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Rock-Strength and Characteristic Length-Scales for Orogenic Relief

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There has been increasing focus in recent years in understanding the evolution of topographic relief in tectonically active landscapes, from length scales ranging from a local river channel or glacial valley to an entire mountain belt.Topographic relief is defined relative to the geoid, which represents the shape that the Earth would have if it were composed solely of a self-gravitating fluid. On orogenic time scales (~10 Ma),the upper ~20 km of the crust and the upper 20 to 40 km of the mantle behave as a frictional solid, rather than a viscous fluid. Frictional materials are plastic, in that they can support large deviatoric stresses without yielding. It would be nearly impossible for an orogen to develop its topography, both the mountainous topography at the surface and the inverse topography of the orogenic root, without this finite strength.

The depth transition between different types of rheological behavior sets up different horizontal length scales for relief at the surface. (1) Cohesive strength dominates at depths < 4 km. Cohesion is maximized in arid regions or fast eroding regions (where weathering is minimized). Steep to vertical slopes can be sustained in these settings, with local relief up to the cohesive skin-depth. (2) Frictional shear strength dominates at depths from ~4 to ~20 km. Valleys large than this vertical scale will tend to have threshold slopes, where the dip approaches the shear friction strength of the bedrock (~35 degrees). The maximum depth for frictional shear strength also limits the upper limit for the relief that can be produced by a frictional convergent wedge. Isostatic balance and typical taper angles indicate that frictional wedges can produce up to ~4 km of relief over a horizontal distance of ~75 to 100 km. (3) Viscous strength of the crust imposes another important length scale. The friction-viscous transition occurs at ~15 to 20 km beneath many convergent orogens. The frictional part of the wedge can maintain a ~4 percent gradient, but that gradient will be greatly will tend to decrease as the internal part of the orogen becomes more viscous. The ultimate limit will be a plateau, at which point the crust is no longer strong enough to maintain a topographic gradient.

Flexural isostasy also influences the horizontal length scales for relief. This elastic phenomenon is much more apparent in rocks that have a finite yield strength (i.e. the frictional plastic rocks of the lithosphere). The flexural strength of the lithosphere is most strongly dependent on the thickness of the frictional plastic layers, which in turn is dependent on the thermal age of the lithosphere. A cooler lithosphere will provide greater flexural support, and will allow larger horizontal gradients in relief.

Fractal analysis indicates that topographic relief is, in part, scale invariant. The observation is that the amplitude of relief increases with the square root of distance. In other words, the maximum difference in elevation within a 25 km-diameter circle will be about 5 times greater than that within a 5 km-diameter circle. This fractal scaling is not unexpected, given that topography varies smoothly at local scales (i.e. correlated at local scales). The fractal scaling does not predict the overall shape of the topography, but it does indicate that measurements of relief and slope angles are a function of the length scale used in those measurements.

Thermochronology provides practically the only record that can be obtained in terms of vertical motions of rocks towards the surface.Noting that the thermal field of the uppermost crust is sensitive to characteristics of the topography, low temperature systems can provide independent estimates of exhumation rates and relief changes at various length scales. Our interest here is to illustrate studies that have used low temperature thermochronology to quantify changes in relief at the length scale discussed above.