Collaborative Research: Lithospheric removal: The Sierra Nevada as the prototype of a fundamental process in mountain building

Project Summary

Removal of the lower parts of the lithosphere may play a fundamental role in both continental tectonics and the development of continental crust. 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 geophysical and geologic studies of the Sierra Nevada in eastern California. Recent work in the Sierra Nevada has revealed that garnet-rich eclogite facies rocks and peridotitic mantle lithosphere under the range since the Mesozoic were removed by about 3.5 Ma and now sink as one or more drips beneath the Central Valley. Removal of this material may have caused the late Cenozoic rise of the Sierra, subsidence of its western foothills, Quaternary volcanism and extension in Long Valley and along the eastern edge of the Sierra, shortening in the California Coast Ranges, and a possible reduction in the slip rate of the San Andreas fault system. These possible effects can be tested through comparison with the history of lithospheric foundering and numerical experimentation.

Intellectual Merit. The young age of this event allows us to pose a number of questions that bear on the general process of removal of lower continental lithosphere:

1. What geologic events accompany removal, both at the surface and at greater depth?
2. How has material been removed?
3. What conditions facilitate removal of lithosphere?

New magnetotelluric profiles across the Sierra will be complemented by analysis of volcanic rocks along the Sierra, the xenoliths that they carry, geomorphic expression of the resulting patterns of rock uplift and subsidence, seismotectonics above the drips, and numerical experimentation. These will constrain 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 be employed to provide a physical test for connections between geologic observations and lithospheric foundering and to better constrain the physics of lithospheric foundering. Our investigations will be coordinated with an associated EarthScope project. The EarthScope project focuses on seismological investigations using the FlexArray and Transportable Array components of the EarthScope facility.

A major goal of this study is to gain understanding of how mantle lithosphere is removed, and the conditions that facilitate such removal, so that this understanding can be exported to other regions. Removal of lithosphere is commonly cited as an explanation for disparate observations, in some cases almost as a *deus ex machina*: the general understanding could make such inferences testable. The collaboration across multiple disciplines is essential to developing a robust understanding of this process that can be applied elsewhere.

Broader Impact. We will support several graduate students, involving them in the multidisciplinary nature of this project. We will bring several teachers into the field and develop classroom materials with them, simultaneously strengthening the solid earth component of a broader science outreach program. We will also expand efforts currently underway with National Parks in the Sierra to train their staff in interpreting the geology of the region and will provide at least one new display within the park. Integration of results and products of this project with the overall community effort to produce EarthScope products and the NAVDAT database will be emphasized.

C. Project Description*

Budget summary, in thousands of dollars

Institution	Year 1	Year 2	Year 3	Year 4	Total
U. Colorado, Boulder (seismology, geodynamic modeling, outreach, workshops, volcanic studies, geomorphology)	$265.1	$307.9	$119.8	$64.0	$757
UC Riverside (MT)	$75.4	$146.0	$127.4	$86.3	$435
U Arizona (xenoliths/batholith petrology)	$84.2	$86.4	$84.8	$0.0	$255
Calif. Inst. Tech.(batholith petrology)	$69.5	$76.8	$72.2	$0.0	$219
U. N. Carolina (volcanic studies)	$75.0	$76.6	$24.5	$12.6	$189
U. Michigan (geomorphology)	$36.4	$40.1	$17.7	$17.6	$112
Brown Univ. (experimental petrology/ geodynamics)	$11.0	$37.0	$39.0	$15.0	$102
William Lettis and Assoc. (seismotectonics)	$13.0	$21.2	$56.6	$67.6	$158
TOTAL	**$630**	**$792**	**$542**	**$263**	**$2,227**

Fundamental questions for which the Sierra Nevada offers the best field laboratory

Of the many processes proposed to affect continental evolution, perhaps the most prominent process that is not a part of basic plate tectonic theory is removal of the continental mantle lithosphere. *Bird* [1978] first proposed delamination, the peeling away of the mantle lithosphere, to explain the elevation of the Colorado Plateau and the thermal structure of Himalaya [*Bird*, 1979] (**Fig. 1a**). Others have since suggested different processes for both removal of mantle lithosphere and alteration of the thermal structure of the crust and remaining mantle lithosphere, including convective removal of part or all of the mantle lithosphere (**Fig. 1b**) [e.g., *Houseman, et al*., 1981], slab breakoff [e.g., *Wortel and Spakman*, 2000], and the creation of a slab window in the gap where negligibly thin lithosphere has been subducted [e.g., *Dickinson*, 1997]. Removal of mantle lithosphere may have played a key role in regions with histories and structures as diverse as the southern Sierra Nevada [*Ducea and Saleeby*, 1996], the Alboran Sea [*Calvert, et al*., 2000; *Platt, et al*., 1998], the Tibetan Plateau [*England and Houseman*, 1989; *Turner, et al*., 1996], the Apennines [*Wortel and Spakman*, 1992; 2000], the Appalachians [*Nelson*, 1992], central Andes [*Kay and Mahlburg-Kay*, 1991; *Beck and Zandt*, 2002], the Carpathians [*Girbacea and Frisch*, 1998; *Wortel and Spakman*, 2000], Precambrian South Africa [*Jordan*, 2004], the Tien Shan [*Chen, et al*., 1997; *Oreshin, et al*., 2002], the North China Craton [*Gao, et al*., 2004], and the Basin and Range [*Platt and England*, 1994; *Humphreys*, 1995]. Several workers have suggested that removal of mafic lithosphere could be important in understanding the deformational and chemical history of the Earth [*Arndt and Goldstein*, 1989; *Dewey, et al*., 1993; *Kay and Kay*, 1993; *Kay and Mahlburg-Kay*, 1991; *Lustrino*, 2005; *Nelson*, 1992; 1991; *Plank*, 2005; *Richardson and England*, 1979; *Rudnick*, 1995; *Zandt and Ammon*, 1995; *Zegers and van Keken*, 2001; *Meissner and Mooney*, 1998]. The removal of eclogitic material may also be responsible for the andesitic composition of average continental crust, despite having been originally formed from mafic arc magmatism [e.g., *Kay and Mahlburg-Kay*, 1991; *Ducea*, 2002]. For a variety of reasons, we consider the Sierra Nevada to offer the best laboratory for studying and understanding how mantle lithosphere has been removed.

* Color figures and compiled work plans at http://cires.colorado.edu/people/jones.craig/SierraDripsNSF

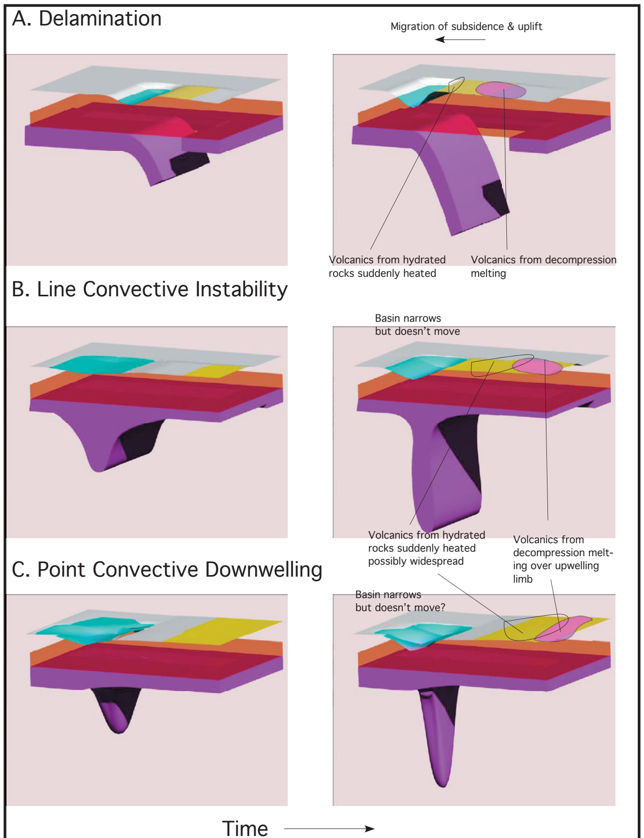

Fig. 1. Cartoons highlighting some of the potential differences between removing dense lithosphere (purple) through (a) delamination and (b) convective instability. Subsidence of the surface (top surface) is blue, uplift yellow. The bottom panels (c) illustrate a kinematic concept where the downwelling focuses into a cylinder as upwelling remains linear. Such a possibility has not yet been simulated numerically. Note that (c) has an asymmetric removal of material, which we suspect is likely in view of the plutonic origin of eclogite, but again is untested to our knowledge. In all cases shear between the continent and underlying asthenosphere could skew the geometry of the downwelling material. Animations can be found at http://cires.colorado.edu/people/jones.craig/SierraDripsNSF/

The Sierra Nevada south of about 38°N lost mantle lithosphere and mafic lower crust between ~10 and 3.5 Ma; lavas erupted at ~10-12 Ma contained garnet pyroxenite ("eclogite") xenoliths, but those erupted at 3.5 Ma equilibrated at higher temperatures and are devoid of eclogite [*Ducea and Saleeby*, 1998a; *Ducea and Saleeby*, 1996; *Farmer, et al.*, 2002; *Manley, et al.*, 2000]. Near this area lies one of the largest P-wavespeed anomalies in the upper mantle of the western U.S., which suggests downwelling of cold, dense material that presumably was removed from beneath the Sierra Nevada [*Benz and Zandt*, 1993; *Biasi and Humphreys*, 1992; *Jones, et al.*, 1994; *Raikes*, 1980; *Humphreys, et al.*, 1984]. Removal of this material may have led to a rise of the Sierran crest, subsidence of its western foothills, volcanism in the otherwise volcanically quiet southern Sierra Nevada, volcanism and horizontal extension in the Long Valley region and elsewhere along the eastern edge of the Sierra, horizontal shortening in the California Coast Ranges, and possibly a reduction in the slip rate of the San Andreas fault system [*Saleeby and Foster*, 2004; *Jones, et al.*, 2004; *Zandt*, 2003].

The broad impact that mantle removal may have had on the face of California, alone, justifies a comprehensive test of this hypothesis. Comparably important, however, will be applying the understanding gained from such a test to other belts where mantle lithosphere many have been removed, but where the removal is either too old or in an environment too complex, or logistically too difficult, to expect a record as clear as in the Sierra. Thus, understanding how lithosphere that included a thick eclogitic root was removed from beneath the Sierra Nevada makes an ideal target for a broad interdisciplinary CD project, which in turn can build on two previous CD projects, the Southern Sierra Continental Dynamics Project (that found that the southern part of the range was supported not by thick crust, but by a hot, low-density upper mantle) and the Sierran Paradox Experiment (that discovered that eclogite had been removed from the base of the crust in the latest Miocene or Pliocene time).

We propose to study this process and its consequences:

- What geologic events occur as dense material is removed, and how are they related in space and time to removal? Surface uplift, accelerated erosion, normal faulting, subsidence and sedimentation, volcanism, and changes in plate boundary structures have all been suggested as responses to lithospheric removal.
- How has material been removed from below the Sierra? Through the development of a convective instability or some form of delamination?
- What conditions are necessary for lithosphere removal? Typical or atypical chemical or mineralogical compositions of the lithosphere, such as an eclogite? A change from subduction to a largely transform boundary? Evolution of horizontal extension in the Basin and Range Province to the east? Slow thermal re-equilibration from an unusually cold geotherm?

Relationship to the Sierra Nevada EarthScope Project (SNEP). This proposal is paired with a project by G. Zandt, T. Owens, and C. Jones that has been funded by EarthScope to conduct a seismological investigation with the FlexArray component of EarthScope in the central Sierra Nevada. Currently focused on the northern edge of the region where lithosphere is known to have been removed, the seismological work will place limits on the extent of lithosphere removal and delineate the seismological structures resulting from that removal. This CD proposal explores the variations in geological and other geophysical observations across the same region with the goal of identifying those features clearly associated with removal of the lithosphere. Although each of these studies will yield useful results without the other, the combination of them should exceed the sum of the separate parts. Logistically, the EarthScope project includes funding for a future workshop in which the PIs on this proposal are committed to participate; we include three additional workshops in this proposal to which the seismologists will be invited.

Background

Continental lithosphere differs from that beneath oceans because of its more silica-rich composition. Since Archean time the process of continent formation has involved the creation of basaltic-andesitic arcs on continental margins followed by their evolution to a chemical composition similar to andesite. One process through which that final transition can occur is the removal of a ultrabasic residue from an overlying silica-rich batholith. This could be an exceptionally common process: for instance, *Plank* [2005] has suggested that 25-60% of all cumulates over time have to have been removed from the crust in order to explain the fractionation of thorium and lanthanum in continental crust as a whole. Mesozoic southern Sierran granitoid thickness [e.g., *Fliedner, et al.*, 1996; *Fliedner, et al.*, 2000] and xenolith data [*Ducea and Saleeby*, 1998b] imply a thick (~30 km) felsic layer in the Mesozoic batholith. The thicker the felsic layer, the more likely that the ultrabasic residuum lies deep enough to form eclogitic rocks instead of granulites [e.g., *Ducea*, 2002]. Petrologically, these residual rocks represent the MASH (mixing, assimilation, storage, and homogenization) zone postulated to represent the root zone of large continental arcs [*Hildreth and Moorbath*, 1988]. The high density of residual pyroxenites (3.45-3.55 Mg/m^3) when crystallized at pressures in excess of ~1.5 GPa [*Jull and Kelemen*, 2001] should create a markedly unstable layer beneath at least some large batholiths.

The existence of such eclogitic residuum has been documented in the southern Sierra from the garnet-rich xenoliths entrained in 12-8 Ma basaltic lavas that were erupted in the San Joaquin and Kings volcanic fields (**Fig. 2**). No eclogitic xenoliths are found in lavas younger than 4 Ma in the southern half of the Sierra; instead, spinel

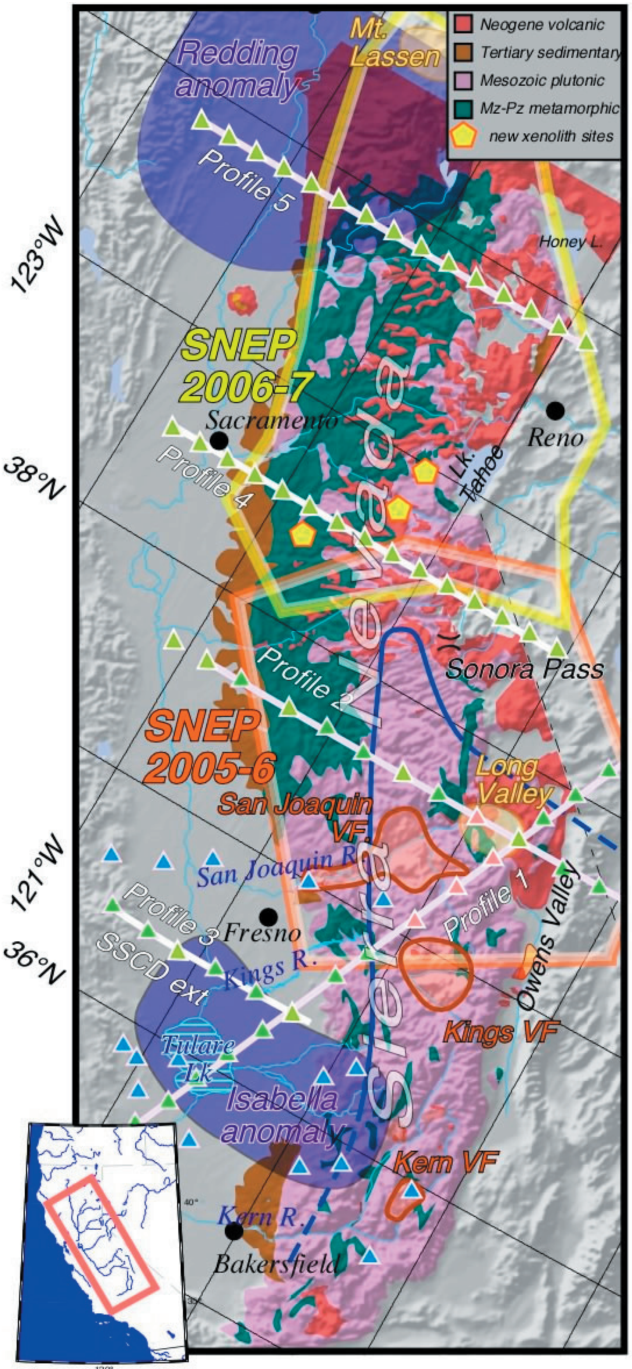

Figure 2. Simplified geology of the Sierra, with Neogene volcanic fields in the southern Sierra as indicated in orange outline. $^{87}Sr/^{86}Sr$ = 0.7060 line in blue. High P-wave speed anomalies in purple. Note the north to south changes in the width of the Cenozoic sedimentary rocks on the west flank of the Sierra, and the extensive volcanic cover in the northern Sierra. MT profiles in white; existing broadband MT site blue triangles. New xenolith localities as yellow pentagons. Outline of ongoing (orange) and phase 2 (yellow) SNEP seismometer deployment shown.

peridotites are present as xenoliths. The low ε_{Nd} and high $^{87}Sr/^{86}Sr$ values unique to the highly potassic 3.5 Ma volcanic rocks also indicate that the eclogitic rock was physically removed [*Farmer, et al.*, 2002].

The original northern extent of the deeper, garnet-rich batholith structure is unknown (**Fig. 2**), but the northward continuation of the Sierra Nevada batholith suggests that these eclogitic rocks should have been produced north of the San Joaquin volcanic field. Some ambiguity exists: the Sierran arc becomes more spread out north of about 38°N, with Mesozoic plutonic rocks under the Sacramento Valley and the western Great Basin. This broader arc might produce a wider, thinner eclogite, no eclogite at all, or a similar thickness if the eclogite is dominantly from the final massive intrusive event within the Late Cretaceous arc [e.g., *Ducea*, 2001].

With the documentation of young (between ~12-8 and ~3.5 Ma) removal of the eclogite from beneath much of the southern Sierra came recognition both that this material should be identifiable somewhere in the subsurface and that the removal of a large, negatively buoyant mass should produce a number of tectonic effects. 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 [*Benz and Zandt*, 1993; *Biasi and Humphreys*, 1992; *Jones, et al.*, 1994] (**Fig. 2**). This "Isabella anomaly" does not underlie the main exposures of the Sierran batholith but lies to its southwest. New seismic tomography from the 1997 Sierran Paradox experiment (**Fig. 3),** however, suggests that the Isabella anomaly plunges to the east and that its overall characteristics (wavespeed, v_p/v_s, seismic attenuation) are more consistent with being cool garnet peridotite than garnet pyroxenite [*Boyd, et al.*, 2004]. *Boyd et al.* [2004] suggested that a previously unrecognized low P-wavespeed body immediately above the high wavespeed body has the seismological characteristics of the eclogitic rocks.

Our knowledge of the extent and history of this event permit several possible scenarios (**Fig. 4**). Removal could be a local event requiring special conditions to occur (**Fig. 4a**), or it could have occurred along the entire arc and thus be a common result of arc magmatism (**Fig. 4b**). Removal could result in downward flow in localized pipes (**Fig. 4b, 1c**) or in delamination of narrow strips of lithosphere (**Fig. 1a**). Foundering material could produce large P-wave wavespeed anomalies or be unrecognized on P-wave images because the eclogitic rocks could have low P wave speeds [*Boyd, et al.*, 2004].

From the limited extent of known eclogitic xenoliths and highly potassic volcanic rocks **(Fig. 2)** and the limited north-south extent of the Isabella anomaly, *Zandt* [2003] suggested that only a small portion of the Sierra overlies asthenosphere that replaced eclogite. Drowning of Sierran topography at the western margin of the range also seems to have a limited north-south extent [*Zandt*, 2003], as does increased sedimentation in the southern San Joaquin Valley [*Saleeby and Foster*, 2004]. *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 lateral flow in the asthenosphere. This scenario would suggest that eclogite generation or removal requires a particular set of events not achieved throughout the Mesozoic arc and furthermore limits Neogene arc-wide tectonic events to be unrelated to removal of the lower lithosphere. If correct, this interpretation would render the removal of mantle lithosphere and eclogitic crust from the

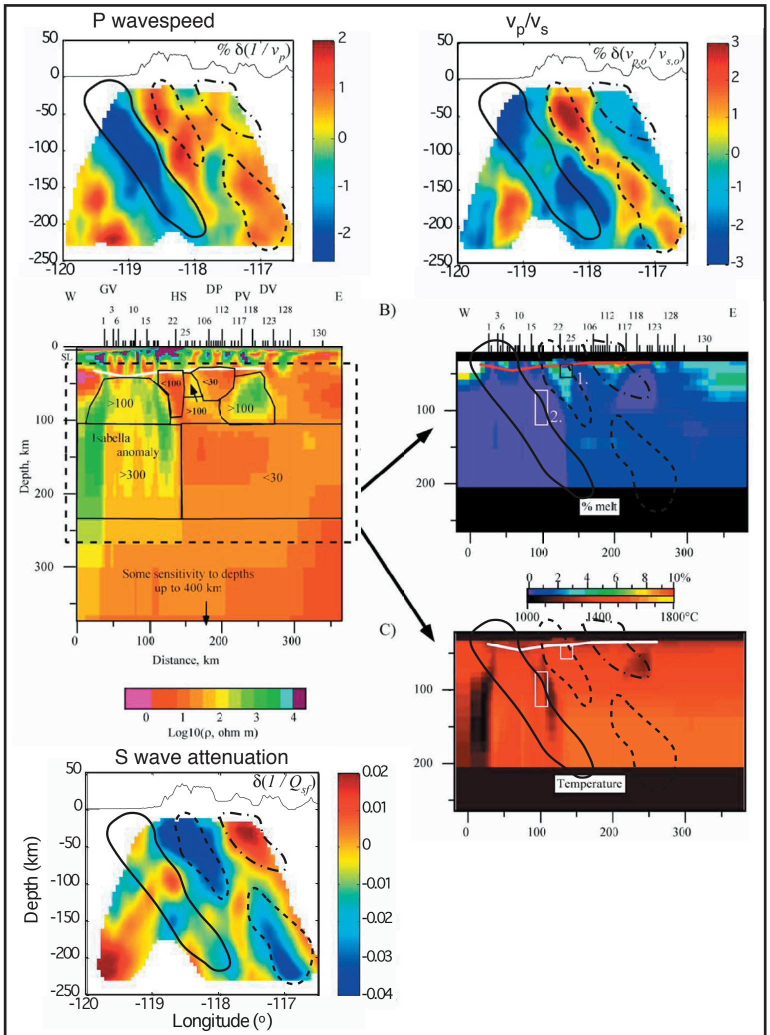

Fig. 3. Comparison of east-west geophysical profiles through the southern Sierra by Park [2004] and Boyd et al. [2004]. Profiles at left are more typical geophysical profiles (P wavespeed and resistivity); at the right are more unusual sections (v_p/v_s and attenuation, resistivity-derived temperature and melt). Outlines of bodies from Boyd et al superimposed on all profiles; solid outline to left is inferred garnet peridotite, dashed line outlines possible eclogites, dash-dot is likely warm spinel peridotite. In light of the resistivity structure, it is possible that the seismologically inferred eclogite is in fact melt-rich peridotite and the eclogite is in fact richer in garnet and present between the dashed and solid line bodies.

Sierra a special event not necessarily typical of mantle dynamics beneath mountain belts.

A different interpretation has come from considering the tectonic consequences of removal of dense eclogite. The isostatic response to removal should raise the Sierra and promote crustal extension, perhaps leading to 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 major normal faulting initiated along the east front of the Sierra began [references cited by *Jones, et al.*, 2004]. Effects could extend to thrust faulting in the Coast Ranges and an eastward shift of some Pacific-North American plate motion [*Jones, et al.*, 2004]. If these phenomena resulted from removal of eclogite, then removal should extend material far north of Lake Tahoe should also have been removed (**Fig. 2, 4B**). If downwelling material is limited to high wavespeed bodies imaged in previous seismological studies, then 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 (**Fig. 2**) [*Jones, et al.*, 2004]. This scenario suggests that removal of dense lithosphere occurred beneath much, if not all, of the Sierra and produced uplift of the entire range and normal faulting along its eastern margin. Moreover, this scenario implies that downward motion did not occur by delamination, but instead as flow localized into steep cylinders, much as rain drips off a roof, and therefore as growth of convective instability (**Fig. 1c**).

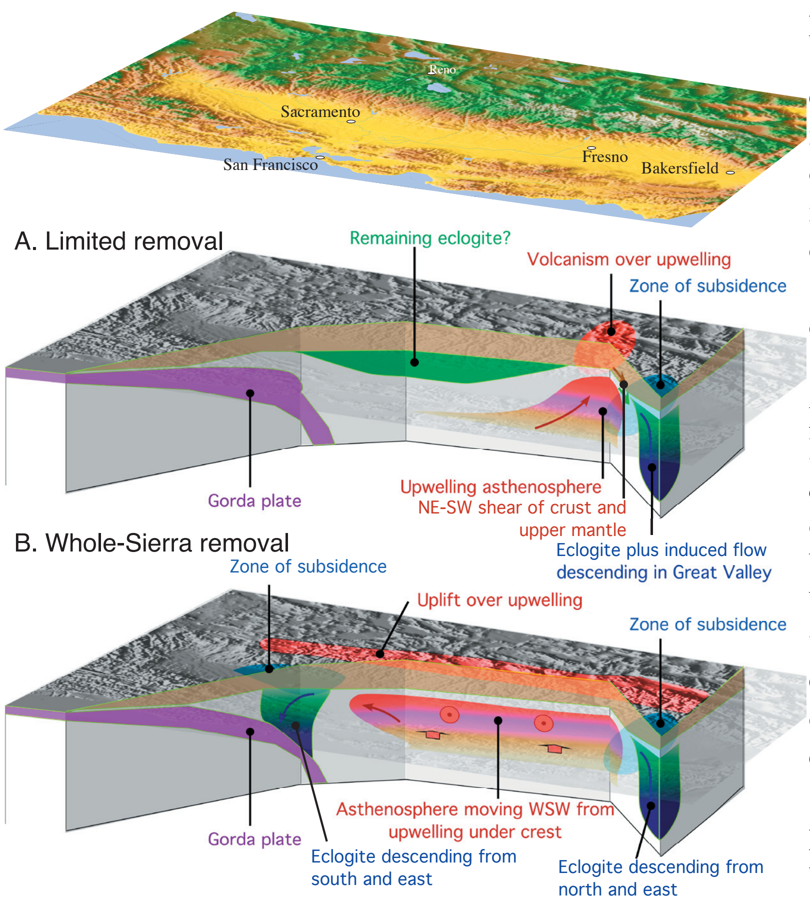

Figure 4. Two views of Sierran geodynamics (a) eclogite and lithosphere only removed in the Kings-San Joaquin area and (b) eclogite and lithosphere removed from nearly the full length of the Sierra.

A variation of this second interpretation is that downwelling of low wavespeed eclogite [*Boyd, et al.*, 2004] occurs along the length of the western Sierra (**Fig. 1b**) but that the high wavespeed Isabella and Redding anomalies arise where cold garnet peridotites are entrained in the more extensive downwelling. Differences between electrical sections, which are sensitive less to lithology than to temperature, and seismic sections can test this idea.

Our current inability to distinguish between lithospheric foundering producing the Sierra Nevada from foundering generating only some peculiar volcanic rocks and limited surface uplift highlights the present limitations of lithospheric foundering as a scientific hypothesis: it could be the key to major tectonic elements of the Cordilleran orogen, or it could be unlikely to generate much observable signal in the geologic record. Because the dense material known to have departed from the southern Sierra is tied to creation of the Mesozoic Sierran arc, the resolution of this problem lies in discovering the extent of lithospheric removal along the length of the Sierran arc. Furthermore, if observations of surface uplift, subsidence or volcanism are to be used to infer lithospheric removal, we require an improved understanding of the physical process of removal that allows us to make specific, testable predictions. Arriving at a process-based test for lithospheric foundering will require iterative comparisons of the field observations with results from numerical experiments, with each iteration both reducing the possible range of physical models agreeing with observations and identifying which observations are indicative of removal of lithosphere. Only by combining this full suite of studies in one project can we hope to know if removal of mantle lithosphere is a fundamental process of continental dynamics or of only local significance.

Problems to be studied

The general issues associated with removal of mantle lithosphere and creation of continental crust discussed above— what effects does removal produce, how is it removed, and what conditions are necessary for removal—are addressed through more observation-oriented problems discussed below.

1. What events occur as material is removed?

In order to test hypotheses of lithospheric removal in other orogens, we need to relate geologic observations to lithospheric removal both by correlation in space and time and through development of physical models of the process that are capable of predicting such observations in different environments. The primary consequence of removal of dense lithosphere would be a rise of the overlying surface [e.g., *Bird*, 1978; *England and Houseman*, 1989]. A rise of the surface can manifest itself as accelerated erosion, deformation of surrounding regions (due to the increased force per unit length applied by the higher region), and even perturbations of regional climate. Replacement of a cold mass by rising hot material can generate melt both by direct heating of fertile material and through decompression of rising material [*Farmer, et al*., 2002]. Descent of a hydrated cold body can, under certain circumstances, also yield melt [*Elkins-Tanton*, 2005; in review]. Thickening or descent of negatively buoyant material as a drip develops can produce subsidence of the overlying surface [*Bindschadler and Parmentier*, 1990; *McKenzie*, 1977; *Morgan*, 1965; *Fleitout and Froidevaux*, 1982]. The presence of loads acting on the base of the crust can induce flow within the lower crust [e.g., *Liu and Shen*, 1998; *Houseman, et al*., 2000; *Molnar and Houseman*, 2004; *Hackel*, 1966; *Pysklywec and Cruden*, 2004], and the descent of dripping material will induce horizontal flow in the upper mantle. Therefore we seek evidence from sedimentation and landscape evolution for changes in elevation; from volcanism for an abrupt heating event or changes in the sources and/or patterns in magmatic activity; and from seismic and magnetotelluric techniques for evidence of flow in the lower crust and upper mantle. Integrating these observations with numerical experiments should both greatly limit the possible causes of these signals and the physical parameters existing during this process in the Sierra.

Sedimentation of the Great Valley. Subsidence is expressed within a circular zone ~150 km in diameter where sediment-drowned mountainous bedrock exposures at the western edge of the southern Sierra [*Saleeby and Foster*, 2004] abut areas of accelerated sedimentation in the adjacent San Joaquin Valley [*Bartow*, 1991; *Moxon and Graham*, 1987]. This results in an onlap embayment reaching up to ~50 km into the western Sierra relative to adjacent areas of the foothills to the north and south.

Ongoing work by co-PI Saleeby reveals a distinct subsidence event in the Tulare sub-basin in the San Joaquin Valley commencing at ca. 3 Ma and accelerating to its highest rate at between ca. 1.2 Ma and 700 ka, after which rates declined markedly. Initial examination of additional subsurface data from industrial sources and water agencies suggests a southwestward migration of the principal depocenter over the first ~1.5 m.y. of subsidence. Such a migration pattern is consistent with models of the Isabella anomaly nucleating as a Rayleigh-Taylor instability beneath and concentrating into the densest western domain of the Sierra Nevada batholith [*Saleeby, et al*., 2003; *Zandt, et al*., 2004]. Ongoing stratigraphic work in the San Joaquin Valley also includes the subsurface mapping of a series of Neogene submarine fans and river delta fronts whose age and geometry could help resolve some of the paleolandscape issues pursued in this project by Anderson and Clark. These activities in the San Joaquin Valley are supported by the Caltech Tectonic Observatory but form an integral part of the overall scientific objective of this proposal, and the results of these studies will be openly shared as such.

Topographic evolution of the Sierra Nevada. If the rise of the present mountain range is a consequence of density contrasts formed by lithospheric foundering, then the erosional response of river systems to changes in surface elevation will uniquely record spatial information about the magnitude and timing of deformation at depth. Erosional patterns may also be affected by westward tilting of the range due to faulting [*Huber*, 1981; *Unruh*, 1991]; an isostatic response to erosional unloading of the range and simultaneous flexural loading of the Great Valley [*Small and Anderson*, 1995]; changes in erosional efficacy due to climate fluctuations, orographic precipitation, and glaciations [*Stock, et al*., 2004]; and lithological variations within the range [*Stock, et al*., 2004]. All aspects of the erosional system must be considered in order to isolate the tectonic signals of interest here.

Low-temperature thermochronology from apatite (U-Th)/He ages suggests that a protracted period of slow erosion (0.04 mm/yr) existed from the end of arc magmatism until at least middle Cenozoic time (~80 – 32 Ma) in the southern range [*Clark, et al*., 2005; *House, et al*., 2001; *House, et al*., 1997]. These cooling ages can be related to low-relief relict landscapes still present throughout the range in the upper portions of tributary streams. Ancient trunk river profiles reconstructed from streams on the relict landscape indicate that the southern crest rose ~2500 m since <~ 32 Ma [*Clark, et al*., 2005] and modern transient river profiles suggest that the Sierran landscape is still responding to this elevation change [*Clark, et al*., 2005; *Stock, et al*., 2005a]. While climate conditions have likely played a role in affecting river incision rates through time, a significant increase in elevation since 32 Ma is no doubt required to explain the modern transient landscape.

Although helium ages record slow erosion rates from 80 – 32 Ma, late Pliocene – early Quaternary incision rates are much higher. These elevated erosion rates are coeval with a pulse of potassic magmatism at 3.5 Ma [*Manley, et al*., 2000] and increased sedimentation rates in the Great Valley [*Saleeby and Foster*, 2004, Saleeby and Foster, unpublished data]. On five rivers draining the western Sierra, burial dating [*Granger, et al*., 2001; *Granger and Muzikar*, 2001] of sediments as old as 3 Ma, washed into caves once at river level and now up to 400 m above the river, reveals that rapid incision from 3 (oldest preserved cave sediments) to 1.5 Ma was followed by much slower incision [Fig. 5, *Stock, et al*., 2004; 2005a; 2005b]. Preliminary modeling of river profile evolution in the face of instantaneous tilting of the range at ~5 Ma shows that both the present Kings river profile and the ages of caves within the inner gorge are consistent with a transient response to a tilting event with the timing and amplitude suggested for the development of the drip [Fig. 6, *Stock, et al.*, 2004].

We lack a record of incision between about 30 Ma (from the youngest apatite helium ages) and ~3 Ma (cave deposits and volcanic-capped fluvial terraces), during which time roughly half of the total incision into the relict landscape occurred. The full history of incision is essential to understanding the earliest phase of initial foundering and possible external triggers to foundering events, such as the passage of a slab window or Basin and Range extension. PI Clark will explore a newly developed technique ($^4He/^3He$ thermochronology) [*Shuster and Farley*, 2004] that should allow us to date lower temperature events. Doing so may allow us to determine when the first phase of river incision occurred, and by proxy when the first phase of elevation increase began. $^4He/^3He$ thermochronometry provides information on the distribution of helium within a grain, which is sensitive indicator of the cooling path through the partial retention zone. $^4He/^3He$ data coupled with the bulk ^4He age from the same sample will provide information about a sample to uniquely low temperatures of ~30°C. Limited amounts of bedrock river incision (~ 1 km) should produce thermal perturbations that will be resolvable by this approach [**Fig. 7**]. Application of this technique promises to bridge the gap between cosmogenically-derived erosion rates from terraces and caves and low-temperature thermochronology rates determined from traditional ("bulk") (U-Th)/He ages.

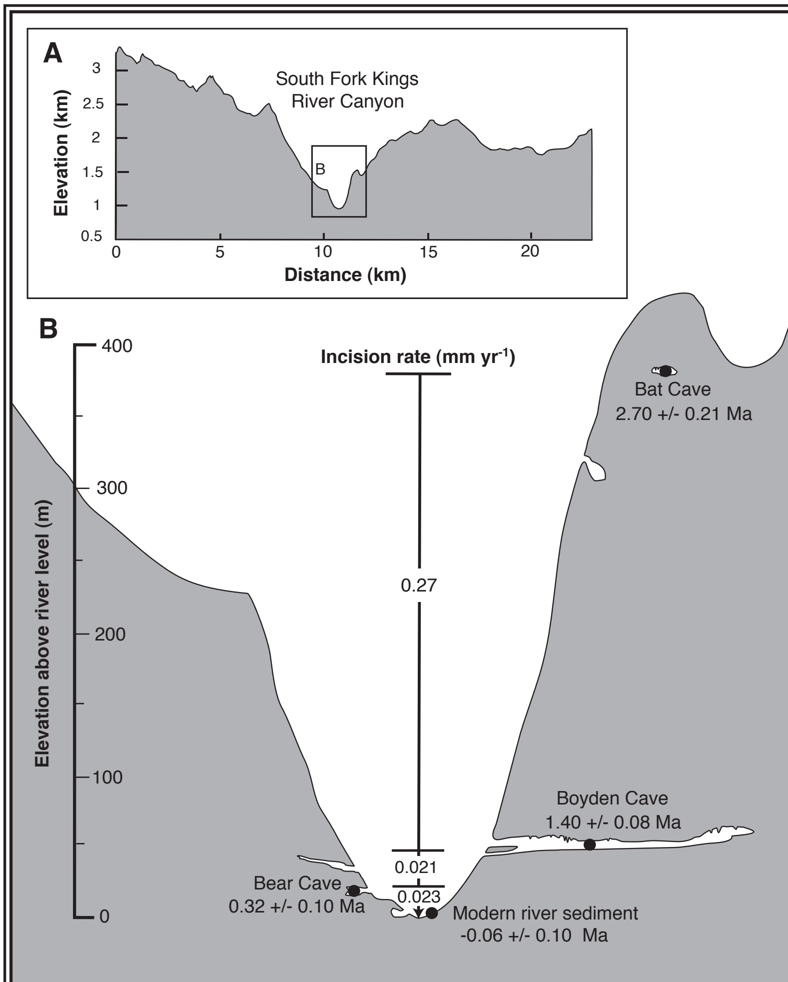

Fig. 5. Cave-derived river incision rates in South Fork Kings River canyon. A: Topographic profile across South Fork Kings River canyon in vicinity of Boyden Cave. Note ~2 km local relief. B: Inner gorge of South Fork Kings River canyon, containing suite of dated caves preserved by exceptionally steep canyon walls. These caves reveal order of magnitude decline in incision rate toward present. While oldest cave demonstrates 400 m of canyon cutting in past 2.7 m.y., larger context shown in A shows that this represents only ~20% of present local relief. [Stock et al., 2004]

PI Clark will sample the low elevation portions of the main rivers and major tributaries in the Merced, San Joaquin, Kings and Kern drainages where fluvial incision beneath the relict landscape is > 1 km. Samples collected along the stream channel will allow us to sample the lowest, local elevation and therefore locally deepest samples. The deepest samples have the greatest likelihood of experiencing a thermal perturbation due to increased fluvial incision, and will also minimize the effect of 2D/3D lateral cooling. We aim to sample horizontally along river channels in order to track the spatial propagation of river incision. This sampling strategy is complementary to data from three vertical profiles proposed in a separate pending submission to study bedrock fluvial processes by PI Clark.

In addition to determining the early history of rejuvenated incision, better control on the variation of the young incision in space and time will help constrain the geodynamic models of foundering lithosphere. PI Anderson, working with G. Stock (see letter of collaboration), will seek further constraints on the timing of incision from new cave and terrace studies. Unnamed caves within the upper Kern River drainage will first be targeted for potential dating to compare with existing dated cave sites in other southern drainages [Fig. 5, *Stock, et al*., 2004; 2005a]. We will date fluvial terraces on the edge of the Great Valley using cosmogenic radionuclide dating of the abundant quartz from the batholith in these surfaces [e.g., *Anderson, et al*., 1996; *Repka, et al*., 1997]. In addition, we will briefly explore a subset of potentially useful caves of the central and northern Sierra (e.g. Snells Cave on the Stanislaus; Crystal Tuolumne, Crystal Consumnes, Helbing Ranch on the Mokelumne, and Kloppenburg on the Feather). As one moves north in the range, the likelihood of preservation of fluvial terraces in river canyons increases. Where scraps of terraces exist we will collect profiles for exposure dating, again with the aim of constraining rates of fluvial incision over the last few million years.

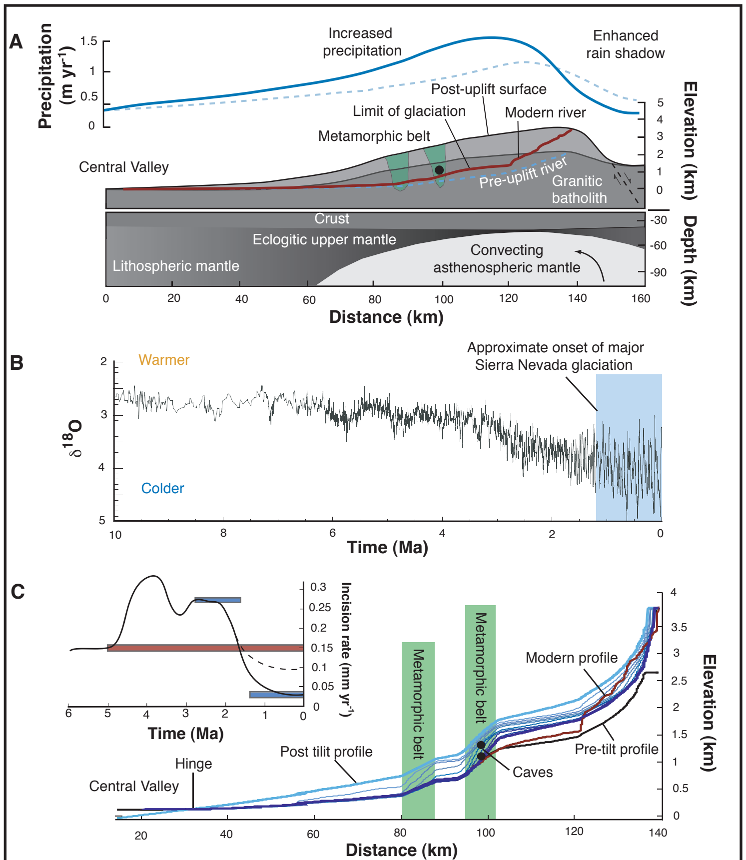

Fig. 6. Response of South Fork Kings River to late Cenozoic tectonic and climatic events. A: Conceptual model of late Cenozoic uplift. Westward tilting steepens pre-uplift surface (dark gray) and river profile (dashed red); surface uplift increases orographic precipitation on western slope of range and enhances rain shadow to east. Thin crust beneath range crest [Wernicke et al., 1996] likely reflects delamination of batholithic root [Ducea and Saleeby, 1998]. B: Example of stream power-based numerical simulation. Steady river profile (dashed red) with steps corresponding to quartzite in two metamorphic belts is subjected to ~1.5 km of crestal uplift. 1 m.y. profiles (blue) show that over next 9 m.y., wave of rapid incision begins at hinge line and propagates up profile. Inset shows 6 m.y. incision history at cave site; wave of rapid incision passes between ca. 5 and 2 Ma, followed by return to low pre-uplift rates (dashed curve after 2 Ma). Further reduction in late Quaternary rates (solid curve after 2 Ma) reflects sediment mantling of bed associated with large glaciers in headwaters. Final modeled river profile (purple) fits modern profile (red) to just upstream of cave site, above which glacial erosion, not represented in our river incision rule, has dominated past few million years. [Stock et al., 2004]

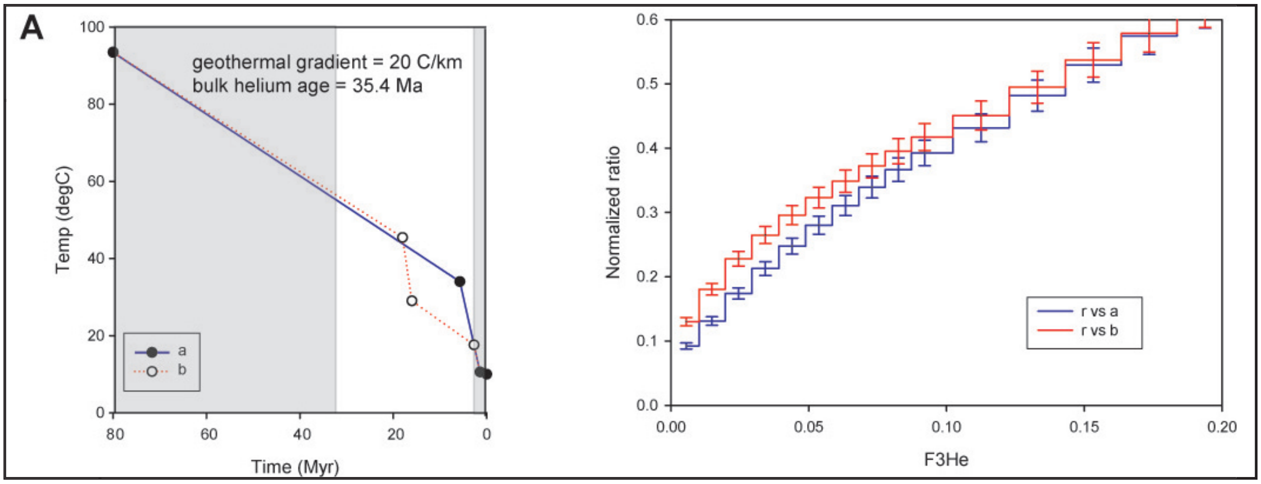

Figure 7. Theoretical thermal histories derived from river incision histories and modeled $^4He/^3He$ data. We compare a 1-step erosion history (a) where the entire river gorge is formed in one event to a 2-step history (b) where the river canyon is formed in two events that yield identical bulk ^4He age, but distinguishable $^4He/^3He$ ratios. Known incision histories are constrained by (U-Th)/He vertical profiles [*Clark, et al.*, 2005] and references therein] and cosmogenic dating of cave sediments [*Stock, et al.*, 2004] (grey). Thermal histories are calculated from linear cooling rates, geothermal gradient, incision rate and a surface temperature of 10°C. White region represents time period of unknown incision history that we aim to constrain. A) We linearly extrapolate the 0.27 mm/yr erosion rate measure between 2.7 - 1.4 Ma [*Stock, et al.*, 2004] to 5.7 Ma, to account for 1200 m of incision during this interval. We assume that the incision rate of the river prior to this event was equal to 0.04 mm/yr, implied by the helium data, and that this incision rate in the channel is equal to the overall landscape lowering. Likewise, we assume that the < 1.4 Ma incision rate of 0.02 mm/yr [*Stock, et al.*, 2004] also represents the overall landscape lowering such that no net gain or loss of relief occurs in the river during this time period. The 2-step model (b) describes a history where the 1200 m of river incision occurs in two discrete time periods: 820 m of incision between 18-16 Ma, and 350 m between 2.7 - 1.4 Ma. Both of these scenarios yield identical bulk helium ages of 35.4 Ma but discernable $^4He/^3He$ ratio evolution curves. B) Evolution of the $^4He/^3He$ ratio (normalized to the bulk ratio) during step heating. Qualitatively, the difference in the two isotopic ratio evolution occurs because the red sample (b) cools quickly through much of the PRZ at an earlier time, whereas the blue sample (a) initially cools slowly through the PRZ then is rapidly cooled at a later time. In effect, the earlier history of sample (a) is detectable by more ^4He accumulation at the outer edge of the grain.

We stress that the combination of cosmogenic and the new $^4He/^3He$ methods are complementary in both space and time. Samples from caves are obviously limited to where the river incises through belts of marble within the metamorphic belt, whereas those for $^4He/^3He$ are not. In addition, if the deepest incision into the relict landscape is of order 1-1.5 km, as in Kings Canyon, then the $^4He/^3He$ record most likely records the first 500-1000 m of incision and the cave record likely covers the last few hundred meters of incision, because caves are scarce above several hundred meters in the canyon walls. The $^4He/^3He$ and cosmogenic techniques will document two distinct time periods in the incision history that are not available from one technique alone.

The incision history determined from both thermochronology and cosmogenic dating will be integrated through simulation of river evolution for each of the major rivers draining the Sierra, directed by PI Anderson. These simulations [e.g., *Stock, et al.*, 2004, Fig. 6] predict the evolution of the full river profile, and hence the exhumation history at each point along the river profile. We can therefore predict both the time the river incises past a particular cave site, and the incision history at each of the $^4He/^3He$ sites. The latter can be used to address the expected thermal evolution of a sample presently found at the riverbed, providing very specific time-temperature paths against which to assess the $^4He/^3He$ data.

We will use the rivers as probes for the most consistent history of tectonic and climatic forcing – much like solving several simultaneous equations for the few important parameters. The models must remain faithful to the following real features:

- Incision and deposition: Cave histories, dated lava flows, low-temperature thermal histories, and depositional history within the adjacent Great Valley and tilting of the strata, the latter aided by ongoing investigations of Saleeby (see above)
- Drainage basin characteristics: topographic profiles, drainage area as a function of position
- Orographic precipitation [*Roe, et al.*, 2002; 2003], which will evolve in response to both climate change and evolution of the average topographic profile of the Sierra
- Lithology (resistant quartzite bands within the metamorphic belt can persist as knicks in the profile [*Stock, et al.*, 2004])
- Repeated glaciation of the headwaters of these rivers [*Kessler, et al.*, in press], which will both efficiently erode (unload) the headwaters, and send a slug of sediment downstream into the fluvial portion of the profile capable of stalling river incision during glacial periods [*Stock, et al.*, 2004].

In constructing models of the history of these rivers, we will be testing hypotheses developing out of the numerical experiments of lithospheric foundering (described below). Instead of simply constructing a best-fit model, we will be able to explicitly test contrasting tectonic histories suggested by these numerical experiments. We seek patterns and magnitudes of uplift and subsidence derived from these experiments that are consistent with the observations collected along the rivers. In doing this, we will consider the effects of variation in flexural rigidity [e.g., *Granger and Stock*, 2004; *Stock, et al.*, 2004] and climatic forcing specific to this region. We anticipate that the pattern, magnitude and duration of fluvial incision and subsidence and the location of magmatism will provide constraints on both the process (i.e. delamination versus convective removal) and the relevant geophysical parameters (e.g., density change from mantle loads).

Volcanism in the Sierra: Determining source conditions with experimental petrology. As lithospheric material founders, adjacent asthenosphere moving upward may melt through decompression. Volatiles in the foundering lithosphere can either flux into adjacent asthenosphere and trigger melting or cause the foundering material itself to melt as it warms sufficiently to cross its solidus. Determining the composition of source rocks and the pressure and temperature when primary melts were derived provides a strong constraint on the relationship of observed volcanic rocks to lithospheric foundering. Producing a phase equilibrium study for a primitive melt composition is arguably the most complete and accurate method for determining these parameters. The temperature and pressure of the multiple saturation point determined by the phase equilibrium experiments either represent the conditions under which the melt composition last equilibrated with its source, if it was produced by batch melting, or the average of the ascent path if the melt was produced by adiabatic ascent. Ages for the natural samples also provide important time control on flow beneath the lithosphere. These constraints in turn can be directly compared with numerical experiments of convective downwellings, as discussed below.

Elkins-Tanton and Grove [2003] produced a

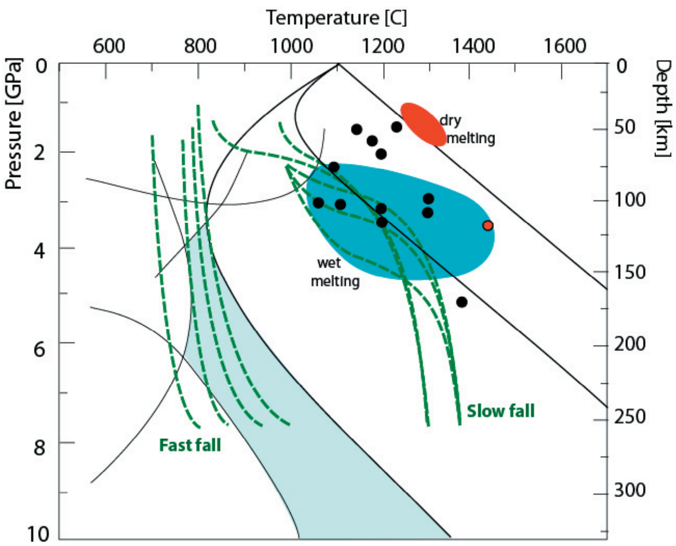

Figure 8. Paths through pressure-temperature space taken by the sinking instabilities (dashed lines) in numerical experiments. Instabilities that sink quickly are not conductively heated effectively at low pressures; their paths are shown on the left. Instabilities that sink more slowly (paths on the right) may themselves melt or may trigger damp melting of the surrounding asthenosphere. The depths of melting suggested by the numerical experiments (blue shaded region) is in agreement with experimentally-determined melting conditions of potassic continental magmas (black dots) and the melting conditions of the Sierran olivine leucitite from *Elkins-Tanton and Grove* [2003] (red dot), though this last requires either higher mantle temperatures or larger volatile contents. The region of dry adiabatic melting (red shaded oval) in shallow convection currents just below the lithosphere would produce significantly different compositions. Phase boundaries and melting conditions from *Ohtani et al.* [2004], *Herzberg et al.* [2000], *Hirth and Kohlstedt* [1996; 2003], *Takahashi et al.* [1993], *Edgar and Condliffe* [1978], and Edgar *et al.* [1976; 1980], *Barton and Hamilton* [1978; 1979], *Nicholls and Whitford* [1983], *Esperanca and Holloway* [1987], *Righter and Carmichael* [1996], and *Sato* [1997].

phase equilibrium study of a primitive olivine leucitite (a highly potassic basaltic lava) from the Kings Canyon volcanic field. Their experimental results demonstrate that the magma melted from a phlogopite-clinopyroxene metasomatized peridotite. The 6% H_2O composition (consistent with pre-eruptive water content estimated by *Feldstein and Lange* [1999]) is multiply saturated in experiments at 3.7 GPa and a mantle potential temperature of 1390 °C. This hydrous multiple saturation point can be regarded as the approximate depth and pressure of last equilibration of the magma with the metasomatized, phlogopite-clinopyroxene peridotite source it melted from.

The depth of melting of this particular primitive magma is consistent with melting of descending, volatile-rich lithosphere in the numerical experiments on lithospheric gravitational instabilities of *Elkins-Tanton* [in review] . Results of these experiments demonstrate that if delaminating lithosphere is volatile-rich, it may melt as it heats conductively during descent into the asthenosphere. Thus, the calculations by *Elkins-Tanton* [in review] for a simple Rayleigh-Taylor-like instability of a dense body show that melting and lithospheric removal could be intimately tied. The experimentally determined multiple saturation point is shown in **Fig. 8**.

Issues still exist with reconciling the experimental data with the isotopic constraints on the 3.5 Ma igneous event in the southern Sierra. For example, if the mantle lithosphere that foundered around 3.5 Ma was pervasively hydrated, why didn't it melt during the Miocene magmatic event? If the 3.5 Ma igneous event is from conduction into a cold body, why was it so short-lived? Reconciling isotopic compositions from mantle xenoliths of varying ages with those of the lavas that may have melted from the xenolith source also remains to be completed. We aim to develop models for the origins of these volcanic rocks that are consistent with xenoliths and volcanic rocks geochemistry, experimental data, and geodynamic constraints, as is described below.

Numerical experiments indicate that melting is also expected in normal asthenosphere close to the new bottom of the thinned lithosphere (red oval in **Fig. 8**). Melting in this setting may be drier and can result in less potassic lavas than the composition used in *Elkins-Tanton and Grove* [2003; see also *Gao, et al.*, 2004]. We propose to search for candidate compositions for a shallower, drier melt that is contemporaneous with the potassic Sierran lavas. Higher silica magmas from the southern Sierra are candidates, but more interesting are little-studied Cenozoic lavas in the northern Sierra, to be characterized as part of this project.

Seismotectonics. Downwelling material directly below the crust should induce stress within the crust [e.g., *Fleitout and Froidevaux*, 1982; *Bindschadler and Parmentier*, 1990]. Active deformation associated with such stress may be expressed in patterns of background seismicity. Previous studies in California have demonstrated that focal mechanisms of small to moderate earthquakes can be analyzed to obtain a snapshot of upper crustal deformation [*Unruh, et al.*, 1996; 1997; 2002; *Unruh and Lettis*, 1998]. From preliminary studies of seismicity in southern California, we have correlated seismogenic crustal thickening in the Transverse Ranges with thickened and negatively buoyant upper mantle, and seismogenic crustal thinning in the southern Sierra Nevada with thin and positively buoyant upper mantle [*Unruh, et al.*, 1998]. We will test the hypothesis that similar correlations between vertical deformation, downwelling material, and thinned lithosphere are present in the vicinity of the high-speed anomalies at opposite ends of the Central Valley.

Seismicity in the southwestern Sierra is sparse directly above the Isabella anomaly, possibly because the crust is strong, the drip is too deep, or the drip is neutrally buoyant. In contrast, the high Sierra directly east of the Isabella anomaly is seismically active. That seismicity [*Unruh and Hauksson*, 2004] reveals crustal thinning and radial horizontal extension above some areas where lithosphere was removed (**Fig. 9**), as should occur over a cylindrical zone of upwelling [e.g., *Fleitout and Froidevaux*, 1982]. A sharp transition separates extension and crustal thinning in the southern Sierra from horizontal plane strain and crustal shearing in the Walker Lane belt.

In the central and northern Sierra Nevada, seismicity occurs deep in the crust [*Mooney and Weaver*, 1989; *Edwards and Jones*, 1998; *Wong and Chapman*, 1990; *Miller and Mooney*, 1994]. Preliminary analysis of focal mechanisms in the vicinity of the Redding anomaly indicates that deformation includes components of both crustal shearing and vertical thickening. Downwelling dense material may induce radial compression superimposed on regional right-lateral shear [*Unruh, et al.*, 2003].

To evaluate seismogenic deformation, we will invert groups of focal mechanisms from earthquakes for a reduced deformation rate tensor including both rotational and strain rate components [fully described with examples in *Unruh, et al.*, 1996; 1997; *Unruh, et al.*, 2003; *Unruh, et al.*, 2002]. The tensor components characterize the 3D deformation of the crustal volume containing the earthquakes. We will use these results to test theoretical predictions for horizontal variations in deformation associated with both thickened and thinned lithosphere [e.g., *Fleitout and Froidevaux*, 1982; *Bindschadler and Parmentier*, 1990].

Integration. Although we expect vertical deformation and volcanism to be primary signals from lithospheric foundering, they can also be the result of unrelated processes (e.g., dynamic topography and volcanism associated with passage of the Mendicino triple junction). We will evaluate numerical experiments of lithospheric foundering (described below) using the observations collected here to test how much of the observed signal is related to this foundering event. In engaging in this give-and-take between observations and theory, we expect to find what observables are potentially related to foundering and the physical basis for that relationship. In addition to improving our understanding of processes specific to the Sierra, this will yield understanding more easily transferred to other orogens because of the physical underpinnings of our study.

2. How has material been removed from below the Sierra?

As noted above, several possible mechanisms have been proposed to remove mantle lithosphere and eclogitic lower crust. Although the results to date strongly suggest that lithosphere has been removed from the base of the southern Sierra, it is unlikely that this occurred through the breaking of a slab or heating following the removal of the slab when the Mendocino triple junction moved past the Sierra. Geochemical analyses of xenoliths erupted 8-12 Ma reveal that this now-foundered material was not altered oceanic lithosphere [*Ducea and Saleeby*, 1998b; 1996] and so it could not have been part of a slab that broke off after 8 Ma. Similarly, xenoliths in lavas erupted since 3 Ma from the southern Sierra lack the geochemical signature of the older rocks and thus cannot be reheated older lithosphere [*Ducea and Saleeby*, 1996]. More likely possibilities include delamination *sensu stricto* and convective removal of dense material, but both our understanding of these processes and the range of plausible spatial and temporal dimensions associated with them makes it difficult to discriminate between them.

To understand what has allowed removal of the lower lithosphere, we need to know where this process has occurred and what differences exist between those regions and others where lithospheric founder-

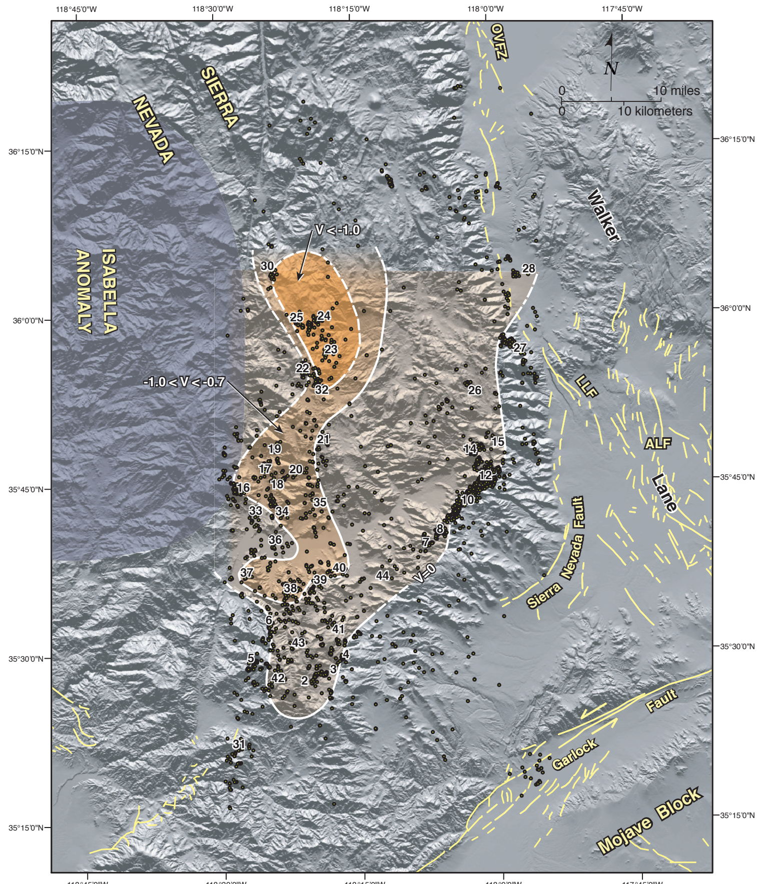

Fig. 9. Map of the southern Sierra Nevada and western Walker Lane belt showing results of kinematic analyses of background seismicity [modified from Unruh and Hauksson, 2004]. Focal mechanisms from individual groups of earthquakes (numbered) have been inverted for components of a reduced strain rate tensor [Twiss and Unruh, 1998]. Values of the vertical deformation parameter V, defined as the vertical component of the strain rate tensor normalized by the maximum extensional principal strain rate, are contoured to determine areas characterized by strike-slip faulting (V = 0), transtensional shearing (-0.7 < V < 0), horizontal extension (-1.0 < V < -0.7), and oblate flattening or "pancaking" of the crust (V < -1.0). Note that horizontal crustal extension in the southern high Sierra occurs in an approximately 25 km wide, north-south trending region directly east of the Isabella anomaly. There is a 20-30 km wide "transtensional" domain between the extensional southern High Sierra and the dominantly strike-slip Walker Lane belt. ALF = Airport Lake fault; LLF = Little Lake fault; OVFZ = Owens Valley fault zone.

ing has not occurred. Petrological studies can constrain how lithospheric chemistry and thickness varied in both space and time during arc magmatism; complementary geophysical, volcanic, and xenolith studies can map its subsequent history. Because the eclogite is probably produced by arc magmatism [e.g., *Ducea and Saleeby*, 1998a; *Ducea and Saleeby*, 1996], it is reasonable to focus on other parts of the Sierran arc, which are most likely to have had garnet pyroxenites and similar rock types at depth. Three approaches to constraining the composition of the Sierran lithosphere are pertinent: estimating the amount of eclogite produced under the batholith, determining how the sources of the volcanic rocks changed over time, and inferring from geophysical observations those properties of the modern lower crust or upper mantle that discriminate eclogite from asthenosphere.

How much eclogite was created under the Sierra? Although the Sierran arc continues north from the vents that yielded eclogitic xenoliths, the greater width of the arc to the north, the greater fraction of metamorphic rock in the north, and emplacement of the batholith into accreted terrains could cause the thickness and petrology of eclogitic material in the north to differ from that in the south. Four investigations can help resolve this issue: (1) Is the felsic batholith as thick in the north? (2) Was it created by punctuated high flux events that are thought to have led to development of the root in the south? (3) Are there garnet pyroxenite xenoliths in young volcanic rocks that can attest to the existence of such rocks at depth? And (4) do the exposed plutons present the same trace element patterns from south to north (e.g. the pronounced light rare element enrichments suggesting garnet is an important phase in the residue)?

Arc variations. Petrologic arguments suggest that the thickness of eclogites produced under an arc is related to the thickness of the overlying felsic batholith [*Ducea*, 2002]. Seismological constraints from the companion Earthscope project will constrain the modern thickness of the northern felsic batholith relative to the well-documented southern segment [*Fliedner, et al.*, 2000; *Fliedner, et al.*, 1996; *Ruppert, et al.*, 1998]. There are also significant variations in the batholith east-to-west, and these might contribute to production of high-density crust. Arc-related gabbroic rocks occur along the western margin of the southern and central Sierra [*Mack, et al.*, 1979; *Saleeby and Sharp*, 1980; *Clemens-Knott and Saleeby*, 1999; *Clemens-Knott, et al.*, 2000] and in basement cores from the axial region of the Sacramento Valley [*Saleeby and Williams*, 1978; *Williams and Curtis*, 1977]. In the deep levels exposed in the southernmost batholith, hornblende-rich cumulates have undergone partial dehydration remelting by hornblende breakdown with the production of copious garnet as a residue phase [*Ross*, 1989]. Such melting is within the plagioclase stability field resulting in the production of local garnet granulitic residues. Preferential dehydration remelting of hornblende-rich cumulates is a common feature of deep-level exposures in magmatic arcs [c.f., *Klepeis, et al.*, 2003; *Yamamoto and Yoshino*, 1998; *Kidder, et al.*, 2003], thus these rocks could represent loci of substantial production of garnet common to many arcs.

High flux events. The evolution of magmatism in time and space is not well known in the northern Sierra, in large part because of the limited number of reliable U-Pb crystallization ages and in part because the arc extends under the Sacramento Valley. When all available northern Sierra ages are used (e.g. K-Ar cooling ages, Rb-Sr ages, etc), the temporal distribution of the magmatic flux is similar to that in the southern Sierra (Ducea, unpublished compilation). We propose to greatly improve the understanding of the northern arc to better constrain the original distribution of dense lithospheric rocks. The addition of geochemical and geochronological data on Sierran plutonic rocks to the NAVDAT database (navdat.geongrid.org), a task commenced in early 2005 under PI Glazner's direction under a separate grant, will get additional attention in this project. We will also exploit the evolving understanding of the evolution of batholiths that is emerging from the BATHOLITHS CD project that PI Ducea is leading to understand the batholith in British Columbia. BATHOLITHS focuses on the questions surrounding the differentiation of continental masses in arcs, and not on the mechanisms of lower crustal and upper mantle removal examined here.

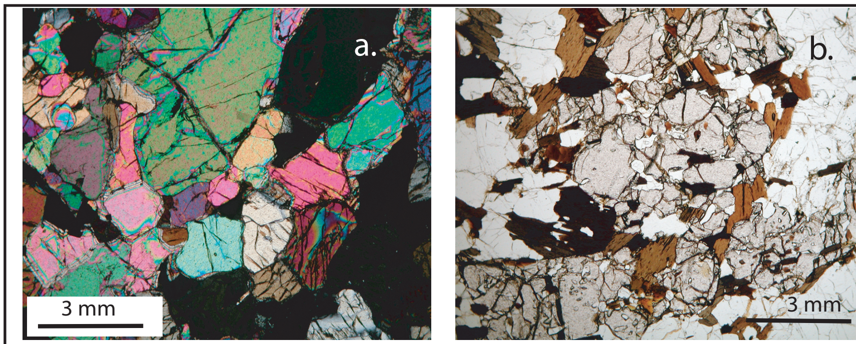

Fig. 10. A spinel peridotite (a) and a garnet amphibolite (b) from Jackson Butte. Peridotite is in cross polars, amphibolite in in plane view.

Xenolith studies. More direct examination of the lithospheric column will rely on acquisition of new collections of xenoliths from the lower crust and upper mantle from the northern Sierra [*Rose*, 1959; *Ducea, et al.*, 2005]. Recently collected samples from three localities, Jackson Butte, Leek Springs, and Donner Pass (**Figs. 2, 10**) in the northern Sierra are being examined petrographically (Ducea and Saleeby, work in progress). Glazner and Farmer located a new xenolith locality in 2002 north of Sonora Pass that contains lower-crustal granulite xenoliths, and we are confident that careful field examination will disclose more such sites. These samples will be studied for thermobarometry; in addition, we will perform trace element and isotopic studies as well as geochronology measurements in order to establish if these deep crustal rocks are cogenetic with the surface batholith.

REE analysis. The depth of melt generation of shallow exposures of batholithic rocks can be estimated and used as a monitor of paleo-crustal thickness in batholithic terrains. Trace element concentrations, especially of rare earth elements (REE), constrain the depth of pluton generation [e.g., *Gromet and Silver*, 1987]. Specifically, a garnet-rich and plagioclase-poor residue is characterized by highly fractionated REE patterns and lacks Eu anomalies, as is the case for the Dinkey Creek pluton in the central Sierra Nevada [*Dodge, et al.*, 1982]. In contrast, granitoids that equilibrated with a granulitic or amphibolitic residue show a negative Eu anomaly due to retention of Eu by residual plagioclase. They will also lack the steep normalized pattern of heavy REE, because of the low abundance, or lack, of garnet in the residue. Consequently, such signatures, when studied in conjunction with isotopic tracers, can detect the existence of eclogitic residual materials within the arc and the timing of crustal thickening/thinning [*Kay and Mpodozis*, 2001]. The main rock types that will be targeted for measurement in this study are tonalites and granodiorites that make up the bulk of the Sierra Nevada batholith. We plan to measure whole rock trace element concentrations along and across strike of the northern half of the batholith. These data will be contrasted with available data from the southern Sierra to constrain variations in paleo-crustal thickness and the amount and composition of arc residue-

Summary of batholith studies. The batholithic studies provide the initial conditions for the geodynamic experimentation proposed below as well as a framework for separating regions never having had dense lithosphere from those that lost it in the Cenozoic; such regions might be indistinguishable geophysically. The new focus on the more poorly considered western phase of the batholith is particularly critical to evaluating the likely locus and cause of initial downwelling. Furthermore, petrologic information can be critical to interpreting seismological data; for instance, as discussed more below, the particular petrography of garnet pyroxenite xenoliths led *Boyd et al.* [2004] to propose that such eclogitic rocks would not have unusually high P wavespeeds.

How has sub-Sierran lithosphere evolved? Although xenoliths provide the most direct sampling of the upper mantle and lowest crust, the mineralogic, chemical, and isotopic compositions of volcanic rocks provide another proxy record of the temporal evolution of the deep continental lithosphere and underlying convecting mantle. Volcanic rocks can also reveal information about lithospheric evolution that geophysical methods cannot. In this study, we propose new geochronologic and geochemical studies of Cenozoic volcanic rocks in the northern half of the Sierra Nevada (north of 38°N), rocks for which little such data is currently available. When combined with existing data from southern Sierra Nevada volcanic rocks [*Farmer, et al.*, 2002; *Feldstein and Lange*, 1999; *Manley, et al.*, 2000; *Van Kooten*, 1981], our new data should provide an assessment of the timing and north-south extent of lithospheric removal beneath the entire Sierra Nevada, and allow us to address whether variations in lithospheric structure and composition influenced the timing and locus of that removal.

Cenozoic volcanic activity north of 38°N is more widespread and voluminous that in the southern Sierra, although both regions contain examples of Miocene, Pliocene and Quaternary volcanism [*Huber*, 1983a; b; *Slemmons*, 1966]. There exists so little age and compositional information on the northern Sierra volcanic rocks, however, that it is not possible to assess whether space-time-composition-source patterns exist in the northern Sierra that could reasonably be linked to lithospheric foundering, as was done to the south [*Farmer, et al.*, 2002]. Here we describe both the current understanding and our planned studies of the northern Sierra volcanic rocks.

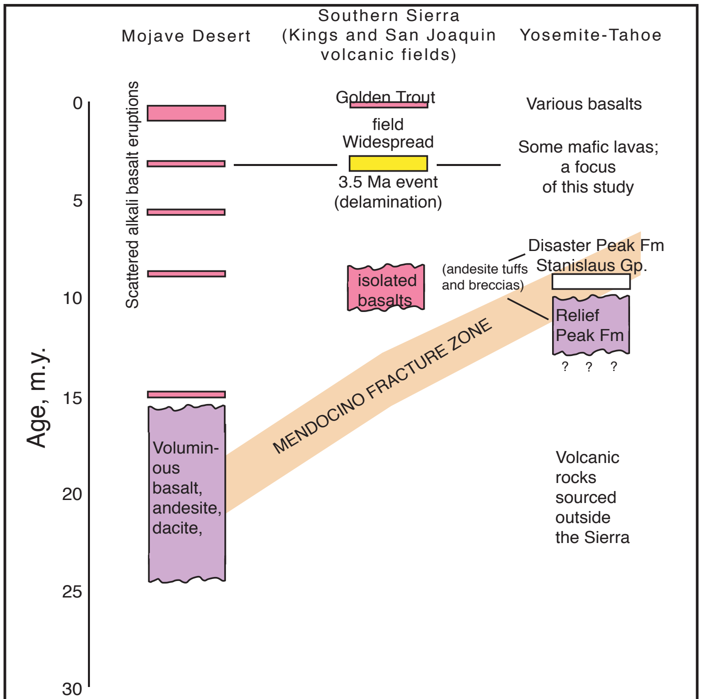

Fig. 11. Stratigraphy of volcanic units in selected parts of California. Generalized stratigraphic columns for the Mojave Desert, southern Sierra Nevada, and proposed study area. Tan swath give the approximate time of passage of the Mendocino fracture zone under the various regions, based on the reconstruction of Atwater and Stock [1998]. There is little correlation between these plate-boundary events and volcanism.

Miocene volcanic rocks. Miocene volcanic rocks comprise 10% or more of the total rock outcrop area in the northern Sierra Nevada. In the Sonora Pass area (**Fig. 2**) at ~38° N, potassic andesitic volcanic strata of Miocene (7-20? Ma) age locally exceed 1 km [Fig. 11, *Roelofs, et al.*, 2004; *Roelofs*, 2004; *Slemmons*, 1966; *Busby, et al.*, 2004; *Rood, et al.*, 2004]. These volcanic, volcaniclastic, and shallow intrusive rocks were derived from vents within and directly adjacent to the range, and likely represent remnants of stratovolcanoes associated with the ancestral Cascades arc [*Brem*, 1977; *Priest*, 1979; *Henry, et al.*, 2004]. These are similar chemically to Miocene volcanic rocks in the southern Sierra Nevada (**Fig. 12**), but considerably more voluminous.

We will concentrate our studies of Miocene volcanic rocks around the Sonora Pass corridor because this region marks the north to south transition from sparse to abundant Cenozoic volcanism in the Sierra Nevada. As a result, the sources, composition, and ages of volcanic rocks in the Sonora Pass area should provide important insights into what this transition represents. Does 38°N mark the northern edge of Precambrian continental lithosphere, given that it is coincident with the $^{87}Sr/^{86}Sr$=0.7060 in the Sierra, and if so did a change in composition or thickness of mantle beneath northern Sierra affect Miocene melt productivity in this region (**Fig. 2**)? Knowing how the potential sources of Cenozoic magmatism change from south to north will be critical to linking any variation in volcanic rock compositions in the northern Sierra to lithospheric foundering. The Sonora Pass corridor is also unique because it is the only area between Lake Tahoe and Yosemite where a laterally extensive, potentially "arc-normal", volcanic transect can be investigated. This is possible because of the wide separation of vent localities for the Miocene volcanism both west and east of the current Sierran crest. Establishing an arc setting for the Miocene rocks is critical to the overall goals of this project as subarc erosion of lithosphere mantle during the Miocene beneath the northern Sierra Nevada should influence the amount of lithosphere mantle available for foundering later in the Cenozoic. By comparing the sources and compositions of magmas along the Sonora Pass corridor to those of active portions of the southern Cascade arc, we hope to separate hydrous subduction-generated melts from anhydrous decompression melts[e.g., *Grove, et al.*, 2003; *Tanton, et al.*, 2001]. We note that high-alumina tholeiitic composition volcanic rocks in the Sonora Pass region occur east of calc-alkaline andesites, similar to their spatial arrangement in the Cascades. However, only with additional age, compositional and isotopic data will we be able to demonstrate whether regular chemical and/or isotopic variations actually occur as a function of space and time within the Miocene volcanic rocks and whether these variations are consistent with their generation in an active arc setting. We also note that through the NAVDAT database we can readily place the Miocene Sonora Pass volcanic activity in the context of Late Cenozoic volcanic activity occurring throughout adjacent portions of the Great Basin. In this fashion we can address the extent to which magmatic activity in the northern Sierra Nevada represents a continuation of space-time patterns in Late Cenozoic magmatism that initiated fur-

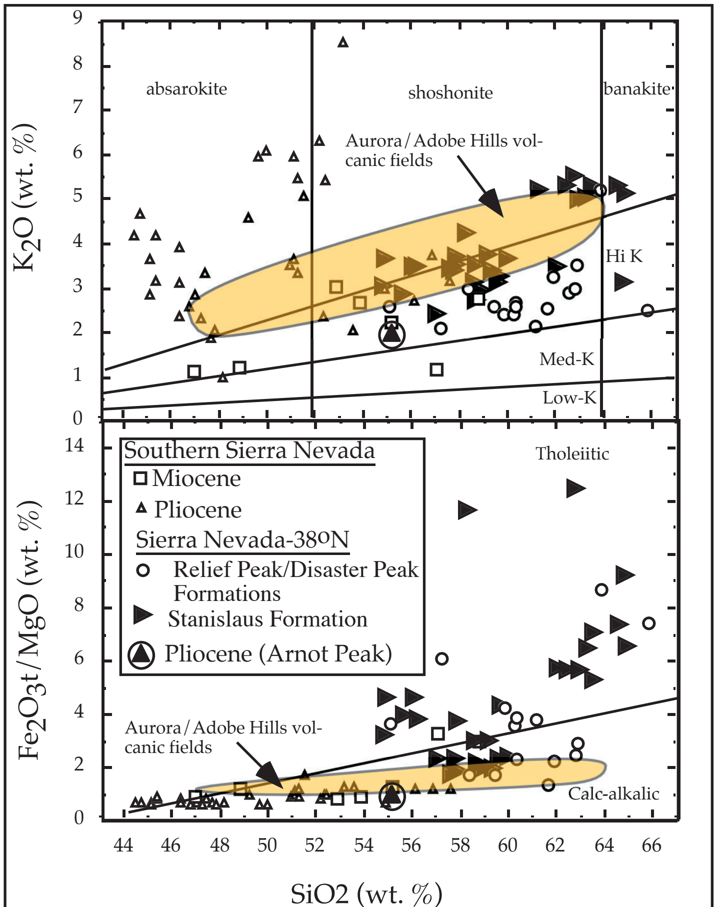

Fig. 12. Wt. %K_2O, and Wt. % Fe_2O_3t/MgO vs. wt. % SiO_2 for late Cenozoic igneous rocks at ~38°N in the northern Sierra Nevada. Data from Brem [1977], Priest [1979], Farmer et al. [2002], Roelofs [2004] and Farmer (unpublished).

ther to the east.

Pliocene volcanic rocks. Highly potassic, Pliocene volcanic rocks south of 38°N have been linked to lithospheric foundering, but the full distribution and compositions of any such rocks in the northern Sierra are scarcely known [*Armin and John*, 1983; *John, et al.*, 1981; *Huber*, 1983a; b; *Armin, et al.*, 1984]. For example, mafic volcanic rocks present just west of Lake Tahoe yield Pliocene (2-4 Ma) whole rock K-Ar [unpublished data reported in *Saucedo and Wagner*, 1992] and $^{40}Ar/^{39}Ar$ ages (Farmer, unpublished data, 2005). No published chemical and isotopic data exist for any possible Pliocene volcanic rocks in the northern Sierra, or for the few known Quaternary volcanic rocks known in this area [*Huber*, 1983a; b], with the exception of Pliocene rocks described along the northern margin of Lake Tahoe [*Cousens, et al.*, 2000]. We plan a reconnaissance study of the entire area between western Lake Tahoe and Sonora Pass with the intent of defining the timing and composition of Pliocene magmatism in this region. Initial targets include known Pliocene rocks west of Lake Tahoe and possible Pliocene rocks reported elsewhere in the region, including the basalt of Arnot Peak [*Giusso*, 1981] and the Dardanelles west of Sonora Pass. The intent of this work will be to determine if there is any evidence of abrupt magmatic event analogous to 3.5 Ma potassic magmatism in southern Sierra. Differences in age and composition of any such pulse compared to their southern Sierran counterparts may reflect differences in timing of lithosphere removal, as well as differences in composition of lithosphere related, for instance, to lack of Precambrian mantle lithosphere north of 38°N.

What underlies the Sierra today? As in the southern Sierra, geophysical study of the modern lithosphere can complement limited spatial and temporal sampling of the lithosphere

Table 1A. Effects on seismic parameters and electrical resistivity of physical state in upper mantle

Factor	***Change to Observable:***					
Increasing:	*P wavespeed*	*v_p/v_s ratio*	*Attenuation*	*Anisotropy*	*Density*	*Resistivity*
Temperature	⇓ decrease	⇑ increase	⇑ **increase**	No change	⇓ decrease	⇓ decrease
Melt	⇓ decrease	⇑ increase	*	?	⇓ decrease	⇓ **decrease**
Magnesium	⇑ increase	⇓ decrease	No change	No change	⇓ decrease	⇑ increase
Garnet/ olivine ratio	⇑ increase	⇑ increase	No change	⇓ decrease	⇑ increase	⇓ decrease
Hydration	⇓ decrease	⇑ increase	⇑ increase	Change orientation?	Small decrease	⇓ decrease

Table 1B. Effects of anisotropy on seismic wavespeeds and electrical resistivity in olivine-dominant mantle

Observation	*a axis alignment*	*Olivine state*	*resistivity, V_p/V_s, attenuation*
Fast seismic direction parallel to high resistivity direction	*a* parallel to strain	dry, strained	high resistivity, low attenuation
	a perpendicular to strain	fluid wetted, strained	low resistivity, high attenuation
Fast seismic direction perpendicular to high resistivity direction	*a* parallel to strain	hydrated, strained	low resistivity, low attenuation(?)

by volcanic eruptions. Electrical properties are largely insensitive to bulk mineralogy but very sensitive to temperature and fluids, including partial melt. Seismic wavespeeds depend largely on bulk mineralogy but also are affected by temperature and fluids. Seismic attenuation is most strongly affected by temperature (**Table 1A**). Seismic and electrical anisotropy in the mantle are both indicative of the mineralogy [e.g., eclogites are not anisotropic *Fountain and Christensen*, 1989] and the strain field in the mantle. These geophysical techniques can limit the possible geometry of both ascending and descending material, important constraints to evaluating the effect and geodynamics of lithospheric foundering.

From seismic tomography of P and S wavespeeds and attenuation, *Boyd et al*. [2004] inferred that the high P-wavespeed Isabella anomaly under the western foothills of the southern Sierra is cold garnet peridotite (**Fig. 3**). *Park* [2004] showed that electrical resistivity in the region of this anomaly is at least ten times greater than in its surroundings, which he attributes to a temperature at least 200°C colder than in the surrounding mantle. Although the electrical and seismic results are mutually consistent for the Isabella anomaly, *Park* [2004] and *Boyd et al*. [2004] disagree about the body just to the east that dips east just below the Moho beneath the Sierra Nevada. *Boyd et al*. [2004] inferred from low P wavespeeds, low attenuation, and high v_p/v_s that this body is cold eclogite. The low resistivity, < 10 ohm m, led *Park* [2004] to suggest the presence of warm, partially melted mantle. The common position of these features suggests that the different interpretations do not result from differences in resolution, but from fundamental ambiguities in inferring earth properties from these measurements. Joint interpretation (and, ideally, inversion) of temperature and composition may resolve this difficulty in concert with constraints from study of volcanic rocks and xenoliths. One possible reconciliation is that the low attenuation that led Boyd et al. to infer eclogite is more likely due to low attenuation that can occur at fairly high temperatures [*Anderson and Given*, 1982]; eclogitic material might instead be in a zone of intermediate P wavespeed, low resistivity, and anomalous v_p/v_s ratio just above the high P-wavespeed "Isabella anomaly". Our proposed work seeks to solidify gains from both techniques.

Passive seismic experiment. The seismological experiment funded separately by the EarthScope program will provide detailed images of P and S wavespeeds, seismic attenuation, seismic interfaces, and seismic anisotropy. Seismological characteristics of the Sierran crust and mantle are being obtained from a two-year (2005-2007) deployment of broadband sensors into the northern Sierra (**Fig. 2**). Anisotropic properties will be extracted from both teleseismic body waves and locally converted (*Ps*) phases. PI Jones will work under both grants to integrate the tomographic analysis of the new data funded under the EarthScope proposal with existing datasets [*Boyd, et al*., 2004; *Jones, et al*., 1994], and, as is discussed below, he will work with PI Park under this grant toward a joint inversion of seismic and magnetotelluric data to infer variations in temperature, melt, and composition.

Locating the bottom of the Isabella anomaly constrains the rate of foundering. Because subduction of oceanic lithosphere has not occurred beneath this part of the Sierra for over 10 My [*Atwater and Stock*, 1998], the bottom of this anomaly presumably constrains the amount of downwelling, and with limits on the date of initiation, it constrains the rate. The bottom has not been defined, largely because of vertical smearing in tomographic inversions and the inability of MT surveys to penetrate here below 200 km, but the anomaly extends to 200 km depth and perhaps deeper [*Benz and Zandt*, 1993; *Jones, et al*., 1994; *Biasi and Humphreys*, 1992]. Although we will try to constrain the wavespeed anomalies from the tomographic work (e.g., employing squeezing tests), an alternative to tomography is to examine the top of the transition zone for interaction with downwelling material [e.g., *Chen, et al.*, 1997]. Although the presence of garnet pyroxenites might complicate the behavior of the phase changes as this material descends, we expect that cold garnet peridotites will dominate the signal, and that we will observe the 410 km discontinuity elevated relative to the surroundings, if this material extends to these depths. Such topography has been observed by stacking the P to S conversions that are generated at the discontinuities in the Transition Zone at their conversion points [e.g., *Boyd, et al.*, 2005; *Gilbert and Sheehan*, 2004; *Gilbert, et al.*, 2003; *Dueker and Sheehan*, 1997; 1998]. PI Jones will work with Hersh Gilbert (Univ. of Arizona, see letter of support) to construct such CCP stack converted wave images from the temporary broadband seismometers, Bigfoot, and permanent broadband station recordings of teleseismic waves traversing the transition zone under and around the Isabella anomaly. Gilbert is funded to construct CCP images of the Transition Zone from EarthScope stations for a broad region, but the effort we propose will have a higher resolution and will more carefully explore the impact of wavespeed anomalies of the Great Valley and Isabella anomaly on Transition Zone topography. This analysis builds upon an extensive body of related work produced by the seismology group at CU that more fully documents the techniques to be applied [*Dueker and Sheehan*, 1997; 1998; *Gilbert and Sheehan*, 2004; *Gilbert, et al.*, 2003; *Gilbert, et al.*, 2001; *Jones and Phinney*, 1998; *Wilson, et al.*, 2003; *Wilson, et al.*, 2004; *Boyd, et al.*, 2005].

Magnetotelluric experiment. Electrical resistivity of a mantle rock can be reduced by high temperature, hydration of the mantle [*Mackwell and Kohlstedt*, 1990], high iron content [*Hirsch, et al.*, 1993], or the presence of a small amount (< 1%) of partial melt [*Shankland and Waff*, 1977] (**Table 1**). Although the electrical resistivity of fluid-free eclogite differs little from that of peridotite at the same temperature [*Park*, 2004], asthenosphere rising to replace lithosphere under the southern Sierra will be less resistive than the mantle lithosphere because it is hotter than that lithosphere and may contain a few percent partial melt [*Park, et al.*, 1996]. *Park* [2004] inferred from the Isabella anomaly's high resistivity that it must be cooler than its surroundings and free of partial melt (**Fig. 3**). Thus MT can isolate cold downwelling eclogite or peridotite.

There are no comparable images for the Sierra north of the earlier MT profile. In order to test whether the Redding and Isabella anomalies are isolated drips (**Fig. 1c**) or part of a sheet (**Fig. 1b**), three east-west profiles across the central and northern Sierra Nevada (**Fig. 2**) will determine the extent of resistive bodies similar to that in **Fig. 3** juxtaposing cold with warm or melt-laden material. The original SSCD MT profile will be extended west to the Coast Ranges in order to determine whether the western edge of the Isabella anomaly also appears as a boundary between resistive and conductive materials (**Fig. 2**). Although the electrical structure is likely to vary in three dimensions, our choice of multiple profiles reflects a balance between the need for the greater detail available from a 2-D MT section, and the need to account for effect of off-profile electrical structures.

An additional profile (Profile 3; **Fig. 2**), oriented NE-SW across the Sierra Nevada, will be used in conjunction with the two southern profiles to constrain electrical anisotropy. This profile passes from the region where mantle lithosphere is likely missing in the central Sierra Nevada into the region where it currently sinks (the Isabella anomaly). Where it crosses the other profiles, directional-dependent electrical resistivity can be used to estimate electrical anisotropy [*Shock, et al.*, 1989]. Because fluids, hydration, and strain affect the seismic and electrical anisotropy differently)[Table 1, *Bahr and Duba*, 2000; *Boyd, et al.*, 2004; *Jung and Karato*, 2001; *Kaminski*, 2002; *Shock, et al.*, 1989; *Zhang and Karato*, 1995], we plan to use joint interpretation of both data sets to identify the orientation of a mantle fabric. Joint analysis of seismic and electrical anisotropy can yield not only strain orientation but also hydration in the upper mantle.

A lingering problem with resistivity images derived from MT measurements is that uncertainties in the derived properties are usually determined ad hoc, if at all. Formal procedures exist for calculating the resolution and covariance matrices for model properties [e.g., *Tarantola and Valette*, 1982] are not very helpful for electromagnetic studies because the resolution and covariance matrices depend strongly on the resistivity structure itself [e.g., *Mackie and Madden*, 1993]. Most approaches for estimating parameter resolution rely on selectively sampling models close to the one derived from the inversion and assessing goodness of fit for alternative models [*Park, et al*., 1996]. Such approaches are neither objective nor thorough.

We propose to extend the ad hoc approach of *Park et al*. [1996] by randomly sampling the parameter space in the vicinity of a best-fit model. *Mosegaard and Tarantola* [1995] use a Monte Carlo technique to sample the parameter space, but attempts to globally sample parameter space in MT are computationally intensive even for 1-D models [*Dosso and Oldenburg*, 1991]. Instead, we will use *Mosegaard and Tarantola's* [1995] Monte Carlo technique in order to assess parameter resolution for a model derived from the MT data.

Joint analysis of MT and seismic data. As highlighted above, seismological and magnetotelluric interpretations along the same profile in the southern Sierra yielded diametrically opposite results, with *Boyd et al*. [2004] focusing on seismic attenuation and Poisson's ratio and *Park* [2004] using electrical resistivity to infer variations in temperature, fluid content, and lithology. These methods have different sensitivities to these parameters that can be exploited if considered simultaneously. Mutually compatible solutions are most likely to yield the kind of results of greatest use in other aspects of this proposal; in turn, they are informed by the petrologic work of lithologies and conditions likely to exist in the region.

A direct, joint inversion from MT soundings and seismic waveforms to lithology, temperature, strain, and fluid content would be an ideal goal. This cannot be done at present both because of limited laboratory data and because of the computational cost for the MT inversion; one MT inversion to produce a 2-D section such as in **Fig. 3** may require several days to run. Therefore, we initially will explore joint interpretations of independently derived wavespeed, attenuation, and resistivity models. One way to link the electrical and seismic interpretations is to use predictions of temperature, melt fraction, and lithology from the MT section as a starting model for seismic inversion. The seismic inversions will be recast from v_p, v_{sfast}, v_{sslow}, and attenuation as used in *Boyd et al*. [2004] to v_p, v_p/v_s, percent transverse anisotropy, and attenuation. These values are more directly related to the characteristics of the Earth we are interested in, such as temperature, melt, and eclogite. Once we have robust inversion results with this approach, we will explore directly inverting the seismic data for temperature, Fe depletion, percent garnet, and melt. Such inversions are more difficult because of the uncertainties in relations between these values and seismic observables, but with the different sensitivity of the electrical results, inclusion of the electrical results as a priori constraints could stabilize the inversion enough to make it practical. Incorporation of xenolith observations by PI Ducea in both the seismic and MT interpretations are essential. This effort will include a statistical analysis of the mineralogy in the xenoliths in the southern Sierra, as well as a consideration of petrologic models that that examine whether the xenolith populations represent a biased sample of the basic residuum under the batholith.

3. What conditions are necessary for lithosphere removal? (Molnar and Elkins-

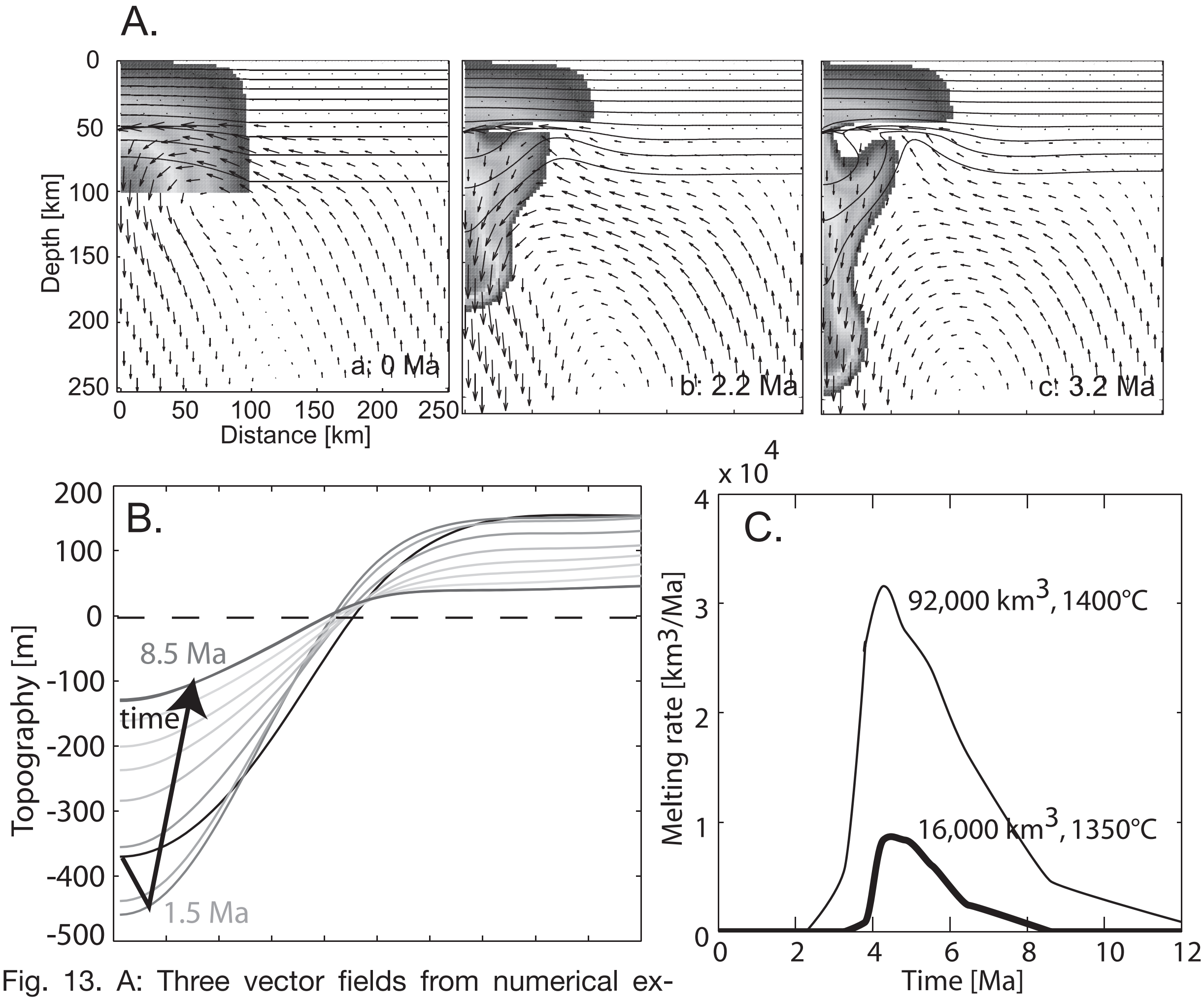

Fig. 13. A: Three vector fields from numerical experiment d8 by *Elkins-Tanton* [in review], with Newtonian rheology and a weak layer in the mid-lithosphere. The images show cross-sections from the top of the crust into the mantle. The left boundary is an axis of symmetry, passing through the center of the downwelling, axi-symmetric plume. The scaled model box represents 250 km in width and height. Arrows show the velocity vector field and shadings represent density. Solid contours are isotherms. Detachment along the horizon of low viscosity allows strong upwelling to form in an annulus around the instability, creating the opportunity for adiabatic melting. Shortly after the final image the downgoing plume, hot enough to have dehydrated, sinks out of the model box and is detached from the lithosphere. B: Surface topographic evolution of the gravitational instabilities from model d8. Topography is given in meters, and distance from the axis of symmetry in km. Arrows in this figures show the sense of time evolution of the topography and give the scaled end time of the experiment. C. Melting rate from dry adiabatic melting in the annulus of upwelling flow induced by the sinking plume. Dry adiabatic melting occurs mainly in a pulse during growth of the instability and initial fall. Wetter melting is predicted by these experiments to follow dry melting, as the instability devolatilizes, just as a subducting slab does.

Tanton)

Clearly one necessary condition is the creation of negatively buoyant material, either through cooling and thermal contraction or by the formation of dense minerals. For the Sierra, the existence of negatively buoyant material alone was not a sufficient condition for rapid removal of lithosphere, because eclogite had formed by about 80-100 Ma [*Ducea and Saleeby*, 1998b] but did not descend until at least 70 Myr later. Some other factor must also play a role. A commonly cited trigger for removal of mantle lithosphere is tectonic thickening [e.g., *Houseman, et al*., 1981], but such thickening does not seem to have occurred beneath the Sierra since the Cretaceous. In contrast, the Sierra seems to have lost its eclogitic root at a transform boundary within an extensional tectonic regime. Was triggering the result of loss of strength through heating, as a cold slab was replaced by asthenosphere [e.g., *Zandt and Carrigan*, 1993], or might it have been exposure of the Moho to the asthenosphere [e.g., *Bird and Baumgardner*, 1981; *Morency and Doin*, 2004]? Could removal of mantle lithosphere have been facilitated by mechanical decoupling of eclogite from overlying crust by localized shear [*Molnar and Jones*, 2004; *Elkins-Tanton*, 2005; *Schott, et al*., 2000; *Pysklywec and Cruden*, 2004]? Each such trigger carries predictions about the extent, duration and evolution of removal of the lithosphere that can be tested observationally. In turn, understanding of the trigger informs us about the conditions leading to removal of lithosphere that can be applied to other orogens. At the opposite extreme, if mantle lithosphere obeys power-law creep, triggering removal could be difficult to detect, because growth of an instability is very slow for a long period and then suddenly becomes very rapid [e.g., *Houseman and Molnar*, 1997]. Thus, perhaps we witness only the late stages of a process that merely requires the precondition of a thick layer of garnet pyroxenites or eclogites, *sensu lato* underlying the region [*Kay and Mahlburg-Kay*, 1991; *Kay and Kay*, 1993; *Ducea and Saleeby*, 1996; 1998a; *Jull and Kelemen*, 2001; *Meissner and Mooney*, 1998].

We expect to obtain some of the best observational constraints on how lithosphere is removed. Although the studies proposed above could be treated as individual disciplinary projects, incorporation into a single CD project allows the studies to run concurrently and thus exchange tradeoffs and uncertainties. This exchange will allow constraints from the work of others to modify experimental designs; conversely, early numerical experiments will highlight particular observations differing between different modes of foundering that can refocus limited resources in field studies. Integrating these constraints into the numerical experiments will be a major task; some observations may imply delamination, others may be more consistent with convective removal, and some may not be predicted by either.

We plan no numerical experimentation of delamination *sensu stricto*, as *Bird* [1978] defined the term with regard to the lithosphere. Previous work shows that dense material can be removed as a crack propagates between it and overlying less dense material [e.g., *Bird and Baumgardner*, 1981; e.g., *Morency and Doin*, 2004; *Schott and Schmeling*, 1998]. These studies generally show that as delamination proceeds, an area of subsidence can overlie the descending material where it remains attached to the upper layer and surface uplift occurs where the material has been removed. The subsidence and subsequent surface uplift propagates with the tip of the crack. Two key predictions of delamination are that the descending material retains any initial stratification and that the system propagates away from the area of surface uplift. The discovery either of a propagating locus of rapid incision along the Sierra, due to a rapid rise of the surface and detected with geomorphic techniques, or of a propagating locus of subsidence, detected with sediment accumulation and facies in the Great Valley, would support the occurrence of delamination. The presence of a subsided region [*Saleeby and Foster*, 2004] directly over a steeply inclined cylinder of high-wavespeed material in the mantle [e.g., *Boyd, et al*., 2004; *Jones, et al*., 1994] and the absence of any propagation in the locus of rapid incision [*Stock, et al*., 2005b] argue against delamination, but are not conclusive.

These two features, preserved laminar structure and a propagating zone of subsidence, contrast with patterns observed in numerical experiments on convective or Rayleigh-Taylor instability; such experiments show material descending below where the base of the unstable layer is initially perturbed downward, and most applications to the Earth imply that only the lower part of the mantle lithosphere is removed (**Fig. 13**). Yet, as discussed below, numerical experiments to date on Rayleigh-Taylor instability have not explored all conditions that might be pertinent both to removal of mantle lithosphere and to related volcanism. We propose to fill this gap.

Mantle lithosphere may be sufficiently gravitationally unstable that when perturbed enough, it sinks rapidly into the underlying asthenosphere. Continental convergence and crustal thickening provide an obvious perturbation, and numerous studies suggest rapid removal of at least half of the mantle lithosphere under these conditions [e.g., *Houseman and Molnar*, 2001], but no such forcing affected mantle lithosphere beneath the Sierra Nevada. Nevertheless, such rapid removal between ~10 and 3 Ma after a prolonged period of quiescence is consistent with perturbation to the base of an unstable non-Newtonian fluid [*Molnar and Jones*, 2004]. More interesting than the absence of crustal shortening are two features of the Sierra unanticipated by most previous analyses: downwelling flow is located to the side of where eclogitic rocks may have been thickest, and virtually all lithosphere below the seismic Moho (apparently) has been removed. The timing, the role of volcanism, and the apparent geometry of flow focus our attention on two obvious tasks: (1) to understand how such instabilities depend on relevant parameters describing rheology, boundary conditions, and dimensions so that not just the bottom half, but perhaps the entire mantle lithosphere can be removed, and (2) to determine how the resulting flow patterns affect topography and melt generation and its resulting volcanism.

If lithosphere has been removed by some form of convective instability, the rapidity with which this occurred should allow it to be treated as Rayleigh-Taylor instability, for which diffusion of heat can be ignored. Numerical experiments on convective instability by *Conrad* [2000; *Conrad and Molnar*, 1999] replicated scaling laws derived for Rayleigh-Taylor instability [*Houseman and Molnar*, 1997; *Molnar, et al.*, 1998], and show that diffusion of heat is too slow to affect growth, once perturbations to the unstable layer are sufficiently large.

Removal of Sierran lithosphere, however, exposes an inadequacy in most of the work of Conrad, Houseman, Molnar, and Neil. They employed a rigid upper boundary condition; in effect their mantle lithosphere was glued to a rigid lower crust, and when applied to the earth, *Houseman and Molnar's* [1997] scaling law for Rayleigh-Taylor instability, and its extensions, invariably call for removal of only the lower half of the mantle lithosphere in geologically reasonable times. Both the rapidity of removal of Sierran mantle lithosphere and its extent suggest that a stress-free upper boundary condition is a closer approximation than a rigid top boundary [*Canright and Morris*, 1993; *Houseman and Molnar*, 1997; *Elkins-Tanton*, 2005; in review; *Morency and Doin*, 2004; *Schott, et al.*, 2000; *Meissner and Mooney*, 1998; *Pysklywec and Cruden*, 2004], a suggestion applicable to the Sierra Nevada only if low-temperature lithospheric strength reaches a limit as suggested by laboratory results of *Evans and Goetze* [1979] (and supported by *Wenk et al*. [2004]) [*Molnar and Jones*, 2004].

Independently, *Elkins-Tanton* [2005; in review] investigated lithospheric convective instabilities using an axisymmetric code with pressure, temperature, and stress-dependent viscosity, incorporating a low-viscosity layer in the lower crust in some cases. The initial conditions in these numerical experiments include a lithosphere with a region of denser (1, 3, or 5% denser than adjacent mantle lithosphere) and warmer material, as predicted petrologically to exist beneath continental arcs [e.g., *Jull and Kelemen*, 2001]. Not only do these experiments consider downwelling flow induced by the dense material, but they also predict and measure dry adiabatic melting of the mantle, as well as devolatilization of the sinking blob that leads to wet melting of either the blob itself or the surrounding asthenosphere, as predicted by *Kay and Kay* [1993]. Moreover, these calculations include deflections of the surface (see **Fig. 13**).

We plan a two-pronged attack on understanding both how convective instability developed beneath the Sierra Nevada and how what is learned from it can be exported elsewhere. Molnar and CU graduate student Chris Harig plan further numerical experiments on Rayleigh-Taylor instability that consider idealized conditions with the goal of developing scaling laws that are simple enough that they can be applied for general conditions. Concurrently, Elkins-Tanton will pursue calculations for more realistic conditions that consider more than just dynamics of flow but also melting in various settings. She will be considering, in particular, the initial stages of growth of the instability, when volcanism left its signature on this process, and numerical experiments will be designed to simulate conditions in the Sierra as indicated by seismic, petrologic, and tectonic observations from other members of this team. Although we describe these plans separately, a goal is to mesh the work so that much is done in parallel, and we each gain from the other. Elkins-Tanton will base experiments on some initial conditions from the range investigated by Molnar and Harig, and will also investigate the possibility of instabilities in their experiments that could trigger wet melting.

Harig and Molnar will begin in year 1 to extend *Canright and Morris's* [1993] scaling laws to include depth-varying material properties, using Greg Houseman's numerical code *basil* (see attached letter of support), which has been modified to allow a free top [*Billen and Houseman*, 2004]. We will carry out numerical experiments with non-Newtonian viscosity and with both density and the viscosity coefficient varying with depth, conditions that do not permit analytic solutions like that of *Canright and Morris* [1993], but for which their approach suggests obvious scaling relationships that require numerical experiments to determine dimensionless scaling factors. Although Rayleigh-Taylor instability of a layer of constant and uniform material properties grows most rapidly for perturbations approaching an infinite wavelength, we will examine perturbations over plausible finite lengths. In addition, we will not restrict ourselves to two-dimensional cases. Houseman has modified his code to include radial symmetry [e.g., *Hoogenboom and Houseman*, in press]. This code will allow tests of *Canright and Morris's* [1993] solution for such symmetry and extensions of it as well as comparison with calculations by *Elkins-Tanton* [2005; in review] for more realistic conditions. Moreover, Houseman now has a 3-D code [*Houseman and Gemmer*, submitted], which will allow us to examine conditions that might permit cylindrical downwelling adjacent to a linear feature like the Sierra Nevada.

In year 2, we will incorporate a flow law that includes an effectively plastic layer. We see little point in trying to incorporate the flow law employed by *Evans and Goetze* [1979] because it has little basis in theory and can be approximated well as plastic. We will first consider a single homogeneous, unstable, plastic layer, so that we can carry out numerical experiments to derive scaling laws appropriate for it. We will then construct layered structures that include a plastic upper part to mimic the cold upper part of the lithosphere and a lower layer in which viscosity decreases exponentially with depth, to mimic the lower lithosphere. The goal will be to examine the extent to which an effectively plastic layer either prevents or limits removal of lithosphere. (Perhaps under some conditions, a plastic constitutive law will prevent removal.)

The observation that virtually all of the mantle lithosphere and eclogitic layer have been removed suggests that flow includes shear on (approximately) horizontal planes near the Moho, which could manifest itself as anisotropy of minerals like olivine undergoing non-Newtonian flow. Thus, we hope to understand flow producing seismic anisotropy that is a target of the EarthScope project. With a free-slip (stress-free) top boundary condition, however, no such shear will develop. Moreover, surely if shear does localize near the Moho, it does not do so with no shear stress at all. Thus, in year 2 we plan experiments that examine finite shear stress on the top boundary of the unstable layer. To do so, we will include a crustal layer with low viscosity at its base, as *Houseman et al*. [2000] and *Molnar and Houseman* [2004] did, but incorporating more elements to allow large contrasts in viscosity. In developing scaling laws, we will use results of *Pysklywec and Cruden* [2004] as tests for various rheological structures.

The smaller the shear stress at the top boundary of the unstable layer, the greater that thinning of the unstable layer can be. With numerical experiments, we will quantify the dependence of the amount of thinning on both the depth dependence of the viscosity coefficient and the magnitude of shear stress at the top boundary, as implemented with a low-viscosity zone within an overlying crustal layer, at or near the Moho. With appropriate scaling laws and seismological constraints on the thickness of remaining mantle lithosphere, we will quantify both the viscosity of the Sierran mantle lithosphere before its removal and the effective strength (or viscosity) near the Moho that resists flow there, for comparison with ranges of such values inferred from laboratory measurements or other approaches.

In all experiments, we will consider initial sinusoidal perturbations to the thickness of the unstable layer as well as an abrupt, marked lateral variation in thickness, conditions that *Elkins-Tanton* [in review] and *Canright and Morris* [1993] employed. We will quantify the growth in time as a function of the wavelength (or wavenumber) of the perturbation to the base of the unstable layer, surface deformation, and the free-air gravity anomaly produced over the region. We seek scaling relationships for temporal growth, corresponding surface displacements, and gravity anomalies as functions of wavenumber and ratios of buoyancy (density anomaly times gravity times layer thickness) and viscosity coefficients. Performing these experiments concurrently with related field and laboratory work will allow us to incorporate and examine physical constraints on the Sierran removal process when they are first observed. As a start, we will exploit observed surface subsidence [e.g., *Saleeby and Foster*, 2004] and gravity anomalies over the area.

Concurrently, but not independently, Elkins-Tanton will carry out experiments to assess how different constitutive laws and different geometrical shapes of density anomalies not only affect flow, but also produce both dry adiabatic melting of the asthenosphere and volatile-driven melting from the sinking instability. First, experiments similar to those carried out by Elkins-Tanton [in review] will be designed to match the observations in the Sierra. Pressure-, temperature-, and stress-dependent viscosity laws will be used for a lithospheric thickness and composition that approximates what is found in the Sierra. A range of reasonable initial viscosities and density structures will be used in an attempt to find conditions that reproduce the topographic signal indicated by concurrent tectonic studies.

Secondly, the rate of crustal recycling through these processes will be estimated and compared to the global geochemical mass balance arguments made by *Lee* [in review] and *Plank* [2005]. By tracking the mass flux of crustal material in these numerical experiments, the role of instabilities in former arcs can be assessed. The techniques for predicting wet, alkaline melts resulting from instabilities (as manifested in the Sierra by high-potassium lavas) will be extended from *Elkins-Tanton's* [in review] results to those from Harig and Molnar's experiments. Predictions of melt volumes and compositions, topography, geometry, and speed of fall can all be directly compared with observables from the Sierras.

Broader Impacts of this study. As a major integrated science project, we 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 study and the EarthScope experiment will interact with students and faculty in other subdisciplines that are equally important to addressing a large-scale problem in lithospheric dynamics. We will involve high school teachers in this project; PI Park (now an accredited high school teacher himself) will bring teachers and students into the field each year and work with the teachers to develop classroom materials growing out of this project. A CU outreach scientist (Sandra Laursen) will work with Park and/or park ranger education efforts and bring back lessons from this experience for use in several CU-based K-12 education efforts. Because they bring our science to the public, we will work with three 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. We have also budgeted travel money for PIs and graduate students to help train park rangers. Our group is well positioned to make this happen, as two of the PIs (Glazner and Anderson) are in an advisory group to Yosemite National Park, and Glazner has been involved in training park rangers. As these activities are conducted, we will be seeking to maximize the reuse of materials (e.g., leaving text and figures for park staff, using public or park lectures for training K-12 teachers, etc.). Park representatives are enthusiastic about these parts of the project (see attached letters of support from Yosemite and Sequoia-Kings Canyon National Parks).

Work Plan

We will meet as a group at least once a year during the duration of the proposal. Three meetings are explicitly included in this proposal, and one more (2008) is in the EarthScope project (SNEP). In addition to project PIs and EarthScope project PIs, we have included money in both proposals for a couple of other participants yet to be identified to participate.

Although at these times we will review progress and set goals for the coming year, close collaboration between smaller groups will occur yearlong: Jones and Park will be working jointly on geophysical studies of the upper mantle, Ducea, Farmer, Elkins-Tanton, Saleeby, and Glazner will be consulting on the volcanic rocks and their xenoliths, Anderson, Clark, and Saleeby will be considering the young evolution of topography, and Elkins-Tanton and Molnar will meet annually to incorporate these developments into numerical experiments.

An overview of goals and milestones (*italics* are related to the SNEP):

2005: *California Bigfoot and first SNEP deployment completed 10/05*

2006: **First Project Assembly** of PIs, summer/fall, Univ. Colorado (or central California)

- Initial coordination of field work
- Review and consolidation of recent work in Sierra, *esp. initial SNEP results*
- Discussions of collaborations

- Setting of goals for first year

Redeployment of 46 FlexArray broadband seismometers to northernmost Sierra

Permitting of magnetotelluric profiles

Geologic/geochemical studies of plutonic, volcanic rocks and xenoliths, locate new xenolith localities

Field investigations of datable caves and terraces and thermochron sampling sites; development of river evolution models

Numerical experiments examining effects of depth-dependent density and viscosity and plastic flow laws on Rayleigh-Taylor instability, and specific applications to volcanism related to removal of Sierran lithosphere

2007: **Second Project Assembly** of PIs, fall, central California or Boulder, CO

- *SNEP principal results from first deployment*, including 410 discon. topography
- Review of integration of seismic and electrical interpretations
- Petrologic studies bearing on geophysical interpretation of upper mantle
- Discussion of location of northern MT profiles
- Principal results of numerical experiments
- Implication of numerical experiments for upcoming field work
- Setting goals for second year

Acquisition of magnetotelluric data on Profiles 1, 2, and 3, late summer/fall

Geologic/geochemical studies of Mesozoic batholithic rocks, Cenozoic volcanic rocks and xenoliths.

Integration of new geomorphic dates with erosion models

Removal of SNEP seismometers, fall

Numerical experiments on Rayleigh-Taylor instability examining different shear stress conditions at the Moho and the role of melting, and preparation for publication

2008: **Third Project Assembly** of PIs, fall, *Univ. Arizona*

- *SNEP principal results from second deployment*
- Initial MT results
- Implications of geophysics for geologic observations; initial integration
- Coordination of publication of results for completed studies
- Set goals for final year

Reduction and analysis of volcanic and geomorphologic datasets, publications

Acquisition of magnetotelluric data on Profiles 4,5 (northern profiles)

Seismotectonic analysis of northern Sierra and foothills

Examination of northern Sierra for datable terraces and caves

Reduction and analysis of magnetotelluric data

Initial investigation of focal mechanisms in the Sierra and foothills

Final year of major volcanic rocks geochemical studies

Bigfoot array begins to leave California, October

2009: **Fourth Project Assembly** of PIs, Fall, CU Boulder

- Seismotectonic analysis presented
- *Results of seismological experiment presented*
- Integration of results for publication

Completion of analysis of field seismological data (tomography, receiver functions, etc.)

Seismotectonic analysis of northcentral Sierra and foothills

Dating of geomorphic surfaces and interpretation with geomorphic models.

Integration of results, including new numerical experiments

Publication of seismological and integrated results

Geomorphology Work Plan (Clark and Anderson)

Samples for helium dating will be collected in years 1 and 2 (Clark). 30 samples will be collected for initial evaluation, and a subset (15) will be chosen for $^4He/^3He$ analysis. We will begin by collecting a suite of samples for mineral separation. Only samples with sufficient apatite yield of unbroken, inclusion-free grains will be selected for SEM imaging and bulk ^4He dating. SEM images (backscatter and CL) provide qualitative information about chemical zoning in the grain and can identify problematic, abundant sub-microscopic mineral inclusions. Only the highest quality samples will be selected for $^4He/^3He$ analysis. Sample preparation and imaging will take place at the University of Michigan and the helium analyses at Caltech (see attached letter of support from K. Farley).

In both helium and cosmogenic sampling, we will target the Merced, San Joaquin, Kings, and Kern Rivers where the deepest incision into the relict landscape has occurred. Where possible, sampling locations for helium dating (PI Clark) and cosmogenic radionuclides (PI Anderson) will be coordinated to assure good age control on the younger incision record from cave deposits and/or river terraces. Initial dating of helium samples will begin in year 1, and the preliminary dating of these samples will guide sampling efforts in year 2. Sample preparation of 40 cosmogenic samples will occur after collection in year 1 and will be completed in year 2.

Integration of the early results will start in year 2 with fluvial modeling efforts by PI Anderson, to be continued through years 3 and 4. Likewise, in year 2 we will begin integration with PIs Elkins-Tanton and Molnar on numerical modeling efforts that predict topographic response to the initial stages of drip formation. In years 3 and 4 we will integrate data with numerical experiments.

Age, chemical and isotopic studies work plan (Farmer and Glazner)

Our plan is to obtain ages, major and trace element, and Pb, Sr, and Nd isotopic data, for volcanic rocks from the Sonora Pass and selected areas north to Lake Tahoe. Aside from a few Pb and Sr isotopic analyses [*Noble, et al.*, 1976; *Brem*, 1977], there are no isotopic, and no modern major and trace element, studies of these rocks. We consider such data, especially Nd isotopes, essential to determining the sources of these volcanic rocks. Our preliminary data [Fig. 14, *Roelofs*, 2004] show wide variations in the ε_{Nd} values of the Miocene igneous rocks (from 0 to -6), similar to values determined for Miocene rocks in the southern Sierra Nevada. Although no dated Pliocene rocks have yet been found, two lavas that are likely Pliocene (basaltic andesite of Arnot Peak and an unmapped flow near the Dardanelles) also exhibit a wide range in ε_{Nd} (+1 to -6). These lavas lack the highly potassic bulk compositions of Pliocene volcanic rocks in the southern Sierra, but do suggest that low ε_{Nd}

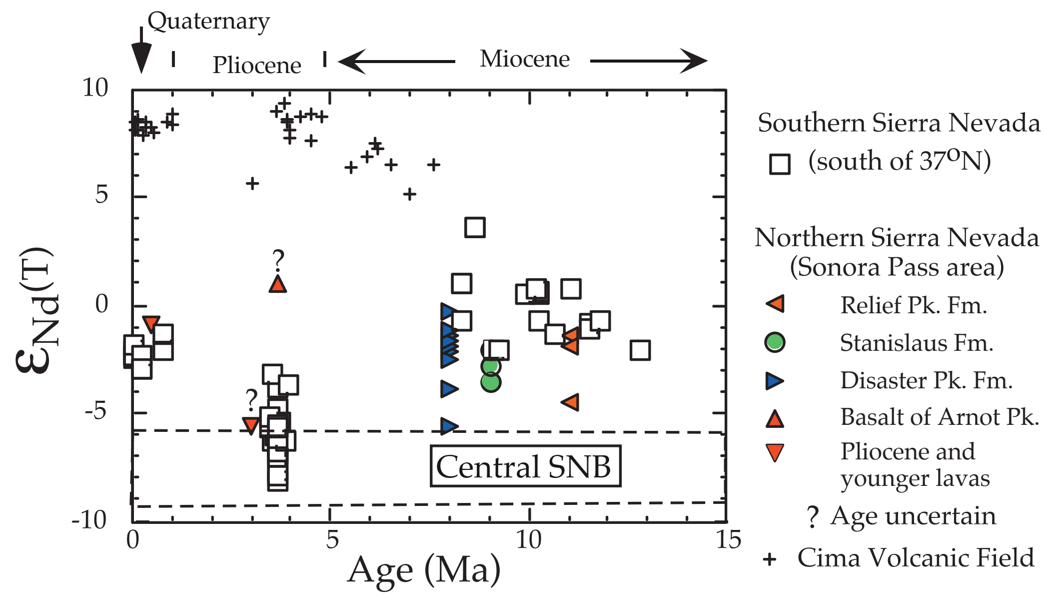

Fig. 14. Initial ε_{Nd} vs. age for northern Sierra Nevada volcanic rocks. Data from *Farmer et al.* [2002], *Farmer* (unpublished), and *Roelofs* [2004].

(Precambrian?) mantle may have been a source for some northern Sierra volcanic rocks. The only dated Quaternary basalt in the Sonora Pass area has $\varepsilon_{Nd} = -1$ (**Fig. 14**).

The puzzlingly wide range in the isotopic compositions of volcanic rocks at ~38°N suggests that there may be multiple mantle sources involved in the production of the northern Sierran volcanic rocks, and that potential Pliocene lavas may lack the unusually potassic compositions of their southern Sierra counterparts. However, without additional chemical and isotopic data, combined with the new age determinations, it will not be possible to further assess the source regions of these rocks, or the role of crustal contamination in influencing their chemical and isotopic compositions. We are well versed in methods of chemically assessing crustal contamination in volcanic rocks [e.g., *Beard and Glazner*, 1998; *Glazner, et al.*, 1991; *Farmer, et al.*, 2002]. While other isotopic datasets might be useful, including Li isotopic studies being carried out for Sierran rocks by others (W. Leeman, pers. comm. 2003), such work is premature in the northern Sierra before the basic age, chemical and isotopic work are obtained. With the new chemical data from the volcanic rocks, we will test further our ability to estimate depths and extent of mantle melting through an assessment of major element composition from the volcanic rocks [cf. *Wang, et al.*, 2002]

Chemical, isotopic, and geochronological work necessary to complete limited existing measurements will be acquired from several critical sites in the Sonora Pass region: (1) Relief Peak Formation and a basalt near Brown Bear Pass that might be the oldest Cenozoic mantle-derived rock in this part of the Sierra, (2) the potassic Stanislaus Group, especially the most mafic rocks found at Mahogany Ridge in the Little Walker volcanic field (the vent area of the Stanislaus Group), (3) Tertiary intrusive andesites mapped by *Giusso* [1981], (4) potential Pliocene and Quaternary mafic and intermediate lavas. In addition to the work in the Sonora Pass area, we will also continue our studies of Pliocene intermediate to mafic composition volcanic rocks west of Lake Tahoe in the Crystal Basin Recreational Area, for which no chemical or isotopic data currently exist (although they similar in age to rocks in the north Tahoe region studied by *Cousens et al.* [2000]). Similar reconnaissance studies of volcanic rocks in the corridor between Lake Tahoe and Sonora Pass will also be undertaken, including studies of silicic and mafic composition volcanic rocks from the Ebbetts Pass (and nearby Highland Lakes) area [*Ostendorf*, 1981] will also be carried out. When the project is completed we will have both a detailed picture of the geochronology and the geochemical characteristics of Cenozoic volcanic rocks in the Sonora Pass region, and a reconnaissance overview of the ages and compositions of similar volcanic rocks north to Lake Tahoe.

Experimental Petrology Work Plan (Elkins-Tanton)

Because the purpose of this experimental study is to determine the mantle melting conditions and compositions that lead to the production of a drier, lower-potassium Sierran magma, it is first necessary to ensure that the starting composition used is as close to a primary mantle melt as possible. One of the traditional tests is for equilibrium with mantle olivine, expected to have a forsterite content that lies within the range of 89 to 93. Several candidate magmas will be examined in detail, including whole rock analyses, microprobe analyses of individual phases (in particular, olivine cores to assure their equilibrium with the whole-rock composition), and compositional relation to the rest of the suite of related rocks.

Once an experimental composition is chosen, starting materials will be made from high-purity oxides, because even finely ground natural rocks have prohibitively long equilibration times. Some initial experiments may be carried out in a one-atmosphere furnace as reconnaissance for higher-pressure experiments, and would be an ideal senior thesis project for an undergraduate. The P.I. will seek geology majors with an interest in lab work for this project; in the past two Brown university undergraduates have complete honors theses doing a similar experimental study [*Elkins-Tanton, et al.*, submitted].

Experiments up to 4.0 GPa can be done in Yan Liang's lab at Brown University with his 0.5-inch piston cylinder apparatus [*Boyd and England*, 1960], using the hot piston-in technique [*Johannes, et al.*, 1971]. For each experiment ~10 mg of conditioned starting material will be packed into a graphite crucible and capped with graphite, and the assembly positioned in the hot spot of a graphite heater with MgO spacers, using salt as the pressure medium. Graphite appears to be an efficient barrier against water loss for experiments with low water contents. These techniques were successfully used by the P.I. for studies published in *Elkins-Tanton et al.* [2000; 2003]. It is anticipated that approximately 40 experiments will be needed.

The P.I. has previously carried out a number of high-pressure and temperature phase equilibria experiments to ascertain the formation conditions of terrestrial and lunar magmas, including the Sierra Nevadan olivine leucitite referred to here [*Elkins-Tanton and Grove*, 2003]; deep, dry magmas from Hawaii (unpublished); shallow, wet magmas from the Cascades [*Grove, et al.*, 2003], and dry lunar picrites [*Elkins, et al.*, 2000; *Elkins-Tanton, et al.*, 2003], and a new study on a high-magnesian, potassic, hydrous magma from the Siberian flood basaslts [*Elkins-Tanton, et al.*, submitted].

Surface batholith and xenolith studies work plan (Ducea and Saleeby):

The effort of determining the composition, age and vertical structure of the northern batholith (and comparing it to the southern counterpart) will be conducted in three components: (1) determining the ages and major element chemistry of the exposed part of the northern Sierra Nevada arc, (2) characterizing the trace element (and particularly REE) chemistry of the same rocks, and (3) resolving the petrogenetic history of lower crustal and mantle xenoliths from the area.

<u>Batholith bulk composition and ages.</u> To complement the current sparse data base for the

northern batholith, we will measure the bulk chemistry of about fifty plutonic rocks collected .along two transects across the northern Sierra. We chose these transects along interstate 80 and California highway 50 for their easy access and outstanding exposure. Major element analyses will be analyzed at Washington State University. We will use a modified version of MELTS [*Ghiorso, et al*., 2002] to calculate end-members for the vertical extent, compositions and physical properties of plausible residual assemblages [*Ducea*, 2002], thereby constraining the composition and size of the batholithic root. We will also analyze ~15 samples of this collection for U-Pb zircon geochronology, using the Arizona Laserprobe. These dates will help us determine if the northern batholith evolved in a pattern of flare-ups separated by magmatic lulls, similar to that in the southern Sierra [*Ducea*, 2001]. This is important because we believe that it is during these high flux events that major ultrabasic roots develop beneath batholiths.

We will also analyze 10 samples of arc-related rocks from the Central Valley basement for ages, major and trace element concentrations, and use the age and compositional data, core locations and the gravity-magnetic anomaly patterns to construct a generalized map of the cryptic western zone of the northern segment of the batholith beneath the Sacramento Valley. This map, and its compositional and age information will then be integrated into the broader data base for the northern segment of the batholith, and used to more accurately define regional magmatic flux rates, and to further evaluate the extent to which eclogitic residues may have resided in the north. Co-PI J. Saleeby has retained the basement core collection acquired by Howell Williams during his classic study of the Sutter Buttes, and has added to this from industrial sources.

<u>Trace element analyses, with an emphasis on Rare-Earth Elements (REE) in granitoids.</u> Trace elements, especially REE, provide an important constraint on the depth of pluton generation [e.g., *Gromet and Silver*, 1987]. Specifically, a garnet-rich and plagioclase-poor residue is characterized by highly fractionated REE patterns and lack of Eu anomalies. In contrast, granitoids that equilibrated with a granulitic or amphibolitic residue will show a negative Eu anomaly due to retention of Eu by residual plagioclase. They will also lack the steep normalized pattern of heavy REE, because of low abundance or lack of garnet in the residue. For instance, changes of pluton sources from garnet bearing (thick crust) to garnet absent (thin crust) coupled with progressive lowering of the depth of emplacement of plutons may fingerprint the removal of a dense crustal root and subsequent uplift of mid-crustal rocks [see *Kay and Mpodozis*, 2001].

Trace element studies in both the Sierra Nevada and Peninsular Ranges batholith indicate that specific domains of these batholiths retain their source characteristics, and that higher-level fractionation and assimilation are of second order importance [*Dodge, et al*., 1982; *Gromet and Silver*, 1987; *Kistler, et al*., 1986; *Pickett and Saleeby*, 1994; *Silver, et al*., 1988; *Ross*, 1989]. Both trace element variation patterns in Andean volcanoes [cf. *Hildreth and Moorbath*, 1988]). Furthermore, and the growing evidence for the incremental growth of large Sierran plutons considered in the light of trace element and isotopic data further argues for a dominance of source over ascent/emplacement level in imparting geochemical signatures [*Mack, et al*., 1979; *Clemens-Knott and Saleeby*, 1999; *Coleman, et al*., 2004; *Glazner, et al*., 2004]. We plan to analyze 50 whole rock trace element patterns for the same samples that were selected for major element work. The main effort of PI's Ducea and Saleeby for years 1 and 2 of the project will be to determine the bulk chemistry and geochronology.

<u>Xenoliths.</u> We plan to collect representative samples from the three known lower crustal and upper mantle xenolith locations in the northern Sierra (Jackson Butte, Donner Pass, Leek Springs) and the newly discovered locality at Sonora Pass (Farmer and Glazner, unpublished

work) for thermobarometry [*Ducea and Saleeby*, 1996]. We will also perform Sm-Nd garnet geochronologic measurements on garnet-bearing lower crustal rocks in order to establish if these are cogenetic with the surface batholith. Garnet-bearing amphibolite and granulite rocks collected from Jackson Butte are ideal for both thermobarometry and geochronology (**Fig. 10**).

The most direct way to determine the composition and thermal history of the mantle is by thermometry of four-phase lherzolites and geobarometry and geothermometry of garnet peridotites [*Brey and Kohler*, 1990]. Xenolith petrology and thermobarometry will constitute the bulk of the third year of this project for PIs Ducea and Saleeby.

MT Work Plan. (Park).

The first year will focus primarily on locating and permitting the MT sites. Data along Profiles 1-3 (**Fig. 2**) will be acquired in the last 6 months of 2007 and along Profiles 4-5 in summer 2008. A total of 10 long period MT instruments and 2 broadband instruments have been requested from EMSOC for these periods. Past experience has shown that each 10-station deployment requires 6-8 weeks to complete, and approximately 4 deployments will be needed to complete Profiles 1, 2, and the extension of the SSCD profile. Deployment of these instruments in wilderness areas (as in the 1997 SSCD project) should be no problem. PI Park will be responsible for the MT component of this project, and will be assisted by one graduate student, 1-2 undergraduates, high school teachers, and a high school student.

The 30 soundings on the northern profiles (Profiles 4, 5) will be acquired in 3 deployments in summer, 2008. Data will be processed as it is acquired with robust processing techniques [*Egbert*, 1997; *Larsen, et al.*, 1996], taking advantage of the multistation array for improved impedance estimation. Data from all profiles will be modeled initially with Rodi and Mackie's [2001] 2-D inversion and then ultimately with Mackie's 3-D inversion. At later stages, we will also model the data with a version of the Rodi and Mackie code that incorporates anisotropy.

Seismology Work Plan (Jones)

New seismological work will focus on improving the inversion strategies in year 1, applying them to datasets previously presented by *Jones et al.*[1994] and *Boyd et al.* [2004]. This will be coordinated with PI Park as we seek a formalism for simultaneous analysis of electrical and seismological data. Initial efforts will focus on making stable inversions for what are often derived seismological parameters like vp/vs and percent anisotropy. We will then explore direct seismological inversions for physical parameters like temperature and lithology [e.g., *Bosch*, 1999]. This will extend into the second year, in which we will finally approach the possibility of including either electrical interpretations or the MT observations themselves in the inversion.

Seismological imaging (tomography and receiver functions in the Transition Zone) using these inversions will be mainly in years 2-3 as sufficient data from the Bigfoot and SNEP deployments becomes available. Jones will also be working with Unruh to collect focal mechanisms from these deployments as needed for the seismotectonic analysis in years 3 and 4.

Jones also acts as the lead PI and so will be involved with efforts to integrate all the materials from this project and run the workshops.

Seismotectonics Work Plan (Unruh)

The bulk of the seismotectonic analysis will begin in Year 3 when new focal mechanisms from the Bigfoot and SNEP deployments become available. Unruh will work with PI Jones to assess these new data, as well as previously determined focal mechanisms from the northern Sacramento Valley and northern and central Sierra available from the USGS Northern California Seismic Network catalog. Based on a preliminary review of the USGS catalog, we anticipate that sufficient focal mechanism data are available for detailed analysis of seismogenic deformation in the vicinity of the “Redding” high wavespeed anomaly beneath the northern Sacramento Valley, as well as a more general characterization of seismicity in the central Sierra. After compiling a catalog of all earthquakes for which focal mechanisms are available, Unruh will assess the 3D distribution of hypocenters (using the ArcView 3-D Analyst tool), and select spatially distinct clusters for kinematic analysis. Seismic P and T axes from groups of earthquakes will be inverted for components of a reduced deformation rate tensor using the code FLTSLP (R. Twiss, University of California, Davis). Standard bootstrap methods will be used to determine 95% confidence intervals for the best-fit model parameters.

In the fourth year, Unruh will synthesize the inversion results into maps of the seismogenic deformation field, with emphasis on characterizing lateral and vertical variations in strain geometry (if any) adjacent to the “Redding anomaly”. Unruh will work closely with PI Jones to integrate the seismotectonic analysis with tomographic imaging, including additional analysis of seismicity in the southern Sierra Nevada where *Boyd et al*. (2004) have obtained detailed images of the “Isabella anomaly”.

Geodynamics (Molnar and Elkins-Tanton)

The work planned and its coordination is discussed in the “What conditions are necessary for lithospheric removal?” section.

Outreach Work Plan

Communication of the results of this project extends beyond the usual scientific outlets such as publications and meetings and will span the duration of the project. New public displays will be developed for Yosemite National Park, including the installation of an interactive seismic display in the first year of this project. All PIs will participate in a program to train the rangers to give talks to the public about our disciplines and results. PI Park has developed a plan to include high school teachers and a high school student from a local rural area (see letter of support from Bishop Union High School) and other schools in southern California in the field research activities during all four years of the project. This will include student and teacher training in the scientific process, public talks, and development of age-appropriate classroom exercises based on the results of our project. University of Colorado outreach scientist Sandra Laursen (<http://cires.colorado.edu/education/k12/people/laursen/>) will assist Park to develop classroom materials with the teachers, and she will bring some of these materials and lessons back to CU to improve an existing early career K-12 earth science outreach program (EarthWorks, <http://cires.colorado.edu/education/k12/earthworks/>).

Results from Prior NSF Support

C. H. Jones Prior Support

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 and new tomography results, which led to expansion of Sierran lid removal hypothesis.

Publications

Boyd et al. [2004], Jones and Phinney [1998], Jones et al. [2004], Molnar and Jones [2004], Zandt et al. [2004]

Dataset: Jones, C H., and R. A. Phinney, Sierran Paradox Experiment, PASSCAL XJ 97, 54 Gb of continuous data, http://www.passcal.nmt.edu/schedules/experiment_profiles/historical/subs/9709Continental_Mountains_in_Extensional_Environments:_The_Sierran_Paradox.html, 1998.

Other PI Prior Support in Supplemental Documents.

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