THE ANZA BROADBAND AND STRONG MOTION SEISMIC NETWORK

USGS #01HQ-AG-0021

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FINAL REPORT

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FINAL REPORT ABSTRACT

The ANZA seismic network (http://eqinfo.ucsd.edu) utilizes state-of-the-art broadband and strong motion sensors with 24-bit dataloggers combined with real-time telemetry to monitor local and regional seismicity in southernmost California and is operated by the University of California at San Diego (UCSD). The goal of this project is to provide on-scale digital recording of high-resolution three-component seismic data for all earthquakes, provide real-time data to the California Integrated Seismic Network (CISN), other regional networks, and the Advanced National Seismic System (ANSS), and provide near real-time information to the greater San Diego community. This proposal requests funds to support the continued operations of the ANZA network.

The ANZA network is centered on the Anza segment of the San Jacinto fault zone, which has a maximum expected characteristic earthquake magnitude of 7.5. On 10/31/2001, a M5.1 earthquake occurred in the middle of the ANZA network (8 broadband stations were within 20 km of the epicenter) that spans the San Jacinto fault zone in Southern California. To date the ANZA database contains ~3000 aftershocks of this event, complete to M≈0.0. Rarely are *continuous* aftershock data of such high quality available. These data, in combination with an additional ~58,000 events in the Anza region recorded during the past 21 years by the ANZA seismic network, offer a unique opportunity to study earthquake processes.

To provide better coverage in the metropolitan San Diego area, we operate stations on Mt. Soledad in La Jolla and have recently added three additional stations (FLV, HWB, MTRP). These stations provide extended broadband and strong motion coverage to San Diego County and the offshore region while complementing TriNet station coverage. In the University of California Cooperative Laboratory/Campus (UC-CLC) Campus Earthquake Program, a set of borehole accelerometers has been installed next to the Thornton Hospital on the UCSD campus. The Thornton station is adjacent to the planned I5 composite bridge, which will be heavily instrumented for structural monitoring by CalTrans and the UCSD Structural Engineering Department. Data from these strong motion sensors are included in the ANZA real-time processing system and transmitted to TriNet in real-time. Borehole accelerometers have also been installed at UC Santa Barbara (UCSB) and UC Riverside as part of the UC CLC project, which telemeter real-time data to the ANZA network through the Internet.

The complete waveform data, which consists of over 58,180 events, and response metadata, is stored on-line on a RAID mass storage. The IRIS Data Management Center is maintaining a complete copy of our data archive (updated in real-time) and ANZA data is integrated into their standard FARM database and BUD real-time data distributions. Researchers from academia and industry have complete access to all ANZA data and results directly through UCSD or can access data through the SCEC Datacenter or the IRIS DMC.

The ANZA Broadband and Strong Motion Seismic Network

1. Final Report

1.1 Overview

The ANZA seismic network (http://eqinfo.ucsd.edu) utilizes state-of-the-art broadband and strong motion sensors with 24-bit dataloggers combined with real-time telemetry to monitor local and regional seismicity in southernmost California (Figure 1) and is operated by the University of California at San Diego (UCSD). The goal of this project is to provide on-scale digital recording of high-resolution three-component seismic data for all earthquakes (Vernon, 1989), provide real-time data to the California Integrated Seismic Network (CISN), other regional networks, and the Advanced National Seismic System (ANSS), and provide near real-time information to the greater San Diego community.

The ANZA network has been a leader in developing techniques for real-time data delivery over the Internet. Through the joint efforts of the personnel at the USGS in Pasadena and Caltech, we developed a system in 1995 that sent phase picks and event waveforms to the Southern California Seismic Network (SCSN). By the end of 1996, we had implemented the Object Ring Buffer (ORB) real-time software developed by the University of Colorado supported by funding from IRIS. To effect rapid data transfer to the SCSN, and to its successor TriNet, we installed an ORB server on a computer at Caltech, wrote a software module to interface with the TriNet system, and use this mechanism to routinely transfer all the ANZA data within ten seconds of real-time. In this way, the broadband and strong motion data is seamlessly integrated with the TriNet real-time data processing system. In 2000, a full bi-directional real-time data exchange between ANZA and TriNet was established using the ORB system. Real-time data exchanges between UCSD - UC Berkeley (UCB) and UCSD - University of Nevada-Reno (UNR) have been operational since late 1998.

The ANZA network enhances the broadband coverage provided by the TriNet in southernmost California. ANZA stations are designed to operate in remote areas without any supporting infrastructure such as AC power, telephone or computer communications. Each station can operate using solar power and all

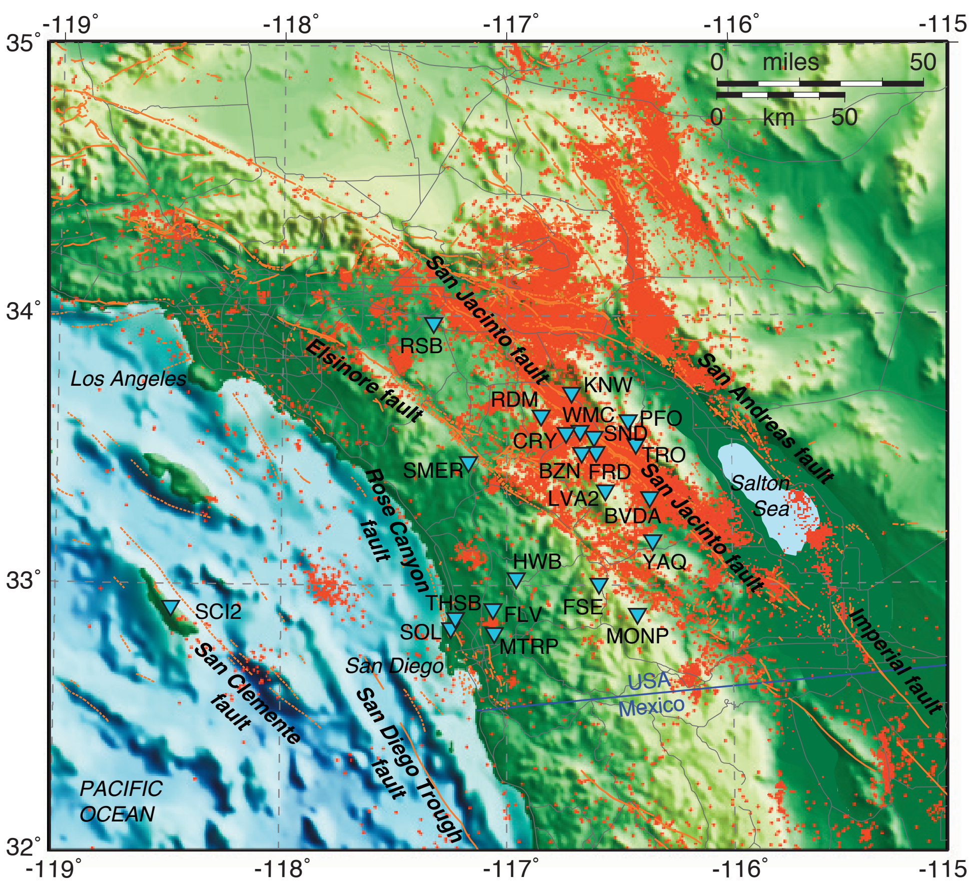

Figure 1. The ANZA seismic network. Current ANZA stations are designated by inverted blue triangles. Seismicity is marked by red dots (58,180 recorded events). Faults are marked by orange lines, with the most important ones named. Highways are markedby solid gray lines. Station names are defined in the text.

communications between stations and the Insitiute of Geophysics and Planetary Physics (IGPP) are dedicated spread spectrum radio links.

The ANZA network is centered on the Anza segment of the San Jacinto fault zone (Figure 1), which has a maximum expected characteristic earthquake magnitude of 7.5 (Working Group, 1995). On 10/31/2001, a M5.1 earthquake occurred in the middle of the ANZA network (8 broadband stations were within 20 km of the epicenter) that spans the San Jacinto fault zone in Southern California. To date the ANZA database contains ~3000 aftershocks of this event, complete to M≈0.0. Rarely are *continuous* aftershock data of such high quality available. These data, in combination with an additional ~58,000 events in the Anza region recorded during the past 21 years by the ANZA seismic network, offer a unique opportunity to study earthquake processes.

There is a high level of microseismicity (Ml < 4.5) in the Anza region. It is also located in a region where there are a large number of significant events. The 1986 North Palm Springs (Mw = 6.2), 1987 Superstition Hills (Mw = 6.5), 1987 Elmore Ranch (Mw = 5.9), 1992 Joshua Tree (Mw = 6.1), 1992 Landers (Mw = 7.3), 1992 Big Bear (Mw = 6.2), 1999 Hector Mine (Mw = 7.1) have all occurred within 100 km of the center of the ANZA network since it was installed in 1982. In addition, the Southern California batholith is widely exposed on both sides of the San Jacinto fault near Anza and provides for exceptionally low-loss and homogeneous transmission paths, and consequently high accuracy in determining locations and source parameters (Scott, 1992).

To provide better coverage in the metropolitan San Diego area, we operate stations on Mt. Soledad in La Jolla (Figure 1) and have recently added three additional stations (FLV, HWB, MTRP). These stations provide extended broadband and strong motion coverage to San Diego County and the offshore region while complementing TriNet station coverage. In the University of California Cooperative Laboratory/Campus (UC-CLC) Campus Earthquake Program, a set of borehole accelerometers has been installed next to the Thornton Hospital on the UCSD campus. The Thornton station is adjacent to the planned I5 composite bridge, which will be heavily instrumented for structural monitoring by CalTrans and the UCSD Structural Engineering Department. Data from these strong motion sensors are included in the ANZA real-time processing system and transmitted to TriNet in real-time. Borehole accelerometers have also been installed at UC Santa Barbara (UCSB) and UC Riverside as part of the UC CLC project, which telemeter real-time data to the ANZA network through the Internet.

1.2 Network Instrumentation

1.2.1 Reftek Based Broadband and Strong Motion Stations

The Reftek component of the ANZA system (Figure 2) is designed for remote three-component digital seismic stations with sampling rates of 100, 40, and 1 samples per second (sps) for broadband components and 100 sps for strong motion components. At each remote station there is a Streckeisen STS-2 seismometer and a Kinemetrics Episensor, digitized by a Reftek 72A-08 datalogger. With the addition of YAQ and MONP, provided by internal IGPP funding in 1997, the data from a total of twelve stations are transmitted via 900 MHz spread spectrum digital radio link to a relay station on the 2655-m summit of Toro Peak. On Toro Peak, data are recorded on a Sun computer operating the Antelope real-time processing system developed by Boulder Real Time Technologies, Inc. (http://www.brtt.com). The Sun server (and its backup) is connected to UCSD's High Performance Wireless Research and Education Network (HPWREN, Figure 3). HPWREN (http://hpwren.ucsd.edu/) has created a wireless backbone network in southern California (see Institutional Qualifications section below) that currently includes nodes on the UCSD campus and multiple mountaintops in San Diego and Riverside Counties including Mt. Woodson, North Peak, Monument Peak, Toro Peak (central data collection point for the ANZA network), Mt. Laguna, and Mt. Palomar (Figure 3). All components of the system have a battery backup power system or an uninterruptible power supply to minimize the possibility of losing data.

The terminus for the Reftek-Freewave telemetry is on Toro Peak (Figures 2,3). Reference time data is broadcast to all the remote stations on a spread spectrum radio link using a synchronous timing feature in the Freewave radios. Each of the one-second data buffers from each station is received by an IGPP Data Concentrator that forwards data packets to a local Sun computer. The Sun forwards data through HPWREN to IGPP using

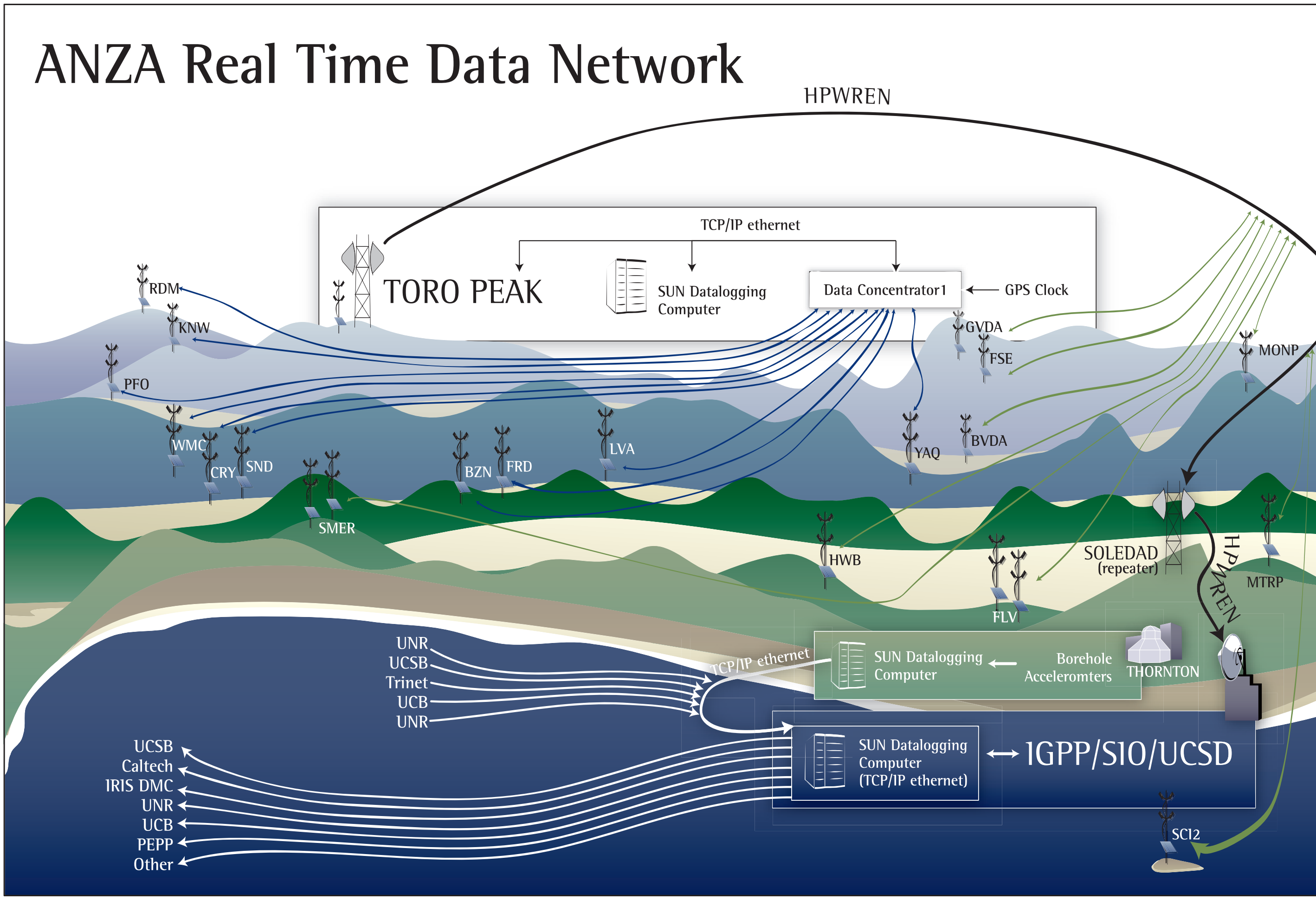

Figure 2. Data flow through the ANZA network. Data packets are sent from the stations to Toro Peak or HPWREN via spread spectrum radios. From Toro Peak the packets are retransmitted to IGPP through HPWREN. At IGPP the data packets are both processed locally in real-time and sent over the Internet to Caltech, UNR, UCB, IRIS DMC,and PEPP. Data are stored locally and at the IRIS DMC.

a standard TCP/IP protocols; and also provides several weeks of local backup data storage. The HPWREN microwave data link utilizes Glenayre equipment operating in the 5.8 GHz spread spectrum band. The current maximum bit rate for the HPWREN system is 45Mbps.

1.2.2 HPWREN and Quanterra Based Broadband and Strong Motion Stations

Leveraging the wireless Internet connectivity provided by HPWREN (Figure 2), the ANZA network can now locate permanent or temporary stations throughout San Diego, Riverside, and Imperial Counties, and all the way out to San Clemente Island, 72 miles offshore. Through non-USGS related IGPP funding sources, and using HPWREN telemetry, the ANZA network has been able to deploy additional broadband/strong motion stations using Quanterra 4120 and Q330 dataloggers. Five of these have been deployed in San Diego County (SOL, HWB, FSE, FLV, SMER) and the sixth has been deployed on San Clemente Island (SCI2) to provide additional coverage in the southern California offshore region. Four of these stations use either STS2 or CMG40 and Episensors, and two stations have only Episensors.

UCSB currently operates the Borrego Valley Downhole Array (BVDA), which has 4 borehole strong motion accelerometers, and 2 surface linear strong motion accelerometer arrays. We have installed 2 8-channel Q4120s that use the ANZA telemetry infrastructure to send data to UCSB and to incorporate selected channels into the ANZA real-time processing.

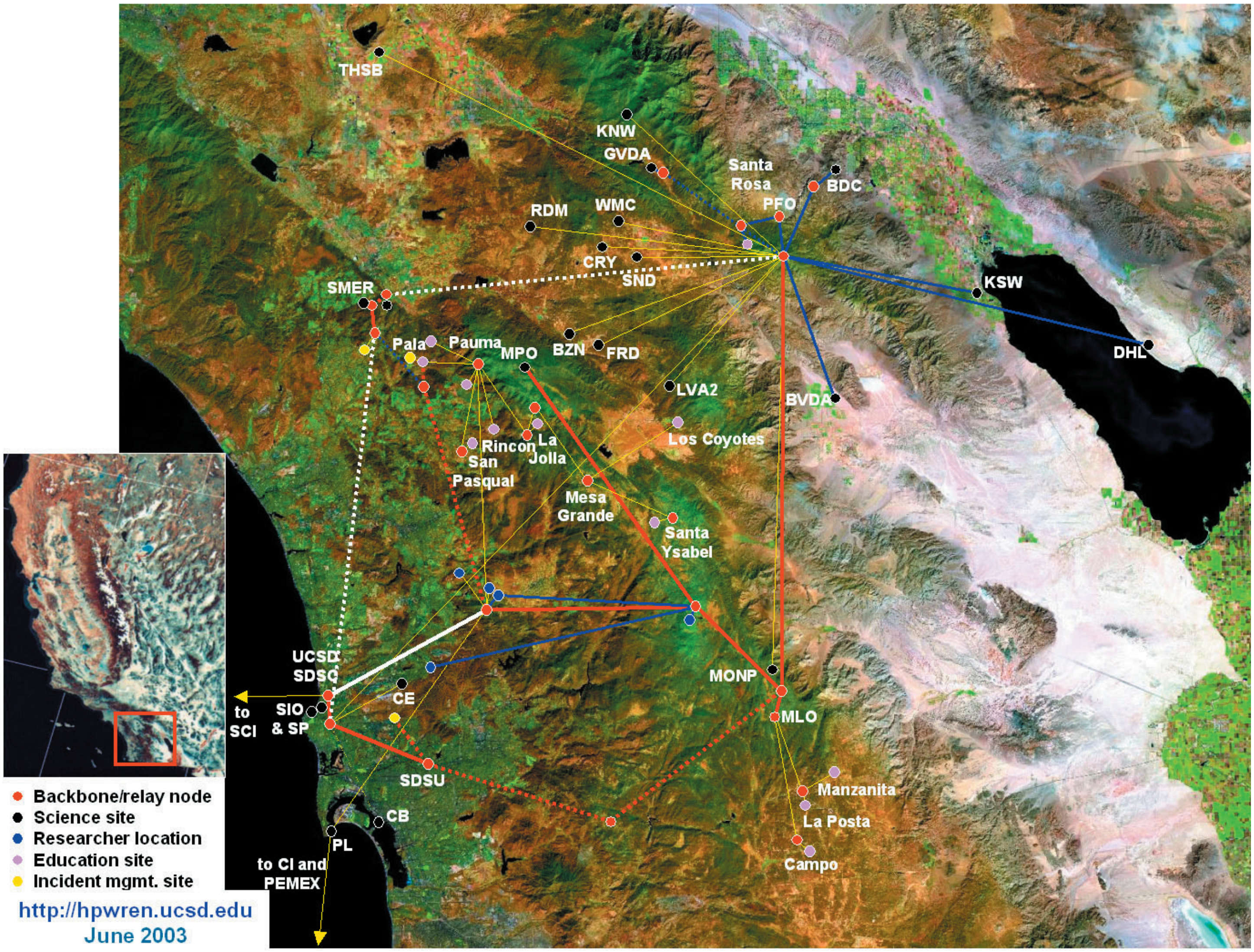

Figure 3. Layout of the High Performance Wireless Research and Education Network (HPWREN). Dashed lines are planned, red lines are unlicensed, white lines are licensed. The solid white is UCSD-MW, the vertical dashed white needs to be completed. The horizontal dashed white is planned and will create network redundancy. Red and white links are 45 Mbit/s, blue are WiLan 2.4 Ghz with at least 1 Mbit/sec, yellow are 802.11b with at least 1 Mbit/s or 900Mhz links with 128Kbits/s.

1.2.3 Real-Time Processing and Data Distribution

At IGPP, data are received by a SUN workstation (Figure 2) operating the Antelope real-time processing system developed by Boulder Real Time Technologies, Inc. (http://www.brtt.com). The Antelope system is a complete real-time system, which includes estimating P and S wave arrival times, event detection in multiple frequency bands, event triggers, location and magnitude estimation, data distribution, and data archiving. The existing Antelope system can provide a ring buffer capacity of 24 hours of data for the ANZA network. In addition, a complete disk resident waveform database is kept online containing the most recent 40 days of data. The Antelope Real-Time system performed extremely well during the very active 31 October 2001 5.1 Mw Anza aftershock sequence. Two analysts reviewing data were able to process over 3000 events in November, completely eliminating any backlog of events.

During the last three years, improvements to hardware and software have led to a more reliable and a higher resolution system. In the first 19 years of operation (1982-2000:107) the ANZA catalog contained 32,340 events, in only three years since then the catalog has increased by 25,840 events! (Figure 4)

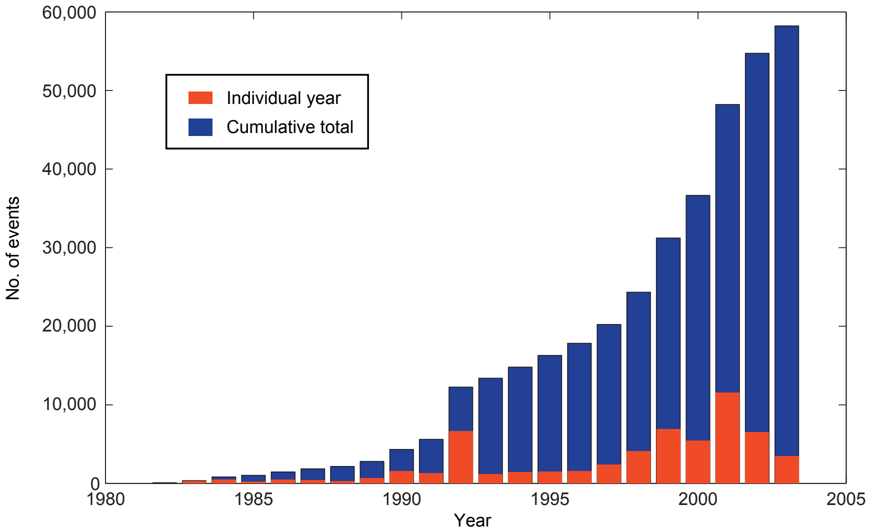

Figure 4. Histogram of the annual and cummulative events recorded by the ANZA seismic network.

1.2.4 Real-Time Data Exchange

Using the Antelope system, all waveform data are delivered in real-time via the Internet to TriNet, UCSB, UCB, UNR, IRIS Data Management Center (DMC), and the Indiana University PEPP network (Figure 5). The ANZA data are included in the TriNet real-time event association, location, magnitude and ShakeMap processing. ANZA waveform data are received at Caltech by the TriNet system within 5 to 10 seconds of real time. The TriNet catalog, which includes the ANZA network data, is the authoritative catalog for southern California and is included in the composite earthquake catalog of the ANSS.

1.2.5 Data Review and Archive

Routine seismic processing occurs on a daily basis (Figure 6). All new seismic data are automatically copied to DLT tape on a daily basis for off-line storage at UCSD. The next step is to review the automatic P and S phase picks from all events and calculate the hypocenters and magnitudes. Standard spectral source parameters are calculated for all events within 50 km of the network. Teleseismic phases are associated with the QED (which is also updated daily via the Internet) and PDE catalogs. Finally, these parameters are stored in a permanent on-line Datascope relational database that includes complete event segmented waveforms.

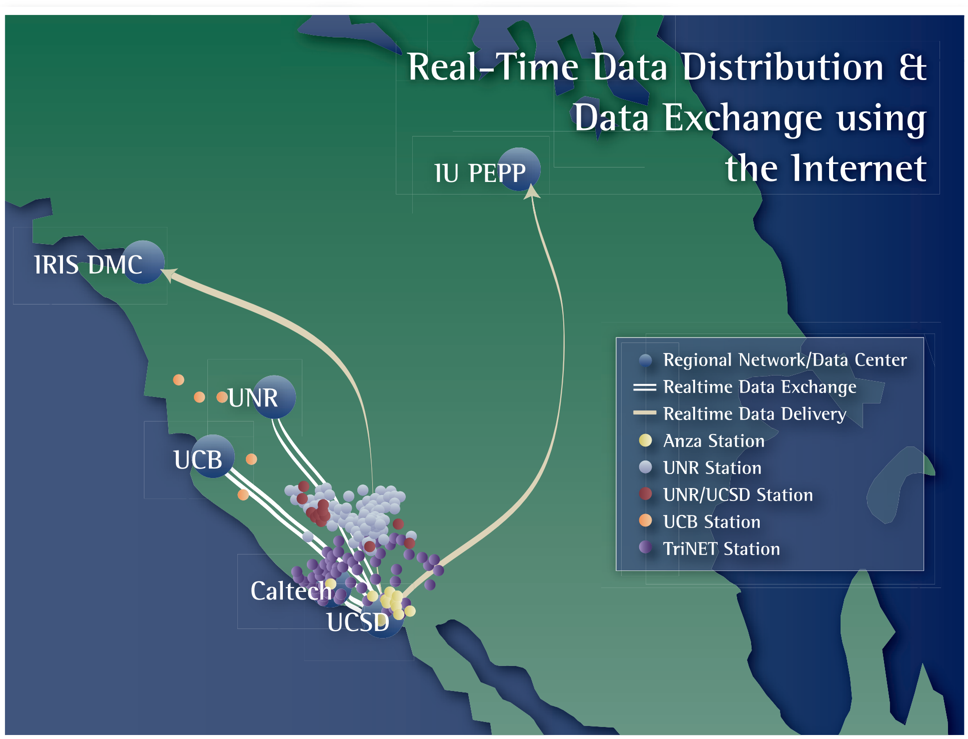

Figure 5. Real-time data distribution and data exchange using the Internet. TriNet, UNR, UCB, Indiana University (PEPP), and the IRIS DMC all receive ANZA data in real-time. Data from selected Trinet, UNR and UCB are also received at UCSD.

All 40 and 1 sps data (BH, LH) and event segmented 100 sps data (HH, HL) data are sent directly to the IRIS Data Management Center (DMC) in Seattle, Washington for permanent archiving and data distribution. In November 1999, a Sun computer running the Antelope software was installed at the IRIS DMC. At this time we started transferring ANZA data over the Internet to the DMC in real-time where automatic processes move these data into the permanent DMC archive on a daily basis (Figure 5). This is an extremely reliable mechanism for archiving data at the DMC, saving time for personnel at the DMC and IGPP, saving the costs of shipping and tapes, and making data immediately available to the seismological community. Since June 2000 there have been 1135

Figure 6. Undergraduate data analyst processing ANZA network data.

requests for ANZA data at the IRIS DMC for a total of nearly 9 Gbytes of data for 123,291 waveforms.

1.3 Education and Outreach

An important aspect of the ANZA network operations is our interaction with policy makers, educators (Figure 7), students and the general public. The primary modes of communication include web pages, teaching in classrooms, presentations to media and site visits by policy makers. In early 2002 UCSD opened the SIO Visualization Center (http://siovizcenter.ucsd.edu) located at IGPP. Many demonstrations using the ANZA network real-time data and capabilities have been made to policy makers including the President's Science Advisor, Dr. John Marburger, senior staffers (in chronological order of visit) from the offices of Susan Davis (Congress, CA), Judd Gregg (Senator, NH), Bart Gordon (Congress, TN), Duncan Hunter (Congress, CA), as well as various representatives from DARPA, CalEPA, Cal OES, VA/HUD/IA, and the National Defense University (see http://siovizcenter.ucsd.edu/news_events.shtml).

1.3.1 The Anza website [http://eqinfo.ucsd.edu]

A unique aspect of the ANZA seismic network web pages (http://eqinfo.ucsd.edu) is that in addition to general seismic information, we also attempt to provide complementary yet novel information that is not as readily available elsewhere (described below). The Internet now has a wealth of information on earthquakes, seismic hazards and earthquake engineering (e.g., www.anss.org, www.cisn.org, www.scec.org, and www.iris.edu), and consequently some of the information contained on our web pages duplicates information that can be found elsewhere. Some duplication is helpful in educational settings as it teaches aspiring scientists how to check various sources and determine which sources are the most appropriate for the task at hand by asking questions such as: based on the earthquakes location and magnitude which seismic network would assist in giving you the best estimate of the earthquake depth? What type of seismic sensors recorded the earthquake -- a strong ground motion sensor or a broadband sensor? To guide our web-based visitors to other pertinent websites we maintain a 'Relevant Links' webpage (http://eqinfo.ucsd.edu/links.htm). This information is essential for our interactions with the San Diego news media when large earthquakes occur and in situations where public information is immediately required. For special events (e.g. large earthquakes globally or smaller earthquakes locally), we collaborate with other institutions, such as the IRIS-DMC, to provide additional figures to augment their web pages. Reasonably some information such as the USGS 'Did you feel it' page (http://pasadena.wr.usgs.gov/shake/) should be housed in only one location; we direct as many people as possible from our site to theirs by adding links to their page at the top of each of our 'special events' pages (described below).

***1.3.1.1 dbrecenteqs* [http://eqinfo.ucsd.edu/dbrecenteqs/anza]**

One of the founding principals of the original Broadband Seismic Data Collection Center website was to allow public access to "up-to-the-minute" earthquake data (such as location maps, event parameters such as magnitude and depth, and waveforms) for local and regional events in southern California and global seismicity (where detected by the ANZA seismic network). With the development of a stand-alone application (*dbrecenteqs*) this information is collected and disseminated within the context of scaled topographic maps of different regions. Essentially *dbrecenteqs* "watches" a real-time Antelope database of hypocenters, customizing pre-generated stock maps for a series of defined regions and creating individual maps for each earthquake as it occurs. *dbrecenteqs* creates the html code and images for a complete web-site of recently detected earthquakes. Staff in the Anza group have been working closely with *dbrecenteqs* author Dr. Kent Lindquist to implement the application for the ANZA seismic network and also extend the capabilities of the application. We have customized the UCSD installation of the *dbrecenteqs* interface to allow multiple seismicity maps including local, regional, California, Western USA and global views.

1.3.1.2 Special Events **[http://eqinfo.ucsd.edu/special_events]**

'Special events' are considered to be local (Southern Californian) events greater than magnitude 3, regional events greater than magnitude 5, or teleseismic events greater than magnitude 7. After an event occurs, automated webpages in English and Spanish are constructed that map where the event occurred on a small globe, where the event occurred relative to the ANZA seismic network, the initial source parameters, plus several views of waveforms recorded by instruments in the ANZA network. These normally consist of the closest station to the event hypocenter, vertical components from all stations in the ANZA network, and the waveforms recorded at Mt. Soledad – the closest station to the UCSD campus and a local landmark for all San Diego residents. These pages are updated as authoritative hypocenter and magnitude values are provided by the appropriate network or agency. Links are provided to the USGS and IRIS Seismic Monitor, and also searches Google.com with keywords associated with the event. These pages are extremely popular, and normally precipitate feedback to the ANZA webmaster. For example, the recent May 21st 2003 magnitude 6.7 Algeria earthquake was visited 184 times in the last ten days of May 2003.

1.3.1.3 Information and Interactivity

Expansion of the ANZA website has included more background information about recent seismically active regions, for example http://eqinfo.ucsd.edu/special_events/oregon/index.shtml, where the regional plate tectonic configuration is illustrated to show why so many earthquakes occur in the region. Other information includes building a glossary of geological terms to help visitors understand the terminology we often use (http://eqinfo.ucsd.edu/glossary/index.html), allowing more interactivity and online learning with activities such as online earthquake quizzes (http://eqinfo.ucsd.edu/faq/quiz.html), and what to do in the event of an earthquake (http://eqinfo.ucsd.edu/faq/concerns2.html). We have also improved the 'Research' section of the website (http://eqinfo.ucsd.edu/research/index.html), which now contains recently submitted abstracts and journal articles for the scientifically inquisitive visitor.

1.3.2 Mission Trails Regional Park

The most unique station we have recently added to our network is at Mission Trails Regional Park in San Diego (station code MTRP). The exhibit is located at the Mission Trails Interpretative Center, a museum at the Mission Trails Regional Park within the City of San Diego. The museum foundation purchased their own strong motion sensor (a KMI Etna system) and a workstation with dual-monitors for a real-time display in their Visitor Center. The public unveiling of the exhibit was held on Thursday, February 7, 2002, at 11:00 a.m. in the Visitor & Interpretive Center. Joe Morse, President of Mission Trails Regional Park Foundation, was Master of Ceremonies for the event with the City of San Diego Mayor Dick Murphy and Council Member Jim Madaffer participating in the ceremony. The collaborative efforts of staff and researchers from IGPP and SDSU were highlighted in this ceremony.

Attendance at the museum is approximately 60,000 per year and the Center is a popular field trip destination for K-12 school groups. The educational component on earthquakes and seismology that this display produces is highly relevant in Southern California and San Diego. The communities served by the Center are less than 100 km west of the Elsinore and the San Jacinto faults, both of which are seismically active strands of the right-lateral strike-slip San Andreas fault system that defines the Pacific/North American plate boundary in this area (Figure 1). Several other less active faults fall within the city of San Diego or lie just offshore. Earthquakes large enough to be felt first-hand by people occur several times per year with damaging events occurring on the order of every ten to twenty years, usually from large events at regional distances. Consequently, the need for awareness of earthquake causes and potential hazards is high in the region.

The MTRP strong motion sensor is located under the display, allowing people to jump, stamp feet, and otherwise create seismic waves that appear almost immediately on a computer monitor. An event map, updated in real-time, is also displayed with a choice of local, regional, and worldwide views of recent earthquake locations. During periods of little museum activity, which is at least 14 hours per day, the sensor records useful low noise data that are merged in real-time with ANZA seismic network data for scientific analysis. We have a data exchange with Mission Trails so they can display the regional events and real-time event locations from the ANZA network, and the ANZA network gained a new urban San Diego real-time strong motion station. This is, to our knowledge, the first case of a museum seismology display being used simultaneously as an active station in a real-time seismic network. We are currently discussing two similar implementations in other urban museum settings in San Diego county (the Stephen Birch Aquarium and the San Diego Natural History Museum).

1.3.3 Data visualization and the Geowall

The ANZA data is routinely used in 3D visualizations geared toward education and outreach (Figure 7). Many of these visualizations can be ported to large custom built immersive centers such as the SIO Visualization Center (http://siovizcenter.ucsd.edu) and also small-scale desktop visualization systems such as the Geowall (http://www.geowall.org) and are available via a real-time streaming web-server (http://siovizcenter.ucsd.edu/streaming/). Many of the visualizations developed are available in Quicktime movie format via a real-time streaming web-server (http://siovizcenter.ucsd.edu/streaming/) or as interactive 3-D models (http://siovizcenter.ucsd.edu/library/objects/index.shtml) for use in the classroom at the K-12 or college level.

One example of a new visualization technique is the WiggleView Open GL application developed at the Electronic Visualization Laboratory at the University of Illinois at Chicago with funding by IRIS. The application imports and displays 3-component seismic waveforms for specific earthquakes at seismic station locations plotted on a 3-D global basemap. This map can be rotated, enlarged, and shrunk and the waveforms at each station can be enlarged or shrunk which allows close examination of individual stations or regional or global views of network arrays. The Anza group is currently working with the author of the application to allow immediate import and display of real-time ANZA network detected seismic events. This has tremendous potential in teaching seismicity to the general public, especially in terms of how earthquakes travel through the earth and are detected at different stations at different times. The application also has a 3-D interface that can be viewed on 3D visualization systems such as the Geowall.

1.3.4 Seismic Data in the Classroom

ANZA data are currently used in various courses at UCSD and SDSU. Prof. Catherine Johnson of UCSD uses the ANZA special events webpages (e.g., Alabama earthquake and the three May 26, 2003 Mindanao, Halmahera, and Honshu quakes, see http://www.eqinfo.ucsd.edu/special_events/index.html for an index of these events) in her introductory class on Planets (~300 undergraduates). Dr. Frank Vernon uses ANZA data in his graduate SIO223 Time Series Analysis class as well as in his informal seismogram reading class. Since Spring 2000, Prof. Rob Mellors at SDSU has used ANZA data in the online version of the Geology 101 laboratory course (http://www.geology.sdsu.edu/visualgeology/geology101/seis_frames.htm). Enrollment in the Geology 101 course is approximately 170 mostly non-geology majors per semester, so about 1200 students from diverse backgrounds have benefited from the availability of ANZA network data.

1.4 Seismic Hazards of the Region

The southern California region has generated nearly 50 magnitude 6 or greater earthquakes since 1850 (Ellsworth, 1990). Sixty percent of these moderate to large earthquakes are associated with the San Andreas and

Figure 7. 3-D visualization of ANZA data during a recent workshop at IGPP helps teachers learn greater spatial and temporal understanding of seismic events to better educate their students about local and regional seismicity and geology. Source: Earthquake Education Workshop, May 24 2003 (http://siovizcenter.ucsd.edu/workshop/)

San Jacinto fault systems and their continuations into Baja California. It is interesting to note that only seven of these events have significant surface rupture. These events include the 1857 Fort Tejon (Mw = 7.8) along the Cholame and Mojave segments of the San Andreas, the 1940 (Mw = 6.9) and 1979 (Mw = 6.4) on the Imperial Fault, the 1968 (Mw = 6.5) Borrego Mountain and 1987 (Mw = 6.5) Superstition Hills located on the southern San Jacinto fault, and the 1952 (Mw = 7.5) Kern County, the 1992 (Mw = 7.4) Landers, and the 1999 Hector Mine (Mw = 7.1) which are not directly associated with the San Andreas-San Jacinto fault system. These historical surface ruptures are shown in Figures 8 and 9 which also highlight the two major sections without significant surface offsets: the San Bernardino and Coachella Valley segments of the San Andreas fault and the San Bernardino, San Jacinto Valley, Anza, and the Coyote Creek segments of the San Jacinto fault.

The San Jacinto fault zone is one of the most active strike-slip faults in southern California. The long-term slip rate is 1 cm/year, determined from 29 kilometers offset of geologic formations across the fault in the last 3 million years (Sharp, 1967). Recent measurements of offset sediments in the Anza Valley yield a similar slip rate (Rockwell, et al. 1990). The Anza segment of the San Jacinto fault zone has been identified by Thatcher et al. (1975) as a seismic slip gap for a $6 \le M \le 7$ earthquake. The study of Sanders and Kanamori (1984) revealed a 15 km element of the estimated seismic gap that has been virtually aseismic in modern times. Klinger and Rockwell (1989) trenched the San Jacinto Fault at Hog Lake located in the center of the Anza seismic gap and found evidence for surface rupture from three events since 1210. Additional evidence suggests that these events occurred about 1210, 1530, and 1750.

In 1988, the Working Group on California Earthquake Probabilities (USGS Open File Report 88-398) defined the Anza segment to be the 50 km section between the southern end of the inferred 1899 M=6.4 (Abe, 1988), 1918 M=6.8 (Ellsworth, 1990) rupture just north of Anza and the north end of the 1968 Borrego Mountain M=6.8 surface rupture (Figure 9). They used a slip rate of 11 mm/yr, a recurrence interval of 142 years, and assumed the previous event in this segment was 1892. Based on this information a probability of 0.3 was assigned for a magnitude 7 earthquake in the Anza area in the next 30 years.

The Southern California Earthquake Center presented its Phase II report which reassesses the results of the 1988 report. Using the results of Klinger and Rockwell (1989) and Rockwell et al. (1990), the Anza segment of the San Jacinto fault zone is considered by the Working Group on California Earthquake Probabilities (1995) to be the entire 90 km long Clark fault with an average repeat time for a magnitude 7.0 to 7.5 to be 250 (+321, -145) years. Because the dimension of the segment increased, the characteristic slip is now 3.0 m (Figure 9).

The most significant recent information to be developed for the seismic potential of the Anza segment is the 1750 date for the last major earthquake. Using the 142-year recurrence interval of the 1988 report a magnitude 7 earthquake is now 100 years overdue. If one prefers the Phase II report then the characteristic earthquake can be a magnitude 7.5 with the peak in the conditional probability distribution in the year 2000. In either scenario, the characteristic earthquake can generate significant damage in the major population areas of San Diego (90 km distant), the San Bernardino Valley (60 km), and the Los Angeles basin (90-150 km) (Figure 8). In similar situations, significant damage was caused in San Francisco at 120 km distance by the magnitude 6.9 1989 Loma Prieta and in various parts of the Los Angeles basin by the magnitude 6.7 1994 Northridge earthquake over 100 km from the source.

1.5 Seismicity Recorded by the ANZA Network

Since the installation of the ANZA network in 1982, there have been nine earthquakes in southern California with magnitudes 6.0 or greater. The ANZA network recorded eight of these mainshocks, the exception being the 1986 Mw = 6.2 North Palm Springs event (Figure 9). Numerous aftershocks from each of these events were recorded on scale and in the cases of the 1987 Elmore Ranch and Superstition Hills events, the 1992 Landers and Joshua Tree earthquakes, and the 1999 Hector Mine earthquake, foreshocks were recorded as well.

The evolution of the ANZA network instrumentation has greatly increased the quality of the data from regional and teleseismic events. During the 1992 Joshua Tree-Landers-Big Bear sequence, when the ANZA stations used short-period sensors with 16-bit dynamic range, only the events with magnitudes less than 5.5 were

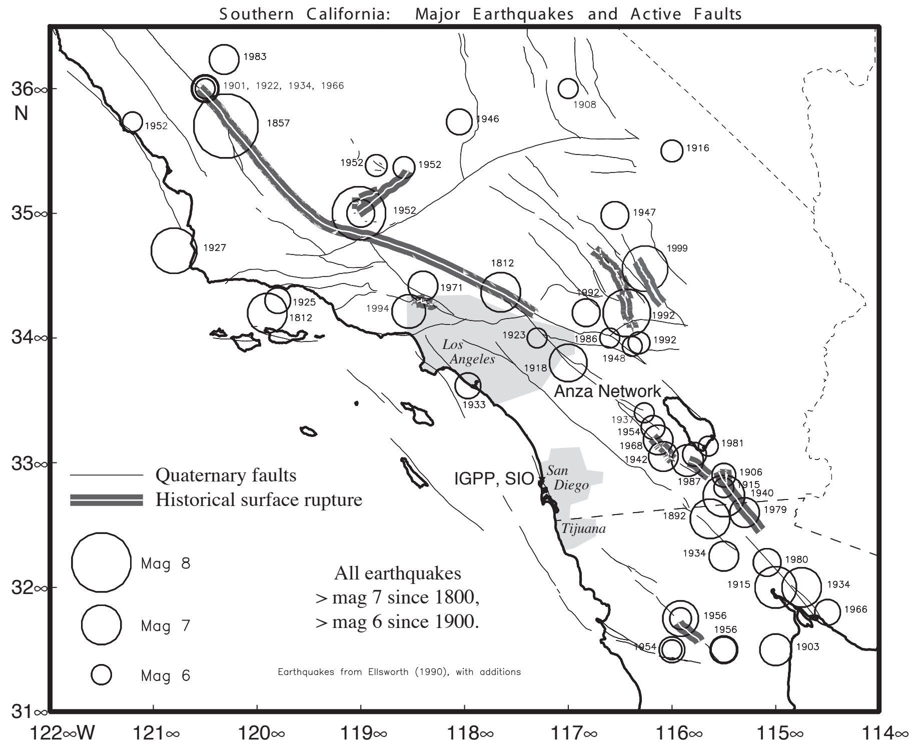

Figure 8. Major earthquakes in historical times in the southern California region. Surface ruptures are defined by the dark gray lines and epicenters are designated by circles scaled by magnitude. The ANZA network is centered on the middle part of the San Jacinto fault zone.

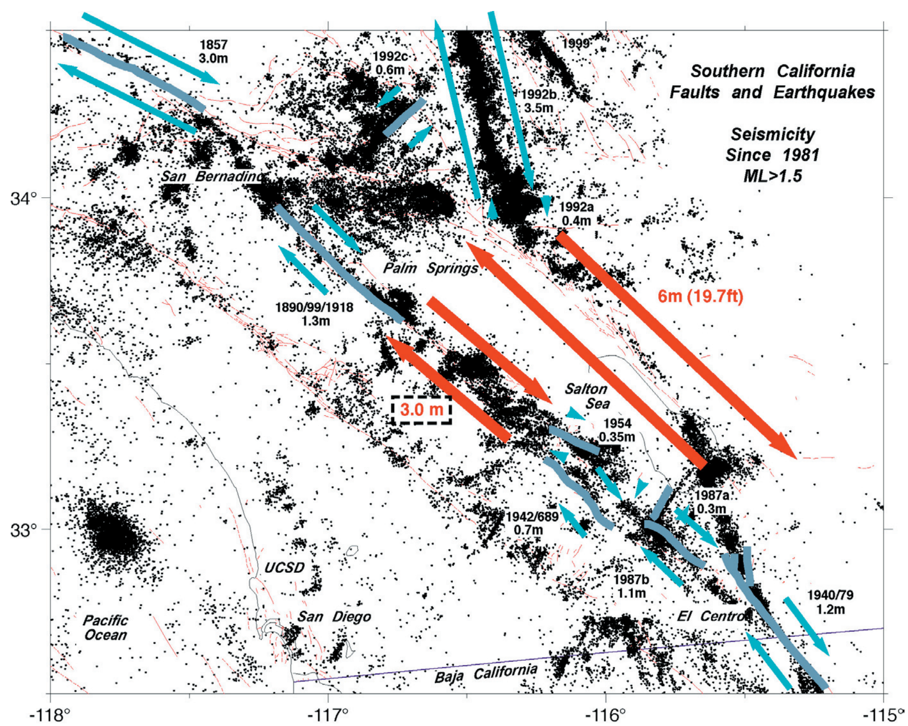

Figure 9. Seismicity in the southern California region since 1981 with Ml > 1.5. Major earthquakes with observed or inferred offsets are shown with blue arrows. The red arrows designate the two major slip deficits in southern California, 3 meters for the Anza gap on the San Jacinto fault and 6 meters for the Coachella segment of the SanAndreas fault. Earthquakes of magnitudes 7+ and 8+ respectively are required to eliminate these slip deficits.

unclipped. After the 1993 upgrade to broadband sensors with 24-bit dynamic range, the 17 January 1994, Mw = 6.8, Northridge earthquake was recorded on-scale. However the 16 October 1999, Mw 7.1, Hector Mine clipped all stations after the S wave arrivals. Another interesting example of the broadband capability for recording teleseismic events by the ANZA network is shown in Figure 10 for the 25 May 2003, Ms= 6.8, Honshu, Japan earthquake which occurred at a distance of 77˚. For comparison, the next day an example of a local Ml = 2.4 is shown with recordings on braodband and strong motion sensors at the same site.

Smaller earthquakes along the San Jacinto fault zone have a strong tendency to occur in one of four clusters of activity (Figure 11). These clusters have in general been persistent seismic features of the entire eighteen-year operational period, but with systematic variations within clusters. The Cahuilla cluster, which is ~ 15 km west of the trace of the San Jacinto fault, has shallow seismicity, less than 6 km from the surface. The Hot Springs cluster at the north end of the array lies between the mapped traces of the Hot Springs faults at depths of 15 to 22 km. The Table Mountain/Toro Peak cluster is a more diffuse zone of seismicity that spans the trifurcation of the San Jacinto fault into the Buck Ridge and Coyote Creek faults, and the seismicity ranges from about 7 to 17 km deep. There are a few events along the trace of the San Jacinto, e.g., a smaller cluster right beneath the town of Anza; however, the dominant pattern of activity lies off the main trace of the fault. Each of these clusters has produced at least one magnitude 4 event during the operational period of the ANZA network.

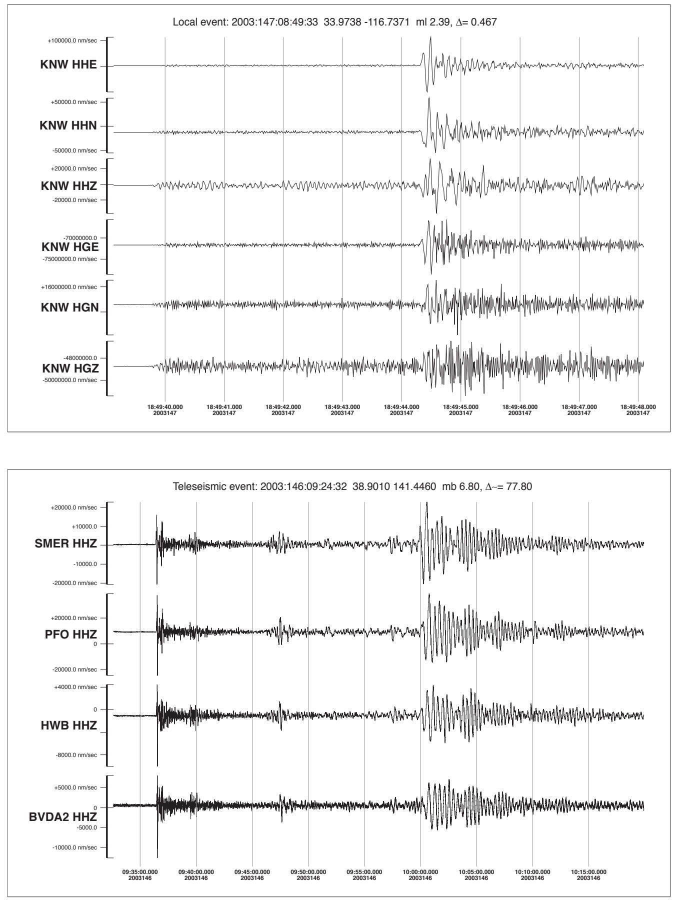

Figure 10. Example seismograms demonstrating broadband and strong motion recordings of a local M=2.4 earthquake (top) and braodband recordings of the 25 May 2003 M=6.9 Honshu earthquake (bottom)

1.6 Current Research and Results Based on ANZA Data

1.6.1 Halloween Earthquake (10/31/2001) and Aftershock Studies

On 10/31/2001, a M5.1 earthquake occurred in the middle of the ANZA network (8 24-bit broadband stations were within 20 km of the epicenter) that spans the San Jacinto fault zone in Southern California. The ANZA database contains ~3000 aftershocks of this event (Figure 12), complete to M≈0.0. Rarely are *continuous* aftershock data of such high quality available. These data, in combination with an additional ~58,000 events in the Anza region recorded during the past 20 years by the ANZA seismic network, offer a unique opportunity to study earthquake processes. Using these data, Debi Kilb and Frank Vernon are funded through a separate USGS NEHERP grant to conduct the following research :

- Identify regions where closely located (< 2km) earthquake clusters have dissimilar waveforms. We will investigate possible causes for this variability, which include complexity in: (1) fault plane orientations, (2) source processes (e.g., directivity), or (3) near source velocity structure variations. We will investigate

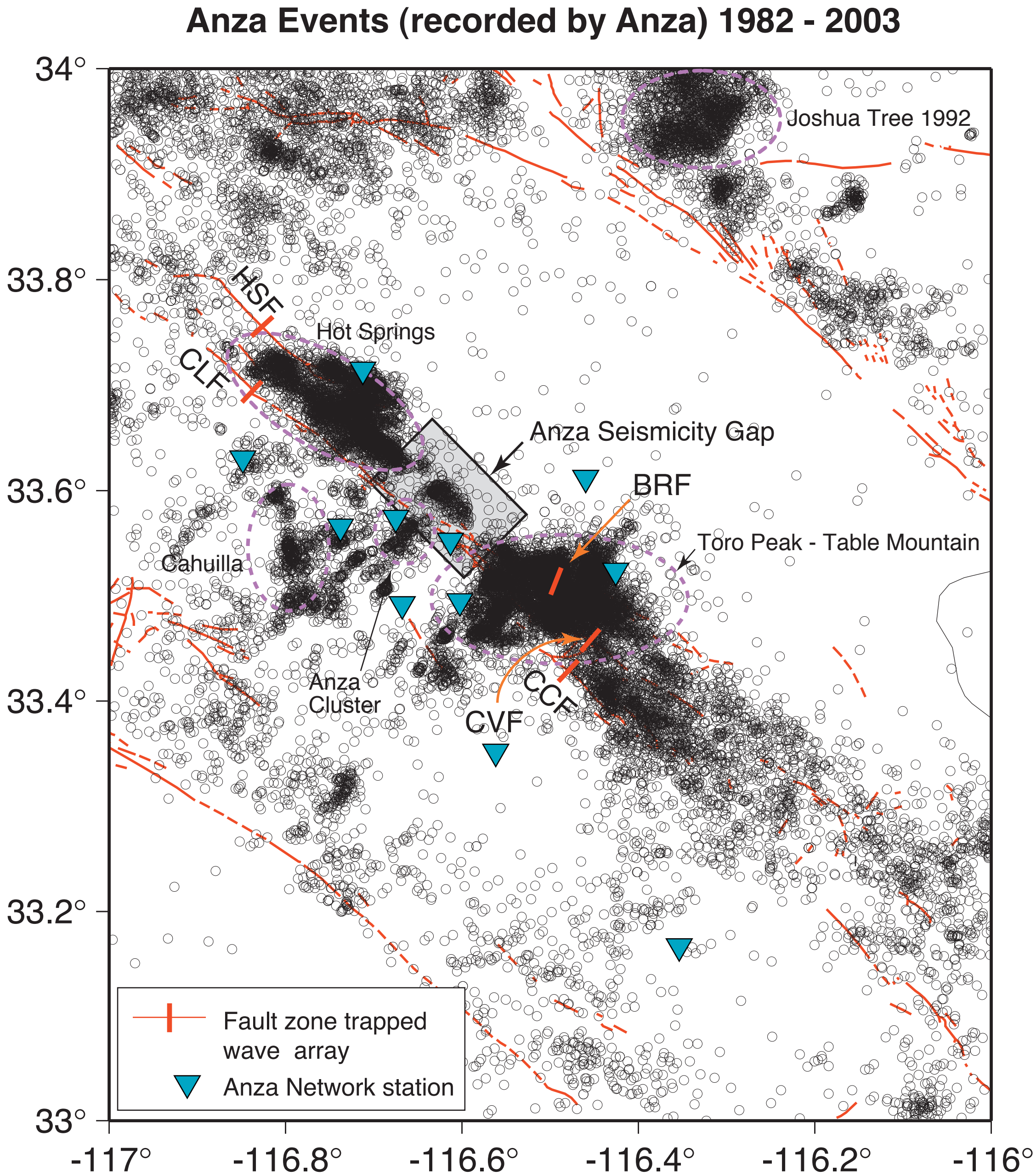

Figure 11. Local seismicity of all events recorded between 1982 and 2000 in the central region of the ANZA network. The four local clusters of activity, Hot Springs, Cahuilla, Anza, and Toro Peak-Table Mountain are designated by dashed ellipses. The Anza Seismicity Gap first described by Sanders and Kanamori (1984) is shown in the gray box.

these possibilities by computing and comparing focal mechanisms of nearby earthquakes, quantifying the temporal/spatial variability of the seismic waveforms using cross-correlation coefficients, and identifying rupture directivity using variations in waveform amplitudes.

- Investigate causes for the bimodal distribution of earthquake magnitudes (peaks at M=0.1 and M=1.5) for earthquakes recorded by the ANZA network within the last two years. A similar bimodal distribution exists in data from deep gold mines in South Africa. It has been proposed that the larger magnitude events occur on existing faults and primarily respond to tectonic loading, whereas the smaller magnitude events represent rupture on "new" faults that did not previously exist. The small events are clustered in time and space, and the waveforms have similar P and S wave amplitudes, which differs from the signature of the

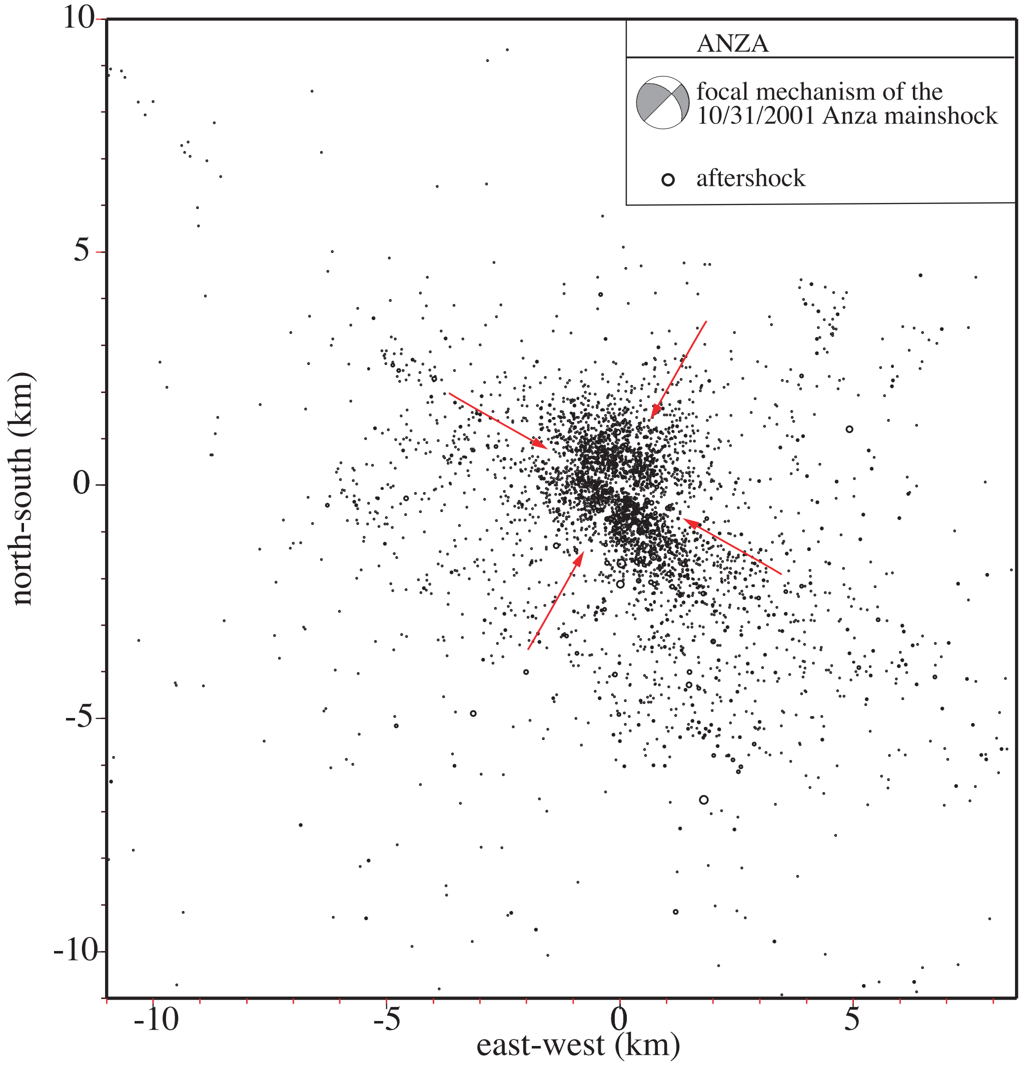

Figure12. Original catalogue data of ~3000 aftershocks of the Anza M5.1 10/31/2001 earthquake centered about (33.52°, 116.5°). Circle sizes indicate approximate earthquake rupture size based on the moment-magnitude scaling relationship of Abercrombie (1996) and an assumed stress drop of 3 MPa. Note the void of seismicity that trends ~N45W as well as the void of seismicity that trends ~N45E (indicated by the red arrows).

larger magnitude events. We will determine if these observations are consistent with the ANZA data.

- Study the development of the aftershock sequence of the M5.1 10/31/2001 earthquake in which there is a 30-second time-lag before the first M>1 aftershock. We will determine if similar time-lags are detectable in five other sequences recorded by the ANZA network, in which the mainshock magnitude is above 4.0. A non-zero lag-time is inconsistent with the hypothesis that stress change triggering occurs instantaneously.

In combination, our results will identify fault complexity within the Anza region, determine if the triggering mechanism of aftershocks is similar to the triggering mechanism of earthquakes that respond to tectonic loading, and quantify the temporal and spatial evolution of aftershocks immediately following a mainshock.

1.6.2 Seismic attenuation: Kappa Studies

The parameter kappa was defined by Anderson and Hough (1984) to describe the high-frequency spectral roll-off of the strong motion spectrum. It has subsequently been used in the seismic hazard analysis applied to Yucca Mountain. The numerical value used in the seismic hazard analysis is small (20 ms based on Su et al, 1996), where smaller values lead to higher estimated ground motions. An increase of 10 ms in kappa could result in a substantial decrease in the expected ground motions. A fundamental question is why do the network sites with the smallest values of kappa have low ground motions?

John Andersen and Jim Brune from UNR with Debi Kilb and Frank Vernon from UCSD are using similar methods applied by Su et al. (1996) to examine the magnitude dependence of kappa in Anza data for both local and regional earthquakes. This study examines the assumption of magnitude independence (0.0 < Ml < 5.2). Determining how well the M3-4.5 earthquakes can predict the behavior of the M5.2 events can test the extrapolation to larger events. An interesting part of this study is the comparison of the magnitude dependence of kappa and spectral amplitudes for regional earthquakes in both southern Nevada and Anza, over the magnitude range from M<1 to M>5.0.

1.6.3 Microseisms

Recent hindcasting efforts for global warming investigations use seismic records on land as a proxy for past ocean climate. These studies rely on a strong correlation between ocean wave height and the amplitude of ocean-generated seismic signals known as microseismic noise. The seismic data predate oceanic buoy records by decades, providing important information for studies of global climate change. Using recent ocean wave models and ANZA seismic data, Schulte-Pelkum et al. (manuscript in review 2003) demonstrate the importance of propagation directions rather than only amplitudes of storm swells and microseisms for climate hindcasting. Analysis of ocean swells and concurrent microseisms reveals a direct causal relationship between swells arriving at different North American coastal areas and the triggered microseisms. Schulte-Pelkum et al. find dominant source areas for microseismic noise observed in southern California from locations as distant as Newfoundland and British Columbia, and show that microseisms strongly reflect ocean swell directions, establishing the importance of directional rather than only amplitude information for climate hindcast studies.

1.6.4 Large teleseismic P wavefront deflections observed with broadband arrays

Vera Schulte-Pelkum et al. (1998. 1999. 2003) measure the plane wave front incidence azimuth for teleseismic P-waves at large aperture (~50 km) broadband arrays. The incidence azimuth is determined by crosscorrelation of the P arrivals on the vertical component seismograms filtered in successive frequency bands. The periods considered range from 10 to 35 s. At the ANZA array in southern California, the plane wave direction is deflected from the great circle azimuth of the event by up to 20 deg. In addition, we find a surprisingly strong frequency dependence of the same magnitude, and a striking antisymmetric pattern of the deflection as a function of backazimuth, while the curvature of the wavefront is small. Similar characteristics are found at the Grafenberg array in Germany and the Norsar array in Norway, however with much weaker amplitudes of 5 deg. We ascribe the behavior at Anza to structure in the lower crust and uppermost mantle beneath the array, given that the observations are only a function of source backazimuth and not of source depth and source mechanism, that the wavelengths under consideration range from 50 to 270~km, and that the sign of the deviation is opposite to that predicted from shallow crustal structure and Moho topography. We are able to reproduce the magnitude and frequency dependence of the wavefront deflection using finite difference numerical modeling of plane wave propagation through simple 2-dimensional structures.

1.6.5 Receiver Functions

Lewis et al. (2000,2001) analyzed teleseismic P waves recorded at the ANZAbroadband stations. They selected records from 67 earthquakes with impulsive, high signal-to-noise P waves and used the teleseismic receiver function technique to obtain a profile of the crustal thickness of the eastern Peninsular Ranges batholith. Based on their analysis, the Moho appears to have an unusually steep dip (compared to other studies such as Richards-Dinger and Shearer (1997) and Zhu and Kanamori (2000) beneath the eastern Peninsular Ranges batholith. The results show that the estimated crustal thickness does not correspond to surface topography. Furthermore, the results are incompatible with the Airy compensation mechanism. Lewis et al. (2000, 2001) suggest that the thinning of the crust beneath the eastern Peninsular Ranges is a result of significant extension of the lower crust of the Eastern Peninsular Ranges that is related to the rifting of the Salton trough.

1.6.6 Fault Zone Trapped Waves

Li, et al. (1997) showed fault-zone guided waves recorded at the seismic arrays deployed above the Hot Springs cluster (Figure 11) in the San Jacinto fault zone (SJFZ) near Anza. Three linear arrays were deployed, two on the Casa Loma strand and one on the Hot Springs strand, observing microearthquakes occurring within the fault zone. The guided wavetrains characterized by relatively large amplitudes and long period following S-waves were observed only when both the stations and events were located within or close to the fault. The amplitude spectra of guided waves showed peaks at frequencies of 4 to 6 Hz, which decreased sharply with distance from the fault.

We further found that the significant fault-zone guided waves were only recorded at the seismic arrays across the Casa Loma fault (CLF), which is the southern strand of the SJFZ northwest of Anza, but not at the array deployed across the Hot Springs fault (HSF) that crosses the northern strand of the SJFZ. This suggests that a low-velocity waveguide exists on the southern fault strand but is absent at northern fault strand. The locations of events for which we observed fault-zone guided waves suggest that this waveguide extends about 30 km along the CLF between the towns of Hemet and Anza. The deepest event for which we observed fault-zone guided waves at the CLF, 18 km, which we interpret as the maximum extent of the waveguide. This is consistent with the floor of the seismogenic layer in this region. The data also show that the waveguide on the CLF dips northeastward at 75-80° while it becomes nearly vertical in the Anza slip gap.

In a follow-on project, we installed three 350-m-long 12-element seismic arrays in 1999, across the Coyote Creek fault (CCF), Clark Valley fault (CVF), and Buck Ridge fault (BRF) of the SJFZ southeast of Anza, California, to record microearthquakes (Li and Vernon, 2001). We observed fault-zone trapped waves (4-7 Hz) at stations located close to the fault trace for events occurring within the fault zone. From this we resolve the width of the waveguide to be 75-100 m on the BRF and CVF but only ~75 m on the CCF. The low-velocity waveguides on the BRF, CCF, and CVF are similar but narrower to the waveguide on the Casa Loma fault strand northwest of Anza (Li et al., 1997). Trapped waves also reveal that the waveguide on the BRF dips southwestward while the waveguide on the CVF dips northeastward. They merge into a single waveguide at seismogenic depths, running northward through Anza slip gap. The waveguide on the CCF in Coyote Ridge is nearly vertical. The precise earthquake locations provided by the ANZA network were essential for the interpretations in this study.

2. Reports and Dissemination of Information and Data

The complete waveform data set, which consists of over 58,180 events, is stored on-line on a RAID mass storage. This data is stored in the standard CSS 3.0 format complete with instrument responses and is accessible over the Internet. A data request is satisfied by placing the data in our anonymous FTP directory for retrieval via the Internet or by sending a tape copy. At present we provide data in the following formats: CSS 3.0, SAC, or SEED. The IRIS Data Management Center is maintaining a complete copy of our data archive (updated in real-time) and ANZA data is integrated into their standard FARM database and BUD real-time data distributions. Researchers from academia and industry have complete access to all ANZA data and results directly through UCSD or can access data through the SCEC Datacenter or the IRIS DMC.

We have a world-wide-web home-page for the ANZA network, http://eqinfo.ucsd.edu, which provides maps and information about our database, stations, hardware configurations, including all network metadata in dataless seed volumes. We make special event web pages for significant local, regional, and teleseismic events and maintain our *dbrecenteqs* webpages showing the latest seismicity on local, regional, and global scales as described in section 1.3.1.1 of this report.

Primary users of our data and results are the general public and San Diego based media through our www homepage, our education and outreach real-time seismic displays in IGPP, Scripps Institution of Oceanography Visualization Center, Mission Trails Regional Park Visitor Center, the Stephan Birch Aquarium at the Scripps Institution of Oceanography, San Diego State University, and soon at the San Diego Natural History Museum.

3. Related Efforts

Our main focus area of coordination is with TriNet. We are delivering all the ANZA network data in real-time so that the ANZA data can be combined with all the TriNet data to produce earthquake locations and magnitudes based on both datasets. To minimize confusion, TriNet will maintain a master catalog which they will submit to the composite earthquake catalog of the CISN and hence to ANSS. As new equipment becomes available, we will coordinate the locations of new station deployments to optimize the broadband coverage for southern California.

The ANZA network will continue to provide real-time data to San Diego State University for use in their educational program and media presentations.

The IRIS PASSCAL telemetry arrays have been designed and built at IGPP based on the ANZA system design. Deployments of the IRIS PASSCAL system include Wyoming, South Africa, Montana, San Jacinto Fault Zone, and Parkfield. Current IRIS sponsored telemetry testing by ANZA personnel include the successful integration of the new Quanterra Q330 and Reftek RT130 dataloggers into the ANZA/IRIS PASSCAL telemetry system. In December 2002, IRIS PASSCAL tasked IGPP to deploy a prototype USArray Transportable Array station collocated with the ANZA PFO station. This prototype station consists of a Streckeisen STS-2 seismometer, a Quanterra Q330 digitizer, with Spacenet satellite telemetry system. This system has worked flawlessly since its installation.

The design of the ANZA system has also been used for the Kyrgyz Broadband National Network (operating since1991) sponsored by IRIS, now operated by two institutes in Kyrgyzstan and sending data in real-time to the IRIS DMC. In turn, the ANZA project has directly benefited from these other projects by reincorporating the new developments back into the ANZA system.

The continuing operation of the ANZA Seismic Network is important to our Institute in several ways. Firstly, it provides a mechanism to have a real-time view of the local, regional, and teleseismic seismicity. This is important for our interactions with the San Diego news media when large earthquakes occur and in other situations where public information is needed. San Diego is the 6th largest city in the United States. Secondly, the network is important as an educational tool. Five PhDs at IGPP have been based on ANZA data as well as at least two more from other universities. At present, we have two graduate students who are using ANZA data in their research. More than fifteen undergraduate students have participated in data processing and data analysis over the years and several of those currently work in earthquake research or engineering.

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