A Paleoelevation History of the Basin and Range and Its Relation to Cenozoic Extensional Tectonism

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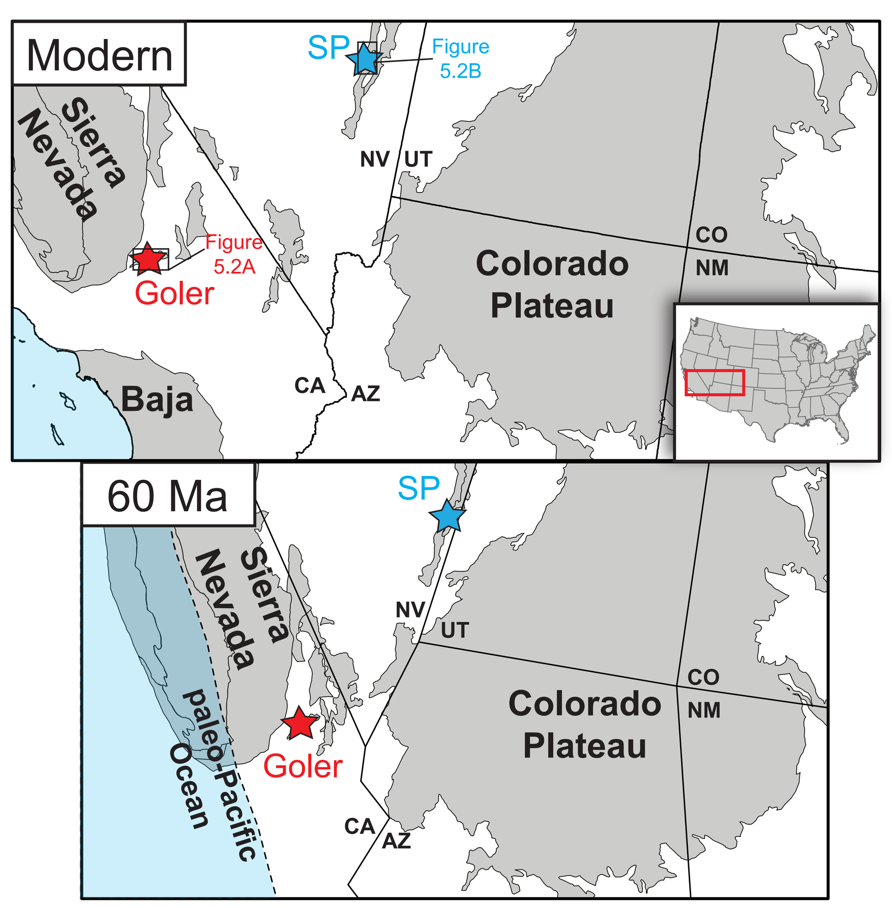
Abstract

The Basin and Range Province of the western United States is one of the premier examples of diffuse continental extension in the world. Estimates of extension across the Basin and Range during the Cenozoic range from 200% province-wide to locally as great as 400%. However, crustal thicknesses across this region, as derived from a variety of geophysical methods, are remarkably uniform and, at ~35 km thick, are similar to global averages. Reconciling large-magnitude crustal extension with observed crustal thicknesses is difficult without calling on one of three possible alternatives: (1) an Andean-plateau crustal thickness of ~60 km at the termination of the Sevier Orogeny and prior to extension; (2) substantial addition of material to the crust by syn-extensional magmatism or (3) mobilization and redistribution of fluid lower crust during extension. Quantitative paleoelevation histories can help discriminate between these competing mechanisms for widespread Cenozoic extension. New estimates of pre-extensional paleoelevations for the northern and central Basin and Range are presented using clumped isotope (Δ47) thermometry of lacustrine carbonates that suggest modest (~2-3 km) pre-extensional elevations for the northern Basin and Range and quite low (< 1 km) elevations for the southern Basin and Range. These paleoelevations are incompatible with mass balance considerations based on the observed magnitude of crustal extension and modern crustal thicknesses, and imply that crustal mass was added to the Basin and Range during extension, either from magmatism or crustal flow.

Background and Methods

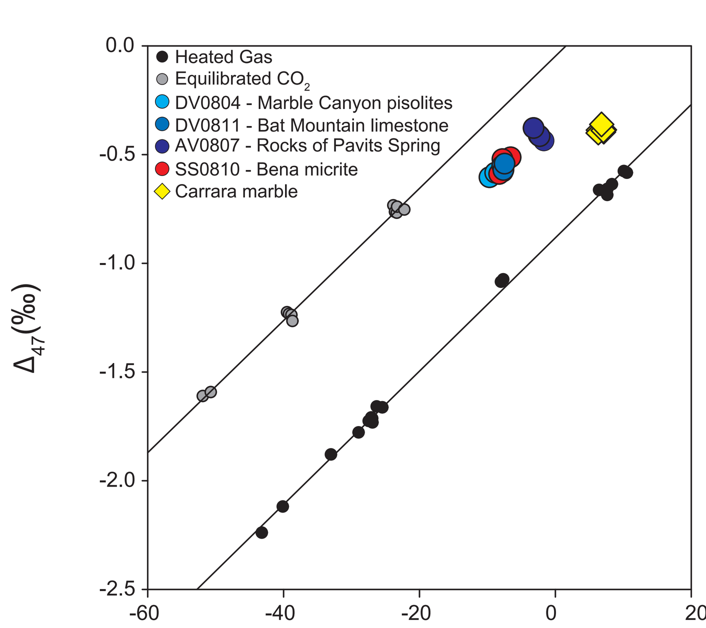
Study Area



Map of sample locations. Upper map shows carbonate sample locations (stars) in modern geographic coordinates with major physiographic provinces of the western US shown in gray. Inset map of the continental US indicates map extent. Lower map shows sample site locations in their Paleocene paleogeographic positions prior to Tertiary Basin and Range extension. Paleocene sample locations and paleogeography of retrodeformed state boundaries and physiographic provinces are based on palinspastic reconstructions of McQuarrie and Wernicke (2005). SP = Sheep Pass Formation; Goler = Goler Formation.

Clumped Isotope Thermometry

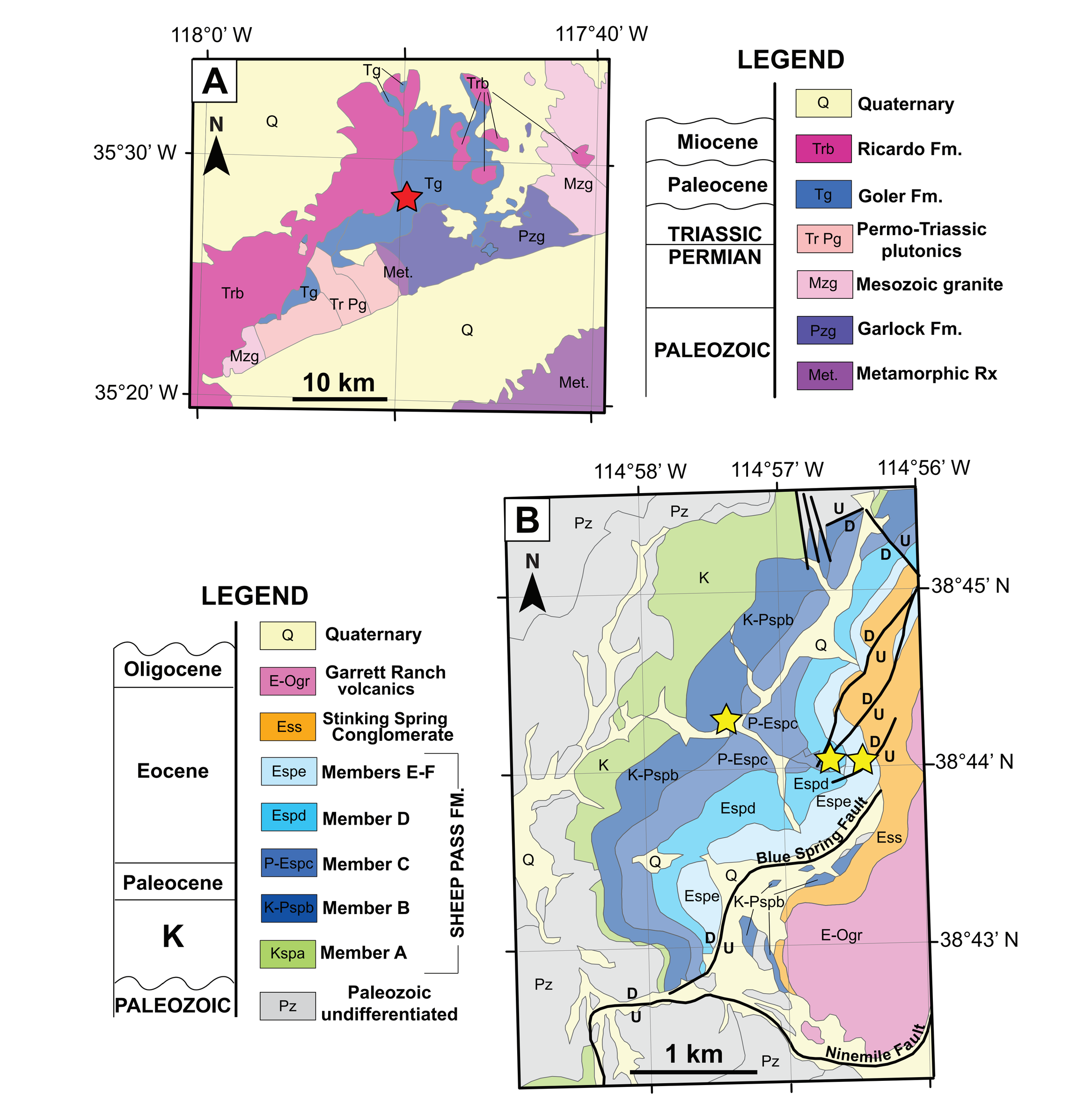
Clumped isotope thermometry is based on the temperature dependence of the "clumping" of rare heavy isotopes in isotopologues. For paleoelevation studies, the isotopologue of mass 47 of CO_3 in calcium carbonate is frequently used to measure the formation temperature of carbonate, a ubiquitous geologic material in lakes, soils, and other archives. The occurrence of this particular isotopologue can be used to infer paleo-surface temperatures.



Heated gas line and isotopologue data. δ_{47} versus Δ_{47} for Goler and Sheep Pass carbonate samples, the Carrara marble interlab carbonate standard, and heated CO_2 gases. See text for discussion of heated gas line. Linear regression of heated gas isotopologue values includes analyses of heated CO_2 gases with δ_{47} values ranging from -54 to +10‰. Temperature values for carbonate samples are determined by normalizing measured Δ_{47} values using stochastic heated gas compositions at equal δ_{47} values. analytical results and calculated temperatures.

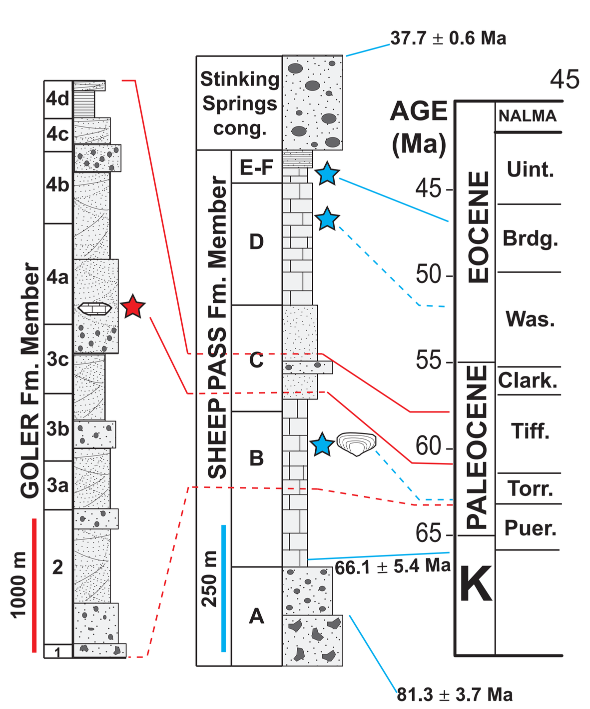
Eocene Paleoelevations

Geologic Setting



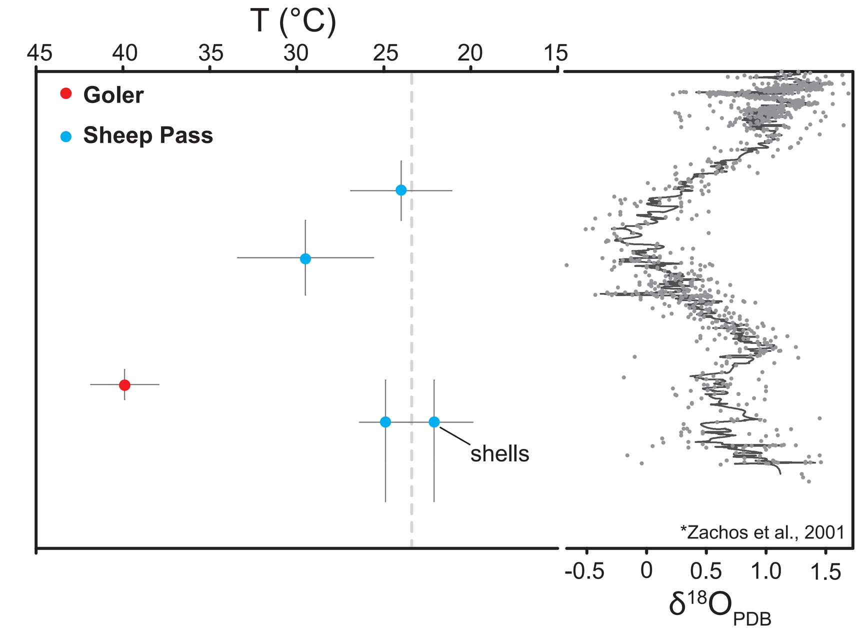
Geologic setting of Sheep Pass and Goler Formations carbonate sample locations. (A) Geologic map of the El Paso Mountains of southeastern California, modified from Cox [1982]. The Paleocene Goler Formation unconformably overlies metamorphic rocks of the Paleozoic Garlock Formation and Mesozoic plutonic rocks associated with the onset of regional Sierra Nevada arc magmatism and is unconformably overlain by Miocene Ricardo Formation volcanics. Red star marks location of Goler Formation Member 4a micritic carbonate sample. (B) Detailed geology of Sheep Pass Canyon, southern Egan Range, Nevada where the type section of the late Cretaceous-Eocene Sheep Pass Formation is exposed [modified from Druschke et al., 2009b]. Yellow stars mark Sheep Pass carbonate sample locations. Both lacustrine carbonate and fossil mollusc shells were collected from the same location within Member B (K-Pspb).

Sampled Localities



Simplified stratigraphic columns (Goler Fm. - Cox, 1982; Sheep Pass - Fouch, 1979; Druschke et al., 2009b) are included to provide stratigraphic correlation of the Goler (red lines) and Sheep Pass (blue lines) Formations. Dashed lines indicate approximate correlations. Stars mark approximate stratigraphic position of analyzed carbonate samples. Sampled molluscs from Sheep Pass Member B also shown. North American Land Mammal Age (NALMA) assignments and age uncertainties are based on Sheep Pass molluscan biostratigraphy (Good, 1987) and radiometric dating (Druschke et al., 2009b) and Goler Formation biostratigraphy (e.g. Lofgren et al., 2008) and magnetostratigraphy (Albright et al., 2009). NALMA abbreviations: Puer. = Puercan, Torr. = Torrejonian, Tiff. = Tiffanian, Clark. = Clarkforkian, Was. = Wasatchian, Brdg. = Bridgerian, Uint. = Uintan.

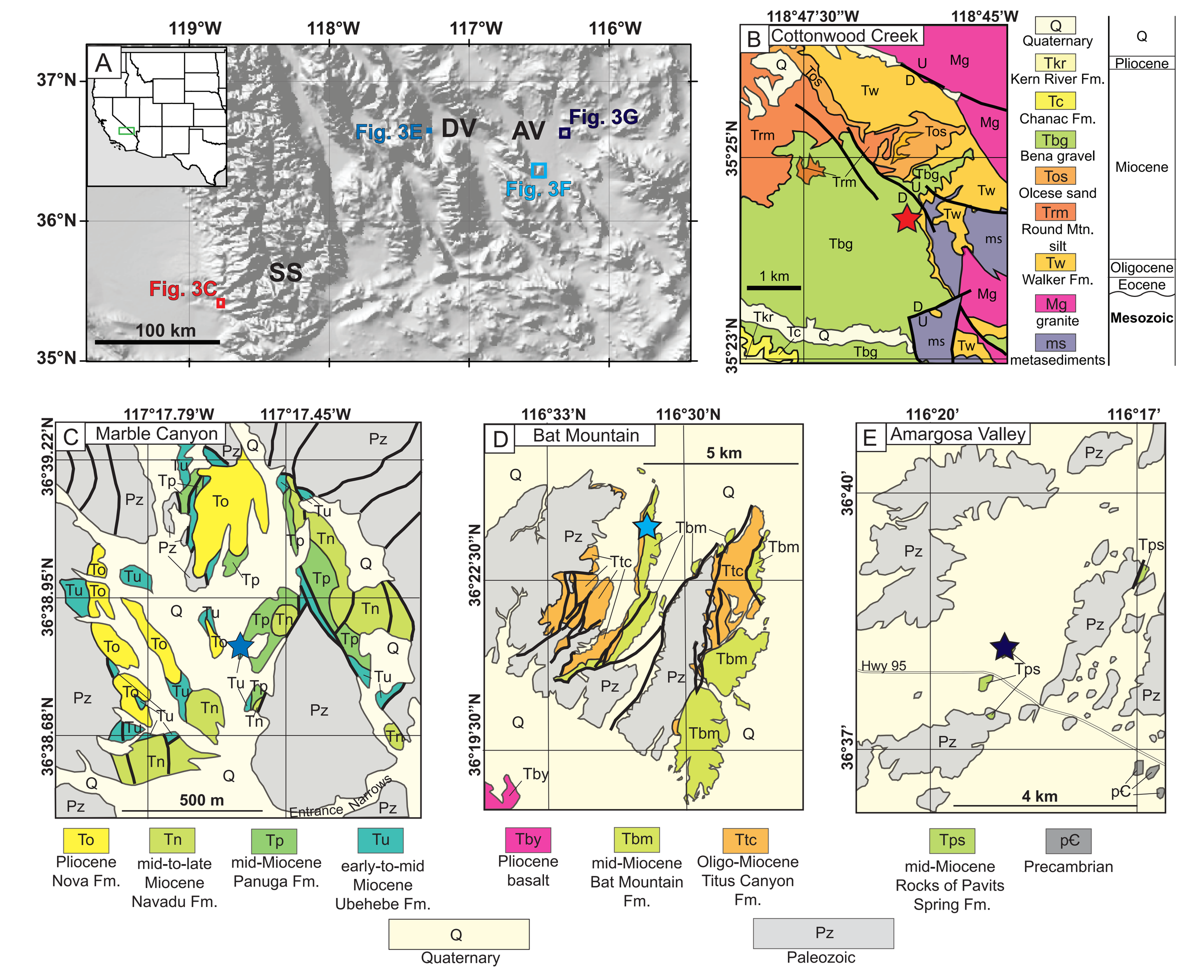
Paleotemperature Results from Clumped-Isotope Thermometry



Carbonate clumped isotope temperature record. Age-temperature plot for Goler and Sheep Pass carbonate samples. Dashed gray line marks average carbonate clumped isotope temperature for Sheep Pass Formation Members B and E (~ 23.5°C). Zachos et al. (2001) marine $\delta^{18}O$ record is shown for reference. Temperature difference between Sheep Pass Formation and presumed Paleocene sea-level temperatures at that time suggest that the paleoelevation of the Sheep Pass Formation was not significantly different from its modern elevation. This implies that there was not significant topographic change in concert with large-magnitude extension of the northern Basin and Range.

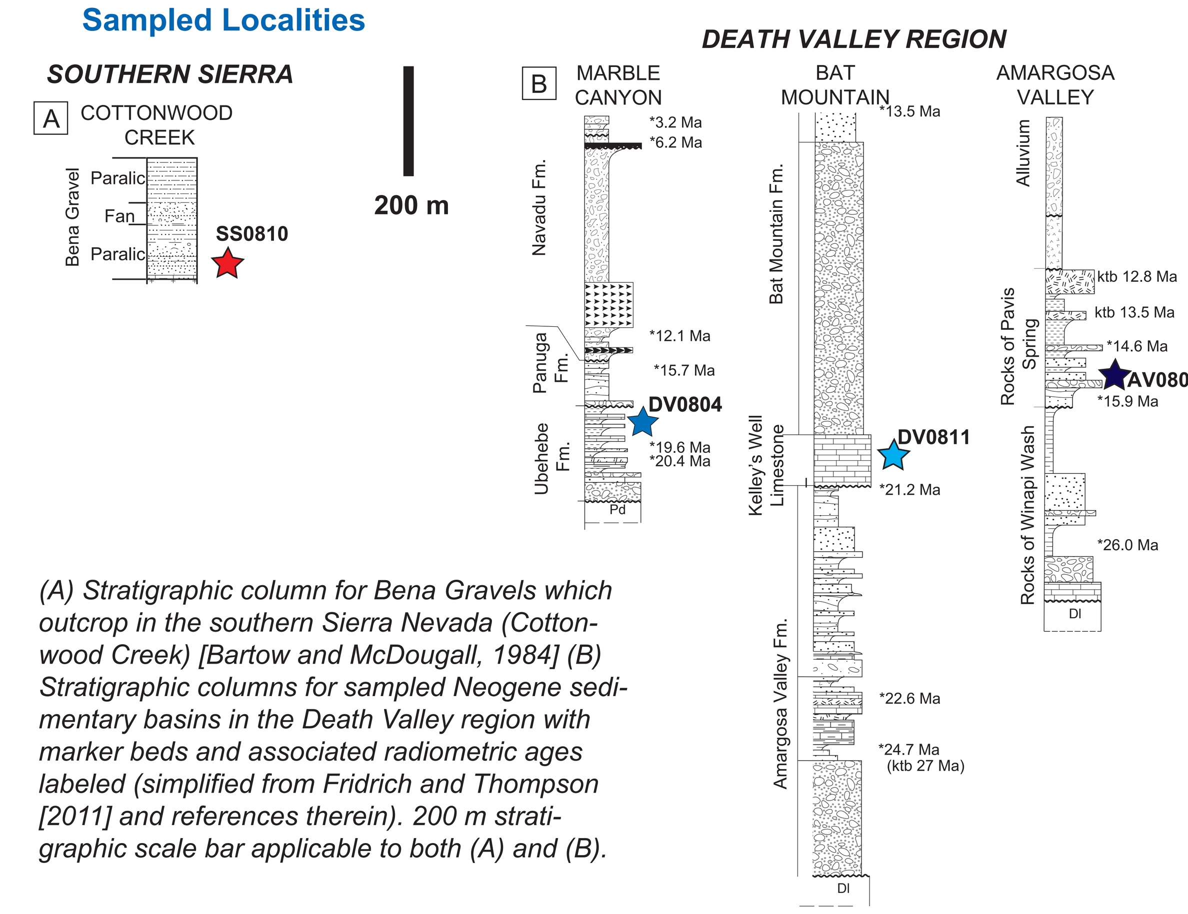
Miocene Paleoelevations

Geologic Setting



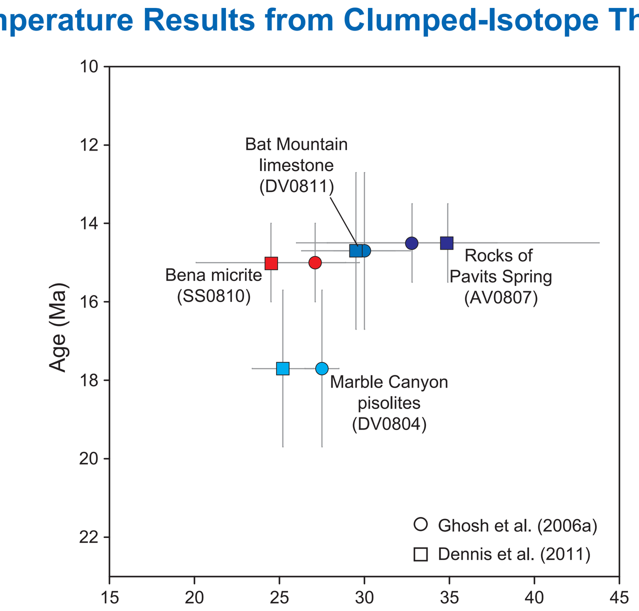
Geologic setting of sampled Miocene localities in the Sierra Nevada and Death Valley region. (A) Hillshade map of the southern Sierra Nevada-Death Valley region with extents of Cottonwood Creek (B), Marble Canyon (C), Bat Mountain (D), and Amargosa Valley (E) simplified geologic maps. Map extents are outlined and color-coded by sample localities, as shown in stratigraphic columns (below). Inset shows location and extent of hillshade map. SS = southern Sierra Nevada; DV = Death Valley; AV = Amargosa Valley. (B) Simplified geologic map of the Cottonwood Creek area of the southern Sierra Nevada where the peralic facies of the Bena Gravels were sampled (red star; modified from Bartow [1981]). (C) Simplified geologic map of the Marble Canyon area of the Cottonwood Mountains (modified from Snow and Lux [1999]) with sample location of Ubehebe Formation pisolites marked by blue star. (D) Simplified geologic map of the Bat Mountain area of the Funeral Mountains (modified from Fridrich et al. [2008]), where the Kelley's Well Limestone member of the Bat Mountain Formation was sampled (light blue star). (E) Simplified geologic map of the Amargosa Valley area where the Rocks of Pavits Spring were sampled (purple star; simplified from Burchfiel [1966]). Thick, black lines on geologic maps mark mapped surface faults.

Sampled Localities



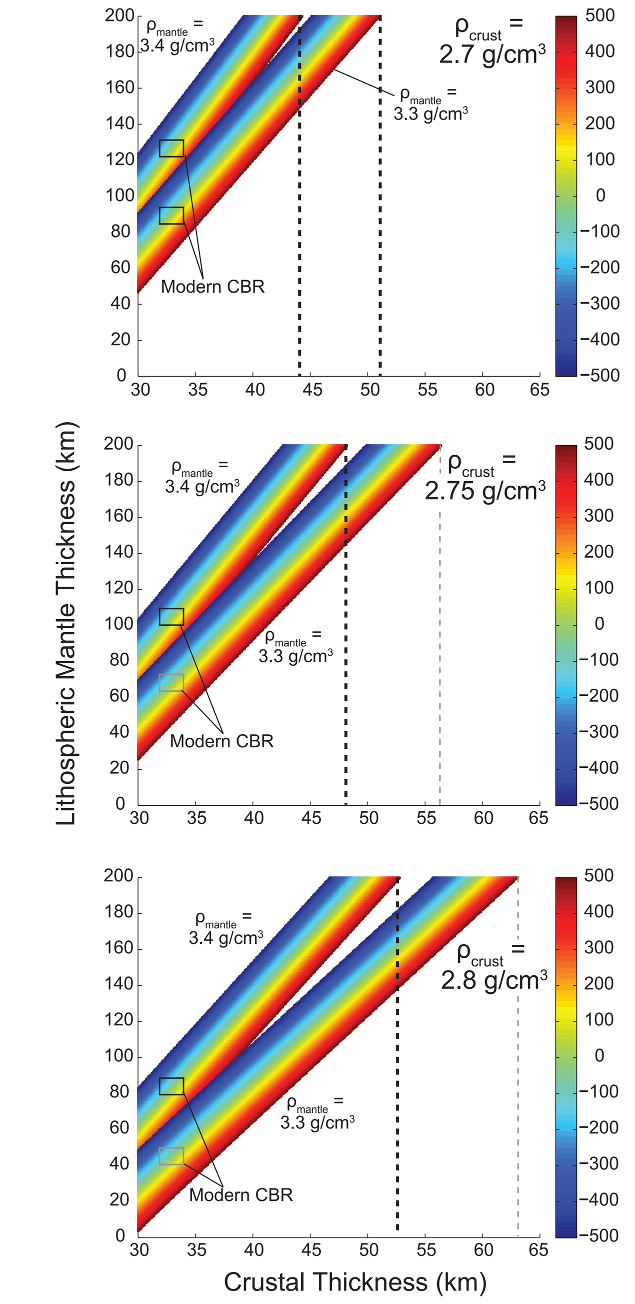
(A) Stratigraphic column for Bena Gravels which outcrop in the southern Sierra Nevada (Cottonwood Creek) [Bartow and McDougall, 1984] (B) Stratigraphic columns for sampled Neogene sedimentary basins in the Death Valley region with marker beds and associated radiometric ages labeled (simplified from Fridrich and Thompson [2011] and references therein). 200 m stratigraphic scale bar applicable to both (A) and (B).

Paleotemperature Results from Clumped-Isotope Thermometry

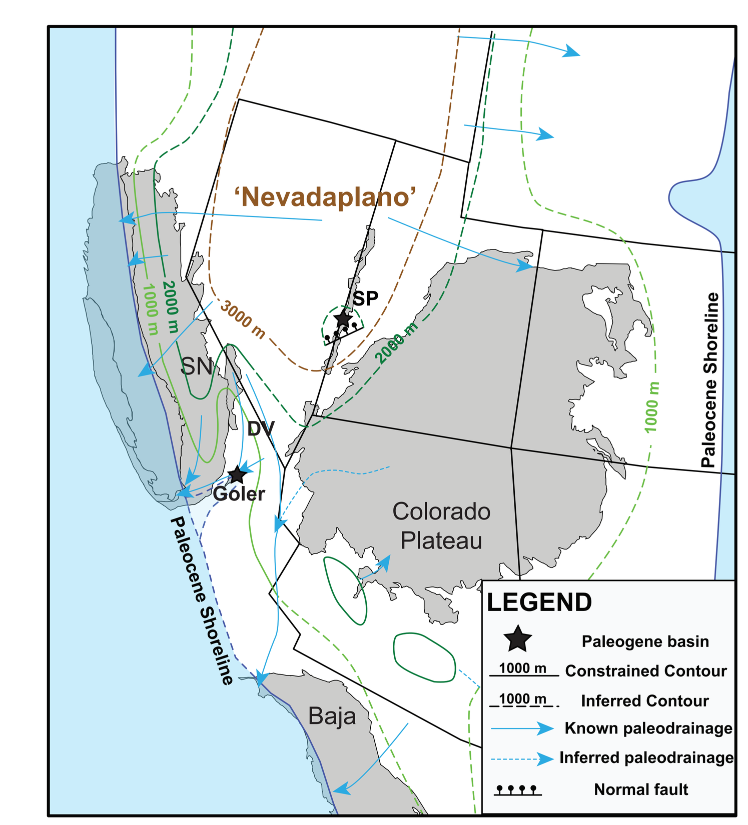


Age- Δ_{47} temperature plot for Bena Gravels and Death Valley area carbonate samples. Temperatures are plotted for Δ_{47}-temperature calibrations of Ghosh et al. [2006a; circles] and Dennis et al. [2011; squares]. Samples are color-coded and labeled for clarification. Temperature differences between Bena micrite from the Sierra Nevada and samples in Death Valley indicate that the Death Valley region was not colder than the sea-level samples from the Sierra Nevada, suggesting that the Death Valley region was at low elevations prior to the onset of extension in middle-late Miocene time.

Discussion



Isostatic calculations of central Basin and Range (CBR) (paleo)elevations following the method of Lachenbruch and Morgan [1990] and Schulte-Pelkum et al. [2011]. Elevation calculations are presented for crust = 2.7, 2.75, and 2.8 g/cm³ and mantle (mantle lithosphere) = 3.3 and 3.4 g/cm³. Colorbar shows calculated elevation values relative to modern mean CBR elevations of 1 km; the –500 to 500 m range equates to paleoelevations of 500 – 1500 m, which is the constrained paleoelevation range for the Middle Miocene Death Valley area based on carbonate Δ47 analysis. Dashed lines show maximum crustal thicknesses permitted for ~ 1500 m paleoelevations (heavy, black lines and boxes for density combinations that produce total lithospheric thickness comparable to modern CBR estimates [> 100 km; Schulte-Pelkum et al.,2011], gray lines and boxes for thicknesses that do not match modern observations).



Early Cenozoic paleotopography and paleogeography of the western U.S. Cordillera with retrodeformed state boundaries. Locations of reference physiographic provinces (gray polygons) from McQuarrie and Wernicke [2005]. Paleotopographic contours and paleodrainages for the southern Sierra Nevada-Death Valley domain and _Nevadaplano' region are based on the results of this and published studies [Gregory-Wodzicki, 1004 1997; Wolfe et al., 1998; Cassel et al., 2009a; Lechler and Niemi, 2011b]. Remaining contours and paleodrainages compiled from 1006 various sources (Sierra Nevada: Mulch et al. [2006]; Cassel et al. [2009b]; Hren et al. [2010]; Cecil et al. [2010]; Henry et al. [2012]; southern Basin and Range: Abbott and Smith [1989]; Howard [2000]; Wernicke [2011]; Sevier orogen: Henry [2008]; Fan and Dettman [2009]). SN =Sierra Nevada, SP = Sheep Pass, DV = Death Valley.

Conclusions

This preliminary study of Basin and Range paleoelevations from the Paleocene, just at the end of the compressional Sevier Orogeny, and from the Miocene, just prior to the onset of Basin and Range extension, suggests that paleoelevations of the Basin and Range are similar to observed modern elevations, despite >200% extension. These results suggest that crustal extension and thinning must be countered by another process that adds material to the crust to compensate for extensional strain. Lower crustal flow and magmatic addition are both possible mechanisms to accomplish this. Further work is required to discriminate between these two possibilities.

Acknowledgements

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