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Evolution of rock strength and relief during incipient mountain building

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Rock strength is a fundamental property of earth materials that influences the morphology of landscapes and modulates feedbacks between surface processes, tectonics, and climate. However, the factors that control rock strength in the near surface environment and their role in setting relief in active orogens remains poorly understood. Here we evaluate the evolution of rock strength and relief in a fold and thrust belt by substituting space for time in the eastern Topatopa Mountains of southern California, USA, where stratigraphic units ranging from Miocene to Plio-Pleistocene age are exposed in a broad homocline dipping parallel to the range front. We quantify hillslope-scale, near-surface rock strength by exploiting two slope-stability models, which explicitly relate the balance of forces within a hillslope to Mohr-Coulomb strength parameters, and 3 m resolution digital topography. We first use the Culmann finite-slope stability model to back-calculate strength with high-density measurements of ridge-to-channel hillslope height and gradient. We then invert the Newmark infinite-slope stability model for hillslope-scale strength over the same regions using the 1994 Mw 6.7 Northridge Earthquake PGA Shakemap and co-seismic landslide inventory to provide an independent check on strength values. We find that the strength estimates produced using the two slope stability models show similar trends with respect to stratigraphic position and inferred maximum burial depth and overlap with direct-shear test data and in-situ field measurements from these geologic units. Cohesion estimates are low, and range from effectively zero to 60 kPa, while friction angle estimates range from 23 to 38 degrees. Both rock strength and local relief increase from east to west with increasing burial depth and exhumation of stratigraphic units. Within the stratigraphically lowest unit, cohesive strength varies from 20 to 60 kPa across a north-to-south transect. Here both strength and local relief are highest over the cores of anticlines, where rocks from deeper in the section are exposed at the surface and which apatite helium thermochronometric data indicates burial depths of at least two kilometers before exhumation. Burial depth likely exerts a strong control on the strength of these young stratigraphic units through diagenetic changes in porosity, cementation, and ultimately lithification. These findings suggest that relief in the early stages of fold and thrust belt propagation grows not just as a consequence of rock uplift, but with increasing rock strength as deeper stratigraphic units are exhumed.