Quantifying paleorelief using (U-Th)/He thermochronology: an example from the Sierra Nevada, U.S.A.

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The upward motion of rock masses near the Earth's surface is accompanied by changes in temperature, and so the unroofing history of nearly every major mountain belt on earth has been accurately measured using thermochronologic techniques. More fundamental to continental dynamics, however, is resolving the motion of the Earth's surface with respect to the geoid. Constraining these motions has remained elusive because variations in temperature at the Earth's surface, while dependent on elevation, are not resolvable using traditional thermochronologic methods. We introduce a new technique for estimating the time of topographic uplift of a mountain range by mapping out the low-temperature thermal structure imparted by river incision using U-Th/He ages of apatites. Our first results from the southern Sierra Nevada, U.S.A., suggest that the two largest transverse rivers in the range had cut deep canyons by 80 Ma. The data require significant topographic relief at that time, contrary to previous studies suggesting the range was a low-standing plateau prior to Late Cenozoic uplift.

The technique exploits the fact that horizontal variations in temperature in the uppermost part of the continental lithosphere will result from the development of orogen-normal river drainages along the edge of a mountain belt or plateau. This structure results in cooling of samples collected beneath ancient river valleys faster than those collected at the same structural level beneath intervening ridges (Fig. 1). If broad constraints on the unroofing rate and geotherm are available, the age difference between valleys and ridges may be used to estimate paleorelief, and therefore the minimum height of a mountain range, at some time in the past.

Assuming nominal values for the geotherm and soil lapse rate, the amplitide of horizontal temperature variation near the Earth's surface ranges from ~10–80°C for relief of 1–3 km. Neglecting lateral variations in reduced heat flux, radioactive heat production, mean surface temperature and advection of heat due to erosion, the temperature T below a

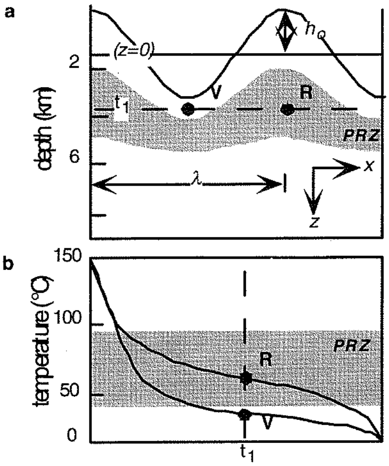

FIG. 1.

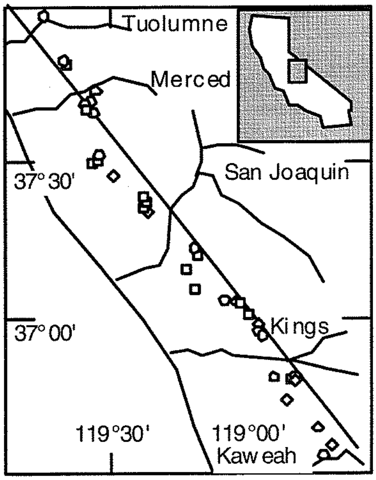

FIG. 2.

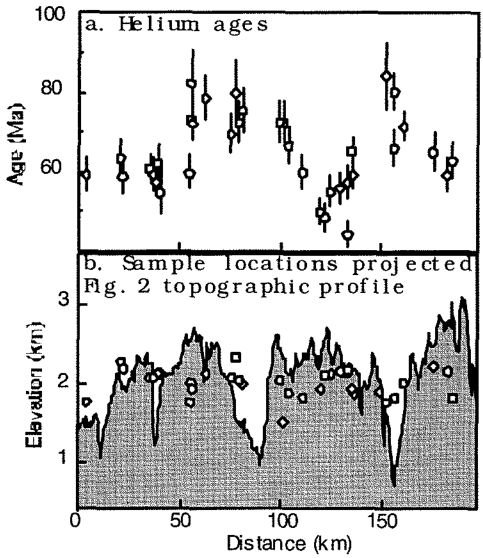

FIG. 3.

periodic topography is

$$T(x,z) \alpha h_0 \cos(\pi x/\lambda) \exp -(2\pi z/\lambda)$$

where x and z are horizontal distance and depth, respectively, and h_0 and λ are the amplitude and wavelength of relief, respectively (Turcotte and Schubert, 1982), (Fig. 1). Because the horizontal variation attenuates with characteristic depth $(1/2\pi)\lambda$, and given that at least a few tens of degrees would be necessary to produce thermochronologic age contrasts, the effect may be difficult to detect below the characteristic depth. The thermochronometer with the best potential for measuring these effects is the U-Th/He apatite method, which has a closure temperature of ~75°C (Wolf *et al.*, 1996. Given a typical geotherm and erosion rate, the expected temperature variations are sufficient to result in detectable age variations (Δt), and therefore first order limits on h_0.

We collected samples for U-Th/He dating along a 200 km orogen-parallel transect through the southern Sierra Nevada, California from the Toulumne to the Kaweah river valleys, at an elevation of about 2000 m (Fig. 2). We chose the Sierra because it is a relatively simple west-tilted block whose western margin has been near sea-level since at least 80 Ma (Huber, 1981) and the heat production of Sierran plutons varies mainly in a direction normal to the range axis (Saltus and Lachenbruch, 1991). The sampling strategy exploits short wavelength topography such that samples near the modern valleys were collected from peaks (e.g. Glacier Point in Yosemite Valley) and those from intervening ridges were collected from the bottoms of secondary valleys. The sampling transect cuts these drainages at the points of their maximum incision, therefore any topographic imprint on cooling ages will be most pronounced along this profile.

Total erosion of this region of the Sierra since the end of granitic plutonism yields an average erosion rate of 0.08–0.10 mm/yr, consistent with rates implied by Late Cenozoic westward tilting of the range (Huber, 1981). Fission track elevation transects in the Kings and Merced River drainages indicate rapid cooling from 270–100°C from 65–75 Ma, with little variation of age over 2000–2500 m of elevation; U-Th/He ages from the same apatite separates yielded ages ranging from 30–75 Ma with a well-defined elevation gradient of ~20 Myr/km (House *et al.*, 1997). The data, combined with the modern heat flow measurements in the Sierra, indicate low to moderate geothermal gradients (10–25°C/km) in the uppermost crust since ~70 Ma.

Euhedral, inclusion-free igneous apatite from undeformed granitic plutons were analysed in replicate, with mean ages ranging from 44.5 to 84.6 Ma (Fig. 3a). The ages have a well defined periodicity with λ = 70 km and Δt ~20–30 Ma, in-phase with the first-order topography of the range (Fig. 3b).

The age profile, if primarily the result of paleotopography, suggests the large canyons of the San Joaquin and Kings Rivers were in existence by 80 Ma. Our calculations relating age variations to topographic amplitude imply that the observed 20–30 Ma periodicity in helium ages reflects cooling under a long-wavelength topographic amplitude of 1000–2000 m. Several considerations suggest this would be a minimum for the height of the range. First, by analogy with the modern topography in the Sierra and elsewhere, we expect the amplitude of short-wavelength topography (λ<20 km) to have been at least 250 m. Second, we note the crest of the modern Sierra lies 50 km northeast of our profile, with both mean and summit elevations about 30% higher than ridge elevations along the profile. Therefore, if we incorporate these assumptions into a model with long-wavelength relief of 3000 m (corresponding to Δt of 25 Ma), we infer a Late Cretaceous elevation at the Sierran crest of ~4500 m. This estimate is considerably higher than indicated by previous workers and supports the hypothesis that a high-standing plateau with large canyons, similar to the modern Andes, was developed in this region at this time (Wernicke *et al.*, 1996).