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TSUNAMI WARNING SYSTEM WORKSHOP REPORT (SEPTEMBER 14-15, 1994)

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UNITED STATES
DEPARTMENT OF COMMERCE

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Tsunami Warning System Workshop Report
September 14–15, 1994

Michael Blackford[1] and Hiroo Kanamori[2]

Executive Summary

The workshop attendees agreed that it is feasible to issue tsunami warnings within 5 minutes of earthquake origin time using existing instrumentation for earthquakes occurring along U.S. coastal areas. They further acknowledged that the existing tide gauge system is inadequate to detect and monitor a tsunami in excess of 1 meter along the U.S. coastline.

To implement 5-minute warnings, we recommend:

1. Upgrade the existing west coast seismic net to include real time telemetry of strong motion/broad band seismometers at several additional sites.
2. Increase the staff at the Alaska and Pacific Tsunami Warning Centers (ATWC and PTWC) to provide 24 hour/day in office operations.
3. Aggressively improve the automation of the processing of seismic data at the seismic centers and distribute these processed products via emergency communications (including internet).
4. Implement a plan to coordinate information exchange between ATWC, PTWC, National Earthquake Information Center (NEIC), and the west coast regional seismic networks. This will require additional hardware, software, and personnel for the existing seismic centers.
5. Add broad band seismometers to ATWC and PTWC, and access to existing broad band stations.

To establish an adequate water level system for tsunami warnings we recommend:

1. Install network of real-time reporting deep water tsunami gauges.
2. Modify and utilize the existing network of NOAA tide gauges and Coastal Data Information Program instruments for the monitoring of tsunamis up to 5 m.
3. Make all water level data available on internet for use by a wide range of users.
4. Conduct a siting study to determine the optimal configuration of deep, shallow, and coastal instrumentation for tsunami detection and monitoring.
5. Develop warning procedures that incorporate water level data to forecast tsunami impact.

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1. Introduction

The Tsunami Warning System Workshop represents a continuation of the effort of NOAA to establish an improved tsunami hazard reduction program. The overall goals of the program are to (1) develop model-based tsunami inundation maps for at-risk communities, (2) improve the tsunami detection/warning system, and (3) conduct research to improve tsunami modeling and data collection. The first goal was addressed at a tsunami inundation modeling workshop held November 16–18, 1993, in Honolulu, Hawaii and is reported in NOAA Technical Memorandum ERL PMEL-100. This workshop addressed the present state of the tsunami warning system and examined a number of other existing seismic and water level networks and data processing strategies that may be able to make significant improvements to the tsunami warning system.

Fifteen people attended the Workshop, including the Geophysicists-in-Charge of the Pacific Tsunami Warning Center (PTWC) and the Alaska Tsunami Warning Center (ATWC), representatives of agencies and institutions operating extensive automated seismic networks in the western United States and operating a variety of water wave measurement systems, and others who have developed techniques applicable to timely tsunami analysis. A list of the participants may be found in Appendix A.

Although there was a formal agenda, which is listed in Appendix B, the workshop assumed a relatively free form almost immediately. This promoted lively and fruitful discussions at the expense of adhering to a strict time schedule. All speakers did, however, have an opportunity to make their presentations. The presentations followed the general themes already mentioned, namely current status of warning systems, existing seismic and water wave measurement systems, and seismic and tsunami analysis techniques. On the second day the group, as a whole, discussed and developed a set of recommendations for improving the tsunami warning system. A summary of the presentations and details of the recommendations are given in the following sections. Appendices where additional information on presentations may be found are indicated in parentheses following the italicized title or theme of a presentation.

2. Presentations

2.1 Current Status of Tsunami Warning Systems

Alaska Tsunami Warning Center (Appendix C)—The ATWC provides regional tsunami warning service for Alaska, Oregon, Washington, California, and the Province of British Columbia, Canada. This area includes the tsunamigenic Alaska-Aleutian and Cascadian subduction zones. ATWC maintains a network of 15 seismic stations throughout Alaska and receives additional data from the National Earthquake Information Center (NEIC) that enables it automatically to locate and determine the size of earthquakes within its region within seconds after sufficient seismic data have been processed. Duty personnel, who must reside, as well as remain, within 5 minutes transit time of the office when on duty, are alerted by the seismic events. Depending on the location and severity of the event, the duty personnel will issue appropriate messages, typically within 12 minutes of the earthquake origin time. The type of message issued is based on the surface wave magnitude (Ms) of the earthquake. Because of the need to disseminate messages rapidly, water-level measurements are not considered in the initial message issued. Eight real-time and 45 dial-in water-level instruments are used by the ATWC to verify the generation of a tsunami and to aid in the decision to continue or cancel tsunami warnings and watches. The ATWC employs a system of networked microcomputers to accomplish its analysis and message generation tasks.

Pacific Tsunami Warning Center (Appendix D)—The PTWC functions primarily as the operational center for the Tsunami Warning System of the Pacific, which is comprised of a group of representatives of nations and states with interests in the Pacific basin who seek to coordinate tsunami detection and warning efforts within the area. In addition, the PTWC acts as a national tsunami warning center for events outside of the ATWC's area of responsibility that may affect the United States' interests and as a regional warning center for Hawaii. Similar to the ATWC, the PTWC operates a network of nine seismic stations and five tide stations within Hawaii to assist in meeting its responsibilities as a regional tsunami warning center and it also receives data from the NEIC to assist with events occurring outside of Hawaii. The real-time seismic data, however, is not routinely used for earthquake location determination. Instead, the PTWC receives, via Internet, automatic solutions from the NEIC for Pacific basin events and automatic solutions from the Hawaii Volcano Observatory (HVO) for local Hawaiian earthquakes. The real-time seismic data is used as a backup if the automated solutions fail or are not available. The PTWC determines magnitudes from its own instrumentation. The type of message PTWC disseminates is also based on the M_s. For local events in Hawaii the PTWC can typically issue a voice message or warning, based strictly on earthquake data, to local authorities within 6 to 10 minutes of the earthquake origin time. For events elsewhere, the PTWC's response ranges from 30 minutes to an hour after the earthquake origin time, mainly due to the time required for the magnitude-determining seismic waves to reach the PTWC instruments. The PTWC uses a mixed network of microcomputers and workstations for data acquisition and processing and for message generation and dissemination.

Tsunami Warning System in Japan (Appendix E)—The Japanese Meteorological Agency (JMA) is responsible for the issuance of tsunami advisories and warnings in Japan. The JMA has six regional Tsunami Warning Centers (TWC) distributed among the islands of Japan from Hokkaido in the north to Okinawa in the south. Each center is staffed 24 hours a day and is equipped with an Earthquake and Tsunami Observation System (ETOS) that automatically detects earthquakes, picks P and S wave arrivals, estimates location, depth, and size, and generates tsunami messages based on these parameters. Seismologists determine dissemination of the messages. An ETOS acquires telemetered seismic and water level data from within a TWC region and processes it on a super-minicomputer. Tsunami messages are distributed to the government, TV and radio stations, and to JMA over a variety of telecommunications. Typical response time for message dissemination is currently about 5 minutes. JMA is working toward warnings issued in 3 minutes.

2.2 *Seismic Networks*

National Seismic Network (Appendix F)—The National Seismic Network (NSN), when complete, will consist of a relatively sparse nation-wide network of highly reliable, highly linear, real-time, three-component, calibrated, broad-band instruments capable of on-scale monitoring of moderate to large earthquakes at local, regional, and teleseismic distances. As of 1 April 1994 the NSN had 17 stations in operation with another five planned for installation during the year. An additional 11 cooperating stations had been established with another 11 planned for installation during the year. The NSN is projected to grow to a network of 60 stations located in the 48 contiguous United States. A network processor automatically determines seismic phase arrival times and generates a preliminary event location. Later arrivals associated with the event are incorporated into subsequent solutions of the earthquake's location. The network processor software has been designed to be very flexible, both in terms of load and capability. A multi-processing design with automatic load balancing provides redundancy and handles the highly variable real-time load. The results of the automatic processing are broadcast to the NEIC duty personnel and to a limited number of users with public safety responsibility. The results for larger events are also sent to the IRIS Data Management Center to trigger a data retrieval process from IRIS stations world-wide.

Southern California Seismic Network (Appendix G)—A network of 224 high, low, and ultra-low gain seismic instruments, including forced balance accelerometers, and data from the broad band, high dynamic range, TERRAscope array make up the Southern California Seismic Network. On-scale data from at least a portion of the integrated network allow for the rapid determination of both earthquake location and magnitude. Initial epicenters and magnitudes are available within a minute of the earthquake origin time and event parameters are typically finalized in about 90 seconds. The automatically processed results are disseminated over the CalTech/USGS Broadcast of Earthquakes (CUBE) system and are made available through the E-mail and finger capabilities of Internet around 2 minutes after the earthquake origin time. For larger events the initial magnitude estimate may be updated by data from the TERRAscope array at about 4 minutes after the origin time. The CUBE system transmits the earthquake parametric data to a commercial radio pager service where it is broadcast to over 120 pagers in the southern California area.

Northern California Seismic Network (Appendix H)—The U.S. Geological Survey and the University of California at Berkeley operate two separate seismic networks to monitor earthquake activity in central and northern California. These two seismic networks transmit seismic data in real time from 356 sites with short-period, high- and low-gain seismometers, and 12 sites with broadband instruments and accelerometers to central facilities where computers analyze these data in order to detect the occurrence of an earthquake. When an earthquake is detected, its location and magnitude are automatically calculated within 3 minutes and the information is made immediately available to the public throught a variety of facilities, such as "finger quake," e-mail, paging systems, and autodrm software. Moment tensor solutions are automatically computed within 15 minutes. Although the two networks overlap each other, they record different parts of the seismic specturm and consequently complement each other. Both networks share real-time data and store their information on a common, public access data facility. New hardware and software is under development that will provide earthquake notification within seconds of occurrence.

Pacific Northwest Seismograph Network (Appendix I)—The Pacific Northwest Seismograph Network (PNSN) is a network of 134 short period and 6 broad band seismic instruments. The network covers Washington and western Oregon and is operated by the University of Washington, the University of Oregon, and Oregon State University. Data acquisition and processing is performed on a Concurrent 5600 computer using the HAWK real-time seismic recording and processing system. Since the end of 1989 the PNSN has been equipped with an automated detection and alert system that pages local seismologists on the occurrence of earthquakes over magnitude 2.9. In addition, the system E-mails the parametric information to other regional networks and the NEIC, and FAXes the location and size of the event to local emergency managers. This information is updated as soon as it is reviewed by a seismologist, usually within an hour after the event.

IRIS Rapid Data Access Systems (Appendix I)—The Incorporated Research Institutes for Seismology (IRIS) Data Management Center (DMC) is located at the University of Washington and operates the SPYDER system to provide wave-form data of large earthquakes to seismologists worldwide within a few minutes to hours. One task of IRIS is to provide seismologists around the world with relatively rapid access to reliable, calibrated and standardized, broad-band seismic waveform data through electronic data transfer. The IRIS SPYDER system, using the NEIS preliminary earthquake location as input, calculates the P-wave arrival times to 60 of the Global Seismic Network stations around the world, and retrieves the data by telephoning each station and down-loading selected time wave-form segments to the main DMC machine. The actual telephone calls are placed by several different computers around the world interconnected by the Internet. Since several different computers actually place telephone calls to stations physically near them, data retrieval from several stations takes place at the same time. Another system, CHEETAH, developed through a joint effort between NEIC and IRIS and in operation at the DMC, is a much more rapid data access system that allows the NEIC to have access to a limited set of stations that are important for a better earthquake location, within only a few minutes of the automatic alert request for data sent out by the NEIC.

2.3. Water Level Measurement Networks

Near-Source Tsunami Measurements for Forecast and Warning (Appendix J)—Direct sea level measurements acquired near potential tsunami sources such as the Cascadia or Alaska-Aleutian Subduction zones could greatly improve the speed and accuracy of tsunami hazard assessment, forecast and warning. The technology is now available to develop a deep ocean, real-time tsunami reporting system to provide these direct tsunami measurements near potential source regions in deep offshore waters. Subsurface acoustic links and deep ocean surface buoys that report in near real-time via satellite are now available. Improved satellite links, capable of reporting relatively high data rates in real-time, should be available within 2 years. Tsunami hazard assessments made on the basis of seismic data are, in the final analysis, indirect. The greatest advance in improving the accuracy of tsunami forecast is the direct measurement of the tsunami before the waves strike the shoreline. Coastal tide gauge data are invaluable in assessing tsunami conditions, yet these data are often difficult to interpret because of a large number of factors that can affect the environment of the gauge location. Also, it is only possible to make an assessment after a tsunami has arrived and affected the coastal area.

Coastal Data Information Program (Appendix K)—The Coastal Data Information Program (CDIP) is a cooperative effort managed jointly by the U.S. Army Engineers, Waterways Experiment Station and the State of California, Department of Boating and Waterways. The program is conducted by the University of California, Scripps Institution of Oceanography (SIO) for the purpose of collecting, analyzing and disseminating coastal environmental data, with an emphasis on nearshore wave climate. The CDIP typically relies on an inventory of five or six systems to measure shallow and deep water wave energy and directional distributions, as well as wind and currents. Most stations consist of offshore pressure sensors mounted on the bottom at depths between 5 and 15 meters. Instruments are typically configured in a 6-m square array of four pressure sensors or a single pressure sensor and a current meter located at a single point. The instruments are connected to a field station on shore by an armored cable. Coastal data is typically collected by accelerometers on buoys that measure the pitch and roll of the buoys. The data are radioed to field stations on the nearby shore. Several times a day the central data gathering, processing and dissemination facility at SIO dials each field station and downloads the stored data. The data are screened for accuracy, analyzed and archived for research use. A window of data remains online and is available to a limited number of dial-up users. The station dial-up schedule can be modified to accommodate unusual circumstances, including intense storms or a tsunami alert. Under a cooperative arrangement with the Pacific Marine Environmental Laboratory (PMEL), a procedure has been developed to activate continuous sampling of certain modified stations when NOAA determines a tsunami is pending. The CDIP is a successful cooperation between federal and state government and academia.

2.4 Tsunami Analysis Strategies

Recent Analyses Using the TREMORS (Appendix L)—The TREMORS, or Tsunami Risk Evaluation through seismic MOment in a Real-time System, has been fully operational at the Geophysical Laboratory in Papeete, Tahiti (PPT) since mid-1987. Its features include automatic detection of seismic waves, evaluation of the epicenter from the three-component record at a single station, and evaluation of the seismic moment through computation of the mantle magnitude, Mm. The system performs in real time and, at regional distances, begins computation of Mm as soon as the Airy R phase (in practice, the S-wave) is received. The computations are regularly updated using longer and longer period waves. The system works at regional distances greater than 150 km. Six recent earthquakes, most with locally destructive tsunamis, were analyzed. The single station locations were adequate but not very accurate, especially in the azimuthal estimate. The moment magnitude calculations made at PPT at epicentral distances ranging from 68 to 94 degrees compared quite favorably with calculations made at stations at much closer, or regional, distances that ranged from 7.7 to 24 degrees. The average difference was about 0.1 magnitude unit. It was concluded from the analyses that the moment could be correctly assessed for events at regional distances, even for "tsunami earthquakes." The real-time estimation of the moment should make warnings possible for tsunamis generated at an offshore trench. For local earthquake and tsunami, a global network of TREMORS-equipped broad-band stations at 15-degree intervals along coastlines with high tsunami potential would be a significant step towards efficient tsunami warnings.

3. Summary of Current Systems

Based on reports from the existing U.S. seismic systems represented at the workshop, there exists an extensive earthquake detection system of about 1000 seismic instruments reporting in real time (see Fig. 1). The existing system is composed of the following elements:

Network (Funding source)	Real Time Seismic Stations	Capital Cost ($M)	Annual Operating Costs ($M)
Alaska (NOAA)	15	0.5	0.2
Hawaii (NOAA)	9	0.5	0.1
National Net (USGS)	50	7.0	1.5
Southern California (USGS/Cal Tech)	224	6.0	1.5
Central and Northern California (USGS/Berkeley)	368	4.5	3.0
Northwest (USGS/U. Washington)	134	1.5	0.6
Alaska (USGS/University of Alaska)*	129	1.8	0.8
Hawaii (USGS)*	53	1.5	1.0
TOTALS	982	23.3	8.7

*These networks were not discussed during the workshop, but have been included here for completeness. All data were obtained from network managers.

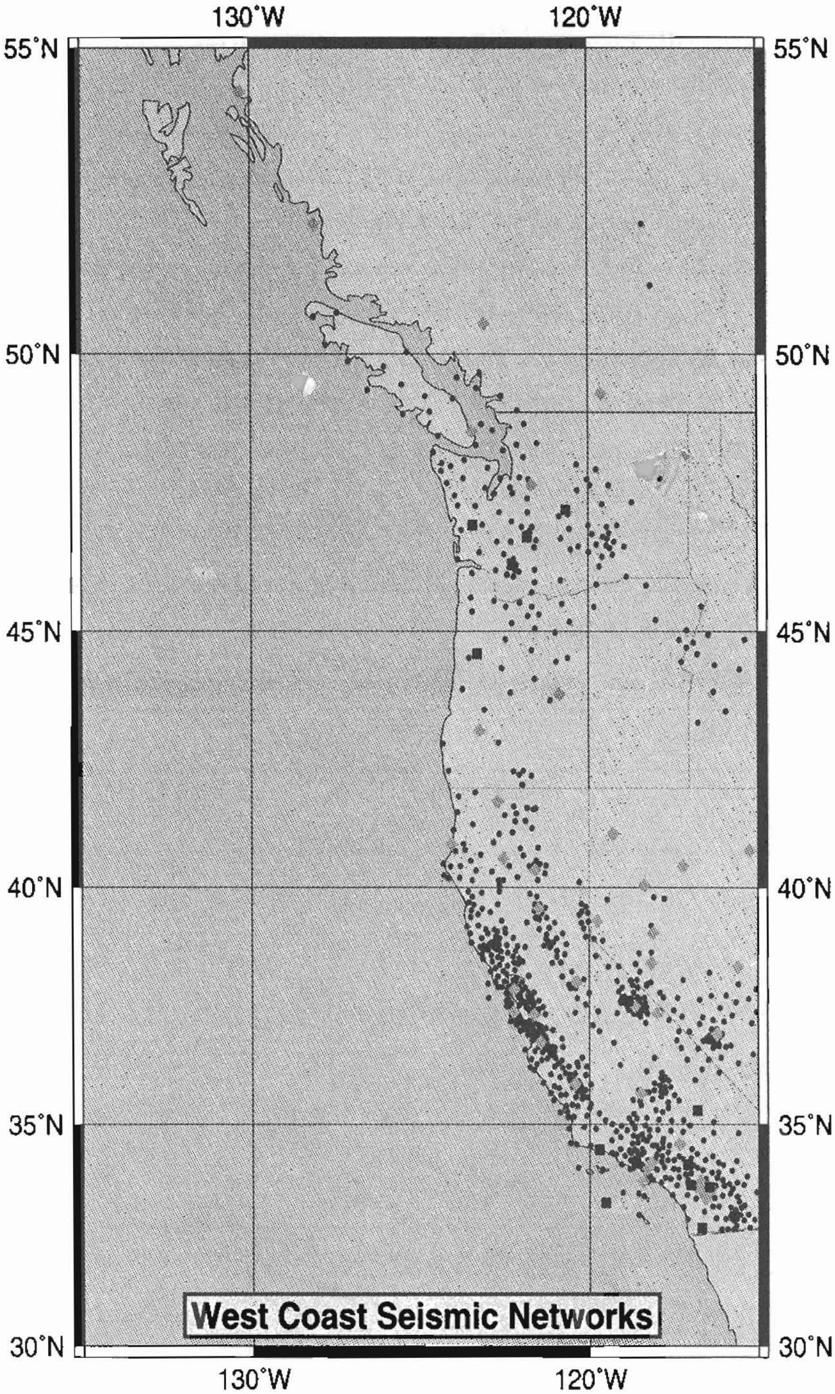
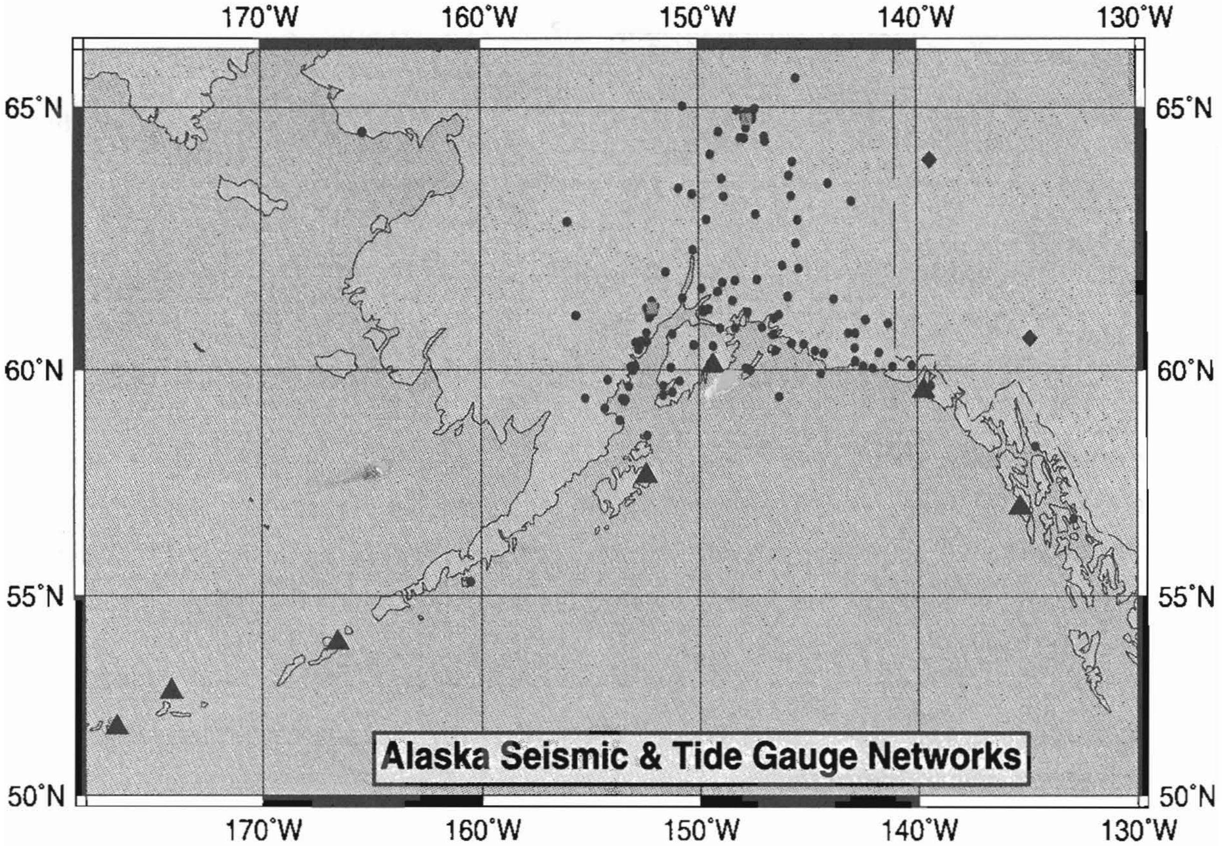


Fig. 1. Map of western U.S. real-time seismograph stations. Dots are short-period analog stations, triangles are real-time tide gauge stations, diamonds are telemetered three-component broad-band stations, squares are dial-up three-component broad-band stations. Organizations operating and recording these stations are: Canadian National Seismograph Network, U.S. National Seismograph Network, Pacific Geoscience Centre, Pacific Northwest Seismograph Network, Boise State University Seismograph Network, U.S. Geological Survey (Menlo Park and University of California Berkeley), University of Nevada-Reno, Southern California Seismograph Network, Alaska Seismic Network, Hawaii Volcano Observatory Network.



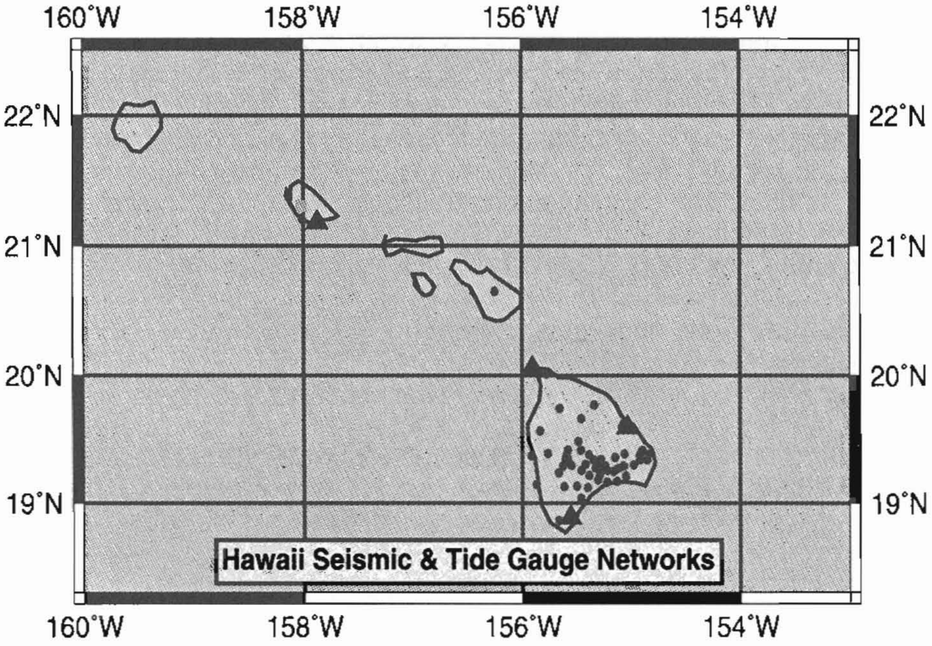


Fig. 1. (Continued)

For U.S. water level information, the existing network consists of:

Network (Funding source)	Real Time Water Level	Capital Cost ($ M)	Annual Operating Costs ($M)
Alaska (NOAA)	8	1.0	0.2
Hawaii (NOAA)	5	0.6	0.1
CDIP (ACOE/California)	10	1.0	0.5
TOTALS	23	2.6	0.8

4. Recommendations

The Workshop group met on the second day and discussed a number of issues that arose out of the presentations. The group arrived at two sets of recommendations, one for seismic considerations and another for water level measurement considerations that should be made for tsunami hazard reduction.

4.1 Recommendations for Improving the Warning Centers' Capabilities for Parameterizing Earthquakes

1. Implement continuous Internet at ATWC so the Center can gain access to processed seismic data generated by other real-time networks and can have an additional means to disseminate tsunami information.
2. Adopt the use of moment calculations and moment magnitudes as a basis for generating appropriate tsunami information messages, watches, and warnings.
3. Expand the Centers' access to broad-band and strong motion data in order to provide them with an independent capability to make moment calculations.
4. Develop a fully-automated earthquake detection, location, and magnitude-determination system that can respond to nearby potentially tsunamigenic earthquakes and issue alarms in 5 or less minutes. The only human intervention would be to cancel the alarm.
5. Develop and implement a coordinated plan for information exchange between the Warning Centers, the NEIC, and the agencies and institutions operating seismic networks on the Pacific coast.
6. Use the real-time links between the Warning Centers and the NEIC to access the National Seismic Network more efficiently.
7. Staff both PTWC and ATWC to the extent necessary to provide 24-hour onsite operational service. This recommendation followed from the data from ATWC that showed warning response times averaged 6 minutes when the earthquake occurred while staff was in the office. In contrast, response was 15 minutes if staff were not in the office.

4.2 Recommendations for Improving the Warning Centers' Capabilities for Making More Efficient Use of Available Water Level Measurement Technology

1. Install deep water level measurement instrumentation to characterize tsunami signals before the waves strike U.S. coastal areas.
2. Conduct siting surveys designed to optimize the water level measurement network, taking into consideration population density, tsunamigenic earthquake sources, and landslide potential.
3. Make use of the Coastal Data Information Program network of pressure sensors, and upgrade these facilities through sensor improvements, making the system real time, and "hardening" the facilities to withstand damaging tsunamis.
4. Increase the amount of near real-time water level data available to the Centers through the use of communications systems capable of transmitting relatively low sample rate data such as the Internet.
5. Preserve the subset of tide gauges that are particularly responsive to tsunami signals as a tie to older data sets.
6. Concentrate on the installation of pressure sensors in lieu of other types of water level measurement instrumentation and where possible co-locate with seismic instruments.

5. Conclusions

Workshop participants agreed that the seismic detection of large earthquakes along U.S. coastlines was covered well by the existing networks of about 1000 real-time reporting seismic stations. Coordination of data exchange among the existing networks could improve the speed and accuracy of earthquake location and magnitude determinations. They also agreed that the measurements and detection of the tsunami near its source offered the best opportunity to improve tsunami forecasting for U.S. coastal areas.

These recommendations involve the "systems" approach needed to coordinate all of the different types of data to generate a tsunami warning. The distribution of warning information (and updates/cancellations) to the people/organizations that can use them includes the NOAA system of National Weather Wire Service, NOAA weather radio, and the National Warning System (NAWAS). There are very active e-mail/news-group discussions going on organized by the California Office of Emergency management regarding the rapid exchange of emergency management information over a variety of communications links including the Internet. There are procedures and standards being proposed to provide a "new" type of Internet "service" that would be for emergency notification information. While this is just starting, we recommend keeping up-to-date on such developments and coordinating our information distribution techniques with those of the emergency management community.

APPENDIX A

LETTER OF INVITATION

Over the past 3 years, the National Oceanic and Atmospheric Administration (NOAA) has been developing a modernization plan for improving U.S. tsunami warning services. The plan has evolved into a three-part, intertwined approach to reduce the impact of tsunamis on U.S. coastal communities. The three parts include:

1. Hazard assessment (identify and map tsunami inundation potential)
2. Real-time tsunami monitoring and warning systems (alert the people)
3. Public education (population awareness and community response)

This concept evolved from earlier plans and was presented in November 1993, at a tsunami inundation modeling workshop attended by tsunami scientists, state emergency planners, and state emergency operators. Workshop participants focussed on hazard assessment, but strongly endorsed the three-prong approach and recommended that workshops be held for the remaining two components as soon as possible. They further recommended that the resulting workshop reports and recommendations should serve as the primary guidance for tsunami services modernization.

Using this process, the workshop schedule is as follows:

1. Hazard Assessment. Convener: E. N. Bernard, November 16–18, 1993, in Honolulu, Hawaii. Report: Bernard, E. N. and F. I. Gonzalez, "Tsunami Inundation Modeling Workshop Report," NOAA/ERL/PMEL 100, 139 pp., 1994.
2. Tsunami Warning System Workshop. Co-conveners: Hiroo Kanamori and Mike Blackford, September 14 and 15, 1994, Pasadena, California. Report: to be completed by December 1994.
3. Tsunami Education Workshop. Co-conveners: Jim Good, Dennis Sigrist, and Tom Sokolowski, October 1994, Newport, Oregon. Report: to be completed by January 1995.

We anticipate the completion of a synthesis report, which recommends a course of action for modernization, by March 1995.

Because of your expertise, we are inviting you to participate in the Tsunami Warning System Workshop in Pasadena, California, on September 14 and 15, 1994. If you accept, NOAA will cover your travel and living expenses to participate in the workshop. A block of rooms has been reserved at the Doubletree Hotel (under Tsunami Workshop), phone (818) 795-7669, where the workshop meetings will be held. If time permits, we will tour the Caltech Seismological Laboratory.

The purpose of the workshop is to identify existing methods or technologies that can be used to improve tsunami warnings especially for locally generated tsunamis along the U. S. coastlines. The workshop is structured to first assess the present state of local tsunami warning in the U.S. Then, a series of presentations will be made on other existing networks (seismic and water level) to determine if these activities can improve the present system. After learning of the present status of these networks, the group will identify opportunities for improvements. Once a list of opportunities has been compiled, the group will try to rank these opportunities through a set of recommendations. If the 13 people we have invited are able to attend, we envision an agenda like this:

AGENDA

Introduction: Kanamori (10 min)
Present state of TWS—Sokolowski and Blackford (30 min)

Seismic Network
  National Seismic Network—Filson (15 min)
  Southern California Seismic Network—Heaton (15 min)
  Northern California Seismic Network—Oppenheimer (15 min)
  Cascadia Seismic Network—Malone (15 min)
  IRIS—Malone (15 min)
New Developments—Okal (15 min)
Discussion
  Possible improvements—Led by Satake

LUNCH

Water Level Network

  Army Corps of Engineers National Wave
    Network—McGehee (15 min)
  California Wave Network—Flick (15 min)
  NOAA Tsunami Measurement Network—Gonzalez (15 min)
  Water Level Telecommunications—Milburn (15 min)

Discussion on possible improvements—Led by Bernard

DAY 2

Group discussion on opportunities—Kanamori and Blackford
Recommendations—Kanamori and Blackford

Each presenter should prepare a summary (no more than 5 pages) of their presentation so that the workshop report accurately reflects their comments. The summaries should be sent via e-mail by September 10, 1994, for ease in compilation with other summaries. If you need audiovisual equipment other than an overhead projector, please let us know.

TRAVEL INSTRUCTIONS FOR PARTICIPANTS

NOAA will cover travel and living expenses for workshop participants.

1. Participants will be issued government Travel Orders and will be required to complete government Travel Vouchers, which will be provided.

2. Airline tickets will be provided using Government contract city-pair carriers. Tickets will be expressed or pre-paid with the carrier at the city of departure. The only exception would be for government employees who might wish to purchase their tickets on their government-issued American Express cards.

3. Receipts are required for any expenses which exceed $25.00 other than meals. A meal and incidental expense allowance for Pasadena is $38.00 per day for full days of travel.

2. Please call Florence Cooke (NOAA travel coordinator) at (206) 526-6237 or FAX: (206) 526-6815, to request your preferences for airline and hotel reservations.

We hope you can participate. Please let Hiroo know as soon as possible if you can participate. An e-mail response to this invitation would be appreciated, otherwise, call (818) 356-6914.

Sincerely,

Hiroo Kanamori and
Mike Blackford

APPENDIX B

LIST OF PARTICIPANTS

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APPENDIX C

The Alaska Tsunami Warning Center

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Overview

The primary mission of the Alaska Tsunami Warning Center (ATWC) is to provide timely tsunami watches and warnings for Alaska, California, Oregon, Washington, and British Columbia in Canada, for potentially tsunamigenic earthquakes that occur in those regions. Tsunami warnings and other critical information are immediately disseminated to emergency offices in each of these areas, plus others such as the Federal Emergency Management Agency, U.S. Coast Guard, Pacific Tsunami Warning Center in Hawaii, media, and to many other recipients including both State and Federal disaster preparedness agencies. Although numerous world-wide earthquakes are automatically detected and processed each day, only a small number of these earthquakes are released to officials and the public.

This service is provided on a 24-hour basis, for each day of the year, by two duty personnel. During those times that the Center is not staffed, the duty personnel are in a paid standby duty status which requires that they respond to the Center within 5 minutes after being alerted that a significant earthquake has occurred. To ensure a rapid response to earthquakes occurring at night, weekends, or holidays, all personnel are required to live within 5 minutes travel time to the Center. They are notified of the occurrence of an earthquake, or irregularities in the Center's operations, by a radio-alarm system which is linked to a computer system. Tsunami warnings and other critical information are typically disseminated within about 12 minutes from the origin time of an earthquake. In addition to the above mission, the ATWC personnel process and disseminate collected data, maintain the current system, participate in fulfilling interagency cooperative agreements, create and implement software, develop equipment, and conduct applied research development to improve the present system. We do not have funding for contract work.

The ATWC continues to improve its operations by developing and implementing an expert system which starts with the detection of a tsunami hazard and culminates in providing intended users with the degree of threat to mitigate this hazard. This system is expected to (1) automatically detect and analyze seismic data in real time, (2) immediately disseminate critical earthquake and tsunami information in near real time, (3) automatically detect and analyze tsunamis in real time or near real time from tidal data, (4) rapidly discriminate tsunamigenic from non-tsunamigenic earthquakes, and (5) reasonably determine estimates of probable tsunami wave heights and areas of inundation in the path of a tsunami. Neither 4 or 5 can be accurately done with the present seismic data accumulated at the Center. A network of broad-band data are necessary for source mechanism studies and for input to tsunami models.

During the past decade, numerous changes have taken place in areas such as operational concepts and procedures—especially in response to emergency situations—microcomputer concepts, computers, peripherals and associated equipment, seismic and tide networks, applied research developments, and communications for disseminating critical information. The integration of microcomputers and applied research developments have already made a considerable improvement in performing ATWC's missions. Due to the accomplishments in (1) and (2) above, the average response time to issue a warning has been reduced by more than 50%. In addition to timeliness, procedures have been considerably simplified and standardized.

In earthquake processing, local, regional, and world-wide earthquake parameters are automatically computed and sized (mb, MI) within seconds after receiving appropriate data at real-time seismic sites distributed throughout Alaska and the lower 49 states. The automatic determination of an earthquake's parameters, plus the resident historical data bases, have enhanced the quality and quantity of resulting information disseminated to the TWS recipients. Long-period seismic instruments have been established at strategic coastal locations in Alaska to decrease the response time in computing magnitudes. The real-time data are automatically sized (MS), cycle by cycle, by the computer. Earthquake parameters are immediately available at the Center, and/or transmitted by a computer and the radio alarm system to the ATWC staff for an immediate response. As funding becomes available for additional microcomputers and broad-band equipment, enhancements to the ATWC system would include source mechanisms, moment magnitudes, and synthesizing earthquake signatures for determining potential tsunamigenesis.

Tsunami modeling and tide height determinations during expected time of arrivals of tsunamis at different locations are continuing efforts at the ATWC. In-house development is coupled with the transfer of scientific techniques and methods developed by other scientists for appropriate application to the ATWC requirements. The current and future modeling efforts use many of the past tsunamigenic earthquakes in duplicating their effects. The minimum expectations in this area include maximum predictive wave heights, or ranges, wave currents and inundation zones for different locations in ATWC's areas of responsibilities. Actual tide heights during expected tsunami arrivals at different locations will be available to many areas from Alaska through southern California. The application of these results, along with others, will serve as valuable input for future artificial intelligence for determining a degree of threat.

Tidal data continue to be accessed in real time from sites in Alaska. Tidal data are accessed and analyzed via microcomputer(s) in near real time from Canada and the U.S. West Coast. New NOS tide equipment, and communications via new circuits, satellite, and microcomputers will be used in the near future to access and analyze Pacific tidal data in real time and near-real time. Detection of tsunamis and dissemination of this critical information to intended recipients can be accomplished in the future. A new satellite system ground station was established at the Center which enhances the ATWC's capabilities to immediately disseminate critical information to numerous areas. This complements the present high speed teletypewriter system.

Getting the public to respond to critical earthquake/tsunami information is a vital part of the ATWC efforts and necessitates a continued educational community preparedness program. This program covers selected areas in large geographical areas, and in cooperation with other agencies and hazard officials. All staff members participate in this important part of the ATWC.

The ATWC maintains historical tsunami and earthquake data bases that were obtained from the National Geophysical Data Center and from the National Earthquake Information Center. The tsunami data base is used during all warnings to determine past hazard occurrences in and about an earthquake source to facilitate decision making. The earthquake data base contains more than 7000 earthquakes of magnitude 6.0 or greater that have occurred in the Pacific Basin. The earthquake data base is cross referenced to the tsunami data base, which contains more than 1100 historical tsunamis that have occurred in the Pacific Basin. The historical earthquake and tsunami data bases are important for future models and during tsunami warnings.

The integration of microcomputers with in-house and cooperative technique developments are critical to improving the tsunami warning services. Figure 1 shows six microcomputers that communicate with each other via a local area network (LAN) to perform their various functions. A block is also shown and designated as Micro X, which indicates that future microcomputer(s) can be added to the LAN system to perform future tasks as they evolve in the reactive or predictive parts of an operational system. Micro X could also eliminate problems that result from an intensity of computations, input/output requirements, or interfacing equipment. The micro systems can communicate with each other using a LAN system, or function independently, to perform both operational and administrative tasks. Several functions are duplicated due to the critical nature of the task, or to facilitate personnel duties and research development. The future microcomputers are expected to be upgraded periodically. Already this system has had a good effect on the ATWC's operations by being cost effective, providing a vehicle for task growth, maximizing aid for personnel, minimizing procedural responses in emergency situations, and permitting more effective use of personnel and their assigned development tasks. More information about the ATWC can be obtained from the below list of references.

Recommendations

- Increase funding by $100K/year/Center to improve and enhance the ATWC by transferring technology from research to applications within both Centers.
- Conduct periodic system reviews to satisfy user needs: Establish an independent review committee of users to review existing tsunami warning centers (ATWC and PTWC) to determine present capabilities and future needs, and provide recommendations to improve the TWS. Emergency officials from AK, HI, WA, OR, CA, and FEMA should be core members with adhoc members added as needed.

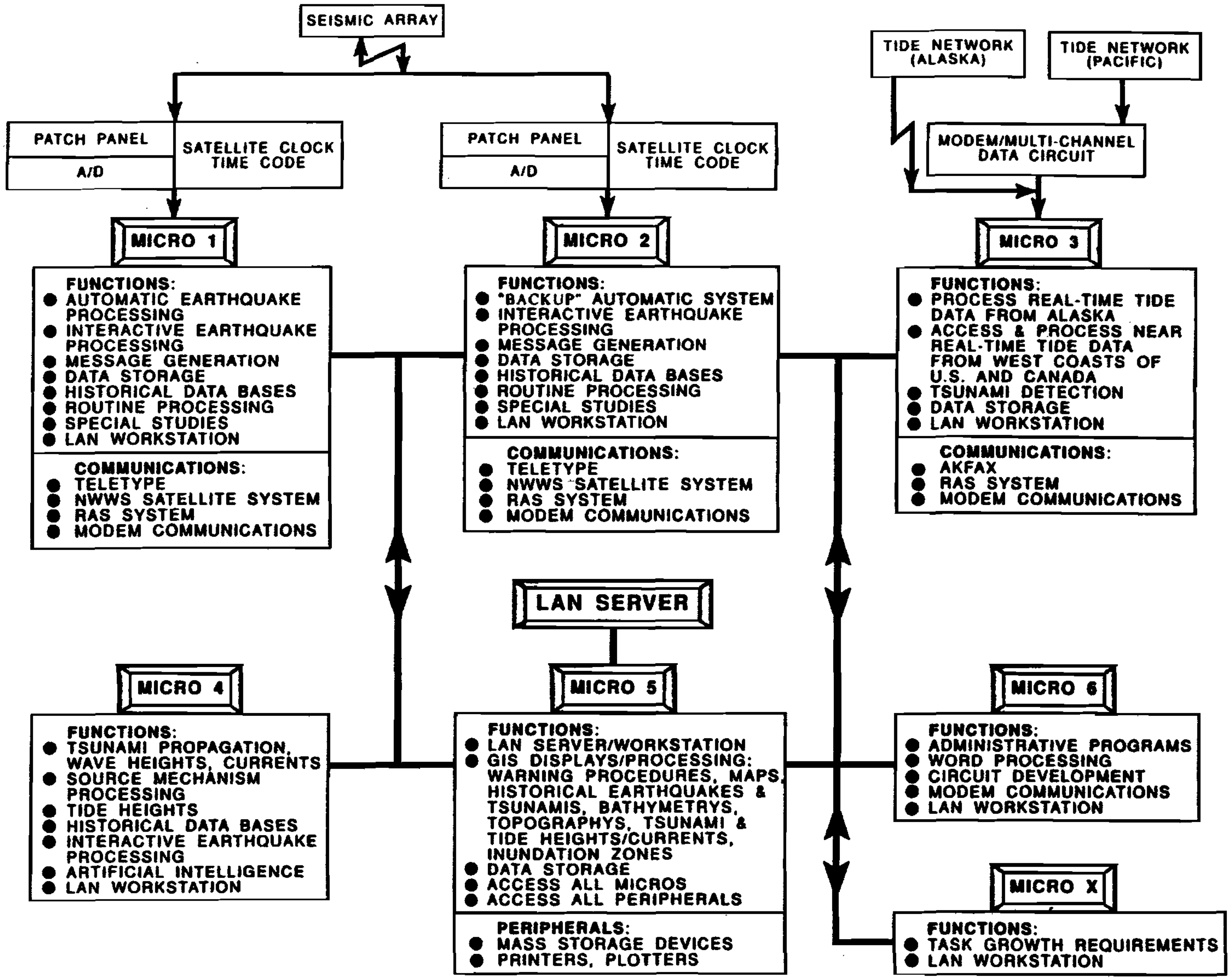

Fig. 1. Block diagram showing a distribution of microcomputers which are networked via a LAN system to perform their indicated functions.

- Integrate emergency officials in all meetings concerning Tsunami Warning System problems, future directions, enhancements, etc., especially for short-fuse situations.
- Provide emergency personnel in coastal communities with expected wave heights or inundation levels for both teleseismic and local tsunamis.
- Replace Center's existing seismic network with broad-band seismometers and base tsunami warnings on moment magnitude (Mw) instead of surface-wave magnitude (Ms).
- Support and increase community preparedness participation along the west coast by appropriate Center's personnel to enhance awareness programs.
- Support research to determine immediately tsunamigenic earthquakes from non-tsunamigenic ones based on the seismic parameters.
- Predict tsunami wave heights, currents, etc., away from the source zone based on earthquake source parameters and a near-source tide gage recording(s).

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APPENDIX D

Pacific Tsunami Warning Center

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Introduction

The Pacific Tsunami Warning Center (PTWC) is situated on a 71-hectare U.S. Government reservation in Ewa Beach, Hawaii. The physical plant consists of 12 permanent buildings and a mobile trailer office unit. Four of the buildings are residences for the watchstanders. Three of the residences are occupied full time by the watchstanders and their families. The fourth residence is shared by the remaining two watchstanders who reside off site when they are not on duty. One building is the main office that contains the operations area, work modules for the geophysicist staff and office automation clerk, and a conference/library area. A shop building is located adjacent to the office. The shop contains desk and bench space for three National Weather Service Pacific Region (NWS/PR) electronics technicians who are assigned to PTWC, storage space for parts and equipment, a UPS system for equipment critical to operations, and a back-up diesel generator for emergency power. Other unoccupied buildings house a variety of equipment involved in PTWC or NWS/PR operations, or cooperative geomagnetic programs. These include a seismic vault, a microwave transceiver facility, a NWS/PR satellite tracking facility, and three buildings devoted to the geomagnetics programs.

The PTWC staff consists of a geophysicist-in-charge (GIC), four full-time geophysicists, one part-time geophysicist, and an office automation clerk. The GIC and the four full-time geophysicists constitute the watchstander staff. In addition, three NWS/PR Systems Integration Branch electronic technicians are assigned to the PTWC facility. About two-thirds of the technical staff's time is spent on PTWC projects and electronic maintenance, with the remaining third being spent on NWSIPR electronic maintenance. The office automation clerk also provides administrative support to the technical staff as well as to PTWC.

Two of the five watchstanders are on duty at any time. The duty schedule is divided into two 2-day tours and one 3-day tour per week. Because of holidays and leave this schedule is often modified, resulting in longer tours of duty. The watchstanders on duty are required to remain on the PTWC reservation to respond to alarms or other indications of the occurrence of potentially tsunamigenic earthquakes. This restriction primarily applies to nights and weekends since all of the staff maintain regular office work hours. During the work day, duty watchstanders can usually hand off their duty responsibility to another geophysicist for a period of time to deal with matters that take them away from the site. Watchstanders receive compensation in addition to their regular salaries for their watchstanding duty.

PTWC receives data and information continuously from a number of sources. The Center maintains a network of nine seismic stations in the Hawaiian Islands that telemeter their data to PTWC either via a PTWC-maintained VHF radio system, via a federal/state microwave radio system that is contractor-maintained, or, for stations on Oahu, via commercial telephone lines. PTWC also receives real-time waveform data from twelve seismic stations distributed across the contiguous United States and Alaska. These data are received over a portion of a leased circuit between PTWC and the National Earthquake Information Center (NEIC), located in Golden, Colorado. NEIC exchanges data in real time with a number of federal and state government agencies, including PTWC, and academic institutions, that operate networks of seismic stations. Data transmitted to PTWC originate at these various networks.

Instrumentation

Within the Hawaiian islands PTWC maintains a network of five real-time and ten dial-up water-level measurement systems. The real-time systems use nitrogen gas pressure transducers to determine the water level and the dial-up systems rely on a float in a stilling well for their measurements. The real-time systems' data are telemetered to PTWC over the same, or similar, circuits over which the seismic data is telemetered. The dial-up systems store about 4 days of 2-minute averaged data that is readily downloaded and plotted by routines on the PTWC computer system.

PTWC also receives water level data from about 100 stations located throughout the Pacific outside of Hawaii. PTWC maintains about 25 of the stations, the University of Hawaii (UH) maintains another 25, and the NOAA/NOS maintains the rest. Each station transmits its data on a regular 1-, 3-, or 4-hour schedule to a downlink in Maryland where the data are fed into a Weather Service circuit for transmission to PTWC and UH. Nearly all of the PTWC and UH stations transmit on a 1-hour basis. A few stations that have not been visited for upgrading still transmit on a 4-hour basis. The NOS stations transmit on a 3-hour basis. PTWC and UH transducers are either the float/stilling well or nitrogen gas pressure types. The NOS instruments use a stilling well and an acoustical pinger to detect the level of the water in the stilling well. PTWC and UH systems collect 2-minute averaged sample data and the NOS system stores, every 6 minutes, a 3-minute average of the pinger data. Two of the stations in the western Caroline Islands transmit their data via the Japanese GMS stationary satellite. These stations are beyond the footprint of the GOES satellite that is used by the other stations. The NOS stations located in the United States, or its possessions, and a few located in other countries, can also be accessed, via a dial-up modem when it's necessary to evaluate data for tsunami warning purposes.

The seismic data from both the PTWC network in the Hawaiian Islands and the data received from NEIC are routed to either one or two PC's equipped with digitizers. One of the PC's, operating in both a continuous and an event mode, records the Hawaiian network data and some of the NEIC data. If a moderate-sized, or larger, earthquake occurs in the Hawaiian Islands and the event is detected by the system, the event data is transferred to another PC that attempts to refine the detections and locate the earthquake. Both the event data and continuous data are transferred via a LAN to Sun Unix-based workstations where it is subjected to further processing. Continuous data are routed to display units that provide a means of visually monitoring the seismic activity. The data are also routed to an archive tape unit for subsequent nonoperational analysis. Programs are also available on the workstations to manually pick earthquake phase arrivals should that be necessary.

The real-time water level data are routed to strip chart recorders where tides and tsunamis can be observed and scaled as necessary. Data from the PTWC dial-up water level network in the Hawaiian Islands are retrieved and plotted through the tailored application of commercial software packages on a PC. Tsunamis on the hard copy output are scaled manually. Similarly, data from NOS gauges are retrieved and plotted via routines developed in house on the Unix workstations. The water level data arriving over the Weather Service circuit is routed into day files on the workstations. A number of routines have been developed to sort, display, and scale the data collected into these files. A window of about 2 months of day files is maintained for analysis. Tsunami events are archived.

Processed data and other messages are sent and received at PTWC over a variety of communication media. Direct voice communications with both the Hawaii Civil Defence (HCD) and NAWAS are available on push-to-talk telephones connected to dedicated circuits. A backup direct radiophone link between the HCD and PTWC also exists should the dedicated circuit fail. Messages to NAWAS can be relayed through HCD, if necessary. Other circuits for the transmission of hard copy products are the Defense Communications System (DCS), the Aeronautical Fixed Telecommunication Network (AFTN), Telex (TLX), the Weather Service circuit to the NOAA Message Center (NMC), the satellite-linked NOAA Weather Wire (NWW), and another dedicated circuit to the Hawaii Civil Defense for hard copy transmission. PTWC also uses another portion of the dedicated circuit between PTWC and NEIC to access NEIC's automatic associated picker system to obtain data for locating earthquakes. In addition, PTWC makes use of the Internet system to both send and receive information on events as it becomes available. PTWC is on distribution for a number of automated location systems and moment/mechanism determination systems.

Procedures

A typical event begins with either an alarm, or a telephone call from the Philippines or Guam if the earthquake is in their vicinities and they beat the alarm. Alarms are associated with waveform signal level thresholds attained on either the long-period or short-period data received at PTWC. The long-period alarms are tied to the local horizontal instruments at PTWC. A seismic wave cycle of sufficient amplitude and duration on either component will trigger an alarm. The short-period alarms require energetic signals on two stations within a certain time frame to trigger an alarm. An exception to this is that an energetic signal on the local short-period vertical instrument alone will trigger an alarm. The station pairs in Alaska, in the central contiguous states, and on the island of Hawaii are used for the alarms.

When the alarm is received on their pagers the two duty geophysicists immediately go to the operations area to determine the cause of the alarm. This takes a matter of seconds during office hours or 1 or 2 minutes if they are in their quarters. Their first action is to observe the monitors to get a sense of whether they are dealing with a local event or a teleseism and a rough idea of its size. If the event is a teleseism, a duty person will log on to the NEIC computer to retrieve data from NEIC's automatic picker. Meanwhile, the other duty person is reviewing message traffic for earthquake phase arrivals sent by other centers. Phase arrivals will usually be sent by various Asian centers for events in the western Pacific. The NEIC data is transferred to a file for input to the PTWC earthquake location program. When the program is executed, any Asian data retrieved is added to the NEIC data to help improve the epicenter accuracy, if the quake is in the western Pacific. Data from arrays in Australia may also be accessed via Internet if azimuthal control of the epicenter from that quadrant is needed. The earthquake solution forecasts the arrival of wave groups that are used to determine the magnitude of the earthquake. At those times the appropriate traces are scaled and the data are added to another run of the location program to obtain a magnitude.

Once the earthquake location and size are determined, appropriate messages based on these parameters are issued. If the earthquake is less than a magnitude 6.5 and/or is located outside of the Pacific basin, the only messages issued will be responses to those centers that normally send us data on the event. If the event is between magnitude 6.5 and 7.5 a tsunami information bulletin will be issued to all who normally receive watches and warnings. This event should be within the Pacific basin, or near its margin, otherwise PTWC will defer to NEIC for the issuance of information on the earthquake. If the earthquake is located in or near the Pacific basin and its size is greater than 7.5, a regional warning is issued for the area within 3 hours tsunami travel time of the epicenter. The area between 3 hours travel time and 6 hours travel time is placed in watch status. If the earthquake's location is within the Alaska Tsunami Warning Center's region, which extends from the western end of the Aleutian Islands to the Mexican border with the United States, certain exceptions to the general guidelines outlined above apply. For earthquakes between magnitude 6.8 and 7.5, PTWC will issue a tsunami investigation message to its addressees after ATWC has issued a warning. For earthquakes in the Aleutian islands greater than 7.0, PTWC will issue warnings and watches to its addressees who are not warned by ATWC. If water level instruments and other reports indicate a tsunami with significant damage potentials exists well outside the epicentral area, a Pacific-wide warning will be issued. Warning and watch messages will be updated at least hourly until a cancellation is issued.

For an earthquake in the Hawaiian Islands PTWC procedures are significantly different. When traces on the monitors indicate a regional event, data from PTWC's automatic detection system and the Hawaiian Volcano Observatory's (HVO's) location are compared to determine the accuracy of the location. Some reworking of the location may be done, if necessary by repicking arrival times. Trace amplitudes on the local short-period horizontal seismograms are scaled to determine the earthquake's magnitude. If the magnitude is greater than 6.8, an immediate verbal warning is issued to the Hawaii Civil Defense via the push-to-talk telephone system. This warning specifies the island, or islands, to be evacuated and gives the preliminary earthquake location and magnitude. If the earthquake is less than a magnitude 6.8, the HCD is given a verbal description of the earthquake, informed that a tsunami is not expected, and told that an evacuation is not required. The verbal messages are backed up by hard copy transmissions to HCD.

The records of the real-time water-level instruments closest to the epicenter are monitored and data from the closest dial-up instruments are downloaded to determine the extent of tsunami generation. If a significant tsunami is observed beyond a hundred kilometers from the epicenter, the warning may be extended to other islands. Historically however, for the largest events thus far observed in the Hawaiian Islands, significant tsunami action dies out quite rapidly as the distance from the earthquake epicenter increases. The average time for PTWC to respond to local events, the time from alarm to the time of verbal transmission to HCD, is about 5 to 10 minutes.

Current Plans

At this time PTWC is focussing on a few areas where improvements in the warning system can be made. In the area of earthquake location PTWC feels that, in most cases, sufficient data is now available in real, or near-real, time to obtain an automatic earthquake location adequate for tsunami warning purposes. For areas of the Pacific basin where automated location systems do not exist, PTWC is working on a smart seismic package that will detect a regional P-phase, and hopefully a teleseismic P-phase, and transmit this parametric information to PTWC via a non-scheduled satellite transmission. Where automatic earthquake location data are available, PTWC is working to streamline procedures to gain access to this data.

Although moment magnitudes and mechanisms are now available within a few hours after an event, this is not quite adequate for tsunami warning purposes. PTWC will be pursuing ways to obtain this information as quickly as possible to further aid in the determination of an earthquake's severity and tsunami potential.

In the area of instrumentation, PTWC will be focussing strongly on improvements in its capability to make, or obtain, water level measurements that better characterize the severity of a tsunami and its progress away from its source area. The Center is testing pressure transducers that are easier to install and maintain than the nitrogen gas transducers now in use. It is hoped that these transducers will have a greater dynamic range and better response to tsunamis than either the present pressure transducers or the various stilling well instruments. Software or firmware associated with these instruments would be capable of sensing high or low pressure thresholds that could be an indication of flooding or withdrawal due to a tsunami. This information would be transmitted to the Center in real, or near-real time. Also PTWC is supporting the development of runup gauges that would be capable of transmitting the presence of tsunami inundation to PTWC in real time. PTWC also strongly supports PMEL's development of deep water bottom pressure recorders that can supply data to the Center in at least near-real time. Such data could be an important early indication of the severity of tsunamis originating in the Cascadia and Alaska/Aleutian subduction zones that are spreading out across the Pacific basin.

Finally, PTWC supports the formation of more regional warning centers that have the expertise and equipment to issue warnings in their regions independent of information provided by PTWC. This is the only way many areas of the Pacific will truly receive a tsunami warning before the waves actually arrive. Ninety-nine percent of the loss of life and property damage due to tsunamis results from waves that travel less than ½ hour from their source area. Because of the travel times of the seismic waves necessary to locate an earthquake and determine its size, PTWC cannot effectively issue warnings to most tsunami prone areas of the Pacific in much less than 1 hour. PTWC's role as the operational center for the Tsunami Warning System of the Pacific is to relay information on the severity of a tsunami provided by regional sources close to the source of the tsunami to other areas of the Pacific and to monitor water level Pacific wide to determine the presence of a potentially damaging Pacific-wide tsunami. PTWC will gladly share any technological advances it should make in its own regional system with other regions that are developing or maintaining tsunami warning systems.

APPENDIX E

Tsunami Warning System in Japan

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Japan, where the word "tsunami" comes from, has often suffered from tsunami hazards. Japan Meteorological Agency (JMA) is responsible for seismological observations and forecasting tsunami heights. JMA has six regional Tsunami Warning Centers (TWC) at Sapporo, Sendai, Tokyo (JMA headquarters), Osaka, Fukuoka, and Okinawa (Fig. 1). Each TWC is equipped with Earthquake and Tsunami Observation System (ETOS) and has seismologists on duty 24 hours a day. JMA has been constantly improving their tsunami warning system. In this article, I review the history, the current status, and the future plan of the JMA's tsunami warning system.

A local tsunami warning organization was first established in 1941 along the Sanriku coast as a result of the 1933 Sanriku earthquake (Magnitude 8.1) tsunami, which killed 3000 people. The nation-wide tsunami warning system of JMA started in 1952. After the 1960 Chilean tsunami, which arrived in Japan about a day after the earthquake (M 9.5) and killed 142 people, JMA started to exchange seismic and tsunami data with foreign countries.

The current tsunami forecast system divides the Japanese coasts into 18 regions (Fig. 1). Each Tsunami Warning Center is responsible for forecasting tsunami heights for 1 to 5 regions. The forecasts are classified as a Tsunami Warning or Tsunami Advisory. There are two types of messages in a Tsunami Warning: "Tsunami expected" for expected tsunami heights up to a maximum of 2 meters, and "Major tsunami expected" for maximum heights over 3 meters. There are two messages in a Tsunami Advisory: "Tsunami attention" for expected heights up to tens of centimeters, and "No tsunami." In addition, there are messages to cancel the warning and advisory. When a large earthquake occurs, one of the four messages (Major tsunami, Tsunami, Tsunami Attention, or No Tsunami) is issued for each coastal region, based on the magnitude, location, and depth of the earthquake, and the distance to each coastal region.

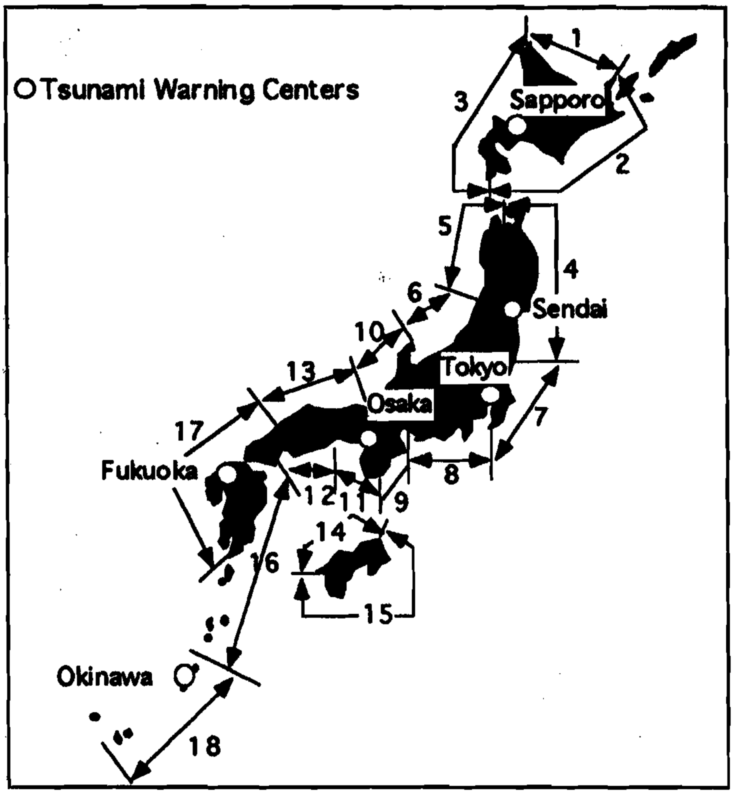

Fig.1. Location of 6 Tsunami Warning Centers and 18 forecast coastal regions.

Table 1. Tsunami Warning and Advisory Messages

Forecast	Message	Contents
Tsunami Advisory	no tsunami	No tsunami is expected.
	tsunami attention	Some minor tsunami may be expected. Height of tsunami is up to several tens cm in the worst.
	clear tsunami attention	Tsunami attention is cleared up.
	clear tsunami warning	Tsunami warning is cleared up.
Tsunami Warning	tsunami expected	Tsunami is expected. Height is generally up to several tens of cm, but up to 2 m in the worst.
	major tsunami expected	Major tsunami is expected. Height is generally up to 1 m, but more than 3 m in the worst.

The 1983 Japan Sea earthquake (M 7.7) generated tsunamis in the Japan Sea. The first tsunami wave hit the west coast of Honshu about 7 minutes after the quake. One hundred people were killed by the tsunami. JMA issued the tsunami warning 14 minutes after the earthquake. This was much shorter than the 20 minutes required by regulation. However, it was too late for thirteen schoolchildren on a beach. After the 1983 event, the JMA revised the seismic observation system. The ETOS at each Warning Center consists of super-minicomputers, telecommunication links, and telemetering facilities connecting more than 60 seismic stations, including two permanent ocean bottom seismographs. The ETOS automatically detects an earthquake, picks P and S wave arrivals, estimates location, depth and magnitude, and issues a tsunami warning based on these parameters. The seismologist on duty is responsible for determining whether the warning messages will be distributed to the government, TV and radio stations.

With the new ETOS in operation, a tsunami warning was issued 5 minutes after the 1993 Southwest Hokkaido earthquake (M 7.8). However, the tsunami from this quake arrived at Okushiri Island within a few minutes of the quake. Two-hundred thirty people lost their lives from this earthquake and tsunami. JMA has increased the number of seismic stations to 173 (at approximately every 60 km) and started to estimate the magnitude from P waves. The improvements made it possible to issue the tsunami warning within 5 minutes after the Kuril earthquake (M 8.1) of October 4, 1994, although this earthquake occurred at a further distance from mainland Japan.

JMA is planning to start issuing quick earthquake information (region and intensity, without location or magnitude) within 2 minutes of earthquakes. This possibly will be followed by a tsunami warning within 3 minutes of the quake. This new system will start March 1995. Starting in 1997, a more accurate and detailed forecast of tsunami heights will update the quick tsunami warning message about 10 minutes after the earthquake. Another improvement of the system is the use of a satellite communication system in case of power failure and disconnection of ground-based communication systems.

APPENDIX F

United States National Seismograph Network

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Introduction

The concept of a United States National Seismograph Network (USNSN) dates back nearly 30 years. The idea was revived several times over the decades, but never funded. For example, a national network was proposed and discussed at great length in the so called Bolt Report (U.S. Earthquake Observatories: Recommendations for a New National Network, National Academy Press, Washington, D.C., 1980, 122 pp.). From the beginning, a national network was viewed as augmenting and complementing the relatively dense, predominantly short-period vertical coverage of selected areas provided by the Regional Seismograph Networks (RSN) with a sparse, well distributed network of three-component, observatory-quality, permanent stations. The opportunity to finally begin developing a national network arose in 1986 with discussions between the U.S. Geological Survey (USGS) and the Nuclear Regulatory Commission (NRC). Under the agreement signed in 1987, the NRC has provided $5 M in new funding for capital equipment (over the period 1987–1992) and the USGS has provided personnel and facilities to develop, deploy, and operate the network. Because the NRC funding was earmarked for the eastern United States, new USNSN station deployments are mostly east of 105°W longitude while the network in the western United States is mostly made up of cooperating stations.

USNSN Design and Implementation

The USNSN was designed, with extensive input from the seismological community and industry, to serve the purposes of the National Earthquake Information Service (NEIS), the NRC, and the seismological research community. The goals that evolved were to provide highly reliable, highly linear, real-time, three-component, calibrated, broad-band, on-scale monitoring of moderate-to-large earthquakes at local, regional, and teleseismic distances. In many ways, the USNSN can be thought of as a continental scale, real-time version of the Global Seismograph Network (GSN) being established by the Incorporated Research Institutions for Seismology (IRIS).

During 1987–1989, the USNSN was planned, specified, and underwent a lengthy competitive procurement process, including rigorous production sample testing. Equipment for the field, telemetry, and the central control and processing system was selected. During 1990, hardware was delivered and development was begun on the critical system integration software. The USNSN was dedicated in April 1991 when station installation began in earnest. Since then, extensive work has been done on stabilizing the real-time processes, enhancing functionality, and adding USNSN and cooperating stations.

The USNSN is based on the following hardware:

1. In the field, Guralp Systems CMG-3 seismometers and CMG-5 accelerometers are interfaced with a six-channel, 80-sample/s, 24-bit Quanterra station processor. There is no local data storage except processor buffer memory. The principle band of interest is from 200 s to 30 Hz.
2. Telemetry is provided by a Scientific Atlanta Ku-band, time division multiple access (TDMA), very small aperture satellite (VSAT) system. A VSAT connects each station processor to the master earth station (MES) located at the National Earthquake Information Center (NEIC) in Golden, Colorado via the GE K-2 geosynchronous telecommunications satellite using the X.25 communications protocol.
3. The network processor system at the NEIC runs on four Digital Equipment Corporation uVAX 3000/4000 32-bit microcomputers (under the VMS operating system) configured as a local area VAXcluster. Scratch storage is provided by two System Industries Clustor III multi-ported disk subsystems. The network processor receives X.25 data from the MES via Simpact coprocessors. Archival data storage is provided by an Aquidneck Systems write once optical disk jukebox.

USNSN Software Architecture

The USNSN components are integrated together by USGS supplied software which extends from the seismological processing in the field to all network processor functionality at the NEIC. In the field, USNSN station processors generate data streams at rates of 1, 10, 20, 40, and 80 samples/s from six analogue-to-digital converters. The 1-sample/s "long period" data is transmitted continuously with a lag of 120 s. The 40-sample/s "broad-band" data is transmitted for events (from either the seismometers or the accelerometers, depending on amplitude). The 80-sample/s "high frequency" data is transmitted from the accelerometers for accelerations exceeding 100 μg. Event detection is done in the frequency domain using a fixed point FFT algorithm. Data is divided into USNSN/RSN telemetry packets in the USNSN compression format for transmission.

The network processor automatically estimates phase arrival times and locates events. Event associated phase and waveform data as well as continuous long-period and high-frequency event data are stored in the on-line data base. Comprehensive review and analysis tools are available for the NEIS analysts. The data base is designed to support waveforms with asynchronous timing, different sample rates, different numbers and types of channels per station, and to efficiently store data arriving in different binary data formats.

The results of the automatic processing are broadcast by pager to NEIC personnel and by pager, e-mail, and automatic fax to a limited number of users with public safety responsibility.

Although the automatic processing system is completely general, locating earthquakes worldwide, the automatic broadcasts outside NEIC are usually filtered to meet user geographical or magnitude range criteria. All events that generate an automatic broadcast outside NEIC are reviewed by an analyst in about 30 minutes.

The automatic results are also sent to the IRIS Data Management Center (DMC) in Seattle which, for larger events, begins to retrieve data through automatic, computer based procedures from IRIS stations worldwide with dial-up capability. Once collected these data are sent to NEIC and included in subsequent processing of large events.

The network processor software has been designed to be very flexible, both in terms of load and capability. The multiprocessing design with automatic load balancing provides redundancy and handles the highly variable (and rapidly growing) real-time load. A multi-programming implementation with extensive interprocess (and interprocessor) communication makes the functionality extensible. In addition, the system is self monitoring and self repairing. Broad-band and traditional short- and long-period data arrives in two different protocols and in three different formats. The front end software treats each type of data separately to maximize capability and then reduces all data to a common format to make data differences transparent to subsequent processing. Support for additional protocols and formats can be added as needed.

Current Network Status

There are currently 88 short-period verticals, 7 long-period verticals, and 1 three-component long-period station coming into the USNSN data base from the so called USNET. These data are subsets of the various RSN's which are digitized at the RSN processing centers using USGS hardware (12-bits at ~20 samples/s), and transmitted via telephone lines to the NEIC. These data continue to be invaluable for earthquake monitoring.

As of 1 April 1994 there were 17 USNSN stations in operation with another five planned for installation during the year.

As of 1 April 1994 11 cooperating USNSN stations had been established with another 11 planned for installation during the year. These stations fall into two broad categories: IRIS (and IRIS-like) stations and other stations. The IRIS and IRIS-like stations now include custom coding provided by Joe Steim of Quanterra to send data of interest in the USNSN transmission format. At the other stations, digital data streams from broad-band sensors have been interfaced to a USGS-developed, Digital Equipment Corporation based, LSI-11/23 station processor which emulates most functions of the USNSN station processor.

Under agreements with cooperating institutions, the USNSN is also providing telemetry (via the NEIC) from field sites back to some of the host institutions. "Loop-back" links have already been established to Harvard, Saint Louis University, and Caltech.

Target

The USNSN is projected to grow to approximately 60 stations spanning the continental United States. Plans to improve this coverage and to extend it into Alaska, Hawaii, and Puerto Rico will be pursued as funding permits. In addition, arrangements to exchange subsets of event-detected waveform data with both the Canadian and the Mexican National Seismograph Networks have been made. Because of the type and quality of the instrumentation and the network distribution, greatly enhanced by the highly cooperative nature of the project, the USNSN has a research potential for new studies on regional and continental scales which is unprecedented.

Regional Network Interactions

The USNSN has a mission responsibility to promote communications among the RSN's. To this end, VSAT's have been installed at Memphis State University, Menlo Park, Caltech, and Saint Louis University with additional installations planned at Lamont, the University of South Carolina, the University of Washington, and the University of Utah. At each site, RSN-triggered short-period data will be sent to the NEIC and USNSN data of interest and possibly RSN data from adjacent networks will be transmitted back. Thus, the RSN component of the USNSN data base will continue to grow, including data at higher sample rates and from more stations. For Memphis State University, Saint Louis University, and Lamont, the USNSN will also act as communications provider for one or more sub-networks from the field to the respective institutions.

Through continued close cooperation between the RSN's and the USNSN, we hope to approach the goal of a National Seismic System (NSS). The USGS has assumed the responsibility for establishing a coordinating body for the NSS. Meanwhile, the USNSN is already providing a practical technological framework in which to begin implementing the NSS.

Data Distribution

Data distribution mentioned above is real-time and is in the USNSN telemetry format. A near-real-time satellite broadcast distribution of all broad-band event data is still under discussion and would be in the same format. USNSN data are currently available through an automatic data request manager operating at NEIC. The data retrieval process may be initiated by sending the e-mail message "Please help" to the e-mail address: autodrm@gldfs.cr.usgs.gov.

APPENDIX G

The Southern California Seismographic Network

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Summary

The Southern California Seismographic Network (SCSN) is jointly operated by the Pasadena Office of the U.S. Geological Survey and the Seismological Laboratory of the California Institute of Technology. The SCSN has 224 remote sites (with 343 components) and gathers data from local, regional and teleseismic earthquakes. These data are used for earthquake hazards reduction as well as for basic scientific research. The earthquake hazards reduction effort has become more important as moderate-sized earthquakes continue to occur within densely populated areas in southern California. Although the USGS operates most of the remote stations in the SCSN, Caltech operates 24 short-period telemetered stations and 15 very broad-band TERRAscope stations. In 1994–1995 we plan to install four more TERRAscope stations. Caltech also maintains drum recorders and other equipment at the central site located in the Seismological Laboratory at Caltech.

The southern California earthquake catalog is prepared by Caltech data analysts under the supervision of Dr. Kate Hutton. More than 10,000 earthquakes were entered into the catalog every year from 1980–1991. Since 1992 an average of 30,000 events per year have been entered into the catalog. Approximately 3.0–5.0 Mbytes of phase data and 30–50 Gbytes of seismograms are archived every year. In addition, USGS personnel participate in the data analysis, software maintenance, hardware maintenance, and other tasks necessary to complete the catalog.

Near real-time reporting to USGS in Reston, FEMA, and the Governor's Office of Emergency Services and other response to any felt or damaging earthquake activity is shared by Caltech and USGS personnel.

The Data Center of the Southern California Earthquake Center (SCEC_DC). The SCEC_DC that is located in the Seismological Laboratory at Caltech was established to facilitate access and distribution of earth science data relevant to earthquake hazards reduction efforts in southern California. This data center has significantly increased the use of the data from SCSN for scientific research. The mass-store system, which became operational on 1 October 1991, provides on-line storage for more than 600 Gbytes of data that are all available via Internet. Jointly the SCSN and SCEC_DC maintain a data base that includes 1) earthquake catalog (1932–present), 2) phase data

(1932–present), 3) photographic paper seismograms (1930–1992), and 4) digital seismograms (1977–present).

Because of limited funding in the past, some data gaps exist in the SCSN data base. The SCEC has provided funds for one data analyst to analyze data and to help close these data gaps. The total effort is estimated to be 6–8 years for one data analyst. This data analyst started working when the Landers sequence happened and has helped with backlogs of data created by the Landers and Northridge sequences, but not the old backlog.

SCEC has also funded the entry of the phase data from 1930–1960 into a digital format. These data are being processed by K. Hutton and are available in preliminary form via the SCEC_DC.

TERRAscope. This project is a Caltech initiative, funded by private foundations, to upgrade the seismograph instrumentation in southern California to IRIS and USNSN standards. The L.K. Whittier Foundation of South Pasadena and the ARCO Foundation have already donated funds to pay for 19 permanent broad-band, high dynamic range stations and two portable broad-band PASSCAL type stations. In addition, the USGS has installed two new broad-band stations in San Bernardino, near the San Andreas fault, and a station on Superstition Mountain. The data from the broad-band stations are available from an on-line data archive at Caltech via the SCEC_DC and from the IRIS/DMS.

TERRAscope data from seven stations are received real-time at the Seismo Lab and used for automatic magnitude determination and testing of new real-time data analysis methods. The stations ISA and SMT are transmitted via the USNSN satellite system. Our future plans include merging the TERRAscope data with the data from SCSN on a routine basis for real-time analysis and for preparing the earthquake catalog.

Future SCSN. It is our goal for the year 2000 to evolve the SCSN into a modern reliable earthquake monitoring network capable of providing real-time information and on-scale high fidelity ground motion data. This ambitious goal has in part evolved from our experience with the 1992 M_w 7.3 Landers and the 1994 M_w 6.7 Northridge earthquakes. As the local governments, the private sector, and the public become more aware of the earthquake problem there is an increased need for accurate information. If reliable real-time earthquake information is available, it can be used by many segments of society to protect life and property. Similarly, there is a dual need for rapid, accurate evaluation of strong ground shaking. First, maps of strong ground shaking are needed to guide emergency operations immediately following a major earthquake. Second, strong ground shaking that in most cases causes over 95% of the earthquake damage needs to be mapped to facilitate our understanding of damage and subsequent improvements of building codes.

Introduction

The objectives of the SCSN continue to evolve with the high rate of earthquake activity in southern California. The present and future objectives of SCSN involve 1) providing reliable near-real-time earthquake information to save lifes and protect property, 2) collecting high fidelity data for ground motion and earthquake source research, and 3) collecting earthquake data for earthquake statistical, seismotectonic and tomographic research.

The strategies needed to accomplish these new objectives consist of 1) new digital instrumentation, 2) digital data transmission, 3) new processing hardware and software; 4) new approaches to real-time notification to remote users, 5) changes in emphasis for routine analysis of data, and 6) new management structure for the network. To meet these new objectives the next 3 years will be a rapid time of change for the SCSN.

The area monitored by the SCSN includes two of the ten largest cities in the United States (Los Angeles and San Diego) and almost 20 million inhabitants. More than one hundred earthquakes (not including aftershocks) are felt each year and an average of 1.5 events per year are potentially damaging (magnitude greater than 5.0) (Fig. 1). The need for information about these earthquakes is great. Immediately after a moderate or large earthquake, information about the size, location and damage from the event is needed to coordinate rescue operations, guide inspectors in the search for damage, and to satisfy public curiosity. The record of earthquake occurrence in California is important to insurers, geotechnical engineers, and city planners. The SCSN has maintained and published a catalog of earthquakes above magnitude 3.0 since 1932 and above magnitude 2.0 since 1980 with consistent magnitudes over the whole time.

Although reliable prediction of the time, place and magnitude of impending earthquakes is not yet possible, scientists can recognize times of increased hazard of damaging earthquakes, for instance after a potential foreshock or during an aftershock sequence. Recent advances have made it possible in some situations to estimate the probability that an event will be followed by a larger earthquake (e.g., Jones, 1985; Agnew and Jones, 1991) and the probabilities of damaging aftershocks (Reasenberg and Jones, 1989). One of the purposes of the Southern California Seismographic Network is to provide the data necessary to make these evaluations. The earthquake data recorded in southern California are processed in near-real time, and if appropriate, probabilities of future earthquakes are calculated. These probabilities and other requested advice are provided to USGS Reston, FEMA, and the State of California and through the Governor's Office of Emergency Services (OES) to the public.

An additional purpose of the Southern California Seismograph Network is to provide data for research in seismology, earthquake physics and prediction, and tectonics. Southern California is the most seismically active region in the contiguous United States and provides a unique seismotectonic environment of moderate convergence along a transform plate boundary. The large numbers of earthquakes (more than 200,000 earthquakes) and the long history of the catalog make this data set an important resource for studies in seismology and earthquake physics. The earthquake data also can provide important constraints in the analysis of the geology of southern California.

We have begun and expect to continue the process of upgrading the network to meet the demands of modern seismology. With the new techniques available for analyzing the waveforms

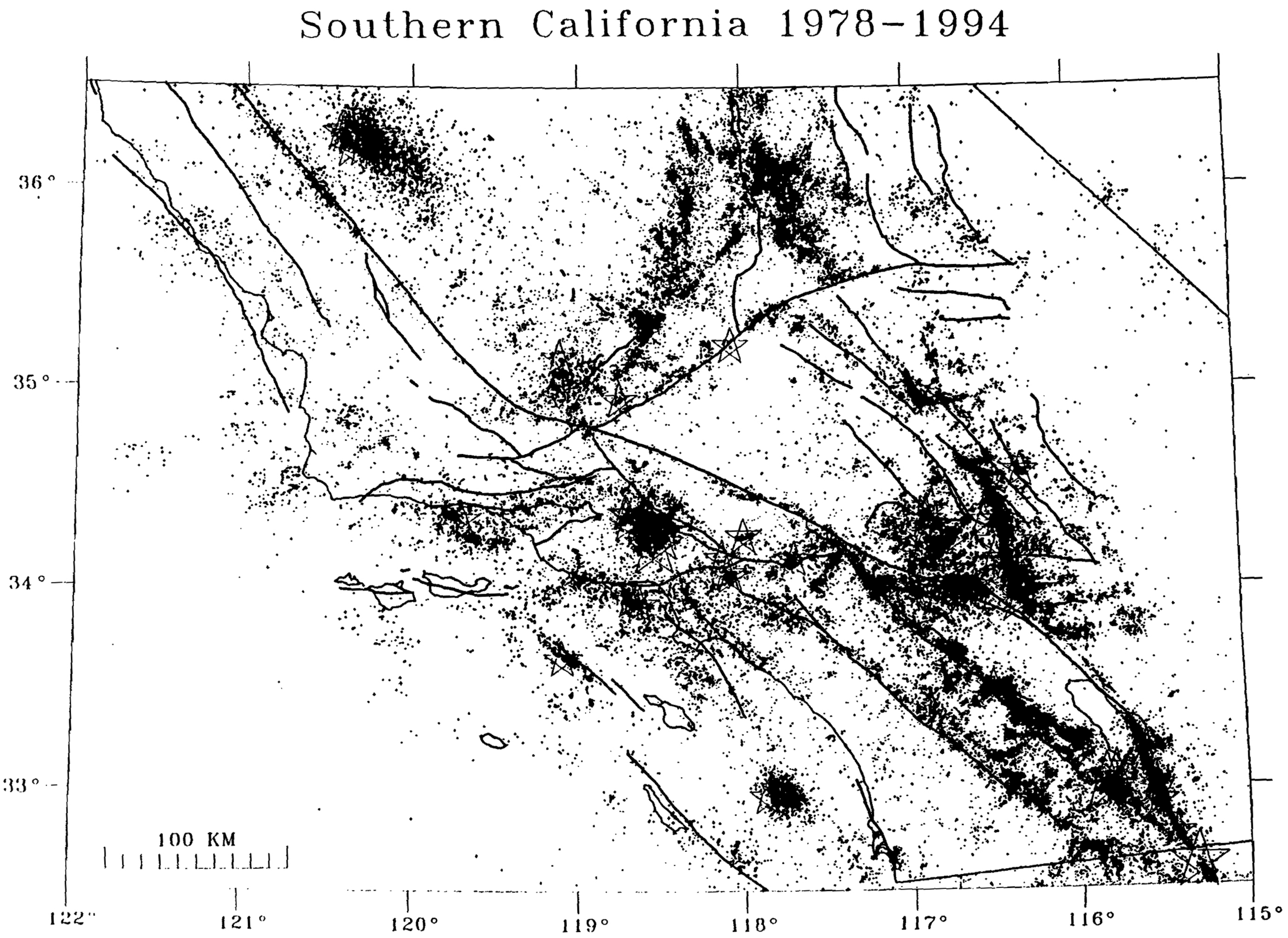


Fig. 1. Seismicity of southern California 1978–1994.

of local earthquakes, the quality, bandwidth and dynamic range of the seismic signals have become much more important. Already 17 (15 Caltech stations and two USGS stations) digital, broad-band, high-dynamic range seismic stations with Streckeisen seismometers have been installed. At least four additional broad-band stations will be installed in 1994–1995. We will also continue to improve the quality of the existing short-period network. The on-scale, calibrated waveforms needed for research also could form the basis of an early warning or SCAN (Seismic Computerized Alert Network) system. Such a system would automatically analyze incoming seismic signals to determine within a few seconds if a large earthquake was starting and, if so, the epicenter and probable magnitude. We expect the network to evolve and in the future to provide an early warning of large earthquakes to the people of southern California.

Several fund-raising efforts are in progress to raise funds for the capital improvement of the SCSN in the wake of the Northridge earthquake. If these efforts are successful, the operation and development of the SCSN may take a quantum leap forward in the next 3 years. If no significant new funds become available, the SCSN operation will evolve at a very slow pace.

Network Operation

The Caltech network operation consists of 1) operating computer hardware/software and other instrumentation for data acquisition at the central site, 2) field maintenance of remote short-period telemetered instruments, and 3) installation and field maintenance of TERRAscope stations and other new digital instruments.

Central Site

The SCSN data are acquired by two microVAX-III computers and the data processing is done on six VAX workstations using a VAX-4000 as a central server. The installation and operation of this equipment that was last upgraded in 1990–1991 is shared by Caltech and USGS personnel.

Data channels arriving at the central recording site at Caltech are demodulated back to analog signals, passed through anti-alias filters at 20 Hz and then converted to 12-bit digital data (±2048 counts) at 100 samples per second by two independent Tustin digitizers. Event detection, phase detection, and rapid location and magnitude determination is done on one of the microVAX-III on-line systems. Event files of time-series data are also saved for off-line processing in CUSP. To avoid duplication, software development for the on-line systems and CUSP is done in cooperation with the USGS in Menlo Park.

Backup is provided by continuous recording of the whole network onto Digital-Audio-Tapes (DAT). In addition to backup recording the DAT-tapes are ideal for recording teleseisms. The DAT-tapes are saved if a significant teleseism has occurred or there are problems with the on-line routine recording. The SCSN is the first network to use this new technology for continuous recording of data.

Remote Stations

At present the SCSN records 343 channels of data from 224 sites (see Table 1). Most of the sites have a short-period (1-sec) vertical seismometer running at the highest gain permitted by the local noise levels. The station spacing is 15 to 30 km (Fig. 2) over an area of roughly 150,000 km^2. We have determined GPS locations for all of the stations. The data at some of the stations are augmented by other sensors. Ten three-component sites include an additional two horizontal seismometers. Ten sites have an additional vertical seismometer running at a lower magnification (typically 1/16 the magnification of the high-gain component). Eight sites have three-component Force Balance Accelerometers (FBA). Figure 3 shows the distribution of the sites that have these additional data channels. The analog data signals are amplified and modulated by Voltage Controlled Oscillators (VCO) at the station and then sent by various combinations of FM telemetry, phone lines and microwave links to the central recording site at Caltech.

Table 1. Stations and channels digitally recorded by the SCSN.

Agency Maintaining Stations	Number of Stations	Number of Components
USGS, Pasadena	172	279
Caltech	24	32
USGS, Menlo Park	8	8
USC	12	16
DWR	6	6
UCB	1	1
UNR	1	1
TOTAL	224	343

Over the last 5 years we have improved the quality of the waveforms recorded by the short-period instruments. Signal quality has been analyzed and the amplification has been decreased at more than 50 stations to improve dynamic range. We have searched for electronic noise and eliminated it whenever possible through repairing and replacing VCO's and discriminators and filtering out high frequency noise in the central recording facility. The average dynamic range of the high gain stations has improved from about 30 dB to 45 dB.

Current information about the configuration of each network station (sensor type, amplifier type, gain settings, etc.) is documented in an easily accessible PC database, which is updated within a few days of any modifications. The database has proved useful to technicians and scientists who wish to obtain detailed instrument information, for example, searching for all sites that have a particular type of electronic amplifier, or tracing the history of gain settings at a particular station. These database files can also be used in a computer program which removes the instrument response from the network waveform data to produce (band-limited) ground displacement or velocity seismograms.

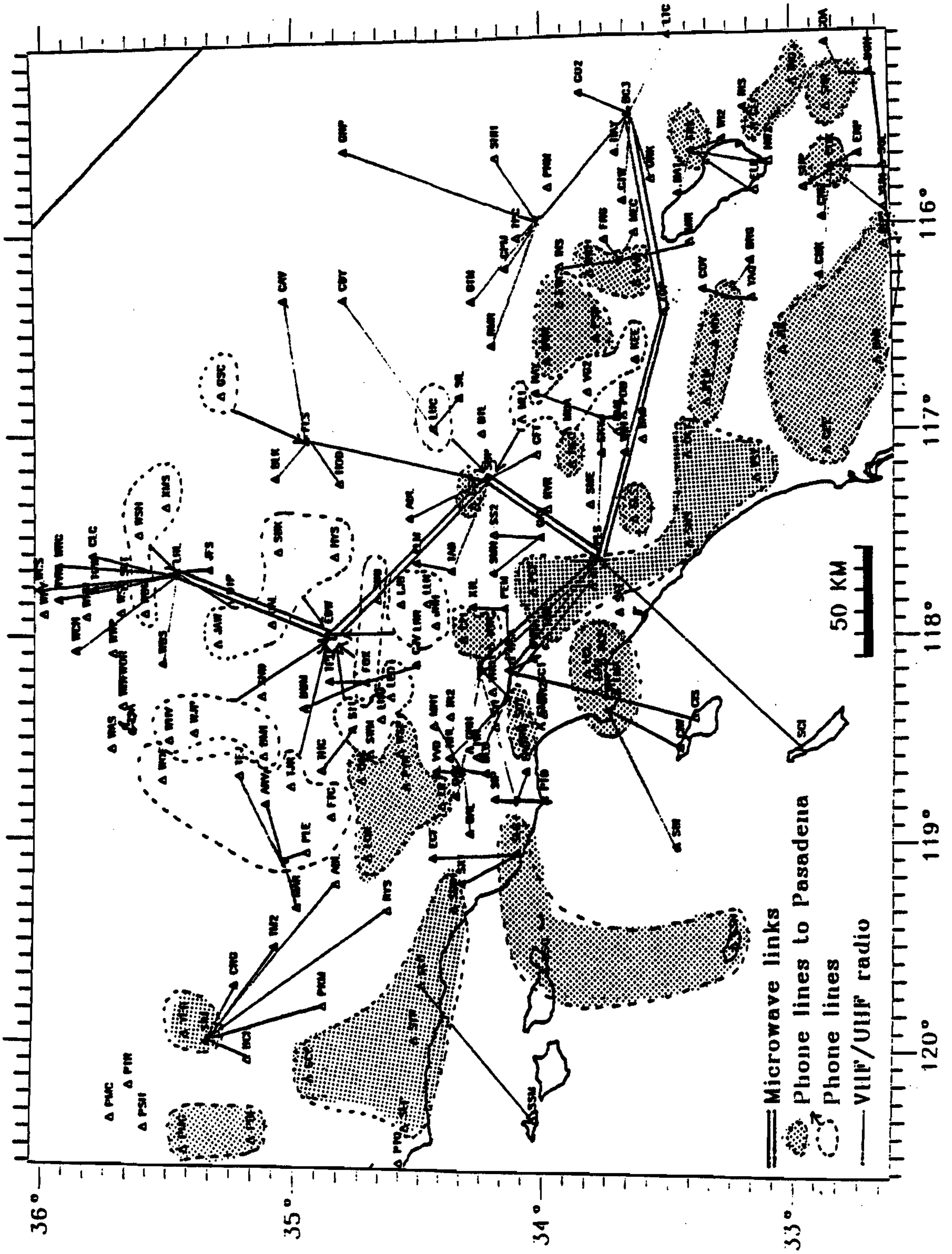


Fig. 2. The Southern California Seismographic Network; triangles indicate locations of stations. Data transmission links are also indicated.

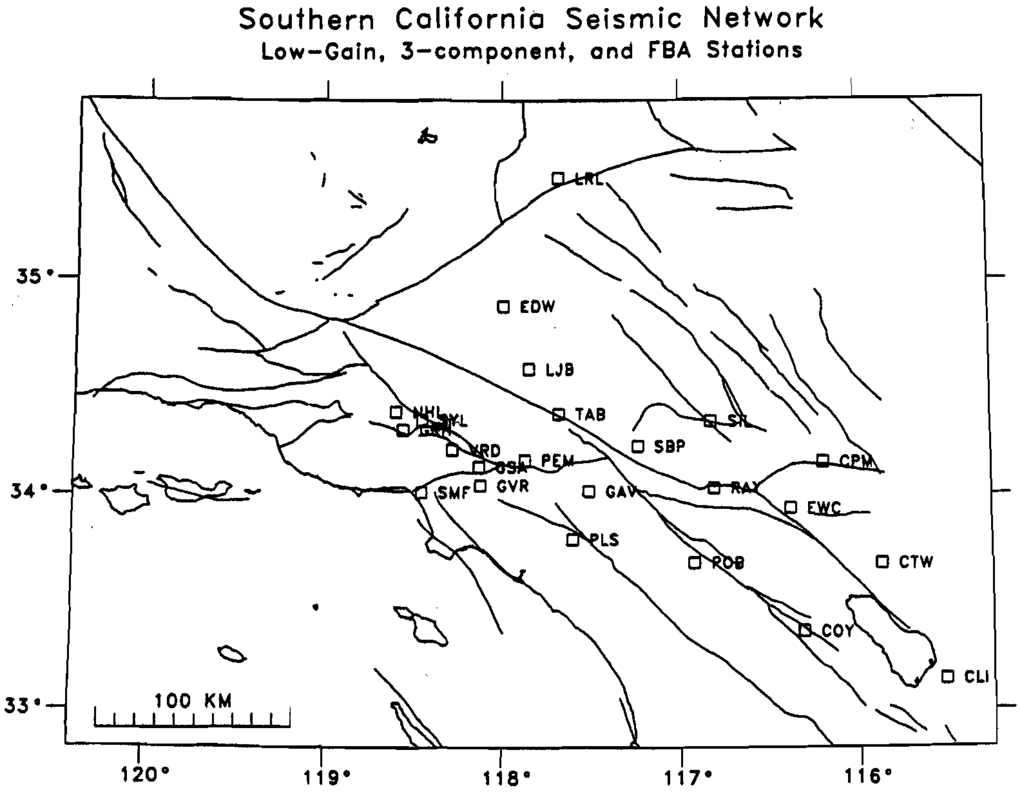


Fig. 3. Low-gain and high-gain seismometer, and ultra-low-gain Force Balanced accelerometers (FBA) stations in the Southern California Seismic Network.

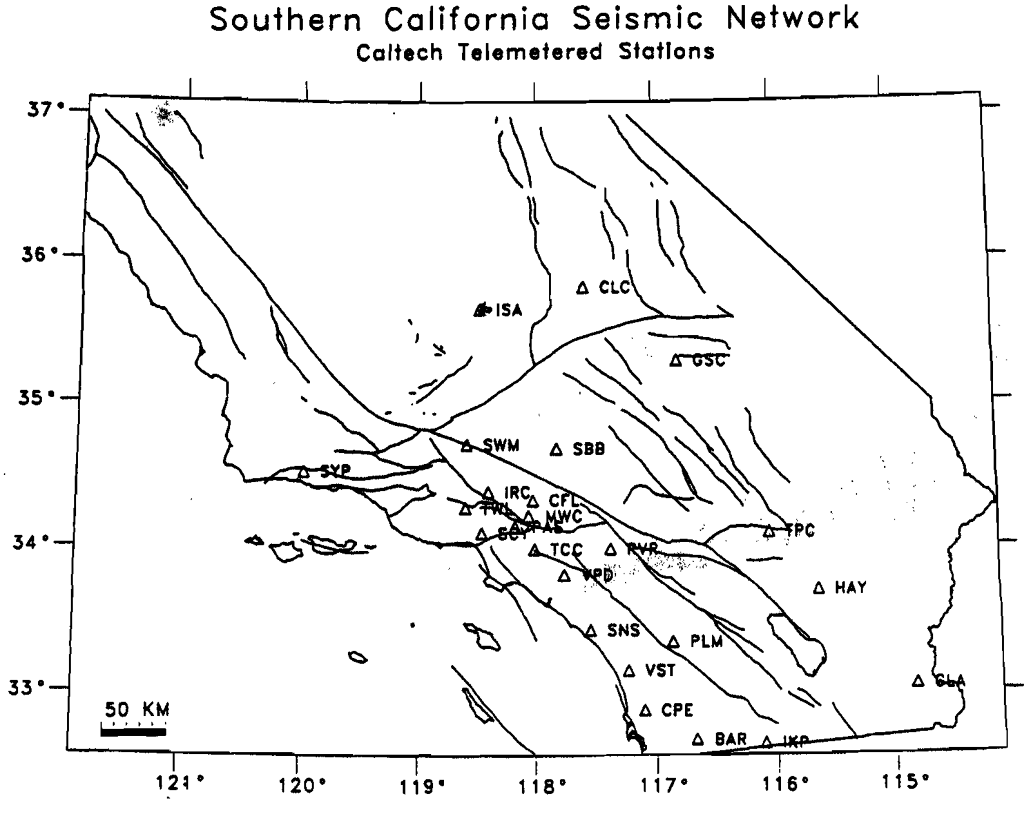


Fig. 4. Telemetered stations operated by Caltech. Triangles indicate locations of stations.

Caltech is responsible for field maintenance of 24 of the 224 remote telemetry stations (Fig. 4), while the USGS Office maintains 172 remote sites. Sixteen channels of data are received from USC, eight channels from the USGS in Menlo Park, and six channels from Department of Water Resources (Table 1).

In addition to the remote telemetered sites, Caltech used to operate seven stations with on-site photographic recording. Most of these stations were installed in the late 1920's. The instrumentation consisted of different combinations of Wood-Anderson seismometers, Benioff seismometers and Press-Ewing 1-90 seismometers. All photographic recording was terminated in late 1992 to early 1993. Some of these stations are now part of TERRAscope and have been upgraded with Streckeisen seismometers and Quanterra data loggers.

TERRAscope

In 1988, when Caltech received a grant from the L.K. Whittier Foundation, the development of TERRAscope began. The initial goals for TERRAscope were to install at least a dozen modern broad-band (10 Hz to DC) and wide dynamic range (nominally 200 db) seismographic stations with "real-time" data retrieval capability. Each station has a broad-band Streckeisen STS-1 or STS-2 seismometer and Quanterra data logger with a 24-bit digitizer and a Kinemetrics FBA-23 strong-motion sensor. As of July 1994, 17 TERRAscope stations are in operation (Fig. 5).

TERRAscope complements and extends the capabilities of the existing 224 station (343 components) short-period SCSN. The data from TERRAscope will also be included in the SCSN data base used for generating the CIT/USGS southern California earthquake catalog. Because of their real-time capability and location in a populous earthquake-prone area, both networks enable seismologists to provide the public, Federal, and State officials with timely information about significant earthquakes.

The TERRAscope stations are also included as a subnetwork of the global seismographic network, operated by IRIS, and of the USNSN, operated by the U.S. Geological Survey.

Analysis of the new high-quality data recorded at PAS from numerous regional earthquakes, including the December 1988 ($M_L = 5.0$) Pasadena earthquake at an epicentral distance of 3 km, have demonstrated that the high-quality broad-band data are the cornerstone needed for significant advances in both regional seismology and studies of teleseisms. In particular, the broad-band data recorded at 10 TERRAscope stations, from the 17 January 1994 (M_w 6.7) Northridge earthquake were easily available immediately after the event to determine the style of faulting and other seismological parameters of the earthquake. The very encouraging results of analyzing TERRAscope data so far have led us to modify the initial goal of a dozen stations to a goal of 21 stations in southern California.

Data Availability. TERRAscope data are recorded in both continuous and event-trigger modes on site. The tape cartridges that contain continuous data are sent to the IRIS/USGS Data Collection

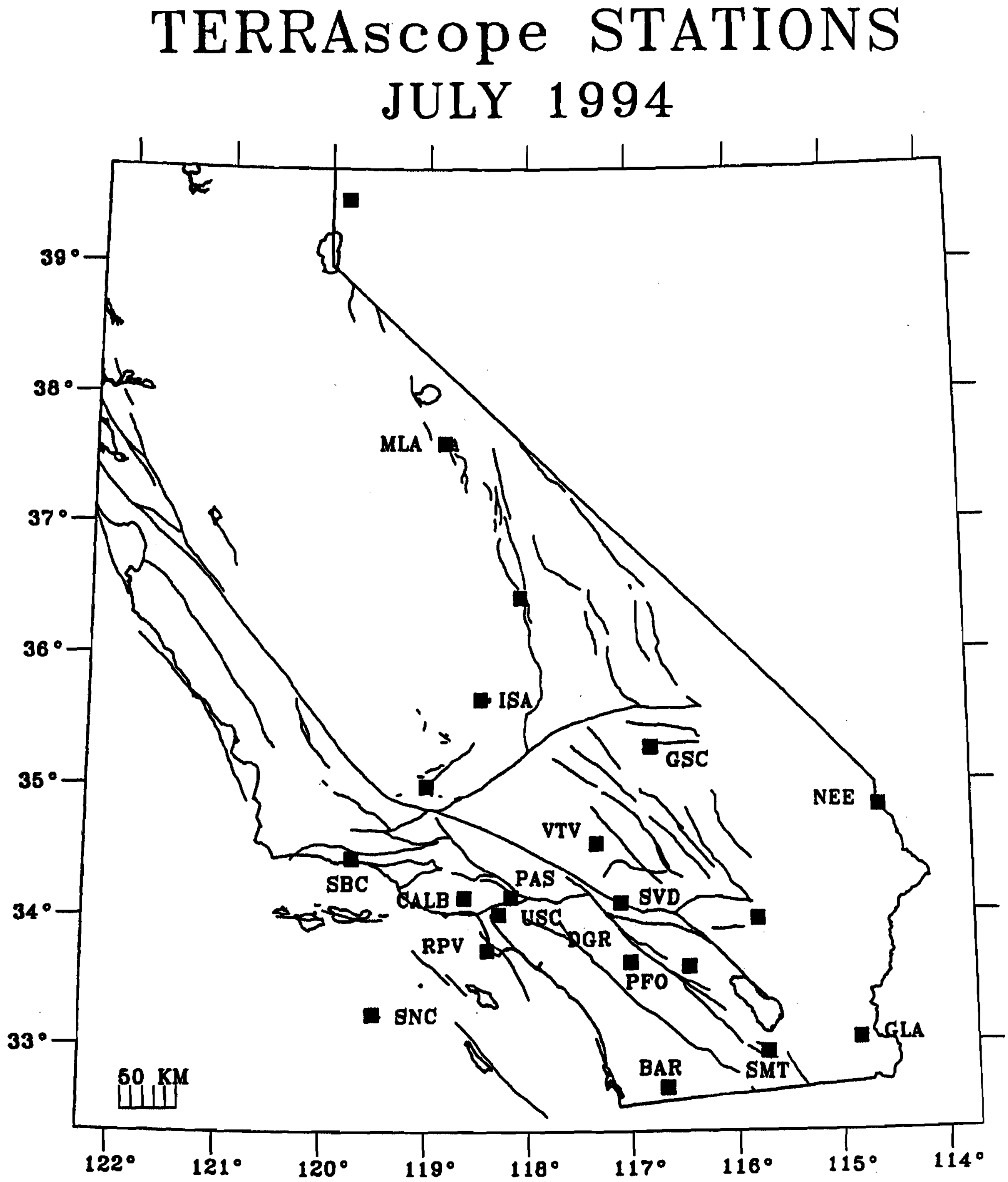


Fig. 5. TERRAscope stations. Squares labeled with three letter codes represent stations already in operation; squares that are not labeled represent stations to be installed in 1994–1995.

Center at Albuquerque and archived at the IRIS Data Management Center. These data are available upon request from the IRIS/DMC.

For quick and efficient data access, an automatic dial-up data retrieving system called Caltech Gopher (adapted from the IRIS Gopher system) has been implemented. The Caltech Gopher receives E-mail from NEIC for teleseisms and the SCSN with origin time, location, and magnitude for regional events. The Gopher retrieves data from 15 TERRAscope stations for these events. The data are available to users through the SCEC_DC. Usually the data are available within 30 minutes after the occurrence of a local or regional event and several hours after the occurrence of a teleseism.

Future Developments. With funds provided by the L.K. Whittier Foundation and ARCO Foundation we plan to deploy four more stations during 1994–1995. Although the actual locations have not been finalized, the following sites are being evaluated: Eastern Mojave, Owens Valley, Coast Ranges, and Reno, Nevada (Fig. 5).

To have the data available for immediate analysis following a major event we are testing two real-time telemetry systems. One is a satellite telemetry system that was installed in cooperation with the USNSN. This has made one TERRAscope station, ISA, a part of the USNSN. The other is based on data transmission over digital telephone lines (ADN) and a local real-time data collection system developed by our senior computer programmer. Because the ADN leased lines are expensive, we plan to start using Frame-Relay, which are virtual dedicated leased lines, as a way of transmitting the TERRAscope data real time. Frame-Relay is more cost effective than ADN because no distance or usage charges are involved.

Catalog Preparation and Data Access

The catalog preparation done by the SCSN staff consists of 1) demultiplexing and removal of noise events, 2) picking of P and S phases and locating the events, 3) magnitude determination, 4) completeness check, and 5) archiving of the data. In addition, the staff involved with production of the catalog responds to earthquake crises, request for information about earthquakes, and assists data users with data access.

Data Products and Access

With over 30,000 earthquakes recorded per year, the SCSN analyzes and archives a huge quantity of data every year, including catalog listings (time, magnitude, location, and location quality), phase data (arrival times, qualities and first motions at each station) and seismograms (Fig. 6). The data from the SCSN are recorded and processed using the CUSP (Caltech/USGS Seismic Processing) system (Johnson, 1983) on a network of VAX/VMS computers. The data are maintained in CUSP binary data bases, accessible through a series of programs.

We distribute these data to researchers and other users primarily through the SCEC_DC, which is accessible via Internet. These data are used by a wide variety of people—researchers from the U.S. Geological Survey, Caltech and other academic institutions, geotechnical consultants, insurers,

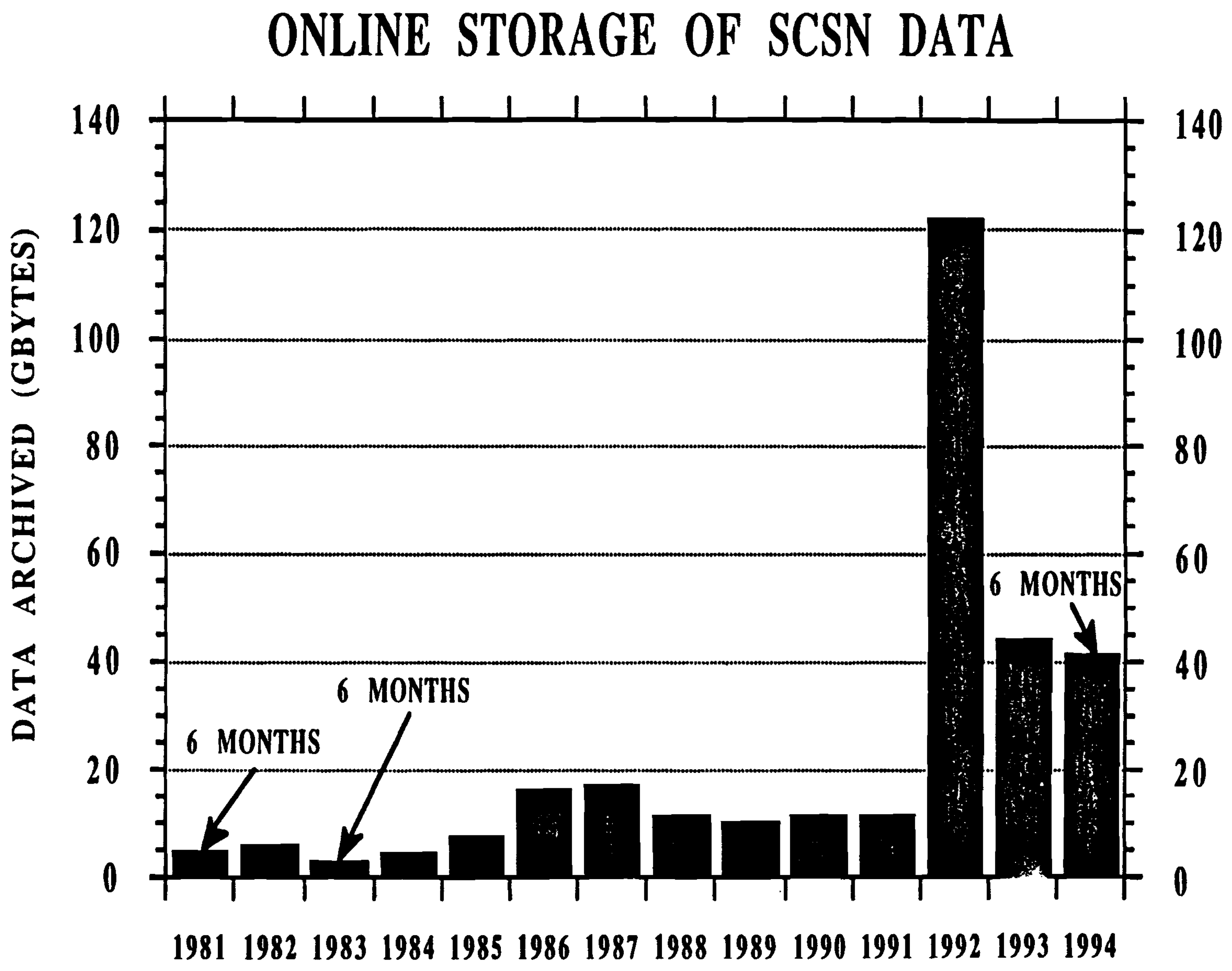


Fig. 6. Histogram showing quantity of seismic data acquired and stored by SCSN per year.

lawyers, and the general public. In Fig. 7 we show schematically how the data reach the various user communities. The three sources of data, SCSN, TERRAscope, and portable instrument data, are shown to the left, the means of distribution are shown in the middle, and the types and numbers of users are shown to the right. This flow chart clearly shows that Internet is the preferred way of obtaining earthquake data.

Earthquake Catalog. The earthquake catalog is the most commonly used of the SCSN data bases. It is complete for events M ≥ 3.0 since 1932 and includes over 200,000 events. It provides a unique resource in seismology because it is the only U.S. catalog in which magnitudes of earthquakes above 3.0 have been determined in the same way for a period this long. To increase the usefulness of the catalog, the staff of the SCSN prepares weekly and quarterly digests of the recorded seismicity. A listing of all earthquakes above 2.5 is prepared quarterly and mailed to 185 recipients, many in industry. This listing and a plot of the events is also available through the World Wide Web on Internet.

Phase Data. The phase data, arrival times and first motions at all timed stations, are more voluminous than the catalog with about 300–500 megabytes of data now created per year. The phase data from 1932 to present are now available in digital format. Two large data gaps exist in this time period for which the digital seismograms have not yet been processed: May 1980–Feb. 1981 and Mar.–June 1983. A subset of the stations were timed off of paper records for earthquakes M ≥ 2.5 in these time periods and these data are available. A small data gap exists for the 1992 Landers sequence where about 10,000 earthquakes still need to be timed (Fig. 8).

Processing of Northridge aftershocks is complete from February 7 to the present. During the early weeks of the earthquake sequence all events recorded between January 17 and February 7 were preliminarily located. Seismic analysts are now resuming processing of those early events and have completed the processing for approximately 75% of the 4300 events recorded during that time period (Fig. 8). This data is available through the SCEC_DC as processing is completed.

Seismogram Data Base. All the seismic signals, except for the Wood-Anderson instruments, have been digitized and recorded on computer since 1977. Because of their size (an *average* of 10–20 megabytes of data per earthquake), seismograms are stored on a dedicated optical platter on the SCEC mass storage jukebox and a backup copy is put on DAT tape within 1 or 2 days of being recorded. All of the digital seismograms have been copied to the SCEC_DC mass-store system.

SCEC_DC

The Data Center of the Southern California Earthquake Center (SCEC_DC) that is funded by the SCEC has greatly increased the use of the data from SCSN for scientific research (Fig. 9). The SCEC_DC is located at Caltech and the staff of both the SCSN and SCEC_DC work together to maintain high data quality and to ensure rapid distribution of data. The mass-store system, which became operational on 1 October 1991, and a 2nd system added in March 1994, provides on-line storage for more than 600 Gbytes of data. The availability of 60 years of catalog, 30 years of phase

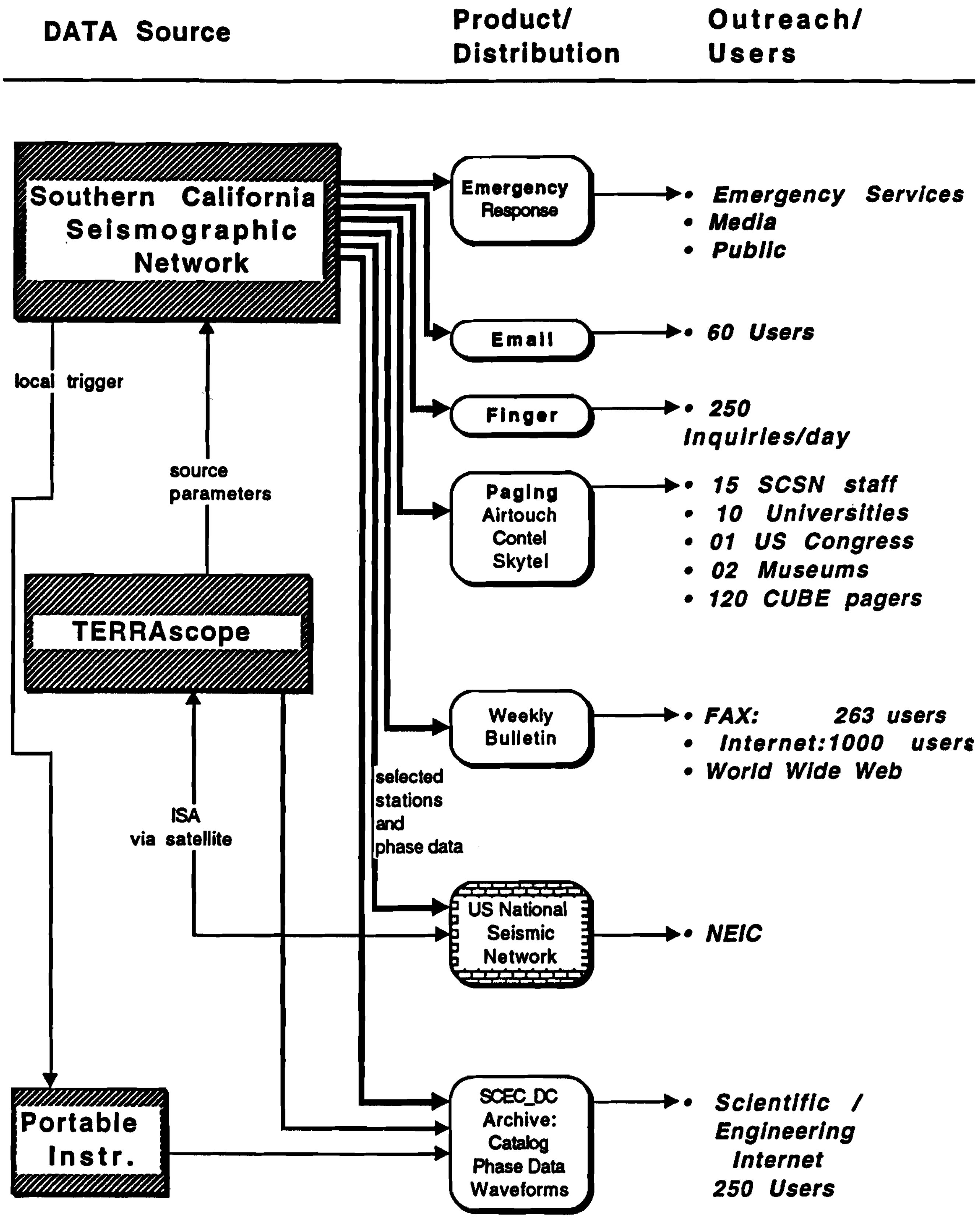


Fig. 7. Flow of information from SCSN and TERRAscope to the users.

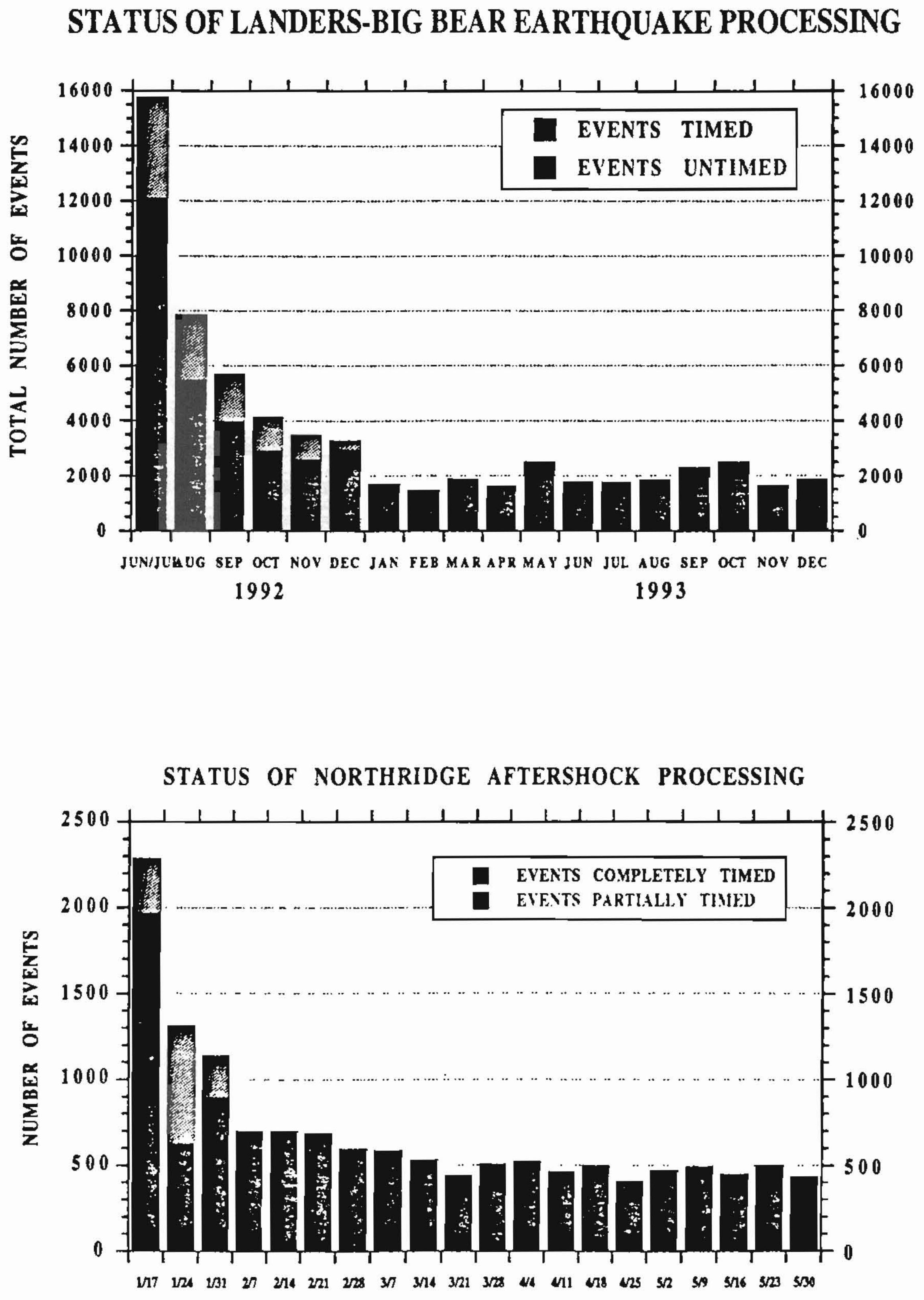


Fig. 8. Status of the 1992 Landers and 1994 Northridge data processing.

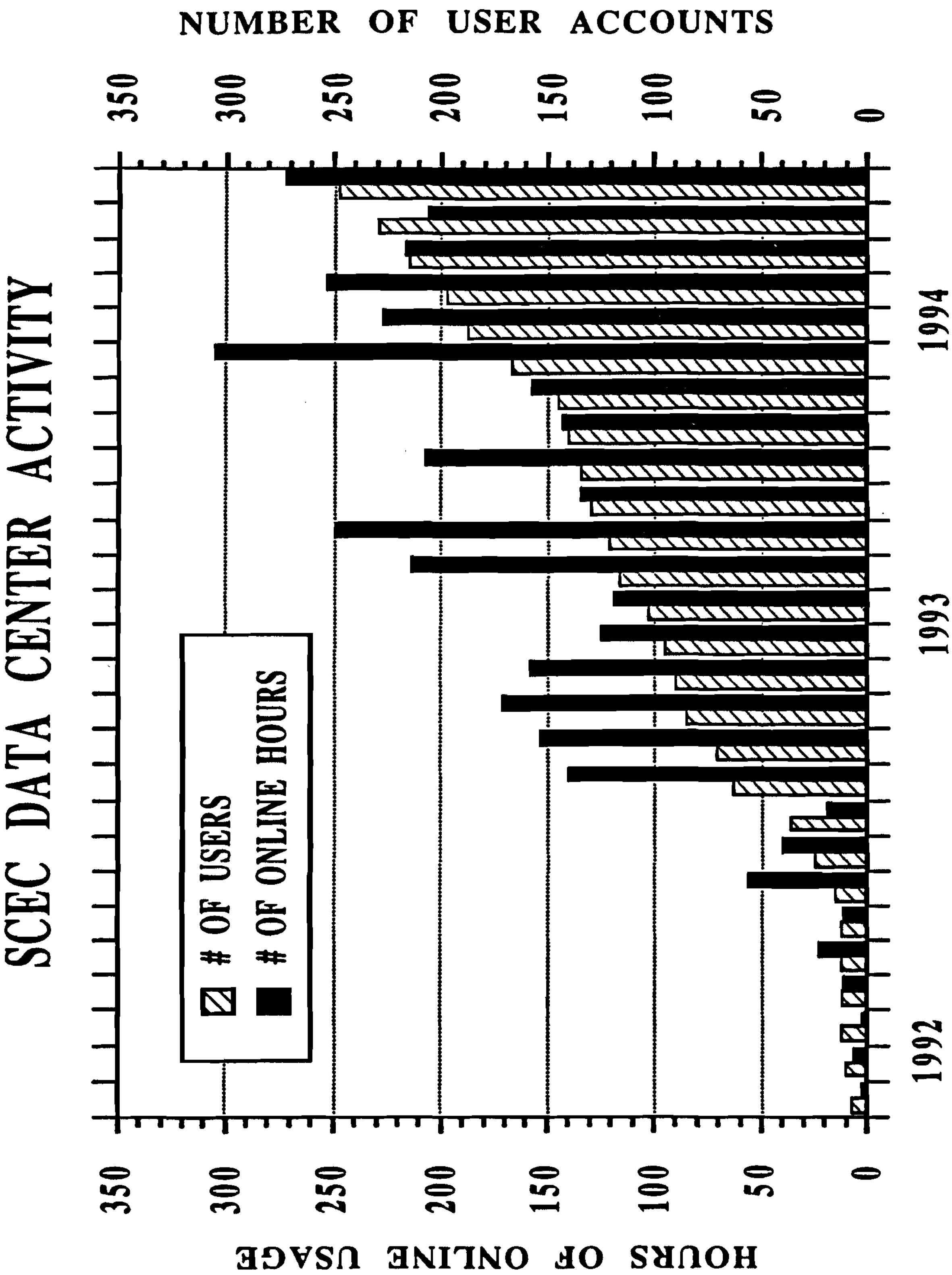


Fig. 9. User activity at the SCEC_DC.

data, and 14 years of digital seismograms on both Unix and VMS computers and on line over Internet/NSFNET greatly improves the access to the data.

The SCEC Data Center (SCEC_DC) has been expanding continually since it came on line approximately 2½ years ago. Access to the SCEC_DC is still primarily through individual user accounts (currently totaling 221), at a rate of approximately 200 hours/month (Fig. 9). In addition, a "bulletin board" system was implemented in April 1994, which allows researchers to request accounts, and obtain information regarding data stored on the SCEC_DC, as well as the availability and access to GPS and Strong Motion Data. We expect to expand the capabilities of this bulletin board system to include such things as anonymous ftp of weekly earthquake reports, as well as conducting routine earthquake catalog searches.

The SCEC_DC activity in 1994 is primarily focused on adding a second mass storage device to our existing system. This addition, which included an upgrade of the operation system, as well as the archival data management software, was completed on March 23, 1994. The new configuration appears to users exactly the same as the previous one-Jukebox configuration, i.e., as a single Unix filesystem. The SCEC_DC's on-line storage capacity is now 600 Gbytes.

Currently the SCEC_DC archive consists of 347 Gbytes of seismic and geodetic data. Approximately 60 Gbytes of this data is made up of raw SCSN data recorded during the Joshua-Tree-Landers Earthquake sequence, as well as all data archived directly by the SCSN on to the Jukebox since the Northridge earthquake of this year. GPS data from UCLA, in RINEX as well as raw data formats, currently occupies approximately 700 mb of storage space. Approximately 80% of the processed SCSN data has been backed up onto 5-Gbyte exabyte tapes since January of this year. A copy of these backup tapes will be stored at the Northern California Data Center.

The SCEC_DC has recently implemented a relational database, in which the indexes into the database are the event ID's associated with individual earthquakes. A description of this database, as well as other features of the SCEC_DC, was presented at the April 1994 meeting of the SSA in Pasadena. A binary version of the database was developed from ASCII files which store earthquake and seismogram attributes, as well as indices into the waveform archives. The format of these ASCII files is identical to the system used at the Northern California Data Center. The ASCII format is also the means by which portable and TERRAscope data are entered into the database. The binary version of the database is accessible through a sort program and a subroutine library. Hierarchical event and phase catalogs are derived from the binary database (Fig. 10). User-created catalogs (e.g., relocated Landers' aftershocks) can be connected to this system through the use of a relational key (the "eventid"). In the next few months we plan to merge TERRAscope and portable data into the binary database. UCSD has already created ASCII files in the SCEC_DC format for portable data recorded during the 1992 Landers-Big Bear earthquake sequence.

To access SCEC_DC do the following: *rlogin scec.gps.caltech.edu -l bulletin*

DATA FLOW

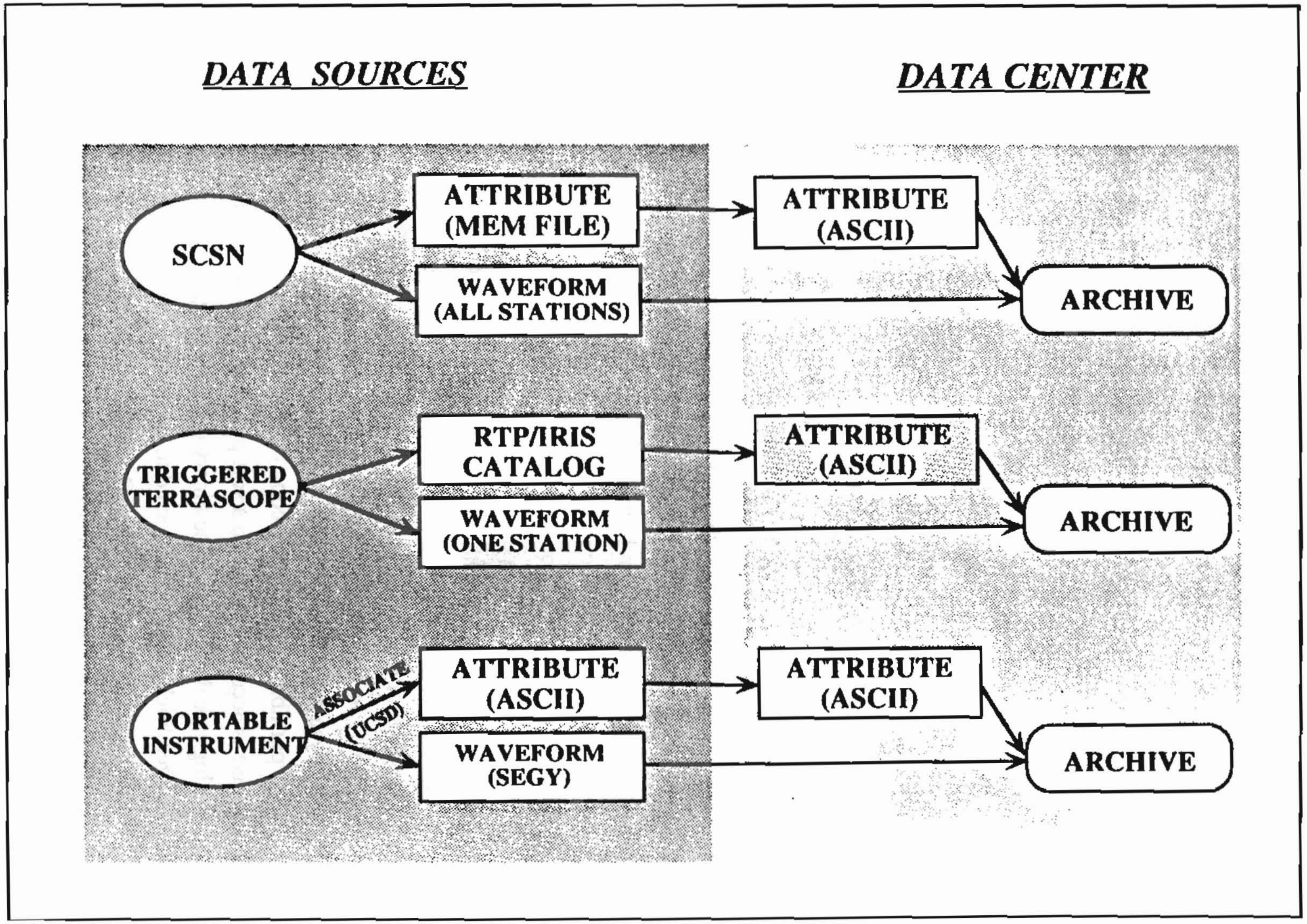


Fig. 10. Schematic data flow for the SCEC_DC.

Caltech/USGS Broadcast of Earthquakes (CUBE)

The CUBE project is an outreach program under Caltech's Earthquake Research Affiliates program. This is a cooperative research project between Caltech, USGS, and several transportation and utility companies to develop a sophisticated real-time seismic information system using data from SCSN and TERRAscope. The CUBE project has 17 contributing members and 10 non-contributing members. The objectives of the CUBE project are 1) develop the capability to provide near-real-time earthquake information to critical users such as utilities and transportation companies, 2) develop user software for remote evaluation of the earthquake information, and 3) educate the members about earthquakes and the most recent research results. The participants in this project are actively involved in the research using a radio pager-computer display system. The feedback from these participants helps Caltech and USGS seismologists to improve the system, thus contributing to seismic hazard reduction and promoting the advancement of seismology.

The CUBE project is for advanced technical users who need the two-way communication to Caltech/USGS Pasadena to ensure receiving reliable earthquake information to save lives and protect property. Many of these CUBE members may establish dedicated communications links, in addition to the pagers, to Caltech/USGS Pasadena to ensure reliable delivery of information. As part of CUBE, we also plan to establish future cooperative efforts that will consist of sharing real-time strong motion data from instruments operated, for instance, by utility companies.

Future Plans: SCSN for the Year 2000

It is our goal for the year 2000 to evolve the SCSN into a modern reliable earthquake monitoring network capable of providing real-time information and on-scale high fidelity ground motion data. This ambitious goal has in part evolved from our experience with the 1992 M_w 7.3 Landers and the M_w 6.7 Northridge earthquakes. As the local governments, the private sector, and the public become more aware of the earthquake problem there is an increased need for accurate information. If reliable real-time earthquake information is available, it can be used by many segments of society to protect life and property. Similarly, there is a dual need for rapid, accurate evaluation of strong ground shaking. First, maps of strong ground shaking are needed to guide emergency operations immediately following a major earthquake. Second, strong ground shaking that in most cases causes over 95% of the earthquake damage needs to be mapped to facilitate our understanding of damage and subsequent improvements of building codes.

New Digital Instrumentation

At present the near-real-time earthquake information that is provided by SCSN is not considered to be reliable because the instrumentation is inferior and the data are often contaminated by electrical noise. New instrumentation for SCSN needs to have minimal electrical noise and to be able to record both weak and strong ground motion onscale at a reasonable cost.

Caltech has a pilot project funded by the Department of Commerce of the State of California to develop a near-real-time reporting strong ground motion network. This project is in cooperation with Kinemetrics Inc. in Pasadena. The objectives are to have Kinemetrics develop a prototype digital strong motion instrument (K2) that can both provide real-time time-series data as well as processing of data on site. Caltech is developing some of the software for the new instrument. As part of this project, four instruments will be deployed in 1994 at remote sites in the Los Angeles area. These instruments will be connected via dedicated Frame-Relay to Caltech in Pasadena. Caltech will develop data analysis tools intended to provide near-real-time ground motion maps from these and other available sites, such as TERRAscope. This project is a pilot project that will influence the future modernization of instrumentation at remote sites in the SCSN.

The future upgrade of SCSN may include six-component sensors with three-component FBA and three-component high-gain velocity sensor at each site.

Digital Data Transmission

At present much of the SCSN analog data are transmitted on dedicated leased analog phone lines, dedicated microwave circuits, and radio links. This mode of transmitting data is not particularly reliable and leads to common electronic noise bursts and several single points of failure. To move our data communications from analog to digital we have sought advice from the local phone companies such as Pacific Bell and GTE.

We have received a grant from the California Research Network (CalREN), a non-profit foundation funded by Pacific Bell. This grant will provide $80K worth of Frame-Relay telecommunication cost for TERRAscope and any USGS or other digital seismographic stations in southern California. The time duration of this grant is from September 1994 to June 1996. Frame-Relay works like a dedicated computer network where virtual dedicated circuits are defined in software by the phone company. Pacific Bell estimates that the usage of the Frame-Relay system will drop following a major earthquake because many businesses that routinely use the Frame-Relay system may be temporarily shut down, due to the earthquake.

This grant will make it possible to receive real-time digital data at a rate of 56K bits/sec from 20 remote stations to Caltech in Pasadena. It will also make it possible to test modern communications methods for seismology. The Frame-Relay service has only installation and monthly fee charges; it has no distance or usage charges. We are hopeful that the Frame-Relay technology may be scaled up easily to a network of 1000 remote stations.

Initially we plan to connect our remote sites via RS-232 ports defined in software on the Frame-Relay. Further development will include connecting remote stations to Caltech using TCP/IP protocol and operating the seismic network as a Local Area Computer Network (LAN).

Real-time Earthquake Notification

The societal need for near-real-time earthquake information is great. First, there is a need to know about small earthquakes that are felt and to confirm that they are indeed small and no emergency response is required (R. Andrews of OES, personal communication, 1994). In general our near-real-time notification system is very good at handling these types of events (Fig. 11a).

Rapid determination of earthquake source parameters after large earthquakes is very important for earthquake hazard mitigation. After a damaging earthquake, the emergency operations made in the first hours can be crucial for saving lives and protecting properties. These operations need to be based on the characteristics of the earthquake that has just occurred. The location, depth, size, mechanism, and rupture direction all directly affect the extent and distribution of damage. If the earthquake source parameters can be quickly and accurately determined after a large earthquake, they can be used effectively, in conjunction with the information of the site and macro seismic data, to determine the resulting ground shaking pattern. We have tried aggressively to provide information about major earthquakes rapidly during the last 3 years. We have had one success and several failures.

Our early success was the notification of the occurrence of the M_w 5.8 1991 Sierra Madre earthquake and subsequent stopping of Santa Fe railroad trains in the Pasadena area. One of our most spectacular failures occurred during the M_w 6.7 Northridge earthquake, when our real-time software (ISAIAH) failed to provide a location and hence we had no information available for more than 20 minutes. At present we have focused our efforts toward fixing software and hardware problems that are known to contribute to the failure of our near-real-time notification system.

ISAIAH. The SCSN real-time notification system is based on a real-time software system, Information About Earthquake Activity in a Hurry (ISAIAH), developed by the USGS in Pasadena, that analyzes data from all 343 channels and provides first estimates of preliminary locations and magnitudes within 30–40 seconds (Fig. 11b). ISAIAH replaced the old 64-channel RTP developed by the USGS in Menlo Park.

This automated software gives fast reliable locations and preliminary magnitudes for events within the network and is used to send magnitude and location information to E-mail, Finger, and pagers carried by USGS, Caltech personnel, and CUBE members. Preliminary magnitudes for smaller events ($M < 4$) are estimated from amplitudes in a window following the S wave (Fig. 11a). Updated magnitudes are estimated from an on-line program which automatically calculates Wood-Anderson response seismograms from the low-gain seismometer and FBA data channels. Amplitudes from these simulated Wood-Andersons are used with the RTP location to get a local magnitude (M_L). For large earthquakes ($M > 4$) we determine a magnitude from TERRAscope data, which is available within 4 minutes of the occurrence of the event.

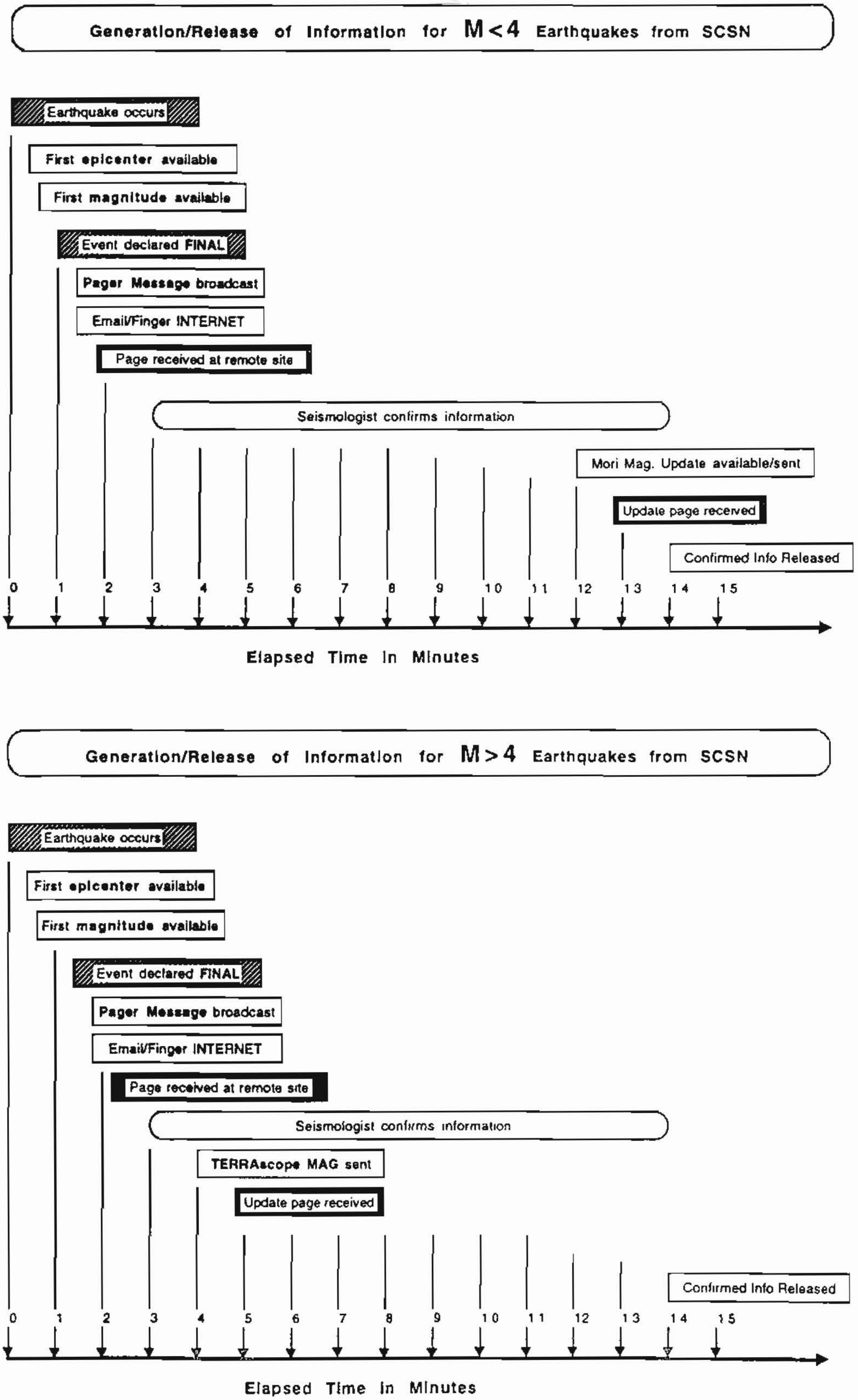


Fig. 11. The sequence of tasks that take place as a small (M < 4) or a large (M > 4) earthquake is located and magnitude is determined by SCSN and TERRAscope automatically.

New Approach to Data Analysis

The most important objective of SCSN is to generate the earthquake catalog for southern California. This objective will remain important because a catalog is necessary as a key to the data base of earthquake data. At present much of our resources are spent on analyzing data from small earthquakes (M < 2) simply because these are most numerous. In the future we plan to decrease the emphasis on analyzing data from these small earthquakes and leave it to the automatic software to analyze and archive these events.

During the next 3 years we plan to evolve the routine data analysis from mostly timing of P and S phases to more sophisticated routine analysis. The new data analysis will evolve with time and may include determination of the distribution of significant ground shaking, point source parameters, and finite source parameters. The distribution of ground shaking can be characterized by several different parameters such as peak acceleration or velocity. These analyses apply mostly to earthquakes of M > 4, which occur a few times per year in southern California. The results of these analyses will be archived at the SCEC_DC and transmitted near-real time to users who need the information to save lives and protect property.

Reliable near-real-time analysis of the data requires human access to the data at all times to be able to correct mistakes or compensate for failure of the real-time systems. Today, it is not possible for an analyst to access the data as a large earthquake is happening. We plan a major rewrite of our software to make it possible to analyze the data in real time and to review the results of the automated analysis.

In the future we envision having one data analyst in the Seismo Lab at all times prepared to analyze, evaluate, correct, and release computer generated information. These data analysts would be alerted by audio alarms in the Seismo Lab that a major earthquake was in progress. The data analyst would move to a command computer station and review the performance of the real-time data processing and correct any analysis if needed. The data analyst would thus provide the necessary input needed to assist the computer software with evaluating the incoming earthquake data in the most efficient manner and would also release the information for quick distribution. This method of data analysis would also allow very quick analysis of data from smaller earthquakes and eliminate the very time consuming process of post processing.

Management Structure

Today the SCSN can be described as a fairly successful academic operation that provides information to emergency services, researchers, and the public. Although the lines of management responsibility are not clearly drawn between the USGS and Caltech, the operation is considered to be fairly successful. However, to change the SCSN to become a seismic network that provides reliable real-time earthquake information, we need to upgrade not only the hardware/software, but also the internal management structure.

In the past the division of responsibilities for the operation of the Southern California Seismographic Network (SCSN) between Caltech and USGS in Pasadena has been flexible and changed from time to time. In general, Caltech has had responsibility for producing the earthquake catalog and archiving phase data and seismograms. The USGS has maintained the bulk of the remote stations and provided hardware and software support for real-time digital recording of data. Recently, Caltech has become more active in terms of the deployment of TERRAscope and software development. Both institutions are actively doing research with the data and share the responsibility for information transfer to the general public, media, and government.

When the SCSN begins to provide real-time information to users who are using the information to save lives and protect property, the organizational structure of the whole operation needs to be formalized to a greater degree. The formal organizational structure is needed to minimize the number of mistakes that may lead to the failure of the SCSN to provide critical earthquake information. A formal steering committee needs to be put in place to facilitate critical decision making for the SCSN. Several teams of SCSN staff need to be formalized to make the operation as efficient as possible and to ensure that all software and technical development is consistent and allows the SCSN to meet its objectives. Such teams will consist of software developers, data analysts, field engineers and technicians, and outreach experts.

APPENDIX H

Seismic Networks in Northern and Central California

DAVID H. OPPENHEIMER
U.S. Geological Survey
Menlo Park, California

Introduction

The U.S. Geological Survey and the University of California at Berkeley operate two separate seismic networks to monitor earthquake activity in central and northern California. These networks transmit data in real time to central facilities where computers analyze these data in order to detect the occurrence of an earthquake. When an earthquake is detected, its location and magnitude are automatically calculated and the information is made available to the public through a variety of facilities. Although the two networks overlap each other, they record different parts of the seismic spectrum and consequently complement each other. Both networks share real-time data and store their information on a common, public-access data facility. This summary describes the current real-time capabilities of both networks and our efforts to improve these capabilities.

Northern California Seismic Network

The Northern California Seismic Network (NCSN) is designed to detect all local earthquakes having signal strength above the background level of microseisms. The network configuration was motivated by the need to monitor active faults and volcanoes with a station density sufficient to determine the focal depth of shallow (0–15 km) crustal earthquakes. Depending on the concentration of stations in a region, the magnitude (*M*) level at which earthquake detection is complete varies from approximately 1.4 in parts of the central Coast Ranges to 2.6 in the immediate offshore region of Cape Mendocino. The network in 1993 operated 356 stations, and recorded an additional 67 stations operated by other networks (Fig. 1). Almost all sites have a high-gain vertical component 1-Hz seismometer, with about 40 sites with horizontal components.

Most of the stations in the NCSN have identical instrumentation but operate at different gains. The amplified output of each seismometer is frequency modulated, multiplexed, and transmitted to Menlo Park, California via a combination of radio, telephone, and microwave communications, so that all stations are digitized in common with the same time base. Most of the network is designed to record ground motion between 0.2 and 20 Hz with 40–50 db of dynamic range, but the passband and dynamic range is greater for special instrument clusters along the Hayward fault and at Parkfield. To provide on-scale recordings for larger earthquakes, the NCSN records 34 stations located throughout the network that have low-gain vertical seismometers. The limited dynamic

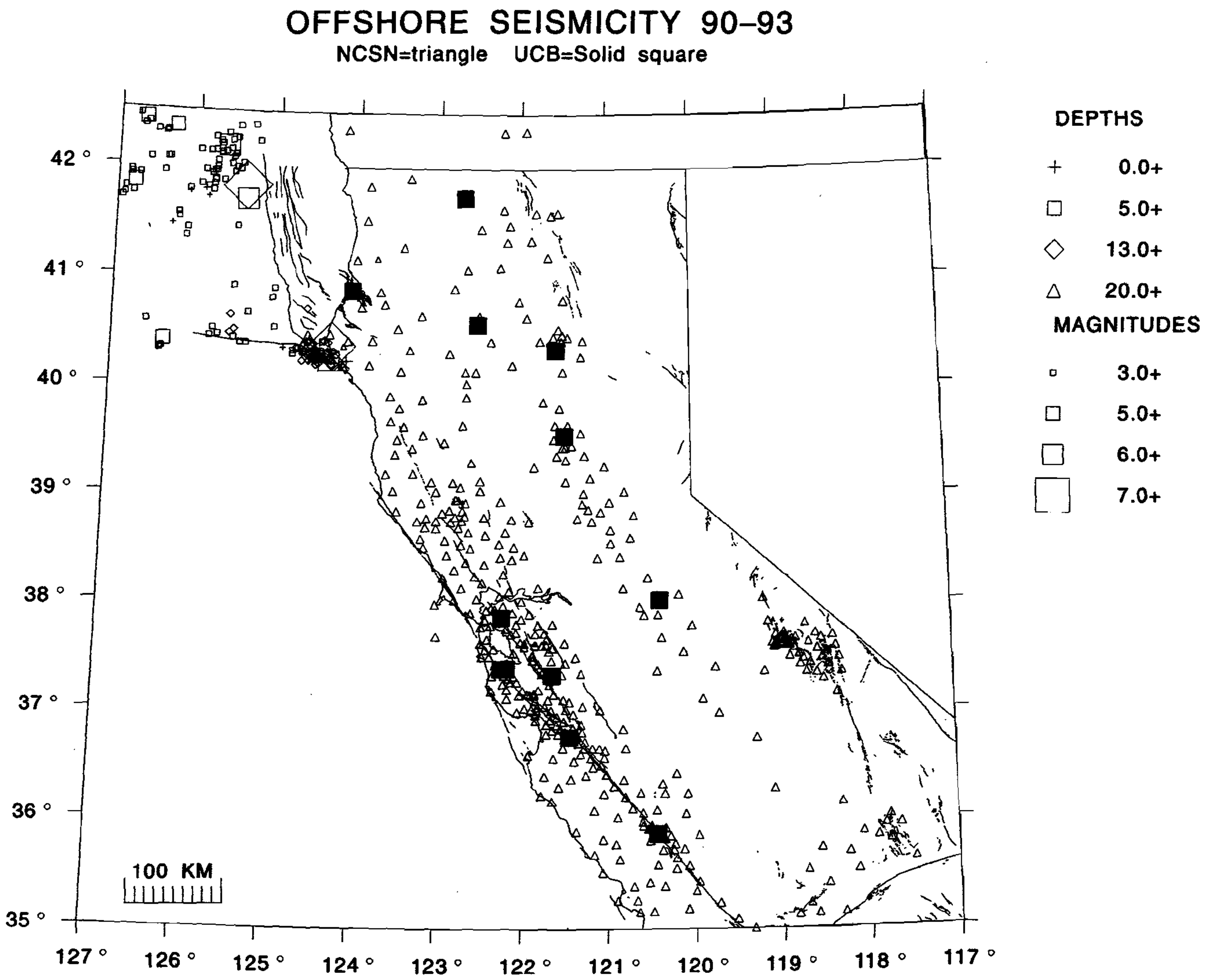


Fig. 1. Location of seismic stations operated by the USGS and UCB in northern and central California. Earthquake locations are from NEIC for the period 1990–1993 for the region north of latitude 40 and west of longitude 123.5.

range of the analog telemetry and the desire to locate small magnitude earthquakes frequently results in "clipped" waveforms.

Earthquake detection and location occurs on two independent data acquisition systems, the Real-Time-Picker (RTP) and CalTech-USGS-Seismic-Processing (CUSP) system. The RTP is a parallel microprocessor system which measures station arrival times and coda durations from all of the stations in the network. This information is then associated to calculate earthquake origin times, locations, and duration magnitudes. The RTP locations form the basis of the NCSN earthquake notification system that automatically alerts seismologists via pagers within minutes of the occurrence of any significant seismicity. Unlike the CUSP system, no seismograms are retained. At present there is a fixed delay of 140 sec following triggering to allow estimation of the coda duration magnitude.

The same data are processed through CUSP, a complete earthquake detection, location, and data management system. The CUSP system digitizes all channels of input at 100 samples/sec with 12-bit A/D resolution, detects earthquakes, demultiplexes the digital data stream, and tags each "trigger" with a unique identification number for data management. The system then automatically computes the *P*-arrival times and coda durations, locates the earthquake, and "posts" the earthquake for review by seismic analysts. The analysts examine the digital seismograms on computer screens and revise the parameters as necessary to properly locate the earthquake. Subsequently the digital seismograms and earthquake locations are stored on magnetic and optical media for later research.

UC Berkeley

In 1991 the UC Berkeley Seismographic Stations began an upgrade of their network of 19 short-period stations to broad-band 24-bit digital instruments with continuous telemetry to the Berkeley campus. The network presently consists of 12 sites which have either a three-component Streckheisen STS-1 or STS-2 sensors in combination with a FBA-23 accelerometers (Fig. 1). The response of the system depends on the sensor, but approximately spans the range 300 s–10 Hz. The network can locate earthquakes above M3 within the network and most earthquakes larger than 5.5 globally. The combination of 24-bit recording and accelerometers ensures on-scale recording of large earthquakes.

Earthquake detection is accomplished through two modes of triggering. Each broad-band channel has an independent triggering algorithm, but at present the automated processing is triggered by both the broad-band event detections and by the NCSN arrival times which are provided via the Internet through a joint software development between the NCSN and UCB. Consequently, there is a minimum delay of 140 sec following detection before processing begins. If the preliminary NCSN amplitude magnitude is greater than 3.0, then the digital data stream is retrieved, and subsequent processing is initiated. The NCSN and broad-band automatically determined arrival time are combined to calculate the earthquake location, synthetic ML magnitudes are determined (from the 20-sps data stream), and notification is initiated via the REDI/CUBE system if the event meets established criteria. For these latter events, estimates of the seismic moment tensor are automatically calculated from inversion of the broad-band body waves or regional surface waves (Fig. 2). At present, the typical delay is approximately 15 minutes from the origin time until the moment tensor solution is determined. As at the NCSN, all locations are ultimately reviewed by seismologists, and revisions to the automatically determined locations, magnitudes, and mechanisms are common. The parametric and waveform data are stored at the Northern California Seismic Data Center (NCEDC) for access by the public.

Realtime Efforts Underway

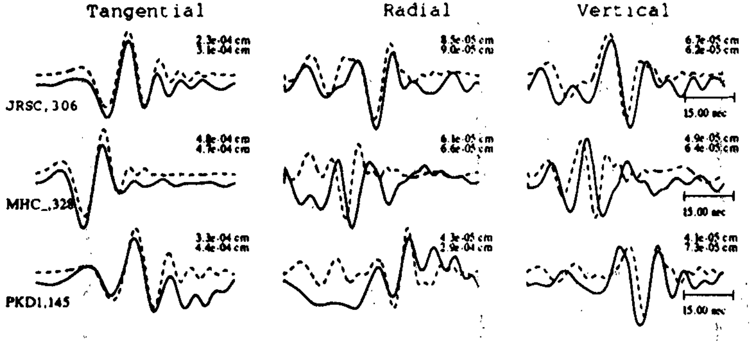
The NCSN is completing a replacement of its real-time detection software with a new system called "Earthworm" (Fig. 3). This system is designed to provide rapid notification of seismic events to critical installations, governmental agencies, and the public (e.g., utilities, transportation corporations, news media). The Earthworm design is based on the ethernet, TCP/IP protocol and the availability of inexpensive PC's, such that each "task" can be assigned to its own computing hardware. These tasks communicate to each other via broadcast messages on the ethernet, so that multiple modules can "listen" to the same ethernet without impacting another module. We are testing a prototype system which is digitizing 512 channels of data at 100 sps using two PC's. Two "picker" modules receive the data broadcast on the ethernet by the A/D modules, and the picks from both "pickers" are then broadcast to a Unix workstation where the data are "associated" in real time and located. Unlike the current RTP's, which impose a 140-second delay to observe the coda, the Earthworm will provide a preliminary location as soon as four arrival times are obtained. The locations will be continuously updated as more arrival time data are determined, so that the locations and magnitudes will presumably become more reliable with time. The goal is to provide earthquake detection as soon as physically possible.

Since the UCB and USGS operate the same associator software and share the pick information over the Internet, the Earthworm data will be simultaneously available for triggering of the broad-band data stream. The combined power of a dense seismic network (to provide early triggering) and broad-band sensors (to provide on-scale waveforms) makes it possible to obtain both reliable locations and focal mechanisms within short time periods. Locations can be computed in seconds, but waveform modeling for moment tensor determination requires a few minutes to record the body and surface data at regional distances. First-motion focal mechanisms could be computed within 30 seconds, but for offshore tsunamigenic events, the mechanisms are quite unreliable because of the limited azimuthal ray coverage on the focal sphere. It is reasonable to expect reliable focal mechanism determination based on body waves within 7 minutes of the origin time for events offshore of California.

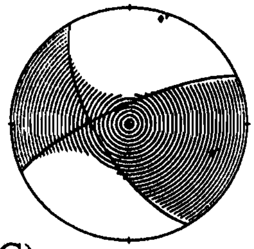
All of the above efforts are still in the development stage. Experience has shown that most systems perform flawlessly except during earthquake crises. Telemetry can fail, power can be interrupted, and algorithms be subjected to unanticipated data streams that cause them to crash.

Automated Moment Tensor: Example 940828012236 (UTC) 9 km ENE of Tres Pinos
REDI Page/Email: approximately 01:28:41 (UTC)

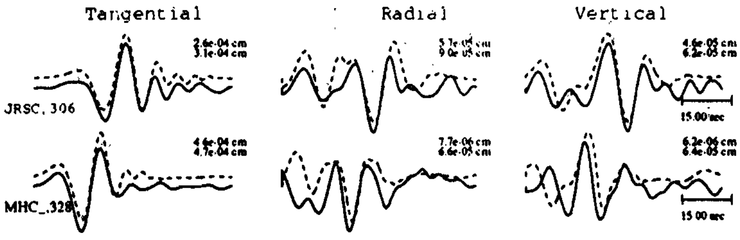
Automated MT Solution: approximately 01:36:11 (UTC)



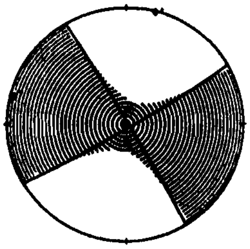
Strike=246 ; 150
Rake =24 ; 165
Dip =77 ; 67
Mo =6.44e+21
Mw =3.8
Percent DC=68
Percent CLVD=32
Variance=3.75e-09
Var. Red=5.70e+01
RES/Pdc.=5.55e-11



Revised MT Solution Released via Email: 01:56:11 (UTC)



Strike=330 ; 60
Rake =177 ; 2
Dip =88 ; 87
Mo =5.56e+21
Mw =3.8
Percent DC=81
Percent CLVD=19
Variance=6.09e-10
Var. Red=8.91e+01
RES/Pdc.=7.53e-12



Elapsed Time ~ 34 minutes

UCB Seismographic Station

Fig. 2. Example of automated and revised moment tensor solutions for Tres Pinos earthquake (M3.8) on 940828. Note time stamp of E-mail. The automatic location was sent about 6 minutes after the origin time, the automatic moment tensor solution was sent about 8 minutes later, and the revised issued 34 minutes after the origin time.

N.C.S.N. Architecture

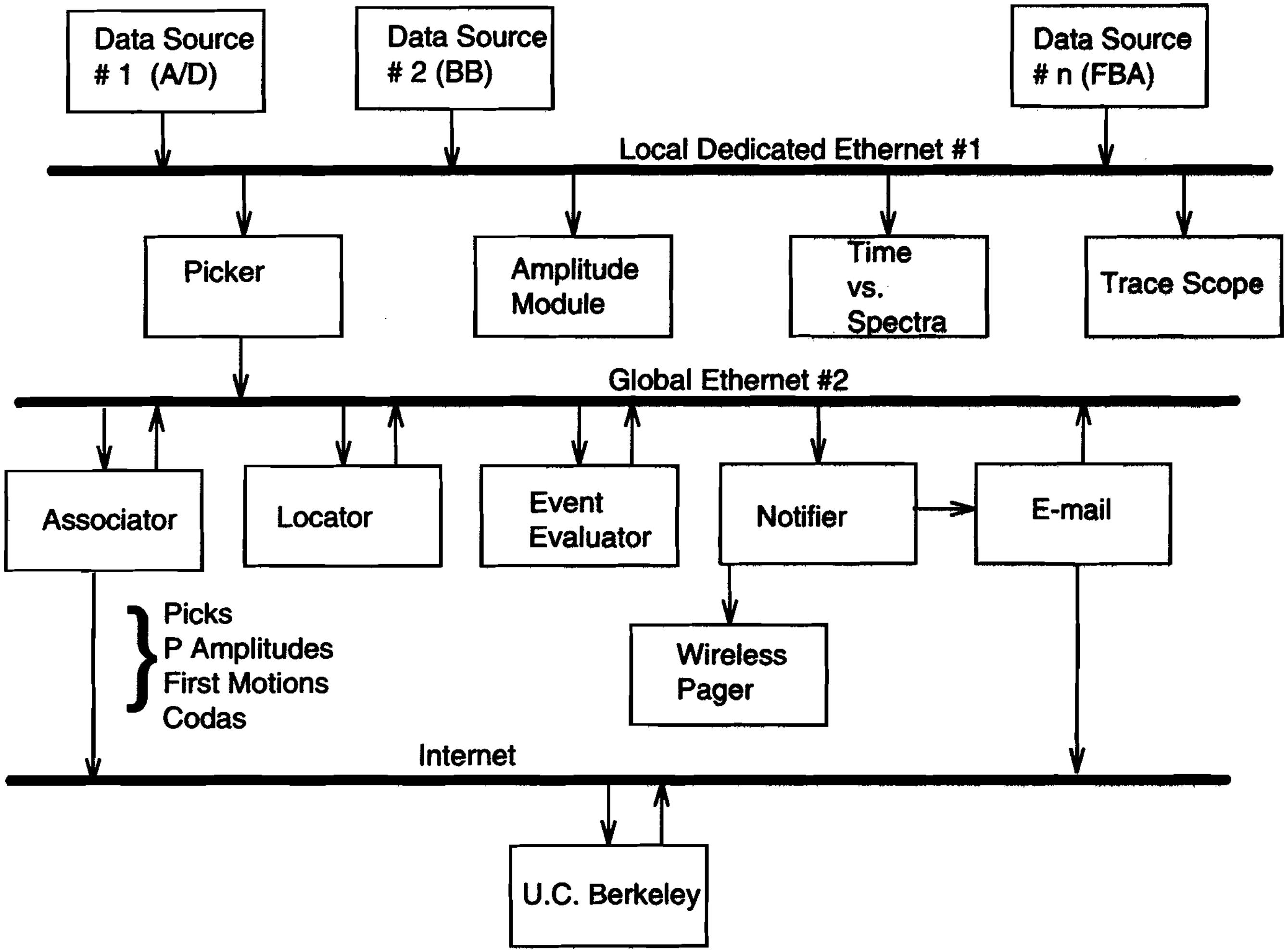


Fig. 3. Architecture of the Earthworm prototype system under development in Menlo Park.

Careful development and monitoring will be required to ensure that a high degree of reliability is provided.

APPENDIX I

The Pacific Northwest Seismograph Network and IRIS Rapid Data Access Systems

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The fundamental goals of most seismic networks have changed little over the years: record and process seismic data for research, educational and public information uses. Recent technological improvements mean that these goals can be met rapidly enough that the results can be used for immediate information to civil authorities and the press and possibly, in the near future, for warnings of strong shaking or local tsunami waves.

The Pacific Northwest Seismograph Network (PNSN) has been meeting the basic rapid information goals since 1989 and hopes to improve the response time to meet the warning goals in the next few years. This network is made up of both short-period and broad-band stations covering the states of Oregon and Washington and operated by the University of Washington, the University of Oregon, and Oregon State University. The IRIS Data Management Center is located at the University of Washington and has operated the *SPYDER* (previously, *GOPHER*) system to provide wave-form data to seismologists within a few minutes to hours of large earthquakes world wide. An important aspect of planned improvements at both the PNSN and the IRIS DMC is the rapid integration of data from many sources, including other regional networks, the USNSN, and IRIS GSN stations. This integration includes both obtaining data from others as well as distributing data.

The University of Washington Geophysics Program operates the routine processing of data for the PNSN and rapidly responds to several different kinds of seismic events. Moderate or large earthquakes in the Pacific Northwest are of interest to civil authorities, life-line and critical service providers, as well as to the press and general public. In addition to damaging or felt earthquakes, we respond to seismic events at volcanos such as earthquake swarms, eruption events, large rock-falls, and mud-flows. Tsunamis, whether locally generated or from a distant source, are a significant hazard along the northwest coast; however, specific responses to potential tsunami situations are currently not implemented. Our response to earthquakes involves a combination of an automated detection and alert system and well trained personnel available to rapidly analyze seismic data soon after an event.

The PNSN is a typical medium-to-large-sized U.S. seismic network made up mostly of field equipment from the 1960's and 1970's and recording technology of the 1980's. Most seismic data are telemetered via telephone, microwave, or radio voice-grade circuits in analog form from single-component field sites to the central recording site in Seattle (Fig. 1). Here they are digitized at 100

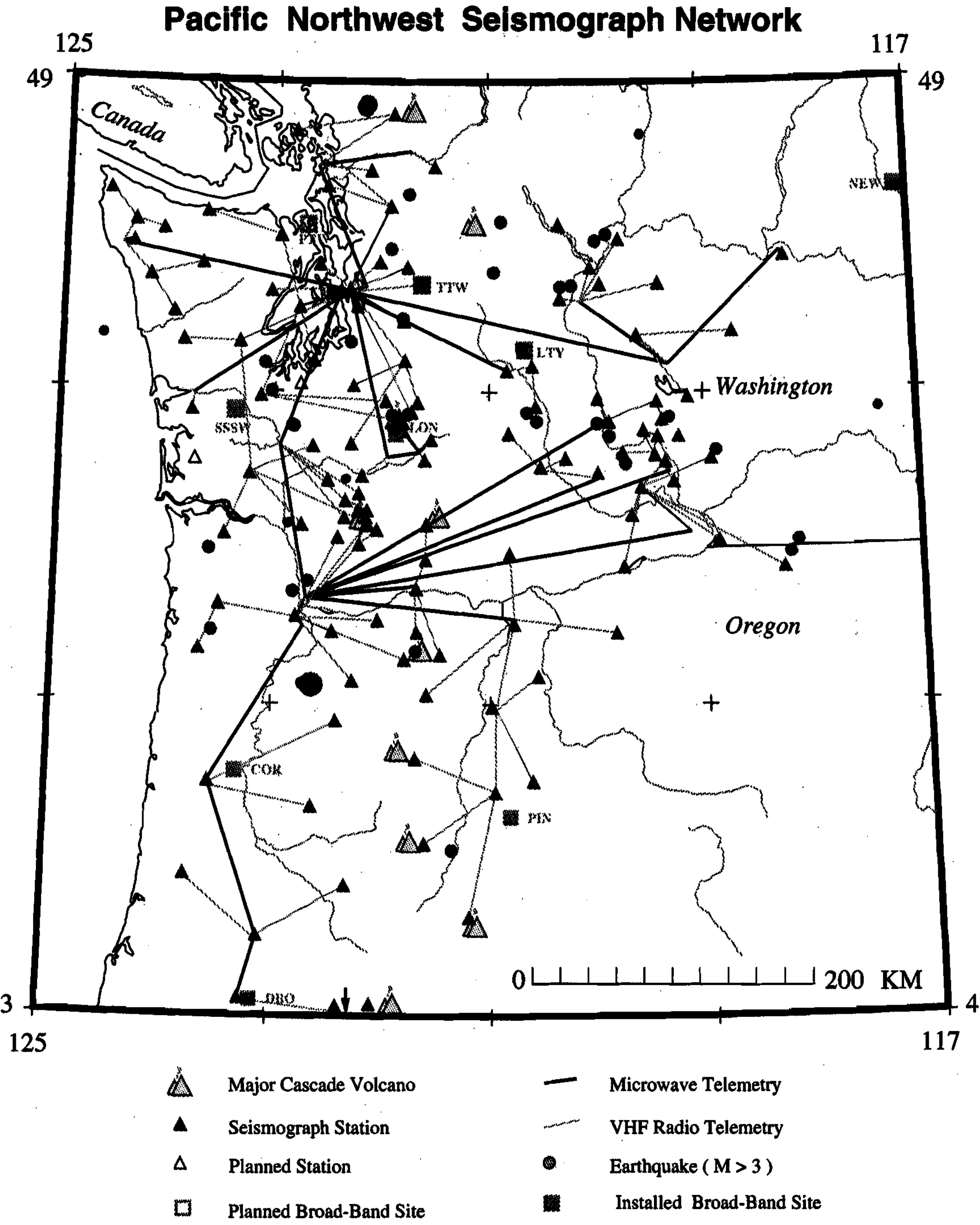

Fig. 1. Pacific Northwest Seismograph Network showing conventional short-period telemetry stations (triangles), new high quality broad-band stations (squares) and recent larger (M > 3) earthquakes (circles).

samples per second per channel and processed automatically for event detection and preliminary location parameters. Routine manual analyses of these data are done using computer graphics displays within a few minutes to a few days of recording to determine location, size, and focal mechanism parameters for each detected earthquake. Automatic processing of larger earthquakes is completed within minutes of the event. Reduced data and earthquake catalogs are provided to other researchers and the public through a variety of means, including electronic mail, FAXes, and Internet services such as the *anonymous FTP*, the *finger* program, and the *World-Wide-Web*.

The heart of the detection and alert mechanism is the *HAWK* real-time seismic recording and processing system. Software running on a Concurrent-5600 computer digitizes (100 sps) all 134 telemetered short-period seismic stations in Washington and Oregon and saves these digital data for time segments it determines to be seismically interesting. A logger process starts an alert routine when it detects an event with a certain number of triggered stations or when a persistent high trigger value occurs on specified volcano stations. The alert process analyzes the information passed from the logger to determine what type of event has occurred and if it is big enough to declare an alarm ($M > 2.9$ and located within the seismic network). Automatically generated pager messages (to local seismologists), E-mail (to other regional networks and the NEIC) and FAXes (to local emergency managers) are sent giving location and size of the event. An update is sent as soon as a seismologist has reviewed the trace data, usually within an hour. This alarm system has been running since the end of 1989, during which time 78 events have triggered the system of which 22 had finalized magnitudes less than the threshold. There were nine events which should have triggered it but did not for one reason or another, and four false alarm events.

With the recent availability of high quality sensors and data-loggers the challenge now is to rapidly integrate data from new instruments with the older analog telemetry data. Because continuous telemetry of three-component high-dynamic range data is not cost effective for the more distant stations, data from these stations are recovered using dial-up telephone calls. Four new broad-band stations, three with only dial-up data access capability, have been installed in Washington State and two telemetered broad-band stations have recently been installed in Oregon by the University of Oregon. Data from these stations are beginning to be integrated with the older short-period data in the PNSN operations.

The IRIS *SPYDER* system was originally designed to provide wave-form data from a few IRIS stations to the IRIS community for large world-wide earthquakes within a day or so of the event. It has changed and evolved to provide more data more rapidly to more users over the past few years. This system, as it runs at the IRIS Data Management Center (DMC), takes as input preliminary location information about world-wide earthquakes from the USGS National Earthquake Information Center (NEIC). P-wave arrival times for an earthquake are computed for each of the GSN stations around the world with dial-up capability. *SPYDER* then retrieves the data by telephoning each station and downloading selected time wave-form segments to the main DMC machine. The actual telephone calls are placed by several different computers around the world interconnected by the Internet. Recently, data from other networks including the USNSN telemetry system, the IRIS/IDA system (both dial-up and telemetry), the French GEOSCOPE system (dial-up only), and the Canadian Seismic Net (telemetry) are being integrated into the *SPYDER* data archive. The list of stations from which to request data currently stands at 60, though only for the largest events are data retrieved from most of these. Data for each event is currently kept in a simple and popular format (SAC) at the IRIS DMC (and other data centers) and a menu-driven user interface is provided on an open login account so anyone can access the data.

One of the IRIS remote *SPYDER* machines is located at the University of Washington, on the same local computer network as the machines used to record and process data from the PNSN. This local *SPYDER* receives requests from the IRIS DMC to dial-up GSN stations in the U.S. and retrieves data for earthquakes of international interest; however, it also receives requests from a PNSN computer to retrieve data for events of local interest from both GSN stations and similar stations operated as part of the PNSN. These data are currently stored locally and are not made available to others as part of the IRIS *SPYDER* archive. They are being integrated into the routine processing of PNSN data and will help with the determination of earthquake source parameters, particularly for larger earthquakes.

While the IRIS *SPYDER* system was originally designed to provide wave-form data within hours of interesting earthquakes, it has been modified to provide some wave-form data to selected sites much more rapidly. The *CHEETAH* system is a cooperative effort between the NEIC and IRIS to provide more reliable and faster earthquake locations by incorporating very remote IRIS GSN data wave-forms into the routine analysis stream of the NEIC. This is done by having the NEIC send their automatic first solutions for an earthquake to the IRIS DMC with a special code indicating its preliminary nature. The IRIS *CHEETAH* system then generates special requests for only the broad-band data streams from a selected group of GSN stations. These broad-band data are then retrieved and immediately sent to the NEIC where they are combined with the USNSN wave-forms to be used by an analyst to determine a reviewed solution for public release. Since several different computers around the world actually place telephone calls to stations physically near them, data retrieval from several stations takes place at the same time. The data are sent from the remote stations to the IRIS DMC and on to the NEIC over the Internet so some data are available to NEIC analysts within only a few minutes of the automatic alert going out. Data from some stations have also been sent to the Pacific Tsunami Warning Center in Hawaii for their use.

APPENDIX J

Near-Source Tsunami Measurements for Forecast and Warning

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Background and Motivation

A number of specific regions, most notably the Cascadia Subduction Zone (CSZ) and the Alaska-Aleutian Subduction Zone (AASZ), are believed to have significant potential for large earthquakes that would generate destructive tsunamis, threatening U.S. coastal communities both near and far from the source.

Direct sea level measurements acquired near these potential tsunami sources could greatly improve the speed and accuracy of tsunami hazard assessment, forecast and warning. Thus, a rapid and unequivocal determination of the existence or absence of a tsunami could be made shortly after the occurrence of a large earthquake. Assuming a tsunami was generated and detected, measured wave height (and wave direction, with two or more station observations) would provide fundamental information to assess the hazard. When combined with appropriate algorithms and additional environmental information, such as background coastal sea level, forecasts could then be made of the impact on coastal communities. Warning decisions based on such a process could be made more rapidly and with greater confidence and accuracy, since they involve direct measurement of the tsunami near the source. In the post-warning phase, the near-source stations would continue to provide off-shore wave data that would be invaluable to monitoring and assessing the continuing hazard level and provide a basis for the decision to issue an "all-clear."

Existing Technology

The technology is now available to develop a deep ocean, real-time tsunami reporting system (RTRS) to provide these direct tsunami measurements near potential source regions in deep offshore waters (Fig. 1). Bottom pressure recorders (BPRs) deployed at depths of up to 6000 m are characterized by a sensitivity on the order of 1 mm, and have successfully measured tsunamis as small as 1 cm (González *et al.*, 1991; Eble and González, 1991; Boss and González, 1994). At present, these systems do not report data in real time. However, acoustic links could transmit BPR data to an overhead surface buoy which would then relay the data to warning centers and/or local community officials via satellite link. Subsurface acoustic links (Catipovic, 1990) and deep ocean surface buoys that report in near-real time via satellite (McPhaden, 1993) are available now. A prototype local tsunami warning system, based on existing satellite telecommunications technology,

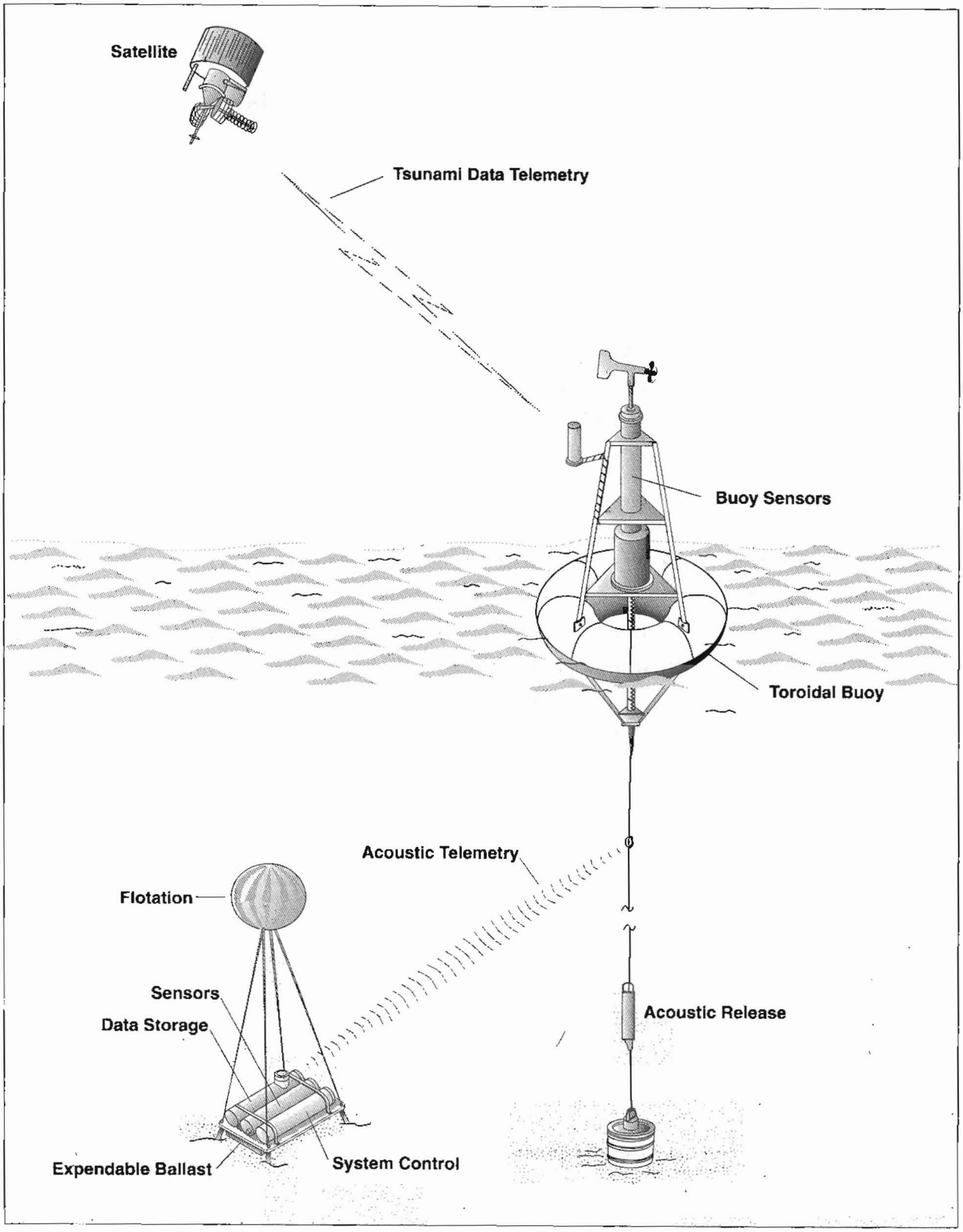

Fig. 1. Design of a real-time tsunami buoy. Sensors on the seafloor detect minute changes in wave height and telemeter those measurements to a surface buoy. Equipment on the buoy retransmit these data to the warning centers in real time.

has been in continuous operation since 1986 (Bernard *et al.*, 1988); low data rate satellite transmissions of hazard alerts are received by local officials less than 20 s after initiation by a seismic trigger (Bernard and Milburn, 1991). Improved satellite links, capable of reporting relatively high RTRS data rates in true real time, should be available within 2 years.

Utility of Near-source Tsunami Measurements to Forecast and Warning

Seismic data are, of course, absolutely essential in the tsunami hazard assessment phase. Earthquake location and magnitude are fundamental to this process, and relatively rapid assessments of tsunami potential can be made, especially if broad-band data are available. However, while further research and experience will undoubtedly continue to improve tsunami hazard assessments made on the basis of seismic data, such methods are, in the final analysis, indirect. Similarly, coastal tide gauge data are invaluable in assessing conditions at that particular tide gauge location. But this is possible *only after a tsunami has arrived.* Furthermore, since these instruments are designed and deployed specifically to measure tides, they do have some shortcomings when adapted to tsunami warning functions. They are located in harbors that are intended to provide a protected environment from ocean wave energy; measured tsunami amplitude may therefore be less than amplitudes along an unprotected coastline. Furthermore, because of runup surveys made after large recent earthquakes and tsunamis, we now know that coastal amplitudes exhibit large variations over short distances along a coast. It is also clear that in many cases the response of the harbor itself can dominate the tsunami signal, making interpretation difficult. For all these reasons, assessing the potential hazard to coastal communities short distances from the harbor tide gauge may be problematic. Finally, as presently configured, tide gauges suffer to a greater or lesser degree from limitations in the maximum and minimum tsunami amplitude values that can be measured. For instance, a combination of high tides or other background sea level events can lead to "clipping" of the tsunami signal. This has the potential for complicating both the initial hazard assessment, as well as the monitoring of water levels that is needed to establish when it is safe to issue an "all clear."

Near-source tsunami measurement systems are not a panacea, but hold great promise as an important and valuable complement to existing seismic and sea level monitoring systems. The utility of the data provided by such systems depends fundamentally on whether enough tsunami data can be acquired in a short enough time to be useful in the hazard assessment process. Preliminary examination of information from observations and numerical modeling of the Okushiri tsunami (Takahashi *et al.*, 1994) and numerical simulations of potential CSZ earthquakes (Bernard *et al.*, 1994) suggests that travel times from the source to the coast can vary from a few minutes to tens of minutes, and that the "half-period" associated with the first tsunami extremum may be on the order of 5 minutes. These values suggest that near-source, real-time sea level data could be of significant utility if incorporated into tsunami hazard assessment and warning procedures.

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APPENDIX K

The Coastal Data Information Program
A Successful Federal, State and University Cooperation

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Abstract

The Coastal Data Information Program (CDIP) is a cooperative effort managed jointly by the U.S. Army Engineers, Waterways Experiment Station and the State of California, Department of Boating and Waterways. The program is conducted by the University of California, Scripps Institution of Oceanography for the purpose of collecting, analyzing, and disseminating coastal environmental data, with an emphasis on nearshore wave climate.

Introduction

The CDIP network was conceived in the early 1970's to fill the need for continuous instrumental records of nearshore wave height and direction along California and other coastlines of the United States. At that time, only short term wave records were available and no measurements suitable for wave climate determinations existed in the shallow, nearshore waters of California, or any other state. Nearshore wave information was limited to biased ships observations, intermittent shore observations and dubious hindcasts.

In California and elsewhere, waves have long been recognized as the primary driving force for beach and shoreline processes. These include longshore sand transport, beach profile changes and coastal erosion. Coastal engineering problems such as breakwater overtopping and coastal flooding also require quantitative knowledge of wave climate. Finally, all manner of commercial and recreational activities including boating, fishing, swimming, diving and the quintessential California sport of surfing, depend on, or are influenced by, coastal wave conditions. The need for coastal wave climate measurements is akin to the need for weather observations over land.

Since 1975, CDIP has been collecting wave data at over 70 locations, including some on the east coast, the Great Lakes and Hawaii. The wave network's capability is well illustrated in Southern California, a heavily urbanized and utilized shoreline subject to seasonally and interannually varying wave conditions. Understanding these conditions is crucial to effectively managing this important coastline, yet technical hurdles exist that only basic research backed by long term monitoring can address.

This program is an excellent example of a successful cooperation between federal and state government and academia. It produces a valuable, widely used product at reasonable cost, while furthering scientific research and education.

Program Goals

The primary objective of the CDIP program is to provide wave climate data at selected sites. The first CDIP station was installed in 1975 at Imperial Beach, located in the southern part of San Diego County near the international border. Imperial Beach has had a long history of beach erosion and coastal flooding. Wave measurements were desired as part of a plan to develop viable, cost effective coastal defenses for the city. Erosion, flooding, planning, as well as wave measuring, are still ongoing.

An important and continuing goal of the program is to maintain uniform data analysis and timely reporting on a strict, monthly schedule. This has been achieved. In addition to the regular monthly data reports, annual reports and occasional longer term summaries are also issued. Raw measurements from all CDIP sensors are archived to allow for improvements in data analysis methods and computation capability. Over the years, this has created a storage problem since data was archived to magnetic tapes until recently. The transition is now being made to optical laser disk storage.

Basic research has always been an important element of CDIP and is essential for the program to remain a viable university based activity. The research function includes financial and technical support of graduate student dissertation projects. At the same time, the university environment supplies vitality to the program through new ideas and methods. Most importantly, the research feedback ensures that the data gathering and analysis will indeed be useful to address the problems of concern.

This has been demonstrated in Southern California, where the rugged offshore bathymetry and the offshore islands introduce great complexity into the coastal wave conditions. The wave climate is dominated by long swell generated by distant Pacific storms, and occasionally mixed with locally generated, high and steep storm waves. Research efforts have revealed that wave conditions at one coastal site may be much different than those at another site only a few kilometers away. However, experiments have shown that modern computer refraction codes are successful in transforming offshore, deep-water frequency-directional wave spectra into shallow water throughout the Southern California Bight. The basic problem of how to estimate wave information at sites with no measurements can be overcome by using the coastal data as a constraint to construct realistic offshore spectral estimates. These are then refracted toward shore to the site of interest.

These kinds of research results provide a firm footing for the applicability of the CDIP wave monitoring effort. As a final benefit, the University of California provides a cost-effective base for this publicly funded program.

Hardware

CDIP typically relies on an inventory of five or six measurement systems. These include instruments to measure shallow and deep water wave energy and directional distributions, as well as wind and currents.

Most stations consist of offshore pressure sensors mounted on the bottom at depths between 5 and 15 m. To observe ocean wave energy spectra in shallow water applications, a single submerged pressure sensor package is usually deployed. Anchored to a hard rock bottom, or scoured into a sandy bottom, these devices are rugged and economical, with typical lifetimes of over 5 years. These instruments are connected to a shore station by armored cable, which quickly scours into a sandy bottom. In harbors and bays or on offshore platforms, sensors and cables may be fastened to pier pilings or other suitable structures.

A compact pressure sensor array is routinely deployed to measure shallow water directional wave spectra. This compact "slope array" consists of a square frame made of pipe, measuring 6 m on a side and housing four pressure sensors, one on each corner. As with most of the shallow water applications, data is cabled to a nearby shore facility.

Occasionally, a "PUV gauge" is deployed in shallow water to measure directional properties. A PUV gauge is a co-located pressure sensor (P) and a current meter that measures the horizontal velocity components (U and V). Functionally, this arrangement is equivalent to the slope array. It has some advantages, in that all the sensors are located at one position and current velocities are also measured. The chief disadvantage is that flow meters generally require more maintenance, and this usually prohibits using this device for long-term deployments.

Sea surface following buoys are generally used for measurements in deep water. The buoys sense vertical acceleration and are designed to perform on-board signal (double) integration, resulting in a vertical excursion measurement. Data is radioed to shore, since cables are impractical for deep water deployments because of the large distances.

"Pitch and roll" buoys, linked to shore by radio, are used where directional data is required in deep water. These instruments float on the surface sensing vertical motion (pitch) and tilt (roll), and are also functionally equivalent to the slope array. Recently, a pressure sensor array has been deployed on the legs of an offshore oil platform. In this circumstance, a microwave and telephone link was available for data transmission.

Data from the various sensors are held in the station's memory buffer which is continuously filled with the latest data. The data are stored synchronously, such that there is no phase lag between data from different sensors. At predetermined times, usually eight times per day, the field station is called through normal commercial phone lines and downloads its memory buffer to the central facility computer. Considerable flexibility of sampling intervals and durations has been built into the shore stations.

Central Facility

The central data gathering, processing and dissemination facility is based at Scripps Institution of Oceanography in La Jolla, California. Following some preliminary data quality checks, the data are written to an archive tape and transferred to a minicomputer for further processing. In the event the data fail to meet initial quality criteria, the computer automatically redials the station to reacquire the data.

Data are screened and further analyzed and then routed in near-real time to an on-line data bank. From there, summary wave data is available to a limited number of dial-up users. Summaries are also furnished to the National Weather Service (NWS) in near-real time. From the NWS, data are forwarded to appropriate field stations for routine broadcast over the local marine band radio frequencies. This service is broadly popular with the region's many boaters.

The station call-up schedule can be modified to accommodate unusual circumstances, including intense storms or a tsunami alert. During such conditions, the field stations of interest are placed in a continuous interrogation mode and provide uninterrupted observations. Continuous sampling during intense storms helps ensure that peak conditions are captured, providing a better profile of the associated wave intensity. Under a cooperative arrangement with the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory (PMEL), a procedure has been developed to activate continuous sampling of certain modified stations when PMEL determines a tsunami is pending. These stations have expanded memory buffers to record the days-long, continuous time series necessary to accurately monitor water level changes related to tsunamis.

Contract Considerations

The Coastal Data Information Program is operated under a cooperative agreement between the U.S. Army Corps of Engineers, Waterways Experiment Station (WES) and the State of California's Department of Boating and Waterways. The cooperative agreement provides a relatively simple method for federal and state agencies to essentially contract with each other for certain specified products and services. Contracts for services between federal agencies can be issued under a Military Interdepartmental Purchase Request (MIPR), containing a scope of work and fund citation. These can be faxed between parties and be effective in days. Exchange of funds or services between federal agencies to or from a state for activities covered by the cooperative agreement can be facilitated in this way. These contract mechanisms are ideal to accomplish jointly supported environmental monitoring programs such as CDIP.

The actual agreement is a relatively simple 13-page document. It specifies the program's purpose, intent, implementation, management and a dozen other, more mundane contractual items that are either required by law or desirable under the circumstances to protect both parties. In the present case, the governing document was signed by the U.S. Army Chief of Engineers and the Director of the Department of Boating and Waterways. The State of California Department of General Services provided legal review from the state's perspective and final state approval. Unless it is amended, the cooperative agreement remains in place unchanged over time, while the actual work to be performed is specified in a new scope of work each year.

The scope of work is negotiated annually between the federal and state program managers with the input of the university principal investigators. The Corps' approval of the scope of work has been delegated to the Director of the Coastal Engineering Research Center, which is the research unit of WES. Thus, essential control of the work statements remains relatively close to the technically competent personnel best qualified to shape the technical program agenda.

The scope of work consists of a list of gauge site orders specifying sites where measurements will be made and detailing the required instrumentation. Budget information is also specified, including the contributions from the federal and state partners, as well as those from any other cooperating agencies. The federal contribution is paid quarterly to the state in this instance, although the cooperative agreement structure allows the flow of money to be in either direction, as appropriate. The state adds its contribution and, acting with federal approval, contracts with the University of California to provide the specified services.

The contract between the state and the university is a so-called "Standard Agreement." Contracting between a state agency and the University of California is simple, since the university is the research arm of the state. The standard agreement is based on the usual university proposal which incorporates the federal-state scope of work as well as other provisions to satisfy state audit and reporting requirements. Once federal and state budgets are approved, the typical turn-around time from university proposal submission to funding is about 6 weeks.

Conclusion

The Coastal Data Information Program is a successful cooperation between federal and state government and academia. It produces a valuable, widely used product at reasonable cost, while furthering scientific research and education. The cooperative agreement provides an ideal legal mechanism for the federal government and a state agency to jointly fund an environmental data gathering and research effort.

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APPENDIX L

TREMORS: Testing the Performance of an Automated Tsunami Warning System in the Regional Field on Six Tsunamigenic Earthquakes, 1992–1994

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Introduction

The purpose of this report is to evaluate the performance of TREMORS in the regional field ($\Delta < 15°$) for the real-time detection, identification and quantification of major earthquakes. The complete article (Schindele *et al.*, 1994) has been submitted for publication to PAGEOPH.

TREMORS (**T**sunami **R**isk **E**valuation through **MO**ment in a **R**eal-time **S**ystem) is an automated integrated system based on a single three-component broad-band seismic station, which was developed at the Laboratoire de Géophysique, Papeete, Tahiti, and has been operational in Tahiti since 1987 (Reymond *et al.*, 1991; Hyvernaud *et al.*, 1992). It consists of an automatic event detector and locator, and computes an estimate of the seismic moment based on a measurement of the earthquake's mantle magnitude M_m, a concept introduced by Okal and Talandier (1989).

TREMORS has been extensively tested through the routine acquisition of teleseismic data in Tahiti over the past 7 years and we refer to Hyvernaud *et al.* (1992) for a discussion of its performance. However, the setting of the Polynesian islands is such that all potentially tsunamigenic earthquakes must be considered teleseismic, the closest zone of major earthquakes being the Samoa-Tonga corner, 25° away. While Talandier and Okal (1991) have shown that the M_m algorithm gives an accurate estimate of the seismic moment at epicentral distances as close as 1.5°, the question of the accuracy of the detection and location components of TREMORS and of its performance in real time at regional distances had not previously been addressed.

In this report we consider six tsunamigenic earthquakes of 1992–1994 (Table 1). While these events were routinely processed by the TREMORS system in Papeete, Tahiti, we investigate what TREMORS' response would have been, had it been operational at a regional ($\Delta < 15°$) station for each case. In particular, we address the ultimate question of tsunami warning: could TREMORS have generated a real-time, valuable warning? We conclude that (i) in all cases, an appropriate estimate of M_0 could have been obtained; (ii) "tsunami earthquakes" (Nicaragua, 1992; Java, 1994)

Table 1

Source parameters of the earthquakes studied

Date	Region	Epicenter		Depth	m_b	M_s	Moment
		°N	°E	(HRV; km)			10^{20} N.m
02 SEP 1992	Nicaragua	11.74	-87.34	10.0	5.3	7.2	3.4
12 DEC 1992	Flores Sea	-8.51	121.89	20.4	6.5	7.5	5.1
12 JUL 1993	Hokkaido	42.84	139.25	16.5	6.7	7.6	4.7
08 AUG 1993	Guam	12.96	144.78	59.3	7.2	8.1	5.2
21 JAN 1994	Halmahera	1.01	127.73	15.0	6.2	7.2	0.32
02 JUN 1994	Java	-10.47	112.98	15.0	5.5	7.2	3.5

PPT real-time results

Event	USGS Location		TREMORS			
	Δ (°)	Back-Azimuth (°)	Δ (°)	Back-Azimuth (°)	M_m	Moment (10^{20} N.m)
Nicaragua	68.1	69.2	69	71	7.5	3.2
Flores	86.0	262.4	90	261	7.9	8.0
Hokkaido	88.8	315.9	93	305	8.0	10.0
Guam	71.6	290.6	73	283	7.95	9.0
Halmahera	83.3	273.2	96	272	6.9	0.87
Java	93.8	257.8	90	250	7.4	2.5

Near-field results

Event	Station	USGS Location		TREMORS			
		Δ (°)	Back-Azimuth (°)	Δ (°)	Back-Azimuth (°)	M_m	Moment (10^{20} N.m)
Nicaragua	UNM	13.7	121.9	15	133	7.4	2.7
Flores	CTA	26.2	292.6	27	290	7.9	8.6
Hokkaido	INU	7.7	12.3	7.7	11	7.7	5.2
Guam	MAJO	24.2	164.2	23	167	8.0	9.3
Halmahera	GUMO	21.0	235.1	22	240	6.85	0.7
Java	WRA	22.6	291.4	24	289	7.55	3.5

are easily identified through the behavior of their moment rate spectral amplitude with period; and (iii) TREMORS provides a final estimate of the moment within ≈20 mn of the origin time of the earthquake for a station at 15° distance, allowing the issuance of a warning about 20 minutes prior to the arrival of the tsunami waves in the case of an earthquake generated at an offshore trench, typically 100–200 km from the coastline (Nicaragua, Java). In the case of an event in the immediate vicinity of shorelines for which there is practically no time to issue an efficient warning (such as the deadly Flores (1992) and Hokkaido (1993) earthquakes), TREMORS can still provide a useful warning for more distant shores (such as Sulawezi in the case of the Flores event, or Korea in the case of Hokkaido).

Background and Methodology

We refer to Reymond *et al.* (1991) for a detailed discussion of the detection and location algorithms. We simply recall here that the location algorithm estimates the back-azimuth from the station, ϕ, by evaluating the polarization of the horizontal components of the P wave, and the epicentral distance, Δ, from the $S-P$ delay. The typical accuracy achieved at regional distances is on the order of a few degrees, both for Δ and ϕ, which is sufficient to provide a realistic estimate of the epicenter.

In the regional field, as soon as surface waves are received on the vertical component (theoretically the Airy phase of the Rayleigh wave; in practice R may not be differentiated from S), the M_m algorithm is initiated and constantly refined as more data become available, by using a growing window, updated every 50 s. This strikes a balance between providing a rapid estimate of M_0, and making use of the full complement of seismic information. Moreover, it allows keeping a watch on the variation of the moment rate spectrum with frequency, as longer windows are used and lower frequencies received by the sensors, i.e., as the longer-period part of the source spectrum is exploited. This allows the real-time identification of "tsunami earthquakes."

Regarding tsunami earthquakes, it is interesting to note that these events have been defined as featuring a significant $M_s : M_0$ deficiency and *a fortiori* exhibit a pronounced $m_b : M_0$ anomaly. In this respect, it is worth noting that m_b can be computed as early as the arrival time of S waves (the knowledge of $S-P$ is necessary to compute the distance correction), and does not require waiting for surface waves. Thus, and however incomplete and possibly misleading it may often be, m_b remains the first available estimate of the size of the earthquake; on the other hand, as soon as the surface waves have arrived and M_s can be computed, the more significant M_m becomes available, and thus there is no real advantage to computing M_s for the purpose of quantifying the earthquake source. Thus, the real-time analysis of a possible $M_b : M_0$ deficiency, through an automatic computation of m_b incorporated into the location algorithm, can be useful as additional evidence confirming the "tsunami earthquake" character of an event.

Discussion of Individual Events

We discuss here the individual results obtained for each of the six tsunamigenic earthquakes considered (Fig. 1). We start with the 1993 Hokkaido event, since the epicentral distance at the station used (7.7°) was the shortest in our data set. We end with the 1994 Halmahera event, since it was in a much smaller class, even though its tsunami reached run-up heights of 2 m. Otherwise the events are presented in chronological order.

Hokkaido, 12 July 1993

We recall that this earthquake resulted in about 170 tsunami-related deaths on Okushiri Island, in the immediate vicinity of the epicenter.

The closest station for which we obtained data is GEOSCOPE station INU ($\Delta = 7.7°$). TREMORS locates the epicenter 30 km away from the true focus and estimates the seismic moment at 5.2×10^{27} dyn-cm, in excellent agreement with the Harvard CMT value (4.7×10^{27}). The seismic moment rate spectrum builds up very fast between 50 and 70 s, features a rather steady behavior to 170 s and a slow decay beyond that period. Given its extreme vicinity to the epicenter, there was in our opinion no way (TREMORS or otherwise) to produce a realistic tsunami warning in real-time for Okushiri and save its population. However, TREMORS would generate a usable warning for more distant shores in the Sea of Japan (Honshu, Russia, Korea).

Nicaragua, 02 September 1992

We recall that this "tsunami earthquake" was not even felt in some locations of the Nicaraguan coast which were swept by the tsunami 40 to 70 mn later with heavy loss of life.

Our closest broad-band data is from GEOSCOPE station UNM in Mexico City ($\Delta = 13.7°$). TREMORS locates the event on the Pacific continental margin (probably due to multipathing of the *P* wave) and yields a seismic moment (2.7×10^{27} dyn-cm) in good agreement with the Harvard CMT value (3.4×10^{27}). The seismic moment rate spectrum shows a rapid increase beyond 140 s, pointing out to the slow character of the event, widely described in the literature. The final estimate of M_0 is obtained at 00:34 GMT, leaving a lead time of 22 mn before the first waves hit the coast of Nicaragua.

Flores Sea, 12 December 1992

We recall that this earthquake produced a catastrophic tsunami on Flores Island (2000 deaths) and to a much lesser extent across the Flores Sea in Sulawezi (where it caused 22 deaths). Some of the exceptional run-up heights are believed due to underwater landslides off the northeastern tip of Flores Island.

The nearest broad-band station for which we obtained data is the IRIS station at CTAO ($\Delta = 26.2°$). TREMORS locates the event about 150 km from the true focus, pointing to a loss of accuracy when the epicentral distance increases. The seismic moment is estimated at

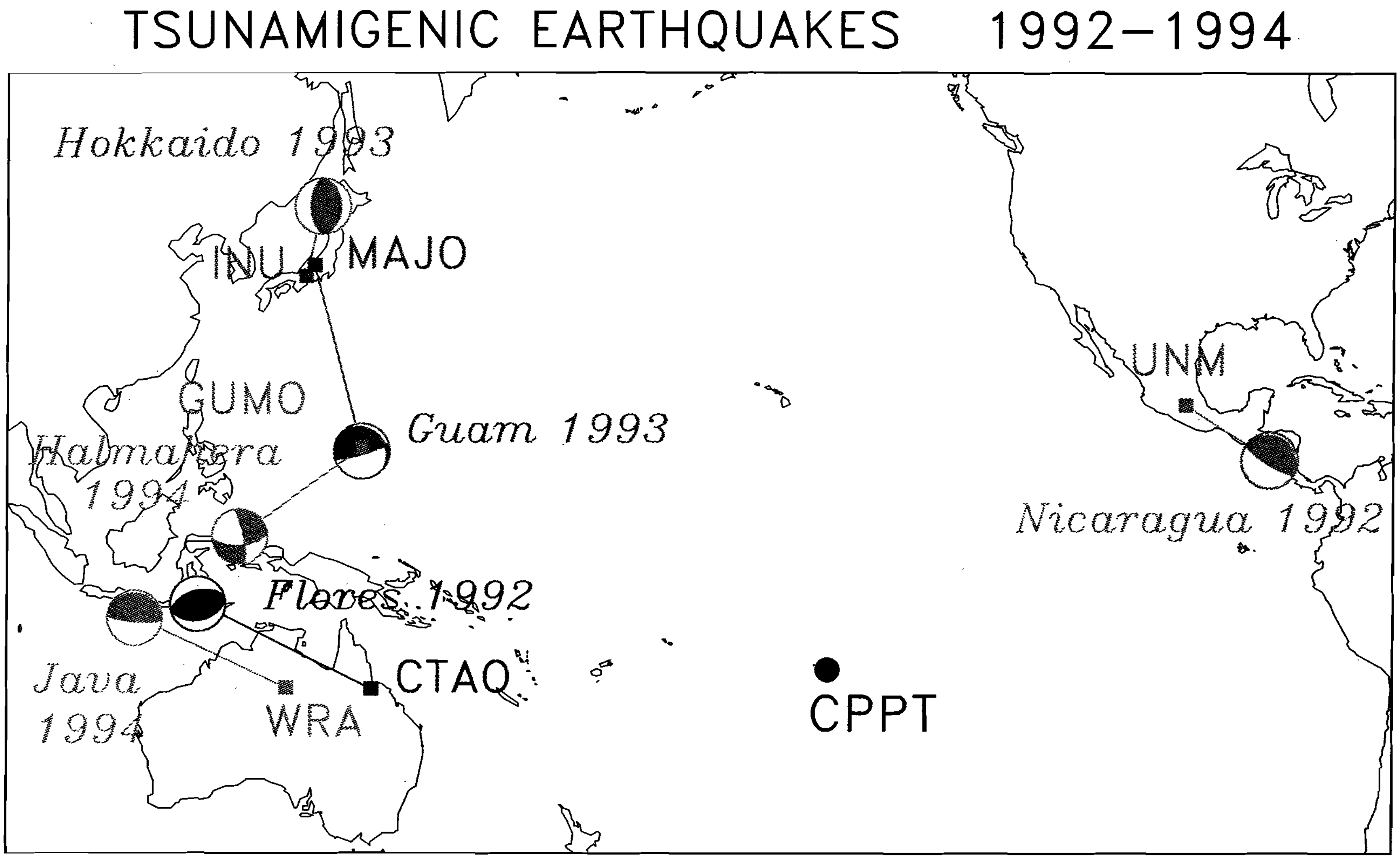

Fig. 1. Map of the event-station pairs used in this study.

8×10^{27} dyn-cm, in reasonable agreement with the Harvard CMT value (5.2×10^{27}). The seismic moment rate spectrum is very stable between 50 and 100 s, and decreases slowly beyond 150 s. As in the case of Hokkaido, the event is too close to the shorelines to allow for a realistic tsunami warning for Flores, but TREMORS could be used for more distant shores such as South Sulawezi and Ambon.

Guam, 8 August 1993

We recall that this very substantial earthquake ($M_0 = 5.2 \times 10^{27}$ dyn-cm – Harvard CMT) generated only a minor tsunami and failed to provoke a single casualty.

The nearest broad-band station for which we obtained data is MAJO, the IRIS station in Japan ($\Delta = 24.2°$); GUMO on Guam Island was knocked out by the event. Once again, at such a large distance, TREMORS located the event about 185 km from the true focus. The seismic moment is estimated at 9.3×10^{27} dyn-cm, significantly larger than the CMT value. It is remarkable that this estimate is obtained at a period of 67 s, with the seismic moment rate release actually decreasing beyond 70 s. This is easily explained as an artifact of the substantial depth of the event (60 km, while the other five earthquakes are shallower than 20 km). This pattern is easily recognizable on the source spectrum, pointing to a relatively low static moment value, and hence to a reduced tsunami danger.

Java, 02 June 1994

We recall that this "tsunami earthquake" killed upwards of 250 people and exhibited a very pronounced $m_b : M_s$ discrepancy.

The nearest broad-band station from which we obtained data is WRA, the IRIS station in Northern Australia ($\Delta = 22.6°$). TREMORS locates the event 125 km from the actual epicenter. The seismic moment (3.5×10^{27} dyn-cm) is identical to the Harvard CMT value. The seismic moment rate spectrum shows a large and continuous increase from 50 to 273 s, underscoring the slow nature of the event. The final M_0 estimate is obtained at 18:40 GMT, leaving a lead time of 18 minutes before the first waves hit the Southeastern coast of Java.

Halmahera, 21 January 1994

Finally, and despite its much smaller size, we study this event which gives us insight into a reasonable threshold for tsunami warning in the near field. The earthquake did kill 9 people on Halmahera, even though no deaths were attributable to the tsunami.

The nearest broad-band station for which we obtained data is GUMO, the IRIS station on Guam ($\Delta = 21°$). TREMORS locates the event 200 km from the true focus, and overestimates the moment (7.3×10^{26} dyn-cm as compared to 3.2×10^{26} (Harvard)), an artifact of the station geometry. At any rate, the low value of M_0, adequately recognized by TREMORS, suggests that this range of moments constitutes the limit for the generation of a warning in the near field.

All the results are summarized in Figs. 2–4.

Discussion

The present study is motivated fundamentally by the ultimate purpose of all tsunami warning systems: that of providing an accurate warning in a time frame fast enough to allow for the evacuation of people from low-lying areas. In the case of the Flores and Hokkaido tsunamis, the nearmost communities were hit by the tsunami 2 to 5 minutes after the origin time (H_0). In such situations, it is probably illusory to envision an efficient tsunami warming system, and only the alertness of the residents can save them, by running for high ground as soon as the shaking of the earthquake has died down. The seismic moment reaches the warning threshold 4 minutes after the Hokkaido earthquake, and 10 minutes after the Flores one. With both rupture zones close to the coasts, early warning was impossible for the nearmost communities, but remains feasible for more distant locations, such as Honshu, Russia, and Korea in the case of the Hokkaido event, and Sulawezi for the Flores one.

On the other hand, the Nicaragua and Java tsunamis, generated at the relatively distant trenches, hit the coasts an average of 40 minutes after origin time. The seismic moment of the Nicaraguan event exceeded 10^{27} dyn-cm at the Mexican station UNM only 8 minutes after H_0. During the next 10 minutes, the crucial part of the Rayleigh waves (i.e., the long-period mantle waves) arrived, and it would have become feasible to monitor the remarkable build-up of the seismic moment, and to detect the "tsunami earthquake" character of the event 18 minutes after H_0. Thus, a warning could have been issued for the Nicaraguan and Costa Rican coasts at least 22 minutes before the tsunami hit the coast. We recall that this earthquake was not felt by residents of some sections of the coastline, who were to be swept away 40 minutes later.

In the case of the Java tsunami, the seismic moment exceeded 10^{27} dyn-cm at station WRA 12 minutes after H_0. An efficient warning for Java residents could have been issued 18 minutes before the tsunami hit the coast.

Conclusions

Our results show that TREMORS is indeed an efficient system for the rapid, automatic estimation of the seismic moments of strong earthquakes both in the far and near fields (Fig. 2). As such, it can realistically be used as a reliable tsunami warning system. TREMORS can compute automatically an acceptable location, and generate a warning in all the cases studied, except Halmahera, which is justified given the smaller size of the earthquake and of the resulting tsunami, which incidentally did not result in any additional casualty or damage. Thus, our present experience suggests that a warning threshold of 10^{27} dyn-cm seems an appropriate value in the near field for the generation of a dangerous tsunami. Our simulations obtained by computing seismic moments in windows of growing length, show that warnings would be issued within 4 to 9 minutes of H_0, depending on the epicentral distance, and that a final assessment of the seismic moment, including

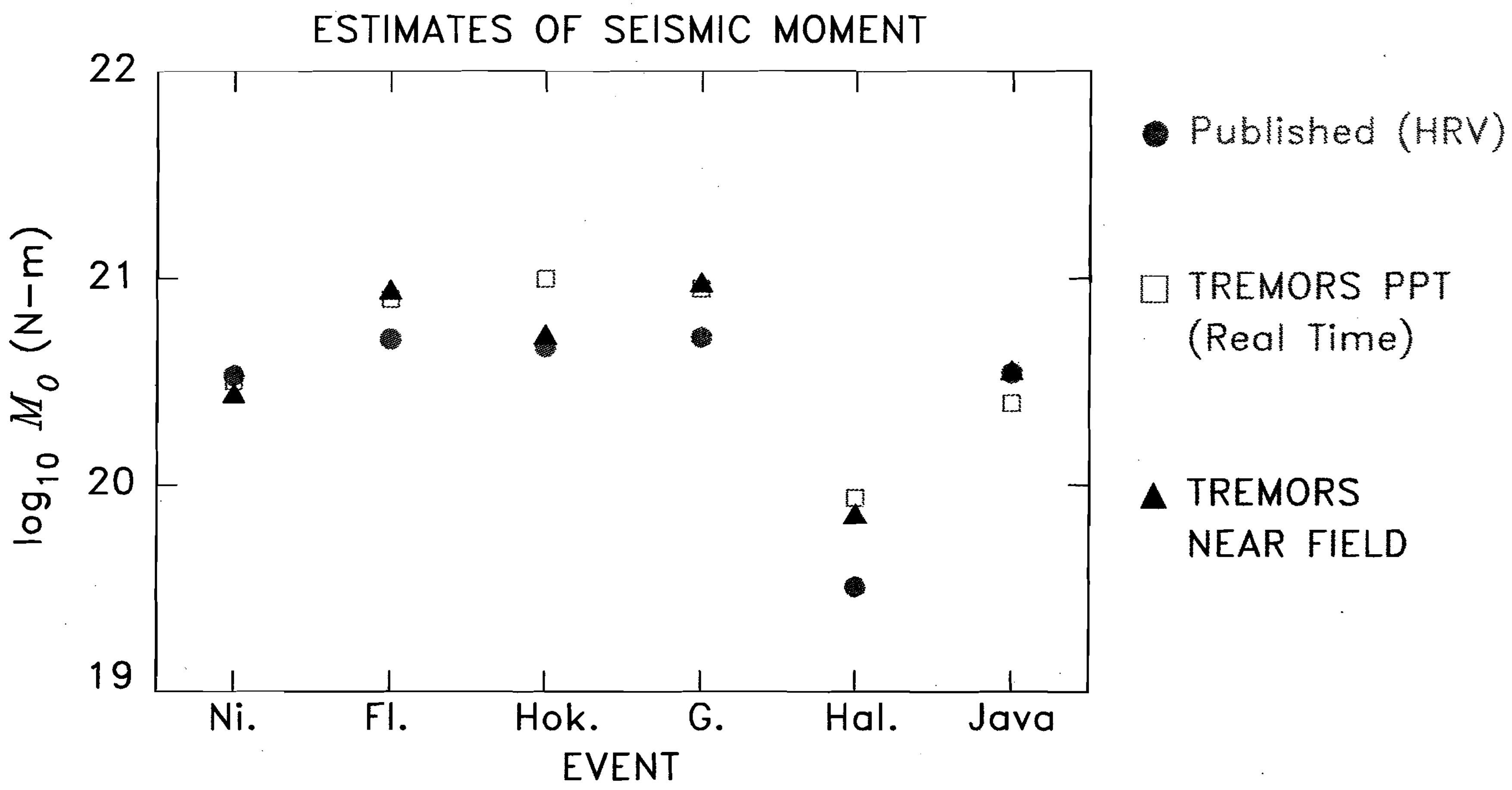

Fig. 2. Comparison of moments obtained in real time at CPPT, and in the regional field, with the CMT values published by the Harvard group (HRV).

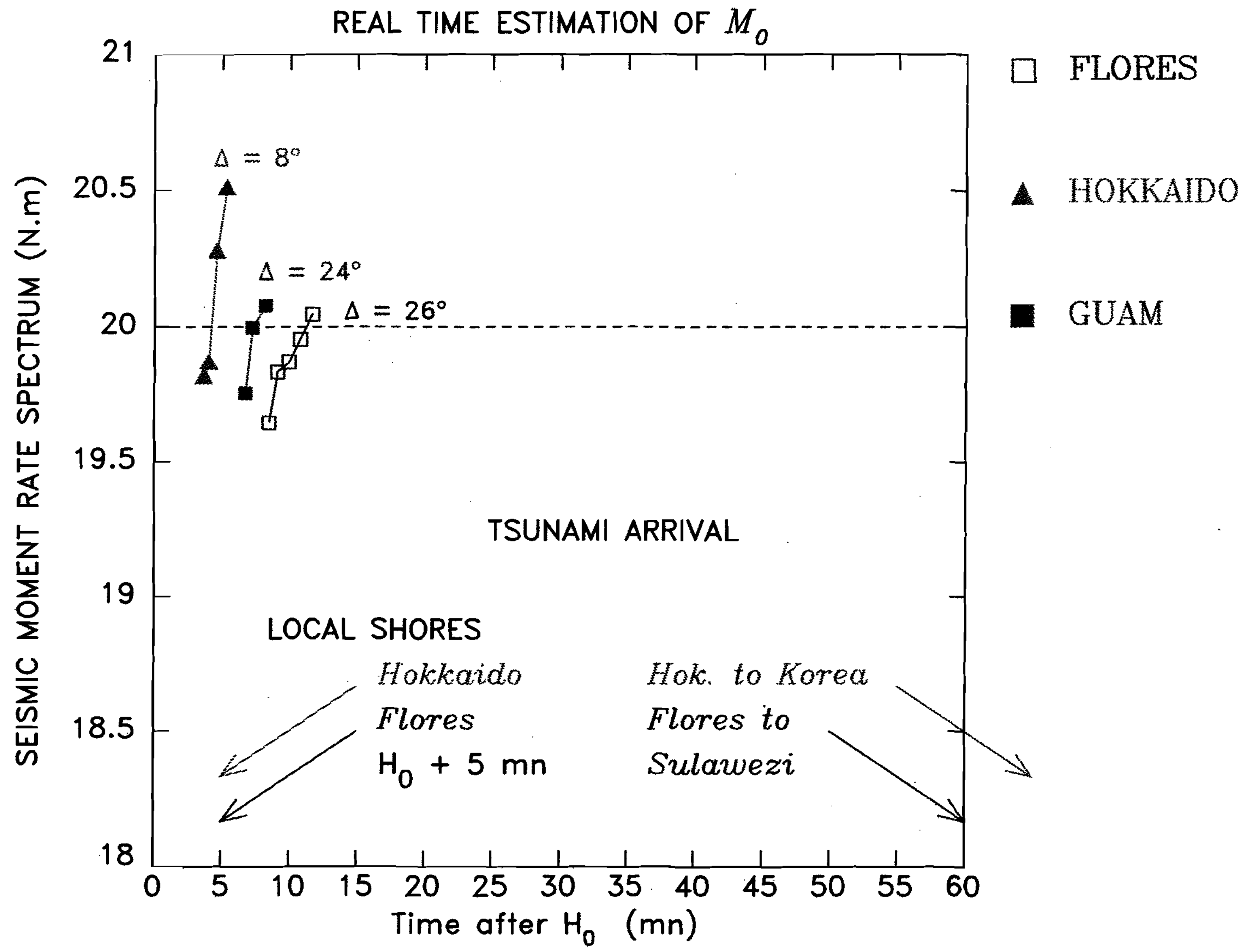

Fig. 3. Evolution with time of the moment rate spectrum in the case of the "regular" tsunamigenic earthquakes (Flores, Hokkaido), and of the Guam event.

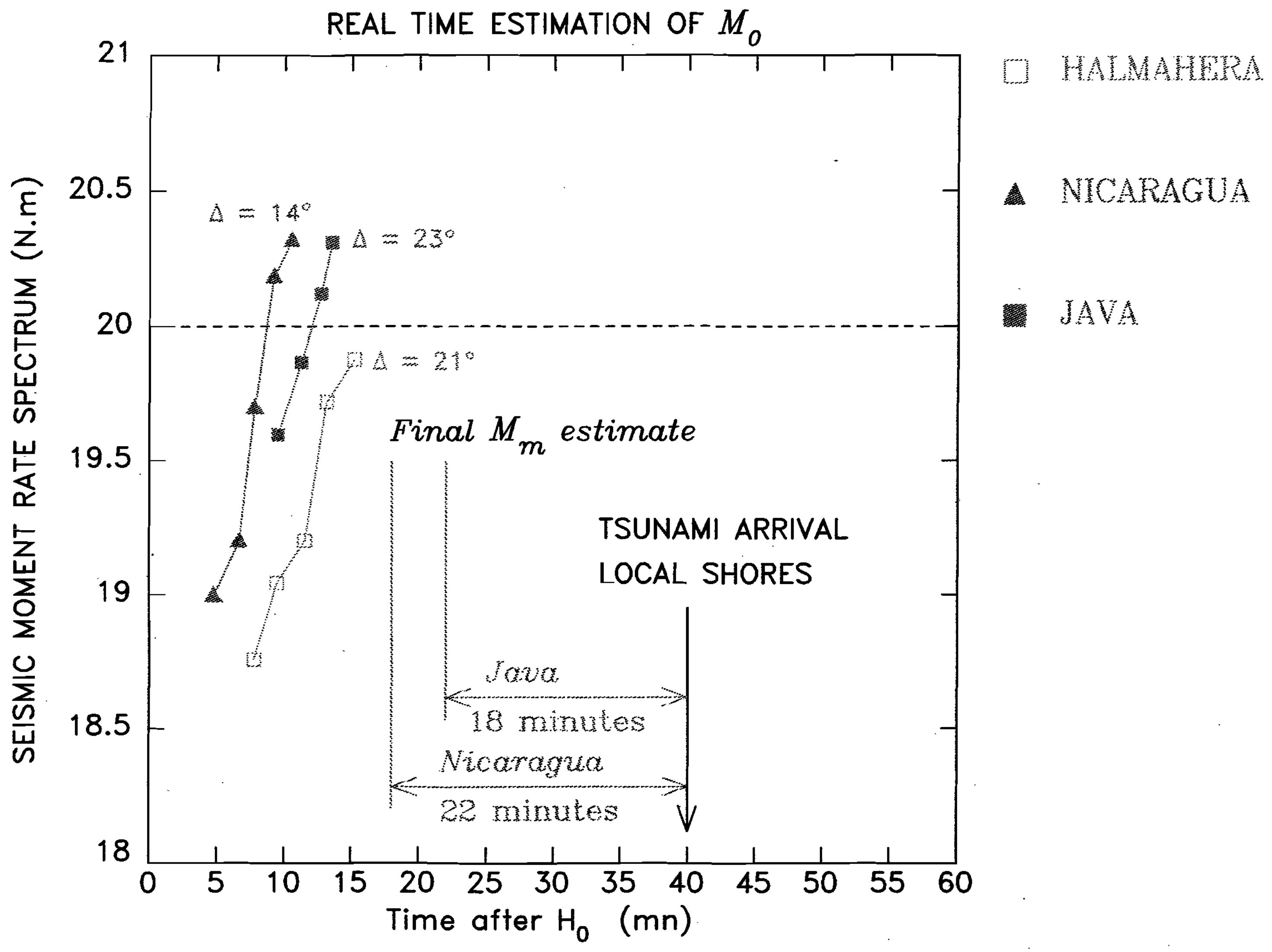

Fig. 4. Evolution with time of the moment rate spectrum in the case of the "tsunami" earthquakes (Nicaragua, Java), and of the Halmahera event. Note the lead time provided in the case of Java and Nicaragua before the tsunami hits the local coasts. Also, note that in the case of Halmahera, the moment rate spectrum fails to reach the critical threshold of 10^{20} N-m.

the possible recognition of "tsunami earthquake" character would be available within 18 to 20 minutes of H_0.

Unfortunately, at present, because of instrumental limitations, the traditional tsunami warning system relies heavily on the 20-second M_s, a magnitude scale notoriously plagued by saturation effects in the precise range of earthquake sizes generating large tsunamis. For slow "tsunami earthquakes" such as the Nicaragua or Java events, the classical magnitudes do not represent the true tsunami potential of the event. On the other hand, TREMORS has the capability of recognizing these events in real time, and of giving a lead time of about 20 minutes in the case of earthquakes generated at the subduction trenches. We want to stress that these figures were obtained using relatively distant VBB stations, situated about 15° from the epicenters. Obviously, better results would be obtained with closer stations. However, we think that a reliable global tsunami warning system could be built around several regional centers equipped with such an automated intelligent system. Each center would be in charge of a seismic zone with a 15° radius. This approach, whose cost and logistics are much lower than those of traditional dense seismic networks, should be a significant step towards effective tsunami warning and hazard reduction.

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