Origin of High Mountains in the Continents: The Southern Sierra Nevada

New active and passive seismic experiments show that the southern Sierra Nevada, despite standing 1800-2800 m higher than its surroundings, is underlain by crust of similar seismic thickness, about 30-40 km. New xenolith barometry and MT profiling indicate the seismic upper mantle is eclogitic (petrologic crust) and resistive to depths of 60 km in the western and central parts of the range. Under the eastern High Sierra, however, much hotter spinel peridotite with melt inclusions and enhanced upper-mantle conductivity just below seismic Moho are observed, suggesting little subcrustal lithosphere is present. The eastward thinning of petrologic crust, and new reconstructions of extension in the adjacent Basin and Range suggest both High Sierra and Basin and Range crust have thinned by about a factor two in the late Cenozoic, underscoring the Cordillera-wide problem of reconciling profound buoyancy loss from crustal thinning with proposed late Cenozoic regional uplift of some 2000 m.
What holds up high mountain belts on continents? The earth's two highest belts, the Himalaya-Tibet collision zone and the central Andes, are supported by 'Airy-type' crustal roots 70-80 km thick, almost twice that of adjacent lowlands (1). Because each kilometer of crustal thickening adds about 140 m of elevation (2), a 30-35 km increase should raise elevation by 4200-4900 m, in excellent agreement with the observed differences in elevation in these two cases (3). The Sierra Nevada, one of the major mountain ranges in North America, lies at 2800 m elevation, but is enigmatic in several respects. It contains the highest point in the lower 48 states (Mt. Whitney, 4419 m), yet just a short distance away, Death Valley lies below sea level, within a zone of strong crustal extension (4). In addition, despite its high elevation, conflicting seismic interpretations have been presented as to whether the High Sierra (roughly the eastern third of the range) is underlain by an Airy-type crustal root some 55 km thick (5), or by crust only 30-40 km thick (6), similar to that of surrounding lowlands of the Basin and Range and Great Valley (Fig. 1). A major multidisciplinary effort, the Southern Sierra Continental Dynamics Project, was undertaken to evaluate the mechanism of support and evolution of the crust and upper mantle beneath the range.

The possibility of an Airy crustal root beneath the Sierra was investigated using new wide-angle refraction/reflection data collected along profiles transverse to (E-W) and parallel to (N-S) the structural grain (Fig. 1). The root question is most clearly addressed by the seismic sections from shot point 5, just east of the High Sierra, and shot point 24, a kiloton chemical explosion near the east end of the line (Fig. 1). As shown in Figure 2a, the $P_mP$ (Moho reflection) phase is evident on stations both to the east and west of the source point. Stations to the west record $P_mP$ reflections from directly beneath the Sierra while recordings to the east are for reflection points beneath the Basin and Range. The key observation is that travel times for the western branch are only ~0.5 s greater than the corresponding times for the eastern branch. Apparent $Pg$ (upper crustal) phase velocities across the Sierra vary <0.2 km/s. For a laterally invariant mean crustal velocity of 6.3 km/s the $P_mP$ delays to the west allow an Airy-type root of only 3-4 km. The absence of a large crustal root (deeper seismic Moho) is particularly clear from $P_n$ (Moho
refraction) recordings from shot point 24, which do not show a major delay or decrease in amplitude when passing under the Sierra (Fig. 2b).

The absence of a large crustal root is also suggested by teleseismic P to S (Ps) mode conversions from the Moho observed at three passive seismic arrays on the E-W refraction line. Beam-formed seismograms (7) penetrating the Moho between arrays in the central and eastern Sierra have a Ps arrival about 4.2 s after the P. Assuming an average P velocity of 6.2 ± 0.2 km/s and Poisson’s ratio of 0.25 ± 0.04 for the crust, the Ps arrivals indicate Moho at 33 ± 5 km below sea level. Similar measurements for an array in the Basin and Range 40 km east of shot point 5 indicate a Moho at ~33 km.

Our preliminary structural model (Fig. 3a) incorporates lateral velocity changes in the top 15 km, but these variations are incapable of supporting the topography. The Pg and Pn travel time observations only permit lateral variations in mean crustal P velocities of about 3%, equivalent to lateral density variations of about 2% using Nafe-Drake or Birch velocity-density relations (8). Such variations would only accommodate elevation differences of ~500-600 m, less than 25% of that observed. Even allowing for large, systematic deviations from commonly used velocity-density relations, at most half of the Sierran topography and gravity signature can be ascribed to lateral density variations in the crust (Fig. 3b). The topography, gravity and crustal structure of the southern Sierra Nevada thus define an especially clear example of a continental mountain range supported mainly by a 'Pratt root,' with major lateral density variations in the upper mantle.

We prefer a model to support Sierran topography through a combination of lateral variations of density in the crust (~25% of the effect, including that of a small Airy root) and in the mantle (~75%). Such a combination explains the main anomalies in the gravity field (Fig. 3b). Variations in Ps conversion amplitudes recorded by the passive arrays might reflect this upper mantle anomaly, as Ps amplitudes are smaller under the High Sierra than elsewhere and are followed by additional conversions between 7 and 9 s after P. Incorporation of such an upper-mantle anomaly would only visibly affect seismic arrivals in the vicinity of the Sierra. Reduction of Pn velocities under the High Sierra by 2-5% improves our fit to Pn arrival times, confirming previously inferred
low $P_n$ velocities from both north-south (6) and east-west (11) profiles. The absence of low $P_n$ velocities outside the High Sierra region corroborates higher $P_n$ values from previous work to the west (e.g., 12) and east (6,13).

The position of an upper mantle seismic anomaly under the High Sierra is independently suggested by an electrical-conductivity anomaly and by variations in mantle-xenoliths suites. New magnetotelluric (MT) data at 30 stations along the seismic line indicate several zones of enhanced conductivity in the lower crust and upper mantle (Fig. 4a). While the most striking features of the model are the localized regions of low resistivity beneath the western Sierra and Great Valley, these may be explained by conductive metasediments in the petrologic lower crust and are not relevant to the Sierran root question. The broad zone of lower resistivity in the upper mantle beneath the eastern Sierra Nevada, while not as striking, is crucial to this question. Upper mantle resistivity is bounded by 3-30 ohm-m, with a preferred range of 10-20 ohm-m (Fig. 4b). The cause of such low resistivities is likely partial melt because of the absence of conductive solid phases in the mantle and because saline fluids cannot maintain interconnected networks in ultramafic rocks at these pressures and temperatures (16).

Using models of partial melt and solid olivine combined to form bulk conductivity (17), partial melt fractions of 1.5-16% can explain the range of resistivities in the upper mantle, but a preferred melt fraction of 2-5% fit the data well. Assuming a magma density of 2740 kg/m$^3$, 5% partial melt reduces the bulk density by only 25 kg/m$^3$. Another 50 kg/m$^3$ decrease results from thermal expansion due to heating to sub-solidus temperatures. The MT data thus suggests a total density decrease of about 75 kg/m$^3$ distributed beneath the eastern Sierra Nevada from 35-80 km (Fig. 3b).

Two groups of xenoliths from Late Cenozoic volcanic flows, one from the central Sierra (CS) and another from the High Sierra, Owens Valley and Inyo Mountains (HS), show variations in texture, composition and thermal history consistent with the MT and seismic anomalies. The CS group includes feldspathic granulites, garnet-pyroxenites, eclogites, cumulate gabbros and amphibolites, garnet and spinel peridotites and garnet websterites (18,19). Preliminary trace
element investigations (20) rule out any link with the host volcanics. HS group xenoliths are mainly spinel lherzolites, harzburgites, spinel dunites, spinel websterites, clinopyroxenites, gabbros and mafic granulites, all lacking garnet. Melt inclusions are common in the HS xenoliths, with an average of 2-3% in thin sections.

Thermobarometric results (Fig. 5) reveal major differences between the CS and HS xenoliths, most notably much higher temperatures recorded in the HS group. Overall, there are three distinct P-T trends. In the CS group, trend A comprises the lower-crustal feldspathic granulites and the garnet clinopyroxenites. The negative slope of trend A is interpreted as a cooling slope recorded in batholith-related rocks whereby deeper rocks in the sequence cooled slower and equilibrated at lower temperatures than shallower rocks. Trend A also shows that the deepest crustal rocks from a petrologic standpoint (mafic in composition) occur at ~60 km, within seismically defined upper mantle. The basalt-eclogite phase transition occurs within the lower-crustal mafic rocks at ~35 km for the recorded temperatures, similar to the depth of seismic Moho. The thermobarometric measurements are consistent with the basalt-eclogite transition predicted by the mineral compositions from the xenoliths (Fig. 5). These results suggest that the petrologic crust is thicker than the modern seismic crust beneath the Sierra Nevada batholith by at least 25 km. Trend B corresponds to deeper rocks in the CS group, mainly garnet peridotites and garnet websterites (19). It has an adiabatic slope and suggests that the convective upper mantle was as shallow as ~60 km during equilibration. Trend C characterizes the HS, which also has an adiabatic slope. In contrast to the CS, however, it is defined to depths as shallow as 30-40 km, and is ~250°C hotter than the CS adiabat.

The high topography, thin crust, low $P_n$ velocity, enhanced upper-mantle conductivity, and shallow, hot, melt-bearing upper mantle xenoliths collectively suggest asthenospheric upper mantle lies near Moho beneath the High Sierra, while in contrast the seismic upper mantle to the west comprises a thick, relatively cold eclogitic root. Under high heat-flow associated with batholith genesis, the base of the seismic and petrologic crust would more closely coincide due to depression of the gabbro-eclogite phase transition, yielding a minimum Cretaceous crustal
thickness of ~60 km in the central Sierra. These results are consistent with heat flow data indicating low mantle heat flux in the western Sierra and relatively high heat flux in the easternmost Sierra and Basin and Range (22), and may suggest relatively recent thinning of the High Sierran mantle lithosphere, perhaps related to Neogene crustal extension in the Basin and Range (24)(Fig. 6).

The pronounced eastward thinning of the petrologic crust, from at least 60 km to as little as 30-40 km beneath the High Sierra, contrasts strongly with the relatively thick crust of the modern central Andes (1), generally considered a close tectonic analog for the pre-extensional Cordillera (25). The High Sierra has similar crustal structure to that of the adjacent Basin and Range, where the upper crust has been tectonically extended some 250-300 km in a WNW direction over the last 15-20 Ma (26). The pattern of upper crustal thinning is strongly heterogeneous, with two domains of extreme upper crustal extension (>300%) interspersed little extended areas (<10-15%) that include parts of the Basin and Range, Sierra and Colorado Plateau (Figs. 1 and 6). If upper crustal extension were extrapolated vertically downward through the entire crust, reconstruction would result in an improbable pattern of 90-100 km-thick crust interposed with areas of 35 km thick crust. Fluid behavior of the deep crust across the region, such that it is hydraulically "pumped" toward areas of upper crustal extension (27) would result in a relatively flat reconstructed Moho (Fig. 6). Allowing for fluid behavior of the deep crust from the High Sierra to the western Colorado Plateau, reconstruction of the extension results in overall thinning by about a factor of two, or an initial crustal thickness of 60-70 km at 20 Ma, depending on the volume of magma added during extension. This would be roughly consistent with the thickness of petrologic crust in the western and central Sierra, and with the crustal thickness of the modern Andes (1).

The buoyancy loss from some 30 km of crustal thinning would lower elevation about 4000 m (2), yet the High Sierra and portions of the Basin and Range are widely believed to have risen 1500-2000 m in the late Cenozoic (28). An extraordinary contribution to buoyancy from the mantle, which not only accounts for the uplift (29) but counteracts the effect of crustal thinning, would be needed. Because the crust's density contrast with asthenosphere is about a factor of 5 greater than its contrast with mantle lithosphere, 30 km of crustal thinning would require over 200
km of mantle thinning to account for the uplift, or a thickness of mantle lithosphere greater than that estimated even for Archean cratons (30).

One solution to this difficulty is that the density change in the upper mantle due to lithospheric thinning is much greater than commonly assumed, perhaps due to a compositional effect such as Fe depletion of the upper mantle from partial melting (31), or metamorphic breakdown of garnet in the upper mantle due to heating from magmatism and extension to the east. The absence of garnetiferous samples in eastern Sierran xenoliths versus the garnet-rich rocks to the west may support this hypothesis. Alternatively, the Sierra may have maintained or even lost elevation in the late Cenozoic, as paleofloral and geomorphic arguments for uplift of the western U.S. have recently been questioned (32). Allowing the possibility of regional topographic lowering, a plausible model for the late Cenozoic evolution of the High Sierra might include thinning of a 65 km crust down to 35 km, accompanied by nearly complete removal of a relatively cold, 70-80 km thick mantle lid (Fig. 6). This would suggest a history where the range lay at about 4000-5500 m, subsiding to 2000-3000 m as a result of extension (33).
REFERENCES AND NOTES


2. Assuming isostatic equilibrium, a change $\Delta h$ in the thickness of any given layer in the lithosphere results in elevation change $\Delta e = \frac{\Delta h (\rho_a - \rho_c)}{\rho_a}$, where $\rho_c$ is the density of the layer. Here we assume $\rho_a = 3250$ kg and the average density of the crust is $2800$ kg/m$^3$.


7. Arrays combine three broad-band (10s or 30s period) and six to eight short-period seismometers in an L-shaped or linear array. Traces are summed into beams using a time-shift so that the teleseismic P arrives simultaneously on all traces, thus greatly reducing scattered and reflected energy.


10. Variations in PmP arrival times for the north-south profile indicate only a 2° northward dip on the Moho, consistent with analysis of fan shots (M. M. Fliedner, S. Ruppert, SSCD Working Group, *unpublished data*), justifying neglect of 3-D effects for the purposes of this analysis.


21. Mineral rim compositions of about 31 CS and HS samples displaying textural equilibrium were determined using the Caltech JEOL 733 electron microprobe. Barometers employed included net-transfer reactions such as Al-in-orthopyroxene co-existing with garnet (S. L. Harley and D. H. Green, *Nature* 300, 697, 1984), while thermometers involved mainly Fe-Mg exchange reactions (e.g. R. Powell, *J. Metamorphic Geol.* 3, 231, 1985).


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Figure captions

Figure 1. Location map showing distribution of receivers for wide-angle reflection/refraction experiment (heavy lines) and shot points (squares) relative to the southern Sierra Nevada and environs. The northwest-trending segment projecting toward shot point (SP) 25 corresponds to the receiver array along the east end of the E-W profile in Fig. 2b. Open circles correspond to the following cities: B, Bishop; K, Kingman; R, Ridgecrest; S, St. George. Thin lines with arrows show major strike-slip faults and senses of slip; GF, Garlock fault; SAF, San Andreas fault. Dotted areas are zones of strong upper crustal extension (>300%) within the Basin and Range province (4).

Figure 2. E-W seismic profiles across the southern Sierra Nevada showing $P_g$, $P_n$ and $PmP$ phases, a) from shot point 5 (Fig. 1); upper panel shows horizontal position and elevation of receivers; b) from shot point 24 (Non-Proliferation Explosion or NPE); receiver locations are approximately the same as those in a), except east of offset -135 km, receivers lie along the NW line projecting toward the shot point (Fig. 1). Note that variations in receiver elevation and basin fill may cause small perturbations in arrival times (<0.5 s). The 1-2 s delays beneath the Great Valley in (b) are mainly due to thick Cenozoic sediments.

Figure 3. a) E-W structural model inferred from seismic data. The top 10-15 km taken from a tomographic analysis (9), primarily reflects the static time delays introduced by the sediment-filled basins. The mid- to lower part of the model was verified by finite-difference modeling of the E-W shot points. The positioning of the Moho depth at 33 km is based on Ps conversions, but may be over 40 km in some areas, especially north of latitude 37°N (10). Arrows show boundaries of MT profile in Figure 4a. b) Bouguer gravity and gravity models computed by varying crustal density within stippled area proportionally with topography. Upper two models show effect of average crustal density contrasts of 50 and 100 kg/m³ (within local variation proportional to topography),
corresponding to 25% and 50% of the total compensation needed, respectively. Lower model curve shows a 25% crustal contribution and 75% mantle contribution, assuming stippled region in the upper mantle is 80 kg/m³ less dense than unpatterned area.

Figure 4. a) E-W resistivity model resulting from inversion of distortion-corrected MT data for minimum structure model (14, 15). Vertical scale in km; horizontal scale corresponds to model coordinates of Figure 3, showing position of shot point 5 (SP5) and MT site 21. GV, Great Valley; SN, Sierra Nevada; BR, Basin and Range. Box in upper mantle beneath the eastern Sierra Nevada outlines region perturbed for sensitivity tests in (b), sensitivity of MT sounding at site 21 in the Sierra Nevada to upper mantle conductivity. Apparent resistivities for the yx mode (perpendicular to geologic strike) show variations due to perturbation of upper mantle resistivities from 1 to 1000 ohm-m. Trial values of upper mantle resistivity are in the box in a). Values of 3-30 ohm-m for upper mantle resistivity provide acceptable fits.

Figure 5. Equilibration pressure-temperature determinations on Sierra Nevada xenoliths (19, 21). Trends A, B and C are explained in the text. Symbols: open circles - feldspathic granulites; diamonds - garnet clinopyroxene rocks; closed triangles - garnet peridotites and garnet websterites; crosses - spinel peridotites from the CS; black squares - spinel peridotites from the HS. Curves: 1 - present day geotherm in the central Sierra Nevada (22); 2 - the garnet breakdown reaction: pyrope + grossular = anorthite + 2 diopside + spinel; 3 - spinel-garnet peridotite transition; 4, wet peridotite solidus; 5, dry peridotite solidus (23). m₁σ, 1σ minimum error for the dataset; M₁σ, 1σ maximum error for the dataset.

Figure 6. Model of the late Cenozoic Cordilleran crust at lat. 36.5° N. Shading, pre-20 Ma upper crust; unpatterned layer with flow lines, fluid deep crust; crosses, eclogitic upper mantle; dots, mantle lithosphere; dashed line, 1000°C isotherm; bold arrow, locus of asthenospheric upwelling below the High Sierra; GV, Great Valley; SN, Sierra Nevada; BR, Basin and Range; CP,
Colorado Plateau; CS, column of central Sierran xenolith suite; HS, column of High Sierra/Owens Valley xenolith suite.
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