Project Description

Results from Prior NSF Support

Robert W. Clayton, has received support from NSF during the last 5 years, in the form of two equipment grants and support from the Southern California Earthquake Center (SCEC).


The equipment covered by this grant was purchased in early 1999, and has been on-line at the Southern California Earthquake Data Center (SCEDC) since mid-1999. The SCEDC has a nearly complete archive of continuous 20 sps seismograms recorded by TriNet since the Hector Mine Earthquake. Currently over 300 channels are archived. In addition, all earthquake information such as epicenter, phase picks and waveforms are archived for local events down to $M_l$ 2.0 and teleseismic and regional events down to $M_b$ 5.0.


To date we have purchased a ground penetrating radar unit and laptop computers for this class. The radar unit has been successfully used in one class to detect subsurface river channels, ash stratigraphy and faults.


SCEC, which is primarily funded by NSF, has supported the operational aspects of the SCEDC which includes the above described mass-storage system, as well as the Oracle database and user interfaces. These have been described at the last several AGU meetings including the last one. In addition, SCEC provided funds for the LARSE experiment which was conducted in the Fall of 1999, for constructing a unified velocity model for Southern California, and for simulating 3D wave motions in the basin structures of southern California. Data from the LARSE experiment was made available to the project participants in the Fall of 2000, and will be made available to all other scientists in the Fall of 2001. The P.I.’s work on these projects is presented in the papers:


Jeroen Ritsema is a Senior Research Fellow in the Seismological Laboratory and has conducted NSF funded research primarily under supervision of Professor Donald V. Helmberger (E\textit{A}\textit{R}-9896210 and E\textit{A}\textit{R}-9814908). He has worked on both seismological investigations of earthquake rupture processes, and, more recently, on tomographic imaging of the mantle. Five recent publications relevant to this proposal are listed below:


1 Introduction

The Executive Summary of the Rupturing Continental Lithosphere Science Plan (30 November, 2000) states that “The Rupturing Continental Lithosphere initiative must proceed by focussed investigations combining seismic reflection and refraction imaging . . . with passive seismic source experiments to image the crust and mantle of the rift and adjacent regions. Here, we propose to operate an 18-station passive-source seismic network, NARS-Baja, surrounding the Gulf of California (Figure 1). NARS-Baja data will be pivotal for studying earthquake faulting and the structure of the crust and mantle beneath western North America,
which are extremely beneficial to principal research objectives of the MARGINS program. NARS-Baja will be comprised of 18 broadband STS-II ground-motion sensors deployed around the Gulf of California. Three institutions take part in this major endeavor: California Institute of Technology, Pasadena, USA, CICESE, Ensenada, Mexico, and the University of Utrecht, The Netherlands. While NARS-Baja shares several characteristics with deployments operated under the umbrella of the PASSCAL (Program for the Array Seismic Studies of the Continental Lithosphere), we point out two distinct differences:

1. The University of Utrecht and CICESE own the instrumentation that will be used in NARS-Baja. They have made the commitment that their instrumentation will participate in NARS-Baja for at least 5 years. Therefore, we will be independent from PASSCAL for instrumentation needs, and there will be no constraints with regard to the duration of NARS-Baja.

2. NARS-Baja data will be available immediately to every interested research group. Several months after retrieval and inspection, we will archive the data. Both the IRIS Data Management Center in Seattle, Washington, and the SCEC Data Center at Caltech have expressed interest in archiving NARS-Baja data. These centers have extensive experience in data archiving and offer convenient mechanisms for data acquisition via the Internet.

NARS-Baja will be the first comprehensive broadband seismic deployment in the Gulf of California region and offers opportunities to address many outstanding research questions posed by the MARGINS program. NARS-Baja seismic stations will be well distributed around the Gulf of California to facilitate the study of seismicity and earthquake faulting processes in the entire region. NARS-Baja forms a quasi-linear array that points to earthquakes in southern Mexico and the Mendocino region in northern California. It enables a host of seismic arrays studies of crustal and upper mantle structure especially when combined with permanent stations in California.

Active Faulting in the Gulf of California region

With NARS-Baja we will be able to locate earthquakes as small as $M_w$ 2–3. Such earthquakes remain largely undetected by present-day seismic networks. By analyzing broadband waveform recordings, we can estimate source depth and focal mechanisms of earthquakes as small as $M_w$ 4, complementing global catalogs of earthquake faulting mechanisms (e.g., Harvard CMT catalog) which are limited to determining source mechanism of earthquakes larger than about $M_w$ 5. Seismicity maps and earthquake faulting parameters delineate active fault zone, they characterize the depth and sense of slip on active faults, characterize strain orientations, and, in general, and help to constrain the configuration of plate motions in the Gulf of California region.

Crust and mantle structure beneath the Gulf of California region

NARS-Baja fills a gap in instrumentation between present-day networks in California (networks operated by UC Berkeley, Caltech, and UC San Diego) and the UNAM network in southern Mexico. NARS-Baja combined with these networks represents an array that covers 3000 km of the western North America plate boundary. This is indeed the longest regional array in the world, offering a host of new research opportunities involving both forward and inverse modeling of seismic wave recordings. Maps of the Moho depth by receiver-function analysis and by analysis of short-period surface wave dispersion, maps of mantle anisotropy (i.e. mantle flow) through SKS splitting analysis, and models of the structure of the lithosphere
and asthenosphere beneath the Gulf of California region by seismic tomography can readily be produced with existing techniques.

We request funding from the MARGINS program that enables the installation of NARS-Baja network. This includes funding for shipment of the seismic equipment from Utrecht to Ensenada (via Caltech), funding for the construction of seismic stations in Mexico, and part-time salary support for Jeroen Ritsema to assist in the installation and preliminary data analysis at Caltech. A Dutch research grant, awarded to the University of Utrecht, guarantees that the NARS-Baja can operate for 5 years. Professor Rob Clayton serves as the Caltech principal investigator and will spend one summer-month each year to assist in the data processing. After NARS-Baja data acquisition is well underway, we will seek funding from the NSF and other agencies to conduct scientific research.

2 The NARS-Baja project

Since 1983, the University of Utrecht has operated the Network of Autonomously Recording Seismographs (NARS) comprised of 14 portable, three-component broadband seismographs in four different configurations (Figure 2). The NARS was initiated in 1982 [Nolet and Vlaar, 1982] as an antenna from Sweden to Spain directed towards the NW Pacific seismic belt. Since 1988, NARS has operated in Spain, The Netherlands, and in the western part of the New Independent States (Russia, Belarus and the Ukraine). NARS deployments have focussed on the study the upper mantle structure and regional seismicity and have led to more than

Figure 2: Configuration of previous NARS deployments: NARS-europe (black triangles), NARS-nl (white triangles), NARS-deep (black circles), and NARS-iliha (white circles).
100 professional research papers. NARS-Baja will be the first NARS deployment outside of Europe through an international collaboration. It will be the first deployment of state-of-the-art broadband instrumentation surrounding the Gulf of California.

NARS-Baja will consist of 18 broadband STS-II ground-motion sensors; 14 STS-II are owned by the University of Utrecht and 4 are owned by CICESE. Operation of the NARS-Baja network, and the analysis of NARS-Baja data will be a collaborative effort between the University of Utrecht, CICESE, and the California Institute of Technology. We have chosen 12 sites along the Baja-California peninsula and 6 sites in Sonora. Since we intend to operate the NARS-Baja network for at least 5 years, we need to take extreme care in building sites that offer reliable ground-motion recording. We will follow CICESE’s design of small stations to house the STS-II instruments and auxiliary electronic equipment (Figure 3). These stations

![Photograph of seismic stations](image1)

![Photograph of seismic stations](image2)

**Figure 3**: Photographs of the seismic stations HERB in Hermosillo and PUPE in Puerto Peñasco. These stations have been constructed by local companies. They have cement floors, brick walls, and doors that can be locked. The STS-II sensor, data logger (operated on a laptop computer), and car battery are kept inside a station, while the GPS clock and solar panels are placed on the roof. The construction of 4 future NARS-Baja stations is complete. The remaining stations will be constructed similarly, beginning in April of 2001.
protect the expensive equipment against severe weather (e.g., tropical storms) and vandalism, and they prevent wildlife to interfere with the STS-II sensor and other fragile equipment and to get injured by the batteries or cables. We hope to locate most of these stations on the property of local residents. We will offer the land-owners compensation for supervision of the stations and for checking that the instrumentation is functioning properly.

So far, the construction of four stations is complete. We have identified potentially useful sites for the remaining 14 stations and permission from the land-owners to install seismic instruments on their property. We will complete surveying sites in the next two months and prepare the construction of stations in April of 2001, and the installation of seismometers between October and December of 2001.

3 Research opportunities

It is widely acknowledged [e.g., Braile et al., 1995] that a passive-source seismic experiment is a required component of data acquisition programs aimed at resolving the crustal and mantle structures beneath a rift system. Indeed, the MARGINS Science Plan assigns high-priority to the funding of a passive-source seismic deployment in the Gulf of California region. The Gulf of California rift is particular ideal for a passive-source experiment because it is surrounded by land. Land-based stations can be operated at relatively little cost, while seismic studies of earthquake faulting and structure of the Gulf of California are well served by nearly perfect station distribution.

In this section, we summarize research projects and anticipated results on the basis of previous broadband regional deployments, which are directly beneficial to the scientific objectives of the MARGINS program, involving

1. locating and determining source parameters of moderate-size earthquakes,
2. determining the crustal and upper mantle velocity structure of the Gulf of California and surrounding regions.

We also expect that NARS-Baja data will boost seismological investigations of Earth’s core and deep mantle.

3.1 Seismicity and earthquake mechanisms of Gulf of California earthquakes

3.1.1 Location of small earthquakes

The systematic location of earthquakes provides a direct means to identify active faults in the Gulf of California region. On average, the NOAA/PDE catalog contains for each year epicentral information of six southern and central (22°N–28°N) Gulf of California earthquakes with a magnitude larger than 4.5. As shown by Figure 4, the seismicity rate in California and southern Mexico is similar. However, only 14 central and southern Gulf of California earthquakes larger than $M_w$ 3 are reported in this bulletin even though, based on empirical relationships, we should expect at least 60 earthquakes to occur each year. The
number of Gulf of California earthquakes smaller than \( M_w 4 \) in global catalogs is artificially low because small earthquakes are poorly recorded by distant (> 1000 km) seismic instruments.

Better earthquake locations are now obtained in the northern Gulf of California where CICESE is operating a network of short-period seismometers \([\text{Rebollar}, 2000]\) and in southern Baja-California where \( \text{Fletcher} \) and \( \text{Munguia} \) \([2001]\) operate an analog network of seismometers along the La Paz Fault. With NARS-Baja, we will be able to detect small earthquakes throughout the Gulf of California region, and, due to its proximity, locate them more accurately than is possible with global seismic stations. Based on our experience with the TriNet network in southern California \([\text{Kanamori et al.}, 1997]\), we anticipate that we will be able to record \( M_w 3 \) earthquakes well above the background ground-motion noise-level. These events can be located with a 15-km precision, while relative locations of earthquakes in the northern Gulf of California region, where the density of seismic stations is highest, can be estimated as accurate as a few kilometers through cluster analysis \([\text{e.g., Richards-Dinger} \) and \( \text{Shearer}, 2000]\).

### 3.1.2 Depth and source mechanisms of moderate-size earthquakes

The Harvard CMT catalog, spanning from 1977 to 1999, contains source-mechanisms of 73 earthquakes with \( M_w > 5 \) in the Gulf of California region (Figure 5). Using NARS-Baja, we will be able to constrain source mechanism for earthquakes as small as \( M_w 3.5 \), enabling us to increase the number of known source mechanisms by at least a factor of 3.

Various regional waveform inversion procedures have been developed to specifically determine source depth and source mechanisms for regional earthquakes to complement the global CMT catalog \([\text{e.g., Ritsema and Lay}, 1993; \text{Romanowicz et al.}, 1993; \text{Zhu and Helmberger}, 1996]\). One particularly robust source mechanism
inversion procedure has been developed by Zhu and Helmberger [1996]. In this procedure body waves and surface waves are simultaneously inverted (Figure 6). The procedure is routinely applied to earthquakes in southern California, recorded by the TriNet network, and can be easily adapted for application in the Gulf of California.

Focal mechanism solutions provide constraints on the sense of slip on active faults. Several hundred solutions likely yield regional patterns in the strain release and may help to better constrain the mode of deformation in the Gulf of California region. The maximum depth of earthquake faulting beneath mid-ocean ridges and transform faults in not well known. For the Gulf of California, source depth estimates will enable us to determine whether active faulting is present throughout the crust, or confined to the upper crust. Distribution of seismicity with depth provide constraints on the rheological properties of the crust.

\subsection*{3.2 Structure of the crust and upper mantle}

\subsubsection*{3.2.1 P wave coda}

Seismic waves that reflect off discontinuities in the crust and mantle arrive within several minutes after the main P arrival. These signals (also called P coda) provide excellent constraints on the depth of the Moho-discontinuity (the interface between the crust and the mantle) and discontinuities in the mantle.

Receiver-function analysis [e.g., Owens et al., 1984] is a popular technique to image seismic reflectors in the crust. As an example, we show an image of the crust beneath the LARSE-II array in southern California obtained by Zhu [2000] (Figure 7). This stack shows an westward dipping Moho at 30 km depth and an abrupt change of its depth beneath the Transverse Ranges, suggesting that the San Andreas Fault extends
Fig. 6: Recorded (solid lines) and computed seismograms (dashed lines) for the 28 June 1991 Sierra Madre aftershock. At 4 seismic stations, three-component waveform modeling of $P_{nl}$ and surface waves yields a source depth estimate of 8 km, a magnitude of $M_w$ 4.05, and a thrust faulting mechanism.

to at least the bottom of the crust. A similar technique has been applied to modeling the crustal structure beneath northern Baja-California where UC San Diego, San Diego State, and CICESE researchers operated an east-west oriented network of broadband instruments [Lewis et al., 2001]. This study indicates that the Moho beneath the Baja-coast of Gulf of California is at a depth of about 20 km and that it steeply dips to a depth of 35–40 km beneath the Sierra de Juarez mountains. With NARS-Baja data, one can constrain the Moho depth at each NARS-Baja station in Baja-California and Sonora with comparable vertical accuracy. Receiver function studies may in particular, reveal the nature of the crust (i.e. oceanic or continental) in the ‘transitional region’ between active spreading in the southern Gulf and continental extension in the north, which has only been constrained in the Salton Trough area [e.g., Fuis et al., 1984].

Studies of P-to-S converted phases are common to study the depth of seismic discontinuities at a depth of 410 km and 660 km [e.g., Vinnik et al., 1983; Gurrola and Minster, 1998]. These discontinuities are due to the olivine-to-spinel transition and the spinel-to-perovskite transition, respectively. Precise depth estimates of these discontinuities provide information of the thermal structure in the mantle transition zone since thermal anomalies in the mantle transition zone are reflected by perturbed depths of the 410-km and the 660-km discontinuities [e.g., Shen et al., 1998; Nyblade et al., 2000].

### 3.2.2 Surface wave dispersion and head waves

The dispersion of surface waves is sensitive to the structure of the crust and upper mantle. Well established techniques to measure surface wave dispersion include two-station phase velocity measurements [e.g., Dziewonski et al., 1969] and spectral analysis to estimate frequency-dependent surface wave group velocity [e.g., Levshin et al., 1983]. These techniques render group and phase velocity measurements as a function of wave frequency which can be inverted for shear velocity as a function of depth. These studies will particular benefit from the fact that the NARS-Baja network and stations in California are at similar azimuth from earthquakes in southern Mexico and earthquakes in the Mendocino region.
Figure 7: Amplitude of seismic reflections after Common Conversion Point stacking. The colored structures represent reflectors in the crust. Noteworthy is the offset of the Moho (at a depth of about 30 km) beneath the Transverse Ranges. Zhu [2000] infers from this observation that the San Andreas Fault extends to at least the lower crust.

$P_n$ waves (also known as head waves) propagate through the uppermost mantle and constrain the seismic velocity of the mantle directly beneath the Moho. The expansion of Californian network into Mexico via NARS-Baja will allow, for example, an extension of $P_n$ velocity maps derived by Hearn [1996] into the Gulf of California region.

### 3.2.3 Body-wave modeling

Forward modeling of body wave phases such as S, SS, and SSS allow us to constrain the lithospheric and upper mantle structure of the Gulf of California region. Some of the earliest indications that the upper mantle beneath the Gulf of California region is characterized by relatively low seismic velocities (i.e., anomalously high temperatures) have come from the modeling of travel times and waveforms of direct and surface reflected shear waves [e.g., Grand and Helmberger, 1984; Walck, 1984; Neele, 1996]. The recent expansion of broadband network in California has enabled more detailed analyses of upper mantle structure in the Gulf of California region. Melbourne and Helmberger [2000], for example, demonstrate that large (> 20 s) SS-S travel time anomalies and variable SS waveform complexity in seismic recordings from stations in California of earthquakes in the East Pacific Rise (Figure 8). These authors interpret these seismic data with a model in which the thickness of the lithosphere beneath California varies strongly.

NARS-Baja allows similar detailed analyses of the upper mantle structure further south. It will offer us particularly an opportunity to better constrain the transition of lithospheric structure between the western United States (characterized by continental extension) and the Gulf of California region (characterized by the beginning stages of sea-floor spreading).
3.2.4 Shear-wave splitting analysis

Shear wave splitting, typically measured using teleseismic SKS waves [e.g., Silver, 1996], is produced by preferred orientation of mantle materials and provides a direct proxy of flow in the upper mantle and, hence, provide constraints to test dynamical models of rifting.

3.2.5 Seismic tomography

Large-scale models of mantle structure [e.g., Su et al., 1994; Masters et al., 1996; Ritsema et al., 1999] indicate that the upper mantle beneath western North America is anomalous (Figure 9). Relatively low (up to 6% lower than the global average) shear velocity structures are resolved beneath the East Pacific Rise. The continuation of these structures into the upper mantle beneath western North America is remarkable because it suggest that high-temperature anomalies beneath the Gulf of California and the Basin-and-Range provinces of western North America is comparable to anomalies beneath the rapidly spreading East Pacific Rise. Global seismic tomography indicate further that the depth extent and magnitude of the low velocity structure beneath the Gulf of California and western North America is greater than beneath mid-ocean
Figure 9: Regional shear velocity model NA00 [Ritsema and Van Heijst, 2001] at depths of 50 km, 100 km and 150 km. The maximum shear velocity perturbation from PREM is given in brackets. Shear velocities in regions colored blue (red) are higher (lower) than in PREM. White lines represent plate boundaries.

ridges and hot spots such as Hawaii and Iceland.

With NARS-Baja data, tomographic models of western North America can be derived with much greater lateral resolution with regional tomographic inversion techniques [e.g., Van der Lee and Nolet, 1997; Vdovin et al., 1999; Ritsema and Van Heijst, 2001]. Tomographic inversion should focus both on the inversion of surface waves, teleseismic body wave travel times (following the inversion procedure [Aki et al., 1977]), and a combination of both data sets. Ensuing models will constrain much better the structure of the lithospheric and astenosphere in a regional context (i.e. from the East Pacific Rise into the western United States), and, possibly, illuminate the position of the Farallon slab.