SEISMICITY CHARACTERIZATION AND MONITORING AT WESTCARB'S PROPOSED MONTEZUMA HILLS GEOLOGIC SEQUESTRATION SITE

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Introduction

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), in collaboration with Shell Oil Co. performed site characterization for a potential small-scale pilot test of geologic sequestration of carbon dioxide (CO2). The site area, know as Montezuma Hills, is near the town of Rio Vista in northern California. During the process of injection at a CO_2 storage site, there is a potential for seismic events due to slippage upon pre-existing discontinuities or due to creation of new fractures. Observations from many injection projects have shown that the energy from these events can be used for monitoring of processes in the reservoir. Typically, the events are of relatively high frequency and very low amplitude. However, there are also well documented (non-CO2-related) cases in which subsurface injection operations have resulted in ground motion felt by near-by communities. Because of the active tectonics in California (in particular the San Andreas Fault system), and the potential for public concern, WESTCARB developed and followed an induced seismicity protocol (Myer and Daley, 2010). This protocol called for assessing the natural seismicity in the area and deploying a monitoring array if necessary. In this report, we present the results of the natural seismicity assessment and the results of an initial temporary deployment of two seismometers at the Montezuma Hills site. Following the temporary array deployment, the project was suspended and the array removed in August of 2010.

Natural seismicity characterization

We reviewed currently available public information including 25 years of recorded seismic events, location of mapped faults and estimates of the stress state of the region. We have also reviewed proprietary geological information collected by Shell, including seismic reflection imaging in the area, this information was reported in Myer, et al, 2010. There are known faults in this area, the one closest to the proposed injection site is the Kirby Hills Fault. The Kirby Hills fault is associated with earthquakes which are deep (9-17 miles below the surface) with magnitudes up to 3.7 (in 30+ year study period). The Shell data also indicates two unnamed faults in the area. The seismic events (earthquakes) we reviewed were not well located because of lack of nearby seismic stations, especially to the north and east. Therefore, attributing the recorded earthquakes to any single fault is inexact. This was somewhat unexpected given the relatively dense monitoring in California, but the Montezuma Hills site is on the very eastern edge of local networks, which are focused on the San Francisco Bay Area and the San Andreas Fault System. Figure 1 shows the seismic monitoring stations of the Northern California and Berkeley monitoring networks. Because of the relatively poor coverage, we revisited the historical events including visually inspecting seismograms and re-picking arrival times of seismic waves.

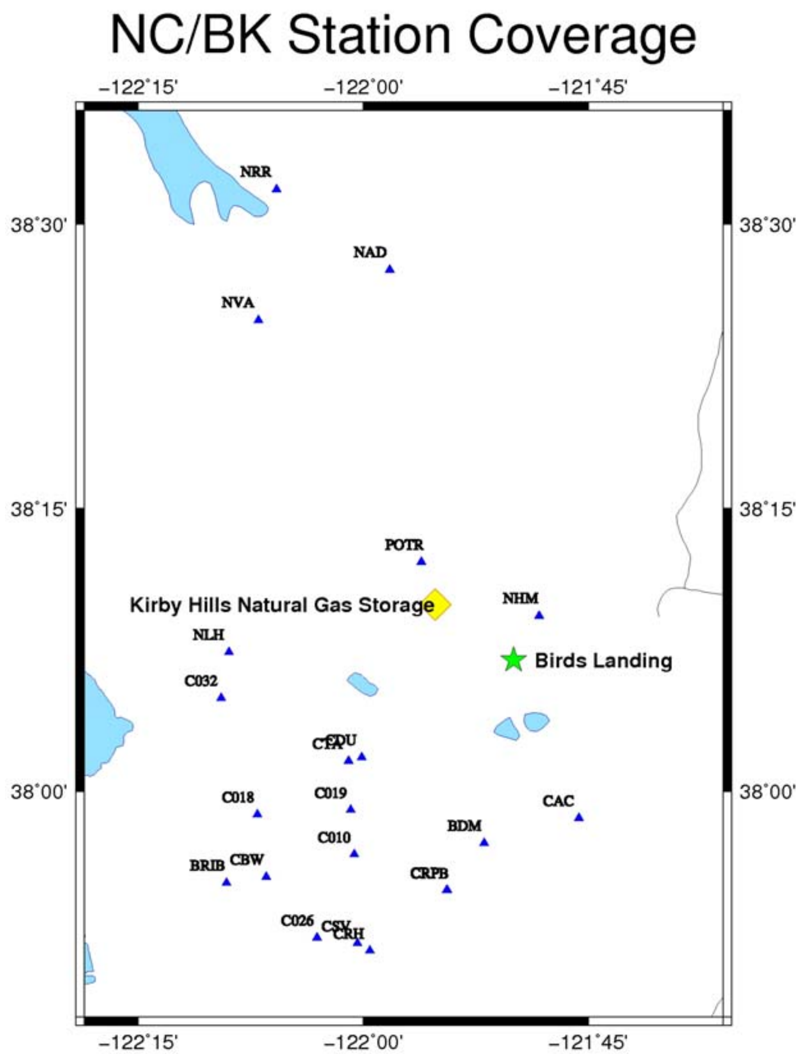

Figure 1. Station locations near the Montezuma Hills (Birds Landing) site for the Northern California Seismic Network (NCSN) and the Berkeley Digital Seismic Network. These stations were used for the event relocation.

We attempted to re-relocate all 111 earthquakes that were listed in the NCSN catalog to have occurred within a 11km x 14 km rectangular area around Birds Landing from 1978 to the present. We also modified the general NCEDC northern California velocity model to a published velocity model specific to the area (Rhie and Dreger). We used HYPOINVERSE to re-locate the earthquake (Klein, 1985). The area and original locations obtained by the NCEDC (red dots) are shown in Figure 2.

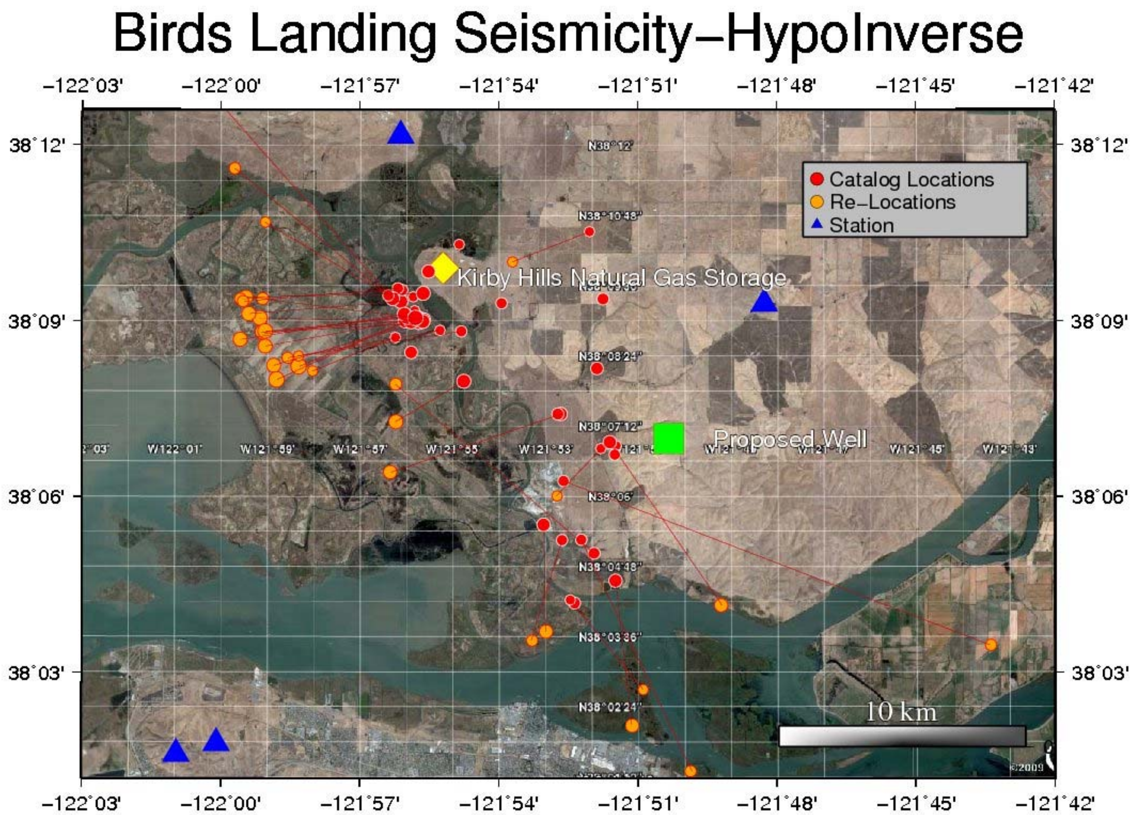

Figure 2. The original NCSN and Berkeley locations for events in the Montezuma Hills area (red) with lines connecting them to the new locations (orange). The green square is the proposed injection well location. Also shown are seismic stations (blue triangle) and the Kirby Hills underground injection facility for natural gas storage.

We obtained waveforms for 80 events for re-location. Of the 80 events, only 56 had sufficient waveform data for us to re-locate. We hand picked these data. We found that many phases were not identified by the auto-picker, but those that were auto-picked appeared to be fairly accurate. When we re-located the events using hand picks, the events moved considerably (up to 10 km), and most moved outside the box. Re-located events are shown as orange dots in Figure 2. One consideration is that if all the events in the region were re-located, many that originally fell outside the box would move into the box.

Temporary monitoring array design and deployment

Because of the number and size of events in the area, we decided to deploy a monitoring network in advance of any subsurface injection. The initial step in the network deployment was installation of two temporary stations to assess data quality. The initial array design was considering both spatial sampling and a focus on the Kirby Hills fault west of the injection site. Figure 3 shows the location of the two temporary sites (MH-1 and MH-2) along with potential locations for the 5 semi-permanent stations. The temporary site locations were put on property with ease of access and permitting, rather than by scientific design. Because the project was suspended, no further work on array design has been undertaken.

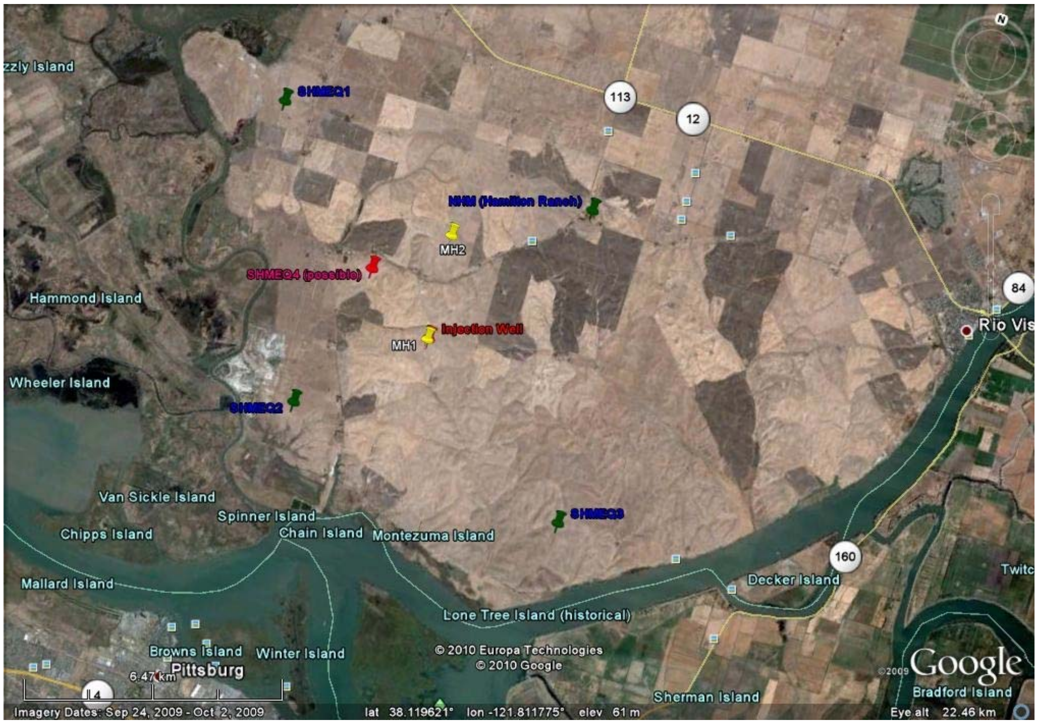

Figure 3. Locations of the temporary seismic stations (yellow markers) and potential stations (green and red markers), along with the injection well location. The town of Rio Vista is on the Eastern edge of the map and Pittsburgh, CA, is to the Southwest.

Observations of the temporary microseismic array at Montezuma Hills

Both temporary stations were deployed close to gravel access roads due to the agricultural use of the area. The station MH-1, accessed using Gate 1, operated from Day 138 to Day 230 (May 18 to August 18). In addition to the continuous acquisition, it also acquired triggered data starting on Day 173 (June 22). The station MH-2, accessed using Gate 3, was also deployed on Day 138 (May 18) but began have problems on Day 182 (July 2). Limited data are available after that. Figure 4 shows a photograph of a site.

Figure 4. (left) A temporary seismic site with solar panel and recording system (inside grey box). (right) A three-component seismometer, placed about 3 m from the station in shallow hole, before being covered with dirt, along with compass used for alignment.

The data was acquired by a seismic recorder manufactured by Refraction Technology (REF TEK) which includes a global positioning system (GPS) clock for accurate time keeping. We recorded data from each station continuously. The REFTEK format data had a sample rate of 500 samples/second. Each file contained one hour of data (3600 seconds), and therefore 1,800, 000 samples. The data was converted to SEG-Y format (defined by the Society of Exploration Geophysicists). Each station had three components, so the SEG-Y file has three traces each 1,800,000 samples long. Standard SEG-Y format limits the data to 32767 samples, so the data needed to be parsed to one minute trace lengths (30,000 samples). These seismograms are scanned manually for events. There were very few discrete events. Noise events were observed, many of which we interpret as being related to traffic on the gravel road. There were also smaller events that did not have characteristics of microseisms, but at 2-4 seconds length, seem to be too short for road traffic. An example of these is shown in Figures 5. These events are characterized by no impulsive onset and a relatively slow ramp up of energy, with an equally slow drop in energy. Figure 6 is another event which has an impulsive onset, but still does not look like a microseism. None of these ‘noise’ events were correlated between the two stations, meaning that even if they were true earth seismic events, they were very small and localized. The background noise at this site was expected to be influenced by commercial windmills which were operating near both stations. However no records of on/off times for the windmills were available, so we can not characterize the windmill noise specifically. Figure 7 show examples of background noise in the frequency domain (spectral content).

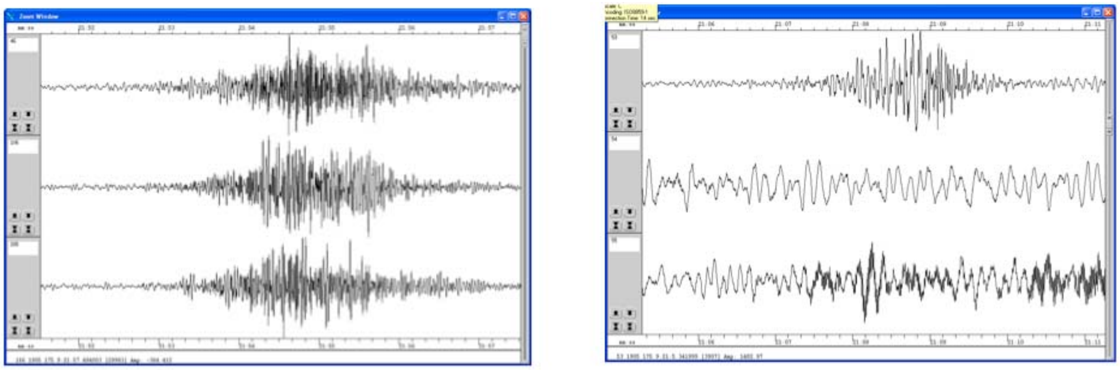

Figure 5. Two typical noise events which are not interpreted as earthquake events because of the lack of clear P- and S-wave arrivals and the non-impulsive onset.

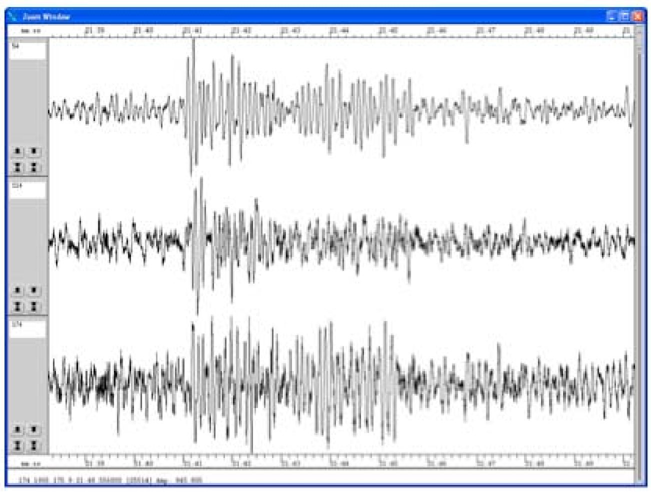

Figure 6. An impulsive event which is not interpreted as earthquake event because of the lack of clear S- wave arrival and the sudden end of high amplitudes.

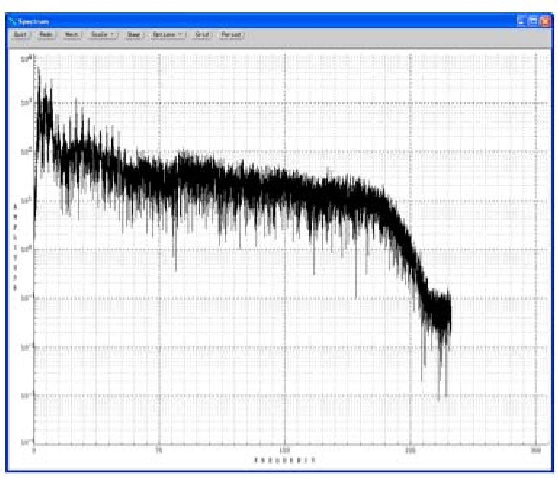

Figure 7. Spectral analysis of a noise recording showing the amplitude as a function of frequency.

One question addressed by the temporary stations was the ability of the REF TEK units to operate on ‘triggered’ event mode versus the continuous recording described previously. The triggered data worked very well. All of the triggered data were scanned and we found that every observable noise event was in the triggered data. This gives confidence that nothing would be missed if only the triggered data was recorded, which makes the identifying of events much more efficient. Also, any noise event was entirely recorded, no matter how long it was. The data for each day took about 5 minutes to manually scan, with some possibility of missing an event. There were between 0 and 10 triggers a day, with an average of 3 triggers, which means a month worth of triggers can be scanned in a few minutes. However, only one component of the data was recorded in triggered mode, so the continuous data is used in this report.

We searched the NCEDC catalog for events within 10 miles during the time of our temporary array deployment, and found 3 in the catalog (Table 1). There did not appear to be any observable events in our data at the time the first two catalog events. However, there was a clear event at the time of the third EQ (2010/06/21 22:29:06.80) shown in Figure 8.

Table 1. Events from the NCEDC data base during our deployment

Date	Time	Lat	Lon	Depth	Mag	Magt	Nst
2010/06/08	16:55:52.90	38.0920	-121.9330	22.93	1.78	Md	13
2010/06/09	11:05:13.10	38.1117	-121.8777	18.97	1.59	Md	10
2010/06/21	22:29:06.80	38.0785	-121.8705	20.63	2.13	Md	45

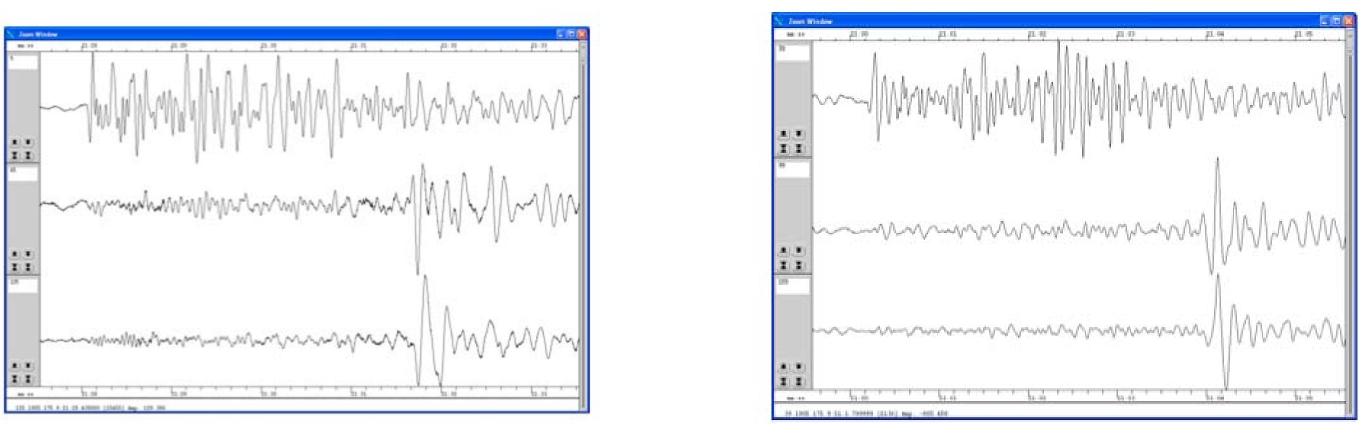

Figure 8. An earthquake event, identified as magnitude 2.1 from the NCEDC database, shown for station MH-1 (left) and MH-2 (right). The three seismograms are vertical, North and East (top, middle, and bottom, respectively).

Conclusions

Initial investigation of natural seismicity in the Montezuma Hills area found that the publicly available data sets were useful in characterizing historical seismicity, but that the locations of events in those databases were not very good for the study area. Our relocation of events showed a significant shift in locations. This highlights the need for dedicated monitoring stations designed for accurate locations in the area of study. The temporary array at Montezuma Hills was successful in characterizing noise sources, sensitivity and data recording parameters. At this point the study is suspended, however future work in the area will benefit from initial investigations.

Acknowledgement

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Appendix 1.

Relocated Events

Date	Time	Lat	Lon	Depth	Mag	Magt	Nst	Gap	Clo	RMS	SRC	Event ID
1980/01/24	05:18:47.49	38.0708	-121.8657	18.12	2.63	Md	41	108	11	0.16	NCSN	1050025
1983/06/09	04:05:51.24	38.1365	-121.8647	17.69	3.10	Md	109	47	6	0.27	NCSN	1096431
1983/09/20	00:35:11.24	38.1585	-121.9360	19.40	2.59	Md	25	91	12	0.19	NCSN	1103125
1984/10/28	11:35:46.61	38.0698	-121.8727	18.27	2.84	Md	46	103	11	0.16	NCSN	30821
1986/04/05	17:32:42.90	38.1717	-121.9142	17.55	2.52	Md	33	64	10	0.19	NCSN	69554
1987/11/17	14:52:18.25	38.1562	-121.8625	17.14	2.86	Md	62	39	5	0.25	NCSN	108533
1988/06/20	01:15:58.30	38.1235	-121.8777	21.05	3.20	Md	50	60	7	0.15	NCSN	119328
1988/06/20	20:06:00.51	38.1235	-121.8787	21.01	2.94	Md	42	85	8	0.14	NCSN	119319
1989/09/11	16:20:35.74	38.0840	-121.8657	19.64	2.87	Md	55	60	10	0.14	NCSN	143902
1989/10/01	12:21:37.36	38.1550	-121.8990	16.62	2.70	Md	78	58	27	0.25	NCSN	144828
1989/10/01	13:10:24.28	38.1410	-121.9315	17.64	3.00	ML	121	35	25	0.28	NCSN	144913
1989/10/01	13:19:27.50	38.1640	-121.9252	15.59	3.20	ML	149	24	28	0.37	NCSN	144978
1989/10/01	21:41:58.64	38.1453	-121.9372	17.84	2.54	Md	36	89	12	0.14	NCSN	144940
1989/10/02	11:20:19.54	38.1470	-121.9135	21.56	2.70	Md	40	61	10	0.13	NCSN	144873
1990/04/18	14:03:04.30	38.1137	-121.8632	20.93	2.52	Md	19	122	7	0.15	NCSN	156402
1992/08/20	02:31:06.64	38.1328	-121.9125	20.18	3.34	Md	52	81	10	0.08	NCSN	311727
1992/11/23	20:59:55.56	38.0762	-121.8580	17.91	3.26	Md	54	61	10	0.10	NCSN	326667
1994/05/10	18:26:35.80	38.1045	-121.8767	20.94	2.68	Md	43	97	9	0.10	NCSN	401972
1994/07/11	18:25:48.81	38.0878	-121.8703	18.74	2.71	Md	37	108	9	0.06	NCSN	30052630
1996/07/15	19:39:47.35	38.1145	-121.8577	21.64	2.62	Md	37	101	7	0.11	NCSN	30113343
1996/07/15	21:44:36.35	38.1155	-121.8600	21.14	3.22	Md	67	90	7	0.12	NCSN	30113368
1996/07/17	11:06:30.65	38.1120	-121.8583	21.56	2.79	Md	53	61	7	0.12	NCSN	30113545
1997/03/26	14:06:24.53	38.1568	-121.9307	22.74	2.58	Md	45	96	11	0.12	NCSN	499512
1997/03/26	15:34:59.51	38.1517	-121.9300	21.67	2.81	Md	48	65	11	0.06	NCSN	499523
1997/03/27	10:10:45.14	38.1507	-121.9287	21.55	3.35	Md	57	86	11	0.06	NCSN	499604
1997/03/27	10:26:35.30	38.1492	-121.9287	21.88	2.92	Md	48	85	11	0.07	NCSN	499607
1997/03/27	11:11:24.51	38.1505	-121.9268	22.02	2.91	Md	51	86	11	0.06	NCSN	499624
1997/03/27	11:30:06.99	38.1500	-121.9335	21.52	3.57	Md	60	65	12	0.09	NCSN	499625
1997/03/27	13:38:08.84	38.1498	-121.9273	21.33	3.33	Md	61	65	11	0.10	NCSN	499649
1997/03/27	14:01:24.23	38.1498	-121.9315	21.64	3.48	Md	60	86	11	0.08	NCSN	499650
1997/03/27	15:39:49.00	38.1510	-121.9307	21.61	3.70	Mw	63	57	11	0.08	NCSN	499656
1997/03/27	17:07:37.80	38.1528	-121.9302	21.68	2.51	Md	51	88	11	0.06	NCSN	499679
1997/03/27	17:16:42.79	38.1578	-121.9272	21.79	3.41	Md	54	90	11	0.08	NCSN	499680
1997/03/27	18:01:43.17	38.1555	-121.9352	21.83	3.38	Md	60	89	12	0.08	NCSN	499681
1997/03/27	22:16:18.77	38.1587	-121.9347	21.68	2.65	Md	59	66	12	0.07	NCSN	499719
1997/03/27	22:47:53.01	38.1510	-121.9328	21.86	3.60	Md	61	65	11	0.08	NCSN	499729
1997/03/27	22:53:07.62	38.1518	-121.9340	21.65	3.46	Md	64	57	12	0.08	NCSN	499730
1997/04/01	01:36:54.86	38.1508	-121.9300	21.57	3.65	Md	63	72	11	0.07	NCSN	500112
1997/04/01	11:25:54.45	38.1592	-121.9363	21.95	2.73	Md	55	91	12	0.06	NCSN	500135
1997/04/01	18:37:18.59	38.1563	-121.9382	21.56	3.38	Md	64	54	12	0.10	NCSN	500154
1997/04/02	12:14:12.37	38.1473	-121.9212	21.90	2.51	Md	35	92	10	0.06	NCSN	500201
1997/04/02	22:27:08.94	38.1572	-121.9397	21.55	2.70	Md	43	67	12	0.10	NCSN	500230
1999/04/04	18:12:15.38	38.0920	-121.8838	20.30	3.19	Md	62	58	10	0.13	NCSN	21006629
2002/08/16	06:06:43.99	38.0877	-121.8772	20.41	2.63	Md	49	60	10	0.09	NCSN	21240822
2007/03/05	21:26:56.29	38.0707	-121.8743	15.99	2.52	Md	43	59	11	0.25	NCSN	40194201
2009/06/04	12:49:48.96	38.1753	-121.8673	21.21	2.57	Md	78	94	6	0.25	NCSN	40237628