THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989:
EARTHQUAKE OCCURRENCE

PRESEISMIC OBSERVATIONS

A SHEAR-STRAIN PRECURSOR

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ABSTRACT

The earthquake provided unique near-field borehole tensor strain observations. Medium-term data from a strainmeter installed at San Juan Bautista, Calif., showed a clear anomalous change in fault-parallel shear strain rate beginning about 1 year before the earthquake. The anomaly ultimately reached 30 percent of the coseismic offset. The signal resembles some of the changes in strain rates reported from the geodetic record and nearby creep anomalies, suggesting a broad regional anomaly. The limited spatial sampling available, however, prevents determination of a causal link useful for prediction between these data and the earthquake.

INTRODUCTION

Measurements of earth strain within several source dimensions of an earthquake in the years before the event should yield information about the processes of strain accumulation and concentration leading to failure, and may contribute to specific prediction of earthquakes.

Because the expected strain rates are about 1 microstrain/yr or less, strain data are potentially contaminated by spurious signals from ground-coupling problems and nontectonic effects from thermal, ground-water, or cultural sources (Agnew, 1986). Early near-surface point measurements provided little useful insight. Significant improvements in signal quality and stability, however, have been achieved with the deployment of borehole strainmeters at depths of about 200 m. Quality borehole strain data have been obtained at such depths in Japan for nearly 20 years (Sacks and others, 1971). Instruments provide almost continuous data at sensitivities more than 1,000 times greater than those of quality geodetic networks and, depending on the borehole depth and the complexity of local geology, operate in a relatively noise free environment. Limitations on the data focus on the representativeness of the small sample of rock surrounding the instrument, and on the reliability of the coupling of the instrument to the rock mass; measurements indicate that performance is not limited by the intrinsic sensitivity or stability of the instrument package itself (Agnew, 1986; Gladwin and others, 1987). The borehole tensor strainmeter used here (Gladwin, 1984) measures both hydrostatic and shear strain in the ground with subnanostrain resolution and a long-term stability better than 100 nanostrain/yr (Gladwin and others, 1987). These stability figures are also evident in the present data.

Two borehole instruments (a Sacks-Evertson dilatometer and a Gladwin tensor strainmeter) were operating in the region of the San Andreas fault at the time of the earthquake. High-resolution recordings were made on each of these instruments before, during, and after the earthquake (Johnston and others, 1990). The tensor strainmeter installed at San Juan Bautista, Calif., was located 40 km southeast of the epicenter and within about 10 km of the southward extent of the rupture zone (fig. 1). The data obtained during the 4-year period before the earthquake provide a rare opportunity to observe local strain processes before a large earthquake. Data from the 2-year period after the earthquake also show significant signals, as discussed in other chapters of this report.

DATA AND PROCESSING

The San Juan Bautista strainmeter was installed in late September 1983 at a depth of 150 m, using an expansive grout. Day averages for the three components of the strainmeter are plotted in figure 2. Immediate postinstallation observations are dominated by grout compression of the instrument and by thermally controlled decay as the instrument site reestablished equilibrium with its surroundings. The installation was immediately after drilling, and so this grout curing was then followed by an exponential recovery of the virgin stress field relieved during the drilling process.

Exponential signals are irrelevant to the monitoring of strain changes that may be occurring in the region, and so they were removed from the raw data by a least-squares analysis to produce the residual component data used in subsequent strain analysis. Residuals for the three gauge components from July 1986 are plotted in figure 3; no smoothing has been applied.

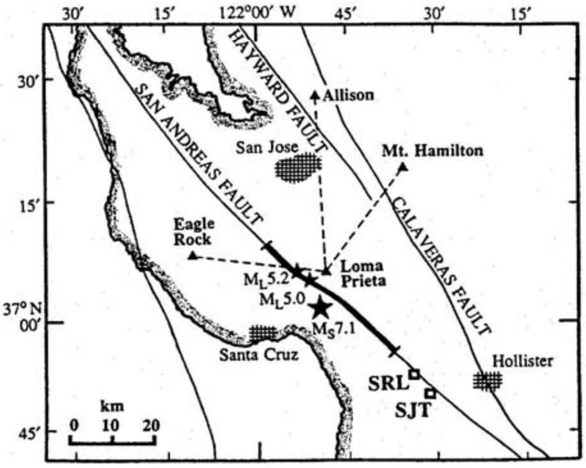

Figure 1.—Loma Prieta region, Calif., showing locations of major faults (solid lines), geodetic stations (triangles), and borehole strainmeter sites (squares): SJT, Gladwin tensor strainmeter; SRL, Sacks-Evertson dilatometer. Heavy line, Loma Prieta rupture zone; dashed lines, relevant geodetic lines; stars, epicenters of main shock (large) and two Lake Elsman foreshocks (small).

The residuals thus produced are sensitive to details of the exponential removal procedure. To obtain meaningful residuals in the present context of a search for possible precursory signals, regions of data that are contaminated by obvious nonexponential processes or are themselves involved in the time window of the precursors to be identified must be excluded from the analysis. Disturbances of the record associated with the Morgan Hill, Calif., earthquake of April 24, 1984, and experiments at the site resulting in large transients due to downhole heating necessitated exclusion of the data from April 1984 to mid-1986. All the data after March 1988, which might relate to the change in gradient evident on the raw records, were also excluded. The same regions were excluded for all components.

A wide range of data windows were investigated to verify that the strain-rate change was not an artifact of the detrending procedure. The onset and characteristics of the linear-strain-rate anomaly was always evident even if the window was extended into 1989. The exponentials determined are plotted (offset for better visibility) in figure 2. These exponential processes are to be expected from all standard rheologic models. The remarkable flatness of the residuals before mid-1988 indicates that the determined exponentials adequately describe the long-term recovery

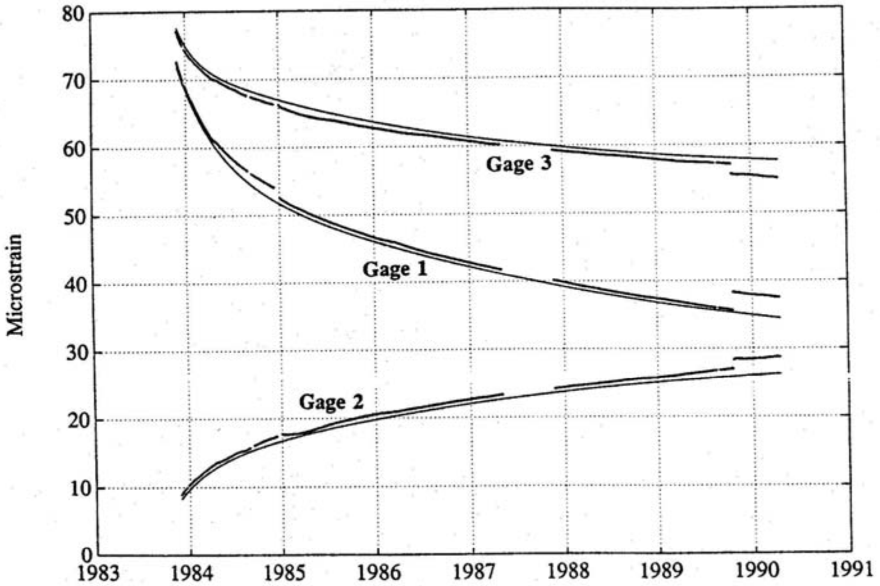

Figure 2.—Three-component raw strain data from San Juan Bautista strainmeter site. Measurements are simple day averages expressed in nominal microstrain measured within instrument. Fitted exponentials are also shown, offset for clarity. Instrument was nonoperational for several months in 1987.

of the hole. The measured grout-curing exponential time constants range from about 90 to 110 days, and the hole-recovery exponentials from about 800 to 1,000 days.

These residuals are combined to produce shear and areal strains, which are scaled by hole-coupling parameters to account for the areal- and shear-strain response of the instrument inclusion (Gladwin and Hart, 1985). These parameters are determined by a calibration procedure involving, for each gage, a comparison of individual tidal components of the theoretical earth-tidal strains (corrected for ocean loading) with tidal components of the strains observed on the instrument. The procedure by which individual channels are tidally calibrated is described in detail by Hart and others (in press).

The resulting areal- and shear-strain records are plotted in figure 4. These records completely specify the strain field in the horizontal plane defined with the *x*-axis east and the *y*-axis north, where γ_1 and γ_2 are shears with the maximum shear across northwest-southeast or northeast-southwest and north-south or east-west planes, respectively; they are related to the tensor strain components e_{ij} by the relations $e_a=e_{xx}+e_{yy}$, $\gamma_1=e_{xx}-e_{yy}$, and $\gamma_2=2e_{xy}$. The convention of extension positive is used. To facilitate comparison of our data with geodetic records in the region, we have chosen to use engineering strains here rather than the tensor definitions used in our previous publications. For areal strain, we use the symbol e_a rather than Δ (areal dilatation) of Prescott and others (1979), because Δ commonly refers to volumetric dilatation. No other processing or filtering has been applied to these records. The data show a negligible response to rainfall, and we have conducted no hydrologic studies of the region.

DISCUSSION

The coseismic areal-strain step seen in figure 4 is +2,140 nanostrain, γ_1=+1,840 nanostrain, and γ_2=−3,790 nanostrain. Strain axes on this figure differ from those previously reported by Johnston and others (1990), which were in non-engineering units and were derived without the gage-specific calibration procedure used here. As noted by Johnston and others (1990), dislocation models based on large-scale geodetic data appear to be inappropriate for the southeast end of the rupture zone and do not at this stage predict the coseismic areal-strain steps for both Searle Road and San Juan Bautista, which recorded comparable expansions. No short-term (seconds to days) precursory signals are evident in the records (Johnston and others, 1990).

Apart from the coseismic step, these records are notable for their overall stability. The areal strain, for example, is constant at the 50-nanostrain level from 1986 to early 1989. Investigation of the instrumental response to the M_2 and O_1 tidal components indicates that coupling conditions have not changed significantly since 1986.

The most significant feature in the records is the onset of a strain-rate change in γ_1 strain clearly identifiable over

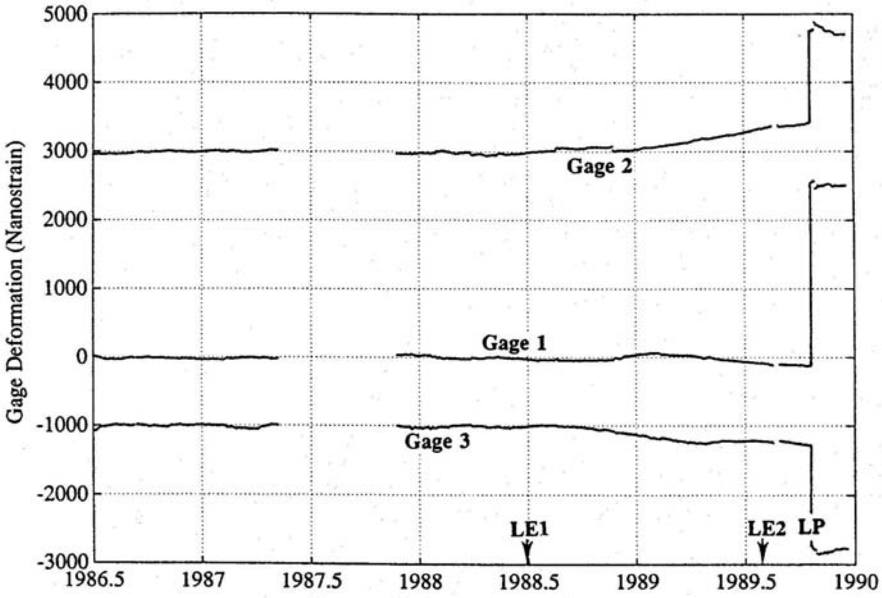

Figure 3.—Three-component residuals of strain data from San Juan Bautista strainmeter after removal of exponentials; data after March 1988 were excluded from fit. Change of slope evident on all components represents nearly 20 percent of coseismic amplitude for gage 3, 25 percent for gage 2, and less than 10 percent for gage 1. LE1 and LE2, times of two Lake Elsman foreshocks; LP, time of Loma Prieta main shock.

3 months in late 1988. A steady additional strain-rate change of 1,140 nanostrain/yr was established, ultimately accumulating more than 30 percent of the coseismic step. Because the e_a component is essentially constant, this change in the strain field is predominantly a shear. Furthermore, γ_1 is the dominant shear, and so the maximum shear is approximately parallel to the San Andreas fault (striking N. 50° W. here), consistent with increased shear stress across the fault in the direction of subsequent failure. The data imply a strain-rate change of approximately 370 nanostrain of compression per year for the e_{yy} component and, during the early part of 1989, of approximately 570 nanostrain of extension for the e_{xx} component.

In fact, this anomaly ceased immediately after the earthquake, and a new and higher rate of fault-parallel shear accumulation was established about 4 months later and has continued for at least 18 months. These data (Gwyther and others, 1992) are discussed in other chapters of this report.

The power spectrum for the 3 years of areal-strain data plotted in figure 5 provides a reasonable estimate of the lowest anomalous signal detectable within any period range. Integration of the spectrum over the period band above 3 months indicates a standard deviation of approximately 20 nanostrain for assumed-stationary data. This same standard deviation would be produced by a single 3-month-duration ramp excursion of 100-nanostrain amplitude at an arbitrary point in our 34-month record. A signal excursion similar to our anomaly can thus be identified as anomalous if it exceeds approximately 100 nanostrain in 3 months. By this criterion, the γ_1 strain record was identifiably anomalous by November 1988, almost a year before the earthquake (fig. 6).

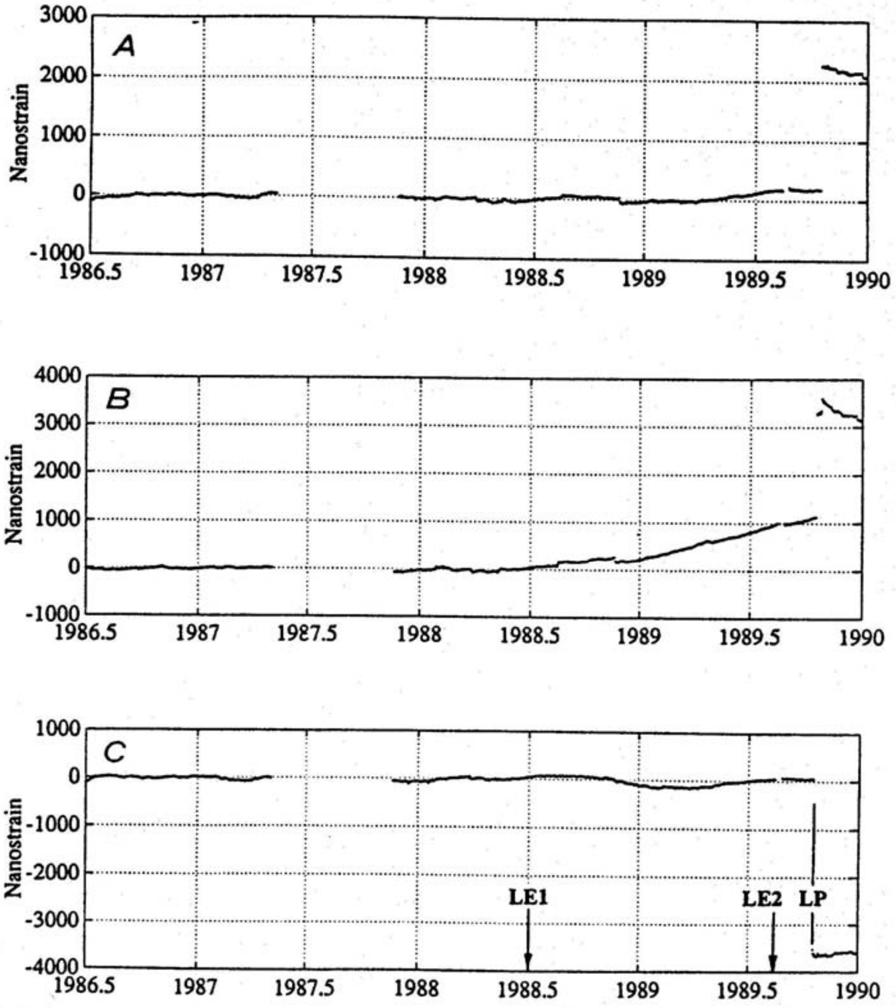

Figure 4.—Reduced areal and shear strains derived from residuals in figure 3. *A*, Areal strain. *B*, γ_1 strain. *C*, γ_2 strain. Data have been calibrated and corrected for borehole amplification effects. LE1 and LE2, times of two Lake Elsman foreshocks; LP, time of Loma Prieta main shock.

As shown in figure 1, the area to the north of the epicenter is covered by a geodetic network of three lines radiating from Loma Prieta to Allison, Mount Hamilton, and Eagle Rock (Lisowski and others, 1990a, b). Lisowski and others reported a marginally significant change in gradient for the Allison and Mount Hamilton lines after the June 1988 Lake Elsman "foreshock." The least-squares-determined change in gradient of the Allison line (−15.1+/−2.6 mm/yr) appears to be better defined than for the Hamilton line (−8.1+/−2.2 mm/yr). Lower rates are suggested by Global Positioning Satellite (GPS) data for the Allison line. The dominant effect is on the Allison line, which runs nearly north-south

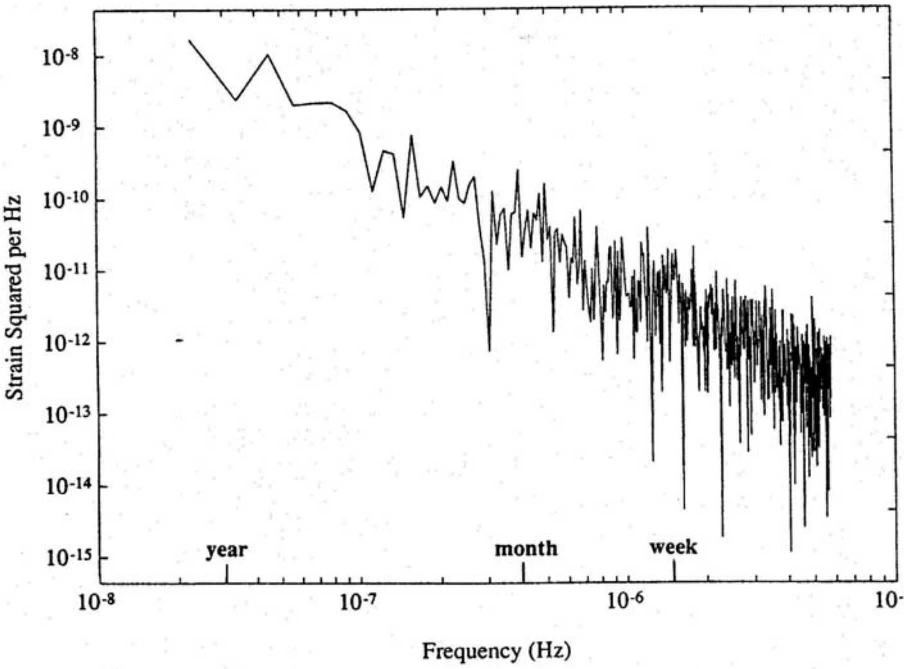

Figure 5.—Power spectrum for 1,024 days of areal-strain data beginning approximately 1986.5.

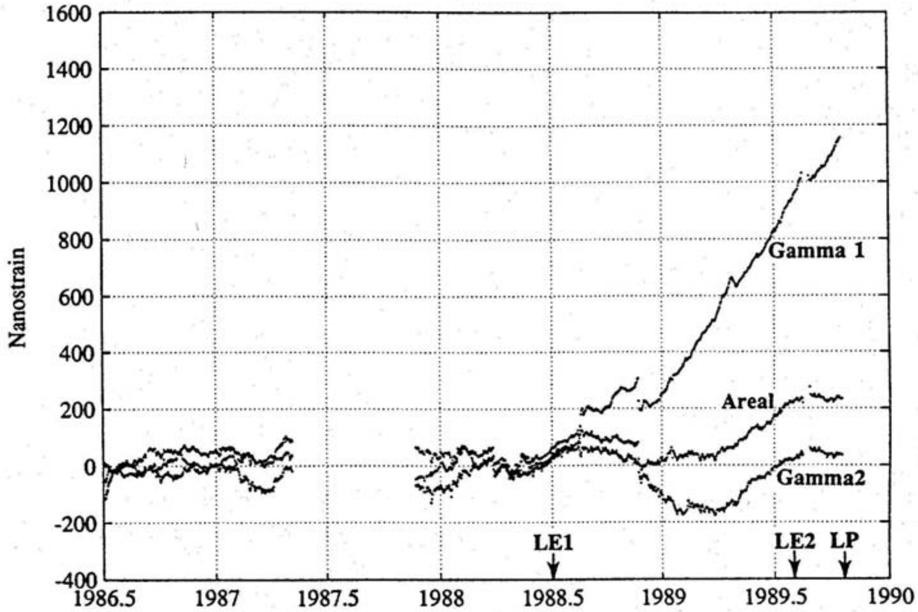

Figure 6.—Areal- and shear-strain data for 3½-year period before Loma Prieta earthquake. LE1 and LE2, times of two Lake Elsman foreshocks; LP, time of Loma Prieta main shock.

and measures the integral of the e_{yy} component along its length. Geodetic data show an increased compressional rate through 1989 equivalent to 300 nanostrain/yr averaged over the line, comparable to the borehole measurement. The Mount Hamilton data indicate an average compressional strain rate of approximately 250 nanostrain/yr, in comparison with the implied value of 180 nanostrain/yr from borehole data for the period mid-1988 to March 1989.

As noted above, our data imply an extension of 570 nanostrain in the e_{xx} component, which would be expected to show on the Loma Prieta-to-Eagle Rock line. No such extension is evident, however, in the geodetic data for this interval, although the GPS data appear to indicate an extension possibly as large as 650 nanostrain/yr over the same interval.

The similarity in the timing and possible magnitude of the borehole data to the change of gradient in mid-1988 of the geodetic measurements may be only coincidental. However there is also some indication of a regional creep anomaly during the 2-year period before the earthquake in the data from several creepmeters within 20 km of San Juan Bautista (Gwyther and others, 1992). Burford (1988) noted creep retardation before moderate earthquakes in adjacent regions. These creep data provide further support for a regional preearthquake strain anomaly, at least in the San Juan Bautista area, independent of the geodetic data.

Although other models are not excluded, the data could imply a regional increase in shear-strain rate acting to increase shear stress across the fault in the direction of failure approximately 1 year before the earthquake. This increase is remarkably linear and shows no evidence of accelerating failure. With such sparse coverage of the region, however, the temptation to identify this anomaly as a precursor must be resisted.

CONCLUSIONS

A well-established change in shear-strain rate was observed at the San Juan Bautista tensor strainmeter site almost a year before the earthquake, with an ultimate amplitude of more than 30 percent of the final coseismic event. Together with geodetic data, this observation may indicate a regional loading of the fault in a direction consistent with final failure. No causal link to the event can be established, however, because of inadequate spatial sampling.

Although the anomaly may have been caused by a source in the immediate vicinity of the instrument, the similarity in amplitude, sense of shear, and time signature to the geodetic observations argue for a regional strain disturbance. Anomalous strain changes reported at the Searle Road dilatometer (Johnston and others, 1990) may also confirm this conclusion, although no compatible areal-strain effects are evident in our data.

The characteristics of the anomaly are not well described by any current theoretical precursor modeling studies, which predict short-term tertiary-creep phenomena. This anomaly is better described as indicating a process of regional stress concentration caused by a localized departure from the regional tectonic strain rates as determined by geodetic studies. A similar anomaly was reported (Wyss and others, 1990) for the active section of the San Andreas fault at Parkfield, Calif.

Immediately after the earthquake, the strain rate returned for about 10 days to its value before the anomaly (that is, mid-1988), then decreased for 2 months. By May 1990, after the Chittenden, Calif., aftershock sequence, a new and higher rate of shear strain accumulation had been established. These data, together with associated creep anomalies, are discussed in other chapters of this report.

As a case study, this observation strongly underlines the need to deploy adequate-size arrays of strain instruments, the importance of measuring the total strain field at each site rather than single components, and the importance and interdependence of short-baseline, high-resolution data and the absolute long-baseline data provided in this case by the geodetic array. Our results demonstrate that minimal processing of borehole data to remove borehole-equilibration processes produces residuals with a stability adequate for short- to intermediate-term tectonic monitoring relevant to precursor studies. In this context, the observations reported here are the only objective pointer to performance expectations for a future array of borehole strainmeters.

ACKNOWLEDGMENTS

This research was supported by U.S. Geological Survey grants 14–08–0001–G1190 and 14–08–0001–G1376. The instruments were previously developed under awards from the Australian Research Grants Scheme and fabricated by R. Willoughby and staff in house. We thank J. Healy, M. Francis, R. Mueller, and R. Liechti for installation and maintenance support, K. Breckenridge for data retrieval, and A.T. Linde and M.J.S. Johnston for their extensive support and cooperation in the program.

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