Subsurface Characterization Beneath the Coso Geothermal Field by Ambient Noise and Coda Wave Interferometry

Proposal in response to

Request for Proposal: Seismic Interferometric Study

SOLICITATION NUMBER N68936-08-R-0034

Navy/DoE Contact: Peggy A. Richter, (760) 939-4272, peggy.richter@navy.mil

Lead Organization: University of Colorado at Boulder
Lead Principal Investigator: Prof. Michael H. Ritzwoller
University of Colorado, Department of Physics/CIEI, CB 390, Boulder, CO 80309
Tel: (303) 492-7075 Fax: (303) 492-7935: E-mail: ritzwoller@ciei.colorado.edu
Co-Principal Investigators: Prof. Craig H. Jones and Dr. Anatoli L. Levshin

Abstract:

The proposed research is to investigate the application of interferometic methods based on ambient seismic noise and earthquake coda waves to image the shallow shear velocity structure beneath the Coso Geothermal Area. The research will be principally observational, focused on characterizing the systematics of ambient noise and coda-waves and their correlation properties between pairs of sensors. These systematics include diurnal and seasonal variability as well as the frequency and geographical dependence of anthropogenic noise, microseismicity, other ambient noise, and coda waves. Data from the existing U.S. Navy GPO microseismic network will be processed and supplemented with data from a PASSCAL experiment in 1998-2000 (operated by co-PI, Jones) and regional broad-band instrumentation operated by CalTech. The supplementary data complement the GPO array by providing information at lower frequencies and tighter station spacings. In addition, data from the GPO temporary array, to be installed during by GPO personnel during the performance of the contract, will also be processed.

Work will progress in four phases: (Phase 1) noise characterization, (Phase 2) advice on siting the temporary array, (Phase 3) tomography, and (Phase 4) contingency. The purpose of Phase 1 is to determine whether ambient noise or coda-wave interferometry are feasible given the frequency content and sensor spacing of the existing GPO array. If so, advice will be given to GPO to optimize the temporary array for imaging and Phase 3 will be pursued. Rayleigh wave fundamental mode phase and group speeds will be measured and attempts will be made to measure Rayleigh wave overtones, which provide sensitivities to greater depths. If the PIs and GPO agree that ambient noise and coda wave interferometry fail to provide suitable information for subsurface imaging using the existing GPO array, then imaging based on a recently developed array method of regional earthquake surface wave tomography will be pursued as part of the Phase 4 contingency plan.

1. Introduction

The purpose of this proposal is to investigate the use of ambient noise and coda-wave interferometry to image shallow Vs structure beneath the Coso Geothermal Area (CGA). The operative word is "investigate" because there are several novel challenges that must be faced prior to application of interferometric methods as imaging tools. As described herein, our preliminary assessments indicate that taken together these challenges are formidable. It is, therefore, important, first, that the proposed research begin with a detailed empirical study of the phenomenology of "noise" near the CGA. Second, it is also prudent for the proposed research to define contingency plans that will take effect if ambient noise and coda wave interferometry fail to produce meaningful information for sub-structural imaging.

The challenges of which we speak are presented by (1) the frequency band of the seismic instruments in place or to be emplaced during the experiment, (2) the existence of exceptionally high levels of microseismicity within and near the CGA, (3) narrow band, presumably predominantly anthropogenic noise, and (4) instrumental irregularities that beset some of the data we would like to use. We will discuss each in turn here before summarizing past research and the work that we propose to perform.

1.1 Frequency band. The U.S. Navy GPO microseismic network consisting of Sercel L10s and L22s will provide little information at frequencies below 2 Hz. This presents two problems. First, a fundamental mode surface wave – which is typically the strongest signal that emerges from either ambient noise or code wave interferometry – typically senses to a depth of no more than about 1/3 of a wavelength. At 2 Hz this translates to a depth of about 400 m, at 4 Hz about 200 m, and so forth. This severely constrains the depth extent of information that can result from interferometric methods. Second, the omnidirectional ambient noise that is the basis for traditional ambient noise tomography is enriched in lower frequencies. We do not know without a careful study whether ambient noise at frequencies above 2-4 Hz is strong enough or well enough distributed in azimuth to be useful for imaging purposes. Nor do we know these properties of coda waves. Additionally, a 10 km station spacing corresponds to ~25 wavelengths for a 5 Hz wave. It is not clear if these waves will propagate coherently over this distance. To partially mitigate these problems we propose to augment the US Navy GPO microseismic network with data from other instruments that were operated or are operating on or near the CGA with either lower frequencies or tighter sensor spacings. In addition, we will investigate whether dispersion information from first and second (or higher) overtones can be obtained from the GPO network stations. Overtones sense deeper than fundamental modes at the same frequency.

1.2 Micro-seismicity. The effect on interferometric imaging presented by the extraordinary level of small earthquakes in the region is not known. **Figure 1a** shows a more or less typical day of data from the Cal Tech broad-band station SLA located ~20 km east of the CGA, with periods of relative quiescence and periods with bursts of noise that we hypothesize to be micro-earthquake activity. The spectra show that the micro-earthquakes manifest mainly at frequencies above 10 Hz, as seen in **Figure 1c**. Our

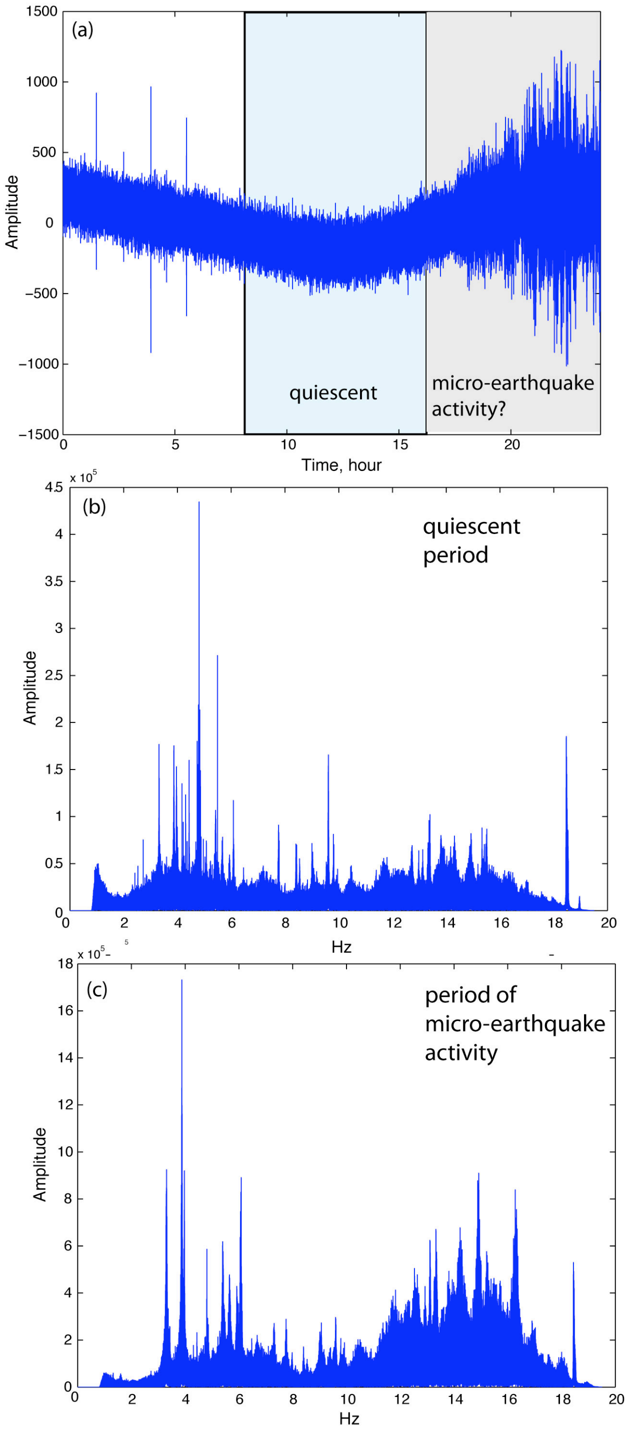

Figure 1. (a) One day of data from the Cal Tech broad-band station SLA located about 20 km east of the Coso Geothermal Area. Periods of relative quiet and activity are observed. (b) Amplitude spectrum between 1 and 20 Hz of the quiescent period. (c) Amplitude spectrum of the period of hypothesized micro-earthquake activity.

previous experience at lower frequencies is that small earthquakes are a degrading nuisance. The larger earthquakes that generate the lower frequencies are not well enough distributed in azimuth to be used as part of ambient noise, but their effect on the data needs to be removed in some way during data processing. Whether this will be true for the microseismicity near the CGA is not known. It would be simplistic to assert without a careful analysis that they are part of background noise and can be used for imaging purposes. Perhaps this is true and they are a feature of the area that will enhance the prospects for ambient noise tomography. We will investigate whether ambient noise methods will work best during time spans of intense microseismic activity or during periods of relative quiescence.

1.3 Human-made noise. Daily spectra observed at station SLA show near resonant peaks between 2 and 10 Hz presumably generated by human-caused activities, although perhaps it is possible that some are volcanic in origin. **Figure 1b** illustrates this. The systematics of this noise remain unknown to us and require study (e.g., daily, seasonal, weather related variations). It is also necessary to learn whether this nearly resonant noise is different in character near the CGA and away from it. We plan a systematic study of these resonances to determine their sources and if they can be effectively circumvented by sampling or other straightforward methods of analysis.

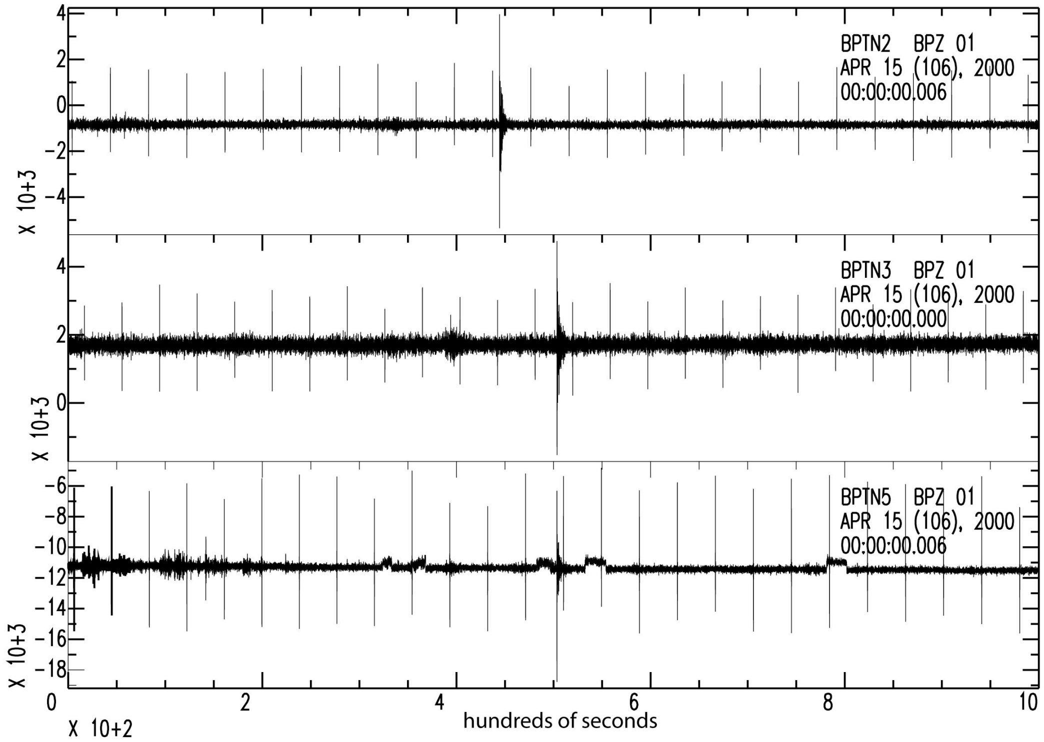

Figure 2. Examples of daily time-series from several stations of the PASSCAL experiment of 1998-2000. Data irregularities such as the glitches seen here need to be processed out prior to ambient noise and coda wave analyses.

1.4 Instrumental irregularities. The proposed studies will be based on analysis of seismograms recorded at the following past, existing or prospective seismic deployments:

(1) **GPO Existing Array:** 16 short-period three-component down-hole GPO seismometers, Sercel L10;
(2) **GPO Temporary Array:** 10-15 temporary, portable GPO instruments (Sercel L22) – to be deployed;
(3) **PASSCAL experiment in 1998-2000:** data are archived at CU and the IRIS-DMC (Mark Products (later Sercel) L-22);
(4) **Cal Tech permanent and temporary broadband networks:** data are archived at IRIS-DMC (STS-2).

The *Request for Proposal* called for analysis only of data types (1) and (2). Because of limitations imposed by the high frequency nature of these data, we propose to supplement analysis of these data with data types (3) and (4) which are, respectively, somewhat and much broader band. Data type (3) has some problems, however, including numerous regular glitches, as seen in **Figure 2**. The use of these data will require developing methods to remove the effects of these and potentially other irregularities. Locations of arrays (1), (3), and (4) are shown in **Figure 3.**

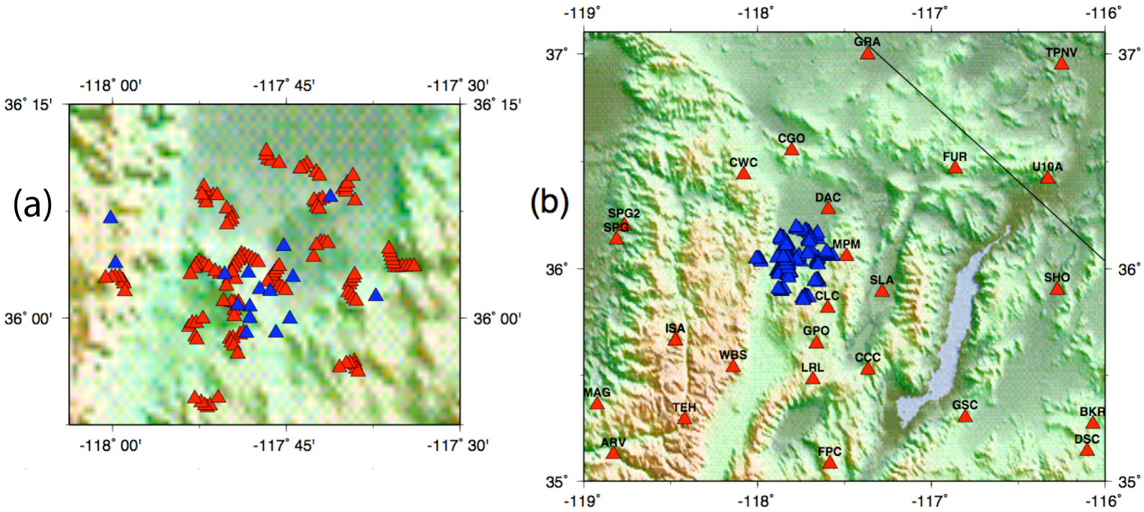

Figure 3. (a) Arrays on or near the Coso Geothermal Area. Blue triangles – Existing GPO array, data type (1). Red triangles – PASSCAL experiment in 1998-2000, data type (3). (b) Stations near the CGA. Red triangles – broad-band network operated by Cal Tech, data type (4). Blue triangles – stations on or near the CGA shown in (a).

1.5 Synopsis of the Proposed Research

The proposed research divides into four phases:

Phase 1. Noise characterization. Study and characterize the systematics of ambient noise and coda waves in and around the CGA. Systematics include frequency dependence as well as seasonal, diurnal, and geographic variability.

Phase 2. Site Temporary Array. Based on the result of the noise characterization, consult and advise GPO on the location, dimension, and geometry of the temporary array. Alternatives include deployment for further noise characterization or for tomography.

Phase 3. Tomography. If results of the noise characterization are positive for the existence of useful signals in one or more of the data types, obtain dispersion measurements for fundamental (and potentially overtone) Rayleigh waves. Invert for Vs structure consistent with the data set.

Phase 4. Contingency. If the PIs and GPO agree that both ambient noise and coda wave interferometry fail to provide suitable information for tomography, other surface wave imaging will be explored. This may include imaging in which human-made noise is used as a source or in which regional earthquakes are utilized in two-plane wave tomography.

Either Phase 3 or Phase 4 will be performed, but not both. GPO will be consulted after Phases 1 and 2 are completed to determine which phase to pursue. In the Work Statement below, each research phase will compose a single task. The final Phase/Task will be delivering a final report to GPO.

1.6 Key Personnel

The “**Research Team**” is composed of the following four seismologists at CU-Boulder.

Prof. Mike Ritzwoller (PI): Prof. Ritzwoller is a theoretical and observational seismologist whose principal interest is to develop and apply methods that use surface waves to image the earth’s interior from the shallow subsurface to the deep upper mantle. His group at CU-Boulder first developed the method of ambient noise tomography and he and his students have applied it successfully under various conditions around the world. He has been PI of numerous applied contracts from DoD, DoE, DTRA, and DSWA as well as basic research grants from NSF. He is the author of more than 100 professional papers and is a Fellow of the American Geophysical Union. His publications can be found at http://ciei.colorado.edu/ritizwoller_m

Prof. Craig Jones (co-PI): Prof. Jones has worked on tectonic issues in and near the Coso region for more than 20 years. A seismological experiment within the China Lake Naval Weapons Center imaged geothermal and magmatic systems using arrays of seismometers (Wilson et al., 2003) as described in section 2.1 below. He has conducted field geophysical surveys in nearby Panamint Valley (MIT 1985 Field Geophysics and Biehler, 1997) and has led several seismological field studies of the Sierra Nevada and environs (Jones et al., 1994; Jones and Phinney, 1998; Boyd et al., 2004, Gilbert et al., 2007). He has also integrated geological and geophysical observations of the Sierra and Basin and Range in order to understand their origin (Jones, 1987; Jones et al., 1996, 1998; Sonder and Jones, 1999; Jones et al., 2004).

Dr. Anatoli Levshin (co-PI): Dr. Levshin has worked in the field of seismic prospecting and earthquake seismology for more than 50 years. In the 1950s and early 1960s he took part in refraction and reflection seismic prospecting in a wide variety of regions of the former Soviet Union. The results he obtained served as the basis for his PhD thesis on seismic wave propagation in young sediments. He then joined the Department of Computational Geophysics of the Institute of Physics of the Earth of the Soviet Academy of Science, where he developed new approaches in the theory and interpretation of seismic surface waves. His FTAN method remains a staple of modern surface wave analysis. He has authored numerous papers and several books on seismic waves. In 1992, he joined Prof. Ritzwoller's group at the Department of Physics, CU-Boulder, where he participated in the development of new methodologies of processing and interpreting seismological data for studying the structure of the Earth's crust and upper mantle on global, regional and local scales, as well as monitoring underground nuclear explosions. He is a Fellow of the American Geophysical Union.

Dr. Michael Barmin (Research Associate, Scientific Programmer): Dr. Barmin has 30 years of experience in data analysis and the development and application of mathematical methods in geophysical computation. As a scientific researcher and the chief of the software division of the Obninsk branch of the Institute of Physics of the Earth, Russian Academy of Sciences, he participated in developing techniques for seismological data management and analysis in the framework of Joint Soviet-American Test Band Treaty Experiment in 1989-1993, as well as for the Geological Survey of Russia. He joined Prof. Ritzwoller's group at the Center for Imaging the Earth's Interior, CU-B, in 1998 as a leading scientific programmer in the field of body and surface tomography. His extensive experience in the software development for data analysis is applied to developing new techniques for surface wave analysis of earthquake records and ambient noise as well as the 3D-modeling of seismic waves.

2. Past Work

We describe here aspects of past work relevant to the proposed research. The Research Team (PI – Ritzwoller, co-PI – Jones, co-PI -– Levshin, Research Associate – Barmin) possesses experience working at the Coso Geothermal Area, knowledge of western US geology and tectonics, and also a wealth of expertise in surface wave data processing, analysis and inversion. Surface wave expertise includes pioneering ambient noise tomography at frequencies from 0.2 – 0.01 Hz and passive and active source surface wave tomography from 0.005 – 10 Hz. The description here is necessarily brief, but Ritzwoller's papers can be found at http://ciei.colorado.edu/ritzwoller and Jones' papers can be found at http://cires.colorado.edu/people/jones.craig/CHJ_cv.html .

2.1 Previous studies of the Coso Geothermal Area

The Coso Geothermal Area (GTA) has been the subject of numerous geophysical studies over the past 30 years. Various seismological techniques have been applied to evaluate the regional stress distribution, velocity and attenuation structure of the subsurface (e.g., Young & Ward, 1980;_ Feng and Lees, 1998; Bhattacharyya et al., 1999, 2002; Hough et al., 1999; Wu & Lees, 1996, 1999). Passive seismic experiments provided travel time information from local, regional and teleseismic events which were used for 3D seismic tomography, receiver function studies, evaluation of shear-wave splitting, crustal anisotropy, etc. (e.g., Walck et al., 1987; Walck, 1988; Feng & Lees, 1998; Lees & Wu, 1999, 2000; Lees, 2001; Wilson et al., 2003). Active reflection prospecting resulted in several P-wave velocity cross-sections to a depth of about 5 km and outlined several shallow faults (Pullammanappalil et al., 2001). None of these studies imaged subsurface shear velocity structure using surface waves generated either by the local micro-earthquakes, regional or teleseismic earthquakes. In addition, none used interferometric methods based on ambient noise or coda waves. For this reason, we do not discuss the previous work done by other groups further, although it does provide the scientific context for the interpretation of shear velocity models that may result from the proposed research.

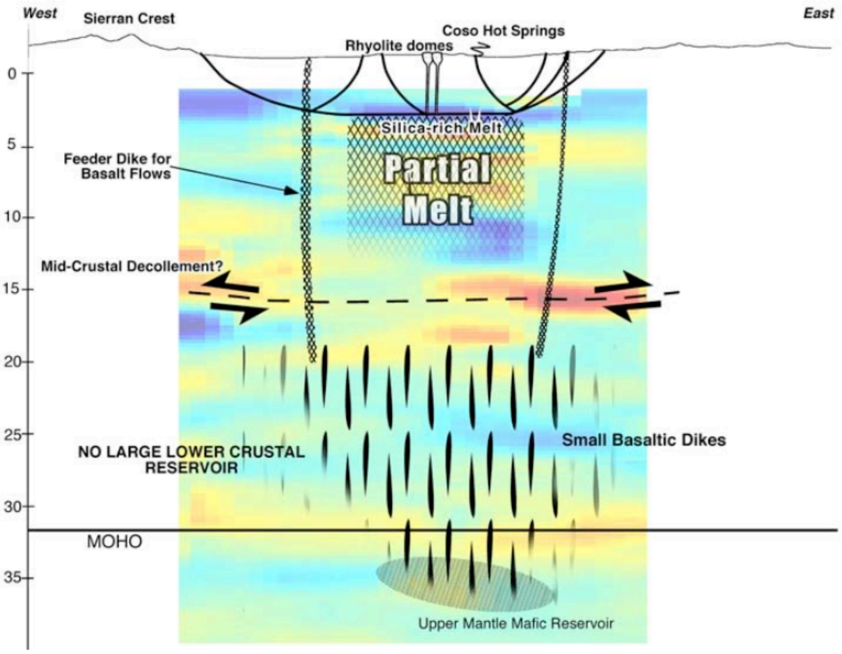

Figure 4. Cartoon from Wilson et al., (2003) showing the inferred large-scale structure of the Coso geothermal field and the possible relationship between the shallow magma body and regional tectonic features. The most important observation is the lack of a lower crustal magma reservoir. The magma body may act as a strain guide in the upper crust which, coupled with lower crustal flow, may signal a change in the deformation mechanism in the Coso area compared with mechanisms believed to exist to the north and possibly the east [Jones and Phinney, 1998].

There was, however, a PASSCAL experiment performed by the co-PI (Prof. Craig Jones) from November 1998 to May 2000 that has direct relevance to the proposed research. This work is described by Wilson et al. (2003) and several principal conclusions are summarized in **Figure 4**. About 220 Gb of three-component seismograms in and around the CGA were recorded that are available for the proposed research. Most of these data can be accessed from the IRIS Data Management Center. With 20 arrays and over 150 sites occupying an area of ~2000 km^2, this is one of the densest portable, passive seismic deployments performed anywhere to date (**Figure 3**). Each array consisted of 5–8 short-period sensors (1 or 2 Hz free period: Mark Products L22 or L4c, and/or Teledyne Geotech S-13) spaced 500 m apart and arranged into two orthogonal lines with, when available, 1–3 broadband sensors (Guralp CMG3-ESP, CMG-40T). The broad-band instruments and the somewhat lower frequency response of the other instruments make this data set a useful complement to the data that the GPO has recorded or will record during the proposal period.

Wilson et al. (2003) computed radial receiver functions for each array from the filtered, beamed seismograms following selected teleseimic events and inverted them for 1D *P* and *S*-velocity cross-sections. The presence of an upper crustal magma reservoir situated 5 km below the center of the modern Coso geothermal field was confirmed and was determined to be between 2 and 15 km thick with greater than ~5% rhyolitic melt. Thinner or more mafic reservoirs require higher melt percentages to satisfy our observations. The receiver function modeling combined with move-out analysis showed that a lower crustal magma reservoir is unlikely to underlie the Coso geothermal area. A possible candidate for an upper mantle reservoir was detected near 35 km depth. This mantle reservoir probably feeds the crustal magma body with periodic injections or continuous flow in dikes (<1 km width). Strain localization in the shallow magma reservoir probably causes the Coso area to extend differently than extensional terranes to the north.

These results as well as the work experience in the Coso area gained by co-PI Jones will be useful in planning new instrument deployment and in possible interpretation of images obtained by means of ambient noise or coda-wave interferometry.

2.2 Ambient noise tomography

Theoretical and laboratory studies showed early on that the cross-correlation of diffuse wavefields (e.g., ambient noise, scattered coda waves) can provide an estimate of the Green's function between the stations (e.g., Weaver and Lobkis, 2001; Derode et al., 2003; Snieder, 2004, 2006; Wapenaar et al., 2005; Larose et al., 2004; Curtis et al., 2006). Seismic observations based on cross-correlations of seismic waveforms between pairs of stations confirmed the theory for surface waves using both coda waves (Campillo and Paul, 2003) and long ambient noise sequences (Shapiro and Campillo, 2004; Sabra et al., 2005a).

The first attempts to use ambient noise for surface wave tomography, called ambient noise tomography, were applied to stations in Southern California by teams from CU-

Boulder (Shapiro et al., 2005) and UCSD (Sabra et al., 2005b). These studies resulted in group speed maps at periods from 7.5 - 15 sec that displayed a striking correlation with the principal geological units in California, with low-speed anomalies corresponding to the major sedimentary basins and high-speed anomalies corresponding to the igneous cores of the main mountain ranges.

These early studies established the promise for the application of ambient noise tomography on a systematic basis to supply new, high resolution information about the crust and uppermost mantle. In response, ambient noise tomography expanded rapidly in the past three years. Recent applications have arisen across the western US (Moschetti et al., 2007; Lin et al., 2008), in South Korea (Cho et al., 2006), in Tibet (Yao et al., 2006), in Europe (Yang et al., 2007; Villasenor et al., 2007), across New Zealand (Lin et al., 2007), in Africa (Yang et al., 2008b), in China (Zheng et al., 2008), and elsewhere in the world. Most of the studies, to date, like the earlier work of Shapiro et al. (2005), have been performed in the microseism band between 7 and 20 sec period. Longer period applications extending to considerably longer periods have also emerged (e.g., Bensen et al., 2007; Yao et al., 2006; Yang et al., 2007) and the method is also being applied to increasingly large areas such as Europe (Yang et al., 2007) and North America (Bensen et al., 2008a, 2008b).

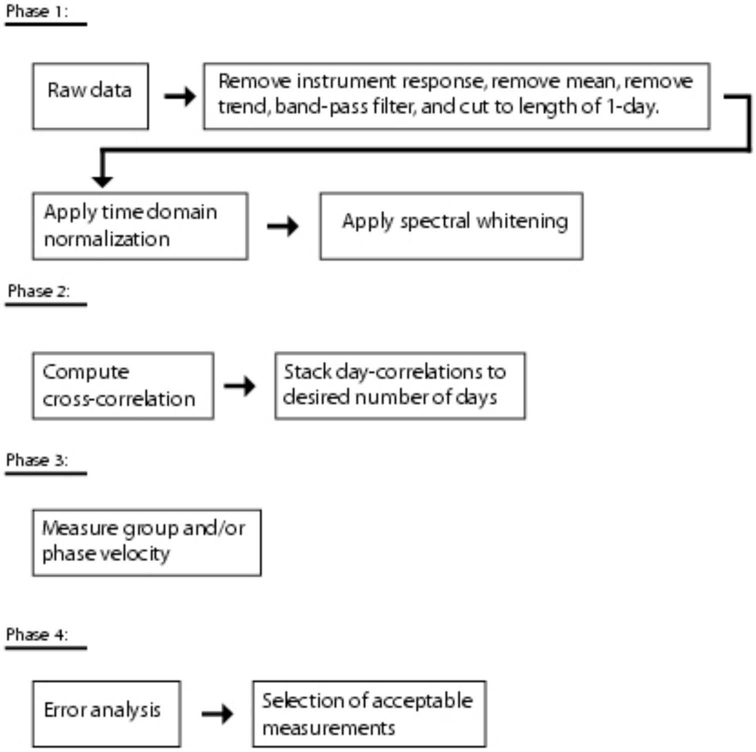

Figure 5. Flowchart showing the procedures used in “traditional” ambient noise data processing. Taken from Bensen et al., 2007.

The Research Team pioneered much of ambient noise tomography and a summary of the data processing procedure can be found in Bensen et al. (2007). What we consider to be the traditional method of data processing, depicted schematically in **Figure 5**, starts by cross-correlating long continuous time series of three-component ambient seismic noise. The negative time-derivative of this time series can, in certain instances, be considered to be an Empirical Green's Function (EGF) on which surface wave dispersion information about the path linking the two stations can be measured. As **Figure 6** shows, this information in the period band above 6 sec period includes Rayleigh and Love waves.

The primary period band for ambient noise analysis, to date, has been from ~6 to ~40 sec. The principal advantage of ambient noise tomography compared with traditional earthquake-based tomography is that surface wave dispersion at short periods (<20 sec), which is difficult to measure using teleseismic earthquake methods due to intrinsic attenuation and scattering from distant sources, can be obtained robustly to provide unique constraints on crustal structure.

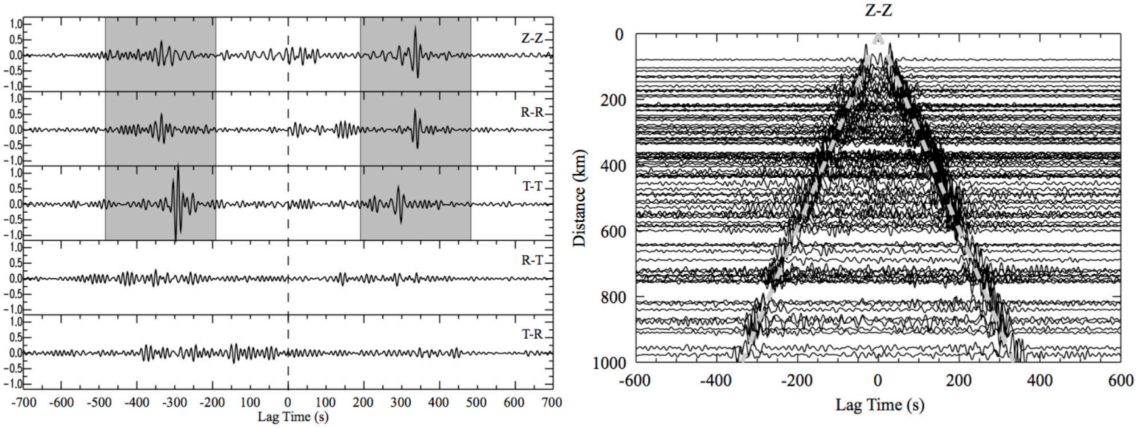

Figure 6. Examples of Empirical Green's Functions computed by cross-correlating long time sequences of ambient seismic noise with a pass-band between 10 and 50 sec period. (Left) Multi-component cross-correlations between the EarthScope TA stations 116A(Eloy, Arrizona) and R06C (Coleville, California). Grey-shading shows an arrival window between 2 and 5 km/s. Both fundamental mode Rayleigh and Love waves are observed. Love waves on the Transverse-Transverse component (T-T) are seen to arrive before Rayleigh waves on the Z-Z (Vertical-Vertical) and R-R (Radial-Radial) components. (Right) Vertical-Vertical record section using EarthScope TA stations centered on the station MOD (Modoc Plateau, California), illustrating an average Rayleigh wave move-out of about 3.0 km/s. Positive and negative correlation lag times correspond to waves traveling in opposite directions between the two stations. (Results taken from Lin et al., 2008.)

The first step in inverting surface wave dispersion measurements (Rayeigh and Love wave group and phase speed as a function of period) obtained on ambient noise Empirical Green's Functions is to produce dispersion maps, such as those shown for the western US in **Figure 7**. These maps over the frequency band of study are the basis for the construction of a 3D shear velocity model. We describe this briefly in the next section.

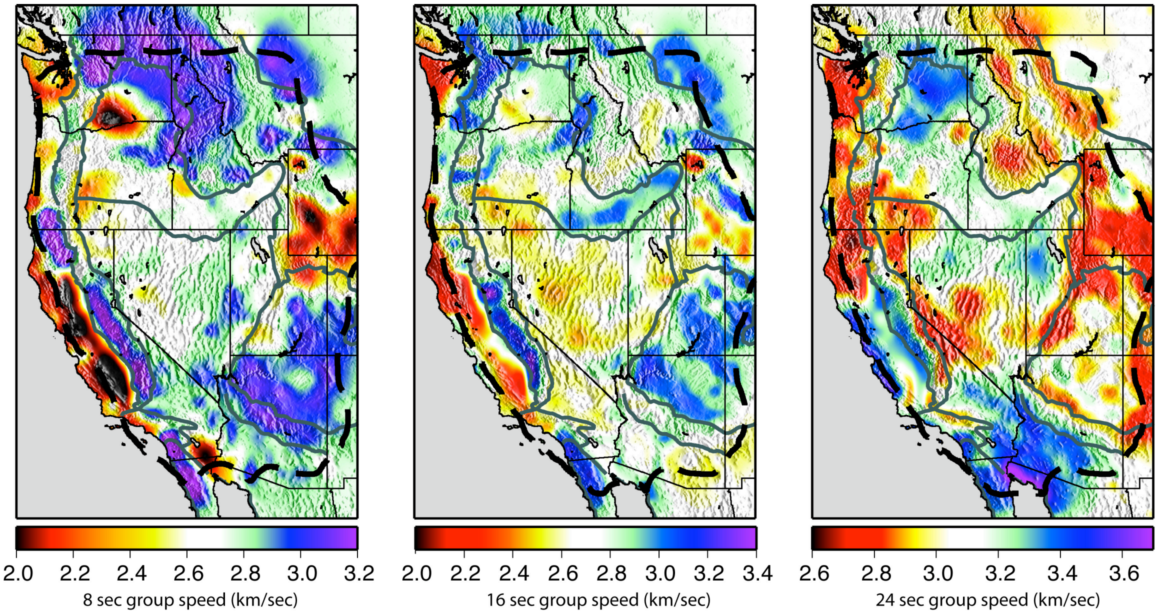

Figure 7. Example Rayleigh wave group velocity dispersion maps across the western US obtained with up to three year long time series from the USArray Transportable Array. Maps at three periods are shown (8, 16, 24 sec) which possess principal sensitivities near depths of about 10 km, 25 km, and 40 km. The bold dashed lines encircle the high resolution region. (Unpublished results from M. Moschetti, CU-B.)

2.3 Regional and teleseismic broad-band surface wave tomography and 3D model construction

The research team has extensive experience applying single-station (non-array) methods in the study of surface-wave dispersion at different length scales, global, regional, and local, by analyzing waves generated by moderate and strong, shallow and intermediate depth earthquakes, as well as underground nuclear explosions. The range of periods for determining phase and group velocities of surface waves varied from 5 sec to 200 sec with wave paths from 300 km to more than 10000 km. This work includes the study of both fundamental mode Rayleigh and Love waves as well as overtone information. We have published numerous papers in this research area including observation, theory, and inversion; e.g., Barmin et al. (2001); Levshin et al. (2005, 2007); Ritzwoller et al. (1998, 2001, 2002, 2004); Shapiro and Ritzwoller (2002); Shapiro et al. (2004, 2008). The web site http://ciei.colorado.edu/ritzwoller has a complete listing.

These dispersion studies form the basis for inversion for 3-D models of the crust and upper mantle. This work is based primarily on a Markov Chain Monte-Carlo method of sampling model space, which yields the 3D model with attendant uncertainties (Shapiro and Ritzwoller, 2002). An example is shown in **Figure 8**. In some studies, physical constraints are applied during the inversion (e.g., Shapiro and Ritzwoller, 2004)ß.

The Research Team also has significant experience with array methods in surface wave analysis. Recently, the group has applied multi-plane wave array tomography together with ambient noise tomography to infer the 3D structure of the crust and uppermost mantle beneath the western US. In multi-plane wave tomography, each incoming teleseismic wavefield is fit with a multiple plane wave expansion where each plane wave has an initially unknown amplitude, phase, and propagation direction. Six plane waves are sufficient to model each incoming wavefield across the western US. We have interpreted the observed phase and amplitude observed across the USArray/TA jointly to model the incoming wavefields and the phase velocity variation across the array. Some of this work has been presented by Yang and Ritzwoller (2008). Example horizontal cross-sections are shown in **Figure 9**.

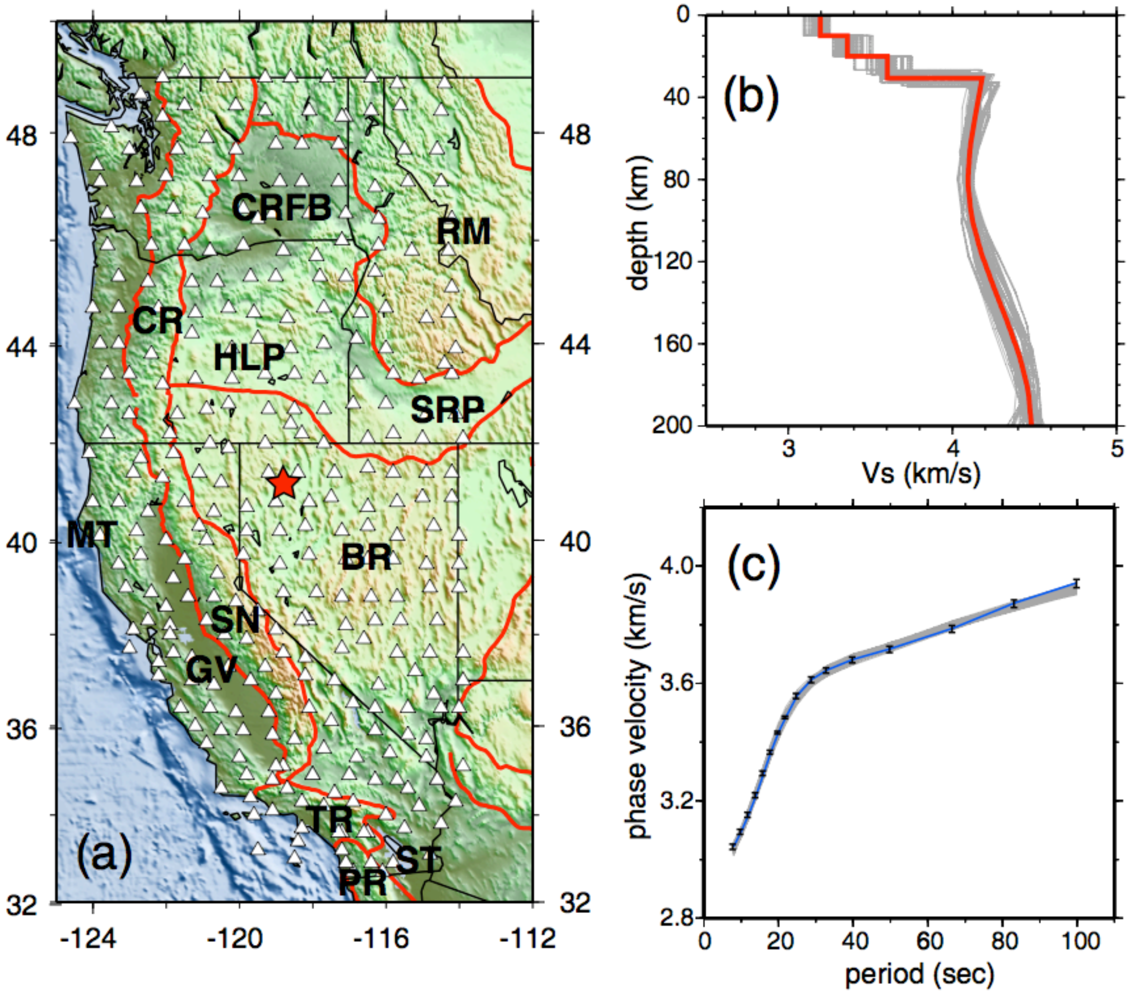

Figure 8. Markov Chain Monte-Carlo inversion method. (Left) EarthScope Transportable Array stations across the western US shown as triangles. (Right) Rayleigh wave phase velocities (error bars, bottom panel) from 8 – 100 sec period and the ensemble of acceptable models (grey lines, top panel) that fit them. The center of the ensemble is shown with the red line and the width of the ensemble defines model uncertainty. Grey lines in the bottom, right panel show predicted data from the ensemble of acceptable models. The plots at right are for the point in northern Nevada shown with a red star at left.

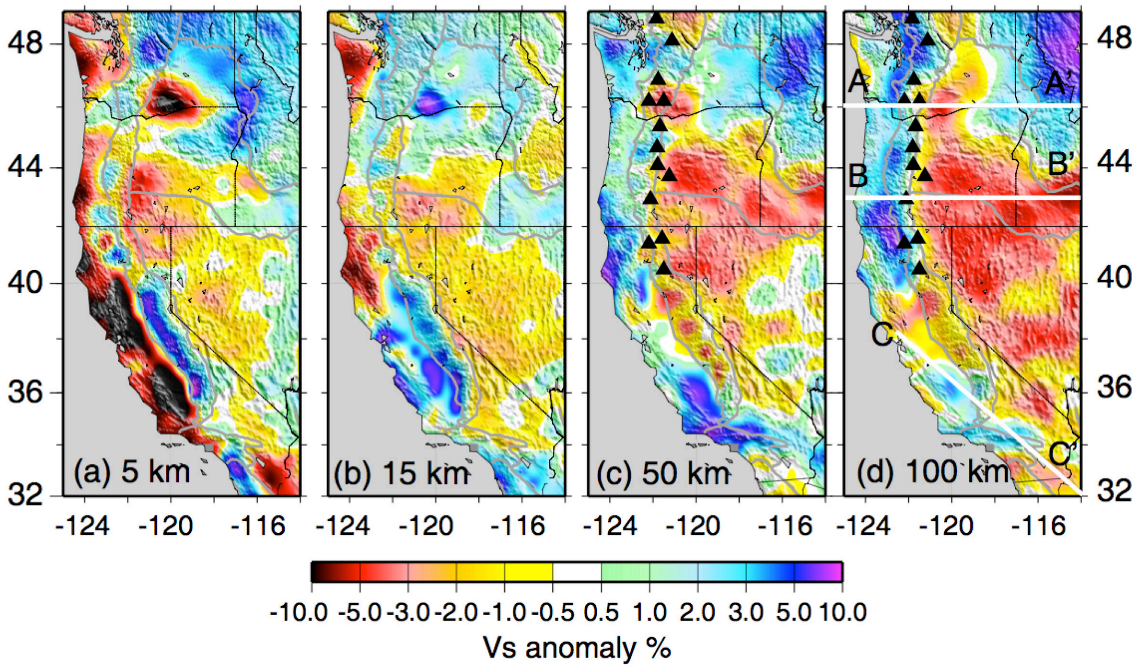

Figure 9. Shear wave speed (Vs) from the 3D model produced from ambient noise and multi-plane wave tomography in the western US. Depths are indicated. Triangles identify volcanic centers in the Pacific Northwest. Results are from Yang et al., 2008.

2.4 Shallow imaging with surface waves

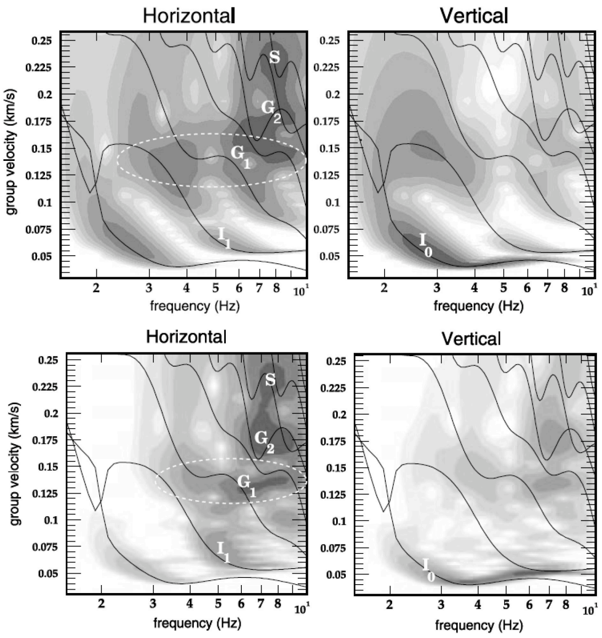

Figure 10. (Top) Simulated frequency-time diagrams showing major wave types observed between 1 and 10 Hz in the Gulf of Mexico. I_0 is the fundamental mode Rayleigh wave, I_1 the first overtone, G_1 and G_2 are guided waves, and S marks the S-wave. Solid lines indicate various dispersion branches. (Bottom) Example observation in the Gulf of Mexico confirming the existence of these wave types in the data. (Panels are from Ritzwoller and Levshin, 2002.)

Surface waves generated by small artificial sources can be used to study shallow shear velocity structure (e.g., Louie, 2001). Ritzwoller and Levshin (2002) used marine multi-component seismic data obtained in the Gulf of Mexico to obtain the shear velocity structure of young sediments down to a depth ~200 m beneath the sea floor. The range of frequencies was 2 – 10 Hz and the data used for inversion included the fundamental mode and several higher Rayleigh modes as well as the travel times of diving *P* and *S* waves. Although the setting for this work differs greatly from the CGA, these studies have several similarities. First, the frequency band is similar (2 - >10 Hz). Second, this work was an extension of techniques developed at lower frequencies to higher frequencies. In the Gulf of Mexico study, we applied earthquake seismology methods developed at longer periods to a higher frequency controlled source study. In the proposed research, we will aim to transfer lower frequency ambient noise and coda wave interferometry to higher frequencies. Our experience is that such a translation is never as straightforward as one would hope and ingenuity is needed.

Figure 10 here shows both synthetic and observed frequency-time images from our Gulf of Mexico study. The images are frequency-time images displaying observed (or predicted) Rayleigh wave group velocity versus frequency. The purpose of showing this figure here is to illustrate the wave content in the data. Fundamental modes are not the only observed wave. Overtones and guided waves are also predicted and observed. The resulting inversion method is based on the inversion of the observed dispersion of several wave types that we called Multi-Wave Inversion. Expectations for the characteristics of these waves at the CGA are discussed further in the proposed research section. An example 1D model produced in the Gulf of Mexico study is shown in **Figure 11**.

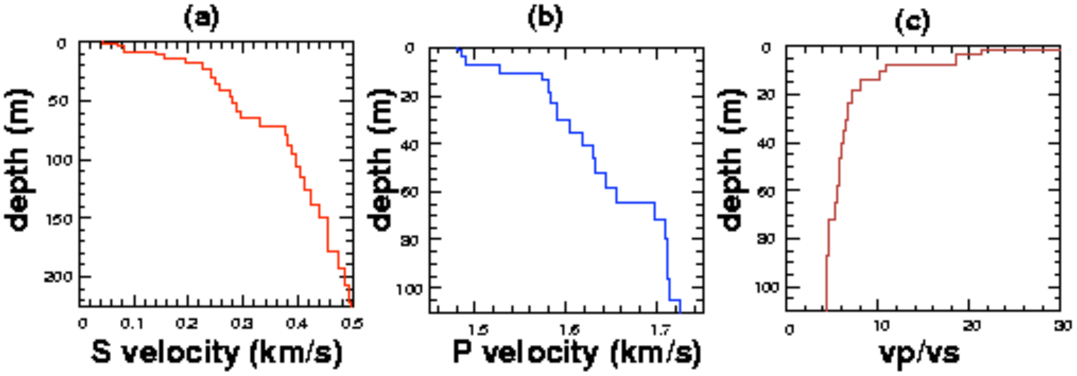

Figure 11. Example 1D model obtained from multi-wave inversion in the Gulf of Mexico. Results are from Ritzwoller and Levshin (2002).

3. Proposed Research and Statement-of-Work

Due to the frequency content of the seismic instrumentation in and around the Coso Geothermal Area (CGA), we anticipate that the frequency range of analysis will be 2 – 12 Hz with the low frequency end of this range coming from the arrays that we will process to complement the GPO arrays. Synthetic experiments provide a guide to what can be learned about substructure in this frequency band.

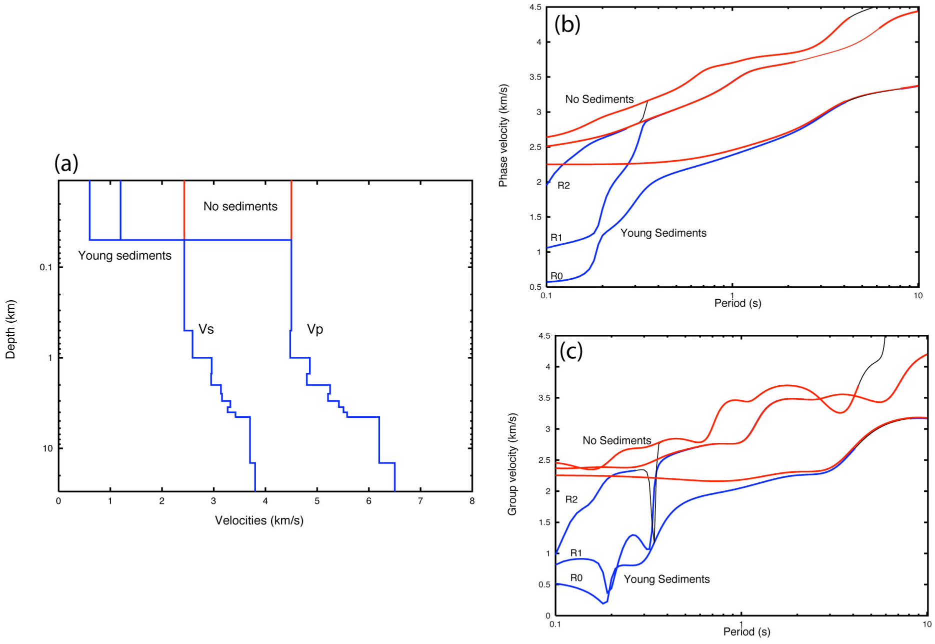

Figure 12. (a) Ad hoc 1D model of the Coso Geothermal Area, with (blue) and without (red) 50 m of sediment. (b) & (c) Rayleigh wave phase and group speed for the fundamental mode (R0) and the first two overtone branches (R1, R2). Red lines are for the model without sediment and blue lines with sediment.

Figure 12a presents an ad hoc shear velocity (Vs) and compressional velocity (Vp) model of the Coso geothermal region, both with and without sediments. Sediment cover is 50 m thick in the model with sediments. The sub-sedimentary velocities are taken from the 1D model of Wu and Lees (1999). Sediment speeds are from unpublished refraction profiles. **Figures 12b and 12c** show Rayleigh wave phase and group speeds predicted from the model. The group velocities determine when waves arrive. Several general conclusions can be reached. Detailed conclusions will depend on the details of the model.

(1) The sedimentary cover will strongly affect the observed wave group arrivals at frequencies above about 4 Hz. At lower frequencies, the arrival times of the fundamental mode and the first two overtones are largely independent of the existence of sediments.

(2) In the absence of sediments, fundamental and first two overtone group speeds are between 2.2 and 2.8 km/sec between 2 and 10 Hz. Separation of the fundamental from the first two overtones may be possible, but the first two overtones will arrive as a guided wave similar to guided waves observed in the Gulf of Mexico (**Fig. 10**).

(3) In the presence of sediments, the fundamental mode and first two overtones will be strongly dispersed. Wave speeds below 1 km/sec at frequencies higher than 7 Hz are expected and may be as low as 250 m/sec near 10 Hz. The second overtone is well separated from the fundamental mode and first overtone, but the fundamental mode and first overtone act as a guided wave.

(4) To provide structural information beneath sedimentary cover from the fundamental mode, observations at frequencies lower than 4-5 Hz are needed. The second overtone, however, provides sub-sedimentary information at frequencies as high as 9 Hz.

In summary, the ability to draw inferences about structures beneath the sediments will depend either on making measurements on the fundamental mode at frequencies below ~4 Hz or making measurements on the second overtone. Thicker sedimentary cover will lower this cut-off frequency.

We will pursue two approaches here to gain information beneath the sediments. As discussed in the Introduction, to attempt to extend the band-width of observation to lower frequencies we propose to utilize non-GPO arrays. We will also attempt to make measurements of overtones as well as the fundamental mode, but do not know if such measurements will be possible.

As discussed in the Introduction, the proposed work prior to writing the technical report breaks into four phases. Phases 3 and 4, however, are mutually exclusive. We will perform either Phase 3 or Phase 4 in response to the outcome of Phases 1 and 2. We consider each phase to constitute a single work task. Thus, three phases will be completed: either 1, 2, and 3 or 1, 2, and 4. Phases 1 and 2 are Tasks 1 and 2. The performance of either Phase 3 or Phase 4 is referred to as Task 3. The final task is preparing the final report (Task 4).

3.1 Phase 1/Task 1: Noise Characterization.

The first phase of research will be to characterize ambient noise and earthquake coda waves as potential sources for imaging information. This will be the major part of the proposed research. First, we will investigate daily and seasonal variability as well as the frequency dependence of various noise sources. Data will be processed from the GPO Existing Array, the PASSCAL experiment, and the Cal Tech network. Information about frequencies below 2 Hz will come from the Cal Tech network. We particularly want to gain insight into the nature of the various signals observed in the area.

Second, we will investigate the correlation characteristics of the noise observed at various stations. Again, it is important to understand daily and seasonal variability, as is the frequency dependence of the correlation properties. Certain times of day or certain frequency bands may yield better information than others. Although focus will be on analysis of the GPO Existing Array, it may turn out that the stations in this network are separated by too great of distances, on average, for ambient noise at frequencies above 4 Hz to propagate coherently between them. The PASSCAL array will be particularly useful to test this hypothesis because stations are as close as 500 m apart. Perhaps station separation is an necessary variable, and stations that are much closer will allow meaningful ambient noise Green's functions to be recovered. But, to use the PASSCAL network data it will be necessary to overcome the instrument irregularities seen in **Figure 2**. In addition, the Cal Tech network will allow study of regional conditions near the CGA, particularly concerning low frequency coherence.

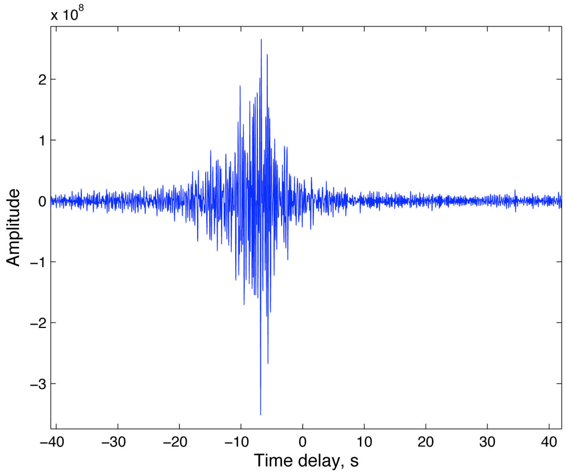

Figure 13. Cross-correlation of 20 days of broad-band data from Cal Tech stations SLA and MPM separated by a distance of 26 km. The waveform is band-passed between 1 and 7 Hz. Neither frequency whitening nor time-domain normalization was performed in this example. We believe that the apparent arrival here is spurious.

An example cross-correlogram is presented in **Figure** 13 using two Cal Tech stations separated by ~26 km. The apparent arrival is spurious, being both too broad and fast to be an empirical Green's function. Many more examples for different station-pairs, under different conditions, with different processing schemes, and in different frequency bands will be investigated in the proposed research.

Third, similar to the investigation of the characteristics of noise and its coherence properties, we will investigate the frequency content and propagation coherence of earthquake coda across the GPO Existing Array. We plan also to process Cal Tech data and PASSCAL data to provide information at larger scales, lower frequencies, and tighter sensor spacing

In both the ambient noise and coda wave parts of this research, we will make concerted efforts to identify overtones as well as fundamental modes in the processing.

3.2 Phase 2/Task 2: Advise on the Siting of the Temporary Array.

As a result of the noise characterization, we will either successfully discover that signals exist in ambient noise or coda waves on which to base interferometric imaging of the subsurface or we will find that waves do not propagate coherently between the stations. In the former case, we will make suggestions to the GPO field office about the location and geometry of the Temporary Array to produce optimal information about the subsurface. In the latter case, we may need more information about the coherence properties of ambient noise at the CGA, particularly for stations spacings that are smaller than the Existing Array. This is a more likely outcome if the instrumental irregularities that beset the PASSCAL data prove to be insurmountable. In this case, we may suggest a temporary deployment of a “logarithmic array” in which station spacings span several orders of magnitude, from 10s of meters to kms. It is not impossible that for ambient noise tomography to succeed at the CGA, 1 km station spacings are needed.

Judgment about the outcome of the noise characterization will be made in consultation with the GPO field office.

3.3 Phase 3/Task 3: Tomography.

In the best case, Phase 1 will have identified signals to form the basis for either ambient noise or coda wave interferometry. Phase 3 of the proposed research is the application of these waves to obtain surface wave dispersion measurements (phase and group speeds) across the relevant region. Following dispersion measurement, phase and group speed maps will be produced, similar to the maps shown in **Figure 7** at lower frequencies over a much larger area. The maps will then be inverted for shear velocity, as **Figures 8** and **9** exemplify, again at a larger scale. Preferably a 3D model will be constructed to a depth of several hundred m.

A key element to this aspect of research is to obtain measurements on overtones as well as the fundamental mode in order to increase the depth extent of the resulting model.

3.4 Phase 4/Task 3: Continency Plan.

It is possible that interferometric imaging using either ambient noise or coda waves will prove impractical with the given instrumentation. In this case, Phases 1 and 2 of the proposed research will provide 2 clear characterization of both ambient noise and coda waves that can form the basis for other investigations in the future, but Phase 3 will not be completed. It will be replaced by Phase 4.

Nevertheless, we believe that other surface wave methods may reveal the information that GPO desires, and as a contingency we will plan to effect two-plane tomography using the Existing GPO array. This method is a new technique in surface wave analysis that is described in detail by Yang and Forsyth (2006a,b), Yang and Ritzwoller (2008c), and Yang et al. (2008). This is an earthquake-based method. It has proven effective for studying crustal surface waves at periods longer than 10 sec, but the proposed research will see its first application at frequencies above 1 Hz. As with the interferometric methods, however, its success will depend on the coherence of earthquake waves across the observing array. Because surface waves arriving directly from earthquakes are stronger than coda, we believe it has a higher probability of success.

3.5 Task 4: Preparation of Final Report.

All principal results will be documented and presented in a final report that will be given in triplicate and on CD to GPO at the termination of the contract.

4. References

(Ritzwoller's papers can be found at http://ciei.colorado.edu/ritzwoller, Jones' are at http://cires.colorado.edu/people/jones.craig/CHJ_cv.html)

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BIOGRAPHICAL SKETCH

MICHAEL H. RITZWOLLER
Director, Center for Imaging the Earth's Interior
Professor, Department of Physics
University of Colorado at Boulder, Boulder, CO 80309-0390
Office: (303) 492-7075 Fax: (303) 492-7935 E-mail: ritzwoller@ciei.colorado.edu

Research Interests

Theoretical, computational, and observational seismology, geophysical imaging and inversion, seismic tomography, seismic surface waves and normal modes, modeling the Earth's crust and mantle, elastodynamic wavefield simulation, use of seismology in nuclear monitoring, shallow subsurface imaging using seismic waves and surface NMR.

Professional Preparation

1977	A.B.	Marquette University
1980	M.A.	University of Illinois
1982	M.S.	University of Wisconsin
1987	Ph.D.	University of California, San Diego (Scripps Insti of Oceanography)
1987-1990		Post-Doct. Fellow, Dept. Earth &Planetary Sciences, Harvard Univ.
1990		Fellow, Institute for Theoretical Physics, Univ. of CA, Santa Barbara

Appointments

2003 to present	Professor, Dept. of Physics, University of Colorado at Boulder
1999 to present	Director, CIEI, University of Colorado at Boulder
1998 to present	Affiliate, CIRES, University of Colorado at Boulder
1997 - 2003	Associate Professor, Dept. of Physics, CU-Boulder
1990 - 1998	Fellow, CIRES, University of Colorado at Boulder
1990 - 1997	Assistant Professor, Dept. of Physics, CU-Boulder

Professional Memberships

American Geophysical Union, Fellow; Royal Astronomical Society; Seismological Society of America; Society for Exploration Geophysicists

Five Publications Closely Related to the Proposed Research

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All publications at ciei.colorado.edu/ritzwoller

Craig Howard Jones

Education

B.S., Geophysics and Planetary Science (with honors) California Institute of Technology.	June, 1981
Ph.D., Geophysics, Massachusetts Institute of Technology, "A Geophysical and Geological Investigation of Extensional Structures, Great Basin, Western United States," Peter H. Molnar, advisor.	October, 1987
California Institute of Technology Weizmann Postdoctoral Fellow, research fellow, Hiroo Kanamori supervisor, B. Hager, sponsor	November 1987-October 1990

Professional Experience

Associate Prof., Dept. of Geological Sciences	August 1998-
Research Asst. Prof., Dept. of Geological Sciences	September 1996-June 1998
Research Associate, CIRES University of Colorado, Boulder	December 1993-
University of Nevada, Reno	
Research Asst. Professor/Research Associate	March 1992-October 1993
Postdoctoral Research Fellow	January 1991-February 1992
California Institute of Technology	
Staff Scientist (part-time)	November 1990-December 1990
Research Fellow in Geophysics	November 1989-October 1990

Relevant Field Experience

Passive seismology experiment, Sierra Nevada (SNEP)	Spring 2005-2007
Short-period/broadband array experiment, Marlborough region, South Island, New Zealand	December 2000-May 2002
Short-period array experiment, China Lake Naval Weapons Center	November 1998-May 2000

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Curriculum Vitae

ANATOLI L. LEVSHIN

Citizenship: U.S.

Education
1954 A.B. Moscow State University (Honors Geology and Geophysics)
1957 M.Sc. Moscow State University (Geophysics)
1962 Ph.D. Institute of Physics of the Earth, Acad.of Sci.USSR (IPE)(Geophysics)1971 D.Sc. IPE, Moscow

Positions Held
1992 to present Research Associate, Department of Physics, University of Colorado (CU), Boulder
1996 to present Lecturer, Department of Physics, CU, Boulder
1990 to 1992 Chief, Laboratory of Wave Fields Interpretation, International Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences, Moscow
1969 to 1989 Chief, Laboratory of Wave Fields Interpretation, IPE, Moscow
1962 to 1968 Senior Researcher, IPE, Moscow
1957 to 1962 Senior Engineer, Institute of Hydrogeology and Civil Engineering, Ministry of Geology of the USSR, Moscow

Recent International Activity
2004 Visiting Professor, Intl. Center of Theoretical Physics, Trieste, Italy
2005 Visiting Professor, Norwegian Seismic Array, Kjeller, Norway
2006 Visiting Professor, University of Utrecht, Utrecht, the Netherlands
Professional Societies
Fellow, American Geophysical Union

Recent Publications

Kaufman, A.A. and A.L. **Levshin**, 2005. Acoustic and elastic wave fields in geophysics. III. Elsevier, Amsterdam. Russian translation: Moscow, Nedra, 2006.

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Curriculum Vitae

MIKHAIL P. BARMINE

Citizenship: U.S. citizen

Education:

1971	A.B.	Moscow State University (Honors in Mathematics)
1984	Ph.D	Institute of Physics of the Earth, Academy of Sciences USSR (Geophysics)

Positions held:

1998 to present	Research Associate, Dept. of Physics, University of Colorado, Boulder, U.S.
1997 to 1998	Head of Division, Central Experimental Methodical Expedition, Geophysical Survey of Russian Academy of Sciences, Obninsk, Russia
1994 to 1997	Chief Geophysicist, Experimental Methodical Expedition, Geophysical Survey of the Russian Academy of Sciences, Obninsk, Russia
1985 to 1994	Chief, Laboratory of Data Management and Processing, Experimental Methodical Expedition, Institute of Physics of the Earth, Acad. of Sci. USSR, Obninsk, Russia
1975 to 1985	System Engineer, Senior Geopysicist, Experimental Methodical Expedition, Institute of Physics of the Earth, Acad. of Sci. USSR, Obninsk, Russia
1971 to 1975	Lecturer, Dept. of Applied Mathematics, Moscow Engineering and Physics Institute, Obninsk, Russia

Professional Memberships: American Geophysical Union

Publications:

Bensen, G.D., M.H. Ritzwoller, M.P. Barmin, A.L. Levshin, F. Lin, M.P. Moschetti, N.M. Shapiro, and Y. Yang, Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, *Geophys. J. Int.*, 169, 1239-1260, doi: 10.1111/j.1365-246X.2007.03374.x, 2007.

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