Examination of Microseism Propagation in Sedimentary Basins

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Examination of Microseism Propagation in Sedimentary Basins

By Douglas Dreger[1] & Shawn Larsen[2]

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Executive Summary

The analysis of the dominant period and amplitude of microseisms has proven useful in determining site amplification characteristics and the seismic velocity structure of deep sedimentary basins. We have found that the period of maximum microseism excitation in the Santa Clara Valley (SCV) is strongly dependent upon basin depth. However efforts to model this behavior using standard 1D approaches have met with limited success (e.g. Dolenc and Dreger, 2005). The SCV has a lateral dimension that is comparable to its maximum depth and therefore 2D and 3D effects are expected to be strong. This is observed in teleseismic arrival delay times and P-wave amplitude as well as local-earthquake S-wave relative amplification. We show that the teleseismic observations correlate strongly with basin thickness and that there is a strong correlation in the maximum period of the horizontal to vertical (H/V) spectral ratio of the microseismic wavefield. Thus, these two complementary data sets have similar sensitivities to basin structure and it is therefore desirable to combine them in an inversion for basin structure. However, before such an inversion is possible it is necessary to investigate and understand the excitation of microseisms and their propagation characteristics. For example, is it possible to simulate microseisms in 3D structure? Is the source localized or is it spatially distributed? What is a suitable equivalent force representation? Can the simulated microseisms match the observed behavior in terms of shifts in the dominant period of the H/V spectra or in terms of a frequency-wavenumber (f-k) analysis? These are basic questions regarding the physics of microseisms that the proposed research will address through simulation. First spatially localized sources at individual periods will be explored. The model will then be expanded to include spatially distributed sources (located along the continental shelf), and also superimposed harmonic source time histories that include a wide range of periods that encompass the actual observed range. In each case simulations will be performed for both 1D and 3D seismic velocity structures so that the effect of structure can be evaluated. Various equivalent force representations such as CLVDs and single-forces will be used to simulate SV and SH polararized wavefields. Thus the proposed research seeks to better understand both the excitation and propagation of microseisms. Numerical simulations will be performed to evaluate the sensitivity of the synthetic microseisms to the various parameters, and the results will be compared to the observations. Although this project necessarily starts as a forward modeling experiment to better understand these phenomena, the results will lay the foundation for using microseism observations in inversions for 3D seismic velocity structure in sedimentary basins.

Technical Description

Introduction

In 1998 a temporary array of 41 short-period, three-component seismometers (USGS/UCB/IRIS Santa Clara Valley Seismic Experiment, SCVSE) were deployed in the Santa Clara Valley (SCV) for a 6 month period (Figure 1). These instruments recorded several local earthquakes including the Mw5 San Juan Bautista event. This array also recorded numerous teleseisms, and since it was set to continuously record motions it also collected a microseism data set. We have modeled these data to investigate the effects of 3D basin structure on the various wavefields. Stidham (1999) forward modeled seismic waveforms and peak ground velocity for the local earthquakesand two recent papers have investigated observations from the teleseismic wavefields (Dolenc et al., 2005) and microseisms (Dolenc and Dreger, 2005). Stidham et al. (1999) investigated the strong motion data set from the 1989 Loma Prieta earthquake. Fletcher et al. (2003) investigated wave propagation and site amplification in the SCV using the SCVSE data. These studies and others indicate that ground motion amplification in the basin is substantial on the order of 3-4 with respect to non-basin sites.

Stidham et al. (1999), Stidham (1999), and Dolenc et al. (2005) modeled seismic wave propagation using seismic velocity models for the region and the e3d finite-difference program developed by Dr. Larsen of LLNL. Two 3D seismic velocity models have been developed, namely the UCB model (Stidham et al., 1999) and the USGS version 2 model (Brocher et al., 1997; Jachens et al., 1997). These models perform reasonably well in terms of explaining the general basin amplification. However, it is clear from the modeling that additional refinement is necessary so that these models can be used to characterize ground motion hazard for future earthquakes in the region.

Nakamura (1989) was the first to estimate site amplification using the spectral ratio between the horizontal and vertical components (H/V ratio) of observed microseism records. The H/V technique is now most often used to study the response of shallow structures, mainly the response of soft soils. Some studies have also applied the H/V technique to deep basins (Yamanaka et al., 1994; Dravinski at al., 1996; Seht and Wohlenberg, 1999; Bodin and Horton, 1999; Bodin et al., 2001). Lermo and Chávez-García (1994) have shown that Nakamura's technique can be used to obtain a rough estimate of the amplification of seismic waves but only when the local geology is simple. Theoretical investigations (Lachet and Bard, 1994; Dravinski et al., 1996), on the other hand, have shown that the H/V method is very efficient for estimating the fundamental frequency of a sedimentary site, but that the H/V ratio is not adequate for estimating ground motion amplification in deep sedimentary basins.

We have applied the H/V technique to microseisms recorded in the SCV (Dolenc and Dreger, 2005), and have found that there is a strong spatial correlation of the dominant period with basin thickness. Stations over the deeper parts of the basin systematically have longer dominant periods. This is illustrated in map-view in Figure 2.

In Figure 3 the observations of teleseismic wavefields in the SCV show a clear correlation between parameters such as arrival delays, P-wave amplification, and P-waveform energy and the specified basin thickness in the USGS V2 seismic velocity model. (e.g. Dolenc et al., 2005). Positive correlation between the wavefield parameters and basin depth is found for basin depths in the range from 0 to 4 km. For basins deeper than 4 km the wavefield parameters are found to saturate. This saturation is likely due to the increase in seismic wave velocity with increasing pressure and temperature in the deepest parts of the basin such that the basin velocities are indistinguishable from the basement rocks (e.g. Dolenc et al., 2005). Correlation between the microseismic H/V dominant period and teleseismic arrival delay and basin thickness are also shown in Figure 3, and it is clear that the teleseismic and microseismic data sets strongly correlated with each other (Figure 3d), and with respect to basin thickness.

Forward modeling of these parameters using the 3D seismic velocity models is generally good (e.g. Dolenc et al., 2005; Dolenc and Dreger, 2005) However additional constraints on the 3D velocity structure can be obtained by inverting these data, which is the topic of David Dolenc's Ph.D. thesis. Before inverting the microseism observations for velocity structure we need to know how to simulate microseisms.

Scientific Motivation

The proposed work is motivated by the need to improve our understanding of 3D seismic velocity structure in the SCV so that a refined or calibrated structure may be used for ground motion simulations of scenario earthquakes. A longer-term goal is to be able to simultaneously invert a combined data set that includes local earthquake, teleseismic and microseismic wavefield parameters such as arrival times, amplitudes, waveforms, wave energy envelopes, and microseism dominant periods. Correlation of these wavefield parameters has been documented in Dolenc et al., (2005) and Dolenc and Dreger (2005) and presented in Figure 3. However, before parameters derived from observed microseisms may be used in such an inversion we must be able to simulate them sufficiently to describe their key behavior with respect to interactions with 3D structure. Thus the primary focus of the proposed project is to learn how to effectively model microseisms in terms of an equivalent force representation, source time and spectra description, spatial distribution (local vs spatially distributed), so that synthetic and observed microseism have the same characteristics. Although this work is focused on the SCV the tools that we will use and the expected results will be generally applicable.

The issue of localized vs. a spatially distributed source representation for the microseism is an important basic question that must be addressed. Schulte-Pelkum et al. (2004) applied an f-k method to the regional southern California broadband network and found that the microseism are directional in nature and that the source of excitation appears to be localized. In fact, they found the source of southern California microseisms varies from locations to the west of southern California to those to the northeast presumably from the Labrador coast. This fascinating observation indicates that it should be possible to utilize microseism observations to invert for 3D structure since if the source is localized it can be numerically modeled. In fact, even if the source has significant spatial extent it may still be possible to simulate the wavefield sufficiently to determine synthetic relative amplification, relative wave energy and dominant period.

Nature of Proposed Work

Before the microseism data may be inverted for structure in a 3d basin it is important to obtain insight into the behavior of such waves. To do this we will simulate microseismic wavefields and the response of the SCV by inputting SH and SV polarized sine waves at discrete periods to determine any period dependency in travelling and standing wave propagation and amplification phenomena. Simulations will be performed for a 1D model as well as the 3D models. A suite of simulations for sine-wave source functions over a range of periods will be performed to examine differences in the wavefield propagation in 3D structure as a function of source period. After this systematic analysis a wider source band will be considered in which the source time history is a superposition of sine waves at discrete periods in an attempt to model the observed dependence of microseism dominant period on basin depth. Finally, it will be possible to specify a source function that matches the microseism spectral properties inferred from the buoy data (e.g. Dolenc and Dreger, 2005) for specific time periods allowing direct comparison with data.

As pointed out by last year's proposal review panel the question of whether microseism can be effectively simulated as a point source (as previously proposed) or as a spatially distributed source fundamentally affects whether the microseismic wavefield may be used in an inverse sense. In the proposed study we will test both possibilities in which the later will be represented as a continuous distribution of point-sources located along the continental margin to the west of the SCV. The e3d finite-difference code we will use allows for this possibility.

In addition, we have been able to perform a preliminary microseism simulation and f-k analysis (Figure 4). The results of the f-k analysis are consistent with the findings of Schulte-Pelkum et al. (2004) in which the microseisms display strong directionality in their propagation and localization of the region of excitation or the source. At longer periods the observed and simulated microseism is found to be generated nearly due west of the SCVSE, while at short periods the pattern becomes chaotic due to forward and backscattering of energy by the basins. This preliminary work shows that the approach we are proposing is capable of obtaining results that will provide insight into the physics of microseism wavefield source excitation and wave propagation.

The following are the major tasks of the proposed study:

1) Single-period sine-wave excitation for idealized equivalent force representations such as single-force and CLVD to generate isotropic Rayleigh wave behavior since microseism wavefields display Rayleigh wave particle motions (Ewing et al., 1957; Haubrich and McCamy, 1969). For completeness SH sources also will be examined and compared to the Rayleigh wave results. It is expected in the severe 3D structure of the SCV that there will be significant Rayleigh-to-Love and Love-to-Rayleigh scattering. These simulations will be performed for several source depths for both localized and spatially distributed sources. A reference 1D simulation will also be performed for comparison.

2) Multi-period sine-wave excitation sources. These simulations also will be performed for several source depths for both localized and spatially distributed sources. The objective here is to see if the simulated microseism displays the same systematic lengthening of dominant period with increasing basin depth that is observed in the data.

3) Finally, buoy data from a specific period of time will be used to shape the microseism source spectrum. Using the results from steps (1) and (2) above the microseism will be simulated and compared with the observations. The simulations will be evaluated in terms of their ability to model relative amplification of basin sites to non-basin sites, relative wave energy, the variation in the dominant period, and in terms of being able to match the f-k characteristics of the observed microseismic wavefield.

4) The results will be reported in a final report submitted to IGPP. At least 1 peer-reviewed publication will result from the proposed research.

Project Personnel

The requested funding will allow David Dolenc, who is pursuing his Ph.D., to continue his work investigating seismic wave propagation in the Santa Clara Valley as a means to refine the 3D velocity structure for the region. His previous work was supported by the USGS and has resulted in two publications (Dolenc et al., 2005, Dolenc and Dreger, 2005). The first paper was a joint UCB-LLNL effort. The funding from that project has ended. The requested funding will allow the described pilot study on the sensitivity of microseisms to 3D velocity structure and will lead to the inversion work that we will approach the USGS or NSF for support.

We will work closely with Dr. Larsen at LLNL who developed the e3d finite-difference code. Dr. Larsen will provide technical and scientific support in utilizing his software to model the continuous excitation sources we will use to simulate the microseism. He will also provide assistance on using his codes on the LLNL super computers on which the PI has an active account. Dr. Larsen is a visiting research geophysicist at UCB. We have worked closely with him over the past several years and several of my students have benefited greatly from his expertise.

This work can lead to a new method for characterizing crustal velocity structure in complex 3D environments that is relevant to some of the objectives of the GNEM program. In addition, the use of microseisms for basin structure could be applicable to the LLNL effort to characterize ground motion amplification in the Las Vegas valley due to seismic sources located at NTS.

The bulk of the modeling work will be performed at the Berkeley Seismological Laboratory since the microseismic wavefields are relatively long-period. For high resolution runs the PI has an account on the LLNL computer system.

Figures

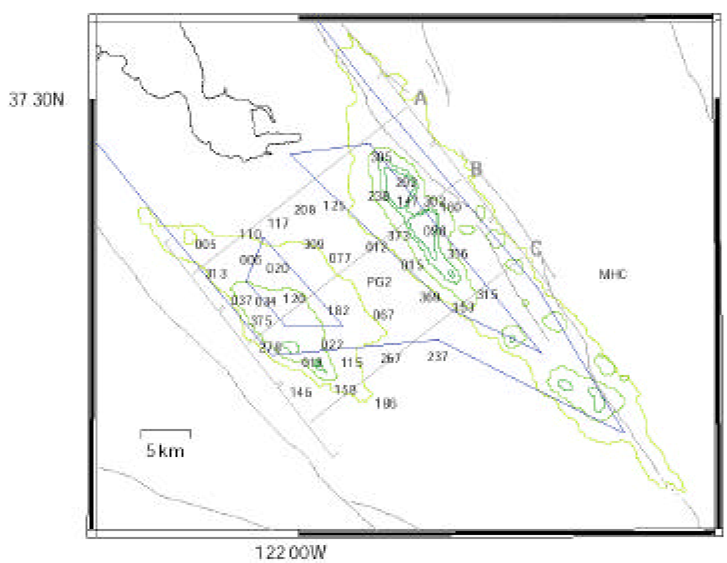

Figure 1. Map shows the locations of SCVSE seismic stations (numbers), the UCB model basin contours at the surface and at 1 km depth (blue), and the USGS velocity model basin depth contours at 1 km, 3 km, 5 km, and 6 km (green).

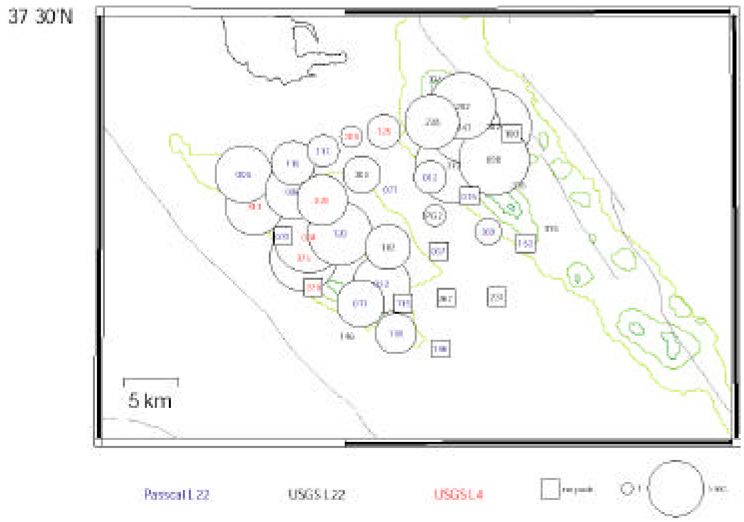

Figure 2. Map showing the H/V period of the maximum in the microseism band averaged over a 5-day period. The circles in the legend show the size representing dominant periods of 1 and 5 seconds, respectively.

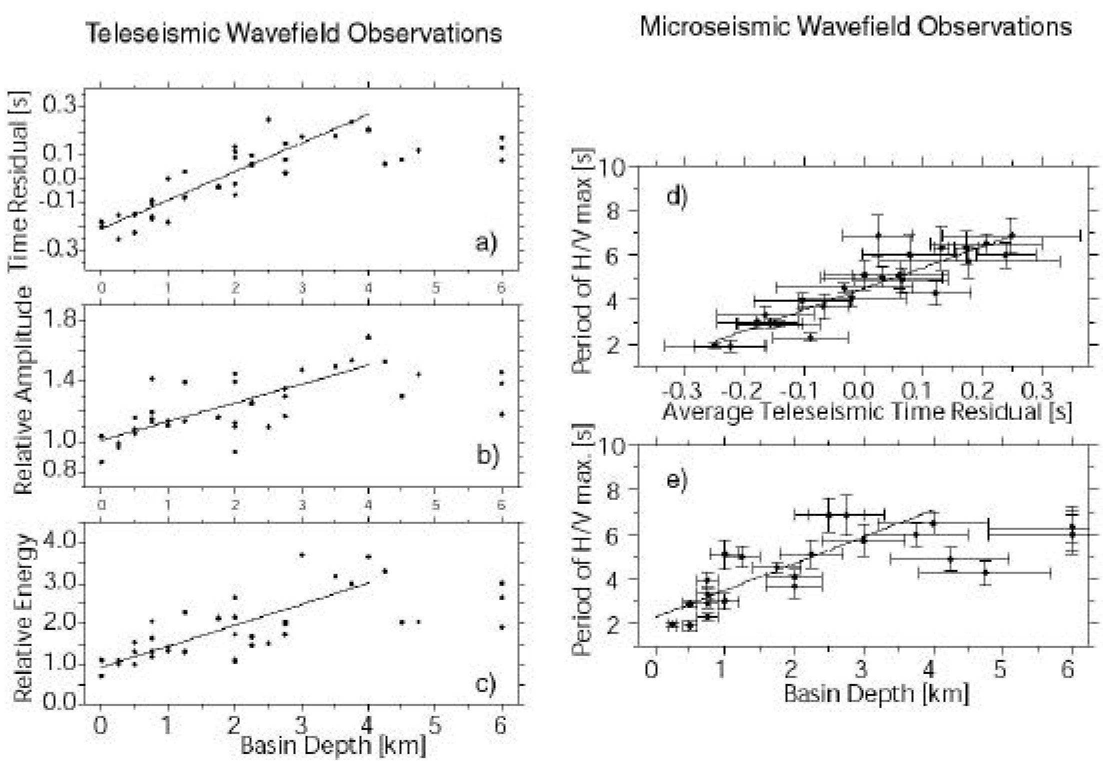

Figure 3. On the left the a) teleseismic P-wave arrival delay, (b) teleseismic P-wave relative amplitude, and (c) teleseismic relative P-wave energy all plotted against USGS basin depth. The arrival delays were determined by measuring times using waveform cross-correlation and then removing a plane-wave pattern to find the residuals. Negative residuals indicate early arrivals. The relative amplitude was found from the ratio of the amplitude of the primary P-wave with respect to an SCVSE site located outside the SCV basins. Relative energy was determined by

integrating the squared velocity over a two-minute interval and then computing the ratio with the same reference station used for the relative amplitude. On the right the top panel (d) shows the period of the maximum H/V ratio plotted as a function of the average teleseismic traveltime residual demonstrating a strong linear correlation between the two types of data. The bottom panel (e) shows the period of the maximum H/V ratio plotted as a function of the basin depth in the USGS velocity model. The period of the H/V ratio saturates for basin depths greater than about 4 km, as was observed for the teleseismic arrival time, amplitude and wave energy measures. It is evident that both the teleseismic and microseismic wavefields have similar sensitivity to the 3D velocity structure of the Santa Clara Valley.

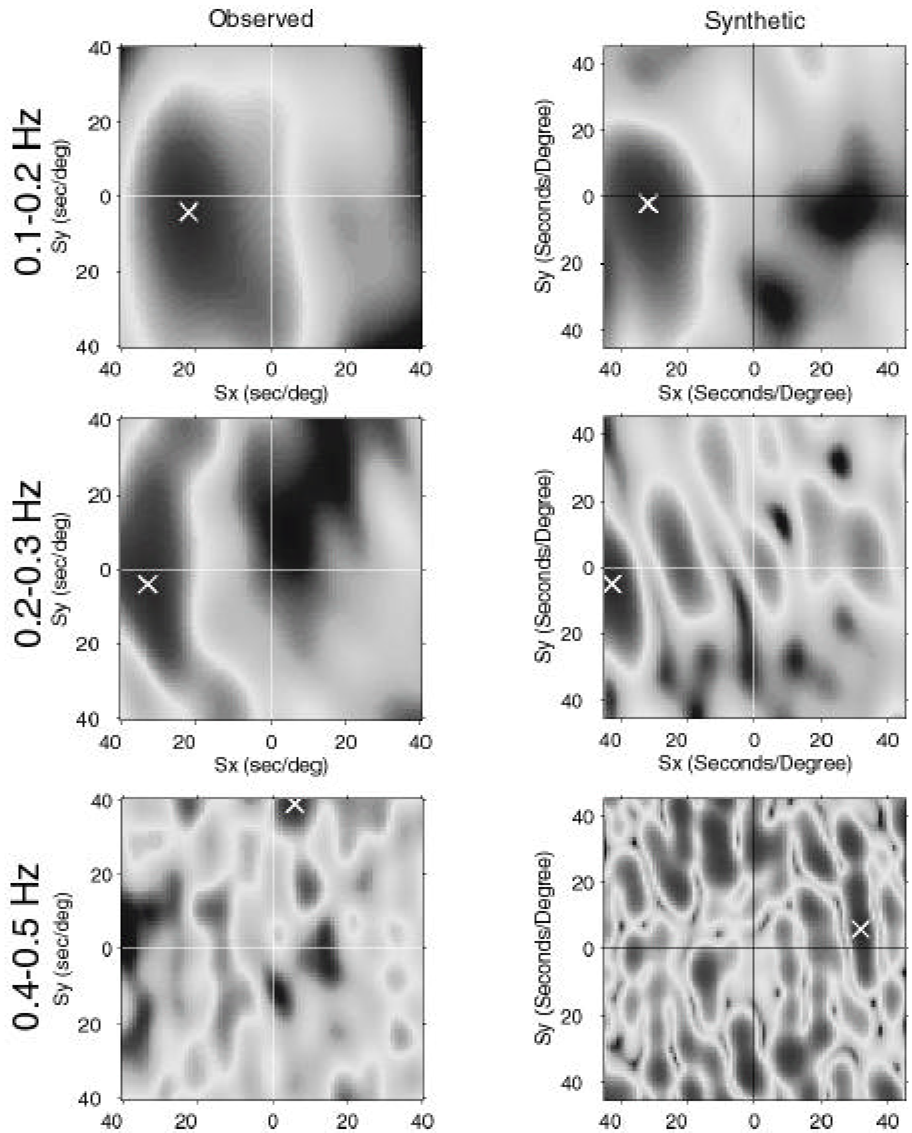

Figure 4 Observed and simulated microseisms in the f-k slowness domain. The white crosses show the location of maximum power. In each case the low frequencies show strong directionality and source localization, and high frequencies show less coherence which is due to forward and back-scattered waves. The simulated microseism is still very preliminary and the objective of the proposed project will investigate improved methods for simulation of the microseism.

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Senior Project Personnel Curriculum Vitae

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Seismological Consultant, Woodward-Clyde Consultants, Pasadena, 1990-1993
Staff Geophysicist, Aragon Geotechnical Consultants, Riverside, CA 1985-1987

Synergistic activities:
- Associate Editor, JGR, (2002-)
- IRIS GSN Standing Committee (1996-1999)
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Five Relevant Publications:
Dolenc, D., D. Dreger, and S. Larsen (2005). Basin structure influences on the propagation of teleseismic waves in the Santa Clara Valley, California, *in press Bull. Seism. Soc. Am.*

Dolenc, D. and D. Dreger (2005). Microseisms observations in the Santa Clara Valley, California, *in press Bull. Seism. Soc. Am.*

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Los Angeles Philanthropic Foundation Scholarship, 1979-1981

GENERAL RESEARCH INTERESTS:

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FIVE RELEVANT PUBLICATIONS:

Dolenc, D., D. Dreger, and S. Larsen (2005). Basin structure influences on the propagation of teleseismic waves in the Santa Clara Valley, California, *in press Bull. Seism. Soc. Am.*

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IGPP-LLNL Proposed Budget
October 1, 2005 – September 30, 2006

Project Title: Examination of Microseism Propagation in Sedimentary Basins

P.I.: Douglas Dreger

Description									UCB	LLNL	TOTAL
Salaries											
Grad. Student Researcher, step 4					(7.5 mos. FTE)						
Acad. Yr.: (10/05)	3,210 /mo.	@	50%	x	9	mos.	14,445				
Summer:	3,210 /mo.	@	100%	x	3	mos.	9,630				
								24,075			
Total Salaries									**$24,075**	**$0**	**$24,075**
Employee Benefits											
Grad. Student Researcher											
Acad. Year			17,655	x	1.61%			284			
Summer (2 mos.)			6,420	x	3.0%			193			
Grad. student health insurance and fee remissions							8,472				
* Non-resident tuition							4,041				
								12,513			
Total Employee Benefits									**12,990**	**0**	**12,990**
Travel											
AGU Meeting, San Francisco, Fall 2005 (for Grad. Student Researcher):											
Registration and Abstract Fees								210			
Per Diem:	5 days	@	$33	/day				165			
Ground Transportation								35			
									410	**0**	**410**
GRAND TOTAL REQUESTED									**$37,475**	**$0**	**$37,475**

* 75% reduction for advancement to candidacy

Salaries are based on current levels with projected annual increases as follows: range adjustment of 2% effective Oct. 1. Graduate student health insurance and fee & tuition remissions are based on current levels with projected increases of 10% effective each August.

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