Collaborative Research: Lithospheric Foundering Beneath the Sierra Nevada

Project Summary

Foundering of ultramafic and mafic composition mantle lithosphere has been used to account for processes in both continental tectonics and the development of continental crust from a more mafic mantle. Despite widespread appeals to this idea, the absence of observations of ongoing removal has left a collection of untested hypotheses. This situation will be rectified by detailed seismological and related geologic studies of the Sierra Nevada in eastern California. Recent work in the Sierra Nevada has revealed that eclogite and peridotitic mantle lithosphere under the range since the Mesozoic were removed by about 3.5 Ma and now sinks beneath the Central Valley. Removal of this material may have led not only to the rise of the Sierran crest but also to subsidence of its western foothills, Quaternary volcanism and extension in Long Valley and along the eastern edge of the Sierra, and perturbations to the stress regime of the San Andreas-Eastern California Shear Zone plate boundary. Situated within the initial deployment of the US Array Bigfoot seismic array, this region makes an ideal target for a Flex Array deployment. In recognition of budgetary limitations, and in consultations with Program Managers, we have limited this proposal to the passive seismic component of the larger interdisciplinary proposal that we submitted last year. The complementary geophysical and geological components will be submitted either as smaller individual proposals to their appropriate disciplinary programs, or as a larger coordinated proposal to the Continental Dynamics Program.

Intellectual Merit. Because of the young age of this event, we can pose a number of questions that bear on the general process of removal of lower continental lithosphere:

1. Is removal of the eclogitic root limited to the southern Sierra or does it continue farther north along the trend of the Mesozoic batholith?
2. Does the eclogite founder by a true delamination (tearing) process, as a convective instability, or some combination? How important is shearing in the process?
3. Is there a structural connection between the removal process and volcanic fields and earthquake zones?

We address these questions in part with new seismological data acquired by a deployment of 40 broadband seismometers to complement USArray instrumentation in California. The stations will be first deployed in a 2D array in the central Sierra Nevada to determine the spatial extent and geometry of the lithospheric foundering. The same stations will then be redeployed into a dense 1D array to investigate the details of the removal process. The total number of broadband sites occupied (including BigFoot sites) will be ~100. The data will be processed to separate areas underlain by melt laden, low-velocity, seismically anisotropic asthenosphere from those retaining resistive, cold, high-speed, seismically isotropic eclogite. Our results will also constrain variations in Moho topography and finite strains affected by the flow of the drip as recorded by seismic anisotropy. A series of workshops will be held to integrate results with complementary geophysical and geological studies.

Broader Impact. In addition to supporting several graduate students, we will conduct a summer camp under a separate REU Site proposal to involve undergraduates and possibly K-12 teachers (through an RET), emphasizing the importance of passive seismology interpretation. We will also work with National Parks in the Sierra to provide materials useful in displays and demonstrations within the park, possibly including computer animations and physical demonstrations of the physics of removal of the mantle lithosphere. Integration of results and products of this project with the overall community effort to produce EarthScope Products will be emphasized.

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C. Project Description

Motivation–Why Study the Sierra Nevada? Of the many processes proposed to affect continental evolution, probably the most prominent process not directly driven from a plate edge is removal of the continental mantle lithosphere. *Bird* [1978] first proposed delamination (peeling away of the mantle lithosphere) to explain the thermal structure of Himalaya [*Bird*, 1979] and the elevation of the Colorado Plateau. Alternatives to delamination include convective removal of lithosphere [*Houseman et al.*, 1981], breaking of a slab [e.g., *Wortel and Spakman*, 2000] and the creation of a slab window [e.g., *Dickinson*, 1997]. Removal of mantle lithosphere may be key to understanding the histories of places as diverse as the southern Sierra Nevada [*Ducea and Saleeby*, 1996], Alboran Sea [*Calvert et al.*, 2000; *Platt et al.*, 1998], Tibetan Plateau [*England and Houseman*, 1989; *Turner et al.*, 1996], Apennines [*Wortel and Spakman*, 1992; 2000], Appalachians [*Nelson*, 1992], central Andes [*Kay and Mahlburg-Kay*, 1991; *Beck and Zandt*, 2002], Carpathians [*Girbacea and Frisch*, 1998; *Wortel and Spakman*, 2000], and the Basin and Range [*Platt and England*, 1994; *Humphreys*, 1995]. The removal of eclogitic material may also be responsible for the fact that average continental crust is andesitic in composition, despite having been originally formed from more mafic arc magmatism [*Ducea*, 2002]. Most of these proposed cases occurred too long ago for the process to be observed today. One of the best exceptions to study is the Sierra Nevada.

The Sierra Nevada south of about 38°N lost mantle lithosphere and mafic lower crust at about 3.5 Ma [*Ducea and Saleeby*, 1998a; 1996; *Farmer et al.*, 2002; *Manley et al.*, 2000]. Close by this area lies one of the largest P-wave velocity anomalies in the upper mantle of the western U.S. (**Fig. 1**), an anomaly with characteristics consistent with those of the removed material [*Benz and Zandt*, 1993; *Biasi and Humphreys*, 1992; *Jones et al.*, 1994; *Raikes*, 1980; *Humphreys et al.*, 1984]. Observations from the xenoliths of the now-absent material indicate it was a mafic root to the Sierra Nevada batholith [*Ducea*, 2002; *Ducea and Saleeby*, 1998b]. Removal of this material may have led to uplift of the Sierran crest, subsidence of its western foothills, volcanism and extension in the Long Valley region and elsewhere along the eastern edge of the Sierra, shortening in the California Coast Ranges, and possibly a reduction in the slip rate of the San Andreas fault system [*Jones et al.*, 2004; *Zandt*, 2003]. In light of the broad impact mantle removal may have had on the face of California, a comprehensive test of this hypothesis makes an ideal target for a Flex Array deployment to complement the USArray in this region.

Mantle lithosphere should be sufficiently gravitationally unstable that when perturbed enough, it could sink rapidly into the underlying asthenosphere, much like a “drip”. Continental convergence and crustal thickening provide an obvious perturbation, and numerous studies show rapid removal of at least half of the mantle lithosphere [e.g., *Conrad and Molnar*, 1997; 1999; *Conrad*, 2000; *Houseman and Molnar*, 1997; 2001; *Houseman et al.*, 1981; 2000; *Molnar and Houseman*, 2003; *Jull and Kelemen*, 2001; *Molnar et al.*, 1998; *Neil and Houseman*, 1999]. *Zandt and Carrigan* [1993], however, pointed out that such an instability may have grown beneath the Sierra Nevada without such forcing. The rapid removal of Sierran lithosphere between ~10 and 3 Ma after a prolonged period of quiescence is consistent with perturbations of unstable non-Newtonian fluids [*Canright and Morris*, 1993; *Houseman and Molnar*, 1997], but the Sierran example has characteristics unanticipated by previous analyses, such as the drip being located to the side of where eclogitic rocks probably were thickest, removal of all lithosphere below the seismic Moho, and the restriction of downwelling to pipes rather than sheets (most models cited above are 2D sheets while observed velocity anomalies are shaped like pipes). While supporting

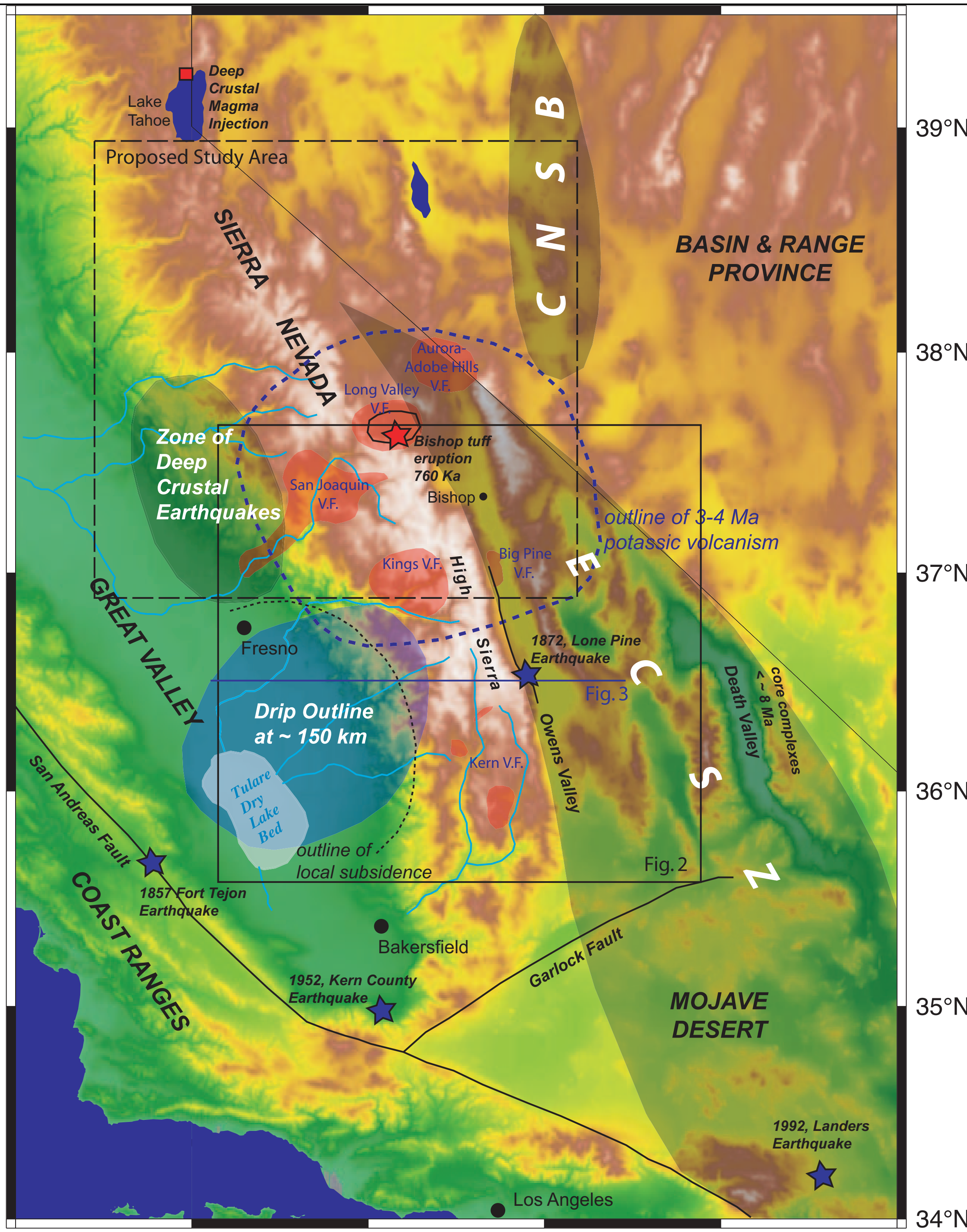


Fig. 1. Major geographic and structural features, major historic earthquakes (blue stars), earthquake and deformation zones (shaded grey), volcanic areas (shaded orange), and Bishop Tuff eruption (red star) shown on a shaded relief map of southern California and western Nevada. Drip at 150 km depth is shaded blue. Box outlined in solid line is the study area shown in Fig. 2 and blue line is location of cross sections in Fig. 3. The box outlined in dashed line is the proposed study area**.** ECSZ, Eastern California Shear Zone. CNSB, Central Nevada Seismic Belt.

some style of convective removal of lithosphere, the Sierra also provides new challenges to these previously untested conceptualizations.

What is the Broader Significance of the Sierra Drip? Although the Southern Sierra removal process is interesting in its own right, lithospheric foundering may play a more general role in continental rifting and intraplate tectonics than currently envisioned. Convective instability driven by a dense batholithic root is an efficient means of thinning continental lithosphere beneath or adjacent to the batholithic belt [*Zandt et al*., 2004]. The opening of the Gulf of California may have been preceded by lithospheric removal of the Peninsular Ranges batholithic root, leading to rifting adjacent to the edge of the batholith. The resulting long linear continental crustal blocks are termed "ribbon continents" and are major building blocks of larger accreted continents [*Sengor and Natalin*, 2004]. A similar rifting process may be in its initial stages in the Sierra Nevada and the Eastern California Shear Zone. The Mojave terrane located between the Sierra Nevada and Peninsular Ranges may be deforming differently because the intervening batholithic root was lost during the Laramide [*Saleeby*, 2003] and was not available to initiate a similar type of rifting in the Late Cenozoic. Understanding more of the details of the foundering process could lead to important insights into the rifting and amalgamation of continents.

The foundering process involves a rapid detachment and sinking of dense eclogitic and periodotitic materials into the underlying mantle and their replacement by asthenosphere. The eventual change in isostatic equilibrium alone would be dramatic. In addition, dynamic processes during the removal event could significantly perturb the tectonic stress field, leading to surface subsidence, uplift, and triggering of magmatism, volcanic eruptions, and earthquakes. The proposed study area is at the transition between the Sierra Nevada-Great Valley block and the Great Basin and is within one of the most seismically and magmatically active areas in the western US (**Fig. 1**). In this region the Eastern California Shear Zone (ECSZ) or the Southern Walker Lane steps eastward to the broader Central Walker Lane and the associated Central Nevada Seismic Belt (CNSB). This location is really a large right-step in the right-lateral shear system east of the Sierra [*Unruh et al*., 2003]. Several Late Cenozoic volcanic fields occur here including the Long Valley caldera, the result of a massive (>1000 km3) ignimbrite eruption about 760 ka. Three of the largest historic earthquakes in California have occurred within 150 km radius of the mantle drip, including the magnitude 7.9 Lone Pine earthquake in 1872 that ruptured the Owens Valley fault directly opposite the area of drip-induced subsidence. An anomalous zone of deep crustal earthquakes (30 km deep) is located north of Fresno, on the periphery of the drip [*Wong and Chapman*, 1990], and more scattered deep earthquakes are found farther south, above the drip [*Edwards and Jones*, 1998]. The subsurface removal event could potentially explain a number of disparate tectonic features that could not be explained by standard plate tectonics concepts. A better understanding of the connections between the southern Sierra Nevada mantle drip and crustal and surface tectonics could lead to a more global appreciation of crust-mantle interactions and their effects in continental tectonics.

Why Just Seismologists? – The Plan for Interdisciplinary Work The seismologists involved in this proposal were part of a multi-institutional, interdisciplinary, and expensive (~$3M) proposal last year to the Earthscope Program. In recognition of the reality that Earthscope science is badly underfunded this year, our group decided to submit a more limited proposal that concentrates on the most time critical part of the project, the passive seismic component that will be embedded into the ongoing deployment of USArray. We plan to eventually complement the new seismological data with MT data (S. Park), examination and analysis of volcanic rocks along the Sierra (L. Farmer and A. Glazner), the xenoliths that they carry (M. Ducea), changes in post-

Miocene sedimentation in the Central Valley of California (J. Saleeby), geomorphic expressions of recent changes in topography (R. Anderson), seismotectonics above the drips (J. Unruh), and numerical experimentation (P. Molnar). The complementary geophysical and geological components will be submitted either as smaller individual proposals to their appropriate disciplinary programs, or as a larger coordinated proposal to the Continental Dynamics Program.

Integrating these constraints will be a major task as no doubt some observations will agree with one of our current models, others with the other, and some with neither. We feel that it is far better to work to integrate these observations in face-to-face discussions, when the workers can convey fully the tradeoffs and uncertainties of their work. We have a good track record of interdisciplinary collaborations and all the P.I.'s have committed to continuing a dialogue with each other. To that end, we have included two workshops within our budgets, one at the Univ. of Colorado in 2005, prior to the main seismologic deployment, and one in 2008 in Tucson, Arizona, after completion of the experiment. All of our colleagues from an earlier proposal who were available to reply have said that they will participate in these workshops (see Appendix).

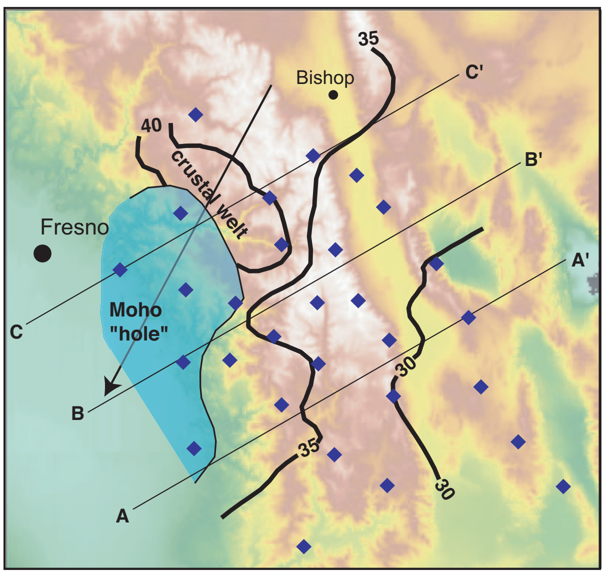
Why Now? – The Need for Embedding in USArray The structure and evolution of the Sierra Nevada and its implications for both California tectonics and the global problem of continental lithospheric evolution is a premier problem within the first "footprint" of BigFoot, the USArray Transportable Array. In 2004, Bigfoot sites began deployment of 50 broadband seismometers in California. Over 20 of those are within or surrounding the proposed study area. They will be in this area until October of 2008, providing expanded coverage and a stable reference frame for the seismic experiment proposed here. This is an unprecedented opportunity to study this unique area. Because of the scale of our 2D deployment, the Bigfoot stations will comprise ~25% of the sites occupied in our proposed study. The USArray project will provide a regional 3D velocity structure in which our results will be embedded. Especially important, the Bigfoot stations will provide overlap with previous deployments that will be essential in merging data sets. Finally, the Bigfoot deployment will provide logistical synergy for permitting and network operations.

Background. Broadly speaking, continental lithosphere differs from that beneath oceans because of its more silica-rich composition. During post-Archean time the process of continent formation has involved the creation of basaltic or basaltic-andesitic arcs on continental margins followed by their evolution to andesitic mean crust. One process through which that final transition can occur is the removal of a mafic residuum from a more silica-rich batholith. Material balance calculations indicate that the ratio of melt to residue in Andean-type arcs ranges from 1:1 to 1:3 [*Kay and Mahlburg-Kay*, 1991]. In the Sierra Nevada, granitoid arc thickness [e.g., *Fliedner et al*., 1996; 2000] and xenolith data [*Ducea and Saleeby*, 1998b] support a melt to residue ratio of 1:1 to 1:2, which would represent a bulk composition of high-Mg basaltic andesite [*Ducea*, 2002]. The thicker a felsic arc, the more likely an eclogite facies residue developed instead of a granulite facies residue. The high density of residual pyroxenites (3.45-3.55 g/cm^3) when crystallized at pressures in excess of ~1.5 GPa should create a markedly unstable layer beneath at least some large batholiths.

The existence of such eclogitic residuum has been documented in the Sierra from the garnet-rich xenoliths entrained in 12-8 Ma basaltic lavas that were erupted in the San Joaquin and Kings volcanic fields in the southern Sierra (**Fig. 1**). The removal of the eclogite is shown from xenoliths in volcanics younger than 4 Ma found in the southern half of the Sierra. The isotopic characteristics of the highly potassic Pliocene volcanic rocks themselves also indicate that the eclogitic rock was physically removed and not merely metamorphosed to garnet-free rock. To date, it is unknown if such a residuum existed farther north than the xenolith locales in the San

Joaquin volcanic field. The most plausible candidate for the descending eclogite is a large body, oval in map view, in the upper mantle with P-wave speeds > 3% greater than surrounding mantle (**Fig. 1**). This high wavespeed anomaly (sometimes referred to as the “Isabella anomaly”) does not underlie the main Sierran batholith but lies to its southwest. Initially, direct evidence connecting the P-wave anomaly to the root zone was lacking. Two recently published studies [*Boyd et al*., 2004; *Zandt et al*., 2004] from the Sierra Paradox PASSCAL broadband experiment have provided new insights into the removal process but have also raised new questions.

The 1997 Sierra Paradox experiment (SPE) consisted of a 22-station broadband deployment in the southern Sierra Nevada. The PASSCAL stations and five permanent stations in the Caltech network in this area (**Fig. 2**) recorded the teleseismic data used to compute and stack receiver functions in common conversion area bins [e.g., *Dueker and Sheehan*, 1997; *Gilbert et al*., 2003]. A crustal thickness map based on contouring the Moho *P*-to-*s*-converted phase (*Ps*)



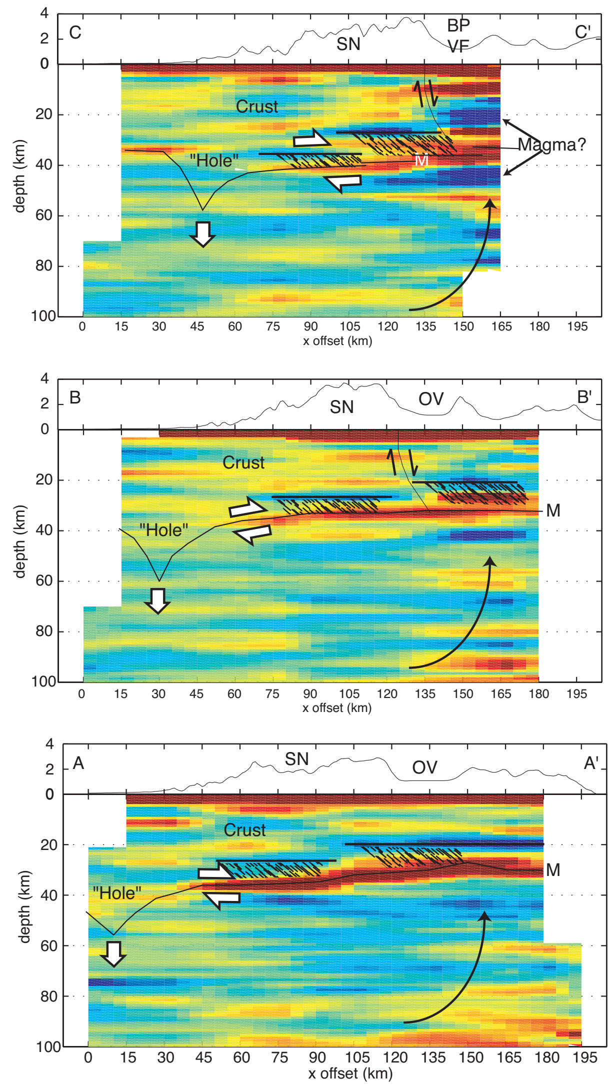


Fig. 2. Blue diamonds are broadband stations used in this study. Thick black lines are contours of Moho depths (in km) estimated from stacked receiver functions. Thin black line with blue transparency outlines region with no Moho arrival in the stacked receiver functions that is interpreted as a Moho hole (see text for further explanation). The three cross sections (A-A', B-B', C-C') are shown to right. The cross sections are from a 3D model of stacked receiver functions migrated into the depth domain. Red areas represent large positive amplitudes (increase in wavespeed with depth), and blue areas represent negative amplitudes (decrease in wavespeed with depth). Hachure beneath prominent blue layers in crust represents east-dipping planar fabric producing seismic anisotropy. The V-shaped Moho holes are discussed in the text. The topography along the cross section is plotted above each section.

reveals a complex pattern of thickness variations in the Sierra Nevada and surrounding regions (**Fig. 2**; *Zandt et al*. [2004). Consistent with previous results from a refraction survey [*Ruppert et al*., 1998] the crust is observed to thicken westward, forming a crustal welt with a maximum thickness of 42 km beneath the Kings volcanic field. A new result was the identification of an area of absence of converted energy from the Moho, or a Moho "hole." This feature is best observed in cross sections.

Three NE-SW receiver function cross sections are shown in **Fig. 2** with some interpretations overlain. The Moho is a large-amplitude, positive-polarity (red) arrival at depths between 30 and 42 km. In all the cross sections, the Moho is a smooth interface, deepening gradually to the west, where the amplitude diminishes abruptly beneath the western foothills and the Great Valley. An absence of a clear wide-angle Moho reflection (PmP) from this portion of the crust was noted in the active source experiments, but it was attributed to noisy recording conditions in the Great Valley [*Fliedner et al.*, 2000]. In contrast, all the broadband stations were located on Mesozoic bedrock sites, and examination of data from the six stations sampling the region of absent Moho, some of which extend well into the western flank of the range, show the disappearance is not due to interference from basin-generated noise.

Crustal features appear to align along a SSW-NNE trend from near Bishop to the Tulare Lake Bed (**Figs. 1 & 2**). Along this trend are the center of the region of potassic volcanism, the crustal welt beneath the Kings volcanic field, the Moho hole beneath the adjacent foothills, the center of the surface projection of the mantle drip, and the Tulare dry lakebed. A related observation is the recognition of a subsiding sub-basin in the Great Valley centered above the mantle anomaly [*Saleeby and Foster*, 2004]. Ongoing work reconstructing sedimentation patterns suggests that the local sub-basin began forming at ~3–4 Ma and that it has migrated southwest to its current position [*Saleeby and Foster*, 2004]. *Zandt et al.* [2004] suggest that an active southwest-migrating convective instability is responsible for connecting all these observations. The alignment of features in the Sierra Nevada and the absence of similar features to the west suggest a strong asymmetry to the process. The localized crustal welt beneath the Kings volcanic field may reflect viscous drag at the base of the crust in the wake of southwest mantle motion. Numerical models of analogous convective instabilities [*Pysklywec et al.*, 2002] show that at the point of downward detachment of the lithosphere, the lower crust will be entrained several tens of kilometers or more into the downward flow, providing an explanation for the V-shaped Moho hole. The surface expression of the this crustal foundering would be subsidence produced by viscous coupling between the downwelling drip and the overlying crust.

Another prominent feature in the cross sections in **Fig. 2** is a series of en echelon negative-polarity arrivals (blue) observed in the mid- to lower crust (at depths of ~20-30 km) throughout the study region. Analysis of directional variations in the negative-polarity arrival on the radial receiver function and its associated arrival on the tangential receiver function [*Levin and Park*, 1998] suggests the presence of an anisotropic layer at the base of the crust composed of an east-dipping fabric. The azimuthally varying observations are consistent with models having a planar fabric striking N-S to NW-SE and dipping at some amount greater than ~45° downward to the E or SE. *Zandt et al.* [2004] suggest the anisotropic fabrics observed near the crust-mantle boundary are associated with a shear zone between the crust and the foundering root. Their preferred interpretation is that the dipping fabric is related to fluid- or melt-filled fractures or veins formed during the initial stage of shearing. Cracks, fractures, or veins formed during shearing will align in a direction antithetic to the shear direction; hence such features would be consistent with bottom-to-the-west shear. Fluids or melts are generally required to open and propagate fractures at these depths. (Perhaps the recent observation of a deep crustal magma injection event near Lake Tahoe (Fig. 1) is a related phenomenon [*Smith et al.*, 2004].) An alternative interpretation is that the anisotropy is due to oriented micas, and the fabric is controlled by the development of an S-C fabric, a typical metamorphic fabric developed in shear zones [*Davis and Reynolds*, 1996]. In this case, the observed orientation of the anisotropy indicates top-to-the-west shear, the opposite sense of the root moving westward into the drip (top-to-the-east sense of shear) but possibly consistent with an earlier phase of extension.

Seismic tomography based upon the Sierran Paradox seismograms simultaneously reinforces the idea that material is foundering and challenges the conceptualizations of how this is occurring. *Boyd et al*. [2004] inverted teleseismic P, S_{fast}, and S_{slow} travel times and t* measurements on S waves to obtain 3-D images of variations in v_P, v_P/v_S, transverse anisotropy, and seismic attenuation beneath the southern Sierra (**Fig. 3**). (The fast and slow components of S waves were

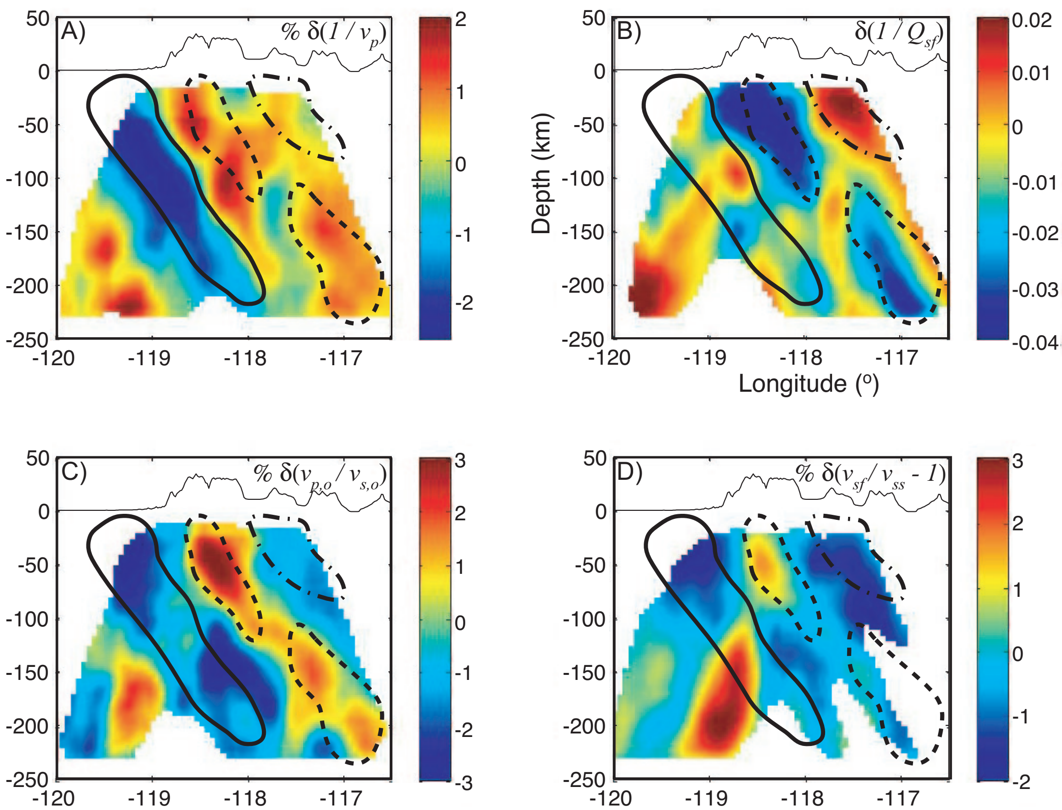


Fig. 3. Vertical slices of southern Sierra tomographic models and derived quantities: percent change in P wave slowness (A), change in attenuation (B), percent change in anharmonic v_P/v_S ratio, where v_S is taken from the average of the fast and slow models (C), and shear wave anisotropy, where the slow model is derived as residuals from the fast model (D). The solid lines indicate regions of descending garnet peridotite, and the dashed lines delineate regions of garnet pyroxenite. The regions of low velocities and high attenuation above the garnet pyroxenite are presumably the infilling of asthenospheric spinel peridotite (dashed-dot outlines). Topography is depicted with 10 times vertical exaggeration. From *Boyd et al*. [2004].

defined as being the components parallel to and perpendicular to the SKS fast direction of N80°E). These revealed east- to south-east plunging anomalies that are most simply separated into a deeper, more westerly high v_P, low v_P/v_S, moderately attenuating body and an adjacent shallower low v_P, high v_P/v_S, but non-attenuating body. The first is essentially the previously described high wavespeed anomaly; the second body was previously thought to be part of upwelling asthensosphere, but the very low attenuation suggests that it is in fact cold. Calculation of the expected seismic wavespeeds of garnet pyroxenite (the eclogitic facies erupted as xenoliths) shows that, largely because these rocks are free of jadeite, they should have low v_P (unlike eclogitized oceanic crust) and high v_P/v_S. Contrary to common wisdom, these particular "eclogites" are seismically distinguishable from garnet peridotites (see Fig. 3 of *Boyd et al*. [2004]). Thus it appears that the garnet peridotites originally below the garnet pyroxenites as inferred by *Ducea and Saleeby* [1996] remain in the same relative structural positions; their current geometry appears most similar to a delamination of lithospheric material from the crust.

The tomography suggests several puzzles that need to be unraveled. The northeast strike of the foundering material is difficult to understand; this might in part prove to be an artifact, as coverage to the northeast was poor for some key parameters. If true, it indicates that asthenospheric upwelling does not cause the modern high elevation of the Sierra, as is currently expected. The presence of fairly shallow pyroxenites under the Big Pine volcanic field is also a challenge because it is not represented in the young xenolith population. The resolution of the tomography remains poor under the San Joaquin volcanic field and could be improved under the Kings and Big Pine volcanic fields; the tomography doesn't yet connect the drip with the regions that experienced potassic volcanism. Improved confirmation that the foundering material remains stratified will pose a major challenge to convective models for lithospheric thinning.

Sierra Nevada Earthscope Project (SNEP) and Problems to be Studied

Seismological characteristics of the Sierran crust and mantle will be obtained from a ~2.5 year deployment of forty broadband sensors, deployed twice occupying 80 sites, and timed to take advantage of the deployment of the Bigfoot component of US Array (**Fig. 4**). The first deployment will cover an area north of existing coverage to extend the results from the Sierra Paradox experiment [*Boyd et al*., 2004; *Zandt et al*., 2004] across the northern terminus of the area of recognized 3-4 Ma potassic volcanism, a possible indicator of the northern extent of root removal. This network will also provide data to resolve how regional crustal structures are related to the Long Valley volcanic complex, encompass the zone of deep crustal earthquakes in the foothills north of Fresno, and provide coverage of the diffuse northern terminus of the ECSZ. Our deployment will improve station spacing from the 70 km Bigfoot spacing to ~25 km, comparable to the Sierra Paradox experiment—and necessary to separate crustal and upper mantle variations in a tomographic inversion and permit correlation of conversions found from receiver functions (**Fig. 5**). Anisotropic properties will be extracted from both teleseismic S and SKS waves and locally-converted (*Ps*) phases. The concurrent deployment of Bigfoot provides a common framework for all three deployments; this will expand our areal coverage and allow us to combine spatially and temporally distinct datasets. Next, the same 40 instruments will be redeployed in a dense (~5 km spacing) transect to study the critical crust/mantle zone with greater resolution. This profile spacing is comparable to those that have produced spectacular images in the Cascades [*Bostock et al*., 2002]. Three possible transects are shown in **Fig. 4**. Transect "A" extends from near the center of the tomographic high-velocity feature northeast across the Owens Valley near Big Pine volcanic field and into the Nevada Basin and Range. This line has the advantage of following the line of root removal from its possible area of origin all the way into the drip (**Fig. 2**). Another possibility (Transect "B") is approximately parallel to A but displaced about 100 km to the northwest. This transect follows highway 120 and may be the easiest to deploy logistically. Another possibility is shown schematically as line "C" and could be very interesting because it would cross some significant crustal transitions and end in Long Valley. We will decide on a final transect location after we have preliminary results from the 2D deployment.

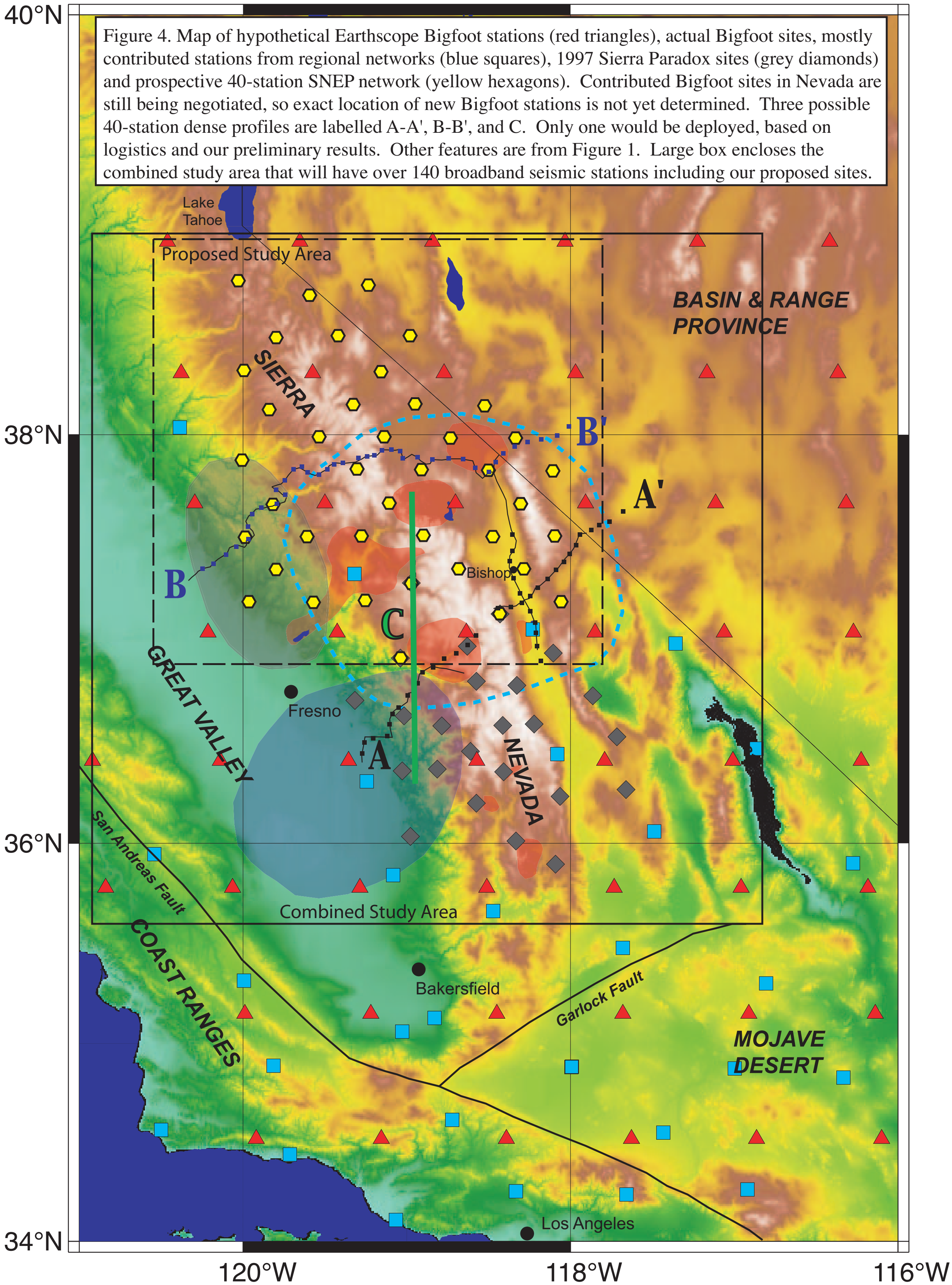


Figure 4. Map of hypothetical Earthscope Bigfoot stations (red triangles), actual Bigfoot sites, mostly contributed stations from regional networks (blue squares), 1997 Sierra Paradox sites (grey diamonds) and prospective 40-station SNEP network (yellow hexagons). Contributed Bigfoot sites in Nevada are still being negotiated, so exact location of new Bigfoot stations is not yet determined. Three possible 40-station dense profiles are labelled A-A', B-B', and C. Only one would be deployed, based on logistics and our preliminary results. Other features are from Figure 1. Large box encloses the combined study area that will have over 140 broadband seismic stations including our proposed sites.

Within the combined study area (**Fig. 4**) there will be ~140 broadband sites (combining 40 SNEP network stations, 40 transect sites, ~40 Bigfoot sites, and ~20 Sierra Paradox sites). With an investment of only 40 instruments, this project will provide sampling similar to SPE for an area 3 times larger in size, and provide a dense transect with unprecedented resolution of crust-mantle interactions. By combining data and analyses from all available stations we will not only extend the coverage but also greatly improve the resolution for the entire region. In addition, the common stations between the 3 networks will help stitch together the data sets. With this expanded coverage and enhanced resolution we will be able to address the following questions.

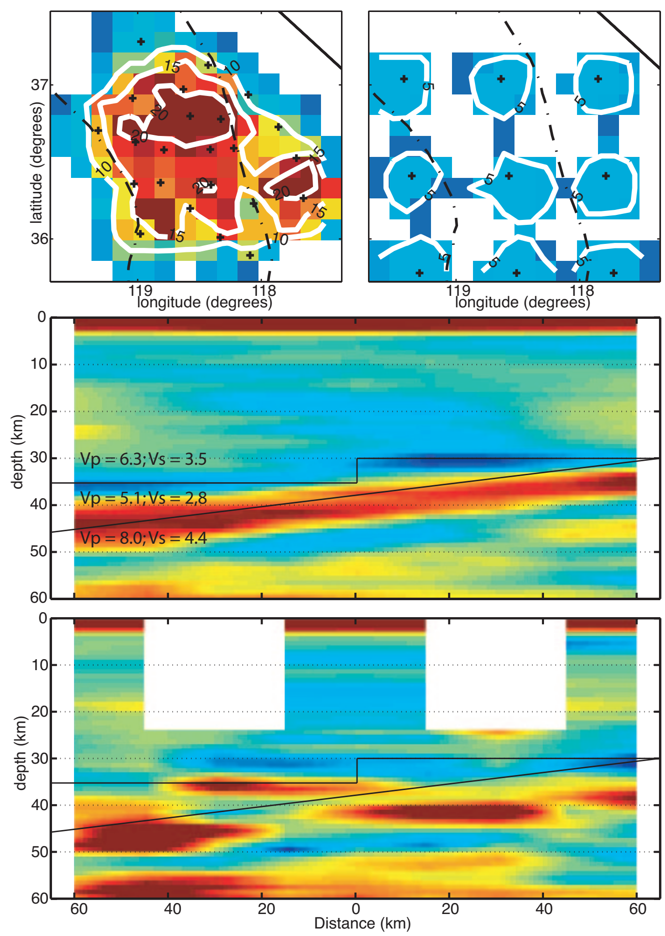


Fig. 5. Top: map views comparing the density of sampling in 15 km^2 bins at 50 km depth for the SPE array (upper left) and USArray Bigfoot array (upper right). Lower: cross-sections illustrate results of stacked synthetic finite-difference receiver functions generated for the seismic structure overlain on the images. Vp and Vs in km/s of each layer is noted on the central panel. Central panel has station distribution similar to SPE array and lower panel uses station spacing closer to that of Bigfoot. White areas have no sampling.

1. Is the removal of the eclogitic root limited to the southern Sierra or does it continue farther north along the trend of the Mesozoic batholith? One of the outstanding issues regarding batholithic root foundering is whether the entire Sierra Nevadan batholith developed and then lost an eclogitic root. The limited extent of known eclogite facies xenoliths and highly potassic volcanic rocks combined with the limited north-south extent of the Isabella anomaly has suggested that only a small portion of the Sierra overlies asthenosphere that replaced eclogite [*Zandt*, 2003]. Drowning of Sierran topography at the western margin of the range also seems to have a limited north-south extent [*Zandt*, 2003; Fig. 1], as does increased sedimentation in the southern San Joaquin Valley [*Saleeby and Foster*, 2003]. *Zandt* [2003] inferred from these observations that eclogite was removed only from a circular region of the Sierra and that in descending into the mantle, the material entrained in its tail became offset to the southwest by flow in the asthenosphere.

A different interpretation has come from considering the tectonic effects of removal of dense eclogite. The isostatic response to removal should raise the Sierra and promote crustal extension, perhaps to the point of driving crustal thinning. Indeed, the northernmost Sierra seems to have risen since 5 Ma [*Unruh*, 1991; *Wakabayashi and Sawyer*, 2000; 2001; *Jones et al.*, 2004], when initiation of major extension along the east front of the Sierra began [references cited by *Jones et al.*, 2004]. If these phenomena resulted from the removal of eclogite, then removal should extend far north of Lake Tahoe. Furthermore, any eclogite removed from the northern Sierra is unlikely to have traveled to the Isabella anomaly but might contribute to the Redding anomaly at the north end of the Sacramento Valley [*Jones et al.*, 2004].

Existing tomography suggests that the Isabella anomaly extends about 100 km north-to-south, yet high elevations in the Sierra extend at least twice that far and possibly more. If removal of eclogite is responsible for these elevations, then the foundering process changes the dimensions of the foundering body. If this is the case, then the foundering process must be an intrinsically 3D process that cannot be modeled in 2D, as is presently the norm. With the proposed network we should be able to unambiguously determine whether the area of removal is different from the area of the drip (note we are talking about area, not volume), and thereby establish the suitability of the 2D models. Our results will provide critical insights for designing new numerical experiments on this process, a component of the coordinated interdisciplinary studies.

If the eclogite was only removed from a portion of the Sierra, defining that portion will be critical in separating the influence of such a process on surface tectonics from whatever else is supporting the elevations of the remainder of the Sierra. There are two plausible attacks that should address this. Tomography building from the *Boyd et al.* [2004] work can identify the present positions of any eclogite and garnet peridotite as well as upwelling asthenosphere. Identification of structural and anisotropic features in the lower crust or upper mantle associated with the displacement of foundering material should also provide an important constraint on the extent of eclogite removal.

2. Does the eclogite founder by a true delamination (tearing) process, as a convective instability, or some combination? How important is shearing in the process? The structures seen in the Zandt et al. [2004] work suggest that subhorizontal simple shear across the Moho was important in the process of removing eclogitic material that used to be below, yet a true delamination process would have pure vertical elongation across the Moho prior to injection of asthenosphere between eclogite and modern crust (**Fig. 6**). One possibility is that the lower crustal fabrics seen by *Zandt et al.* [2004] are in fact the deep roots of extensional faults farther east, in which case they put little constraint on the mode of foundering. Another is that asymmetry in development of a Rayleigh-Taylor (R-T) instability can preserve existing compositional layering, leaving a structure like that imaged by *Boyd et al.* [2004]. A key constraint on this will be mapping the extent of the lower crustal fabric and any variations in its orientation over the Sierra and surroundings and contrasting that with the presence or absence of eclogitic rocks as determined from the tomography. The proposed dense (5-km-spacing) transect will greatly improve on the resolution available from the Sierra Paradox data (**Fig. 2**). These observational constraints will be critical to evaluating any new modeling of R-T instabilities in the presence of strong asymmetry.

Closely related to the lower crustal flow discussed above is the certainty that any sinking of eclogite must induce flow of material to replace it. With the presence of overlying, less mobile crust, strong structural fabrics should develop in the deformed rocks, which xenoliths erupted in the past million years show to be peridotite. This flow could be modified by an asthenospheric wind as suggested by *Zandt* [2003], but such modifications ought not affect rates of descent or thinning of mantle lithosphere. SKS shear-wave splitting measurements constrain the gross anisotropy in the upper mantle.

Another approach to anisotropy is variation of travel times of lower crustal and upper mantle regional phases with azimuth [e.g., *Hearn*, 1996; *Zhao*, 1993]. With adequate azimuthal and spatial coverage, such phases produce much better depth resolution than teleseismic analyses (because they do not travel deeply). With the active seismicity along the San Andreas fault and portions of western North America, we should acquire sufficient arrivals to use this approach.

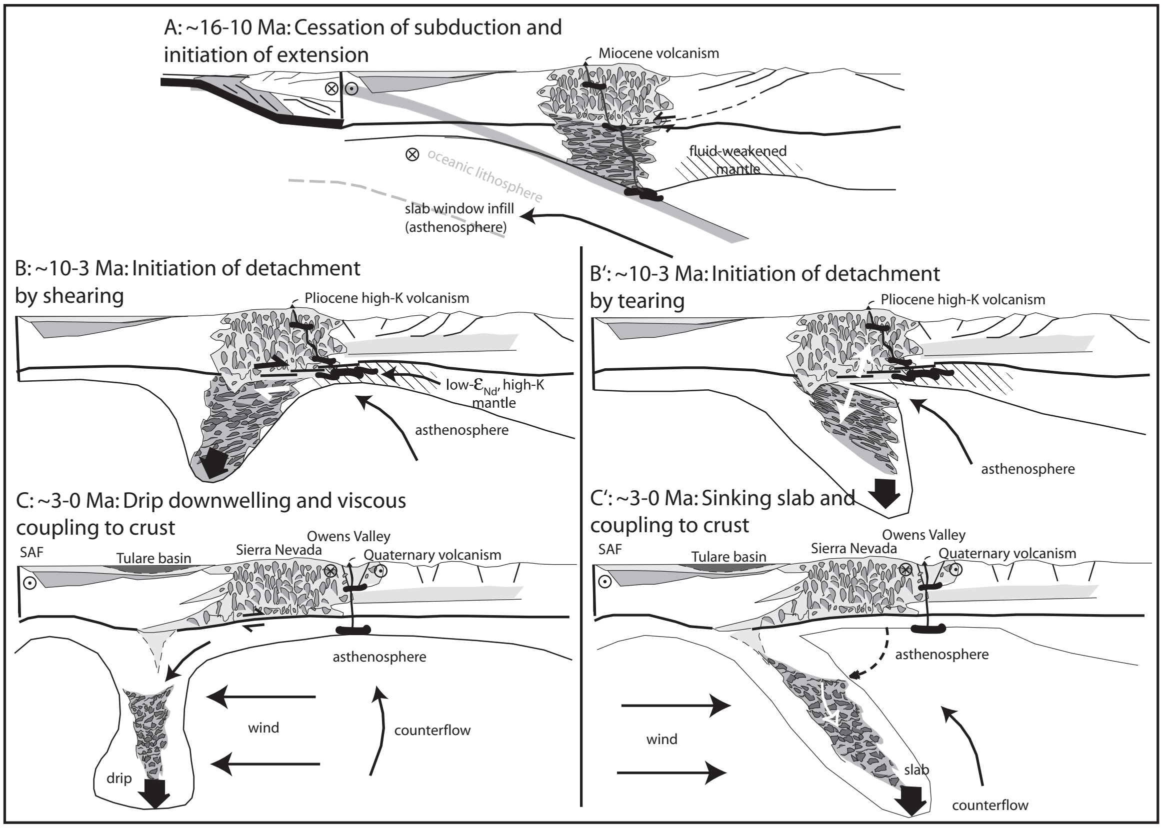


Fig. 6. Two possible sequences of the foundering of the ultramafic root of the southern Sierra Nevada batholith starting from the same initial state (panel A). The left sequence (panels B and C) is dominated by shearing during initial detachment followed by a convective instability (drip). The right sequence (panels B' and C') is initially dominated by tearing then sinking (delamination).

Shear wave splitting, regional phases, and receiver functions provide information on azimuthal variations in shear-wave velocities but are insensitive to radial anisotropy, which is likely to be present in the vicinity of downwelling drips and asthenosphere. Dispersion relations between phase and group velocities of Rayleigh and Love waves over a broad range of frequencies will allow for investigation into the spatial extent and depth range of both radial and azimuthal anisotropy in the crust and upper mantle [e.g., *Anderson*, 1961; *Ritzwoller et al*., 2001; *Forsyth et al*., 1998; *Shapiro et al*., 2002]. The regional coverage provided by USArray stations will be particularly valuable for any surface wave dispersion studies of this type.

3. Is there a structural connection between the removal process and volcanic fields and earthquake zones? Removal of continental lithosphere has been invoked to drive a large number of important tectonic events, yet the evidence connecting events to removal is often nothing more than temporal coincidence or theoretical possibility. For instance, in the Sierra the foundering has been invoked to explain the uplift of the range, Basin and Range tectonism along the entire western edge of the Great Basin, volcanism along that same boundary, the localization of right lateral shear along the east side of the Sierra, and, more indirectly, the creation of the California Coast Ranges [*Ducea and Saleeby*, 1996; *Jones et al.*, 2004; *Zandt*, 2003; *Zandt et al.*, 2004]. A very important piece of information missing at present is the exact extent of foundering, which will be obtained as described above. Assuming that dense lithosphere was removed from regions that have exhibited some of the effects just mentioned, detailed subsurface work will help connect the surficial tectonic features with structures at depth associated with the foundering process. For example, a comparison of crust-mantle structures beneath the dominantly basaltic Big Pine volcanic field and the silicic Long Valley complex would be valuable in understanding the regional scale volcanism. We will address this through the deployment of the dense (5-km-spacing) profile, which will permit imaging of structures to within 5 km of the surface [e.g., *Wilson et al.*, 2003, 2004]. This will form the basic constraints on more fully physical models of the effect of lithospheric removal on crustal tectonics and magmatism.

Downwelling material directly below the crust should induce stress within the crust [e.g., *Fleitout and Froidevaux*, 1982] as well as produce major thermal perturbations. In the southern Sierra and over the Isabella anomaly, seismicity is rare, either because the crust is strong, the drip is too deep, or the drip is neutrally buoyant. What rare seismicity occurs tends to be deep in the crust [*Mooney and Weaver*, 1989; *Edwards and Jones*, 1998], but the central and northern Sierra has long been recognized for its unusually deep seismicity [*Wong and Chapman*, 1990; *Miller and Mooney*, 1994]. Previous studies in California demonstrated that focal mechanisms of small to moderate earthquakes can be analyzed to obtain a 3-D snapshot of upper crustal deformation [*Unruh et al.*, 1996; 2002; *Unruh and Lettis*, 1998; *Unruh et al.*, 1997]. Preliminary studies of seismicity in southern California have correlated crustal thickening in the Transverse Ranges with thickened and negatively buoyant upper mantle, and crustal thinning in the southern Sierra Nevada with thin and positively buoyant upper mantle [*Unruh et al.*, 1998]. The diffuse zone of earthquakes (up to M_L 3.2) in the mid- to lower crust at depths of 10 to 40 km beneath the western Sierra foothills [*Wong and Savage*, 1983; *Wong and Chapman*, 1990] were used in a local tomography study [*Miller and Mooney*, 1994]. A recent swarm in the lower crust beneath Lake Tahoe was interpreted as evidence for deep magma injection [Smith et al., 2004], a process that the authors suggested may also account for the deep earthquakes in the Sierran foothills. We will test the hypothesis that similar correlations between vertical deformation and buoyancy forces are present in the vicinity of the high-speed anomaly south of Fresno. Focal mechanisms and earthquake locations will both greatly improve with observations from this deployment, better resolving the orientation of seismogenic and possible magmatic stresses.

Integrating with Complementary Studies In the end, we expect to obtain some of the best observational constraints on the deep structure of the southern and central Sierra Nevada and how lithosphere is removed through the studies discussed above. We plan to complement the new seismological data with other geophysical and geological studies from ongoing projects and new projects funded through other programs. These will provide further constraints on the lateral extent of lithospheric removal and the time-space-composition evolution of the upper mantle beneath the Sierra Nevada during the Late Cenozoic. Numerical experiments will help integrate the whole and address the core questions of why events have proceeded as observed.

Broader Impacts As a major integrated science project and an early EarthScope Science project, the research funded through this award can make broad, long-term impacts on geoscience research and education. Multi-disciplinary, integrated approaches are increasingly required to address major problems, but most programs still push graduate and undergraduate students into narrower specialties. Graduate students participating in this project will interact with students and faculty in other subdisciplines that are equally important to addressing a large-scale problem in lithospheric dynamics. In conjunction with our colleagues undertaking complementary studies, the investigators will be submitting a separate NSF Research Experiences for Undergraduates (REU) Site proposal to involve undergraduate students in an Integrated Science Camp with the goal of exposing these students to a multi-disciplinary investigation early in their academic careers. Students will both participate in data collection in their area of interest and jointly discuss and integrate their individual results to gain an appreciation for the importance of using a diverse set of observations when trying to understand complex processes. With partners in K-12 outreach (such as CU's CIRES Education Outreach program), we will also seek funding from NSF's Research Experiences for teachers (RET) program to bring K-12 teachers into the field. Because they bring our science to the public, we will work with National Parks in the Sierra to enhance their displays and demonstrations with materials like computer animations of landscape development and hands-on models of the physics of removal of the mantle lithosphere. As the EarthScope Education and Outreach program evolves, we will emphasize integration of results and products of this project with the overall community outreach effort.

Timetable and Project Management The SNEP seismology component consists of two deployments of 40 USArray FlexArray broadband instruments over a 2.5-year period beginning in the Spring of 2005 and ending in the Fall of 2007. These deployments will be linked by the ~20 Bigfoot broadband stations in the region to provide coverage regionally and in other key areas. For the first deployment, with installation beginning in early summer 2005, the 40 broadband instruments give us an effective station spacing of about 25 km throughout the Sierra Nevada. This spacing is comparable to the Sierran Paradox Experiment that has produced good images of crustal and upper mantle variations in the southernmost Sierra. This deployment will require most of the Flexible Array broadband instruments during Year One, but represents a continually decreasing percentage of the pool as acquisitions continue over the course of the experiment. After about 16 months of recording, we will redeploy the 40 instruments into a dense profile with a station spacing of about 5 km. This profile is comparable to those that have produced spectacular images in the Cascades [*Bostock et al.*, 2002]. This will allow us to investigate the transition between the zone of delamination and surrounding regions in high resolution to understand the detailed effects of the causal processes. This second deployment will record for about 10 months, through the summer of 2007.

The seismology field work and analysis will be shared by the University of South Carolina, the University of Arizona, and the University of Colorado-Boulder, all of which have considerable experience managing PASSCAL deployments. A large seismic deployment moving yearly and continuously operating for over two years requires a major commitment of personnel for both field work and analysis. By spreading this load among the three universities, we can keep up with both the analysis and field work over the duration of the project. We have budgeted for one crew from each university during the initial mobilization and redeployment period. Then, we will share responsibility for servicing the array during the year. Our budgets are prepared assuming a standard PASSCAL-style deployment with quarterly servicing of all stations. We would prefer to use telemetry as much as possible since it provides access to the data much sooner for analysis. However, there are still some unknowns in the exact capabilities and conditions on FlexArray telemetry, so we cannot be certain that it will work in the rugged, remote Sierran terrain. During Year 1, we will evaluate the feasibility of using FlexArray telemetry systems. Telemetry costs more initially as the sites are somewhat more difficult to install and have higher power requirements. These costs will be offset by the reduced need for servicing, so we are comfortable that our budget will support either mode of operation or a hybrid. Analyses responsibilities will be divided between the three groups according to interests and expertise and will be determined relative to our most important scientific goals.

The timing of the SNEP project relative to the Bigfoot is critical as Bigfoot sites provide important additional coverage while tying the SNEP deployments together. The timing of the two deployments is ideal. On the front end, we will be installing SNEP near the end of the BigFoot ramp-up in the area. On the back end, our dense deployment concludes a few months before the critical Bigfoot stations migrate out of the region. This provides the necessary overlap of the deployments as well as an adequate preparation period for our deployment. This is summarized in the following timetable.

2005: Bigfoot stations continue to come on-line through Fall, 2005
Seismology Planning Workshop, Tucson, ASAP after funding
First Interdisciplinary Sierra Workshop, Boulder, Colorado, late winter
Permitting seismological deployments, early Spring
Deployment of 40 FlexArray broadband seismometers, beginning in April

2006: Seismometers shifted to dense profile, late summer/early fall
Ongoing analysis of seismological data (tomography, receiver functions, etc.)

2007: Dense profile removed, late summer
Ongoing analysis of seismological data (tomography, receiver functions, etc.)
Seismotectonic analysis of northcentral Sierra and foothills

2008: Second Sierra Workshop, Tucson, Arizona
Integration of results
Publication of seismological and integrated results
Bigfoot array begins to leave California, October

Results of Prior NSF Support

G. Zandt: *Crustal Anisotropy and Mantle Stratigraphy in the Tibetan Plateau and Central Andes*, EAR-0125121, $101,217, 2002-2004, with no-cost extension to 2005. Waveform modeling of receiver functions using a global minimization inversion technique applied to receiver function back-azimuth record sections from the Tibetan Plateau has yielded a suite of crustal models that include anisotropy. Publications to date resulting from this project: [*Sherrington et al.*, 2003; *Frederiksen et al.*, 2003; *Leidig and Zandt*, 2003; *Zandt et al.*, 2003; Zandt et al., 2004]

T.J. Owens: *Reflections under the Scottish Highlands*. EAR-0074002, $284,075, 9/00-8/04. PASSCAL broadband deployment for continental lithospheric structure, includes minority student training and data submission to the IRIS DMC. Publications to date: [*Helffrich et al.*, 2003; *Asencio et al.*, 2003].

C. H. Jones: *Continental mountains in extensional environments: The Sierran paradox: A collaborative research proposal*, EAR-9526974, 1/1/96 to 12/31/98, $274,430 (CHJ). Deployment of 24 broadband seismometers yielded large variations in SKS splitting, whichlead to expansion of Sierran lid removal hypothesis. [*Jones and Phinney*, 1998; *Jones et al.*, 2004; *Boyd et al.*, 2004; *Zandt et al.*, 2004; *IRIS DMC dataset XJ-97*].

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