Final Technical Report
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GPS measurement of fault kinematics of the Rodgers Creek-Maacama fault zone

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Abstract

Teams from UC Riverside conducted three field surveys along and around the Rodgers Creek-Maacama fault zone during the summer, fall and winter of 2010–2011. GPS data were collected at 138 distinct sites for an average of approximately 12–18 hours each. We have thus increased the number of GPS velocities available eight-fold compared to the sparse continuous network of Plate Boundary Observatory sites in the region, from around 20 sites to nearly 160, when including reprocessing of previous surveys. We focused in particular on expanding and updating the geodetic (GPS) velocity coverage in the region from San Francisco Bay and San Pablo Bay in the south to Clear Lake and Point Arena in the north, and from the Pacific coast in the west to Lake Berryessa in the east. This covers the coastal San Andreas and Green Valley faults in addition to the main targets, the Rodgers Creek and southern Maacama faults (Figure 1).

1. Introduction

This project aims to address a current gap in our understanding of the tectonics of the northern San Francisco Bay area (hereafter 'North Bay'), which is itself a reflection of a gap in geodetic data coverage. The North Bay contains a fault currently considered the most hazardous in northern California, the Rodgers Creek fault, whose contemporary slip rate, kinematic behavior and relations to contiguous structures to the northwest and southeast are still the subject of much debate and uncertainty. Successes in other areas, particularly in the central San Francisco Bay area, have showed that horizontal geodetic velocity information derived from GPS data, appropriately analyzed, can provide key constraints on these factors. Continuous GPS measurements, such as those of the Plate Boundary Observatory (PBO) network, are sparse in this area, separated by around 15–25 km. Although precision of deformation rates measured at such sites can be 1 mm/yr or better, this inter-site distance is inadequate for the detailed study of fault motions in the region given that the faults themselves are separated by 30–40 km. Therefore, we have undertaken a campaign of GPS observation in the North Bay, designed to densify the existing continuous and campaign data, and targeted at solving specific problems of current interest and improving inputs to future seismic hazard assessments.

1.1 Research targets for the project

Fault slip rates of the Rodgers Creek-Maacama fault zone
Despite ranking as the most dangerous fault in the region, certain key information about the Rodgers Creek fault is still uncertain, foremost its slip rate. A similar situation exists for the southernmost Maacama fault, thought to be a contiguous structure to the northwest. Accurate estimates of slip rates are an important input into seismic hazard forecast models, reflecting the effective loading rate of the fault. A key objective of the project therefore is to place stronger constraints on the slip rates of the two faults, by measuring surface deformation rates at a range of distances from their surface traces.

Testing the inference of shallow creep on the Rodgers Creek fault
InSAR data from the northern Rodgers Creek fault, between Santa Rosa and Healdsburg, show a step in velocities across the fault that is consistent with shallow right-lateral fault creep (Funning et al., 2007). In order to ground-truth these observations, we aim to measure a number of sites close to, and on either side of the fault trace, along the putative creeping segment, including alignment arrays established in order to measure potential creep deformation.

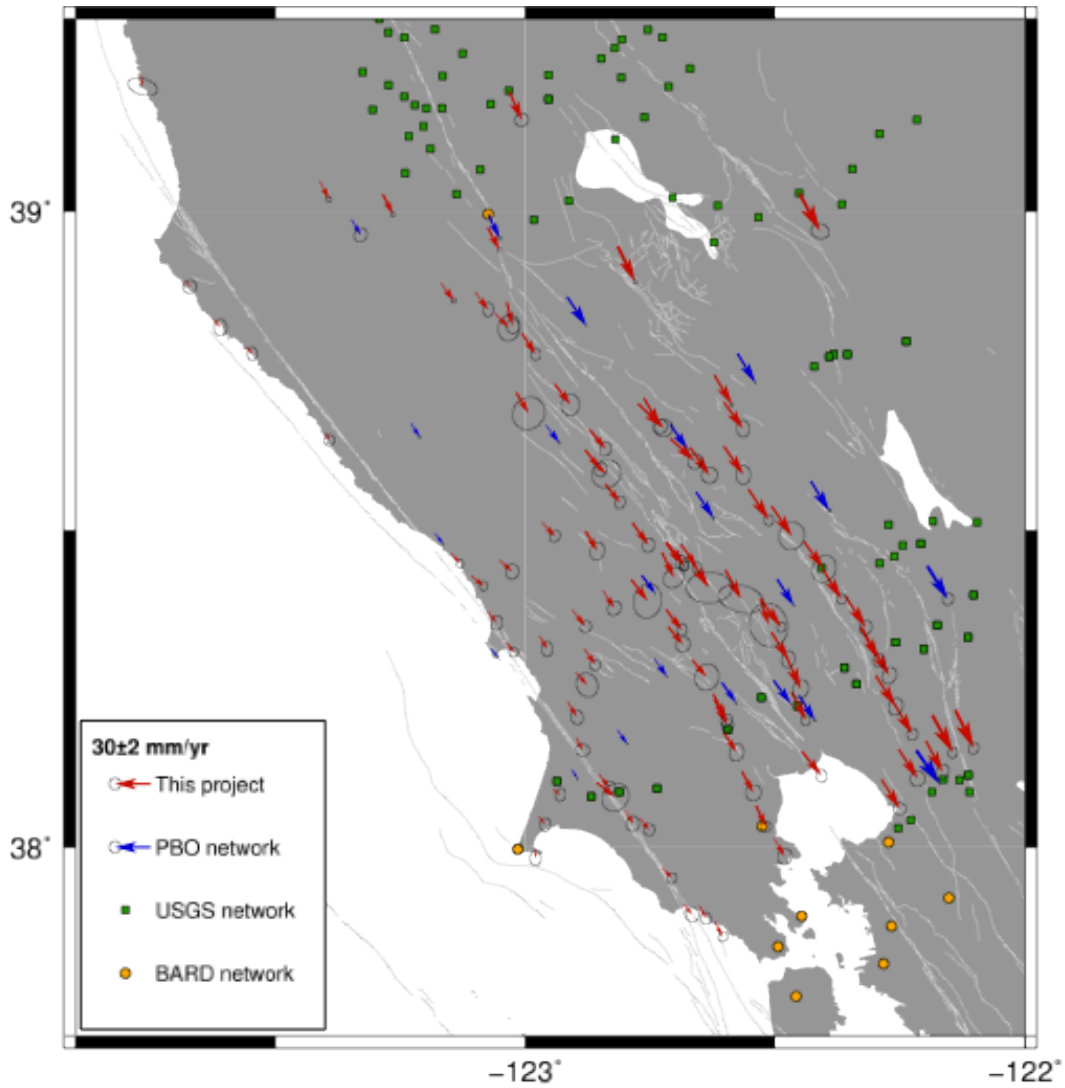

Figure 1: Processed GPS velocities (with respect to the Pacific plate) from data collected during the project (red arrows) and continuous sites from the Plate Boundary Observatory network (blue arrows). Sites from the USGS networks (green squares) and the Bay Area Regional Deformation network (orange circles) have published velocities but have yet to be combined rigorously into our solution. Light gray lines indicate the traces of Quaternary faults (USGS and CGS, 2010).

Preparedness for a future major earthquake on the Rodgers Creek fault

In the event of an earthquake on the Rodgers Creek fault, the knowledge gained from survey campaigns would be vital. In order to be able to respond effectively and quickly, accurately capturing both the coseismic deformation and any postseismic deformation and thus maximizing the scientific information that can be gained, it is necessary to have both accurate pre-event site coordinates and knowledge of the locations of the sites, and how best to find them. An objective of the project, therefore, was to locate, measure and document as many sites as possible in the region of interest, with a view to future post-earthquake response.

1.2 Accordance with program aims

This project directly contributes to the goal of reducing losses from earthquakes in northern California by providing improved estimates of the slip-deficit accumulation rates of locked fault segments along the Rodgers Creek and southern Maacama faults and improved determination of the state of creep along the northern Rodgers Creek fault (and thus the possibility of a major earthquake propagating along it).We directly contribute to the objectives of Elements I and III of the USGS Earthquake Hazards Program (EHP) by providing essential input used in regional seismic hazard assessments and for the development of physical models of earthquake and tectonic processes in the North Bay area. We specifically address a number of the goals for the Northern California (NC) region for research in FY 2010, regarding the utilization of "crustal deformation measurements to constrain regional deformation rate, fault slip rates, role of fault creep, fault mechanics, strain transients, and models of stress evolution for northern California" and application of such research to the "North Bay region".

2. Data acquisition

2.1 Site selection

We prioritized for survey sites with preexisting GPS data, since reoccupation of such sites would straightaway yield velocity estimates. These included sites previously surveyed by UCR, and other academic groups, plus reference networks maintained by state and federal organizations. Several public domain archives exist containing data from the area. Only a fraction of these data have been published in the scientific literature (e.g. Freymueller et al., 1999); the vast majority of pre-existing data were collected for datum definition updates. In many cases, these measurements were made at sites that had only been established within the past decade.

The majority of sites with pre-existing GPS data were surveyed as part of California Height Modernization Projects in the past decade. These were the Northern California survey of late 2004, covering the area north of Clear Lake (see http://csrc.ucsd.edu/projects/pgm/norcal2004.html), and the Central Coast Height Modernization Project of late 2007 to early 2008, which covered a large area both north and south of San Francisco Bay (see http://csrc.ucsd.edu/projects/pgm/cenchm2007.html). These data were collected collaboratively by the California Spatial Reference Center (CSRC) and Towill Inc., and are available through the CSRC PGM server. The majority of the latter sites were new benchmarks installed during that survey campaign. In addition, the Southern California Earthquake Center (SCEC) GPS data archives contain data from the area from predecessor campaigns – the High Precision Geodetic Network surveys of 1991 and 1998.

In addition, the UNAVCO GPS survey archives hold data from several campaigns conducted by other academic groups. These include: seven campaigns conducted by Stanford University from 1991–1996 that measured some sites in our area of interest (and formed the basis of Freymueller et al., 1999); San Andreas Fault surveys conducted in 1996, 1997 and 2000 by the Univeristy of Alaska, Fairbanks; a GeoEarthScope survey in 2007 in support of a LiDAR measurement campaign; and a survey by the University of California, Berkeley around Tomales Bay and Bodega Bay (in which the PI was a participant), also in 2007. In addition, we also targeted a dozen sites previously surveyed by the PI and his group at UCR in the summers of 2008 and 2009, mostly National Geodetic Survey benchmarks located close to the Rodgers Creek fault, in a zone between Sonoma and Healdsburg.

2.2 Field surveys

Three survey campaigns were undertaken within the project period, with a total of 19 days spent in the field. *Survey 1:* Two field teams surveyed the majority (107) of the sites from San Francisco Bay to The Geysers for an average period of 12 hours each over the period July 13–23, 2011. *Survey 2:* one field team surveyed 23 sites along the San Andreas fault zone, along with repeats of sites with bad data from the July survey, for an average occupation of 14.5 hours, over the period October 3–8, 2010. *Survey 3:* one field team surveyed eight sites for an average of 18.5 hours each to the immediate west and south of Clear Lake, as well as the USGS alignment array at Fountaingrove Parkway in Santa Rosa, over the period January 26–27, 2011. A full list of the sites that were surveyed, along with dates of occupation and coordinates is given in Table S1. Sites were measured using the PI's five Trimble R7 receivers, along with five additional Trimble 5700 receivers loaned by UC Berkeley, all with Zephyr Geodetic antennas. Where it was not possible to set up tripods over survey markers, 50 cm-high spike mounts were used instead. Receivers were typically chained to nearby fixtures and left unsupervised between setup and takedown, with no problems.

In order to maximize the number of sites surveyed, and thus the area covered by observation, given constraints on field time and resources, we elected to restrict our measurements to a single occupation of each site. To minimize the propagation of human error into the solution and promote accuracy, utmost care was taken to calibrate our surveying instruments (specifically tribrachs and optical plummets) before each survey and double-check equipment setups, including reconciling ambiguous readings in the field. Any deviations from an optimum setup that could be identified (generally when the center of the antenna was found to be more than 1 mm off-center at site takedown) were noted and accounted for in the processing.

3. Data processing

3.1 UC Riverside surveys

The raw data we collected were converted to RINEX format with appropriate metadata from log sheets completed in the field. These data, along with data from continuous GPS networks in the region (e.g. the Plate Boundary Observatory and the Bay Area Regional Deformation network) and a selection of global sites maintained by the International GNSS Service (IGS) were then processed into daily solutions using the GAMIT/GLOBK (release 10.4) software suite. Next, these daily solutions from each survey campaign were combined into a 'survey solution', i.e. a single network solution spanning the entire survey campaign period.

3.2 Reprocessing archived surveys

Processing of archival survey data followed a similar protocol to that for the data we collected, but with an additional quality control step. Archival data are provided as RINEX format files, including metadata (e.g. measured antenna heights). Where available, the metadata contained in the RINEX headers were checked against field log sheets. Several errors were found, mostly regarding the antenna height information, and corrected before processing into daily solutions.

3.3 Velocity solution

The complete set of survey solutions are then brought together using the Kalman filter in GLOBK to produce a final velocity solution. This solution is aligned to the International Terrestrial Reference Frame 2008 (ITRF2008) using the IGS sites that we incorporated during the original processing stage as a basis

for a global stabilizing network. The final velocity solution may be rotated to be expressed in any given plate reference frame, such as relative to the Pacific plate, as shown in Figure 1.

Formal uncertainties for our velocity solutions depend strongly on the length of time spanned by the set of observations (Figure 2). The majority of sites have been measured twice or more over a period of approximately 2.5 years (the interval between the Central Coast Height Modernization Project survey and our summer 2010 survey), with uncertainties of 2–5 mm/yr. Longer periods of repeat campaign observations (> 6 years) yield reduced velocity uncertainties of ~1 mm/yr.

4. Preliminary analysis

We use a simplified geometry of the faults to estimate the elastic loading rate on the San Andreas, Hayward-Rodgers Creek-Maacama and Green Valley faults. Each fault is treated as a contiguous series of buried rectangular dislocations in an elastic half space; beyond the area covered by our data set we extend the faults along parallel strike to a great distance (2000 km) in order to avoid end effects. Using the formulation of Okada (1985) to relate fault slip rates to our measured velocities, we invert for the best-fitting slip rates in a least-squares sense, using the same locking depths of the faults.

Our best-fitting results (Table 1, Figure 3) differ from existing geologic slip rate estimates, as compiled by the UCERF2 report (WGCEP, 2008). In particular, although the cumulative slip rates across the region are similar, the partitioning of slip between the major faults is different, with a more even distribution of slip between the faults, suggesting a significantly smaller slip rate on the San Andreas fault in particular. We are yet to assess the validity, need for added complexity, uncertainties and correlations in our model. At present, the uncertainties in near-fault site velocities are such that shallow creep on the Rodgers Creek is not required in our models.

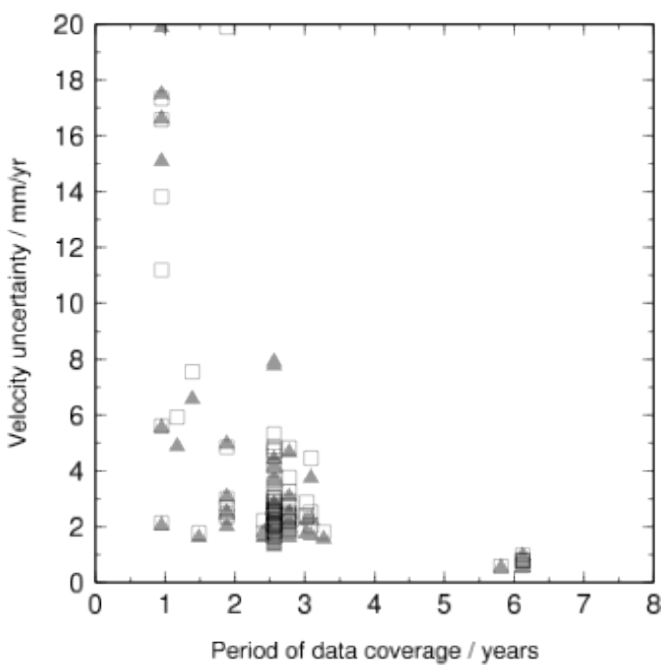

Figure 2: Evolution of velocity uncertainty with period of data coverage for sites surveyed in this study. Filled triangles are the east component; outlined squares are the north component. The majority of sites currently have approximately 2.5 years of data, giving a precision (one standard deviation) of the order of 2–5 mm/yr. Sites with 6 years of data, show precision at the 1 mm/yr level. Accuracy of velocity estimates is still undetermined in most cases, given that only two observations have been made for the majority of sites. Re-surveying in the near future (summer 2013) will increase the number of measurements and extend the time series to 4.5 years, likely reducing these uncertainties to around the 1 mm/yr level, as well as allowing an estimate of the accuracy of the velocities.

Table 1: Comparison of the inversion results for slip rate on three idealized dislocations in an elastic half-space and the UCERF2 (current) model. The depth to which each fault is considered "locked" is given in parentheses and, for first-order purposes, is taken to be identical to the UCERF2 model is all cases here.

Fault	UCERF2	This project
San Andreas (north coast)	24±3 mm/yr (11 km)	15.4 mm/yr (11 km)
Hayward-Rodgers Creek-Maacama	9±2 mm/yr (12 km)	14.3 mm/yr (12 km)
Green Valley	5±3 mm/yr (14 km)	11.4 mm/yr (14 km)

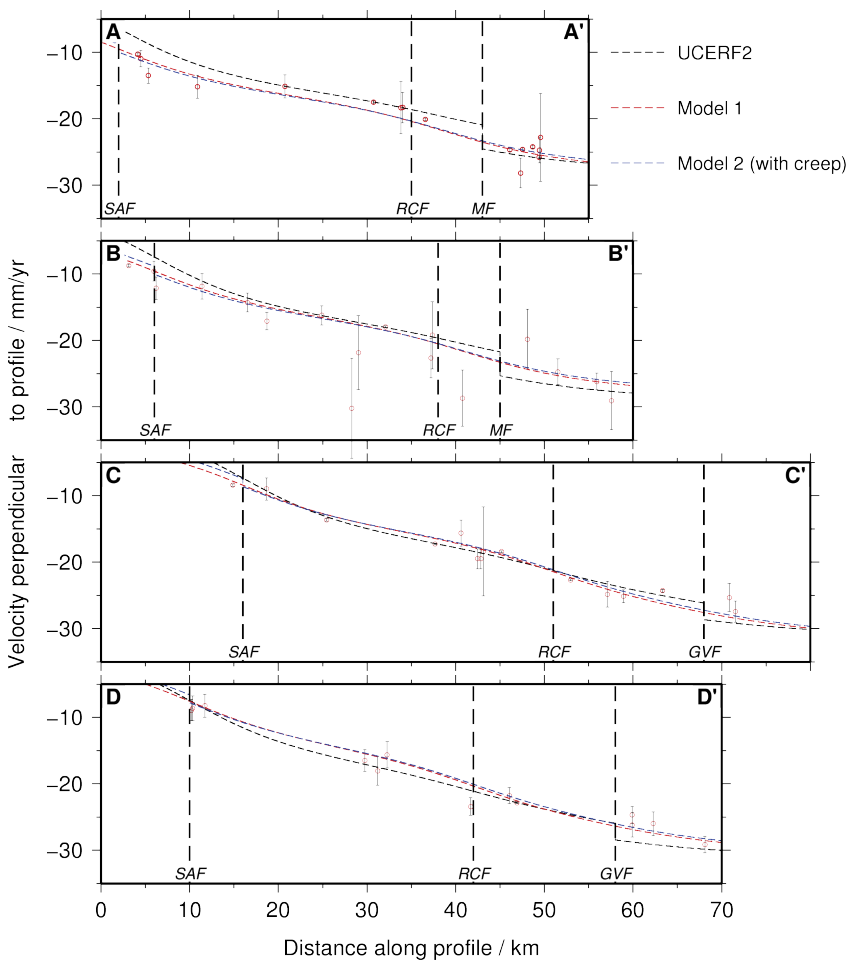

Figure 3: Profiles through our deformation velocity dataset (red circles), comparing the fits of our best-fitting models (red line: model without creep; blue line: model with creep) with the fit of the UCERF2 model (black line). Locations of major fault systems are indicated by vertical lines. The major difference in fit is to sites in the west where the UCERF2 model overpredicts velocities by ~5 mm/yr. [SAF: San Andreas fault; RCF: Rodgers Creek fault; MF: Maacama fault; GVF: Green Valley fault.]

5. Future work

A majority of the sites have only two measurements less than three years apart (Central Coast Height Modernization Project 2007–2008, and 2010). These velocity estimates will greatly improve with additional measurements in the near future (2012 onwards). There is also much to be gained for supporting a larger collaborative group or more field time to ensure that sites can be optimally, rather than minimally, measured.

Furthermore, there are currently no survey marks that we can find evidence for (previous surveys, National Geodetic Survey log sheets, etc.) to the immediate east of the Maacama Fault to the west and south of Clear Lake (see Figure 1), most especially between Middletown and Ukiah. Since the absence, or otherwise, or surface creep has profound influence on the magnitude of strain accumulation, we consider that work to fill this geodetic gap is important for the immediate future.

Work with the current data set is nearing completion and a paper (Floyd and Funning, in prep.) will be submitted to a peer-reviewed journal in the near future. The data will also be submitted to the USGS as soon as it is verified as being complete and correct in accordance with existing site records.

Although this has not been done at the time of writing this report, ultimately we will incorporate directly the results (in the form of SINEX files) of PBO processing. These solution files will also serve as a basis with which to account for time-correlated noise in the site positions, which yield more realistic uncertainties when properly estimated and incorporated into the velocity solution.

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Publications and presentations arising

Floyd, M. A., G. J. Funning and B. P. Lipovsky (2010), Preliminary geodetic observations of motions along the Rodgers Creek and Maacama Faults, 7th Annual Northern California Earthquake Hazards Workshop, Menlo Park, California, January 2010.

Floyd, M. A., G. J. Funning and B. P. Lipovsky (2010), A densified geodetic velocity solution for the North San Francisco Bay region, Southern California Earthquake Center Annual Meeting, Palm Springs, California, September 11–15, 2010.

Floyd, M. A., and G. J. Funning (in preparation for Journal of Geophysical Research), Kinematics of the North San Francisco Bay region from GPS measurements between 1991 and 2011.

Funning, G. J., L. Jin and M. A. Floyd (2010), Evidence for creep on the Rodgers Creek fault, California, 1992-2010, from Persistent Scatterer InSAR and GPS data, EarthScope Institute on the Spectrum of Fault Slip, Portland, Oregon. October 11-14, 2010.

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Table S1: Sites occupied during the project.

ID	Lat.	Long	Occupied	ID	Lat.	Long	Occupied	ID	Lat.	Long	Occupied	ID	Lat.	Long	Occupied
0062	38.8580	-123.0370	26-Jan-2011	2706	38.6443	-122.7108	20-Jul-2010	l244	38.8120	-122.7901	22-Jul-2010	rv69	38.5119	-122.7860	3-Oct-2010
007m	38.6383	-122.7700	18-Jul-2010	2708	38.6386	-122.7706	18-Jul-2010	lyt2	38.6579	-122.8718	18-Jul-2010	rv82	38.3755	-122.7187	17-Jul-2010
01bj	38.9448	-122.8152	27-Jan-2011	36mr	38.7009	-122.9523	16-Jul-2010	lytr	38.5646	-122.5538	18-Jul-2010	s144	39.0469	-123.4118	27-Jan-2011
01c8	38.9747	-123.0757	26-Jan-2011	5020	37.9963	-122.9791	4-Oct-2010	m139	38.1514	-122.4476	13-Jul-2010	shee	38.2266	-122.2622	13-Jul-2010
0409	37.8829	-122.6216	14-Jul-2010	5052	38.0111	-122.5029	13-Jul-2010	m139	38.1514	-122.4475	16-Jul-2010	spur	38.2085	-122.1860	7-Oct-2010
0411	38.3329	-123.0284	15-Jul-2010	5228	38.1020	-122.8573	6-Oct-2010	m625	38.6986	-122.7750	20-Jul-2010	stin	38.3329	-123.0284	14-Jul-2010
0412	38.4411	-122.4068	14-Jul-2010	73dr	38.7612	-122.7245	23-Jul-2010	madr	38.3399	-122.5076	15-Jul-2010	t208	38.3722	-123.0758	17-Jul-2010
047m	38.2767	-122.8996	15-Jul-2010	7rbo	38.8113	-122.8528	21-Jul-2010	n625	38.7006	-122.7654	20-Jul-2010	t238	38.7009	-122.9523	18-Jul-2010
04he	38.3329	-123.0284	14-Jul-2010	addv	38.3339	-122.9721	15-Jul-2010	neg1	38.8222	-122.7580	22-Jul-2010	t243	38.7730	-122.7480	20-Jul-2010
04jd	38.0584	-122.7991	14-Jul-2010	amer	38.1686	-122.1993	13-Jul-2010	ng13	38.8208	-122.7690	22-Jul-2010	tide	38.3329	-123.0284	16-Jul-2010
04je	38.0654	-122.5385	13-Jul-2010	anto	38.1811	-122.6032	16-Jul-2010	nvrd	38.1199	-122.5664	13-Jul-2010	tomp	38.2124	-122.9715	5-Oct-2010
04kd	38.1726	-122.8984	15-Jul-2010	b244	38.7924	-122.7633	20-Jul-2010	oakm	38.4392	-122.5986	17-Jul-2010	tran	38.3210	-122.3092	14-Jul-2010
04ke	38.2424	-122.6233	16-Jul-2010	b245	38.7898	-122.7907	21-Jul-2010	ochr	38.6103	-122.8694	18-Jul-2010	u244	38.8013	-122.8058	22-Jul-2010
04kf	38.2453	-122.4678	14-Jul-2010	b468	38.3473	-122.3287	7-Oct-2010	ocp0	38.8374	-122.8163	23-Jul-2010	u396	38.3985	-122.8392	16-Jul-2010
04kh	38.1548	-122.2535	13-Jul-2010	bale	38.5377	-122.5076	14-Jul-2010	ormt	38.8230	-122.7924	23-Jul-2010	u625	38.7461	-122.7675	21-Jul-2010
04ld	38.3132	-122.8830	15-Jul-2010	boli	37.9090	-122.6823	14-Jul-2010	oyst	38.2059	-122.9250	6-Oct-2010	v625	38.7575	-122.7705	20-Jul-2010
04le	38.3480	-122.7142	16-Jul-2010	c239	38.7009	-122.9523	17-Jul-2010	p625	38.7072	-122.7624	20-Jul-2010	vall	38.4375	-122.7016	18-Jul-2010
04le	38.3480	-122.7142	16-Jul-2010	caul	38.2339	-122.6221	16-Jul-2010	penn	38.2960	-122.6664	17-Jul-2010	veth	38.3968	-122.3598	15-Jul-2010
04lf	38.3041	-122.4781	14-Jul-2010	csg2	38.7902	-122.7347	21-Jul-2010	pp17	38.8236	-122.7790	22-Jul-2010	vis1	38.8012	-122.8239	20-Jul-2010
04lg	38.2711	-122.2994	14-Jul-2010	csg4	38.7795	-122.7367	20-Jul-2010	ptn2	38.2038	-122.9229	16-Jul-2010	w477	38.0923	-122.9445	4-Oct-2010
04lh	38.3986	-122.2041	15-Jul-2010	d245	38.7776	-122.7635	21-Jul-2010	pug1	38.8132	-122.7825	22-Jul-2010	w631	38.2299	-122.9154	5-Oct-2010
04mc	38.6579	-122.8718	17-Jul-2010	divd	38.7688	-122.7284	23-Jul-2010	pug2	38.8204	-122.8197	22-Jul-2010	w631	38.2300	-122.9154	4-Oct-2010
04md	38.6579	-122.8718	16-Jul-2010	dunc	38.4534	-123.0522	17-Jul-2010	q136	38.6386	-122.7706	16-Jul-2010	wild	38.8465	-122.8465	23-Jul-2010
04me	38.4652	-122.7266	18-Jul-2010	dx45	38.8279	-122.7850	23-Jul-2010	q625	38.7207	-122.7645	21-Jul-2010	wohl	38.7009	-122.9523	17-Jul-2010
04mf	38.3914	-122.5293	15-Jul-2010	e244	38.8046	-122.7648	21-Jul-2010	r244	38.8126	-122.8251	22-Jul-2010	wsln	38.6665	-122.8195	18-Jul-2010
04nd	38.6259	-122.8804	17-Jul-2010	e480	38.0480	-122.9740	4-Oct-2010	rdio	38.8386	-122.7988	22-Jul-2010	x134	38.0461	-122.7706	14-Jul-2010
04ne	38.6301	-122.6701	18-Jul-2010	e480	38.0481	-122.9740	6-Oct-2010	redh	38.6316	-122.6034	7-Oct-2010	x135	38.1161	-122.8531	6-Oct-2010
04nf	38.5646	-122.5538	19-Jul-2010	fst5	38.1365	-122.9074	5-Oct-2010	rfge	38.4803	-122.7186	3-Oct-2010	x139	38.7292	-122.9420	3-Oct-2010
04pc	38.8093	-123.0070	26-Jan-2011	g244	38.8148	-122.7736	22-Jul-2010	rfge	38.4803	-122.7186	26-Jan-2011	x552	38.1072	-122.2872	13-Jul-2010
04rs	38.6579	-122.8718	17-Jul-2010	g631	38.6386	-122.7706	17-Jul-2010	rfgi	38.4805	-122.7178	26-Jan-2011	y139	38.8876	-123.1692	27-Jan-2011
10lc	38.2166	-122.1397	13-Jul-2010	gaff	38.3191	-123.0560	15-Jul-2010	rfgi	38.4776	-122.7185	3-Oct-2010	y238	38.5223	-122.8657	17-Jul-2010
12rb	38.7898	-122.8315	20-Jul-2010	goo1	38.8309	-122.7700	22-Jul-2010	rfgo	38.4799	-122.7175	26-Jan-2011	y243	38.7806	-122.7513	22-Jul-2010
15c3	39.0264	-123.2856	27-Jan-2011	goo2	38.8317	-122.7620	22-Jul-2010	rfgo	38.4800	-122.7175	3-Oct-2010	y244	38.7575	-122.7705	21-Jul-2010
18g3	38.7010	-122.6025	7-Oct-2010	h244	38.8134	-122.7666	22-Jul-2010	rosa	38.4577	-122.6719	18-Jul-2010	z204	38.4229	-122.7879	3-Oct-2010
201a	38.4782	-122.6888	18-Jul-2010	knob	38.3206	-123.0342	6-Oct-2010	ru22	38.7159	-123.0180	18-Jul-2010	zinf	38.4828	-122.4427	15-Jul-2010
26rb	38.8099	-122.8199	21-Jul-2010	l138	38.8416	-123.0629	27-Jan-2011	rv59	38.5731	-122.8401	3-Oct-2010				