vices. This site receives data from 6 BDSN stations and operates independently of the UC Berkeley notification system. Although utilizing a small subset of the BDSN, the system has the capability to detect and locate moderate-size earthquake.

To setup this redundant processing facility, we installed a Sun Ultra 140 with a Vanguard 320 FRAD. A 56-Kbps frame-relay connection was established and divided into 7 8-Kbps circuits. 6 of these circuits are used for data acquisition from the stations YBH, ORV, CMB, SAO, BKS, and HOPS, while the 7th circuit is used for a connection between the OES site and UC Berkeley (Figure 8.2). Although 8-Kpbs is a fairly "narrow" telemetry pipe (and we initially experienced some problems in establishing these circuits because of the limited bandwidth), it is sufficient to transmit continuous data at 100 sps from the strong-motion sensors, and 20 and 1 sps from the broadband seismometers installed at these sites. In effect, these 6 stations are supporting 2 data acquisition processes, one in Berkeley and one in Sacramento. The data acquisition in Sacramento does not depend on any operations in Berkeley. The OES system has been operational since late September 1998, using the same REDI software installed at UC Berkeley.

Preliminary analysis indicates that the facility is operating well. In the 4 months from September to December 1998, a number of small events and 8 earthquakes of magnitude 4 and higher were processed. In nearly all cases, the location based on the subset of BDSN stations was within a few km of the joint notification determination. Problems have been experienced with events significantly outside the network and part of this difficulty is due to the lack of S-wave picks to constrain the location outside of the network. Our work with a 3-component picker holds promise for rectifying this situation as well as providing estimates of arrival azimuth that can be used to further constrain the location.

1.0.8 Year 2000 Compliance

We are in the process of updating the REDI processing software for Y2K compliance. Since most of the REDI development has taken place in the last 5 years, the Y2K "problem" is limited to 3 areas.

The first and primary source of non-Y2K compliant codes was the Earthworm related software. Since Earthworm was developed initially as an exact replacement for the RTP systems at USGS/Menlo Park, the software was non-compliant from the start. The USGS installed an updated version of the Earthworm software this summer and we have modified our codes appropriately.

The 2nd problem involved some aspects of the moment tensor codes. These stemmed from issues related to naming data files and the problem has been addressed.

The 3rd - and most challenging - problem involves the standard earthquake location program used in REDI: st-relp. This program was developed on a PC-system in the 1970s and became the standard location program used at the BSL. The program was automated as part of the initial REDI development. Because of the complexities in the code, we have decided against updating the program. Instead, we are working with bw-relp - the new location program developed by Bob Uhrhammer - to replace st-relp. Bw-relp was primarily designed to incorporate the use of azimuth information for earthquake location. However, it emulates the performance of st-relp when using travel-time data alone. We will replace the st-relp elements in REDI in November with the new code and will transition to bw-relp in our standard earthquake location procedures at the beginning of the new year.

2. Routine Earthquake Analysis

On a daily basis, the BSL continues to locate and determine the magnitude of earthquakes in northern California and adjacent regions. As a general rule, events are analyzed if their magnitude is greater than 2.8 in the Central Coast ranges, greater than 3.0 in all of northern California, or greater than 3.8 in the bordering regions. Traditionally, these events were located using hand-picked arrival times from the BDSN stations in conjunction with P-arrival times from the NCSN using the algorithm st-relp. Over the past several years, the BSL has made a transition in the daily analysis to take advantage of the automatic processing system. As part of this transition, events which have been processed by the automatic system are not generally relocated, although phase arrivals are still hand-picked and the synthetic Wood-Anderson readings are checked. Instead, analysts are focusing on the determination of additional parameters, such as phase azimuth, and measures of strong ground shaking.

In addition to the routine analysis of local and regional earthquakes, the BSL also processes teleseismic earthquakes. Taking advantage of the CNSS catalog, analysts review teleseisms of magnitude 5.8 and higher. All events of magnitude 6 and higher are read on the quietest BDSN station, while events of magnitude 6.5 and higher are read on the quietest station and BKS. Earthquakes of magnitude 7 and higher are read on all BDSN stations.

The locations and magnitude determined by the BSL are cataloged on the NCEDC. The phase and amplitude data are provided to the NEIC, along with the locations and magnitudes, as contributions to the global catalogs, such as that of the ISC.

3. Regional Moment Tensor Estimation

Two independent moment tensor inversion methodologies are currently being used in routine earthquake analysis at the Berkeley Seismological Laboratory: a) a regional surface wave inversion method, which is a two-step frequency domain inversion that uses 15 to 50 second surface waves and is adapted from a method originally developed for a global data (*Romanowicz*, 1992) and b) a regional time-domain inversion method using complete waveforms at frequencies between 0.01 and 0.10 Hz (*Dreger and Helmberger*, 1993). Both methods have been fully automated (e.g. *Pasyanos et al.*, 1996) and integrated into REDI (*Gee et al.*, 1996). Human reviewed solutions are still sent out to the community via an e-mail distribution list and also the website: www.seismo.berkeley.edu/ dreger/mtindex.html We estimated 49 moment tensor solutions for events which occurred in and around northern and central California between August 1998 and September 1999 (Figure 8.8 and Tables 8.4 and 8.5). They were determined using one of the methods mentioned above.

4. References

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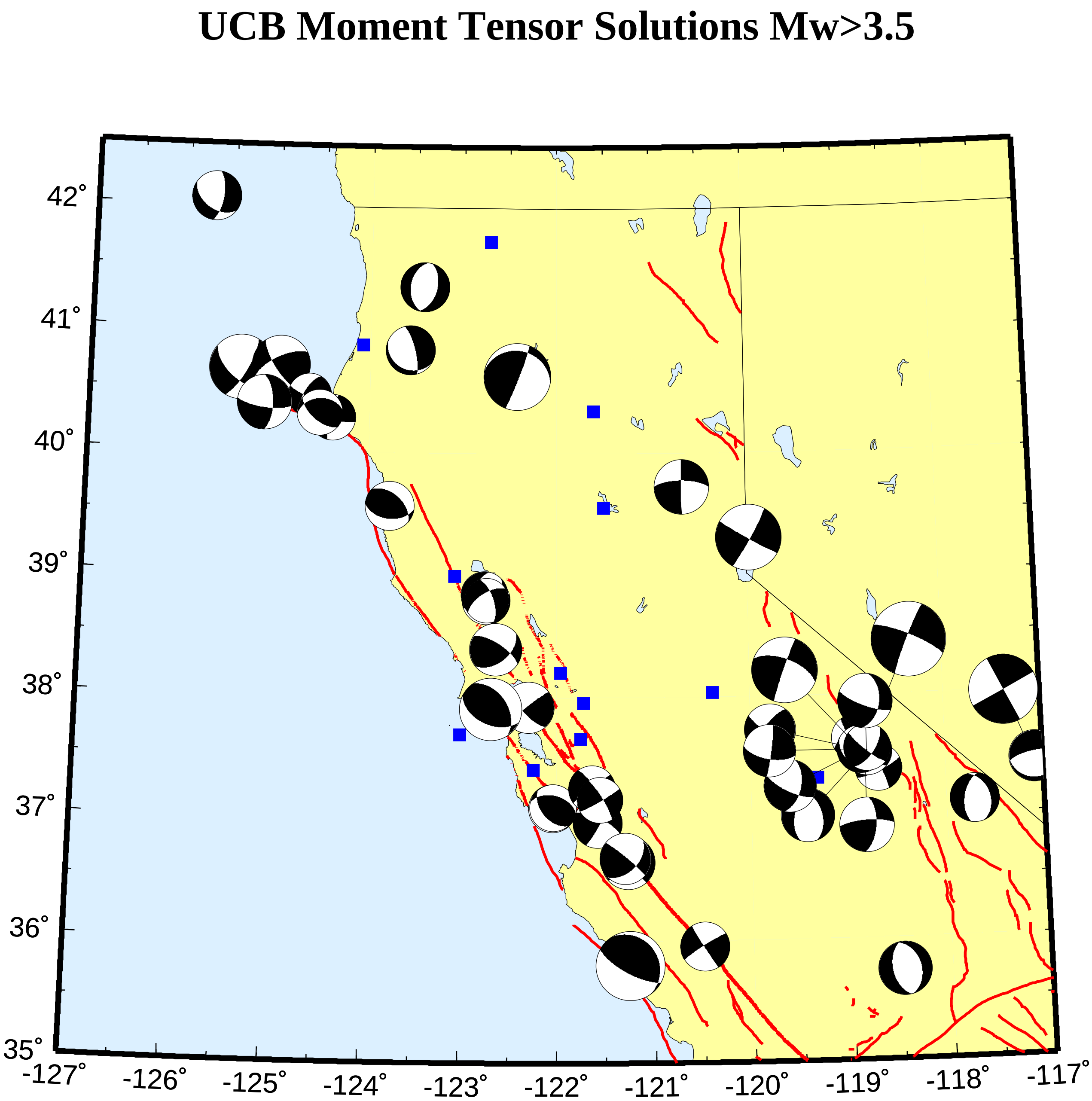


Figure 8.8: Moment tensor solutions for events which occurred in and around northern and central California between August 1998 and September 1999 determined by both moment tensor inversion methodologies. The locations of the BDSN stations are shown (squares).

Location	Date	UTC Time	Lat.	Lon.	Depth	Ml	Mw	Mo	Str.	Dip	Rake	Method
Nevada	08/26/1998	15:50:12.0	37.114	-117.712	8.0	4.0	3.7	4.05e21	341	38	-114	1
B. Columbia	08/30/1998	11:33:34.0	51.1	-130.4	10.0	6.1	6.1	1.56e25	62	79	-43	1
San J. Baut.	09/02/1998	11:24:07.0	36.839	-121.298	8.0	3.9	4.0	10.0e21	165	81	190	2
Bishop	09/11/1998	11:38:42.0	37.388	-118.689	11.0	3.8	3.8	5.80e21	334	83	169	1
Parkfield	09/16/1998	09:00:44.0	35.959	-120.508	14.0	3.5	3.5	2.17e21	154	87	178	1
Gilroy	10/10/1998	06:50:31.0	36.97	-121.58	5.0	4.0	3.8	5.51e21	296	72	172	1
					5.0	4.0	3.9	6.80e21	299	86	-167	2
Arcata	10/15/1998	05:05:46.0	40.840	-123.571	30.0	4.0	4.2	2.69e22	345	75	-74	1
					20.0	4.0	4.1	2.4e22	348	61	-79	2
Portola	10/21/1998	08:31:01.0	39.725	-120.677	11.0	4.4	4.1	1.73e22	180	88	341	1
					22.0	4.4	4.2	2.5e22	280	89	349	2
Truckee	10/30/1998	09:53:30.0	39.303	-119.977	11.0	5.3	4.8	1.77e23	30	85	-3	1
					24.0	5.3	5.0	3.5e23	32	88	-1	2
Redding	11/26/1998	19:49:53.0	40.63	-122.42	24.0	5.4	5.2	6.40e23	21	86	67	1
					24.0	5.4	5.1	4.80e23	289	77	-46	2
Offshore	11/27/1998	00:43:48.0	40.67	-125.38	5.0	5.2	5.4	1.40e24	129	58	-162	1
Berkeley	12/04/1998	12:16:07.0	37.92	-122.29	11.0	4.1	3.9	9.26e21	139	69	174	1
					20.0	4.1	4.2	2.10e22	228	90	-8	2
Mammoth	12/07/1998	16:15:54.0	37.64	-118.93	11.0	3.7	3.4	1.53e21	146	78	-27	1
Mammoth	12/14/1988	04:14:02.0	37.53	-118.798	8.0	4.0	4.0	8.10e21	222	84	17	1
					6.0	4.0	4.0	2.00e22	206	80	0	2
Mammoth	12/17/1998	10:32:12.0	37.524	-118.798	8.0	4.1	3.9	7.14e21	219	73	13	1
					20.0	4.1	4.0	2.10e22	214	75	21	2
Ben Lomond	12/29/1998	12:38:12.0	37.093	-122.041	11.0	3.9	3.9	6.93e21	149	64	106	1
					8.0	3.8	3.9	5.18e21	140	49	115	1
Tres Pinos	01/18/1999	08:48:36.0	36.648	-121.268	11.0	4.3	4.3	2.98e22	48	88	-4	1
					16.0	4.3	4.4	5.20e22	131	88	175	2
Fort Bragg	01/24/1999	15:34:56.0	39.563	-123.767	5.0	4.0	4.1	1.47e22	311	49	115	1
					4.0	4.0	4.0	2.50e22	271	27	47	2
Morgan Hill	01/27/1999	03:58:42.0	37.253	-121.638	8.0	3.8	3.7	4.04e21	324	78	-174	1
Morgan Hill	02/04/1999	00:19:36.0	37.160	-121.554	5.0	3.8	3.5	2.32e21	153	88	-166	1
					6.0	3.8	3.9	8.70e21	51	89	4	2
Morgan Hill	02/04/1999	00:21:41.0	37.162	-121.554	8.0	3.7	3.5	2.05e21	329	80	175	1
					10.0	3.7	3.8	6.20e21	142	88	173	2
Gorda Plate	02/09/1999	14:32:47.7	40.70	-124.96	18.0	4.7	4.1	1.89e22	146	73	156	1
					10.0	4.7	4.1	1.40e22	333	87	-166	2
Punta Gorda	02/15/1999	06:00:04.0	40.28	-124.39	27.0	3.7	4.7	1.25e23	101	80	170	1
					30.0	3.7	4.6	1.00e23	276	90	-178	2
Geysers	02/18/1999	08:58:41.0	38.796	-122.739	5.0	3.9	4.1	1.83e22	167	77	-161	1
					22.	3.9	4.3	3.10e22	333	72	44	2
Parkfield	02/26/1999	15:25:56.7	35.95	-120.50	11.0	4.0	4.0	1.33e22	148	88	174	1
					24.	4.0	4.2	2.30e22	243	73	-19	2
Crescent City	03/16/1999	18:06:31.3	42.062	-125.718	8.0	4.0	4.3	3.13e22	8	66	-51	1
					6.0	4.0	4.4	5.20e22	349	56	-73	2
Tres Pinos	03/23/1999	18:36:40.0	36.676	-121.300	8.0	4.1	4.1	1.72e22	310	84	139	1
Geysers	04/04/1999	06:00:36.0	38.840	-122.754	5.0	3.8	3.9	7.59e21	191	51	-111	1
Pinnacles	04/15/1999	03:20:25.5	36.583	-121.175	6.0	3.8	3.8	6.50e21	314	89	-173	2
Mammoth	04/24/1999	07:56:27.0	37.545	-118.864	8.0	3.9	3.8	2.31e21	343	66	-70	1

Table 8.4: Moment tensor solutions for significant events from August 1998 to September 1999 using both regional methodologies. Epicentral information from the UC Berkeley/USGS Northern California Earthquake Data Center. Moment is in dyne-cm and depth is in km. Key to methods: (1) Complete waveform fitting inversion; (2) Regional surface wave inversion.

Location	Date	UTC Time	Lat.	Lon.	Depth	Ml	Mw	Mo	Str.	Dip	Rake	Method
Mammoth	05/15/1999	13:22:10.0	37.533	-118.833	8.0	6.0	5.5	2.31e24	203	85	-11	1
					8.0	6.0	5.7	4.30e24	203	79	23	2
Mammoth	05/15/1999	17:54:08.0	37.507	-118.832	8.0	5.3	4.6	9.49e22	201	87	-28	1
					8.0	5.3	4.7	2.40e23	202	88	-2	2
Petrolia	05/15/1999	20:58:00.0	40.366	-125.133	11.0	4.0	4.0	1.27e22	279	82	-168	1
Mammoth	05/17/1999	06:37:19.1	37.512	-118.826	4.0	4.3	4.0	1.13e22	343	46	-116	1
					4.0	4.3	4.0	2.10e22	347	46	-97	2
Mammoth	05/25/1999	16:42:46.4	37.529	-118.817	6.0	3.9	3.8	6.20e21	7	60	-80	2
Mammoth	05/26/1999	03:53:53.4	37.556	-118.803	5.0	4.2	3.9	8.89e21	14	55	-22	1
					8.0	4.2	4.4	4.00e22	250	45	-91	2
Mammoth	05/26/1999	18:04:07.2	37.546	-118.806	5.0	4.2	3.8	4.83e21	9	84	-26	1
					4.0	4.2	3.8	6.50e21	3	69	-25	2
Mammoth	05/26/1999	21:22:28.3	37.523	-118.825	5.0	4.4	3.9	9.25e21	5	62	16	1
					6.0	4.4	3.9	9.40e21	358	88	42	2
Mammoth	05/28/1999	20:45:54.2	37.558	-118.801	5.0	3.8	3.6	3.03e21	130	80	-153	1
					4.0	3.8	3.6	2.80e21	290	86	-156	2
Petrolia	06/02/1999	21:26:30.0	40.455	-124.641	11.0	3.5	3.9	8.26e21	208	65	10	1
Mammoth	06/03/1999	21:36:27.7	37.537	-118.806	5.0	4.4	4.2	2.34e22	112	76	-135	1
					4.0	4.4	4.3	3.70e22	209	72	-142	2
Mammoth	07/05/1999	03:06:29.0	40.316	-124.528	4.1	3.7	4.1	1.42e22	129	61	115	1
Isabella	07/11/1999	18:20:46.0	35.735	-118.485	8.0	4.3	4.3	2.76e22	345	39	-93	1
					8.0	4.3	4.4	3.11e22	345	39	-92	2
Petrolia	07/24/1999	00:38:41.0	40.391	-125.127	5.0	4.4	4.5	5.65e22	359	64	-18	1
					4.0	4.4	4.6	9.40e22	217	62	-97	2
Geysers	07/29/1999	04:52:26.6	38.796	-122.733	5.0	3.6	3.7	4.30e21	341	65	-149	1
					8.0	3.6	4.4	4.00e22	359	47	-100	2
CA-NV bdr	08/01/1999	16:06:22.0	37.39	-117.07	0.0	5.6	5.7	3.60e24	64	273	39	1
					8.0	5.6	5.9	7.00e24	216	45	-92	2
CA-NV bdr	08/02/1999	06:05:13.4	37.361	-116.949	11.0	5.5	5.1	4.90E23	251	82	-44	1
					8.0	5.5	5.1	5.60e23	200	55	49	2
Bolinas	08/18/1999	01:06:19.0	37.907	-122.686	8.0	5.0	4.5	7.25e22	115	49	69	1
					6.0	5.0	4.8	2.60e23	221	51	86	2
San Simeon	09/21/1999	15:42:48.0	35.799	-121.255	8.0	5.6	3.6	2.70e21	119	72	81	1
Santa Rosa	09/22/1999	22:27:13.1	38.393	-122.633	5.0	4.2	4.0	9.68e21	51	50	27	1
					6.0	4.2	4.0	1.00e22	113	49	100	2
Nevada	09/26/1999	20:11:22.0	37.43	-117.080	8.0	4.1	4.2	2.53e22	261	72	-92	1
					6.0	4.1	4.0	20.00e21	208	61	-83	2
Petrolia	09/29/1999	06:22:03.0	41.357	-123.424	39.0	4.0	4.0	1.07e22	188	41	-95	1
					40.0	4.0	4.0	2.20e22	9	52	-78	2

Table 8.5: Moment tensor solutions for significant events from August 1998 to September 1999 using both regional methodologies (*continued*). Epicentral information from the UC Berkeley/USGS Northern California Earthquake Data Center. Moment is in dyne-cm and depth is in km. Key to methods: (1) Complete waveform fitting inversion; (2) Regional surface wave inversion.

Chapter 9

Outreach Activities

Lind Gee, Rick McKenzie, Robert Uhrhammer

1. Interactive University Project

The BSL is collaborating with a number of UC Berkeley departments and organized research units to coordinate education and outreach activities through the Interactive University Project (IUP). The goal of the IUP is to foster the use of the Internet and other examples of "information infrastructure" to provide community service. With funding provided by the Department of Commerce, the Berkeley Pledge, and corporate participants such as ATT, Pacific Bell, and IBM, the IUP partners are working with K-12 schools, community-based organizations, small businesses, public libraries, and other local groups.

As part of the IUP, the BSL, the Museum of Paleontology, the Space Sciences Laboratory, and the Center for Particle Astrophysics have formed a science cluster called "Integrating Science, Teaching, and Technology" (ISTAT) with a focus on education in grades 6-12. We received a small 18 month grant in 1996 to initiate this project. Based on our success, we submitted a second proposal last fall and received funding for a 3 year project with Gloria Davis Middle School, Horace Mann Academic Middle School, Galileo High School, Mission High School, and Thurgood Marshall Academic High School in the San Francisco Unified School District.

Over the past 6 months, we have worked with lead teachers to review the new San Francisco science and math standards and to identify "gaps" between existing resources and materials and the required content. With the middle school teachers, we are putting together 2 weeks of curriculum materials, centered around a REDI/CUBE display. We are developing an exercise focused on earthquake data to familiarize students with handling and graphing data, ie, producing maps, histograms, etc. We are supplementing the material under development with resources from FEMA (Tremor Troops and Seismic Sleuths) and from other sources.

Our project with the 9th grade teachers is extremely challenging. San Francisco has recently adopted new textbooks with the goal of teaching Earth and Space Sciences in the 9th grade. This represents a major change, as "Integrated Science" had been the previous paradigm. We are working with the teachers to develop a working outline for the curriculum and to supplement the text with existing resources.

In addition, we worked closely with several summer school teachers this year. Lind Gee gave a day-long workshop on seismology, following the IRIS "Teaching the Teachers" model.

2. Educational Displays

As part of the BSL's outreach activities, we have made REDI earthquake data available to a number of universities, colleges, and museums as educational displays. As noted above, this year marked the expansion of this program to the K-12 environment. Participating organizations receive a REDI pager and the Qpager software to display the earthquake information. The Qpager program maps the previous seven days of seismicity, with earthquake shown as a dot. The size of the dot indicates the magnitude of the event, while the color of the dot indicates its age. These educational displays have been installed at UC Berkeley (McCone Hall, Earthquake Engineering Research Center, LHS), California Academy of Sciences, CSU Fresno, CSU Northridge, Caltech, College of the Redwoods, Humboldt State University, Sonoma State University, Stanford University (Blume Engineering Center, Department of Geophysics), UC Davis, UC Santa Cruz, UC San Diego, and USC.

In addition to the seismicity displays, the BSL provides local waveform feeds for helicorders at several visitor centers associated with BDSN stations (ARC, CMB, MHC, and MIN). Organizations such as LHS, KRON, and KPIX receive feeds from BKS via dedicated phone lines for display, while the USGS Menlo Park uses data from CMB for display in the lobby of the seismology building. The BSL has also loaned a seismometer and helicorder display to the San Leandro Unified School District for their use in science classes.

3. WWW

Over the last year, we have continued to expand our presence on the WWW. Our primary goal has been to provide a source of earthquake information for the public, although we also provide information about the networks, such as station profiles, which benefits the research community as well. We provide such information as seminar schedules, course advertisements, descriptions of operations and research, updates on recent earthquake activity, details on Bay Area seismicity and hazards, and links to other earthquake and earth science servers. We also use the WWW server for our own information distribution, with such details as the computing and operational resources, rosters, and schedules for various purposes.

We are currently working on a new Java program to display real-time seismograms. Undergraduate Sheer El Showk is working on the development of a continuous helicorder-style display. The goal is to provide a new facility for our Web server and to replace the some of the actual helicorders still in use at the BSL.

4. Earthquake Research Affiliates Program

The UC Berkeley Earthquake Research Affiliates (ERA) Program is an outreach project of the BSL, the Department of Geology and Geophysics, and the Earthquake Engineering Research Center. The purpose is to promote the support of earthquake research while involving corporations and governmental agencies in academic investigation and education activities such as conferences and field trips. The ERA program provides an interface between the academic investigation and practical application of earthquake studies.

5. Tours and Presentations

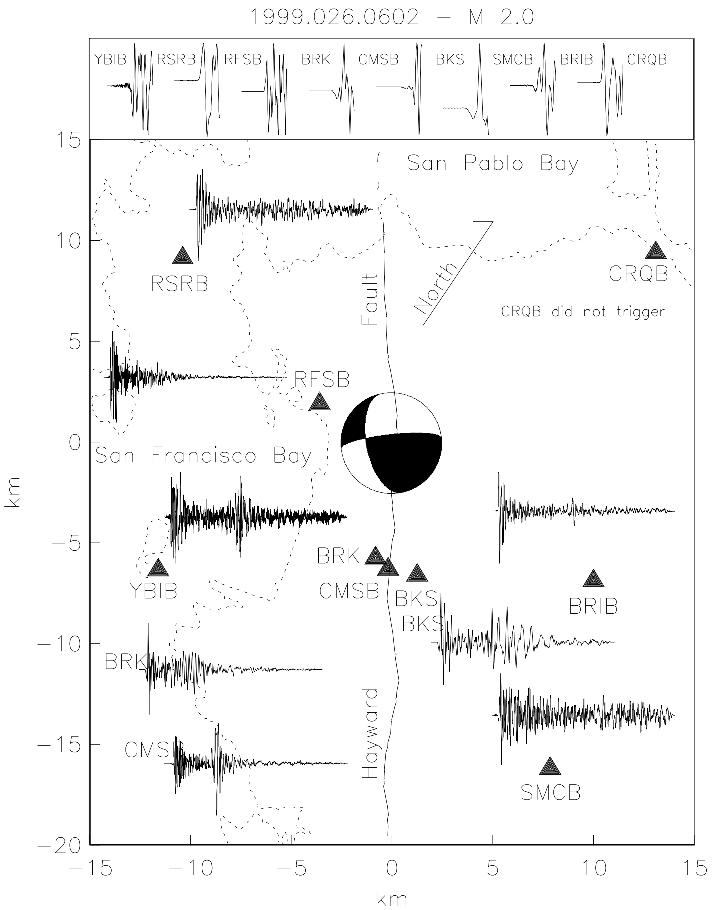
BSL staff have also spent considerable time with public relations activities during the past year. Several tours are given each month, with audiences ranging from middle-school students to scientists and engineers from China, Korea, and Japan. In addition to the usual tours, Drs. Romanowicz, Uhrhammer, and Gee presented talks on earthquakes and related phenomena to public groups. The staff routinely answers questions about earthquakes and seismic activity in response to inquiries from the public. In response to our WWW server and the phenomenal growth of the Internet, we have experienced an enormous volume of questions via e-mail in the last year.

6. Cal Day

For the second time in as many years, the BSL did not participate in in UC Berkeley's Cal Day Open House. After assessing the impact of the McCone Hall renovation project on the potential activities, we decided that it would be too difficult to host open house activities this year. We look forward to participating next year in our newly renovated quarters!

Chapter 10

Ongoing Research - Local and Regional



1. San Francisco Bay Region Historical Earthquake Relocation Project

R. A. Uhrhammer, Jacob Fink, and Sean Ford

1.1 Introduction

As a part of the Working Group on California Earthquake Probability 99 (WGCEP 99) effort to reanalyze the probability of significant earthquakes occurring in the San Francisco Bay Region (SFBR), we have systematically reanalyzed historical earthquakes which have occurred in the SFBR and vicinity (Figure 10.1) since 1951. The goal is to redetermine, using modern analytical algorithms, the location and magnitude, including formal uncertainty estimates, of all SFBR earthquakes at the local magnitude (M_L) 3.0 threshold and extending back as far in time as the data allow. The aim is to develop an uniform and internally consistent catalog of SFBR earthquakes for subsequent probabilistic analyses. Variation in the procedures used when the original BSL analysis sheets were generated, in the number of reporting seismic stations and in the seismic instrumentation over time add complexity to the problem of developing an uniform SFBR seismicity catalog. This project was made possible by funding from the USGS-PG&E CRADA and by the existence of the original analysis sheet and seismogram archives kept on store at the Berkeley Seismological Laboratory (BSL).

The effort involved transcription of the data on the original BSL analysis sheets to computer readable format and systematic reanalysis of the location and magnitude of all M_L 2.9 and larger earthquakes which have occurred from 1951 through 1998 in the SFBR and in a 30 km buffer zone around the SFBR. The 1951 start date was dictated by the requisite data availability on the original BSL analysis sheets. Extension of the reanalysis to pre-1951 SFBR earthquakes will require the manpower intensive task of reading the amplitude data from the original seismograms, kept on store in the BSL seismogram archive, in order to determine the magnitude of the earthquakes.

Once the events were reanalyzed, an interim 1951-1998 SFBR seismicity catalog was created by culling the events that were located outside the SFBR study area or that were below the M_L 3 threshold. This interim catalog differs from existing SFBR seismicity catalogs in that it, spans a longer time interval, has uniformly determined event location and magnitude, and in includes formal location and magnitude uncertainty estimates. The uncertainty estimates are crucial for statistical analyses associated with the probabilistic estimation of earthquake occurrence. The interim 1951-1998 SFBR seismicity catalog was presented at the 1999 Seismolgical Society of America Annual Meeting (Uhrhammer, 1999). Also, the event list, along with appropriate caveats regarding its interim status, are available on the BSL home page at URL: http://www.seismo.berkeley.edu/seismo/herp.

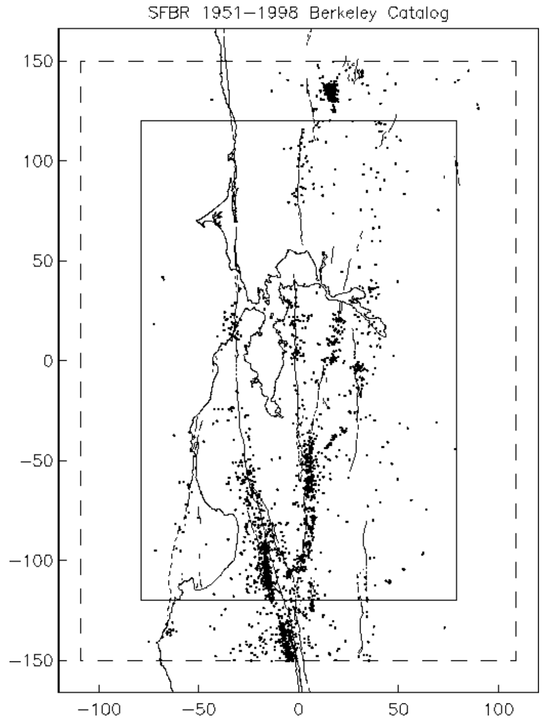


Figure 10.1: Candidate SFBR events to reanalyze are indicated by the small dots. The solid inner rectangle is the WGCEP 99 defined SFBR and the dashed line is a 30 km buffer zone around the SFBR.

A proposal has been submitted to USGS Earthquake Hazards Reduction Program to obtain funding to extend the SFBR catalog back to circa 1928 at the M_L 3.0 threshold and back to 1911 at the M_L ~4.5 threshold. If the proposal is funded, we will undertake a 2 year project to construct a uniform and internally consistent SFBR seismicity catalog which spans most of this century.

1.2 Data Transcription

Prior to 1984, the data on the original BSL analysis sheets were not routinely transcribed to computer readable format. In order to apply modern analytical algorithms to the reanalysis of the SFBR events, the first task was to transcribe the requisite phase and amplitude data. The transcription effort initially focussed on pre-1968 data since USGS Northern California Seismic Network (NCSN) data from 1968 to the present for the SFBR events already exists in computer readable form. We progressed back in time to 1944 and did not proceed any further back once it was discovered that amplitude data were not listed on the original BSL analysis sheets prior to 1951. We then concentrated on transcribing the 1968 through 1983 BSL analysis sheet data so that all the 1951 through present BSL phase and amplitude data would exist in computer readable format.

The transcription process included transcribing not only the phase and amplitude data but also any location, magnitude, felt reports and comments that were on the original BSL analysis sheets. The process required an average of approximately 24 man-hours to transcribe a year's worth of SFBR earthquakes.

1.3 Event Relocation

The SFBR events were systematically relocated using a modified version of the Regional Earthquake Location Program (RELP) (Uhrhammer, 1982) which is routinely used by BSL personnel when locating local and regional earthquakes. For the initial effort, a single linear gradient layer over a half-space velocity model and corresponding station travel time adjustments, as determined for the Central Coast Ranges (McKenzie and Uhrhammer, 1987), were used to relocate all the SFBR candidate events. Since the number of recording seismic stations was generally less than seven for a large fraction of the SFBR events, particularly prior to 1968, it was assumed that all observations had equal weight went calculating the event location. Observations with large residuals were checked against the entries on the original analysis sheets to determine whether they were due to either a typo or an incorrectly identified phase. The observation was then either corrected of removed and the analysis repeated.

1.4 Event Magnitude

The local magnitude (M_L) of each of the SFBR earthquakes was determined from the maximum trace amplitude recorded on standard Wood-Anderson torsion seismograms (Richter, 1935). Eight sites in the SFBR and vicinity have operated Wood-Anderson instruments, as shown in the Table 10.1. Records from these instruments are particularly important for compiling a uniform and internally consistent catalog of seismicity because the instruments were operated by the BSL continuously for more than 65 years (1927-1994) and the records were used routinely to determine the M_L of the earthquakes for most of that time. The station M_L adjustments (Uhrhammer et al., 1996) were applied when determining M_L.

During the analysis we discovered that the original M_L assigned for the larger events ($M_L \sim 5$) recorded prior to circa 1960 is based on Pasadena records. We have evidence that these M_L estimates are biased high, most likely by ~ 0.2 M_L. This has potentially the most significant influence on the statistical inferences drawn from the interim catalog and it needs to be investigated. We have acquired the requisite Caltech Wood-Anderson amplitude data so that this analysis can proceed as time is available.

1.5 Interim SFBR Seismicity Catalog

The events in the interim SFBR seismicity catalog were selected from the reanalyzed events which were located in the SFBR rectangle (dashed line in figure and defined by the vertices: 39.02,-122.08; 37.19,-120.61; 36.43,-122.09; 38.23,-123.61) and which had a M_L of 3.0 or larger. The locations of the 1854 selected SFBR events are shown in Figure 10.2. A few of the events do not have uncertainties listed (due either to inadequate information on the original analysis sheets and/or being in the coda of a previous event) and approximately 120 of the events (about 6.4 percent of the total) have horizontal or depth uncertainties of 10 km or larger and/or magnitude uncertainty of 0.2 M_L or larger. Reducing the uncertainty for these events will require pulling and reading the original seismograms in the BSL archive. This is a manpower intensive effort that will not proceed until funding becomes available.

As a check on the completeness of the interim 1951-1998 SFBR seismicity catalog, we plotted the cumulative number of earthquakes as a function of magnitude (the standard Gutenberg-Richter relation) as shown in Figure 10.3. The linear trend of the cumulative distribution at small M_L indicates that the catalog is complete at the M_L 3 threshold. The annual rate of SFBR earthquake occurrence at a given M_L threshold is r = 10^{logN} where logN = 4.105 - 0.89M_L. For example, at the M_L 5.5 threshold, where damage to weak structures is typically reported, the observed rate of occurrence is 0.16 earthquakes/year. The probability of one or more M_L

Station	Location	Coordinates	Time in Operation	M_L adjustment
ARC	Arcata	40.88, -124.08	1952-1993	+0.209
BKS	Byerly Vault	37.88, -122.24	1962-1993	-0.035
BRK	Berkeley Haviland	37.87, -122.26	1930-1962	+0.198
MHC	Lick Observatory	37.34, -121.64	1928-1993	+0.128
MIN	Mineral	40.35, -121.61	1939-1994	-0.107
PAC	Banner Station	37.42, -122.28	1927-1965	-0.1
USF	Univ. San Francisco	37.77, -122.45	1931-1964	+0.1
VIN	Vineyard	36.75, -121.38	1959-1965	-0.3

Table 10.1: Stations housing Wood-Anderson seismographs.

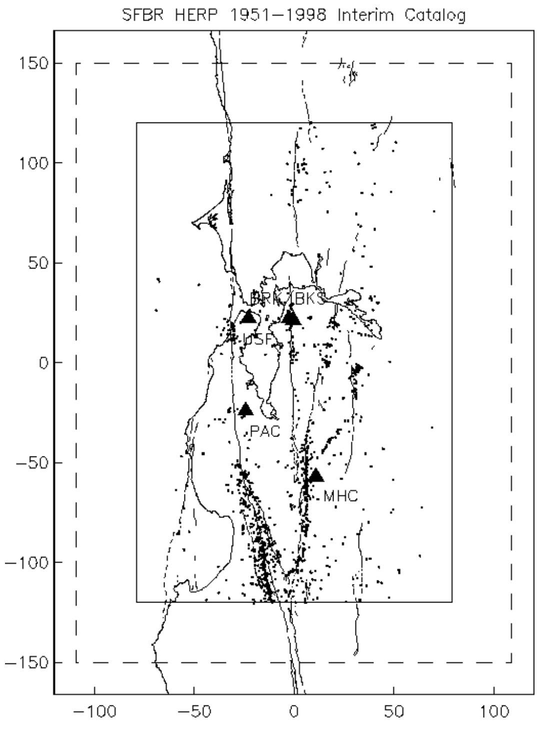


Figure 10.2: Interim SFBR events. The plotted events (small dots) all meet the SFBR location and M_L 3 threshold criteria. The solid triangles are SFBR seismic stations which house Wood-Anderson seismographs.

5.5 or larger earthquakes occurring in any given year in the SFBR is P = 1 - e^{-r} or ~15 percent.

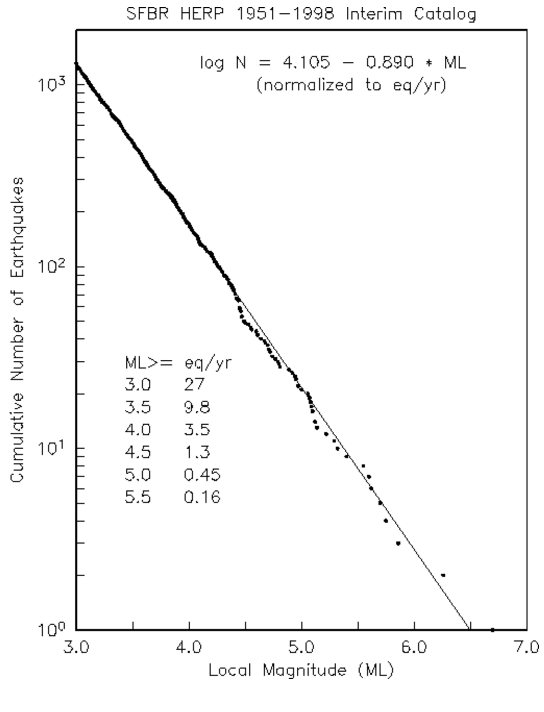


Figure 10.3: Cumulative number of SFBR earthquakes as a function of magnitude. The Gutenberg-Richter relation is given in the upper right and the rate of SFBR earthquake occurrence as a function of magnitude is given in the lower left.

1.6 Acknowledgments

We thank Bill Bakun and Al Lindh of the USGS in Menlo Park for their encouragement and enthusiasm and also the people involved with the USGS-PG&E CRADA for providing the funding that made this initial effort possible.

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2. Interseismic Crustal Deformation in Northern California

Mark Murray

2.1 Introduction

Geodetic measurements provide the best constraints on the rate of strain accumulation on faults within the San Francisco Bay area. Together with paleoseismic and other geologic observations, geodetic data are central in long-term forecasts of earthquake hazards. An enormous amount of relevant geodetic data has been collected over the last century and a half, the vast majority in the last two decades. In collaboration with P. Segall (Stanford), we are integrating existing geodetic data to elucidate the spatial and temporal patterns of crustal deformation within the Bay Area. The focus of our effort is on refining the interseismic deformation field and three-dimensional strain accumulation models that are consistent with it, and on investigating spatio-temporal variations, such as postseismic deformation.

Since the early 1970's, three geodetic techniques have been used to measure horizontal crustal deformation in the Bay Area. Geodolite trilateration (EDM) measurements conducted by the USGS during 1972-1989 show that San Andreas fault (SAF) system in northern California accommodates approximately 34 mm/yr (e.g., *Lisowski et al.,* 1991), but the EDM networks did not span the entire active zone of deformation, which may extend to the Sierra Nevada-Great Valley (SNGV) block (*Argus and Gordon,* 1991). VLBI measurements in the 1980's at 5 stations between the coast and the SNGV spanned the broader deformation field, but were too sparse to assess its spatial distribution (e.g., *Ward,* 1990). Since 1987, the USGS, and many of the local universities, including Stanford and UC Berkeley, have conducted approximately annual Global Positioning System (GPS) surveys of several networks and profiles across the SAF system, including a broad-scale geodetic network from the Sierras to the Farallon Islands, as well as five dense profiles in the Bay Area (e.g., *Williams et al.,* 1994; *Bürgmann et al.,* 1997). Since 1991, the Bay Area Regional Deformation (BARD) permanent network, currently consisting of 40 continuously monitoring GPS receivers, has provided continuous, nearly real-time monitoring of deformation and a regional framework for other GPS surveys in northern California.

Despite this extensive data collection and modeling studies, important questions remain unanswered. Although the cumulative deformation across the Bay Area is reasonably well constrained, it is still not clear how that motion is partitioned amongst the various Bay Area faults. In part, this is due to the non-uniqueness inherent in the inverse problem, in part because rigorous analyses of extremal models have not been conducted, and in part due to lack of knowledge of the fault geometry below the seismogenic crust. There is still a clear need to improve our understanding of the kinematics and mechanics of faulting in the San Francisco Bay area.

2.2 Results

To better address such issues, we are currently finalizing a determination of a self-consistent velocity field for northern California in collaboration with many of the investigators that have made measurements in the past (*Murray et al.,* 1998). For this task, we have obtained solutions of GPS site positions and their covariance derived from observations collected by USGS and Stanford University, as well as the BARD daily site positions estimated by the USGS and UC Berkeley since 1993. These solutions were determined by each of the investigators using different analysis packages and using different processing strategies. For example, 1879 daily solutions for the BARD permanent site positions were estimated by M. Murray at UC Berkeley using GAMIT, which assumes loose a priori constraints on all site positions, satellite orbits, and earth orientation parameters. 176 solutions for Bay Area GPS profile sites were estimated by W. Prescott's group at the USGS using two different GIPSY strategies (fiducial-free network and precise point positioning) that apply loose a priori station constraints but fixed orbits and possibly satellite clocks. 203 solutions for sites near Loma Prieta were estimated by R. Bürgmann using Bernese, many of these using tight or fixed a priori station constraints. We have converted these estimates to the SINEX solution format used by the international GPS community. We have also obtained VLBI position SINEX solutions estimated by the Goddard Space Flight Center, and Geodolite line length changes collected in the Bay Area and near Cape Mendocino.

We have found the task of combining the different GPS solutions to be more challenging than originally envisioned. Our original approach was to use solutions with loosely constrained a priori site coordinates that can be combined by Kalman filter techniques which allow additional constraints to be applied a posteriori to rigorously define a consistent reference frame (e.g., *Herring et al.,* 1990; *Dong et al.,* 1998). This approach, which has been applied to southern California, successfully, as part of a very large multi-year multi-institutional effort (*Shen et al.,* 1997), minimizes biases introduced by using tight or absolute constraints on inaccurate fiducial site coordinates. In practice, we have found the different analysts and analysis packages introduce fundamentally different definitions of the reference frame that hinder rigorous combinations. For example, GAMIT loose constraint allows complete freedom to define the reference frame a posteriori, whereas GIPSY fiducial-free network and precise point positions solutions do not reflect uncertainties in satellite orbits. We are currently investigating an alternative approach, which uses GIPSY precise point positioning solutions (*Zumberge et al.,* 1997) provided by the USGS, that allows for rapid reprocessing of all the primary GPS observations in a self-consistent manner.

The first version of the velocity field will focus on Bay Area deformation excluding the transient effects of the 1989 Loma Prieta earthquake from a combination of the VLBI and Geodolite data collected prior to 1989 and GPS data collected after 1993. A preliminary version of this field, from a combination of BARD and Bay Area profile GPS solutions, shows nearly stable Sierran block motion indicative of Basin and Range spreading, radial deformation associated with the Long Valley Caldera volcanic unrest, predominantly right-lateral strike-slip motion across the Bay Area faults with a suggestion of compression across the East Bay hills (Figure 10.4). We are currently assessing how to best define a "stable" North America velocity reference frame from a combination of globally distributed VLBI and GPS stations, which we suspect may be responsible for some of the non-fault parallel motions.

When the velocity field is finalized, we will begin to explore 3-D interseismic strain accumulation models that allow for along-strike variations in slip rate and the effects of surface creep and variable locking depth, and we will apply methods we developed for a study of the northern California Coast ranges (*Freymueller et al., 1999*) to assess how well the fault slip-rates are resolved. In collaboration with S. Kenner (Stanford), we will also apply physical constraints based on finite element calculations to help distinguish between possible fault models.

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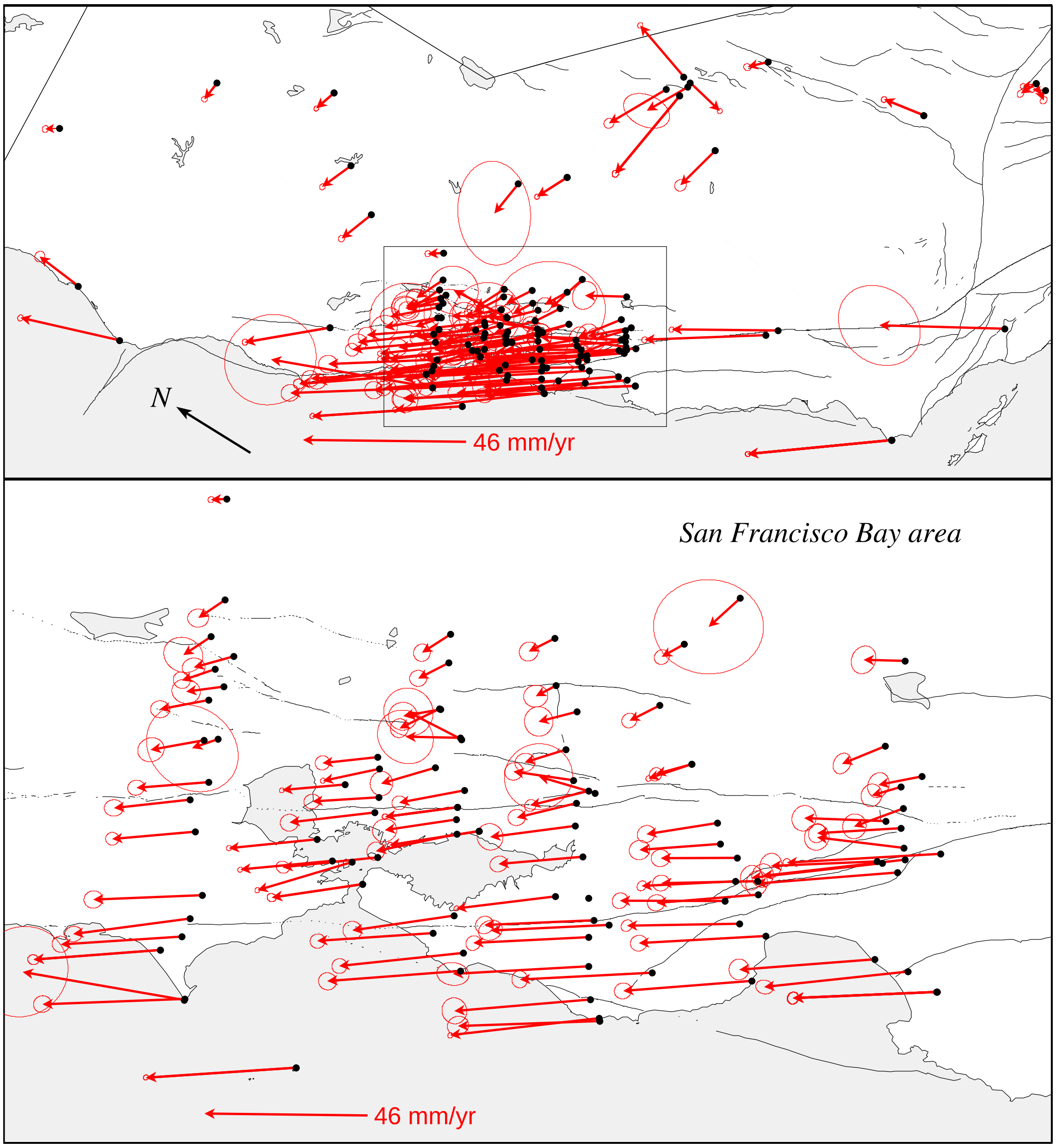

Figure 10.4: The northern California (top) and San Francisco Bay area (bottom) velocity field determined from GPS data collected from 1993-1999, with 95% confidence regions, are shown with respect to stable North America. The NUVEL-1A Pacific-North America relative motion near the Bay area is shown for scale.

3. System Development for Simultaneous Determination of Earthquake Location and Moment-Tensor Using Real-Time Data from a Sparse Broadband Network

Fumiko Tajima, Charles Megnin, Douglas Dreger, and Barbara Romanowicz

3.1 Introduction

The moment tensor (MT) determination in the real-time earthquake notification system by BSL currently relies on the earthquake locations and origin times determined by the USGS using travel-time picks from the dense short period Northern California Seismic Network (NCSN). If only for redundancy purposes, it is desirable, however, to be able to determine a centroid-location and MT (and M_w) of significant earthquakes (M$\geq$4.5) using only waveform data from the sparse (25 stations) broadband Berkeley Digital Seismic Network (BDSN) without relying on the dense short period data. With the quality of broadband waveform data it is possible to develop such a system. This kind of a stand alone system development is especially valuable for the following reasons: (1) in the occurrence of a catastrophic earthquake (M$\geq$5.5) the link to obtain location and origin time information from the USGS may be destroyed or unavailable; (2) such a system would also find applications in the areas of less frequent, but potentially large earthquakes, where the operation of more than a few broadband stations may never be affordable.

3.2 System Configuration and Feasibility Study

As shown by Kawakatsu (1998) the seismic wavefield below $\sim$ 0.1 Hz may be continuously monitored to simultaneously solve for potential point sources and their moment tensors over a spatial grid covering the region of interest. Critical issues in this procedure are to assess whether the system can detect an event over a certain threshold magnitude and determine the location and MT accurately. Recently we have configured such a system using the waveform MT inversion method of Dreger and Romanowicz (1994) with Green's functions tabulated for simple 1-D models of the crust that generally give good results in our standard automatic moment tensor inversion procedure (e.g. Pasyanos et al., 1996).

We carried out a feasibility study of the system in northern California using a sample dataset of 66 events ($M_L \geq 4.2$) which were recorded by the BDSN network since 1993. The large region of northern California was divided into several subregions, i.e., Mendocino, South of the Bay, Mammoth, Northern California, and Geysers, each of which is covered by a mesh with an interval of 0.5 deg, and waveforms were filtered in the frequency band of $\sim$20 (or 10) to 50 sec in which MT source inversion is reasonably stable from our REDI experience. We have tested the accuracy and stability of the analysis in the grid search scheme focusing on the uniqueness of the solution in space and time as well as its frequency dependency of waveforms. The results were compared with the ground truth parameters determined by the REDI system, the Berkeley/USGS joint notification system. We also evaluated results to find adequate threshold values for event detection, and stable determination of centroid-locations and MTs.

This feasibility study showed promising results at a magnitude level above $M_L \geq 4.5$ using data from only 3 stations. Out of a total of 28 such events, 15 were located within 40 km (the grid spacing coverage for this experiment) from the ground truth locations, two events in northern California were mislocated by more than 80 km, and the others fell in between. Including data from additional stations improved the performance. The test results also indicate that a variance reduction (VR) of 75% for the MT inversion seems to be an adequate measure to detect an event occurrence and to obtain a stable solution for it. In the band-pass filtered waveforms, relatively long-period structural noise comparable to source signals can also be emphasized for smaller events. Refinements of the method on a denser mesh (with an interval of $\sim$0.1 deg) also require more accurate path calibration, determining optimal station configuration and number, as well as ways to minimize computing time. The results of this feasibility study will be presented at the Fall 1999 AGU meeting (Tajima et al., 1999)

3.3 Path Calibration for Improvement of the System

There are some events for which MT inversions were not very stable in the northern California, Mendocino and south Bay regions. At present Green's function are chosen from a group of Greens' functions that were calculated for every 5 km in the distance range between

100 and 400 km, and every 3 km in the depth range from 5 to 39 km using either the 1-D southern California model or Gil7 model, not accounting for the 2-D or 3-D structure along specific paths between grid points (virtual source locations) and station locations. To obtain stable solutions using the new system, the structures along paths between grids and stations should be modeled properly to compute Green's functions. The improvement of the structural model is critical for the Mendocino/Gorda plate region and northern California where no optimal models have been established to our knowledge. This work is in progress.

When installation of the new stand alone system is completed, we will be able to immediately determine the earthquake source parameters (location, size and mechanism) using real-time data from the sparse BDSN, and/or the backup subsystem at Sacramento, should a significant event take place.

3.4 References

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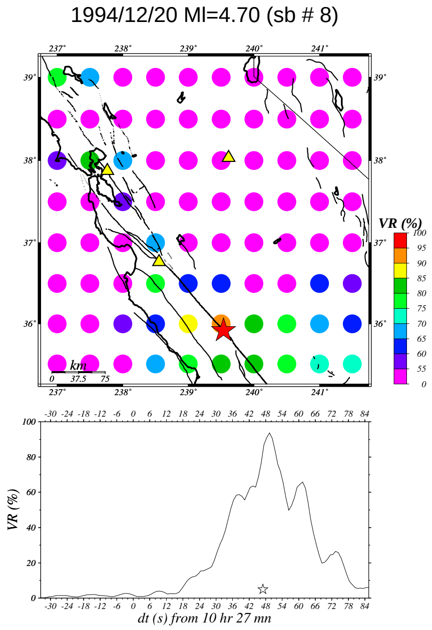

Figure 10.5: Example of resolution of simultaneous determination of location and MT in a grid search scheme. The study area is covered by a grid with an interval of 0.5 deg. Note that the optimal point source location identified with a VR of $\geq$ 90 % is very close to the true location (provided by the USGS) denoted with a star (upper panel) and the VR is maximum at the origin time (lower panel)

Full Moment Tensor Solutions for November 1997 Swarm

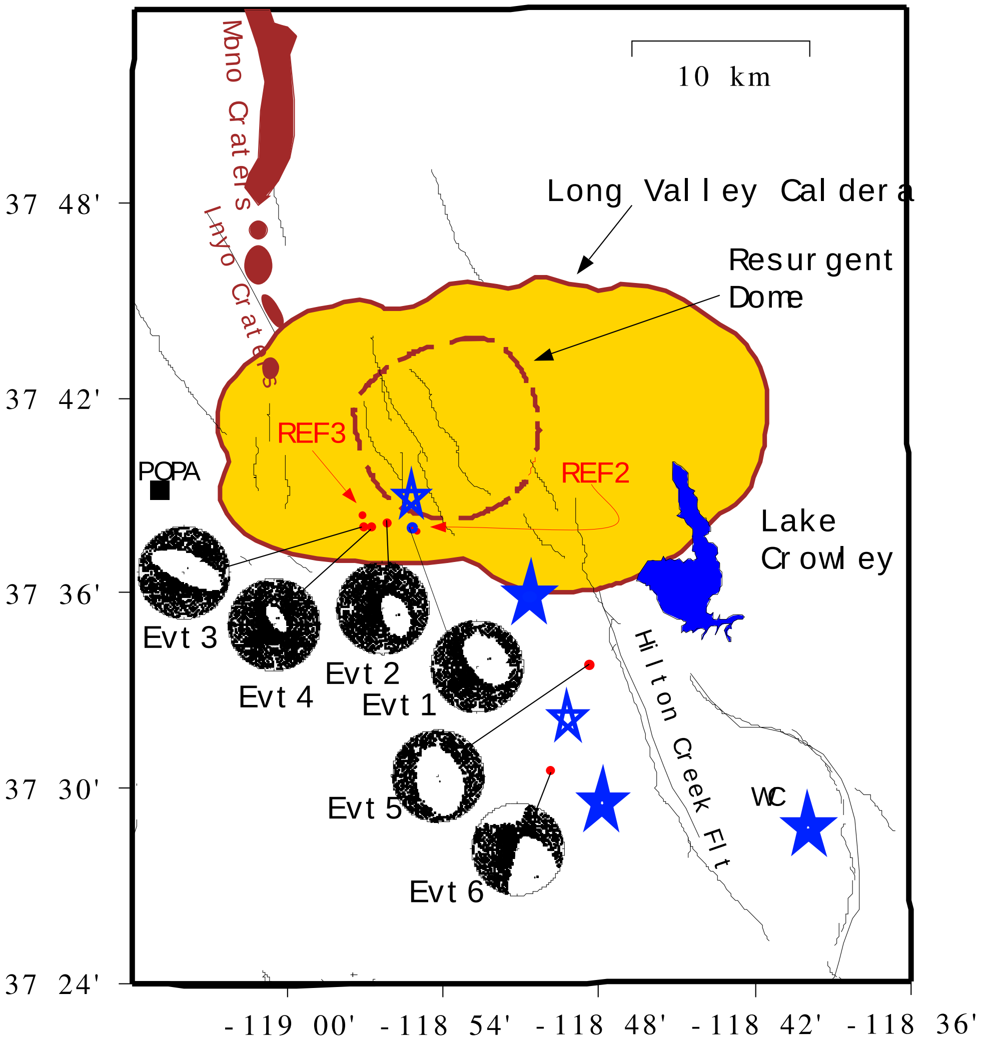

Figure 10.6: Map showing the Long Valley, Caldera, resurgent dome, Inyo-Mono craters chain, and earthquakes we investigated. The P-wave radiation patterns for the full moment tensor solutions are plotted. EVT1, EVT2, EVT3 and EVT4 result in anomalous seismic moment tensors with significant isotropiccomponents indicating volumetric expansion. Note that EVT5 and EVT6 are events that result in nearly pure double-couple solutions. The locations of 1980 Mammoth Lakes earthquakes are shown as stars and those with significant non-double-couple (NDC) components are shown as filled stars. The event labeled WC is the 1978 Wheeler Crest earthquake that also had a large non-double-couple component to the seismic moment tensor. The Devil's Postpile dilatational strain meter (POPA) is located by the filed square.