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TITLE OF PROPOSED PROJECT **Flexarray 3D passive seismic imaging of core-complex extension in the Ruby Range, Nevada**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 136,197	36 months	06/01/09	

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☐ HISTORIC PLACES (GPG II.C.2.j)
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PROJECT SUMMARY

FLEXARRAY 3D PASSIVE SEISMIC IMAGING OF CORE-COMPLEX EXTENSION IN THE RUBY RANGE, NEVADA

This proposal addresses the most controversial aspects of continental extension - the nature of core-complexes and low-angle faults - with dense passive broadband recordings for 2D and locally 3D crustal imaging, enabled by Earthscope's FlexArray.

The Basin-and-Range Province (BRP) in Nevada offers unparalleled exposure of diverse styles of extension, and of one mode in particular that remains controversial: metamorphic core complexes that juxtapose ductilely deformed mid-crustal rocks with unmetamorphosed, brittly-deformed supracrustal rocks. This relationship implies significant horizontal extension, compensated at the scale of the whole crust either by large-magnitude simple shear or significant lateral and vertical flow of the lower crust. Elucidating the relationship between synchronous deformation of the upper and lower crust, however, requires integrating geologic and geochronologic data with geophysical data of sufficient resolution to convincingly show how the surface geology is linked to—or disconnected from—features at depth). Uncertainty in the total stretching involved is a major unknown in tectonic reconstruction of extensional provinces wherever such core complexes occur around the world.

I request funds (to match an awarded, companion, grant from the Petroleum Research Fund of the American Chemical Society) to carry out a 3D passive seismology study of the classic Ruby Mountain Metamorphic Core Complex (RMCC) and its adjacent basins (Lamoille-Huntington Valley & Ruby Valley) to look for evidence of crustal flow into the metamorphic core. This region is targeted because the existing data that surround our target will allow detailed interpretation of our new geophysical results in a 3D volume. The experiment will allow evaluation of models for crustal flow at depth beneath extending regions, and thereby help us understand the progression of lower-crustal strain in space and time across extending regions. Characterizing these processes in more detail is a fundamental step towards advancing our knowledge of continental rifting and the evolution of sedimentary basins world-wide.

North-central Nevada has somewhat thicker crust than adjacent areas in the BRP but significant overall extension – a possible indication that the region had more material added by magmatism or crustal flow. This hypothesis will be addressed by our proposed seismic array, coupled with new gravity and magnetic data to be collected by our USGS partners (not funded by this proposal). The alternate possibility, that the region inherited thicker pre-extensional crust than elsewhere, will be addressed by integrating existing and new geochronologic/geologic data from Stanford and the USGS to add the fourth dimension – time – to our study. Our detailed FlexArray geophysical studies of the crust and upper mantle will provide the necessary link between Transportable Array data and surface geologic data to develop understanding of continental structure, deformation and evolution, and the lithospheric-scale processes involved in extensional orogens. The project is innovative in applying established passive-recording techniques (ambient-noise tomography, receiver-function velocity inversions, common-conversion point imaging, crustal anisotropy analyses) at a higher resolution (5-km spacing) than is yet typical, and will collect data from a 40-station array that may be a model data-set for exploring 3D imaging methodologies for the crust as as well as the uppermost mantle.

***Broader Impacts**:* Results will be of interest to resource companies, as demonstrated by funding from the Petroleum Research Foundation, and letters of support from mining companies whose blasts we will record: the Ruby Range may expose underpinnings of the adjacent Carlin Trend, the largest gold-producing region in the Americas. In addition to acquiring the data for a PhD thesis at Stanford, we will provide research exposure for undergraduates (Klemperer's outstanding mentoring of undergraduate researchers was recently recognized by a university-wide award). We plan education and outreach efforts modeled on our previous Eathscope-FlexArray study in Nevada ("NV-FlexArray-04"): prior to, during and following our experiment we will offer public presentations (in NV-Earthscope-04 we made presentations at a high school, a community center and a National Forest Service center), solicit press and radio interviews, and set up a web-site for non-scientists, all designed to increase public understanding and appreciation of science and local geology. The recent occurrence of Nevada's most destructive earthquake for over 50 years (08/02/21 Wells Mw=6) adjacent to our field area provides special opportunities to interest local citizens in regional geology and hazards. All seismic data will be archived with and publicly released through the USArray-IRIS DMC, and potential-field data through the USGS.

RESULTS OF PRIOR NSF SUPPORT:

EAR-0346245 (EARTHSCOPE) (S.L Klemperer & E.L. Miller) 7/04 - 7/06

USArray FlexArray seismic study of the extension paradox at the northwest margin of the Basin-&-Range Province

CMS-0444696 (NEES-SGER) (S.L. Klemperer) 10/04-9/05

Collaborative Research: Field demonstration of utility of NEES Vibrator to meet EarthScope science objectives for earthquake-hazard and crustal-structure studies

(Note, these grants complemented a sub-equal grant from the Petroleum Research Fund of the American Chemical Society (ACS-PRF) that provided seed funding for our Nevada-Earthscope-2004 seismic profile across NW Nevada)

Our experiments targeted a part of the Basin-&-Range Province (BRP) in NW Nevada that has thin crust (~30 km) despite relatively recent (~12 Ma), low-magnitude supracrustal extension (15-20%) (in contrast to much of the BRP to the south where major extension took place ca. 20-15 Ma and reached magnitudes of 100% or more), in an effort to understand the regional tectonic history that could lead to this paradoxical combination.

We carried out the first EARTHSCOPE "FlexArray" study ("NV-FlexArray-04"), a 2D combined active- and short-period passive-seismic survey across the northwestern BRP, to study crustal modification by lower-crustal flow and by magmatic additions in a region of laterally varying total extension. In September 2004, we mobilized 40 staff and students from multiple institutions to record 5 >1-ton detonations and 3 goldmine blasts on >1000 seismographs along a 260-km long crustal refraction profile. We used an experimental 3-component seismic vibrator to record a high-resolution image of Surprise Valley and low-fold crustal-scale data within our refraction profile. We studied data from the 5 closest USArray-Transportable Array sites, and maintained a 29-station passive array at 2-km spacing for 8 months across the central part of our refraction profile, recording over 200 earthquakes suitable for receiver-function analysis. Although broadband stations were not available to us, even our short-period (L-22 – 2 Hz) stations provided useful data for receiver-function velocity inversions, but proved too noisy for crustal imaging converted-wave crustal imaging (common conversion point stacks) or detailed (multi-layer) crustal anisotropy analyses.

We engaged six Stanford undergraduates in fieldwork (as well as others from UNLV), some of whom have now been motivated to undertake additional research. Our datasets provide large parts of two PhD theses (Lerch, 2007; Gashawbeza, 2008) and one chapter of a third, in progress (Egger, anticipated 2010). The results are fully documented in three published papers (Lerch et al., 2007, 2008a; Gashawbeza et al., 2008) and two submitted papers (Egger et al., in review; Lerch et al., in review), as well as contributing a cross-section to Lerch et al. (2008b) and appearing in numerous published abstracts. All reflection, refraction and passive data are archived with IRIS, and all vibrator data additionally with NEES. Extensive public outreach included school and community lectures and numerous newspaper articles and a dedicated web-site: http://geo.stanford.edu/groups/warners/seismic.html.

Discoveries include (1) imaging the major range-bounding fault in Surprise Valley that dips only 35°; (2) mapping crustal thickness changes from 37 to 31 km (~20% crustal thinning) that, based on field mapping of surface extension, do not require regional lower-crustal flow; (3) demonstrating the absence (consistent with low-magnitude extension in this region) of distributed lower-crustal reflectivity and of a discrete lower-crustal "7.x" km/s layer that have become the hallmark of highly extended terranes; (4) measuring weak crustal anisotropy consistent with NW-SE directed extension; and (5) discovering strong changes in Vp/Vs ratios laterally and with depth that better constrain crustal lithologies including a well-defined, 80 km-wide zone of unusually low upper-crustal velocity (~5.9 - 6.1 km/s) and low Vp/Vs (<1.74) that locates the northern extension of the Sierra Nevada batholith in the subsurface. Methodological developments include extracting crustal lithological information that varies on short spatial scales from the densely-spaced passive array.

4-D geologic reconstructions utilizing the new data lead to the conclusion that crustal thickness prior to extension was only average, c. 40km, so that in this region a high plateau underlain by over-thickened crust (commonly invoked elsewhere in the Basin-and-Range province) was not a precursor to Basin-Range extension. For additional results see text of this proposal, particularly Figures 6, 7 and 8 that summarize some of our passive seismic results that are a partial model for the work proposed here.

PROJECT DESCRIPTION
FLEXARRAY 3D PASSIVE SEISMIC IMAGING OF CORE-COMPLEX EXTENSION IN THE RUBY RANGE, NEVADA

INTRODUCTION

The tectonically active Basin-and-Range province (BRP) of the western U.S. is widely regarded as the world's best and most accessible example of stretched continental crust, thought to have nearly doubled in width since about 40 Ma (Figure 1). Geological and geophysical studies of this province over the last 30 years have generated many conceptual breakthroughs in our understanding of continental extension beyond the BRP. These include the interpretation of low-angle normal faults as large-displacement simple-shear zones (e.g., Wernicke, 1981), or as formed by a "rolling-hinge" mechanism (Buck, 1988; 1991; Wernicke et al., 1988); the appreciation that sub-horizontal seismic reflectivity in the lower crust is produced by extensional processes (e.g., Klemperer et al., 1986; McCarthy & Thompson, 1988); and the realization that large-scale lateral flow can occur in the lower and middle crust flowing from less-extended to more-extended regions to maintain an approximately constant depth to Moho (e.g., Gans, 1987; Block & Royden, 1990; Wernicke, 1990, 1992; McCarthy et al., 1991; Kruse et al., 1991; McKenzie et al., 2000). Decoupling and *lateral* flow of the lower and middle crust during continental extension is now widely accepted and is also rheologically predicted given the compositions and temperatures of the crust in the BRP (e.g. Kusznir and Park, 1987). Most recently, P-T-t data that demonstrate *vertical* rise of deep crustal rocks during partial melting have re-popularized the diapiric gneiss dome concept in both extensional and compressional settings (see papers in Whitney et al., 2004a), providing a new twist on old interpretations of BRP metamorphic core complexes (Armstrong & Hills, 1967; Compton et al., 1977) and offering a new framework in which to re-consider these important structures. However, because the processes of crustal flow at depth cannot be documented or studied directly by surface mapping, many questions remain about its nature, timing, magnitude and direction, and the physical/mechanical driving forces for this flow.

In the northern BRP, in the mid-1980s crustal reflection (COCORP: e.g. Klemperer et al., 1986; Allmendinger et al., 1987) profiles were interpreted to show large degrees of underplating and intra-plating to maintain a constant crustal thickness across areas with different degrees of pure-shear extension (Gans, 1987). But in the twenty years since these first digital seismic profiles were acquired across the BRP, it has become increasingly clear that extension varies significantly across the province in its magnitude, timing, and relationship to magmatism (Figure 1). We will collect new seismic data across the Ruby Mountain Core Complex (RMCC) designed to understand one of the specific modes of extension displayed in the BRP, trying to move beyond "one-size-fits-all" interpretations that characterized the earlier generation of seismic experiments (COCORP and PASSCAL refraction: Holbrook, 1990, Catchings & Mooney, 1991). Important seismic work around the Ruby Range in the 1980s and early 1990s (petroleum exploration (Effimoff & Pinezich, 1981; Satarugsa & Johnson, 2000a), academic crustal reflection (Valasek et al., 1989) and wide-angle refraction (Stoerzel & Smithson, 1998; Satarugsa & Johnson, 1998, 2000b)) (Figures 2 & 3) provides valuable framework knowledge of the adjacent basins but was not designed to map the possible patterns of crustal flow that are now believed to characterize this and other extensional core complexes.

Although our knowledge of its supracrustal extension has increased significantly in the past 20 years, the BRP still poses large-scale fundamental questions that can be answered only by the integration of geological and geophysical information. We still lack understanding of the different ways in which the extensional process has modified the existing crust and mantle, and the ways in which varying crust-mantle properties have controlled the response to uniform extensional forces. We can explore these problems by integrating our current geologic understanding with geophysical data from the proposed passive FlexArray experiment (Figure 2), from the Transportable Array component of EarthScope's USArray, and with new data from potential-field studies (not funded by this proposal, but to be collected by USGS as part of this overall investigation).

We will collect modern geophysical data in the northern BRP (Figure 2b), utilizing both the FlexArray and Transportable Array (TA) components of USArray. Broadband instruments are requested from the FlexArray pool for this proposal. Our previous FlexArray experiment in Nevada (hereafter "NV-FlexArray-04"), funded by NSF EarthScope and the ACS-PRF, is complete and the data and interpretations published or in review (Lerch et al., 2007, 2008a & in review; Gashawbeza et al., 2008) demonstrate most of the techniques and capabilities proposed here (Figures 6, 7, 8). Our planned work will yield better passive data than did NV-FlexArray-04 (longer deployment and broader-band sensors) and so enable some additional seismic methodologies (e.g. crustal CCP profiling and multi-level crustal anisotropy analyses) not feasible with NV-FlexArray-04 data. The 3D deployment proposed (as opposed to a single profile in NV-FlexArray-04) will also permit ambient noise surface-wave tomography.

This new proposal is a collaborative effort between Stanford University ($105k requested from NSF in direct costs), with additional funding already awarded by the Petroleum Research Fund ($100k in direct costs), and the USGS (ongoing projects with both Western Mineral Resources and with Western Earth Surface Processes), with fieldwork to be carried out in 2009-2011 (Figure 2b). Because the Petroleum Research Fund grant requires c. 70% of its value be used directly to support students, this NSF grant requests only minimal student support but additional funding is needed for the proposed fieldwork.

Our proposed experiment targets a key region that poses outstanding unanswered questions and testable hypotheses regarding extension, magmatic modification, and continental evolution at the lithospheric scale. Our 3D passive seismic experiment will be extended to "4D" by our strong focus on the geologic history of the region, integrating with the temporal history of extension and the distribution and volume of magmatism. Our experiment is an excellent opportunity for collaboration between geophysicists (Klemper/Stanford and Jonathan Glen/USGS – see letter of support) and geologists (Elizabeth Miller/Stanford who has made the Basin-&-Range province a major focus of her career for over 25 years, including extensive investigations of core-complexes, and her former student Joseph Colgan/USGS – see letter of support) to integrate an evolving geological and geophysical database and address fundamental geodynamical questions.

REGIONAL SETTING OF THE RUBY MOUNTAINS WITHIN THE BASIN AND RANGE PROVINCE

The Ruby Mountains Core Complex (RMCC), one of the classic examples of an extensional metamorphic core complex, remains controversial in some important respects despite years of detailed research (see recent reviews by Howard, 2003, and Sullivan & Snoke, 2007). The RMCC lies within a physiographically and geologically distinct region of the northern BRP (Figure 1), a broad, NNE-trending topographic high flanked, in near symmetry, by the Lahontan Basin to the west and the Bonneville Basin to the east. Various hypotheses (not necessarily mutually exclusive) have been proposed to explain the central Nevada topographic high. These include suggestions that it is a relict of over-thickened Mesozoic crust (Catchings, 1992) and/or that its elevation is related to Cenozoic magmatic underplating (Gans, 1987; Thompson et al., 1989; Liu & Furlong, 1994) or to the presence of a depleted and less dense upper mantle beneath the region as consequence of this magmatic activity (Parsons et al., 1994; Humphreys & Dueker, 1994; Okaya & Thompson, 1986; Walker et al., 2004). Greater local extension with concomitant lower crustal flow of material into the region (Smith et al., 1993) is yet another explanation. Contemporary thermal processes (a plume head or hot asthenosphere) beneath the region have also been proposed to explain the higher elevations (e.g., Parsons et al., 1994; Saltus & Thompson, 1995; Eaton et al., 1978). The USGS (see letter of support from Colgan) has just published a large body of new work focused on the basic geology of this region (Hofstra & Wallace 2006 a & b, *Geosphere* Special Issue "Great Basin Tectonics and Metallogeny").

The Ruby Mountains Core Complex (RMCC) is an exception to the otherwise low extensional strain characteristic of this region. Unlike other BRP core complexes, the RMCC is not surrounded or overlain by highly extended supracrustal sequences (Howard, 2003), and the exact amount of extension represented by this complex is very dependent on which model is used for its origin (Figure 4). Our experiment will investigate models for core complex formation along with hypothetical causes of the central Nevada topographic high.

The RMCC sits at ~1-km elevation and is underlain by crust up to 35 km thick (Stoerzel & Smithson, 1998) despite being locally highly-extended (up to 50-150%). This crust is apparently reflective (Hauser et al., 1987; Valasek et al., 1989; Figure 3) in a style commonly taken as a hallmark of high extension (Allmendinger et al., 1987). The crustal thickness and degree of extension suggest that either this area inherited much thicker crust than adjacent areas of the BRP at the beginning of the Cenozoic (Coney & Harms, 1984; Catchings, 1992) or has had significant thicknesses of material added by magmatism (Gans, 1987; Thompson et al., 1989; Liu & Furlong, 1994) and/or lateral crustal flow (Hodges & Walker, 1992; Smith et al., 1993). The RMCC is the most highly strained part of this region, but paradoxically the crust beneath the RMCC is not correspondingly thin, and may even form the thickest crust in north-central

Nevada: Stoerzel & Smithson (1998) interpret 34-35 km crust along the U. Wyoming-U. Arizona refraction profile in Ruby Valley (Figure 2 & 3c). An alternative interpretation of the same data suggests that the crust is of average thickness for Nevada (30-33 km; Satarugsa & Johnson, 1998), but source-receiver offsets in that Wyoming-Arizona seismic experiment were typically only up to 50 km, so velocities and depth interpretations relied only on reflections, not on the Ps conversions we will use to better constrain crustal structure.

The RMCC (see recent reviews by Howard, 2003; Sullivan & Snoke, 2007) is a classic example of an extensional metamorphic core complex and illustrates the three distinct domains that define these complexes: (1) in the footwall, a domed, ductilely deformed metamorphic-plutonic assemblage; (2) an overlying or adjacent unmetamorphosed brittlely deformed hanging wall assemblage; and (3) a mylonitic zone of sub-horizontal shearing and detachment separating the upper and lower assemblages (Coney, 1980, 1987). The RMCC records an extensional tectonic setting that is often attributed to the lateral collapse of a 60-km thick crust that developed in the Sevier-Laramide orogenies (Coney and Harms, 1984), yet it still forms the highest topography in the region. Unlike other BRP core complexes, the RMCC is not surrounded by highly extended supracrustal sequences (Howard, 2003), and the exact amount of extension represented by this complex is highly dependent on which model is used for its origin (Figure 4). Howard (2003) suggests 60 to 70 km separation across the RMCC detachment, implying >100% extension since the maximum exposed width of the footwall metamorphic belt is 53 km (Camilleri & Chamberlain, 1997). The proposed experiment will investigate and attempt to distinguish models for core complex formation (Figure 4, parts b, c, d).

The core of the RMCC is composed of relict, highly-attenuated Paleozoic metasediments intruded by sheetlike granitic to pegmatitic bodies that make up >90% of the exposed rock in the most deeply exposed parts of the RMCC (Howard, 2003; Lee et al., 2003; Snoke et al., 1990). The maximum geobarometric assemblage records 9.5 kb (McGrew et al., 2000), whereas the hanging wall exposes unmetamorphosed or low-grade Paleozoic to Cenozoic sedimentary rocks. The core of the RMCC was episodically exhumed during the Cenozoic along a mylonitic shear zone that now dips gently west along the west side of the range (Howard, 2003; Sullivan & Snoke, 2007) (Figure 4a). The presence of rocks exhumed from 30-40 km depth at the surface today requires either that the overlying crust was excised by faulting (i.e., simple shear) (Figure 4b), or that the deep crustal rocks rose diapirically by flow in the crust (i.e., pure shear) (Figure 4d), or a combination "rolling-hinge" model (Figure 4c). In the simple-shear case, the RMCC would be underlain at present by the (itself undeformed) footwall of the west-dipping shear zone; in the pre-shear case it would be underlain by a "welt" of crust strongly modified by magmatic addition and lateral flow of material from adjacent areas; and in the hybrid rolling-hinge case it would be underlain by a crustal "welt" bounded by a west-dipping shear zone that steepens ("rolls") at depth.

If the RMCC was exhumed along a gently west-dipping normal fault that penetrated the crust to a depth of 25-30 km (Figure 4b), the (formerly) deep crust presently exposed in the Ruby Mountains would restore beneath the Adobe and Pinon Ranges (Figure 2) to the west (southern part of the Carlin Trend) (Howard, 2003). Lower-plate crust, modified by Cenozoic deformation and magmatism, would be bounded by a gently west-dipping structure – presumably a prominent seismic converter – that roots beneath the Pinon and Adobe Ranges (Figure 4b). Consistent with this hypothesis, industry seismic reflection studies west of the Ruby Mountains image a bounding detachment fault that dips shallowly to the west but which has only been traced to a depth of about 5 km (Satarugsa & Johnson, 2000a). In this model, low-angle to sub-horizontal features would dominate across our array.

Recent studies of gneiss domes worldwide emphasizing the diapiric rise of migmatite-rich crustal "welts" (e.g., Whitney et al., 2004b) have re-invigorated the debate about the RMCC and other core complexes, by providing a clearly contrasting and testable model. Although gneiss domes were originally interpreted as compressional features due to their widespread occurrence in orogenic belts, recent work has shown that they commonly lie in extensional settings within collapsing orogens (Fayon et al., 2004; Whitney et al., 2004b). If the RMCC formed by this mechanism, we would expect the zone of intensely modified crust to have steeper bounding structures than in the previous model and to be confined to the area beneath the RMCC itself (Figure 4d). Magnetotelluric data from the central and southern Ruby Mountains suggests the RMCC-bounding structures are near-vertical at depth, supporting this hypothesis (Wannamaker & Doerner, 2002). Some regional assessments of isotopic (Tosdal et al., 2000) and of gravity and magnetic (Grauch et al., 2003) trends interpret the Proterozoic continental margin (e.g. Sr(initial) = 0.706 isopleth) west of the RMCC to be a major structure that controlled Tertiary mineralization and tectonics. More significantly, this structure is inferred to extend unbroken—vertically—to the base of the crust. If so, formation of the RMCC must have been by largely vertical motions (Figure 4d), as large-scale horizontal flow (Figure 4b, c) would tend to disrupt the older basement framework. In this hypothesis we should expect to see steep to vertical features dominate our velocity models, structural images and gravity models.

Our experiment is designed to test these end-member models for the exhumation of the RMCC by constraining the overall geometry, velocity structure, and seismic converters within this modified crust and the units that bound it. Although current geophysical data are ambiguous regarding the "low-angle detachment" versus the "vertical diapir" model, these models should be distinguishable with our new data.

It is also reasonable to consider a hybrid model (in the geometric sense) for the formation of the RMCC such as the "rolling hinge" model (e.g., Buck, 1988; 1991; Wernicke et al., 1988), in which a system of initially high-angle "domino-style" normal faults root into a low-angle detachment and are progressively domed upwards by the isostatic rise of a ductilely deformed footwall (Figure 4c). Depending on the geometry of the deformed footwall, the result of rolling-hinge exhumation might be difficult to distinguish geometrically from a gneiss-dome-type diapir, though a rolling-hinge is likely to introduce asymmetry across the structure whereas an ideal diapir would have a symmetric strain pattern. Thus (simplistically) low-angle structures should dominate west of the RMCC, and steep to vertical features dominate east of the RMCC. Ongoing geologic and thermochronologic studies by the USGS carried out in concert with this proposal (e.g., Colgan in progress; Colgan & Metcalf, 2006; cf. Colgan et al., 2006) will provide additional constraints that should help resolve different models for the exhumation of the RMCC. Convincing thermochronologic evidence for progressive E-W unroofing of the RMCC would support either a low-angle fault or rolling-hinge model, whereas nearly instantaneous cooling of the entire footwall would be more consistent with vertical rise of a crustal diapir.

Finally, we note that understanding exhumation of the RMCC may also provide insight into formation of the Carlin Trend, the most productive gold deposit in the Americas (e.g., John et al., 2003). The RMCC may represent the Eocene lower crust of the Carlin Trend (the time of mineralization) exhumed by the core-complex formation (Howard, 2003). The proposed experiment will help evaluate two very different interpretations of Carlin crustal structure, by determining the extent to which the crust in north-central Nevada has been modified (or not) by Cenozoic tectonism, magmatism and crustal flow. If the RMCC was exhumed from beneath the Carlin Trend along a gently west-dipping shear zone, then it represents a "sample" of the Eocene middle/lower crust beneath the area of gold mineralization (e.g., Howard, 2003), and would have disrupted any vertical crust-penetrating structures (Figure 4). Alternatively, in interpretations that largely discount subsequent modification of the crust by Cenozoic magmatism and crustal flow, Henry & Ressel (2000) suggest that extensive Eocene plutons at depth (even though they are not common at the surface) provided the source of heat and fluids for gold-deposit formation; and Grauch et al. (2003 and references therein) infer from gravity, magnetic, resistivity, and isotopic studies that pre-Tertiary crustal boundaries and deeply penetrating fault zones (>30 km) inherited from Precambrian time provided the avenues for ore-bearing fluids. Senior exploration managers for both the multinational mining companies that operate in Nevada - Newmont and Barrick - have expressed their enthusiasm for our projects in this area (see letters of support). Their large open-pit gold mines routinely detonate very large explosive blasts that will provide us with a limited active-source P-wave dataset of travel-times across our array from all directions (Figure 1).

PREVIOUS GEOPHYSICAL DATA IN THE STUDY AREA (FIGURE 2A, 3)

A remarkable network of seismic profiles surrounds, but does not cross, the highest-grade RMCC (Figure 2a). A 1983 COCORP Moho-reflection profile crossed the southernmost Rubies at Overland Pass (location: Figure 2; data: Figure 3a) (Hauser et al., 1997) and a 15-km-long University-of-Wyoming profile imaged into the mid-crust at Secret Pass between the Ruby and East Humboldt Ranges (Figure 3b) (Valasek et al., 1989). Both profiles utilize passes that probably represent major east-west cross-structures disturbing the core-complex geometry, thereby limiting the value of these images for our understanding of core-complex development. In particular, the Secret Pass profile is not only parallel to surface traces of young detachments (Valasek et al., 1989), but directly overlies the inferred boundary between the Archean Wyoming province and Proterozoic Mojave basement (Wright & Snoke, 1993). Both were Vibroseis profiles, and though the high quality of the Wyoming profile clearly demonstrates the feasibility of recording useful reflection images for structural interpretation, it was not designed to image to the Moho, and was too short to provide control on the entire RMCC structure. Networks of oil-exploration profiles in Lamoille/Huntington and Ruby Valleys provide control on adjacent basin depths and good images of fault-plane reflections (Satarugsa & Johnson, 2000a), but these industry profiles typically only image to c. 5 km depth. A wide-angle profile (Figures 2, 3d) was recorded along Ruby Valley at the eastern margin of the Ruby Range (Stoerzel & Smithson, 1998; Satarugsa & Johnson, 1998, 2000b), but was not positioned to show east-west doming of the core-complex, and the alternate interpretations disagree as to whether there is evidence for north-south flow or doming. Along this profile Satarugsa and Johnson (2000b) demonstrated shear-wave anisotropy (fast direction NE-SW) in the direct wave penetrating to about 8 km depth, presumably due to cracks that have not fully closed at this depth, but could not confidently interpret splitting of SmS (Moho reflection) for whole crustal anisotropy. Neither the Wyoming-Arizona profile nor a recent but sparsely-sampled (c. 1.5km receiver spacing) profile through Secret Pass (Heimgartner et al., 2006) crosses the heart of the core complex; nonetheless, all of these profiles provide a framework and compilation of first-arrival and Moho travel-times *around* our target. The only geophysical study that crosses the RMCC is the Harrison Pass magnetotelluric profile of Wannamaker and Doerner (2002) (Figures 2a, 3c), that was interpreted as showing that "resistive crystalline central massifs adjoin the host stratigraphy across crustal-scale, steeply dipping fault zones" above a "quasi one-dimensional" conductive lower crust. When plotted at true scale (Figure 3c), boundaries appear to dip about 45° down to about 15 km, but the poor depth resolution inherent in all magnetotelluric studies as compared to seismic imaging means that this study is far from definitive about the structural evolution of the RMCC, particularly in the middle-lower crust where the major questions remain.

PROPOSED EXPERIMENT AND ANALYSIS (FIGURE 2B)

The goals of this proposal are to investigate structure and evolution of a classic metamorphic core complex and the central Nevada topographic high by determining the thickness (depth to Moho), seismic velocity (including anisotropy), and reflectivity (Ps conversion) structure of the crust, supplemented by density and magnetic property data. The key is therefore multiple crossing ray-paths within the crust. But the narrow cones of upcoming rays arriving at adjacent stations from the epicentral distances of c. 30 to 95° used in receiver function imaging only intersect beneath greater than one station spacing. Thus the chosen Transportable Array nominal station spacing of 70 km only provides crossing ray-paths below the lithosphere of the BRP, and crustal imaging is essentially limited to point sampling (1D measurements) at each TA station (Figure 5a). A recent and very successful project to study continental rifting in the Rio Grande Rift – La RISTRA – used 18-km station spacing and produced excellent images of the Moho (Wilson et al., 2005), but essentially no information about the crust. Hence we need significantly smaller station spacings. A 5-km instrument spacing provides overlapping rays beneath about 8 km (depends on assumed velocity structure) (Figure 5b). Passive array design for crustal imaging must trade-off between the number of stations available (or feasible to deploy) vs. depth of imaging vs. area of coverage.

To study the RMCC needs a cross-strike profile of c. 100 km, in order to compare crust within and beyond the uplift, and to trace out the possible low-angle detachment into the deep crust. The Ruby Mountains are about 100 km long (from Overland Pass (COCORP profile, Figures 2a, 3a) to Secret Pass (Wyoming reflection profile, Figures 2a, 3b)); but to cover an area 100km*100km at 5km spacing requires >400 passive stations – clearly unfeasible. Hence we propose a strategy to use 40 stations, densely instrumented in the core of the RMCC at a minimum 5 km spacing (already a compromise between imaging the uppermost crust and experiment feasibility), broadening to c. 10 km spacing on the margins of the array where the experiment focus is below the basins in the deep crust. Two profiles will span the full cross-strike region of interest on lines through Lamoille Canyon and Harrison Pass; and be supplemented by short intervening profiles of c. 5 stations where Forest Service roads reach up into the core of the range (Figure 2b). This plan provides along-strike coverage of regions exhumed from paleo-depths ranging from 5 to 20 km (Howard, 2003), thereby enabling recognition of along-strike doming or flow if present. The plan also maximizes along-strike coverage of the RMCC while staying clear of the topographic lows at Overland Pass and Secret Pass that may represent important cross-structures that could disrupt wave propagation, and may explain why neither of the existing reflection profiles (COCORP and Wyoming) imaged uplift of the RMCC basement. The proposed five cross-profiles have an average along-strike spacing of 15 km (limited by available roads), so that we will record rays crossing in the north-south direction below c. 25 km (Figure 5b), and provide true multi-fold 3D coverage in the deep crust along about 65 km of the RMCC, adequate at least to form a 3D image of the Moho (Figure 2b). We should be able to answer whether the Moho is essentially flat or uplifted beneath the RMCC, and whether the lower crust beneath the RMCC and its flanking basins are dominated by sub-horizontal reflectivity (cf. Figure 4b) or by steep structures bounding a domal uplift (Figures 4c, d; and MT data of Wannamaker & Doerner, 2002).

Seismic Data Collection and Analysis

We will begin scouting and permitting specific instrument locations in spring 2009 after this proposal is awarded. The 40 broadband sites will be built in summer 2009 (1/day for a 2-person team) by Stanford students. Deployments are targeted for fall 2009 (2 2-person teams plus one USArray technical support staff, deploying two stations per day because of their close spacing). We request telemetry equipment, where it works over this relatively small, but topographically rugged area. Telemetry makes data available earlier but also facilitates monitoring and ensures that we can visit stations when there are problems, thereby improving overall data return. We budget for full service runs after the winter in 2010, and before the winter in late 2010, with final station retrieval in spring 2011. This is an 18-month deployment period, twice that we used in "NV-FlexArray-04". Although we were unusually fortunate in the number of earthquakes during that deployment (Figure 6a), we still lacked some important azimuthal coverage that limited our ability to make anisotropy measurements, and distinguish anisotropy from Moho dip. All our data (active and passive-source) will be archived with and publicly released through the USArray-IRIS DMC. Because of the intense effort required by our students to install the array, we request the normal period of exclusive use extending to one year after the field program concludes (spring 2012). During this period, one station from each cross-line (5) will be open stations, freely available; and of course we will be open to offers of collaboration on analyses not proposed here.

The passive-source data will be analysed at Stanford as it is retrieved. Our priority will be jointly inverting surface-wave dispersion curves and receiver functions for seismic velocity (Figures 6b, 7b) and lithologic analysis (Figure 7c). Currently we are using the method of Julía et al. (2000) for the combined surface-wave/receiver-function inversions (Keranen et al., in review), and for this experiment we will obtain our dispersion curves from ambient noise tomography (Sabra et al., 2005; Shapiro et al., 2005), with periods as short as 2 or 3 s because of the close station spacing, using the implementations developed and available at Stanford (Prieto and Beroza, 2008; Prieto et al., 2008), thus producing a velocity field from the upper crust to below the Moho. The resulting independent 3D velocity field will enable CCP analyses or teleseismic migrations using both direct and reverbatory Ps modes (Wilson et al., 2005; Shragge et al., 2006) for structural imaging. Our velocity and structural images will resolve between competing geologic models shown in figures 4b, 4c and 4d. We plan to use shear-wave splitting analysis of Ps to measure crustal anisotropy (Figure 8), and so to address the claim by Sullivan & Snoke (2007) that along-strike lower-crustal flow (predicts SW-NE fast direction) to balance differential extension (greater to the north) is more important than the cross-strike flow (predicts NW-SE fast direction) preferred by Howard (2003). If sufficiently strong and coherent converters are present (they were not on the short-period data acquired in NV-FlexArray-04) we will use multi-layer splitting analyses (cf. Walker et al., 2005) to test for the degree of anisotropy specifically in the mid/lower crust as a marker for this crustal flow. All these methodologies (except the now standard ambient noise tomography) have been applied in Klemperer's research group on NV-FlexArray-04 or other data sets in the recent past (e.g. Gashawbeza et al., 2004, 2008; Keranen et al., in review; Shragge et al., 2006; Walker et al., 2004, 2005). More than four dozen large mines operate in NE Nevada/NW Utah/S Idaho (Bon & Wakefield, 2008; Driesner & Coyner, 2006; Gilleman & Bennett, 2008) and their regular mine blasts (e.g. as used by Heimgartner et al., 2006; Lerch et al., 2007) will provide a small auxiliary P-wave data-set; these data may simply be interpreted as multi-azimuth fan profiles which have demonstrated capability to distinguish Moho topography (e.g. Fliedner et al., 2000), or may be used to supplement the sparse local earthquake sources if we attempt body-wave tomography.

The principal products of this proposal will be two 100-km-long cross-strike common-conversion point profiles, migrated in an independently determined 3D velocity field, imaging from ~10 km to below the Moho; and a true 3D-migrated image of the deep crust and Moho that spans the width of the exposed core complex and extends ~60 km along strike.

Potential Field Data Collection and Modeling

The potential field component of the proposed study (see letter of support from J. Glen/USGS) will entail gravity data collection to fill in areas of sparse control around and within the proposed seismic array. Joint seismic and potential field modeling offers a powerful tool for identifying a much wider range of crustal features than can be done by either method alone. One Stanford student will participate with the USGS to collect new gravity data, and combine these with existing data (e.g., Glen et al., 2004, Lerch et al., 2007) to produce gravity and derivative maps for regional structural analysis and profiles for forward and inverse modeling. Magnetic data will be derived from statewide compilations (Hildenbrand et al., 2000). An iterative gravity inversion method (Jachens and Moring, 1990), used to determine the depth to pre-Cenozoic basement and thickness of Cenozoic basin deposits, will be applied to obtain a basement gravity map. Basement gravity (isostatic gravity with Cenozoic basin effects removed) reflects lateral density variations in pre-Cenozoic basement rocks and is useful for defining pre-Cenozoic structures. To better define the edges of geophysical sources and to help derive geophysical lineaments and terranes, the maximum horizontal gradients (MHG) of both gravity and magnetic data will be calculated following a method described by Blakely and Simpson (1986). Because the MHG reflect abrupt lateral changes in the density or magnetization and tend to lie over the edges of bodies with near vertical boundaries (Cordell and McCafferty, 1989; Grauch and Cordell, 1987), they are useful for estimating the extent of buried sources. Gravity data collection and reduction will occur during the second summer of the project, including training of the Stanford student by USGS collaborators. Following the data acquisition, Glen will focus on modeling, adding constraints from the seismic data, gravity inversion for depths-to-basement, and detailed investigations of specific structures within the study area. Although the gravity data coverage is quite good in this region (Ponce et al., 1996), because we do not (yet) know the volume fraction of granitic material in the crust it is hard to separate out possible signatures of mid-crustal granites, lower-crustal mafic underplating, or a Moho uplift (cf. Gibbs et al., 1968). Combining gravity modeling with structural constraints from the seismic data will help reduce existing ambiguities (cf. Fliedner et al., 2000; Lerch et al., 2007).

Geologic Interpretation

One of the strengths of our group at Stanford, including Elizabeth Miller/Stanford Geology, and of this proposal, is our ability to integrate new geophysical data with geologic mapping and geochronology studies to properly address the "4D" (temporal) component of Earthscope. Elizabeth Miller requests no support but will help mentor the PhD student's geologic interpretations alongside Joe Colgan and Keith Howard of the USGS (no salary needed for USGS involvement - see letters). Miller and her students are currently carrying out geologic mapping, research and geochronologic studies in the Albion-Raft River-Grouse Creek complex to the NE of the Ruby Mountains, and former Stanford student Joe Colgan (USGS) is actively involved in ongoing studies of the RMCC. A fundamental aspect of our "NV-FlexArray-04" study was this integration, yielding new insights into geologic evolution over the last 100 Ma, most notably our demonstration that in at least that area a high plateau sustained by over-thickened crust was not a precursor to BRP extension (Lerch et al., 2007; Gashawbeza et al., 2008). We will develop similarly detailed geohistories for the current project area, and hope for similar discoveries. Serial geologic sections across the Ruby Core Complex from N to S will provide a 3-D view of this major crustal-scale metamorphic "welt" and determine how it grows and dies out and delimit its 3D extent. Extant and in progress geochronology by the USGS group represents one of the most complete data sets available for core complexes in the Cordillera that will provide fundamental constraints on evolution through time. This effort will proceed hand-in-hand with the seismic modeling, informing that modeling with insights into crustal lithologies and structures, and accepting constraints from the modeling.

INTEGRATION WITH THE USGS AND THE BROADER COMMUNITY

We will interface with two groups from the USGS, including Jonathan Glen and Dave Ponce (potential field modeling), and Joseph Colgan and Keith Howard (geologic mapping and geochronology/thermochronologyh). Our seismic data will be integrated with potential field data (e.g. Lerch et al., 2007, Egger et al., in review) and surface geologic data (e.g. Colgan and Metcalf, 2006) to create a detailed understanding of structure and processes across a range of scales.

This collaboration with multiple groups within the USGS exemplifies the broad interest and activity in the BRP also present in many U.S. research universities. EarthScope studies must be relevant to a broad audience, and for some parts of the USA new interest groups have been formed in response to programs such as GeoSwath. Although the BRP is not a designated part of the GeoSwath transect across the USA, it does not need to be; the BRP remains a key research focus for many groups because this is the best developed, most accessible, best studied active continental rift on Earth, and so new data and new insights arising from this project will naturally interest and inform a large portion of the tectonics, lithospheric seismology and lithospheric geodynamics community in the USA and internationally. As a single example, a letter of support is attached from Prof. Tony Lowry, USU, who wishes to use the proposed new seismic velocity data as constraints on his geodynamic modeling efforts to constrain constrain rheological parameters, thermal structure, and volume of magmatism in different extensional domains of the BRP.

BROADER IMPACTS

We are studying the geologic framework that controls the nation's richest precious metal deposits, the controls on which are still much debated. A companion proposal to ACS-PRF (already funded) and supporting letters from mining companies demonstrates our relevance to these communities. Our NSF proposal will provide the data for a PhD thesis, and partially fund one graduate student. We plan to continue our "NV-FlexArray-04" model to integrate research and undergraduate education. Our fieldwork, related geology fieldtrips, and subsequent research leading to AGU presentations if not published papers, are a vital part of the education of our very best undergraduates at Stanford, and encourage these students to remain in science. Klemperer has previously mentored 8 undergraduates in research programs involving a field component analogous to this Ruby Mountains experiment. 8 AGU presentations first-authored by the undergraduates have resulted, together with two undergraduate-first-authored peer-reviewed papers (Günther et al., 2004, 2006), two undergraduate-first-authored extended abstracts (Cash et al., 2004; Les et al., 2004) and one co-authored paper (Klemperer & Cash, 2007). Of the 8 undergraduates, 5 of 8 were female; 4 of the 5 who have graduated have continued to graduate school; 3 are still juniors or seniors. We hope for similar outcomes in undergraduate training through this proposal. No specific funds are requested for undergraduate training, because such funds have been always available through Stanford internal resources. We plan to provide public outreach by producing a website (e.g., http://geo.stanford.edu/groups/warners/), giving lectures on the experiment at high schools and for the general public, and contributing to articles in local newspapers, all of which were done preceding, during and following our NV-FlexArray-04 experiment. This year, the most destructive earthquake in Nevada for the last half-century occurred in Wells, adjacent to our project area (08/02/21, Mw=6, Figure 1), injuring several people and damaging hundreds of buildings. This event provides a teaching opportunity to interest the public in Earthscope science and USArray and FlexArray studies.

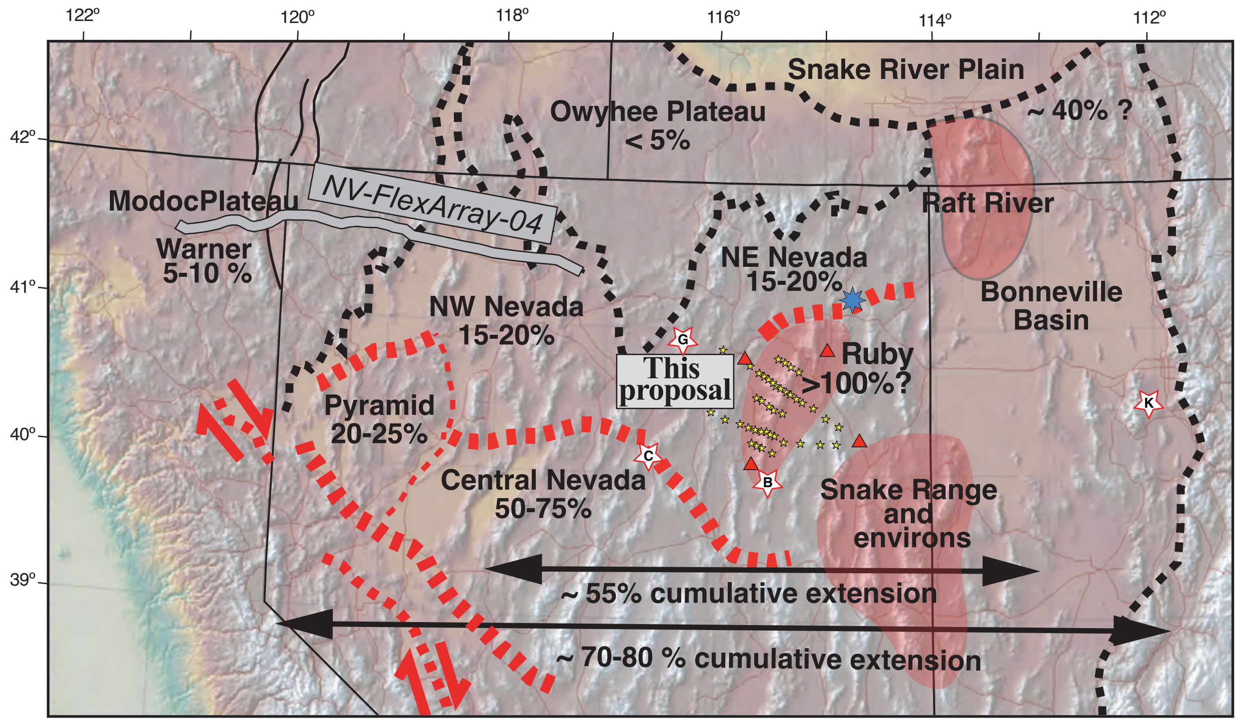


Figure 1.
The planned area of seismic investigations (yellow stars) superimposed on estimates of extension and boundaries of extensional domains across the northern Basin-&-Range Province based on geologic studies and estimates of Wells & Heller (1988). More highly extended core complexes, shown by color overlays, include the Ruby Mountains, Raft River, and Snake Range and environs. Thick red dashed lines: inferred location of transform-like boundaries between lesser extension to the north and greater extension to the south. Black arrows: estimates of % extension across central Nevada based on restoration of normal faults (~55%, Smith et al., 1991; or ~70-80%, including extension farther west – Yerington & Wassuk Ranges, and farther east – Sevier Desert Detachment, Smith et al., 1991).

This proposal: Yellow stars are proposed Flex-Aray deployment of broadband seismic stations (see Figure 2b); red triangles are relevant operating Transportable Array stations.
Red open stars: example major open-pit mines that routinely use large blasts: G, C, B, K are Goldstrike, Cortez, Bald Mountain and Kennecott mines (e.g. Heimgartner et al., 2006).

NV-FlexArray-04: grey line: 2004 Earthscope deployment, passive (Gashawbeza et al., 2008) and active (Lerch et al., 2007). Blue star northeast of Ruby Range: Mw = 6.0 Wells earthquake, 02/21/08.

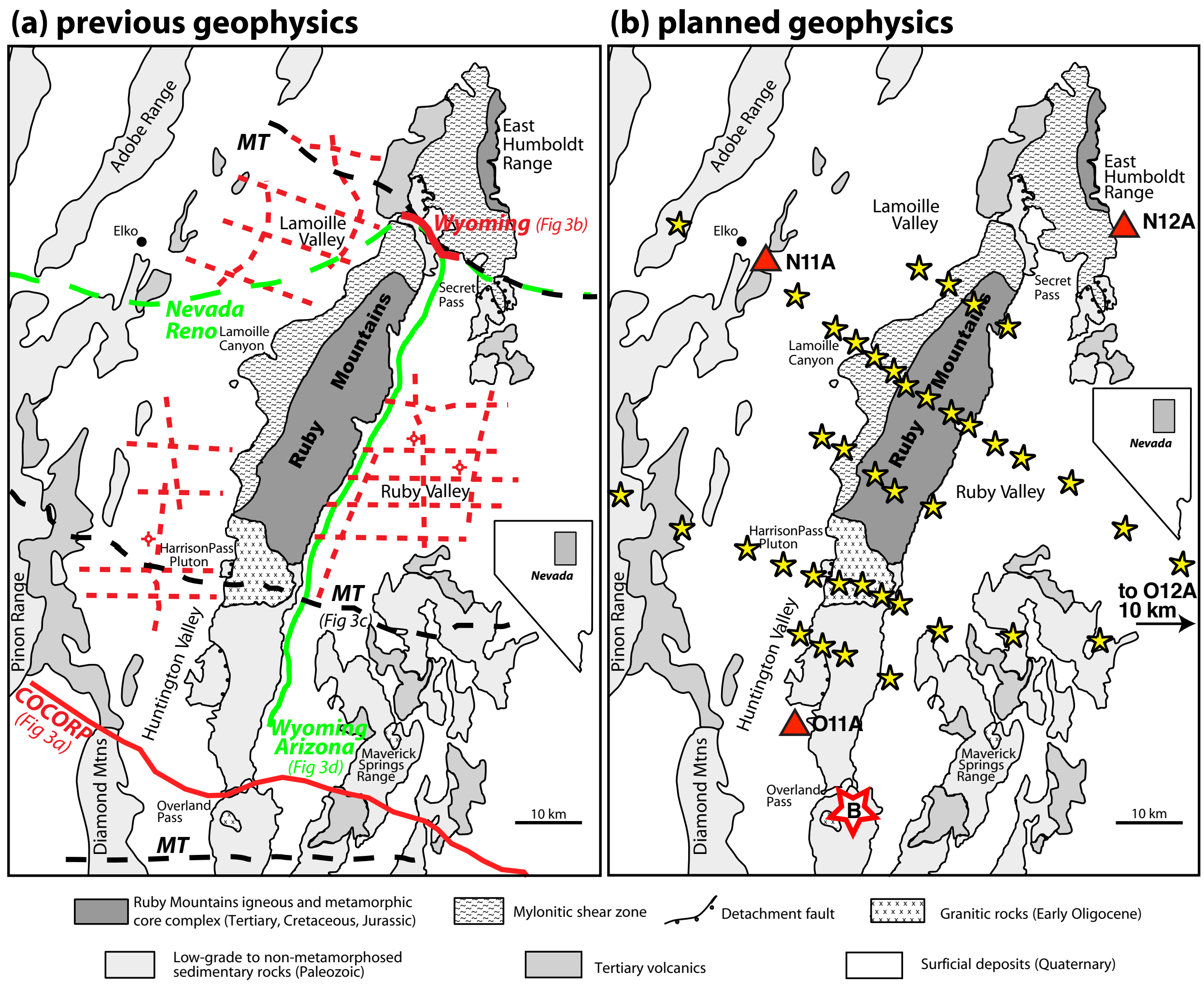


Figure 2. (a) Previous geophysical work skirting the core of the RMCC: no seismic profiles cross the central uplift.

Previous near-vertical reflection: solid red lines: COCORP low-resolution to 15-s (sub-Moho) (Figure 3a) & U.Wyoming high-resolution to 8 s (25 km) (Figure 3b); dashed red lines: petroleum exploration, typically imaging to ~5 km depth.
Previous wide-angle reflection/refraction: solid green line: Wyoming/Arizona (Figure 3d); dashed green line: U.Nevada-Reno sampled only every 1.5 km.
Previous magnetotelluric: dashed black lines: Utah MT profiles (Figure 3c).

Figure 2. (b) Planned seismic deployment across the core of the RMCC:

proposed FlexArray broadband deployment (40 stations), 5 km spacing across RMCC.
existing Transportable Array stations that would be incorporated into the analysis (4 stations, note O12A is 10 km east of map margin).
B Bald Mountain mine, one of several (see Figure 1) whose open-pit blasts will be recorded.

Generalized geologic base map from Satarugsa & Johnson (2000a, b) and Wannamaker & Doerner (2002). For references to geophysical profiles, see text and Figure 3.

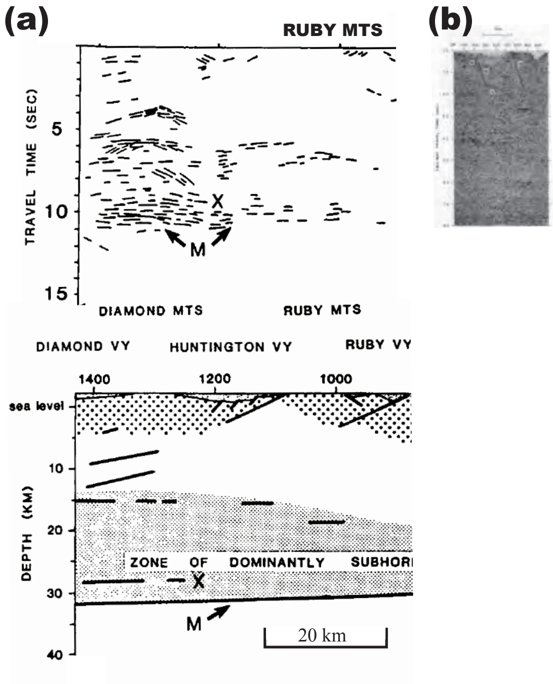
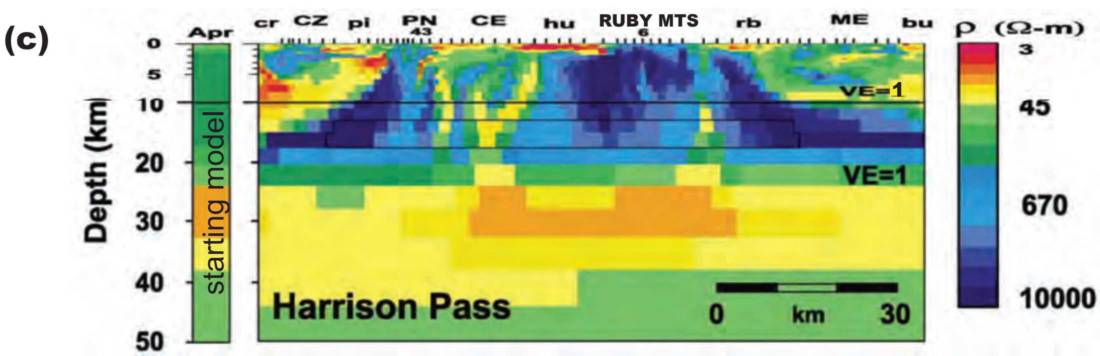


Figure 3: Previous geophysical profiles around the RMCC, all (re-)displayed at the same true scale (horz=vert).
Figure 3a: line-drawing /interpretation of COCORP crustal reflection data (Hauser et al., 1987) south of the high-metamorphic-grade RMCC (Overland Pass), showing no doming of basement reflectivity fabric or increased intrusive activity beneath the southern Ruby Range.
Figure 3b: Entire length of U.Wyoming reflection section through Secret Pass (Valasek et al., 1989), M and N are interpreted mylonites and fold nappes. Profile is high-quality but is too short to show possible doming and does not reach Moho.
Figure 3c: Magnetotelluric profile across Harrison Pass (Wannamaker & Doerner, 2002) interpreted to show "steeply-bounded resistive core complex" in the upper crust, and a "quasi one-dimensional" lower crust. Note MT depth resolution is significantly poorer than for seismic data.



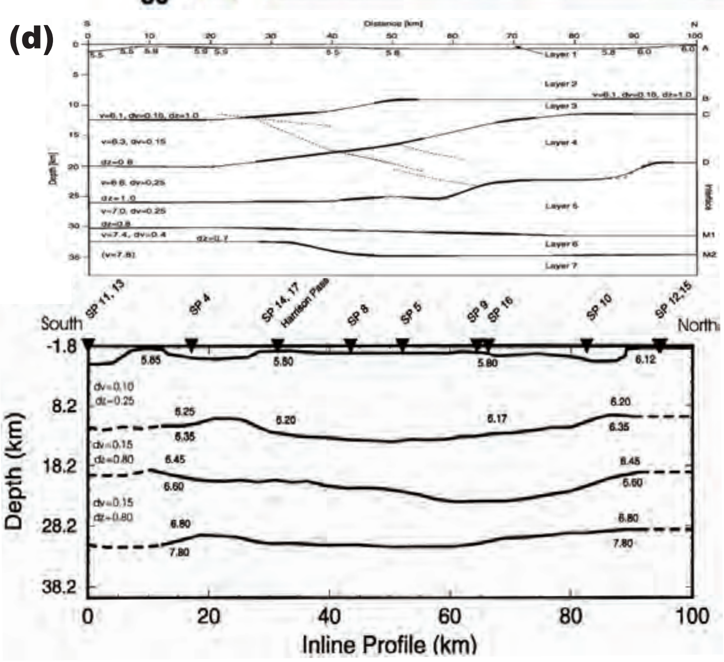


Figure 3d: Alternate interpretations of the 1992/93 Wyoming/Arizona refraction profile, in Ruby Valley (east side of Ruby Range and RMCC). Top: Stoerzel & Smithson, 1998; bottom: Satarugsa & Johnson, 1998. Interpretations differ on whether crustal thickening (top) or mid-crustal thickening (bottom) provides isostatic support; and whether the crust was modified by up to 15 km of mantle-derived material (top) or by intra-crustal processes rather than magmatic underplating (bottom). Uncertainties are due to short source-receiver offsets, and limit ability to detect north-south doming or flow.

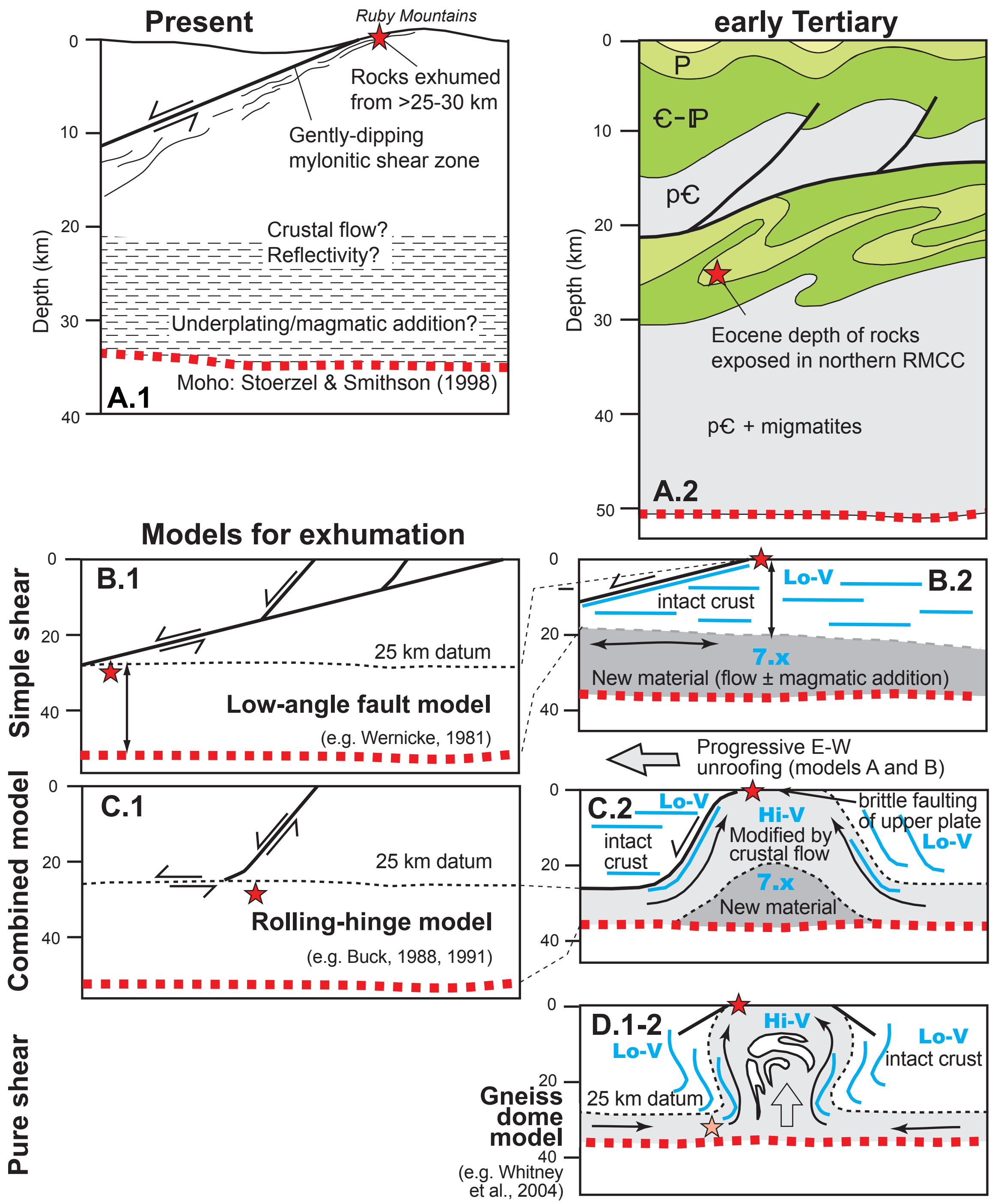


Figure 4: This proposal seeks to distinguish models B2 from C2 from D2 using structural imaging (cyan lines) and velocity measurements (cyan text).
A.1: modern structure of RMCC; **A.2**: presumed structure prior to Tertiary extension, with 50 km crust; red star is initial location of rocks now at the surface in A.1; red dashed line is Moho.
B-D: Three possible models for exhumation of the RMCC. Cyan lines: schematic expectations of seismic converters/reflectors; cyan text: expectations of relative seismic velocity patterns (Lo-V: upper crust; Hi-V: lower crust; 7.x: magmatic underplate derived from mantle with velocity > 7 km/s).
B: Low-angle fault model (simple shear) with significant horizontal translation of an intact footwall.
C: Rolling-hinge model (combined model) with crustal flow and isostatic footwall uplift.
D: Gneiss dome model (pure shear) emphasizing diapiric vertical rise of crustal rocks and migmatites.

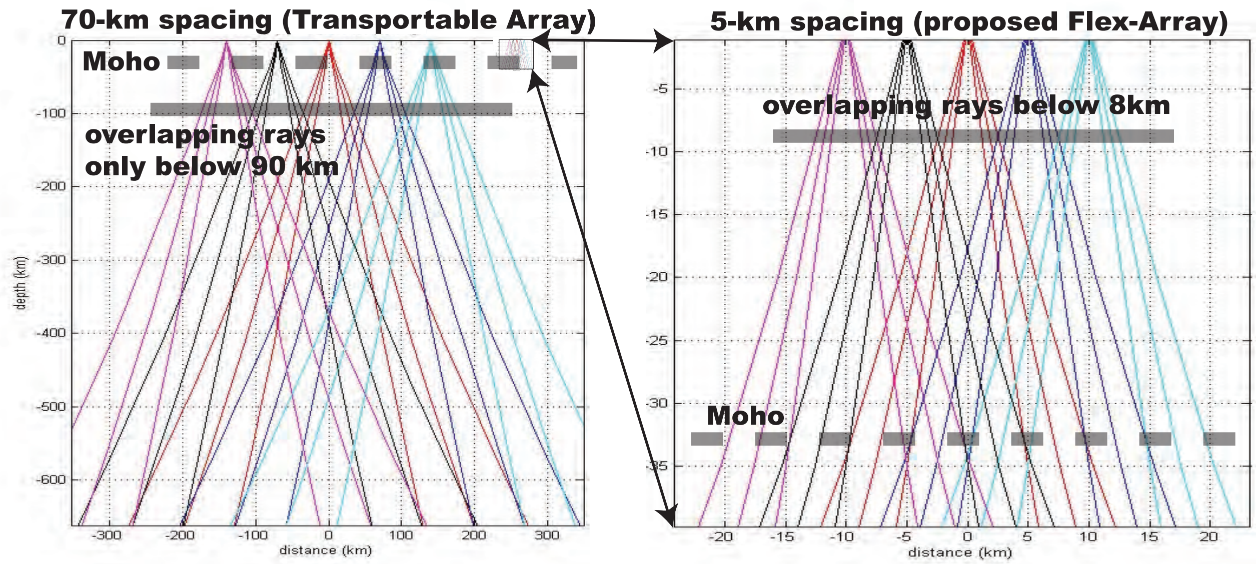


Figure 5a (left): S ray-paths (appropriate for receiver-function inversion) to Transportable Array stations at the USArray nominal 70-km spacing. Overlapping rays occur only below ~90 km depth. Crustal imaging is essentially limited to 1D measurement beneath each station.
Figure 5b (right): S ray-paths for FlexArray stations at the proposed 5-km spacing. Overlapping rays to different stations exist below 8 km. Imaging is possible for the middle and lower crust. True-scale (horz=vert). Ray-trace images from Gurrola (2007).

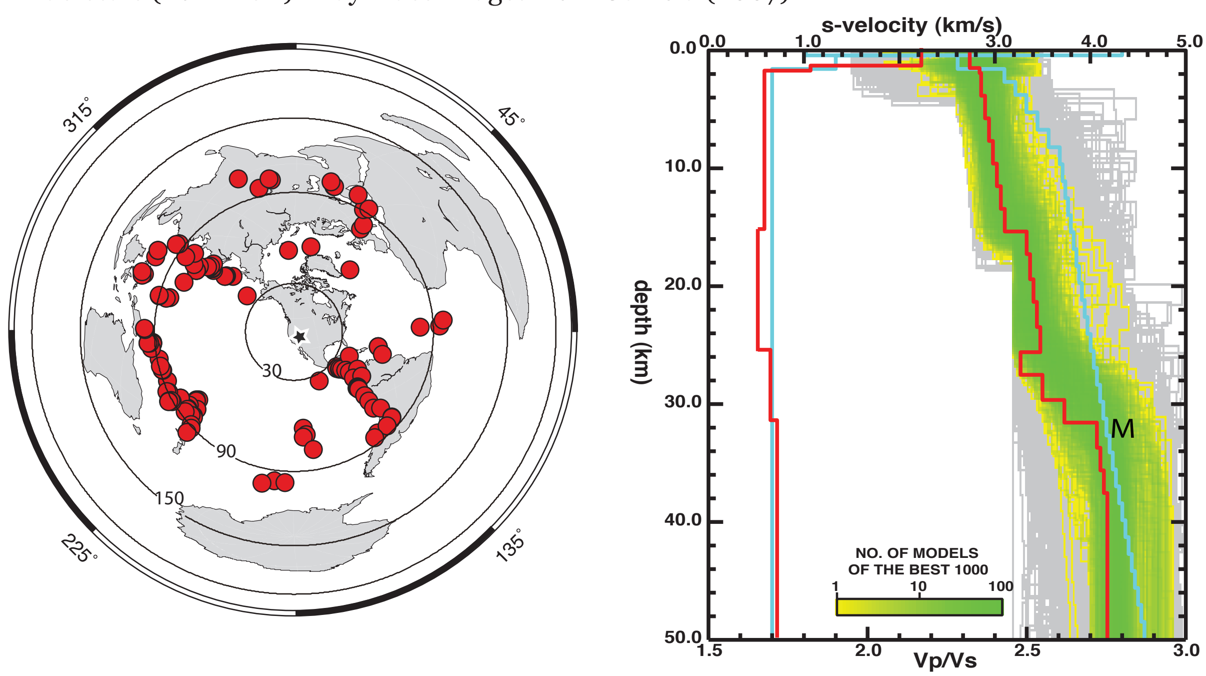


Figure 6a (left): >200 teleseismic events (mb > 5.5 and 30° ≤ epicentral distance ≤ 110°) recorded in 8-month “NV-Earthscope-04” deployment (see Figure 1 for location).
Figure 6b (right): Receiver function inversion (neighborhood algorithm technique of Sambridge, 1999) at a single short-period (2 Hz) station showing the range of models searched in order to find the best-fitting structure. The green regions indicate the models with better fit to the observations; the best fitting model is indicated by the red line that overlies the plot of model-density. The cyan lines superimposed on the model density plot are the starting Vs model and starting Vp/Vs ratio. The red lines are the best fitting Vs and Vp/Vs ratio model. (Gashawbeza et al., 2008).

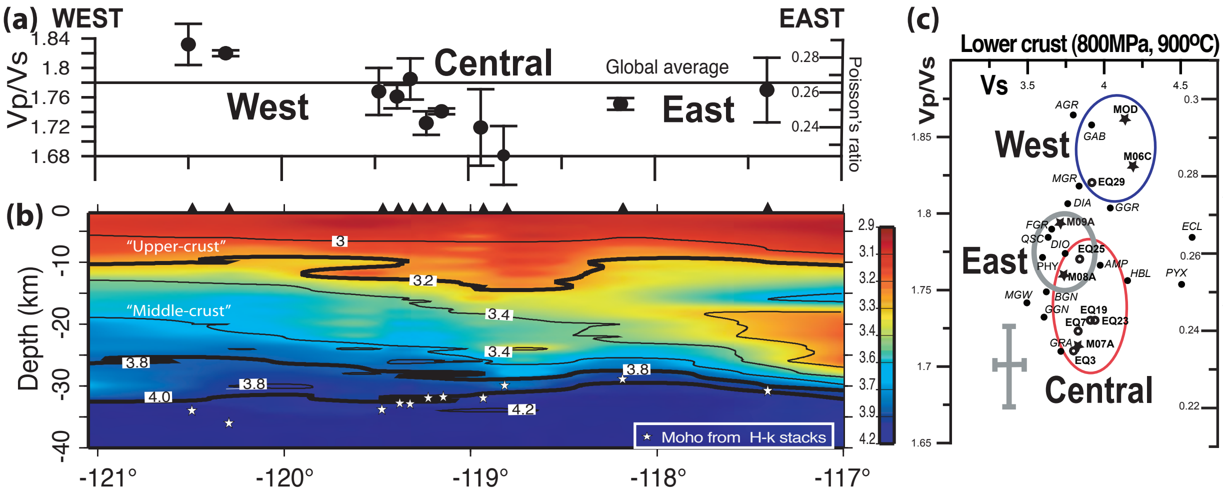


Figure 7: Example velocity and lithology models from analyses of "NV-FlexArray-04" experiment. top to bottom: (a), (b) cross-sections from west-to-east along profile, from 121 to 117°W. (a) mean crustal Vp/Vs from H-k analysis (Zhu & Kanamori, 2000); (b) Vs from FlexArray and Transportable Array receiver function inversions (Figure 6b) and Moho (stars) from H-k analysis.
Right (c) Vp/Vs vs. Vs cross-plot for lower crust. Black circles are laboratory data from Christensen (1996) (three-letter codes are his rock types) and open circles and stars are our data from FlexArray and Transportable Array stations respectively, after correction for p,T. Stations are geographically divided (three ellipses) into "west" (mafic crust of Modoc-Sheldon Plateau); "central" (unusually felsic crust: buried Sierra Nevada batholith); and "east" (typical intermediate crust) (Gashawbeza et al. (2008).
Transportable Array data gave more stable inversions than our FlexArray deployment because of their longer and broader-band deployments, and insufficient data at our FlexArray sites prevented us from forming useful migrated common conversion point images of the crust in this experiment - issues addressed in this proposal with the requested broadband equipment and longer deployment period.

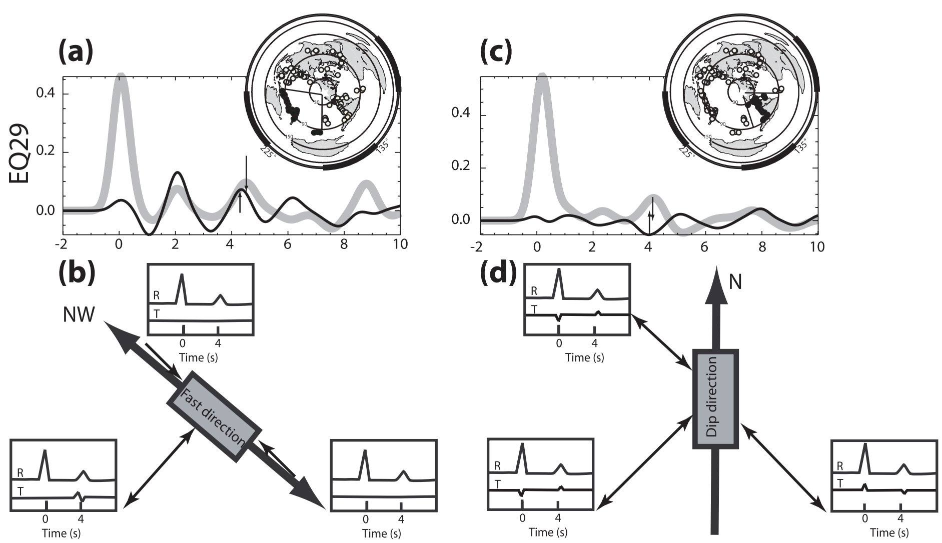


Figure 8: Crustal anisotropy determination from analyses of "NV-FlexArray-04". Radial and transverse receiver-function stacks for station EQ29, plotted at the same scale. Back-azimuthal stacks are for southwest events in (a), southeast events in (b), and northwest events in (c). Inset maps indicate the earthquakes producing the receiver functions stacked to produce each data plot. In (a) the radial Moho Ps conversion from the southwest arrives slightly later than the tangential Moho Ps conversion consistent with northwest-southeast fast anisotropy - see (b) schematic predictions for receiver functions as a function of back-azimuth. In (c) the radial and tangential Moho Ps phase arrives at thesame time but with opposite polarity consistent with a north-dipping Moho - see (f) schematic predictions. (b) and (d) re-drawn after Peng and Humphreys (1997).

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