Rate Change Observed at JPLM after the Northridge Earthquake

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Abstract. Geodetic time series determined with the Global Positioning System indicate that the geodetic rate of a permanent site in Pasadena, California [JPLM] changed significantly after the 17 January 1994 Northridge California earthquake. Subtracting the pre-quake rate and Lx-seismic offset leaves 303 4 mm of integrated eastward excess motion observed in the three years following the cart hquake. North and vertical components show excess motion of -1 1 ± 3 mm and 2 5 ± 1 1 mm respectively. Local surveys to three additional points near JPLM changed by no more than 6 mm E, 3 mm N, and 15 mm V during the two years after the earthquake, ruling out the possibility of a local effect at the JPLM monument. The direction and size of the post-seismic displacements at JPLM are not consistent with additional slip on the fault which ruptured. The most rapid accumulation of excess motion occurs immediately after the earthquake, suggesting a relationship between the two events.

Introduction

The Global Positioning System [GPS] has been instrumental for studies of the 17 January 1994 Northridge earthquake [M_W 6.7], which took place in a region of high geodetic strain accumulation in the Ventura Basin [Donnellan et al. 1993]. Episodic GPS measurements made in the month following the earthquake were used to compute the co-seismic displacement field [*Hudnut et al.*, 1996]. While data from infrequent site occupations has tended to dominate the early history of crustal deformation studies using GPS, continuously operating sites have begun to play an increasingly important role as demonstrated for the 1992 Landers earthquake [*Blewitt et al.*, 1993; *Bock et al.*, 1993; *Savage and Svarc*, 1997; *Wdowinski*, 1997]. Continuous GPS measurements can detect slow post-seismic motions which have a period too long to be observed by seismometers. Annual or semi-:lt)nual sampling is too sparse to properly characterize such events. Data from permanent sites in Pasadena [JPLM] and Goldstone, California [GOLD] collected since 1991 provide evidence for significant post-seismic motion after the Northridge earthquake.

Analysis

Results for this paper were obtained with the GIPSY/OASIS 1 1 software developed at the Jet Propulsion Laboratory, California Institute of Technology [*Webb and Zumberge*, 1995]. Positions, velocities, and time series for JPLM and GOLD were derived as part of a larger solution based on nearly 1 ()(),()()() station-days of GPS data from 180 sites [http://sideshow.jpl.nasa.gov/mbh/series.html]. All daily solutions were computed using a no-fiducial strategy [*Heflin et al.*, 1 992] and point positioning was implemented starting September 1, 1995 [*Zumberge et al.*, 1996]. Daily solutions were combined using the full covariance information available on each day. The global combination, of which JPLM and GOLD are a part, has been tested for stability by rigorous comparison with the NUVEL-1A plate motion model and observations from Vet-y 1 ong Baseline interferometry, proving the ability 01 GPS to measure Earth's tectonic plate motion al an accuracy of about 2 mm/yr [*Argus and Heflin*, 1 995]. Most sites were modeled with a single position and velocity, but GOLD and JPLM were modeled as piece-wi sc linear with resets of position and velocity at both the 1992 June 28 Landers and 1994 January 17 Northridge earthquakes. Data from GOLD and JPLM were nearly continuous with only two gaps between 1991 and 1997. The first gap falls between a two month demonstration in 1991 and the onset of daily global analysis in June of 1992. The second gap was caused by implementation of Anti-Spoofing [AS] by the Department of Defense in 1994. Historical data from other sites was not continuous and is summarized in the analysis of Shen c1 al. [1996].

Results and Interpretation

Time set-ics for the 179 km GOLDJPLM baseline are illustrated in Figure 1. The rate observed between the time of the Landers and Northridge earthquakes has been subtracted from each plot. Co-seismic displacements from both the 2 8 June 1992 Landers and the 17 January 1994 Northridge earthquakes are present in the residual time series, along with a significant post-seismic signal after Northridge. Both linear and logarithmic models were used in an attempt to quantify the time-dependent nature of the observed deformation. The logarithmic fit, $y = \alpha * \ln[\beta * t + 1]$, predicts motion accumulating approximately linearly with log time [*Marone et al.*, 1991]. The values of χ^2 provided by linear and logarithmic fits to the cast baseline component are 147.33 and 146.59 respectively. The best fit value of β is 1.7 ± ().4 inverse years. The most recent six months of data suggest that the rate is returning to its pre-quake value In order to provide a model-independent measure of post-seismic displacement, integrated excess motion was derived by subtracting estimates of the pre-quake velocity and co-seismic offset from each baseline component and averaging over the last 1 80 days of data. The observed excess is 30 ± 4 mm E, 11 ± 3 mm N, and 25 ± 11 mm V over a period of roughly three year.. Results are summarized in '1'able 1. One sigma errors at-c reported for the prc-quake rate, two sigma errors arc given for the co-seismic offsets, and the WRMS scatter of the last 1 80 days is reported for the error of the integrated excess. Since the observed post-seismic transient commences at the time of the Northridge earthquake and since the implications of (his motion may be

significant, we now critically assess various possible causes and error sources.

Local effects such as a slumping of the hillside m settling of the concrete monument on w hich the GPS antenna is mounted could could cause transient motion without invoking any tectonic movement, Wc tested this hypothesis by processing three local surveys. Measurements taken before and after the earth quake indicate than none of the local surveys changed try more than 6 mm E, 2 mm N, and 15 mm V, ruling out the possibility of local deformation at the JPLM monument. One sigma error bars are reported for all GPS ties. Conventional ties derived in 1986 have larger reported errors as expected. Survey results are summarized in Table 2. In addition, the vertical motion at JPLM was upward after the earthquake, ruling out the possibility of subsidence. Wc attempted to quantify the spatial extent of [his transient by comparing the current velocities of additional sites with pre-Northbridge velocities determined from historical measurements. Together, the local surveys and near hy sites provide lower and upper limits on the spatial extent of deformation, which arc 376 m and 20 km respectively.

Having excluded the most likely error sources and local effects, we now consider tectonic explanations. Posl-seismic displacements have beer] observed after many earthquakes. VLBI stations located near the 1987 and 1988 Gulf of Alaska earthquakes and near the 1989 Loma Prieta earthquake show pos(-seismic transients on the order of 10% of the co-seismic signal [*A rgus and Lyzenga,* 1994]. Similar ratios of post-seismic to co-seismic displacement were observed for the great 1960 Chilean earthquake [*Barrientos et al.,* 1992] and after the 1992 Landers earthquake [*e. g. Savage and Svarc,* 1997; *Wdowinski,* 1997]. Higher ratios of 400%" and 40% were observed in Japan after the 1992 [*Kawasaki c/ al.,* 1995] and 1994 [*Webb et al.,* 1997] Sanriku earthquakes respectively, but these displacements took place over a period of several days rather than several years, A ratio of' roughly 100% was observed in the months following the 1994 Sanriku earthquake which was consistent with afterslip on the main rupture plain [*Heki et all* 1997],

The ratio of post-seismic to co-seismic displacement is roughly 300% for the east component at JPLM. The lack of such large pos[.seismic displacements at PSEB, WORK, WLSN, and UCLP rules out an explanation based on afterslip on the Norhtridge rupture plane and suggests deformation of a structure located considerably nearer to JPL. The anomalous eastward motion can be explained by oblique slip on an east-west trending thrust fault it' JPLM is located near the edge of this proposed fault. Aftershocks located to the east of the Northridge rupture show predominantly thrust mechanisms [e.g. *Mori et al.,* 1995; *Hauksson et al.*]. The south-dipping Northridge rupture plane abuts and is truncated by the north-dipping 1971 San Fernando earthquake plane al a depth of about 5 km [*Mori et al.,* 1995; *Hauksson et al.,* 1995]. The 20 km long surface rupture of the 1971 earthquake is located just to the cast of the Northridge rupture. The locations of GPS sites and fault planes arc illustrated in Figure 3. Since JPLM is located directly on the escarpment of the north-dipping Sierra Madre thfList fault system, we hypothesize that triggered aseismic slip may have occurred following the Northridge earthquake.

In order to identify possible tectonic sources of the observed motions, elastic dislocation inversions were performed. The method used approximates the Earth as a uniform elastic halt'-spacc, employing the rectangular dislocation formulae derived by Okada [1985]. Inversion for the best-fltling fault was accomplished using an adaptation of the downhill simplex simulated annealing algorithm discussed by Press et al. [1988]. The present inversion problem is rather poorly constrained because of the sparseness and non-optimality in the distribution of observations. As a result, broad families of candidate solutions. rather than unique inversions, characterize this study. This means that rather than displaying a pronounced unique minimum, the chi-squared goodness-ol-flt results approach unity over a range which may not be well described by simple Gaussian errors. The best models agree in pointing to a single east-west striking oblique fault, dipping moderately to the north. The required slip is generally shallow in order to confine the observed motion to the immediate JPLM region. However, in the absence of more spatially dense observations, it is difficult to set more than broad bounds on fault parameters. For inversions with residual chi-squared values in the range 1.0 - 1.5, source depths range between 0.5 and 8 km, while slip amplitudes are in the range 1-3 cm, divided roughly evenly between reverse and sinistral motion. The dip lies within 20 degrees of 45 degrees and the lateral dimensions of the fault extend not farther than 20 km from JPLM. Data from all the sites shown in Figure 3 were used, although it is principally the sites with statistically significant residual motion and small formal uncertainty that control the res Lilts, Best-ttt models suggest lcll-lateral thrusting on an cast-west trending structure which dips moderately to the north or south, suggestive of transient motion connected with the San Gabriel mountains frontal fault system.

Conclusions

The hypothesis of significant aseismic slip following the Northridge event on a fault that did not rupture in the earthquake carries with it important implications for both seismic hazard assessment and geodetic measurement strategies. Aseismic slip on fault systems in the greater Los Angeles region may appreciably affect estimates of their activity. Evaluating the extent and frequency of such aseismic movements is important in any attempt to fully characterize the tectonic deformation field. If aseismic events turn out to be common, they may explain the hypothesized earthquake deficits in Southern California [*Dolan et al.*, 1995] and other regions of the world. As this study illustrates, continuous temporal and dense spatial geodetic coverage will be essential. Dense spatial sampling will help 10 identify the sources of strain accumulation, while more frequent temporal sampling will improve the characterization of non-linear time dependence.

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Figure 1. Residual time series for the 179 km GOLDJPLM baseline. The baseline rate observed between the time of the Landers and Northridge earthquakes has been subtracted from each plot. One sigma error bars arc included for each component. Daily repeatability is 3 mm N, 4 mm E, and 1 1 mm V.

Figure 2. Map showing locations of GPS geodetic sites i n relation to earthquake fault planes. Shaded areas i ndicate from west to east the approximate sur face projections of the so uth - dipping 1994 Northridge rupture plane and the 197 1 San Fernando rupture plane. Dotted and dashed lines indicate major faults. light vectors with error ellipses indicate the observed change in mean secular rate. Error ellipses represent 95% con fidence bounds.

Figure 1. Residual time series for the 179 km GOLDJPLM baseline. The basel i nc rate observed between t he li me of the Landers and Northridge earthquakes has been subtracted from each plot. One sigma error bars arc included for each component. Daily repeatability is 3 mm N, 4 mm E, and 11 mm V.

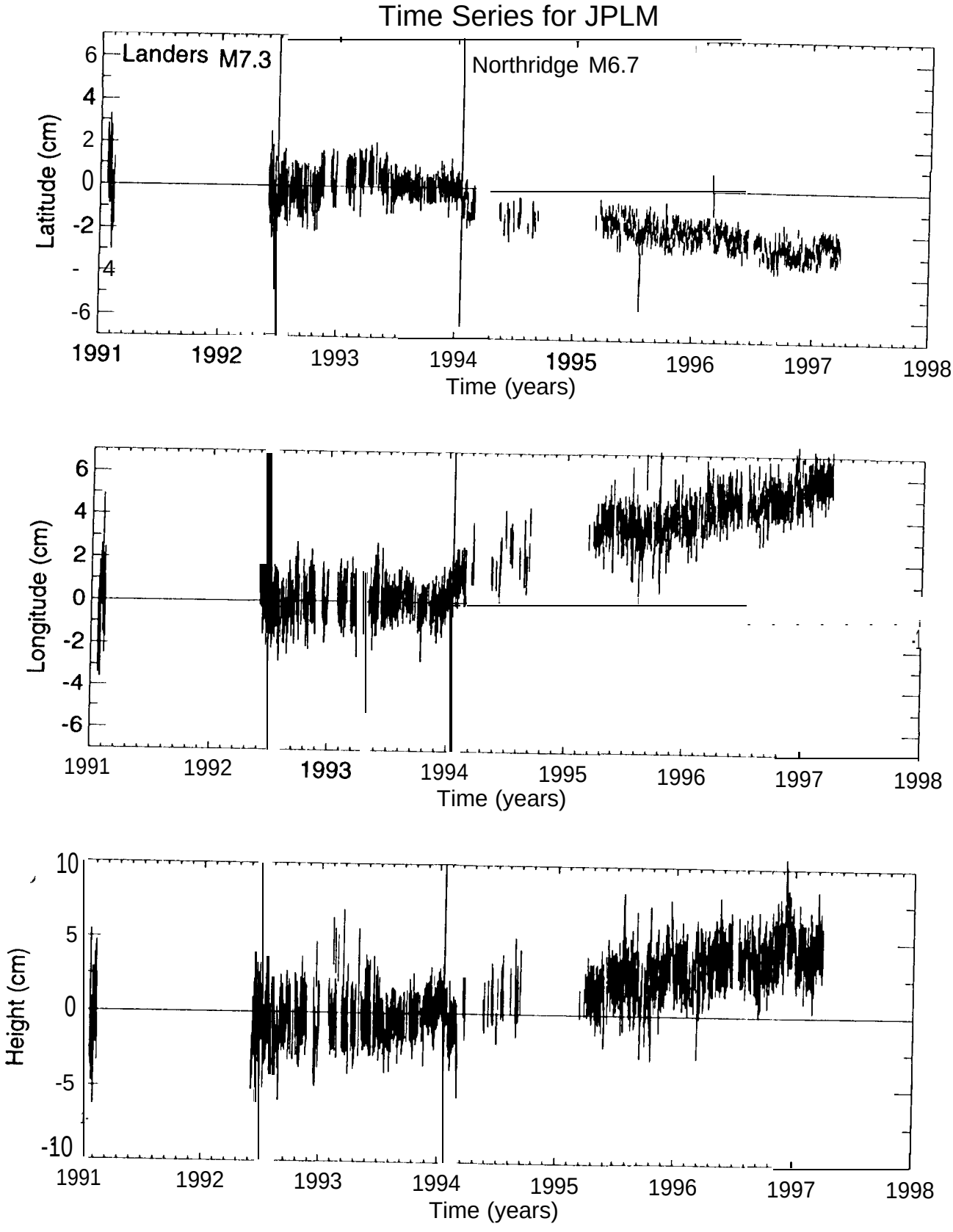
Figure 2. Map showing locations of GPS geodetic sites in relation to earthquake fault planes. Shaded areas indicate from west to east the approximate surface projections of the south-dipping 1994 Northridge rupture plane and the 1971 San Fernando rupture plane, Dotted and dashed lines indicate major faults. Light vectors with error ellipses indicate the observed change in mean secular rate. Error ellipses represent 95% con fidence bounds.

Table 1. Prc-quake rates, cx-seismic offsets, and post-seismic excess computed from the GOLDJPLM baseline.

Component	Pr e-quake Rate [mm/yr]	C()-seismic Offset [mm]	IW-seismic Excess [mm]
North	21 ± 3	-8 ± 1	-11 ± 3
East	-25 ± 3	14 ± 2	30 ± 4
Vertical	-6 ± 7	-2 ± 5	25 ± 11

Table 2. Local surveys before and after the Northridge earthquake.

Component	After [mm]	Date	Before [mm]	Date	Diff [mm]
JPLMJPA2E	87726 +- 3	01/17/97	87722 +-3	09/05/86	4 +-4
JPLMJPA2 N	81382 +-1	01/17/97	81384 +- 3	09/05/86	-2 +- 3
JPLMJPA2 V	17561+- 7	01/17/97	17550 +- 3	09/05/86	11 +- 8
JPLM7263 E	-10279 +-3	01/17/97	-10280 +- 3	09/05/s6	1+- 4
JPLM7263 N	26665 +- 1	01/17/97	26662 +- 3	09/05/s6	3 +- 3
JPLM7263 V	6 +- 6	01/17/97	4 +- 3	09/05/86	2+- 7
JPLMLAB3E	-98723 +- 1	11/17/95	-98718 +- 1	11/30/93	-5+- 1
JPLMLAB3 N	-359240 +- 1	11/17/95	-359238 +- 1	11/30/93	-2 +- 1
JPLMLAB3 V	-51223 +- 5	11/17/95	-51208+- 4	1 1/30/93	-15 +- 7


Time Series for JPLM
Landers M7.3
Northridge M6.7
Latitude (cm)
6
4
2
0
-2
-4
-6
1991
1992
1993
1994
1995
1996
1997
1998
Time (years)
Longitude (cm)
6
4
2
0
-2
-4
-6
1991
1992
1993
1994
1995
1996
1997
1998
Time (years)
Height (cm)
10
5
0
-5
-10
1991
1992
1993
1994
1995
1996
1997
1998
Time (years)

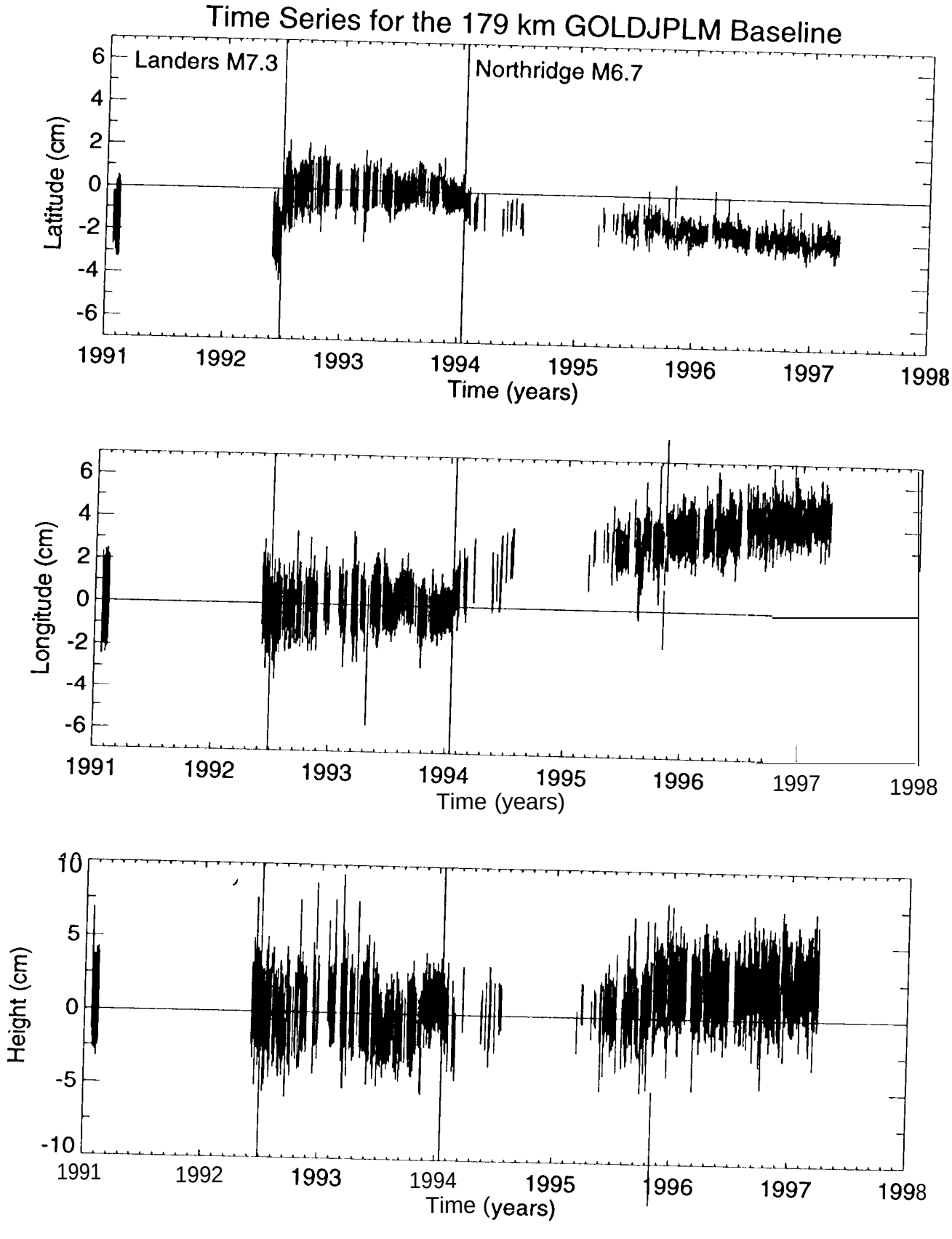
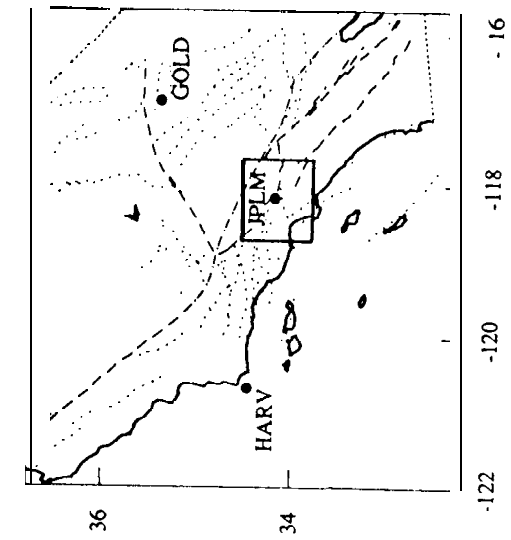

Time Series for the 179 km GOLDJPLM Baseline
Landers M7.3
Northridge M6.7
Latitude (cm)
6
4
2
0
-2
-4
-6
1991
1992
1993
1994
1995
1996
1997
1998
Time (years)
Longitude (cm)
6
4
2
0
-2
-4
-6
1991
1992
1993
1994
1995
1996
1997
1998
Time (years)
Height (cm)
10
5
0
-5
-10
1991
1992
1993
1994
1995
1996
1997
1998
Time (years)

Figure 3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34
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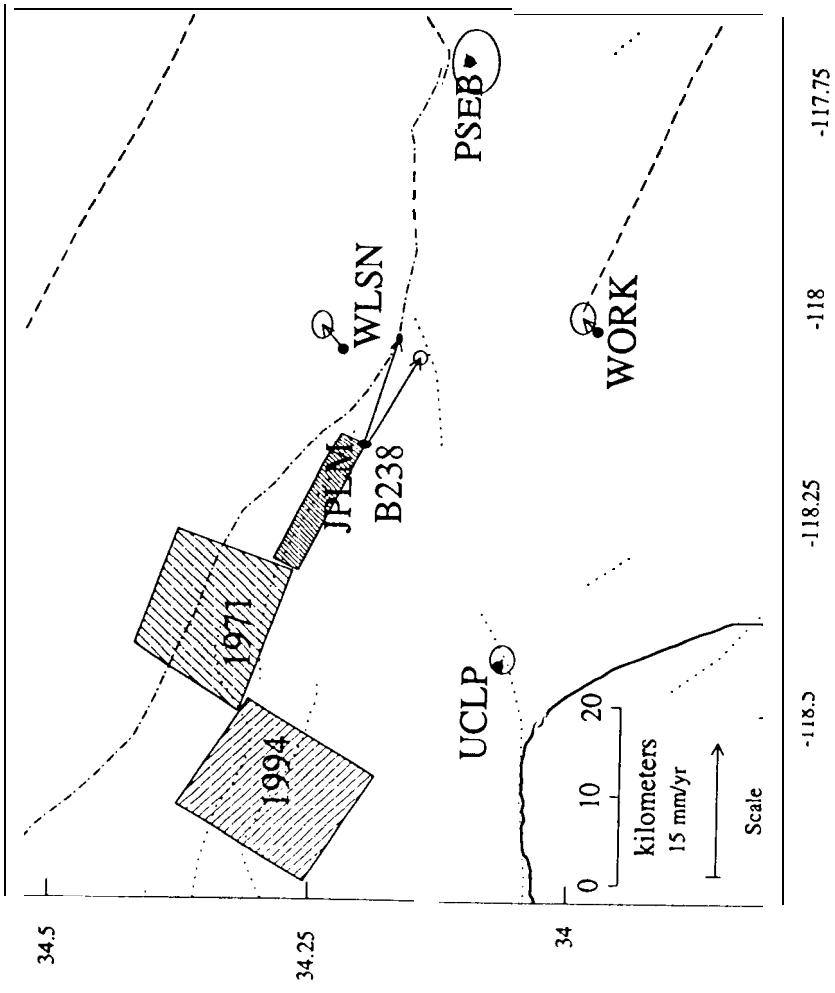
-118
- 16
HARV
GOLD
JPLM


34.5
34.25
34
-118.5
-118.25
-118
-117.75
1994
1971
JPLM
B238
WLSN
PSEB
UCLP
WORK
0
10
20
kilometers
15 mm/yr
Scale