Final Report

ANZA BROADBAND SEISMIC NETWORK

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Abstract

The ANZA Seismic Network (http://eqinfo.ucsd.edu) utilizes broadband and strong motion sensors with 24-bit Reftek dataloggers combined with real-time telemetry to monitor local and regional seismicity in southernmost California. The goal of this project is to provide on-scale digital recording of high-resolution three-component seismic data for earthquakes occurring in southern California, provide real-time data to the California Integrated Seismic Network (CISN), other regional networks, and the Advanced National Seismic System (ANSS), as well as to provide near real-time information and monitoring to the greater San Diego community. Twelve high dynamic range broadband and strong motion sensors adjacent to the San Jacinto Fault zone contribute data for earthquake source studies to the National Earthquake Reduction Program (NEHRP) and continue the monitoring of the seismic activity of the San Jacinto fault initiated 24 years ago.

To provide better coverage in the metropolitan San Diego area, we operate five stations in San Diego including one on Mt. Soledad (SOL) in La Jolla as well as CPE, FLV, HWB, MTRP in the urban and suburban parts of San Diego and an additional station on San Clemente Island (SCI2).

All waveform data are delivered in real-time via the Internet to SCSN, UC Santa Barbara, UC Berkeley, University of Nevada-Reno, IRIS Data Management Center (DMC), and the Indiana University PEPP network. The ANZA data are included in the SCSN real-time event association, location, magnitude and shakemap processing. ANZA waveform data are received at Caltech by the SCSN system within 5 to 10 seconds of real time. The SCSN catalog, which includes the ANZA network data, is the authoritative catalog for southern California and is contributed to the composite earthquake catalog of the ANSS. We have been generating dataless SEED volumes for the Anza network since the mid-1990s. The dataless seed is available from our website and is provided to the IRIS-DMC who also makes it available on-line.

The ANZA network monitors one of the most active seismotectonic regions in the U.S. with stations located in the near field of the San Jacinto fault that help record and locate tremors of a very small magnitude (M~0) which help not only map the fractured crust in this region but help in assessing the seismic hazard and potential for Southern California, in particular for the San Diego county area. During the period of this project 20,567 local, regional, and teleseismic events were recorded.

1. Overview of Project

1.1 Introduction

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 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 TriNet , we installed an ORB server on a computer at Caltech, wrote a software module to interface with the TriNet system, and used 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 in the SCSN real-time data processing system. In 2000, a full bi-directional real-time data exchange between ANZA and Trinet/SCSN was established using the ORB system. Real-time data exchanges between UCSD - UC Berkeley and UCSD - University of Nevada-Reno have been operational since late 1998.

The ANZA network enhances the broadband coverage provided by the SCSN 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 dedicated spread spectrum radio links for all communications between each station and the IGPP.

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 (Working Group, 1995). On October 31, 2001, a Mw = 5.1 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. On June 12, 2005 a Mw = 5.2 earthquake occurred on the San Jacinto fault about 7 km to the northwest of the 2001 event. The 2005 event and its myriad of aftershocks was recorded by all close-in stations of the Anza network which included strong motion sensors deployed since the 2001 event. This sequence has been fully located by analysts at IGPP and in combination with an additional ~90,000 events occurred in the region during the past 24 years and recorded by the ANZA seismic network, they 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 five stations in San Diego including one on Mt. Soledad (SOL) in La Jolla as well as CPE, FLV, HWB, MTRP in the urban and suburban parts of San Diego and an additional station on San Clemente Island (SCI2). These stations provide extended broadband and strong motion coverage to San Diego

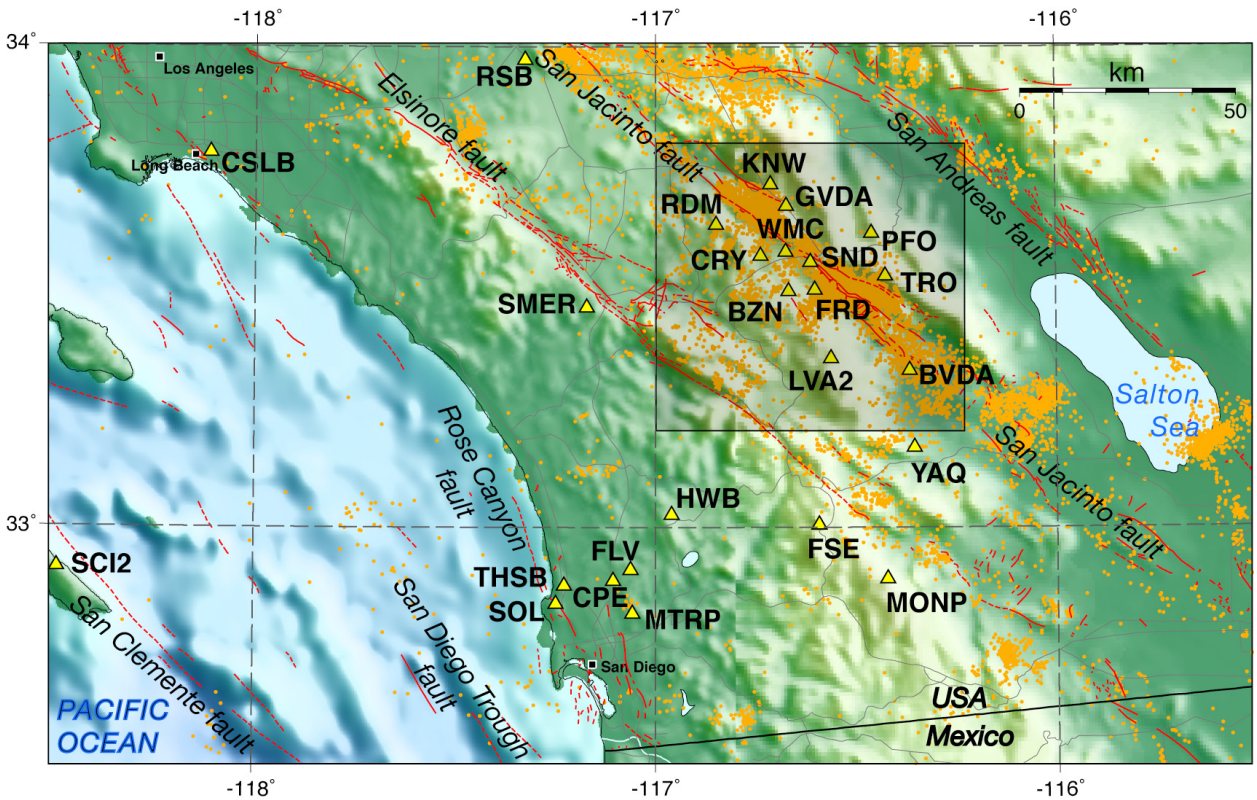

Figure 1. Topography and bathymetry of Southern California, with major roads (gray) and cities (white box) plotted. Fault lines in red and labeled. Seismicity comprising 17,780 events within 300 km recorded by ANZA from January 1st 2004 to December 21th 2006 are orange dots. The twenty-one real-time ANZA stations are yellow triangles.

County and the offshore region complementing the nearest SCSN stations. 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 data from these strong motion sensors are included into the ANZA real-time processing system and transmitted to SCSN in real-time. Borehole accelerometers have also been installed at UC Santa Barbara and UC Riverside as part of the UC CLC project, which telemeter real-time data to the ANZA network through Internet.

1.2 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. 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.

Smaller earthquakes along the San Jacinto fault zone have a strong tendency to occur in one of four clusters of activity. These clusters have in general been persistent seismic features of the entire eighteen-year operational period, but with systematic variations within clusters. The

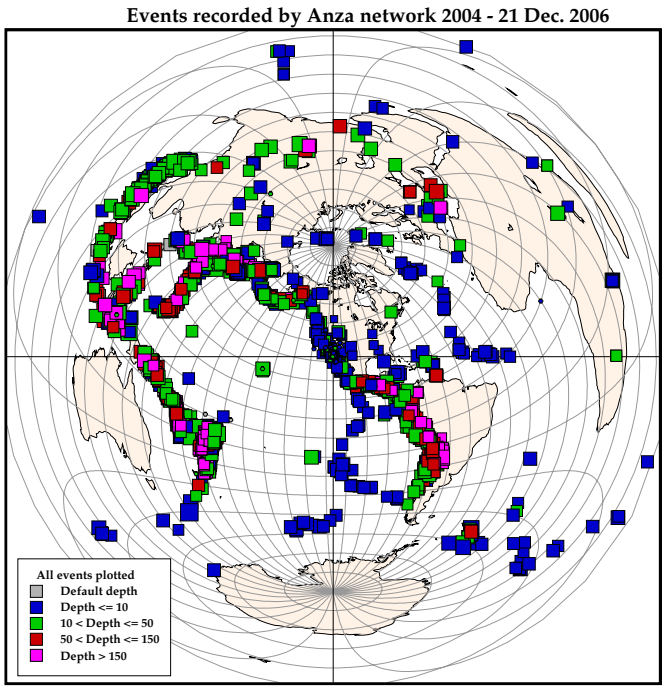

Figure 2. Global seismicity from January 1st 2004 to December 21th 2006 recorded by the ANZA seismic network. A total of 2787 teleseismic events are included in the ANZA catalog for this time period.

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 in depth. 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.

The evolution of the ANZA network instrumentation has greatly increased the quality of the data from regional (Figure 1) and teleseismic events (Figure 2). 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 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 3 for the 13 June 2005, M= 6.8, Moyobamba, Peru earthquake which occurred at a distance of 70˚. For comparison, an example of a local Ml = 4.3 is shown in Figure 4.

1.3 Network Instrumentation

1.3.1 Reftek Based Broadband and Strong Motion Stations

The Reftek component of the ANZA system (Figure 5) is designed for remote three-component digital seismic stations with sampling rates of 1, 40, and 100 samples per second for broadband components and 100 samples per second 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. At present, the data from twelve stations are transmitted via 900 MHz spread spectrum digital radio link to a relay station on the 2655-m summit of Toro Peak. The stations YAQ and MONP, provided by internal IGPP funding, were added to the ANZA network in 1997. 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

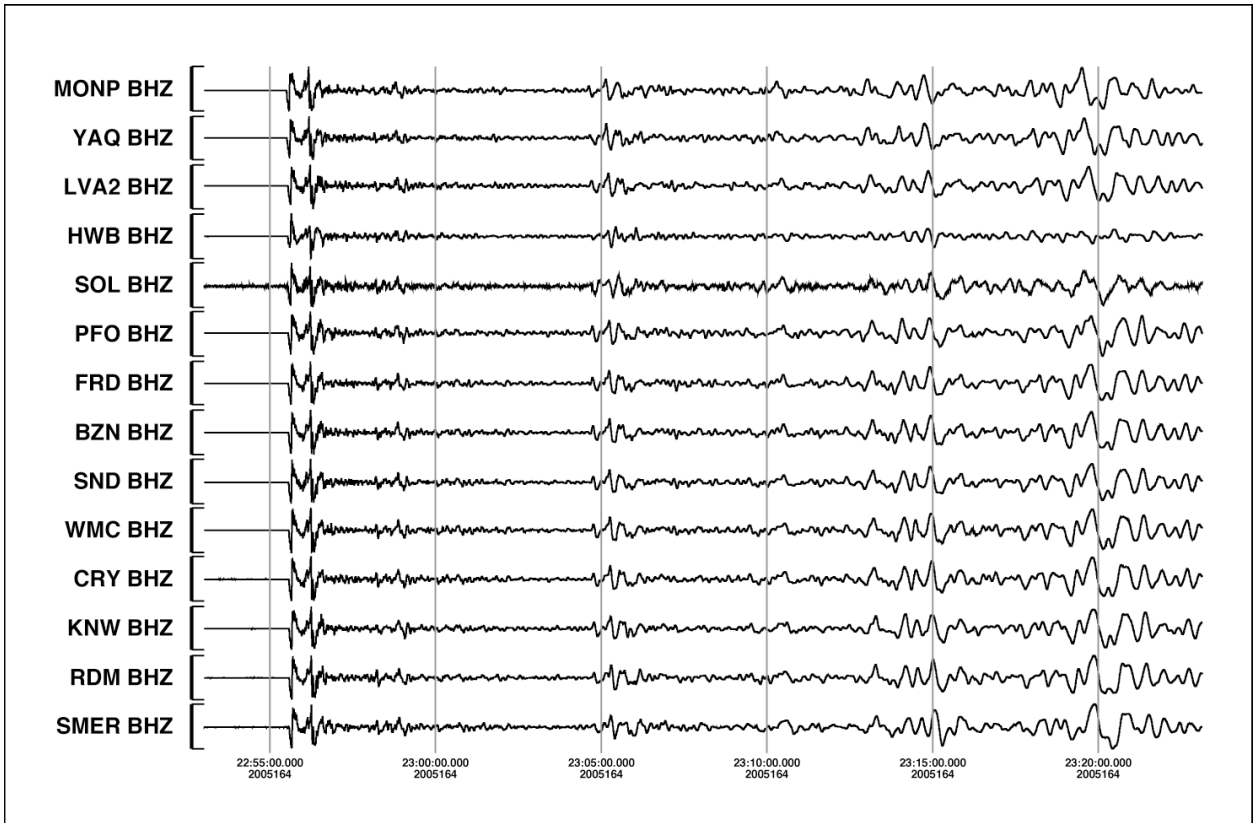

Figure 3. 13 June 2005, M= 6.8, Chile earthquake which occurred at a distance of 70˚.

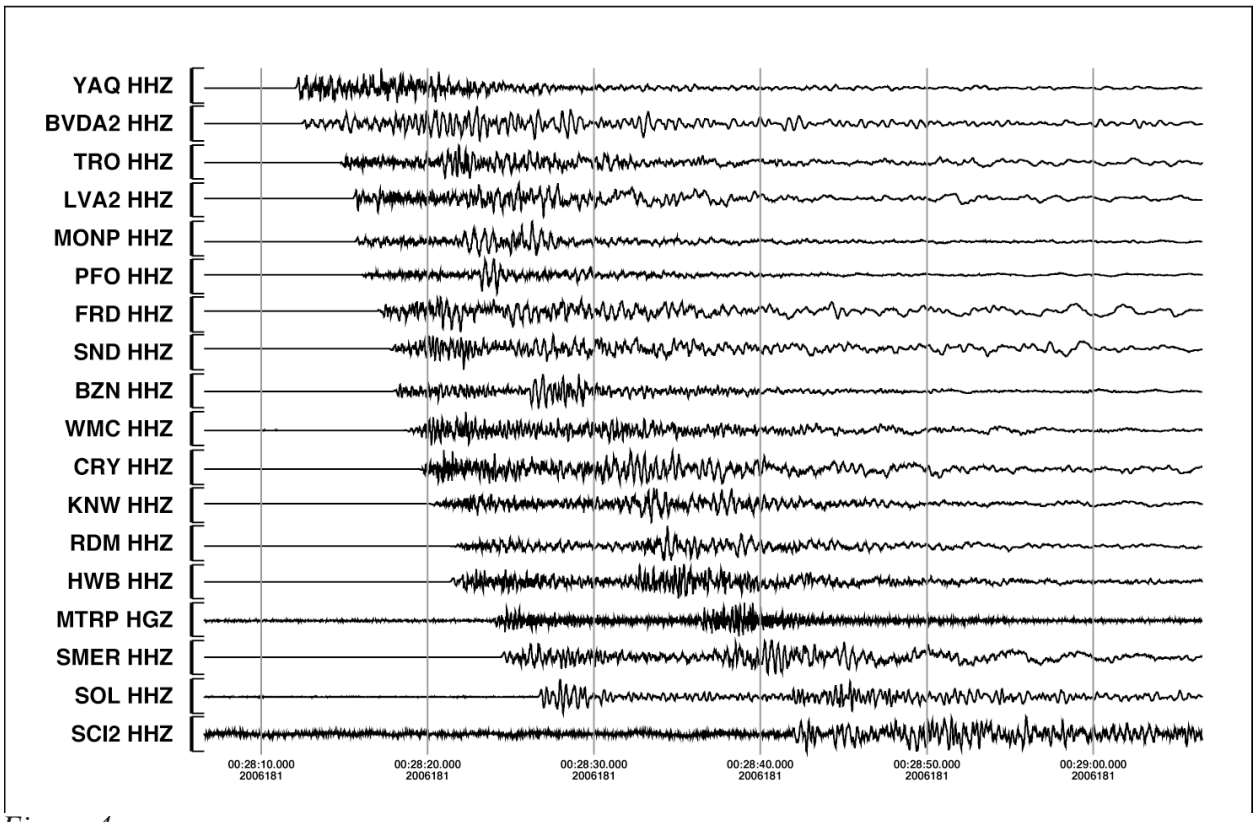

Figure 4

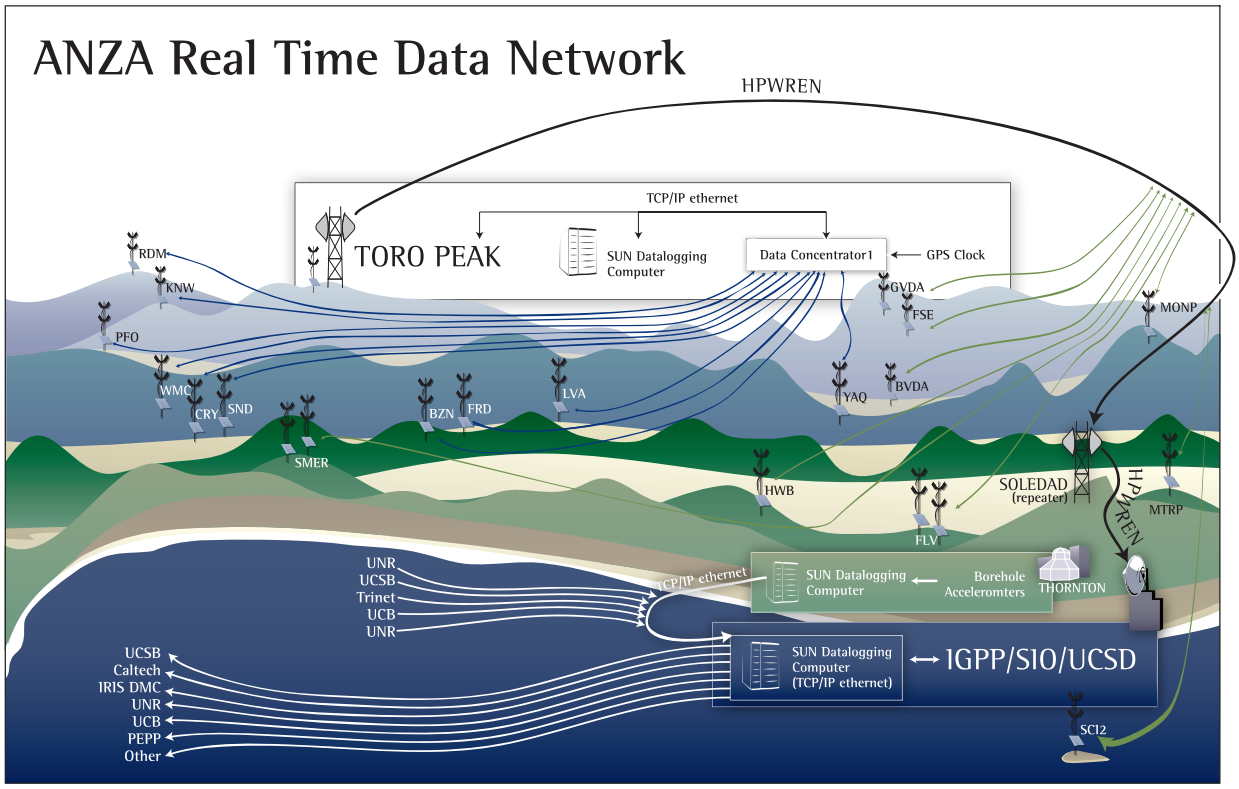

Figure 5. Data flow through the ANZA network. Data packets are sent from the stations to Toro Peak or HPWREN via spread spectrum radios. From Toro Peak the packets are retransmitted to IGPP through HPWREN. At IGPP the data packets are both processed locally in real-time and sent over the Internet to Caltech, UNR, UCB, IRIS DMC,and PEPP. Data are stored locally and at the IRIS DMC.

Education Network (HPWREN). HPWREN has created a wireless backbone network in southern California (see Institutional Qualifications section below) that currently includes nodes on the UC San Diego 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 5). 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 (Figure 5). 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. For each station IGPP receives the one-second data buffers by a Data Concentrator that forwards data packets to a local Sun computer. The Sun forwards data through HPWREN to IGPP using a standard TCP/IP protocols, and also provides several weeks of local backup data storage. The HPWREN microwave data link operating in the 5.8 GHz spread spectrum band. The current maximum bit rate for the HPWREN system is 45Mbps.

1.3.2 HPWREN and Quanterra Based Broadband and Strong Motion Stations

Leveraging the wireless Internet connectivity provided by HPWREN, 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.

1.3.3 Real-Time Processing

At IGPP, data are received by a SUN workstation (Figure 5) 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 October 31, 2001 (Mw=5.1) and June 12, 2005 (Mw=5.2) Anza aftershock sequences.

1.3.4 Data Review, Archive and Distribution

The routine processing and analysis of recorded seismicity occurs on a daily basis. 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. The hypocenters and magnitudes for all events are calculated. 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, which includes complete event segmented waveforms. All 40 and 1 sps data (BH, SH, LH) and event segmented 100 sps data (HH, HL, EH) data are sent directly to the IRIS Data Management Center (DMC) in Seattle, Washington for permanent archiving and data distribution.

2. Reports and Dissemination of Information and Data

The complete waveform data set, which consists of over 91,989events, 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. 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

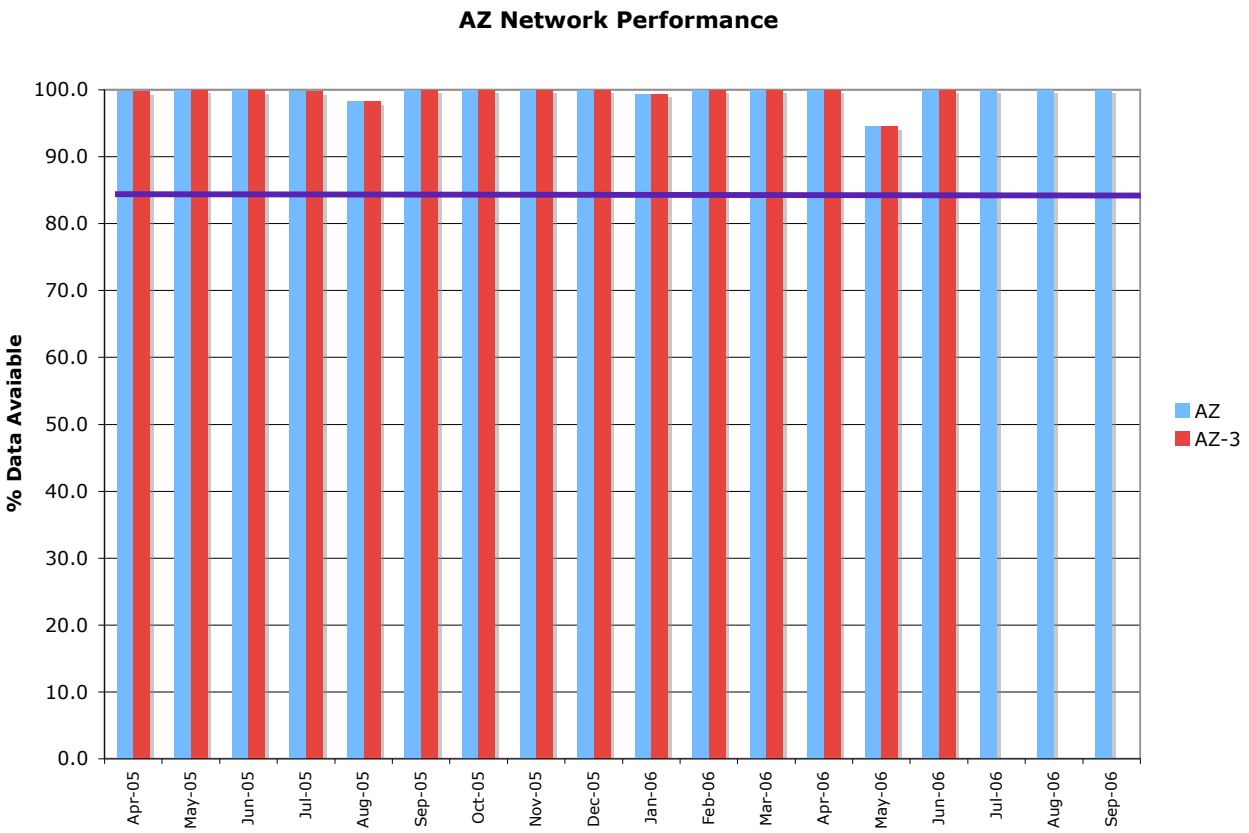

Figure 6. Monthly data availability at the IRIS DMC for the ANZA network from April 2005 to Sept 2006. Blue bars indicate the percentage of data received in real time at the DMC Red bars are data availability at the DMC Archive 3 months after real time. These metrics shown are made by the DMC monthly which are made available to network station operators. Note that data availability for the ANZA (AZ) network has been above the 85% data availability line shown in dark blue for real-time delivery of data.

daily basis This is an extremely reliable mechanism for archiving data at the DMC saving not only time for personnel at the DMC and UCSD, as well as shipping costs and tapes, but making data immediately available to the seismological community. Figure 6 shows data availability for the Anza network at the DMC in real time shown by the blue columns. The percentage of Anza data available 3 months later at the DMC is shown in red.

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.

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.

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

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2.1 Education and Outreach

One of the important aspects of the ANZA network operations is our interaction with policy makers, educators, students and the general public. The primary modes of communication include web pages that contain data and visualizations, teaching in classrooms, presentations to media, and site visits by policy makers. For the last ~4 years we have partnered with members from the SIO Visualization Center (http://siovizcenter.ucsd.edu) to incorporate our tabular data information (i.e., earthquake latitude longitiude depth, time magnitude) into 3-D interactive visualizations, movies and images ('Visual Objects'). These Visual Objects have been used extensively in a multitude of education and outreach venues (averaging >100 per year, for a complete listing see the News & Events listings at http://www.siovizcenter.ucsd.edu).

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

The Anza seismic network web pages have slowly shifted focus over the past 4 years. In addition to providing access to real time data from our deployed networks and stations, originally the pages occasionally duplicated general seismic hazard and earthquake engineering information found elsewhere on the internet (e.g., www.anss.org, www.cisn.org, www.scec.org, and www.iris.edu). However, based on continual analysis of our website statistics (since October 2002), we have refocused the website to provide easy access to our most popular resources - various tools that display and analyze our raw seismic data. Surprisingly (or perhaps not), the most popular pages have been those that display snapshot images of waveform data - both a one hour broadband display and a twenty four hour broadband display - and maps of recent earthquakes recorded by our active networks. A typical example of this are the statistics from May 2006: of the 17740 visits to the website that viewed 90908 pages (~5 pages per visit), 23310 of those pages (26%) were to view waveform data and 18122 (20%) were to view maps and data from recent earthquakes (see waveform and dbrecenteqs sections respectively below). This restructuring of our website has increased our web traffic from an average of 1800 visitors per month (93,591 hits per month) for 2002 to an average of 9389 visitors per month (728,071 hits per month) for 2006. This is over a 500% increase in visitors to the website. (Access to the online archive of our website statistics can be provided on an "as-needed" basis by emailing our webmaster Robert Newman at rlnewman@ucsd.edu.)

This increase in traffic has been a result of the development of new online tools, facilitated by the introduction of the Antelope Interface to PHP. PHP is a scripting language that can be embedded within webpage HTML code (PHP is a recursive acronym for "PHP: Hypertext Preprocessor", see http://www.php.net). A PHP extension to our real-time data acquisition software

(BRTT's Antelope package) has been under continual development over the past two years, and can now access, query, analyze and display server system information, ORB packets and data from Datascope databases (Antelopes relational database system).

2.1.1.1 Station status of active deployed networks [http://eqinfo.ucsd.edu/deployments/anza.php]

The status of active stations can be assessed by analyzing packets from the relevant network ORB combined with information from the network-station master database to determine (a) which stations should be actively acquiring data, (b) which of these stations are "up" (returning data) or "down" (no data return), and (c) the data latency and the last communication time of the station. This is extremely useful in determining network "health" in real time. In addition, meta-data for each station (whether up or down) can be displayed with information on the location of the station, site geology, sensor and datalogger model installed, communications provider, location maps, data return rates over the life of the station, relevant IRIS Power Density Function (PDF) plots for each channel over multiple time periods, and station photographs. Displays such as these help network engineers assess service requirements, analysts assess station state-of-health, and researchers assess data quality for experiments. The public also study these displays to gain an understanding of the flow of data from field instrument to storage archive.

2.1.1.2 Waveform Snapshots [http://eqinfo.ucsd.edu/tools/orbmon/orbmonrtd1hrHHZ.php]

Periodic snapshots of data flowing into the ORB from network stations is an extremely useful analysis tool. The station and channel selection, filter, image size, and image format are all completely customizable. These snapshots allow rapid assessment of station and channel data return rates and quality prior to the data being stored in a database. This has proved invaluable for analysts in noticing when a problem with a station and/or channel occurs, for example when a mass recenter is required or the instrument polarity is incorrect.

2.1.1.3 dbrecenteqs [http://eqinfo.ucsd.edu/dbrecenteqs/]

One of the founding principals of the original 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 and eXtensible Markup Language (XML) event files. 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 XML and HTML code and maps for a complete catalog of recently detected earthquakes. Anza group staff have been working closely with dbrecenteqs author Dr. Kent Lindquist to extend the capabilities of the application, in particular using functionality from the new Antelope Interface to PHP to tie map creation with online mapping tools such as Google Earth (http://maps.google.com).

2.1.1.4 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 6. After an event occurs, automated webpages are constructed that display the event location on

a global scale, event location relative to the Anza seismic network, initial event parameters, plus several views of 3-component 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. Translations into the following languages are provided by auto-querying the translation service provided by Google: Spanish, French, German, Italian, Portugese, Chinese, Korean and Japanese (e.g., http://eqinfo.ucsd.edu/special_events/2006/237/a/index.shtml for the Magnitude 6.4 near Salta, Argentina). 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 with keywords associated with the event. These pages are extremely popular, and often precipitate feedback to the Anza webmaster.

2.1.1.5 Database & waveform query tools

Data collected from active networks can be queried and the results downloaded through a web-based query tool (http://eqinfo.ucsd.edu/tools/eventquery/input.php). Entering a latitude and longitude range, start and end time, and magnitude range queries the Anza database, with the results returned as a database consisting of arrival, event, assoc and origin tables. This is currently being expanded to allow the results to also be returned in ASCII plain text and dataless SEED formats.

A waveform query tool that returns a waveform section based on a similar query (with the addition of station and channel names) is currently under development.

2.1.1.6 Other resources

Expansion of the Anza website has included more information about seismically active regions (e.g., http://eqinfo.ucsd.edu/special_events/oregon), building a glossary of geological terms (http://eqinfo.ucsd.edu/faq/glossary.php), storing question and answers from the public (http://eqinfo.ucsd.edu/faq/) and allowing more interactivity and online learning with activities such as online earthquake quizzes (http://eqinfo.ucsd.edu/faq/quiz.php), word-searches (http://eqinfo.ucsd.edu/education/wordsearch.php) and crosswords (http://eqinfo.ucsd.edu/education/crossword.php). We have also improved the 'Research' section of the website (http://eqinfo.ucsd.edu/research/), which now contains downloadable abstracts and journal articles.

2.1.2 Mission Trails Regional Park

One of the most unique new stations we have added 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 (MTRP) within the City of San Diego. They bought with their own money a strong motion station (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.

Attendance at the museum is roughly 60,000 per year and the Center is a popular field trip destination for K-12 school groups. The primary purpose of the display is to add an educational component on earthquakes and seismology to the content presented in the Center. This material

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. Several other less active faults fall within the city of San Diego or lie just offshore. Earthquakes large enough to be felt 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 fairly high in the area.

The 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. A 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 set up a data exchange with Mission Trails where 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 the best of our knowledge) the first case of a museum seismology display being used simultaneously as an active station in a real-time seismic network.

2.1.3 End-Product Visualizations: portable to high-end visualization systems & simple laptops

We require our Visual Objects to be portable to any platform (e.g., *Windows, Mac OS X, SGI, Linux*), and we provide a range of image resolutions so the file sizes are accessible to large centers such as the SIO Visualization Center (http://siovizcenter.ucsd.edu) and also to small-scale systems such as the Geowall (http://www.geowall.org), or a simple laptop. These products are distributed through the SIO Visualization Center's Visual Objects library (http://www.siovizcenter.ucsd.edu/library.php), and researchers and educators can obtain additional information through the links provided to the ANZA special events pages (i.e., http://eqinfo.ucsd.edu/special_events/index.html).

2.1.4 Seismic Data in the Classroom

ANZA data are currently used in classrooms ranging from the university and college level (e.g., UCSD, SIO, SDSU, Cal State Fullerton), high-schools (i.e., The Preuss School and High Tech High), grade schools (i.e., Lincoln Elementary School, Cardiff Elementary school). The data is also used extensively in formal and informal education workshops, such as the annual SIO Earthquake Education Workshop (http://siovizcenter.ucsd.edu/workshop/index.html). This workshop, now in it's forth year, hosts ~30 educators from the San Diego region, each of who has at least 30 students (i.e., annual audience of ~900). The ANZA data has also been used the last two years in the California State Summer School for Mathematics and Science (COSMOS) project (http://topex.ucsd.edu/cosmos/earthquakes/). In 2006, students in the COSMOS program students collected and used the ANZA data to create 3-D interactive visualizations, which are posted on the SIO Visualization Center's library for use by other formal and informal educators (http://www.siovizcenter.ucsd.edu/library/objects/index.php?category=Scenes).

2.2 Current Research and Results Based on ANZA Data

2.2.1 The Southern California Anza and Yucaipa Earthquakes of June, 2005 [Felzer & Kilb, work in progress 2006]

We examine two unusual events that followed the Mw 5.2 earthquake near the town of Anza, California, on June 12, 2005 (Figure 7). (1) Although the mainshock fault was only several kilometers long, aftershocks stretched for at least 50 km along the San Jacinto Fault zone; and (2) There was a MW 4.9 earthquake 4 days later and 72 km away, near the town of Yucaipa. We test the hypotheses that the extended Anza aftershocks were triggered by aseismic slip that followed the mainshock (Agnew and Wyatt, 2005) and that the close space-time proximity of the Anza and Yucaipa earthquakes was a coincidence. To test the aseismic slip triggering hypothesis we measure the density of the Anza aftershocks as a function of distance, r, from the mainshock fault. If a broad region of aseismic slip triggered these earthquakes we might expect a near constant density, whereas if the earthquakes are typical aftershocks we expect the density to decay as r-1.4 (Felzer and Brodsky, 2005). We observe the latter. Stochastic models of the Anza aftershock sequence based on normal aftershock production, local faulting geometry, and excellent local catalog completeness also look very similar to the observed sequence. This suggests that the apparently long spatial extent of the Anza sequence resulted merely from the dense Anza seismic network that provided the unique ability to catalog the rarely recorded very small aftershocks. To test whether the Anza mainshock triggered the Yucaipa earthquake we extrapolate local aftershock decay relationships in time and space to estimate the probability of the mainshock triggering a Mw 4.9 earthquake near Yucaipa after 4 days. We compare this to the probability of the Yucaipa earthquake occurring randomly. We find that there is a 21% chance that the Anza mainshock triggered the Yucaipa earthquake. We conclude that the extended Anza aftershock sequence is not out of the norm, and that there is a ~20% chance that the Anza mainshock triggered the Yucaipa event.

2.2.2 The 2001 and 2005 Anza Earthquakes: Aftershock Focal Mechanisms [Walker et al., work in progress 2006

Two M ~5 earthquakes occurred generally within the Anza seismic gap along the San Jacinto Fault zone during the last 4 years (M 5.1, October 31, 2001; M 5.2, June 12, 2005). The 2005 event occurred ~9 km southeast of the town of Anza, and the 2001 event was ~6 km farther southeast (Figure 7). These events have significantly different focal mechanisms, and it is unclear if they occurred on a northwest-striking fault parallel to the San Jacinto Fault or a conjugate northeast-striking fault. Both events were followed by productive aftershock sequences (Felzer, and Shearer et al., SCEC 2005). Significant post-seismic creep was recorded several days following the mainshock by strain meters near Anza (Agnew and Wyatt, SCEC 2005). In light of these observations, several questions arise regarding the focal mechanisms and spatial/temporal behavior of the mainshocks and associated aftershocks: (1) how similar are the two sequences; (2) does the data define a well-delineated fault system consistent with surface observations; and (3) is there a spatial/temporal evolution or clustering of the aftershock focal mechanisms? To investigate these questions we calculate focal mechanisms using polarity information from the SCEC catalog, relocate aftershocks using a waveform cross-correlation technique, and explore the data using 3D visualizations (Kilb et al., SCEC 2005). We use a clustering algorithm to identify similar focal mechanism types, and search for trends in the occurrences of these events as a function of space and time. The spatial distribution of the relocated aftershocks appear cloud like not aligning with

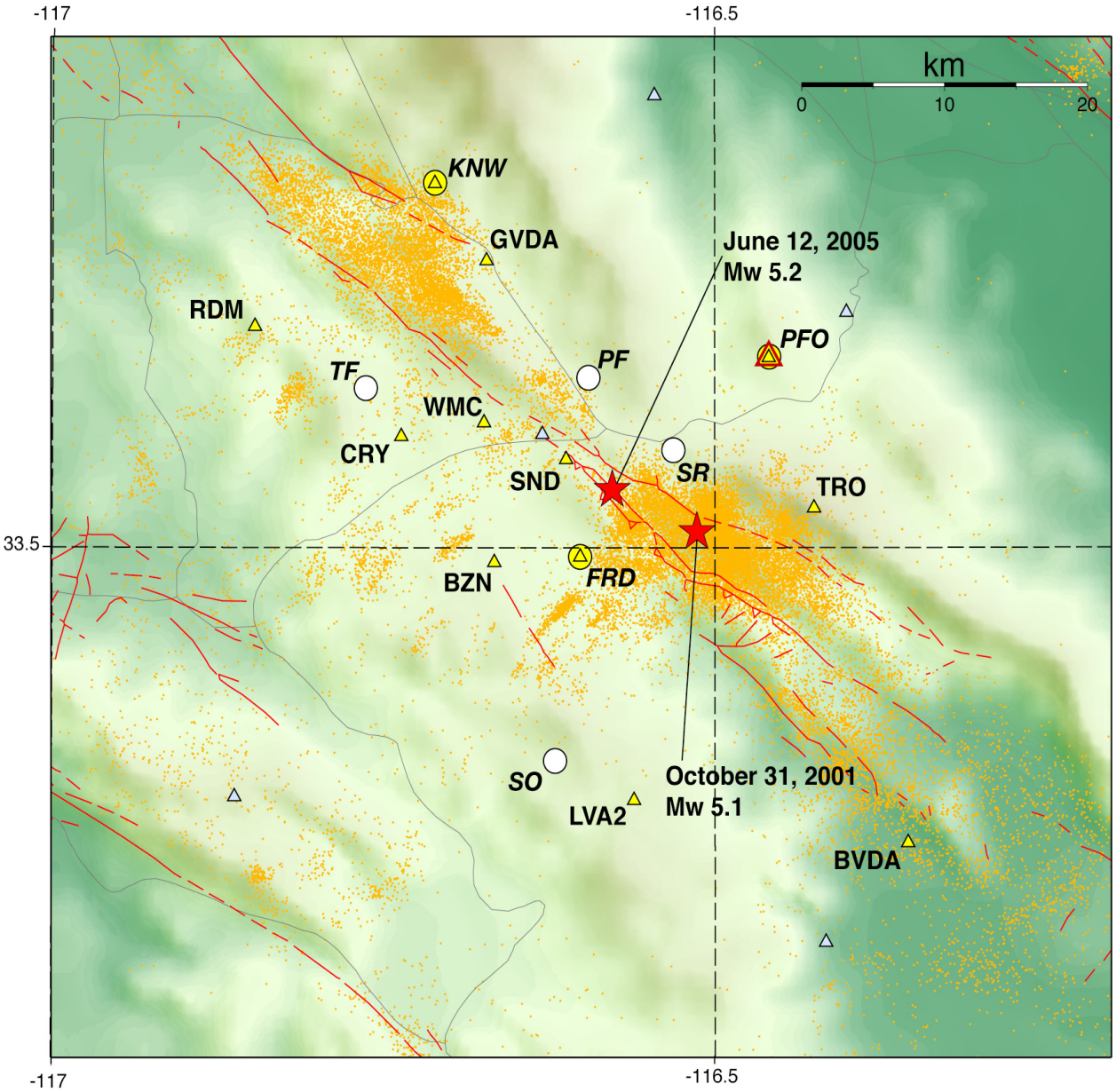

Figure 7. Map illustrating the distribution of four proposed Plate Boundary Observatory (PBO) borehole sites and co-located ANZA/PBO sites. The area of interest is enlarged from the shaded area of Figure 1 and is concentrated on the San Jacinto Fault Zone. Proposed PBO stations (large white circles and italicized station codes); TF - Trip Flats, PF - Path Finder, SO- Sky Oaks, SR - Santa Rosa. ANZA broadband stations are represented by yellow triangles. Co-located ANZA/PBO sites are represented by large yellow circles (behind the yellow triangle ANZA station symbol) with italicized station codes. Contributing stations from SCSN are pale blue triangles, contributing stations from NSMN are pale brown triangles. Seismicity from October 1st 2000 to September 30th 2005 are orange dots. One station (PFO) with a second red triangle border is also a contributing station to the Earthscope USArray project. Note how the proposed borehole sites complement the coverage already provided by current ANZA broadband stations.

a narrow fault core. Similarly, the aftershock focal mechanisms are heterogeneous, in that the 2001 and 2005 sequences are only comprised of 42% and 64% strike-slip events, respectively. These values are reduced to 25% and 46% when we consider only strike-slip mechanisms that are consistent with the strike of the San Jacinto Fault. In addition, there is a relatively large proportion of normal-faulting aftershocks in the 2001 sequence (18%) relative to the 2005 sequence (7%). These results suggest that both aftershock zones are highly fractured and heterogeneous volumes.

*2.2.3 Non-isotropic Scattering of S-Waves in th*e Crust around the San Jacinto f*aulting zone, Southern Califor*nia *[Martynov et al., work in progress 2006]*

We studied the energy distribution of seismic scattering based on the source factor results (SF in the single -backscattering model of Aki and Chouet, 1975, *JGR*) obtained from polarization -dependent *S*-coda amplitudes. We have tested our algorithm on band-passed (2 - 4 Hz) waveforms of a $M_L\}$= 5.1 local crustal earthquake (h = 18.7 km) recorded by the ANZA broadband network in southern California. We analyzed the records of 10 stations, of which 7 are < 20 km away. Over all stations *S*-coda waves with a polarization azimuth of 73° (clockwise from North) and vertical angle of 9° (positive values downward) have the maximum value of SF. We find the polarization direction of the maximum energy of backscattering *S*-waves is consistent with the orientation of a normal plane of the scattering patterns, strike 164° and dip 81°. This suggests the distribution of the scatterers is nonuniform. They are predominantly oriented S16°E and are responsible for the maximum value of the backscattering energy of *S*-waves in the crust beneath ANZA. This orientation is consistent with the axes of compression obtained from results of seismogenic deformation field in southern California. The scatterers (opened cracks?) are parallel the maximum compressional stress.

2.2.4 Examination of the Temporal Lag Between the 31 October 2001 Anza, California, ML 5.1 Mainshock and the First Aftershocks Recorded by the Anza Seismic Network [Kilb et al., in review BSSA 2006]

We study the temporal behavior of the initial part of the 31 October 2001 ML 5.1 aftershock sequence in southern California (Figure 7). This sequence occurred directly below the broadband ANZA seismic network, which recorded continuous waveform data at 13 azimuthally well-distributed stations about the study region (7 had epicentral distances < 20 km). Of the 608 aftershocks (0 < ML < ~2.8) in the initial 2-hours of this sequence, the initial 5 aftershocks were only identifiable at stations within 30 km. Using a cluster (radius~ 1.1km) of 200 representative aftershocks, we track the maximum seismogram amplitude versus earthquake magnitude. This relationship helps us quantify the visibility of aftershocks within the mainshock coda and assess our detection capabilities. We estimate detectable aftershocks within the mainshock coda include those: (1) over magnitude ~4 that are within 11 km of the network centroid that occur 15 seconds or more into the sequence; and (2) over magnitude ~2 that are within 30 km of the centroid of the network that occur 60 seconds or more into the sequence. There is a lack of large aftershocks in the ANZA 2001 sequence, as the 2.3 magnitude differential between the mainshock (ML=5.1) and largest aftershock (ML~2.8) is well above the expected ~1 value. We suggest the size of the magnitude differential is dictated by a combination of factors that include the mainshock energy release, directivity of rupture, complexity of the fault system, in addition to the elapsed time from the previous large earthquake in the region.

2.2.5 Quantifying The Remote Triggering Capabilities of Large Teleseismic Earthquakes Using Data From the ANZA Seismic Network Catalog (Southern California)

[Kane et al., in review JGR 2006]

Various studies have examined remote earthquake triggering in geothermal areas, but few studies have investigated triggering in non-geothermal areas. We search the ANZA (southern California) network catalog for evidence of remote triggering. Using three statistical tests (Binomial, Wilcoxon Rank-sum and Kolmogorov-Smirnov) we determine the significance of quantity and timing of earthquakes in southern California before and after large teleseismic events. To validate our statistical tests, we identify local mainshocks (M≥3.1) with obvious aftershock sequences and local mainshocks (M≥3.0) that lack an obvious aftershock sequence. Our statistical tests quantitatively confirm the triggering (non-triggering) nature of these local mainshocks, and from these we estimate thresholds required for triggering. Among local mainshocks, we find that triggering events generally reach higher spectral amplitudes than non-triggering events, particularly in the 0.5 to 10 Hz frequency band. Assuming that the same triggering mechanism (i.e., seismic wave amplitude and/or frequency) applies to both local and remote mainshocks, we apply the tests to 63 remote mainshocks (M≥7.0) and assess the ability of these events to trigger seismicity in southern California. We find no obvious signature of remote triggering. Comparing the spectral characteristics of local, regional, and remote mainshocks we reassess our threshold estimates. The results are complex, suggesting one or more of the following: (1) the threshold triggering level is a combination of amplitude, frequency and duration of shaking; (2) there is a time-to-failure component we have not accounted for; (3) the triggering mechanisms of remote and local events differ.

2.2.6 Spectral Stacking

We have studied the physics of the earthquake source using the data available from the Anza Network. Given the presence of large number of stations close to the very active San Jacinto Fault region we have been able to extract information about the earthquake source. Using the Empirical Green Functions (EGF) method and spectral stacking (Prieto, 2004; Shearer et al. , 2006) we have analyzed hundreds of spectra from the Anza network and thousands of spectra from Southern California (including the Anza network stations). From this analysis we have concluded that at least for the smaller earthquakes there is a large variability of estimated stress drops (0.2 to 30 MPa) with no clear dependence with earthquake magnitude.

2.2.7 Uncertainty of Earthquake Source Parameter

We have also analyzed the problem of uncertainties of the earthquake source spectrum using EGFs. In order to remove the effects of the propagation of the seismic waves through the earth, it is necessary to use a small earthquake as an approximate Green function, and deconvolve it from the earthquake that we are interested in. But doing this introduces uncertainties and the deconvolved spectrum has larger variability. Using data from the aftershock sequence of the M5.1 2001 Anza Earthquake, we study the errors associated with EGF methods and introduce a way to estimate confidence intervals of some source parameters and reduce the uncertainties.

2.2.8 The M5.1 2001 and M5.2 2005 Earthquakes.

The M 5.2 earthquake (June 12, 2005) in the Anza region was preceded by a M 5.1 event (October 31, 2001) about 7 km to the southeast (Figure 7). Both earthquakes occurred near 17 km depth in

the San Jacinto fault zone within the Anza seismic gap, and were followed by productive aftershock sequences. We apply empirical Greens function deconvolution to strong
motion records from the Anza network to resolve the mainshock P and S displacement pulses. Both earthquakes have shorter pulses to the north, suggesting northward rupture propagation. We relocate 22,056 earthquakes between 1984 and June 2005 in the Anza region using source-specific station terms and waveform cross-correlation. Aftershocks for the 2001 earthquake are very compact and form an approximately 2 km cluster just south of the mainshock. The 2005 aftershocks are more distributed but lie mostly within a wedge of seismicity extending about 6 km southeast of the mainshock. Our results suggest that both aftershock zones are highly fractured and heterogeneous volumes.

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