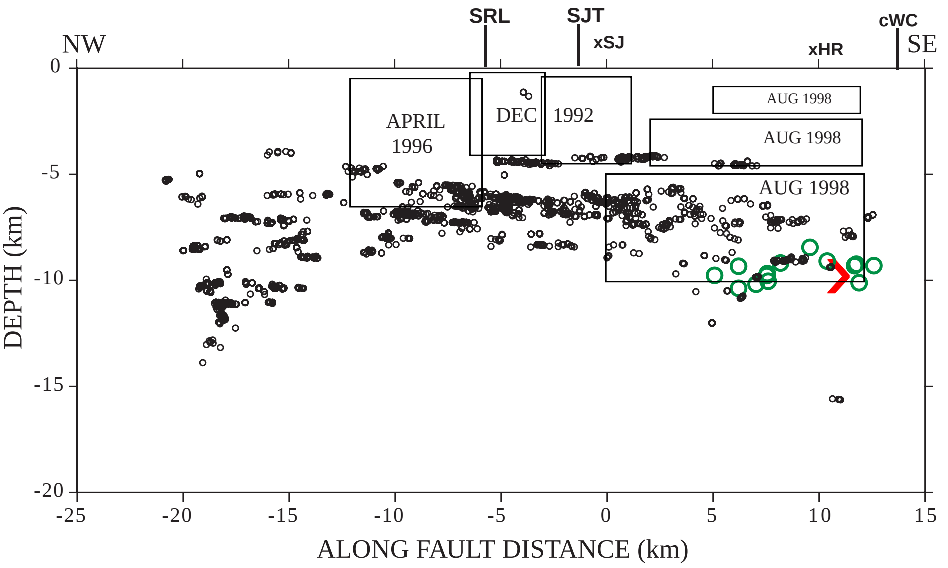

Figure 3*. Mainshock (M 5.3), principal aftershocks (green circles), and historical microseismicity (block dots) for August 12 1998 San Juan Bautista earthquake. The seismic failure surface is shown, and directly above this are the two shallower slow earthquake failure zones with modelled slow slip in the 30 minutes, and 10 days following the earthquake. Failure surface for two previous slow earthquakes (Dec. 1992 and April 1996) observed at this site are also indicated.*

The long term strain dataset for the BTSM at San Juan Bautista is shown in ***Figure 2***. It should be noted how this instrument demonstrates exceptional long term stability in areal strain ($< 2\mu\varepsilon$ drift over 12 years).

The dominant features are the Loma Prieta coseismic offset; slow earthquakes in 1992, 1996 and 1998; 26 episodic strain/creep events (barely distinguishable at the scale of Fig 4); a significant change in shear γ_1 gradient following Loma Prieta; and a significant change in gradient in shear strain γ_2 in 1993.

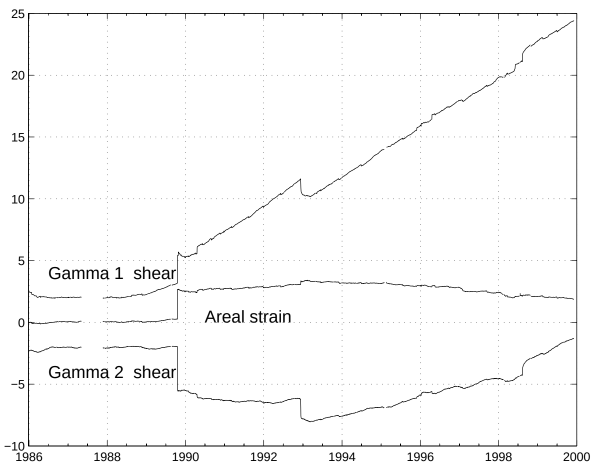

Figure 4. *Long term strain data observed at San Juan Bautista site.*

Parkfield:

The shear strain anomaly identified (*Gwyther et al*., 1996) in the Parkfield BTSM instruments as commencing in 1993 continued until 1997. This anomaly has now been independently verified by 2-color laser strain observations (*Langbein* et al., 1999), and by microearthquake observations of clustered microearthquakes (*Nadeau*, 1999). Modelling studies (*Roeloffs*, 1997 & pers.comm. 1999) indicate that the anomaly is most probably not caused by aquifer changes associated with the cessation of drought conditions in 1993. Data from the DLT instrument is contaminated by an annual hydrological signal caused by a nearby unconfined aquifer. We have processed DLT data to remove the annual hydrological term, and the residual data indicates that a large change in shear strain also occurred at this site in 1993

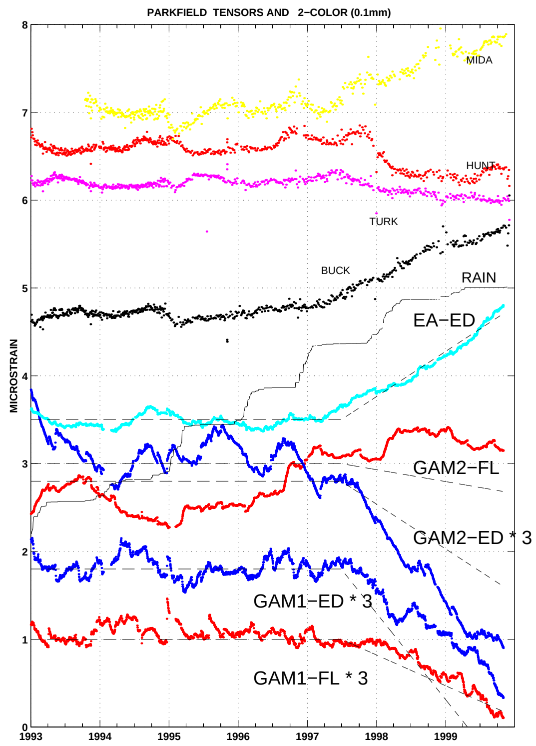

Figure 5 *Strain data from Eades and Frolich tensor strain instruments, with modelled strain changes in 1997 due to reduced slip on surfaces indicated in Figure 6 below, also indicated. At the top of the figure, line lengths measured on the 2-color network are shown, and indicate that a change in rate may also be present in those data.*

A further significant change in strain rate has been identified as occurring in 1997 and continuing to date. Data from the Eades and Frolich sites is shown in Figure 5 Also shown in this figure are two color line length changes (*Langbein*, 1999, pers. comm.) indicating that a change of rate is also evident in the 2-color data. Preliminary inspection of microearthquake data indicates a change in slip rate inferred from microearthquake activity also occurred at this time (1997). These results were reported at Fall 1999 AGU.

Hayward Fault:

Data observed at the site Chabot along the Hayward Fault are shown in Figure 6. These data indicate that an annual hydrological influence is present in the areal strain data. This effect is at a level of less than 250 nanostrain in the shear strain data, and the shear strains at the Chabot site have been remarkably stable over the 5 years of operation.

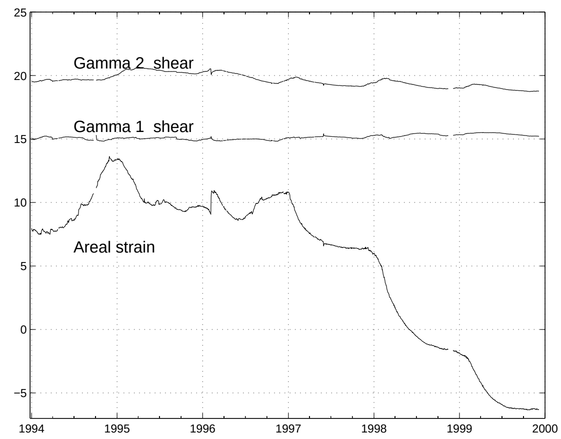

Figure 9 *Strain data observed at Chabot, 5km off the northern section of the Hayward fault.*

In 1996/7, some indication of cable leakage due to damage which occurred 20m from the well head during the installation procedure of the Garin instrument cable was noted as capillary moisture at the pit. Repairs were carried out, but cable erosion continued to a stage in mid-1998 where measured strain data were irretrievably contaminated by the downhole leakage. Repairs to the downhole cable are not physically possible. This site has now been decommissioned.

Data Availability

Archived strain data from the Californian sites is 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).

Data is accessible in *thecove:/home/mick/BASEDATA.* Automatically processed near-realtime data is 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. Home page for access to data plots from all borehole tensor strain instruments is *http://www.dem.csiro.au/~rossg/straincal/straincal.html*

Scientists requiring access to the archived data should contact Dr. R. Gwyther (+617 3212 4586, email*: r.gwyther@cat.csiro.au*) or Dr. M.T. Gladwin (+617 3212 4562).

Publications

Recent Publications 1998-99

Langbein, J., R.L. Gwyther and M.T. Gladwin Possible increase in fault slip rate at Parkfield in 1993 as inferred from deformation measurements from 1986 to 1997 *Seis. Res. Lett*. v69(2), p 151, 1998

Gladwin, M.T., R.L. Gwyther, R.H. Hart & M.Mee Optimising Earthquake Science from Borehole Strain: New Instruments are not the Issue. *EOS. (Trans. Am. Geo. Un.)* 79(45) p F195, 1998

Gwyther R.L., M.T. Gladwin, R.H. Hart & M.Mee Aseismic and Seismic Observations of the 12th August 1998 San Juan Bautista, California M 5.3 Earthquake *EOS. (Trans. Am. Geo. Un.)* 79(45) , p F606,1998

Johnston M.J.S., A. Linde, R. Gwyther & M.T. Gladwin Review of Aseismic Strain Events (Slow Earthquakes) on the San Andreas Fault System and the Long Valley Volcanic Region *EOS. (Trans. Am. Geo. Un.)* 79(45) , p F600,1998.

Linde A.T., I.S. Sacks, M.T. Gladwin, M.J.S. Johnston & P. G. Silver Slow Earthquakes at Plate Boundaries - a Connection with Large Earthquakes *EOS. (Trans. Am. Geo. Un.)* 79(45) , p F600,1998

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

Selected Previous Journal Publications

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.

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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.

Johnston, M.J.S., Linde, A.T. and Gladwin, M.T.(1990) Near-Field High Resolution Strain Measurements Prior to the October 18, 1989, Loma Prieta ML 7.1 Earthquake. *Geophysical Res. Let.* Vol 17 No.10 pp 1777-1780.

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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. .

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Non-Technical Summary

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