Strain Accumulation in the Shumagin Islands: Results of Initial GPS Measurements

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Abstract. Deformation in the Shumagin seismic gap has been monitored with repeated trilateration (EDM) in the 1980-1987 interval and with the Global Positioning System (GPS) in the 1987-1991 interval. The geodetic network extends for 100-km across the Shumagin Islands to the Alaska Peninsula. Results from the GPS surveys are consistent with those previously reported for the EDM surveys: we failed to detect significant strain accumulation in the N30°W direction of plate convergence. Using the method of simultaneous reduction for position and strain rates, we found the average rate of extension in the direction of plate convergence to be -25±25 nanostrain/yr (nstrain/yr) during the 1987-1991 interval of GPS surveys compared with -20±15 nstrain/yr during the 1981-1987 interval of complete EDM surveys. We found a marginally significant -26±12 nstrain/yr extension rate in the 1981-1991 interval covered by the combined EDM and GPS surveys. Strain rates are higher, but not significantly so, in the part of the network closest to the trench. Spatial variation in the deformation is observed in the 1980-1991 average station velocities, where three of the four stations closest to the trench have an arcward velocity of a few mm/yr. The observed strain rates are an order of magnitude lower than the -200 nstrain/yr rate predicted by dislocation models.

Introduction

The rupture zone of the 13 May 1993 Ms 6.9 earthquake was located in the southern portion of the Shumagin Islands geodetic network (Figure 1). Geodetic surveys in this area before the earthquake include triangulation surveys conducted by the U.S. Coast and Geodetic Survey in 1913 and 1950, biennial trilateration (EDM) surveys conducted by the USGS between 1980 and 1987, and GPS measurements in 1987, 1989, and 1991 at approximately one third of the EDM sites.

Lisowski et al. [1988] and *Savage and Lisowski* [1986] found no significant strain accumulation in the 1980-1987 interval monitored with EDM. The strain rates predicted by dislocation models with the locked part of the main thrust zone extending beneath the Shumagin Islands was an order of magnitude larger than the observed strain rates. They concluded that the absence of strain accumulation is most simply explained by aseismic subduction. This would imply that the probability of a great gap-filling earthquake in the region is small. Other models have been proposed to explain the absence of strain accumulation. *Hudnut and Taber* [1987] suggested that the western two thirds of the Shumagin gap may be different than the eastern third, where the geodetic network is located. This would allow the eastern portion of the Shumagins to be freely slipping, and the western portion locked. Strain rates could also be time-dependent, with the strain accumulation in the period between 1980 and 1987 being anomalously small.

The focus of this paper is to discuss the implications of the 1987, 1989, and 1991 GPS surveys. In particular, we consider the following questions: Are the GPS results consistent with previous EDM results or do they suggest an acceleration? Is there any evidence that strain rates vary with distance from the trench? Is there evidence for strain accumulation in the Shumagins in the decade before the May 13 earthquake?

Paper number 94GL00417
0094-8534/94/94GL-00417$03.00

Measurements

The Shumagin Islands geodetic network is shown in Figure 1. The 7 sites occupied with GPS are Alik, Chernabura, Mount, Sand Point, Simeon, Swede, and Wedge. All of the GPS sites, except Mount and Sand Point, were part of the EDM network. Sand Point has also been measured with Very Long Baseline Interferometry.

EDM surveys determine length only with no ties to an external reference frame. The measurement error in a 20-km-long line (the typical length for the Shumagin network) is about 5 mm (0.3 ppm). GPS resolves both the length and orientation of interstation vectors in a reference frame defined by the GPS orbits. EDM lines are rarely longer than 30 km because of visibility limits. The GPS error spectrum is nearly flat between 10 and 100 km, which is the scale of the Shumagin network. For the horizontal components, the GPS error is ~4 mm + 1 part in 10^8 [*Larson and Agnew*, 1991].

The first GPS experiment was conducted in 1987 at the time of the last EDM survey. Only two GPS receivers were used, and thus all vectors were measured relative to Sand Point. Approximately 4 hours of data were collected at each station. Data from the global GPS tracking network were not available during this experiment, and thus less precise broadcast orbits were used for the 7 satellites that were tracked. In 1989, various 4 station networks were successfully observed over a total of 4 days, with Sand Point observed each of these days. Approximately 7 hours of data were collected at each station. The satellite orbits were improved using global tracking sites. The final GPS observations were made in 1991. By this time, the size of the constellation had increased to 15 satellites, and the global tracking network had expanded. Interstation vector estimates from 1991 are based on observations spanning 24 hours at each station.

The GPS data were analyzed with the Gipsy software developed by the Jet Propulsion Laboratory [*Lichten and Border*, 1987]. The global tracking network coordinates were defined by Goddard VLBI coordinate solution GLB 753 [C. Ma, personal communication]. In each experiment, the position of Sand Point was held fixed to maintain a consistent reference frame at each epoch. Other specifics of GPS data analysis using Gipsy are described by *Larson and Agnew* [1991].

GPS Results

The horizontal and vertical components of the interstation vectors and linear rates of change with time are shown in Figure 2. The scatter in vertical components are consistent with the expected precision, with a RMS scatter ranging from 9 mm (Sand Point to Swede) to 22 mm (Sand Point-Mount). As evidenced by the large standard deviations, the vectors measured in 1987 are less precise than those measured 1989 and 1991. This is particularly true for the longer lines, such as Sand Point-Simeon and Sand Point-Chernabura. At baseline lengths of 82 and 92 km, respectively, the broadcast orbits in 1987 are not sufficiently accurate to determine the interstation vectors with sub-centimeter precision.

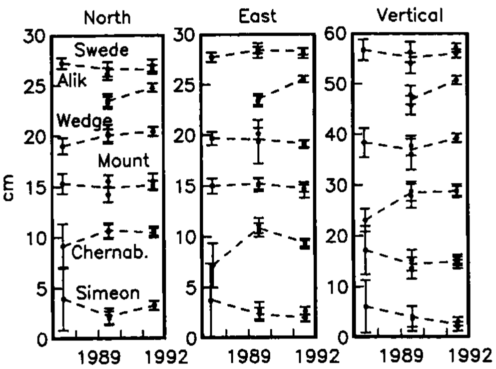

Figure 2. North, east, and vertical components of interstation vectors between Sand Point and Swede, Alik, Wedge, Mount, Chernabura, and Simeon. Errors shown are standard deviations. The weighted linear fit to the data is shown as a dotted line.

For the 6 interstation vectors shown, significant deformation at the one standard deviation level is observed for Sand Point-Alik, Sand Point-Simeon, and the east component of Sand Point-Chernabura. We have no geophysical explanation for the deformation between Alik and Sand Point. The EDM observations between 1980 and 1987 found no significant deformation between Alik and adjacent sites. Unfortunately, the 1987 GPS occupation was not successful, so there are only two observations of the Sand Point-Alik baseline. An independent analysis of these GPS data with the Bernese software found equivalent displacements for Alik [J. Svarc, personal communication]. The displacement of Simeon relative to Sand Point, 5.8±2.8 mm/yr at N48±23°W, is consistent in sign and magnitude with velocity determinations for Simeon using EDM data only [*Lisowski et al.*, 1988]. The linear fit to the east component for Chernabura is very poor, which we attribute to degraded orbits in the 1987 experiment.

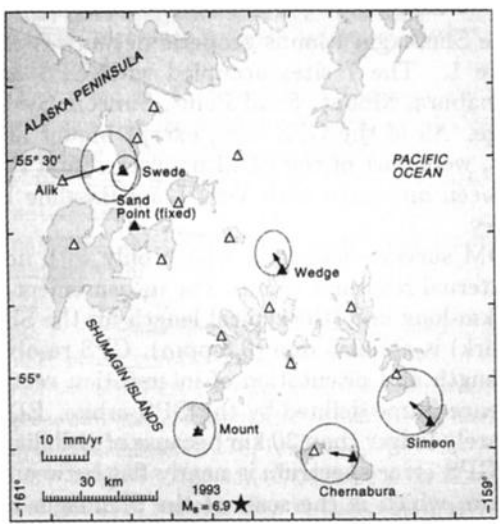

Figure 1. Shumagin Island geodetic network. GPS and EDM points are closed and open triangles, respectively. Station velocities relative to Sand Point derived from the GPS measurements between 1987 and 1991 and 95% confidence limits are shown. Approximate location of the 13 May 1993 earthquake is also shown.

Discussion

We use the GPS data from Shumagin network to determine relative site velocities and strain accumulation rates for the 1987-1991 interval. The strain rates are compared with those calculated using the 1981 to 1987 EDM data. Finally, we combine the data to obtain average strain rates and velocities. GPS station velocities shown in Figure 1 follow directly from the linear fits to the baseline components shown in Figure 2. Only the velocity of station Alik is significant at the 95% confidence limit.

We combine the horizontal components of the GPS vector change rates and EDM line length change rates to determine relative station velocities between 1980 and 1991 (Figure 3). The velocities shown are relative to the geographic centroid of the network (calculated using the so called "inner coordinate" solution of *Brunner*

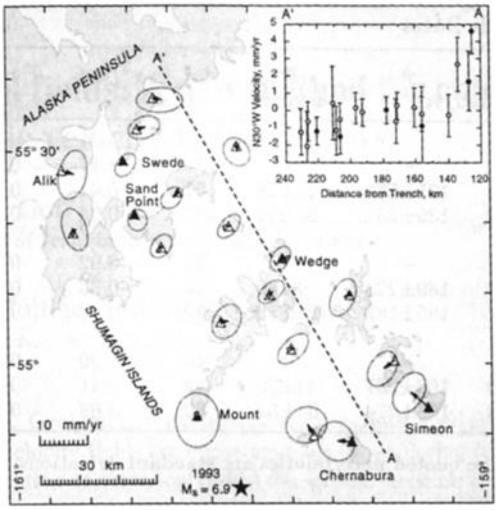

Figure 3. Station velocities for 1980-1991 relative to the centroid of the network. Error ellipses correspond to 95% confidence limits. The inset is a plot of the velocity components in the direction of plate convergence (AA', N30°W) as a function of distance from the trench. Error bars in the inset are 1 sd.

[1979]). In the variation of coordinates adjustment, the 1991 GPS relative position vector from Sand Point to Alik was an outlier, and we deleted it from the data. Otherwise, the data are self-consistent with the residuals from the adjustment being on average smaller than those expected from prior estimates of the data uncertainty. The relative velocities in the direction of plate convergence (N30°W) are plotted as a function of distance from the trench in the inset to Figure 3. The difference of the mean velocities of the four outer Island stations and the four stations on the Alaska Peninsula gives 3.2±2.3 mm/yr of contraction in the direction of plate convergence.

The EDM and GPS data complement one another. Variability of deformation in space is better sampled by the EDM network because there are nearly three times more EDM than GPS stations. Site velocities calculated from the EDM data only, however, are ambiguous because the measurements are internal to the network and rigid-body motions (translation and rotation) of the network as a whole are undetermined. Network rotation is constrained by GPS and the combined solution is uncertain only by a network translation. Since we are interested in deformation across the network, network translation is not important.

Systematic patterns of deformation within the network can be identified by determining strain accumulation rates. We use the DYNAP algorithm [*Drew and Snay*, 1989] to simultaneously calculate the station positions at each epoch and the average rate of strain accumulation between epochs. That is, we allow the positions to change uniformly in time and space with the transformation described by the three components of the surface strain tensor ($\dot{\epsilon}_{11}, \dot{\epsilon}_{12}, \dot{\epsilon}_{22}$), the tilt rate and its direction ($\dot{\tau}$, θ), and the rate of rotation of the network as a whole ($\dot{\Omega}$). We give the components of the surface strain tensor in a coordinate system with the 1-axis directed N60°E and the 2-axis directed N30°W, in the direction of plate convergence. A negative $\dot{\epsilon}_{22}$ corresponds to contraction in the direction of plate convergence.

We determine positions on the WGS 84 ellipsoid and provide corrections from *Rapp et al.* [1991] to convert geoid heights to ellipsoid heights. We were concerned that the 1980 EDM survey, where only 23 of 39 baselines were measured, would bias the strain approximation. Therefore, we omitted all measurements from the 1980 survey.

The results of the strain analysis for the whole network are shown in Table 1. Tilt and rotation are not resolved by the EDM data. Although we estimate rotation and tilt for the GPS and GPS-EDM data, we do not interpret them. The accuracy of the GPS elevations, and thus tilt, is relatively poor. Network rotation could easily be influenced by reference frame errors [*Larson et al.*, 1991]. Nevertheless, the observed rotations are small and are as well resolved as the components of the strain rate tensor. Using GPS data only, the rate of extension in the direction of plate convergence is -25±25 nstrain/yr. During the 1981-1987 interval of the EDM surveys $\dot{\epsilon}_{22}$ = -20±15 nstrain/yr. In the combined EDM-GPS solution $\dot{\epsilon}_{22}$ =-26±12 nstrain/yr. These strain rates are extremely low and are consistent through time. Only the 10-year average rate from the combined solution is marginally significant at the 95% confidence level.

Network strain rates will vary with the location of the locked part of the thrust zone with respect to the geodetic network. Specific dislocation models for the Shumagin Islands were developed and discussed in Table 5 by *Lisowski et al.* [1988]. Depending on the assumptions made, the average strain rate ranges from -170 to -190 nstrain/yr. In the outer Shumagin Islands, predicted strain rates are higher, -260 to -300 nstrain/yr, whereas strain rates across the inner islands will be lower, -130 to -70 nstrain/yr. We have calculated strain rates for both the inner and outer Shumagin Islands. The boundary of the two zones is Nagai Island, where Wedge and Mount are located (Figure 1). The 10-year-average strain rate for the Inner Shumagin Islands is -7±27 nstrain/yr, significantly less than model predictions. The outer Shumagins are more complicated, with the GPS and EDM strain estimates showing great variability. The combined EDM-GPS strain rates show only marginally significant strain in the direction of plate convergence, -40±17 nstrain/yr. This strain rate is 6-7 times smaller than that predicted by the dislocation models.

The data are also consistent within the prior estimates of uncertainty with no change in position through time. We use an F-test to determine whether the reduction in the variance provided by estimating strain rates and positions is significantly better than that for estimating positions only. The F-test probability listed in Table 1 is the probability that the reduction in variance is due to chance. We find that adding the 6 strain parameters to the adjustments reduces the variance at the

Table 1. Average Tensor Strain Rates, Rotation Rates, and Tilt Rates

Network	$\dot{\epsilon}_{11}$	$\dot{\epsilon}_{12}$ nstrain/yr	$\dot{\epsilon}_{22}$	$\dot{\Omega}$	$\dot{\tau}$ nrad/yr	θ^a degrees	dof	χ^2/dof	F test[b]
Whole Network									
EDM, 1981-1987	-20±17	-3±14	-20±15	–	–	–	116	1.17	0.38
GPS, 1987-1991	5±48	51±31	-25±25	-14±29	171±275	49±28	51	0.41	0.03
EDM/GPS, 1981-1991	-38±14	10±11	-26±12	5±19	139±261	50±35	183	0.94	0.03
Inner Shumagins									
EDM, 1981-1987	-15±38	-8±18	13±19	–	–	–	76	0.92	0.85
GPS, 1987-1991	6±54	47±36	-45±35	-28±34	189±223	-9±80	24	0.33	0.55
EDM/GPS, 1981-1991	-8±20	18±14	-7±16	-7±27	189±182	-24±83	112	0.86	0.53
Outer Shumagins									
EDM, 1981-1987	-84±45	0±25	-42±34	–	–	–	40	0.99	0.09
GPS, 1987-1991	9±49	61±33	-16±26	-22±30	166±287	49±30	42	0.41	0.12
EDM/GPS, 1981-1991	-60±17	17±18	-40±17	-2±22	105±274	54±54	89	0.68	0.57

The 1 axis is directed N60°E and the 2 axis is directed N30°W. The quoted uncertainties are standard deviations.
[a]Tilt rate direction, clockwise degrees from North.
[b]Probability that the improvement in variance due to strain estimation could be due to chance.

95% confidence limit (<0.05 F-test probability) for only the whole network GPS and GPS-EDM data sets.

Conclusions

1. The GPS estimates of the average rate of strain accumulation from 1987 through 1991 are in good agreement with rates estimated from trilateration surveys conducted between 1981 and 1987. No significant strain accumulation is measured in either interval, but a marginally significant -26±12 mm/yr rate of extension in the direction of plate convergence is measured over the 10-year interval covered by combined trilateration and GPS surveys. No change in the rate of deformation is apparent through 1991 in the years before the 13 May 1993 Ms 6.9 earthquake.

2. Average strain rates in the outer Shumagin Islands, the part of the network closest to the trench, are not significantly higher than in the inner Shumagin Islands. The analysis of average station velocities, however, shows an arcward velocity of a few mm/yr for three of the four most distant stations. The relative velocity of only one of these stations, Simeon, is significant at a 95% confidence level. The 4.9±1.3 mm/yr at N52±22°W velocity of this station suggests that there may be a locked patch trenchward of the geodetic network.

3. The observed strain accumulation rates are about an order of magnitude lower than those predicted by dislocation models of the subduction zone [*Lisowski et al.*, 1988] that have the locked part of the the main thrust zone extending beneath the outer Shumagin Islands.

Acknowledgments. We thank J. Savage, W. Prescott, K. Wendt, M. Murray J. Svarc, J. Sutton, G. Hamilton, K. Clark, C. Stiffler, J. Beavan and K. Gross for their contributions. K.L. was supported by NAG 5-1908 and EAR-9209385.

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(received September 21, 1993;
accepted December 15, 1993.)