ANNUAL PROJECT SUMMARY

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RAPID EARTHQUAKE DATA INTEGRATION:
Collaborative research between UC Berkeley
and the U.S. Geological Survey, Menlo Park

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INVESTIGATIONS UNDERTAKEN

The Rapid Earthquake Data Integration (REDI) Project is a system for the automated determination of earthquake parameters, based on a sparse, broadband network. We have implemented this system using data from the Berkeley Digital Seismic Network, focusing on local and regional events in northern and central California. Program development was initiated in 1993 and a prototype system began providing automatic location and magnitude information in November of 1993 using commercial pagers and the Internet (*Gee et al.*, 1996a).

In northern California, the BSL and the USGS Menlo Park collaborate to provide the timely and reliable earthquake information to the federal, state, and local governments, to public and private agencies, and to the general public. This joint earthquake notification system provides enhanced earthquake monitoring by building on the strengths of the Northern California Seismic Network, operated by the USGS Menlo Park, and the Berkeley Digital Seismic Network (BDSN), operated by the UC Berkeley Seismological Laboratory. Over the last year, the BSL has focused its efforts to expand the capability of the REDI system and enhance its reliability, including minor modifications required for Y2K. The BSL has completed work to incorporate the finite-fault. estimation procedures of *Dreger and Kaverina* (1999) in the REDI system and has worked with the USGS and CDMG toward the implementation of "Shake Maps" in the San Francisco Bay Area.

Background

Current Status

On April 18, 1996, the BSL and the USGS announced the formation of a joint notification system for northern and central California earthquakes (*Gee et al.,* 1996b). The system merges the programs in Menlo Park and Berkeley into a single earthquake notification system, combining data from the NCSN and the BDSN. On the USGS side, incoming analog data from the NCSN are digitized, picked, and associated as part of the Earthworm system (*Johnson et al.*, 1995). Preliminary locations, based on phase picks from the NCSN, are available within seconds, based on the association of a few arrivals, while final locations and preliminary coda magnitudes are available within 2-4 minutes. Earthworm reports events - both the "quick-look" 25 station hypocenters (without magnitudes) and the more final solutions (with magnitudes) to the Earlybird alarm module in Menlo Park. This system sends the Hypoinverse archive file to the BSL for additional processing, generates pages to USGS and UC Berkeley personnel, and updates the northern California earthquake WWW server.

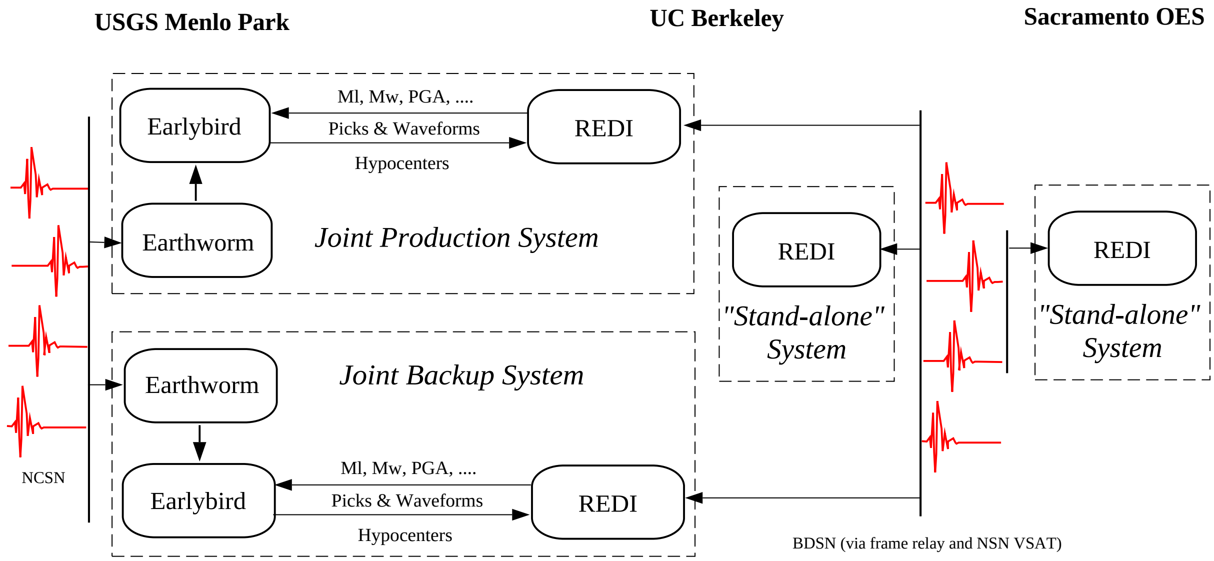

Figure 1: Schematic diagram illustrating the connectivity between the real-time processing systems at the USGS Menlo Park and UC Berkeley. The combined system forms the joint earthquake notification project in Northern California. In addition to the joint system components, the BSL operates a "stand-alone" REDI system at UC Berkeley (to provide event information if the communication link between Berkeley and Menlo Park is severed) and at Sacramento. The Sacramento system is a pilot project to provide earthquake information to OES in case of a damaging Bay Area earthquake.

On the UC Berkeley side, the Hypoinverse archive file is used to drive the REDI processing system. This is a modification of the original REDI design, which identified and located events using raw phase data from the BDSN and NCSN (*Gee et al.*, 1996a). In the revised REDI processing, the magnitude of each hypocenter is assessed. If the coda magnitude is greater than or equal to 3.0, waveforms from the BDSN are analyzed to estimate local magnitude. Once an updated magnitude is obtained, the event information is paged to USGS and UC Berkeley personnel, notification is sent to emergency response agencies, and the revised magnitude is transmitted to the Earlybird system in Menlo Park. The earthquake is then evaluated for the next level of REDI processing. If the local magnitude is greater than 3.5, waveforms from the BDSN strong-motion instruments are analyzed to determine peak ground acceleration, velocity, and displacement and to estimate the duration of strong shaking. When the strong-ground motion processing is complete, these values are distributed by email and pager and the event is scheduled for moment tensor estimation. In this stage of REDI processing, both the waveform modeling method of *Dreger and Romanowicz*

Stage	Qualification	Processing
1	All events	Location
2	M $>$ 3.0	Local magnitude, *Energy magnitude*
3	M $>$ 3.5	Peak ground motion
4	M $>$ 3.5	Moment tensor
5	M $>$ 6.0	*Line source finite fault*
6	M $>$ 6.0	*2D finite fault*

Table 1: Current REDI processing stages. The location procedures in Stage 1 are skipped in normal operation of the joint system, but are utilized if problems prevent the flow of hypocenter information from the USGS. The items in italics are recent extensions to the REDI system.

(1994) and the surface wave inversion technique of *Romanowicz et al.* (1993) are run for every qualifying event (earthquakes with M_L greater than 3.5). Each algorithm produces an estimate of the seismic moment, the moment tensor solution, the centroid depth, and solution quality. The REDI system uses the individual solution qualities to compute a weighted average of moment magnitude, to compare the mechanisms using normalized root-mean-square of the moment tensor elements (*Pasyanos et al.*, 1996), and to determine a ”total” mechanism quality.

At present, two Earthworm-Earlybird systems in Menlo Park feed two REDI processing systems at UC Berkeley (Figure 1). One of these systems is the production or paging system; the other is set up as a hot backup. The second system is frequently used to test new software developments before migrating them to the production environment. In addition, the BSL operates a third system, which uses BDSN picks to form an independent list of associated events. This third system provides redundancy in case the communication links with the USGS Menlo Park are disrupted. A fourth system is installed in Sacramento in order to provide a redundant notification facility outside of the Bay Area.

Earthquake information from the joint notification system is distributed by pager, e-mail, and the WWW. The first two mechanisms ”push” the information to recipients, while the current Web interface requires interested parties to actively seek the information. Consequently, paging and, to a lesser extent, e-mail are the preferred methods for emergency response notification. The Northern California Web site has enjoyed enormous popularity since its introduction and provides a valuable resource for information whose bandwidth exceeds the limits of wireless systems and for access to information which is useful not only in the seconds immediately after an earthquake, but in the following hours and days as well.

RESULTS

New developments

Year 2000 compliance

The REDI system did not experience any major problems due to Y2K issues. Modifications to the Earthworm components of the REDI system had been implemented and thoroughly tested by the end of the year. Only small changes were required in the REDI software, primarily in the moment tensor codes. One small bug slipped through the cracks, and turned up during the first event which qualified for moment tensor processing in 2000. This bug was quickly identified and fixed.

Comserv

The BSL uses the `comserv` program for central data acquisition, which was developed by Quanterra. The `comserv` program receives data from a remote Quanterra datalogger, and redistributes the data to one or more comserv client programs. The comserv clients used by REDI include `datalog`, which writes the data to disk files for archival purposes, `cdafill`, which writes the data to the shared memory region for REDI analysis, and other programs such as the seismic alarm process, the DAC480 system, and the feed for the Momento Mori Web page (Figure 2).

The two computers that perform data acquisition also serve as REDI processing systems. In order to facilitate REDI processing, each system maintains a shared memory region that contains the most recent 30 minutes of data for each channel used by the REDI analysis system. All REDI analysis routines first attempt to use data in the shared memory region, and will only revert to retrieving data from disk files if the requested data is unavailable in the shared memory region.

Most BDSN and HFN stations transmit data to only one or the other of the two REDI systems. In earlier system configurations, each station would transmit data to one of the two systems, which would write the data to local disk files, copy the data in its own shared memory region, and transmit the data via a socket to the other system's shared memory region. Each REDI system's shared memory region contained data from all stations, but each computer's filesystem contained data from only one half of the network. The REDI systems use the Network File System (NFS) to access remote files that reside on other computers. If a REDI analysis program required data that was not in the shared memory region, it would attempt to retrieve the data from the disk files from both REDI computers. If one of the two REDI computers was unavailable, this could cause the REDI processing to hang waiting for access to the other computer's files.

During the past year, we revised our data acquisition procedure to use two programs developed at Caltech. The comserv client program `cs2m` receives data from a comserv and multicasts the data over a private ethernet. The program `mcast`, a modified version of Quanterra's `comserv` program, receives the multicast data from `cs2m`, and provides a comserv-like interface to local comserv clients. This allows each REDI system to have a comserv server for every BDSN station. We added additional disk space to both of the REDI computers so that we use `datalog` to write a copy of data to each computer's filesystem. We reconfigured the REDI computers to only retrieve data from their own filesystems, thereby preventing a loss of one REDI computer from possibly hanging the other REDI computer's processing.

We extended the multicasting approach to handle data received from other networks such as the NCSN and UNR. These data are received by Earthworm data exchange programs, and are then converted to MiniSEED and multicast in the same manner as the BDSN data. We use `mserv` on both REDI computers to receive the multicast data, and handle it in an identical fashion to the BDSN MiniSEED data.

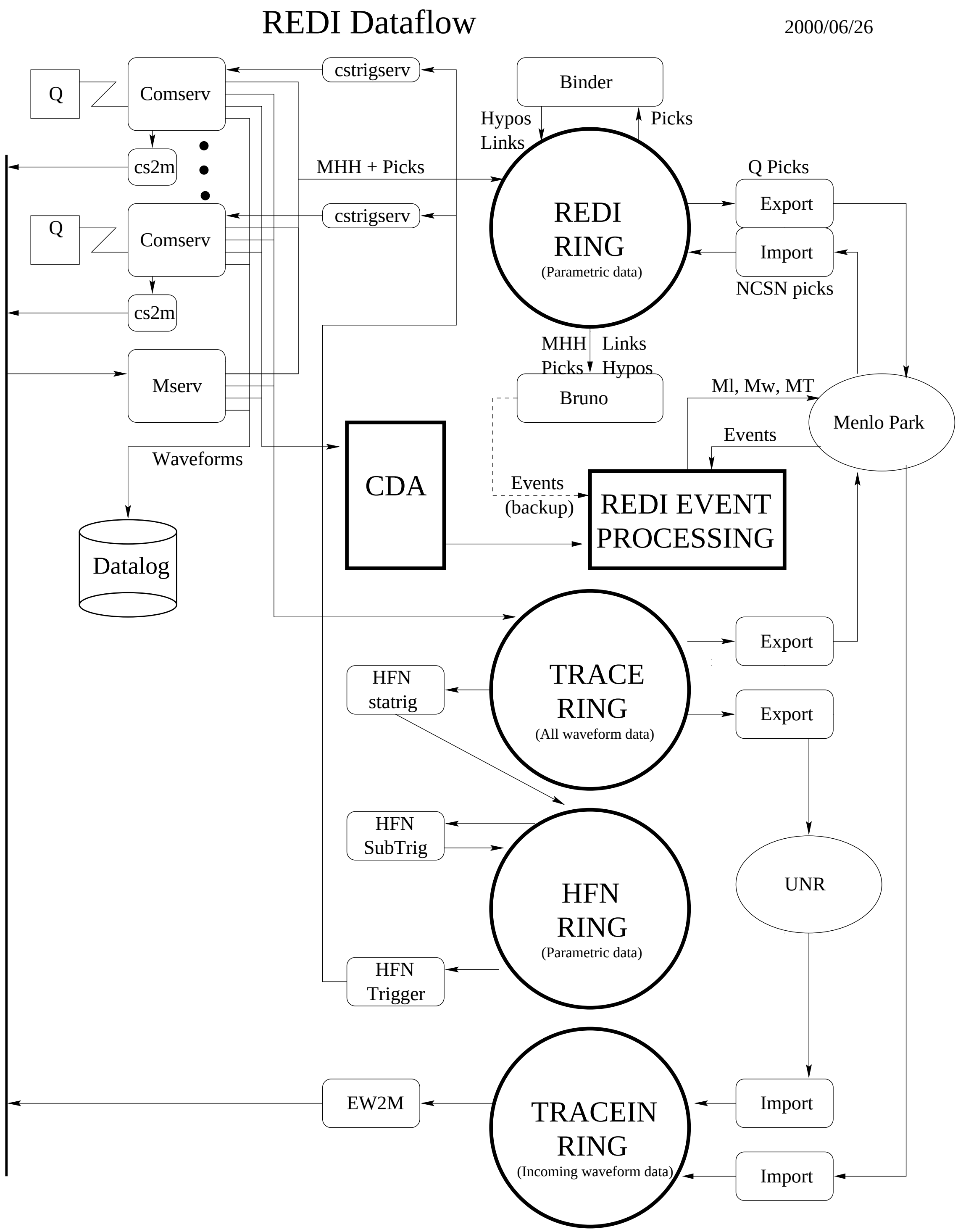

Figure 2: Dataflow in the REDI processing environment, showing waveform data coming in from the Quanterra dataloggers (Q) into `comserv`. From comserv, data are logged to disk (via `datalog`), distributed to other computers (`mserv`), fed into the CDA for REDI processing, and spooled into a tracering for export.

Three-Component Picker

In the last year, we have worked to stabilize the picker for an operational environment. This has included numerous bug fixes and development of error handling conditions (for example, how to treat telemetry outages). The code has been put into a software distribution package and is ready to be exported to potential users.

At present, the picker is running on a test system, feeding a stand-alone REDI system. Our remaining effort is focusing on testing the picker in conjunction with the associator. This work is being done in real time and by running historical events through an off-line version. We are also working on the issue of phase identification and upgrading the associator to take advantage of azimuth and phase id.

As an illustration, we show the results for the M4.8 earthquake near Bolinas. Figure 3 shows three sets of P travel-time residuals for a human, the picker, and the Murdock-Hutt (MHH) detector computed from the BSL catalog readings. Picks from the BH, HH, and HL channels are included. The scatter shown in the three plots is similar (around 1 to 1.5 sec), although the distribution of MHH is more compact. The scatter in the analysts' picks is somewhat surprising, but is primarily limited to the BH picks (HH and HL picks show better agreement). As this event illustrates, the picker is performing reasonably well, although it seems to pick slightly later than either the MHH or the analyst. The tendency to pick later is correlated with distance, as arrivals become more emergent. The picker, which was tuned on BH data, behaves more reliably on the BH and HH channels than on the HL channels. At near distances to an event, better picks are obtained from the HH data as the higher sampling rate reduces problems associated with the acausal FIR filters.

The picker can identify S as well as P arrivals, although it has some difficulty at short distances.

Figure 4 illustrates how the association algorithm performs with output from the picker. The locations computed from the BH (downward triangle), HH (upward triangle), and HL (square) are shown, in comparison with the location from the BSL catalog. The BH and HH locations are within a few km of the catalog location, while the HL location is shifted to the west. The picker made fewer detections on the HL data, which reduced the quality of the location.

Finite-Fault Parameterization

Over the last year, we have expanded the REDI processing environment to include the estimation of finite-fault parameters. This approach is based on the use of theoretical Green's functions and is an extension of the finite-source inversions that are commonly performed on local strong-motion data (for example, *Wald et al.* (1996) and *Cohee and Beroza* (1994)). Using a pre-computed set of Green's functions for an appropriate 1-D velocity model, it is possible to consider an arbitrarily oriented source using parameters obtained from the automated moment tensor analysis and a directivity model of an expanding circular rupture with a constant rupture velocity and dislocation rise time.

Based on the development of *Kaverina et al.* (1997) and *Dreger and Kaverina* (1999), we have implemented the finite-fault estimation procedure in two REDI stages. In stage 5, BDSN broadband and strong-motion waveform data are prepared for inversion and rough estimates of the fault dimensions are derived using the empirical scaling relationships of *Wells and Coppersmith* (1994). Using these parameters to constrain the overall dimensions of the extended source, the process tests the two possible fault planes (determined in stage 4) over a range of rupture velocities by performing a series of inversions using a line-source representation.

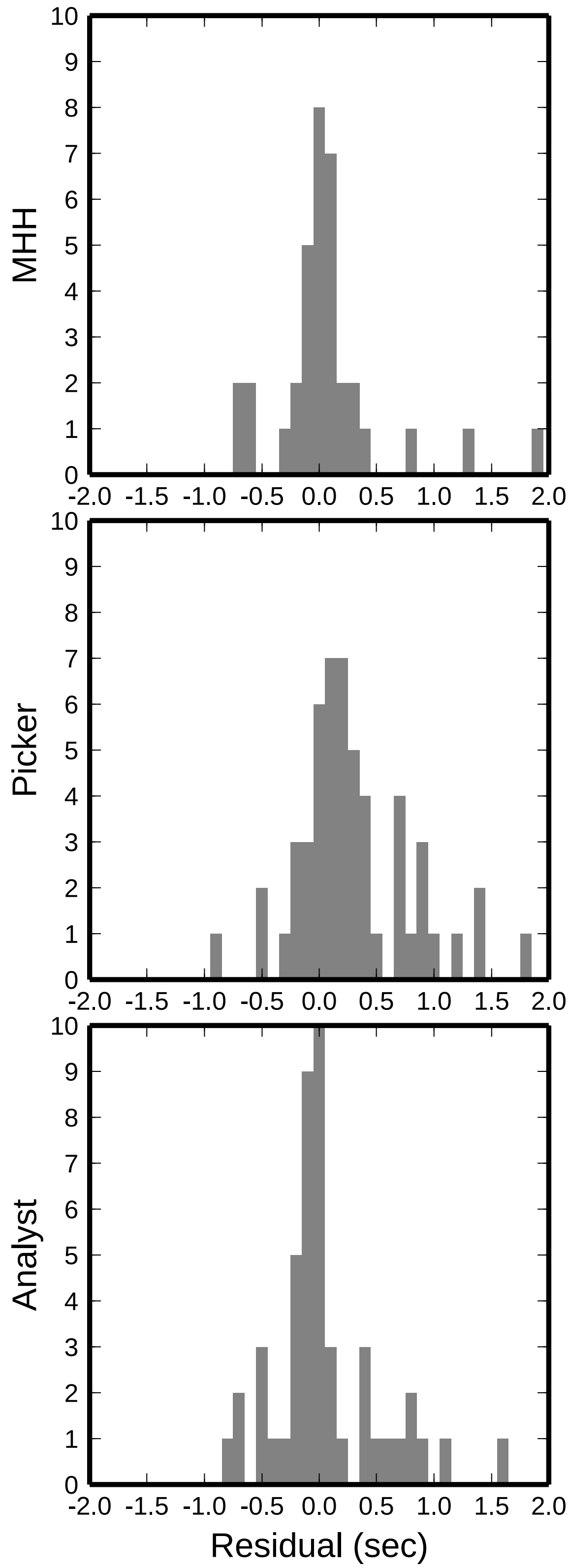

Figure 3: Distribution of P travel-time residuals for an analyst, the picker, and the MHH detector. The residuals for BH, HH, and HL channels are computed from the phase readings from the BSL catalog (typically made on the HH data stream).

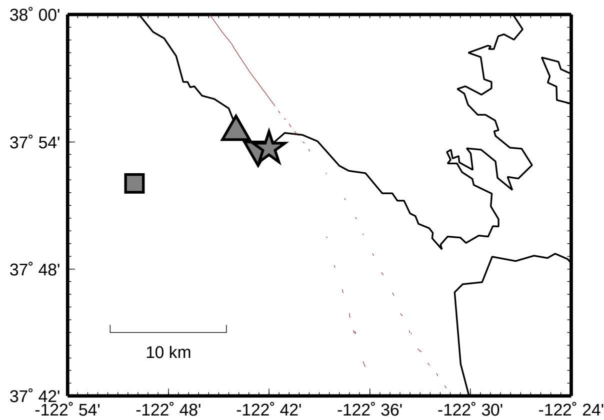

Figure 4: Map comparing the different locations obtained from combining the picker with the associator. The star is the location from the BSL catalog. The downward triangle is the location based on the BH picks, the upward triangle is the location based on the HH picks, and the square is the location based on the HL picks. The differences between the BSL catalog location and the BH and HH picks are only a few km. The HL location is shifted significantly west.

Each line-source computation is quite rapid. Calculations for the 1992 Landers and 1994 Northridge earthquakes required approximately 3.5 minutes to test 7 rupture velocities for the two different planes (*Dreger and Kaverina*, 1999). In tests based on the Landers and Northridge earthquakes, the fault plane was clearly defined by the variance reduction from the line-source inversions. In addition to the identification of the fault plane and apparent rupture velocity, this stage yields preliminary estimates of the rupture length, dislocation rise time, and the distribution of slip in one dimension.

The second component of the finite-fault parameterization uses the best-fitting fault plane and rupture velocity from Stage 5 to obtain a more refined image of the fault slip through a full two-dimensional inversion. If Stage 5 fails to identify the probable fault (due to insufficient separation in variance reduction), Stage 6 computes the full inversion for both fault planes. In the present implementation, the full inversion requires an additional 20-30 minutes per plane, depending on the resolution, on a Sun UltraSPARC1/200e.

This extension of REDI processing is running on a development system at the BSL, where it is being tested. We anticipate migrating these modules to the production systems in the fall of 2000. At the time of the 1999 Hector Mine earthquake, the REDI implementation was not complete. However, the approach was tested using several regional-distance stations from TriNet. *Dreger and Kaverina* (2000) first used the line-source inversion to identify the causative fault plane and then obtained the distribution of slip on the NW-trending plane using the best-fitting rupture velocity. The image of the finite rupture obtained by this procedure agreed well with aftershock locations and observed surface rupture.

Shake Maps

During the past year, the USGS Menlo Park implemented version 1.0 of the ShakeMap software for northern California earthquakes (*Boatwright et al.*, 1999). This software package, developed as part of the TriNet project in southern California (*Wald et al.*, 1999), combines observed values of ground motion with predicted values (primarily based on attenuation relations) in order provide maps of strong shaking. During the past year, we implemented software to push ground motion data from the BDSN to the USGS for use in ShakeMaps. The northern California maps combine data from the primary earthquake monitoring agencies (USGS, CDMG, BSL) with other sources of strong motion data (such as PG&E) in order to provide the most complete view of ground motion following an event.

The first ”official” northern California ShakeMap was produced for the August 18, 1999, earthquake near Bolinas, California (see discussion below). As presently implemented, the REDI system pushes ground motion data to the ShakeMap system in Menlo Park for events of M3.5 and higher at the completion of the stage 2 processing.

The USGS Menlo Park is currently testing ShakeMap version 2.0, which provides improved corrections for geology and greater flexibility for different attenuation corrections and other sources of predicted ground motions. Once version 2.0 is implemented in Menlo Park, we intend to install the ShakeMap codes as part of the REDI system at the BSL.

Data exchange

In order to improve our capabilities on the edges of the network, we have initiated efforts to establish mechanisms of data exchange with neighboring networks.

We have recently completed an agreement with the University of Nevada, Reno, to enhance the earthquake monitoring capabilities in northern California and Nevada. As part of this agreement, we agreed to exchange waveform data. At the present, three-component data from CMB, WDC, MOD, and ORV and vertical component data from YBH, ARC, HOPS, WENL, SAO, and KCC are being sent to UNR. In exchange, the BSL is receiving three-component data from BEK, OMM, PAH, and WCN. In addition, UNR is forwarding data from the NSN stations WVOR, MNV, DAC, and ELK. The UNR sensors are Guralp 40Ts and these stations will enhance the REDI capabilities in eastern California and western Nevada.

The UNR data exchange is implemented using the Earthworm import/export mechanism, over the Internet. This is the same protocol we use for waveform exchange with the USGS Menlo Park. Figure 2 illustrates the current dataflow in the REDI environment. Data for export via Earthworm is fed into the Trace Ring, using a comserv client. An Earthworm export process picks data of the ring and transmits it to the UNR client and a separate process does the same for the USGS Menlo Park client. Data imported via Earthworm is brought into the Tracein Ring. A module converts from Earthworm to MiniSEED packets (ew2m) and the data is distributed to the two acquisition systems. Each acquisition system ”logs” the data using mserv.

The exchange with UNR has just gotten off the ground. Based on the experience of a few weeks, it seems as if there are a number of issues with reliability. We do not see as many problems with the Earthworm feed to Menlo Park, which may be attributed to the robustness of the frame-relay connection (as opposed to the Internet connection with UNR). We will be exploring other options in the coming months.

In addition to the exchange with UNR, the BSL exchanges waveform data with UCSD via a public domain Orb. We are currently working out the details of an exchange with Caltech.

In the coming year, we anticipate improving our capabilities within the network by expanding our data exchange with the USGS Menlo Park.

QDDS

We installed the ”Quake Data Delivery Service” or QDDS software at the BSL in the last year. This software was developed by the USGS to allow for the exchange of parametric earthquake data, such as locations and magnitudes. QDDS provides the earthquake information for the ”recenteqs” maps as well as for other applications. We are currently running QDDS and the ”recenteqs” software.

At present, the REDI system is not contributing data to QDDS. The USGS Menlo Park pushes information from the joint notification system to the two QDDS hubs. In the long run, we intend to modify the REDI system so that it provides information to one hub and the USGS provides information to the other. However, this modification requires restructuring some aspects of the way REDI tracks information (essentially, the use of version numbers) and we intend to implement this when we transition to a database environment.

Database

With the recent developments in the finite-fault processing and the planned expansion of the ShakeMap computations, it has become clear that the current use of flat files in REDI for information flow is not adequate to meet future needs. We have been considering two models for incorporating a database system in the REDI environment. The first is the database schema developed as part of the Northern California Earthquake Data Center in cooperation with Caltech. This database has been used by Caltech and the USGS in Pasadena in the TriNet realtime processing system as well as in the SCEC Data Center environment. In contrast, the USGS Menlo Park has been working with the Earthworm database schema, focusing primarily on the realtime environment.

We have begun exploring the issues of interfacing one database schema to another. The effort to incorporate a database within the REDI software is expected to be a major project for the coming year. We anticipate this revision of the REDI software will significantly expand and enhance our capabilities.

CISN

During the past year, we have worked toward coordinating our earthquake monitoring activities with southern California and on improving the collaboration in northern California. These efforts span the range of activities from realtime earthquake information to catalog generation to long-term archive and distribution.

This effort to coordinate is in part an outgrowth from the interest of the State of California in uniform earthquake reporting and in part a response of the development of the Advanced National Seismic System or ANSS. As the ANSS moves forward, national earthquake monitoring will be coordinated on a regional basis. California is evolving as one of those regions through the development of the California Integrated Seismic Network (CISN). Participating organizations are the

Berkeley Seismological Laboratory, the Caltech Seismological Laboratory, the California Division of Mines and Geology, the USGS Pasadena, and the USGS Menlo Park.

In practical terms, the development of the CISN is leading to better coordination among the participating agencies. Progress is being made in terms of sharing data and software. One of the most important components of the CISN is the Standards committee, which meets monthly to work on issues of coordination.

System Performance

From 07/01/1999 through 06/30/2000, the northern California joint notification system processed nearly 10,000 events. Approximately 3,000 of these events were distributed by the REDI system and just over 350 qualified for higher-level REDI processing (Figure 5).

Most of the 10,000 events were small to moderate earthquakes in northern California. In addition, the joint notification system processed the M7.1 Hector Mine, M6.3 Furnace Creek, and M5.8 earthquakes in southern California, Nevada, and offshore of Cape Mendocino respectively. The largest earthquake in the San Francisco Bay Area was the M4.8 earthquake near Bolinas. For more details on the system performance, the reader is referred to the Annual Report Summary at

seismo.berkeley.edu/seismo/annual_report/ar99_00.node12.html

which describes the performance of the joint notification system in some detail. As an example, however, we describe the performance for a recent event.

The September 3, 2000, Napa earthquake provides another recent example of the performance of the joint notification system. This earthquake occurred 5 km WSW of Yountville, CA, near the Napa Valley and approximately 5 km west of the West Napa fault. Although the earthquake was initially associated with the West Napa fault, it is now thought that that it is located on an unnamed fault. It is not unusual for earthquakes to occur on unnamed faults in California - for example, the 1983 Coalinga and 1994 Northridge events. The recent event showed the right-lateral strike-slip motion, typical of events in central California. Although there were a number of small aftershocks, very few have been over magnitude 2.5 and higher.

The main shock occurred at 08:36:30.09 UTC (Figure 6). The REDI system received the automatic hypocenter and coda magnitude from Earlybird at 08:40:32.37 (4 min and 2.28 sec later). At approximately the same time, the USGS Menlo Park generated automated pages with the location and coda magnitude to USGS and BSL staff and several clients. The REDI M_L calculation was completed just 19.11 sec later at 08:40:51.48 (4 min and 21.39 sec after the earthquake occurred) and the ML was pushed to Earlybird. At this point, the REDI system distributed the location and local magnitude by pager and email to BSL and USGS staff and to a number of clients. When the M_L was received by Earlybird, it updated the information on the WWW and notified the USGS recipients by pager of the revised magnitude. The next stage of REDI processing computes peak ground motions and this was completed at 08:41:15.85 (4 min and 45.76 sec after the earthquake occurred). At the conclusion of this stage, pages were distributed by REDI and a file containing estimates of PGA, PGV, and PGD was pushed to Menlo Park for use in the Northern California Shake Maps. The final stage in the ”production” REDI processing is the determination of the seismic moment tensor and this processing was completed at 08:45:12.35 (8 min and 42.26 sec after the event), providing both the moment tensor and the moment magnitude.

A couple of additional notes are required. Overall, the joint notification system performed extremely well, delivering rapid and reliable information about the earthquake’s location and magni-

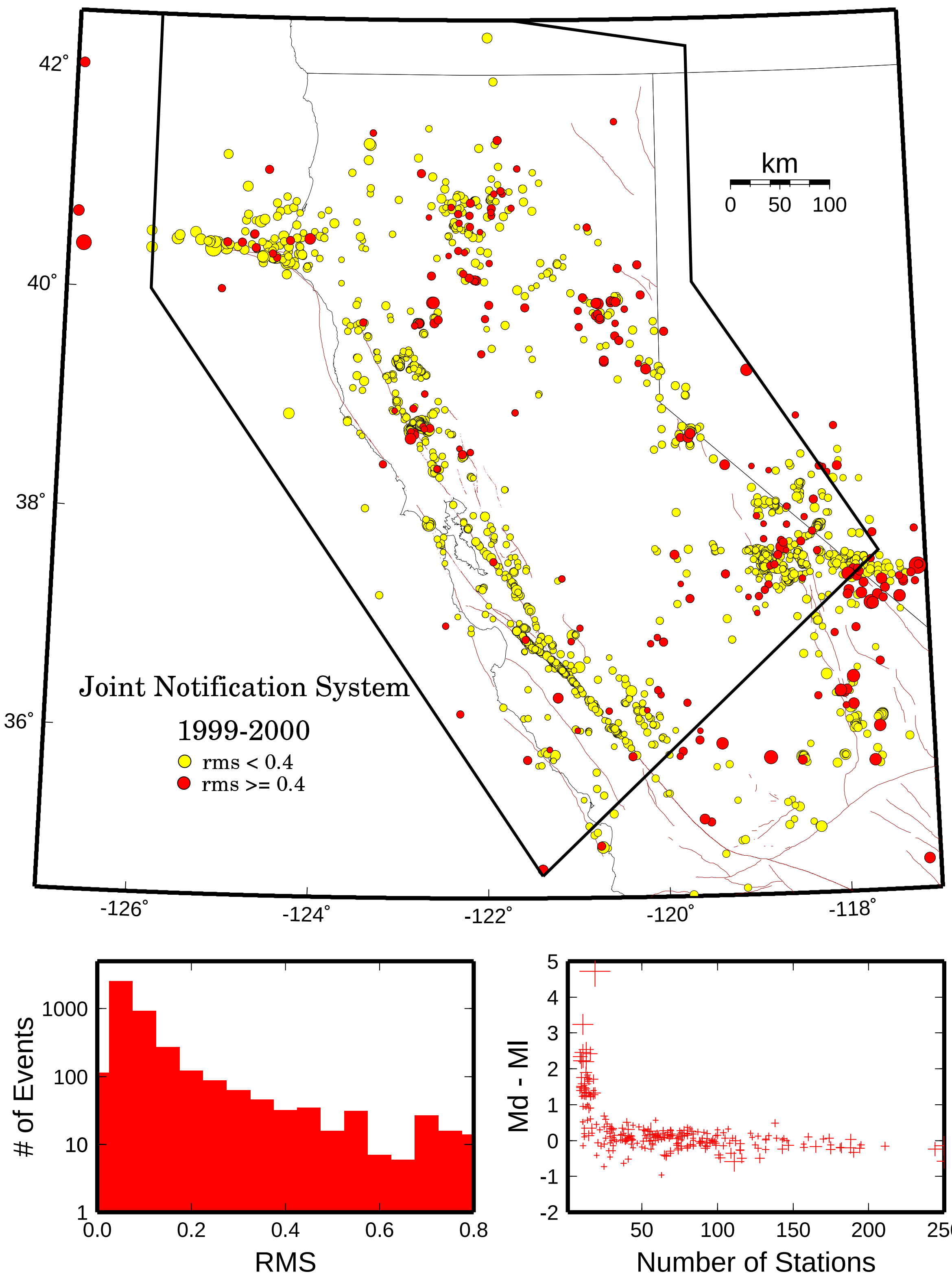

Figure 5: Map showing the events which met the REDI criteria for distribution (number of stations > 10, rms < 0.8) during 1999-2000. Shaded circles are events with rms greater than 0.4. Lower plots show the distribution of solution quality (as measured by the rms) and the difference between the local and coda magnitudes as a function of the number of stations in the location. The thick solid line indicates the "normal" paging boundary currently used by REDI, which will be revised this coming year to reflect collaborative efforts with UNR.

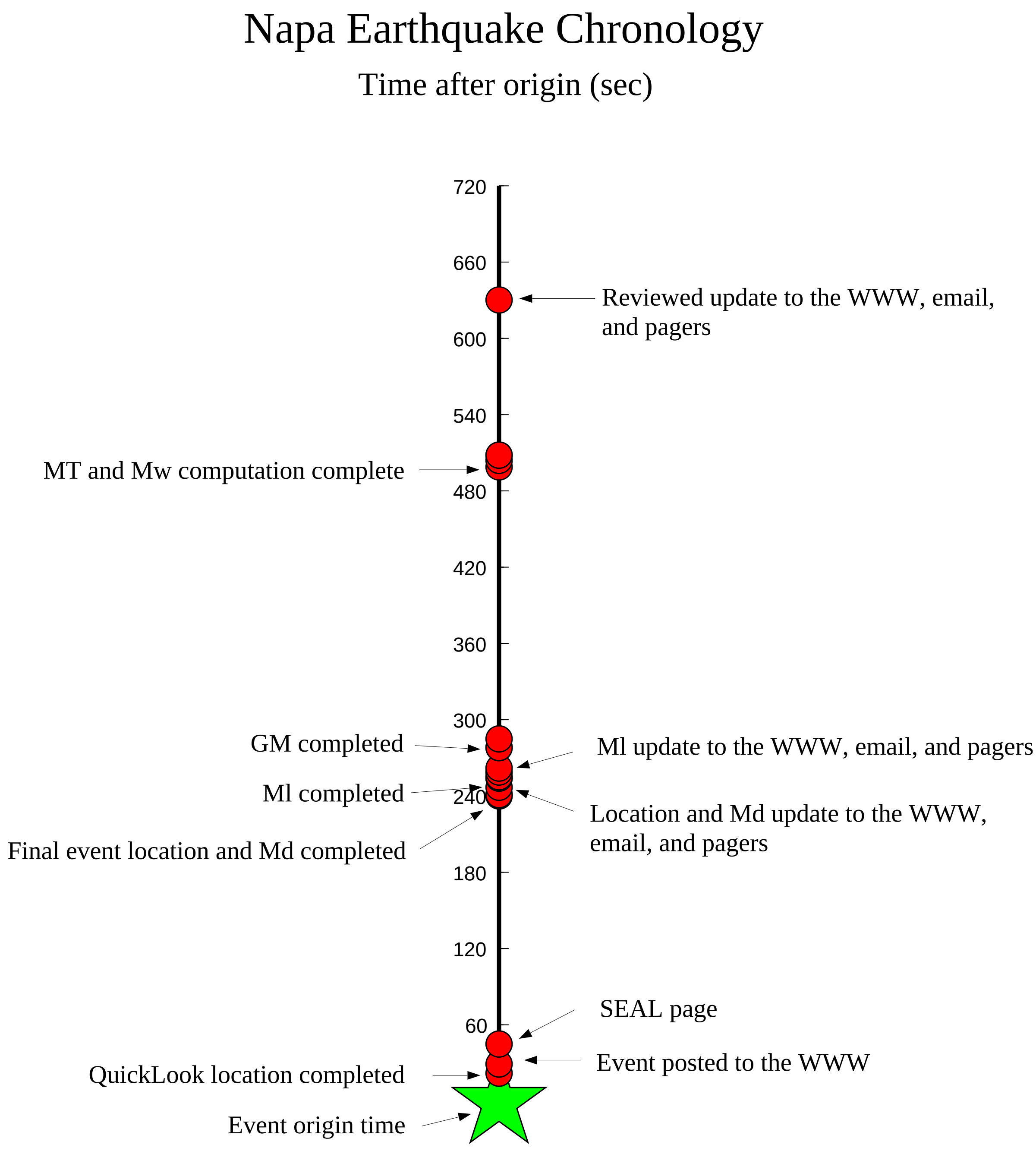

Figure 6: Illustration of the timing associated with processing for the 9/3/2000 Napa earthquake. The left side of the time line indicates operational activities; the right side indicates notification activities.

tude. The REDI system in Sacramento (Figure 1) also performed well. This system receives data from only 6 stations of the BDSN and operates independently of the the BSL systems in order to provide a backup source of earthquake information. Originally implemented as a pilot project, the system provides a source of information if the BSL facilities at UC Berkeley are compromised due to a damaging earthquake. The stand-alone REDI system obtained a comparable location (within 4 km) and fault-plane solution (within a few degrees) for the joint notification system.

On the other hand, there were problems associated with the generation of the Shake Maps. The REDI system has been pushing ground motion data to Menlo Park since Jan 1, 2000 for events of M 3.5 and higher. At present, the BSL data are not automatically included in the northern California Shake Maps - and the BDSN data were not incorporated until late Sunday morning. This is an implementation issue which will be resolved soon.

However, the event highlights a number of issues related to the integration of the USGS and BSL systems which need to be addressed in the future.

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NON-TECHNICAL ABSTRACT

This project focuses on the development and implementation of hardware and software for the rapid assessment of earthquakes. The Berkeley Seismological Laboratory collaborates with the USGS Menlo Park to monitor earthquakes in northern California and to provide rapid notification to public and private agencies for rapid response and assessment of earthquake damage. In the past year we have addressed Y2K issues and developed new software for improved estimates of earthquake size and for the characterization of earthquake ruptures. We have also collaborated with other organizations in northern California for the rapid assessment of strong ground shaking.

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Gee, L., D. Neuhauser, D. Dreger, M. Pasyanos, R. Uhrhammer, and B. Romanowicz, The Rapid Earthquake Data Integration Project, *Handbook of Earthquake and Engineering Seismology*, IASPEI, in press, 2000.

MEETING PRESENTATIONS

Boatwright, J., H. Bundock, J. Luetgert, D. Oppenheimer, L. Baker, J. Fletcher, J Evans, C. Stephens, K. Fogelman, L. Gee, D. Dreger, D. Carver, V. Graizer, C. Scrivner, M. McClaren, Implementing ShakeMap in the San Francisco Bay Area, EOS Trans. AGU, 80(46), F700, 1999.

Gee, L., S. Fulton, D. Dreger, A. Kaverina, D. Neuhauser, M. Murray, and B. Romanowicz, Recent Enhancements to the Rapid Earthquake Data Integration (REDI) System, Seismol. Res. Lett., 71, 232, 2000.

Murray, M. H., D. S. Neuhauser, D. R. Baxter, L. S. Gee, D. S. Dreger, and B. Romanowicz, Combining seismic and geodetic data to improve rapid earthquake notification, Seismol. Res. Lett., 71, 261, 2000. (invited)

DATA AVAILABILITY

Data and results from the REDI project are available at the Northern California Earthquake Data Center (*//www.quake.geo.berkeley.edu*) For additional information on the REDI project, contact

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