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Estimating palaeorelief from detrital mineral age ranges

Jonathan D. Stock and David R. Montgomery

Department of Geological Sciences, University of Washington, Seattle, WA 98195, USA

ABSTRACT

We propose a method that uses the increase in mineral age with elevation in some bedrock landscapes to quantify palaeotopographic relief from the age range of detrital minerals in coeval sediment. We use the rate at which mineral age changes with elevation (its age-gradient, dt/dz) and its age range (Δt) in the sediment to invert for relief: $\Delta z = \Delta t/(dt/dz)$. Relief inversion requires a single-grain dating precision high enough that detrital grains originate from resolvably different elevations (e.g. laser microprobe $^{40}Ar/^{39}Ar$ fusion). The technique assumes that there is no change in mineral age during erosion and transport, that sediment is mixed well enough and (or) sampled sufficiently to capture the extrema of mineral ages, and that isochrons were horizontal during erosion. Subject to these constraints, inversion of the age range of individual grains in synorogenic sedimentary sequences allows quantitative estimation of relief development for eroded mountain ranges. This method provides the only direct quantitative measure of palaeorelief, a poorly constrained, but important aspect of many geological, geomorphological and geodynamic models.

INTRODUCTION

The rise of mountain ranges is the fundamental control on the continental-scale production of sediment (e.g. Gibbs, 1967), and has been invoked as a forcing mechanism for global climate change (Raymo & Ruddiman, 1992), speciation (Miller & Mao, 1995) and human survival strategies (King *et al.,* 1994). Most geological literature on orogens focuses on their tectonic evolution using classic structural methods complemented by thermochronological and geobarometric constraints. Coeval evolution of surface relief is difficult to infer because we lack methods of measuring the long-term (i.e. >100 kyr) spatial variations in erosion rates that incise valleys, thereby generating relief. Nor is there any general, integrated theory for predicting relief as a function of climate, lithology and tectonic setting. Despite the influence of topography on the geological record, we cannot quantitatively constrain the surface evolution of active portions of Earth's crust because we cannot interpret synorogenic sediments or thermochronometric exhumation rates in ways that uniquely constrain palaeotopography. Only in a few places where there is a known initial surface elevation and a record of rock uplift and exhumation rates can surface elevation histories be estimated, because surface elevation is the time-integrated difference of these quantities (Molnar & England, 1990). Evaluating the role of topography on the geological record and testing dynamic models of the interaction of erosion and tectonics (e.g. Ahnert, 1970; Chase, 1992; Anderson, 1994) therefore requires a method for quantifying topographic relief through time. Here we propose a conceptual approach for estimating palaeorelief using the age range of detrital mineral grains. This approach is general enough that one could use it with any mineral property that has an elevation dependence. We then outline the requirements for successful relief inversion, examine current detrital mineral age data in light of this model, and discuss potential field sites for reconstructing palaeorelief.

CONCEPTUAL MODEL

Sediment contains relief information only if some property of the minerals in the bedrock source area has an elevation dependence that is preserved during weathering, erosion and deposition. If we know the functional relationship between this signal and elevation, then its range in mineral grains of the sediment provides a proxy for the range of elevation, or relief. Isotopic cooling age is a mineral property that can depend on elevation. Many deeply exhumed bedrock landscapes contain spatial variations of mineral cooling ages due to spatial variations in exhumation rate, the effects of relief, or some combination thereof. In some cases this variation is dominantly vertical and mineral age increases with elevation (see next section). This signal can persist as individual grains are eroded, routed and mixed through a catchment by hillslope processes and by subsequent transport in rivers or glaciers. Where the isotopic ages in the source area (the area upstream of the sampling site) have a known elevation dependence, detrital minerals with these ages carry quantitative information about the relief of the source area. Subject to certain geological constraints, the age range of detrital minerals can be used to reconstruct the relief of ancient catchments.

Minimum relief needed for the technique

Mineral isochrons in some bedrock landscapes define a 'stratigraphy' in which age increases with elevation. Landscapes with such a cooling age architecture are arguably a product of locally uniform exhumation of deeply buried rock bodies minimally deformed after isotopic ages are set by cooling. In such landscapes, age–elevation relations are resolvable only when the apparent exhumation rate (e.g. the slope on an age vs. elevation plot) is low enough and the relief great enough that the ground surface intersects rock layers with measurably different isotopic ages (Fig. 1). Apparent exhumation rates are not necessarily the true exhumation rate because of the influence of changing geotherms, as discussed below.

A substantial literature (based on fission-track, K–Ar and ^{40}Ar/^{39}Ar dating techniques) documents mineral ages that increase with elevation, suggesting, though not always proving, the presence of horizontal isochrons (proof requires sample sites distributed across the landscape, rather than along a transect where increases in mineral age with elevation are also consistent with tilted isochrons). These are predominantly areas of moderate to high relief (i.e. 1–5 km) such as the Nelson batholith (Sweetkind & Duncan, 1988; Fig. 2a), Mt Washington, New Hampshire, (Eusden & Lux, 1994; Fig. 2b), North-Central Utah range (Kowallis *et al.*, 1990; Fig. 2c) and southern Tibet (Copeland *et al.*, 1987; Fig. 2d). Areas with horizontal isochrons and less than 3 km of relief are likely to contain measurable mineral age gradients (dt/dz) only if apparent exhumation rates were less than 0.5 km Ma^{-1} during cooling of the exposed levels (Fig. 1). For instance, using the inverse of the slope of the age-elevation data on Fig. 2, cooling age ranges of $\approx$ 9–30 Ma are set by apparent exhumation rates of 0.04–0.18 km Ma^{-1}. Only mountains with the highest relief (Fig. 1) would contain measurable age gradients for even larger apparent exhumation rates. In cratonal areas, such as Central Africa or Quebec, local variations of isotopic age (Cosca *et al.*, 1992; Wagner *et al.*, 1992) are probably due to differential exhumation rates associated with faulting, as local relief is too low to intersect more than several isochrons.

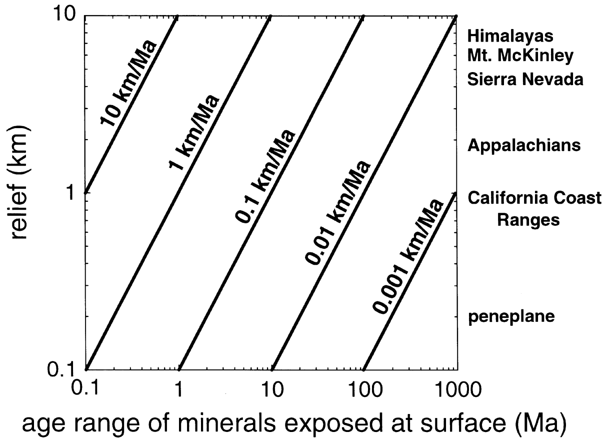

Fig. 1. Relation of relief (Δz), age range of minerals exposed at the ground surface (Δt) and apparent exhumation rate (dz/dt) for landscapes with horizontal isochrons defined by $\Delta t = \Delta z/(dz/dt)$.

Inverting for relief

The absolute mineral age range within a landscape with horizontal bedrock isochrons is a function of: (1) relief, which controls the depth to which the cooling age column is sampled; (2) the geotherm; and (3) exhumation rate, which will influence the age gradient if it alters the geotherm. Since thermal advection can influence apparent exhumation rates during erosion (e.g. Royden & Hodges, 1984; Hubbard *et al.*, 1991), we formulate our model using dt/dz, the age gradient calculated directly from the observed elevation dependence of mineral age. The apparent exhumation rate is by definition the inverse of the age gradient, but it is the true exhumation rate only in the special case when the geotherm is at steady-state while minerals are cooling through their blocking temperatures. A mountain range with horizontal isochrons, a variable age–elevation gradient and a given relief sheds sediments with a cooling age range given by:

$$\Delta t = \sum_{1}^{i} dt/dz_i \cdot \Delta z_i \qquad (1a)$$

where Δt is the age range of detrital mineral grains and Δz is the local relief in isochrons over the ith interval with an age gradient dt/dz_i. Rearranging in terms of relief z yields

$$\Delta z = (\Delta t)/(dt/dz) \qquad (1b)$$

for the case of a constant age gradient (Fig. 3). Hence measurement of the age range of sediment shed from a mountain range, coupled with the knowledge of the elevation gradient in mineral age allows a quantitative estimate of the relief in the source area. If this relief is not steady-state, the age range in the sediment will change at a rate dependent on both the river incision rate (which sets dz/dt to first order and hence dt/dz) and the hillslope response (which dictates the relief for an imposed river incision rate). The rate at which the age range in the sediment changes is the time-derivative of Eq. (1b) rearranged for Δt:

$$\frac{d}{dt}(\Delta t) = \left[\frac{d}{dt}(\Delta z) \cdot \frac{dt}{dz}\right] + \left[\frac{d}{dt}\left(\frac{dt}{dz}\right) \cdot \Delta z\right]. \qquad (2)$$

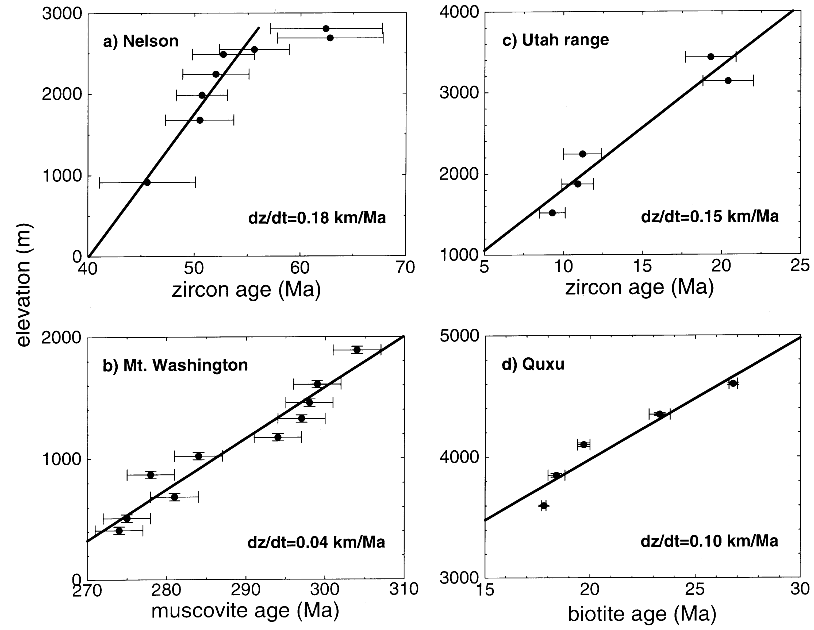

Fig. 2. Sites with an elevation-dependent mineral age: (a) apatite fission-track ages from the Nelson batholith, British Columbia (Sweetkind & Duncan, 1988); (b) muscovite ^{40}Ar/^{39}Ar ages from Mt Washington, New Hampshire (Eusden & Lux, 1994); (c) zircon fission-track ages from the North-Central Utah range (Kowallis *et al.*, 1990); and (d) biotite ^{40}Ar/^{39}Ar ages from the Quxu pluton, southern Tibet (Copeland *et al.*, 1987). Apparent exhumation rate (dz/dt) is the slope of the least squares regression line.

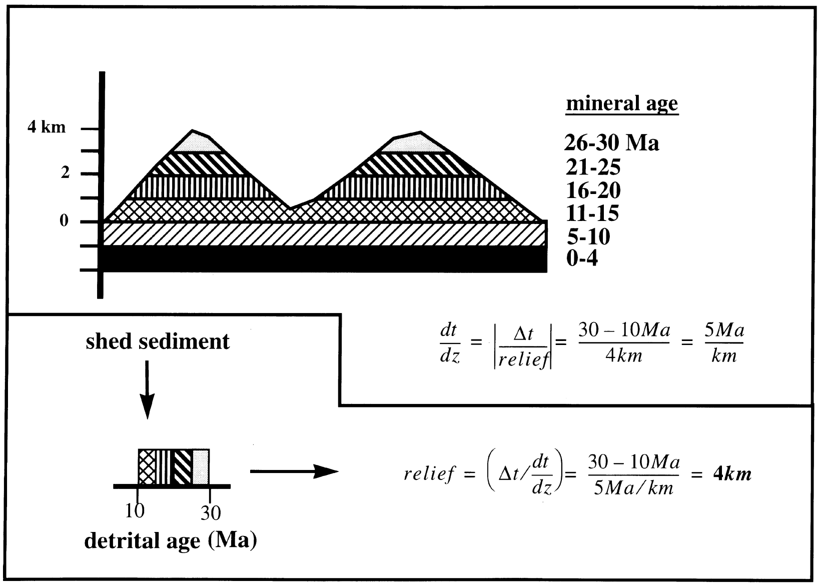

Fig. 3. Hypothetical example of inverting detrital age range (Δt) for relief (Δz) given horizontal isochrons with a known age gradient dt/dz. In this case, the 20 Ma range in detrital mineral age and 5 Ma km^{-1} gradient in mineral age imply a relief of 4 km.

In landscapes where long-term river incision rates are greater than several tenths of a millimetre per year, (d/dt)(Δt) is dominated by the dt/dz term because the rate of relief change is physically limited by local rock and by regional lithospheric strength and is unlikely to exceed several km Ma^{-1}. In landscapes where relief is at the limit imposed by bedrock strength (e.g. Schmidt & Montgomery, 1995), river incision rates are equivalent to exhumation rates and:

$$\frac{\mathrm{d}}{\mathrm{d}t}(\Delta t) = \Delta z \cdot \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}t}{\mathrm{d}z}\right). \tag{3}$$

For the special case in which the geotherm is at steady-state during cooling, dt/dz = 1/(dz/dt) and the age range changes inversely with the regional exhumation rate setting the age gradient. The lag time

$$\delta t = \int_{t_1}^{t_2} \left\{ \left[T_t \Big/ \frac{\mathrm{d}T}{\mathrm{d}z}\left(\frac{\mathrm{d}z}{\mathrm{d}t}\right) \right] \Big/ \frac{\mathrm{d}z}{\mathrm{d}t}(t) \right\} (\mathrm{d}t) \tag{4}$$

is the time for a change in exhumation rate to reach surface topography as an altered age gradient. Here T_t is the blocking temperature of the mineral with the age–elevation dependence and the geotherm (dT/dz) is a function of the time-dependent exhumation rate. This is commonly measured as the difference between the depositional age of the strata and the enclosed grain's isotopic age (plus sediment transport time). In parts of the Himalayas this lag time is less than 5 Ma (e.g. Cerveny *et al.*, 1988; Copeland & Harrison, 1990; Harrison *et al.*, 1993), indicating that changes in exhumation rate can quickly change the range in detrital grain age. In general, because age range is proportional to $\mathrm{d}t/\mathrm{d}z$, greater exhumation rates will lower age range at the ground surface.

Precision of inversion

The precision of relief inversion is equal to the relief of the thickest resolvable isochron across the catchment. Resolution of an isochron depends on both the precision of the dating technique and the magnitude of the age gradient recorded in the rock. The variation in elevation of a resolved isochron depends on its down-dip angle from the horizontal (θ). If $\theta = 0$, precision is the relief of the thickest isochron. For the more general case of tilted isochrons, precision is the relief of an isochron (highest elevation of a particular grain age less its lowest elevation) or $\sin(\theta)L$, where L is the down-dip distance of an isochron across the source area. Given sub-Ma dating precision, typical of ^{40}Ar/^{39}Ar techniques for Cenozoic samples, horizontal isochrons with large age gradients (i.e. 10 Ma km^{-1}) allow relief inversion with a precision of the order of ± 100 m (or 10 resolvable isochrons of 1 Ma in 1 km) while lower gradients (1 Ma km^{-1}) reduce the precision to the order of 1 km (1 resolvable isochron per kilometre).

REQUIREMENTS FOR MODERN RELIEF INVERSION

Before inverting older sediment for palaeorelief, several assumptions should be tested in the modern environment. We discuss these here, and elaborate on the additional requirements for palaeorelief inversion in the next section. Equation (2) implies that if the age gradient(s) of the source catchment are constrained by geochronology, then the total relief of the bedrock catchment ought to be invertible from the age range of its sediment. Such an inversion requires:

1 single-grain mineral dating precision high enough that detrital grains originate from resolvably different elevations;

2 preservation of mineral age during erosion and transport;

3 sediment mixing sufficient to capture the extrema of the age histogram, and transport rapid enough that grain ages from previously eroded rocks are absent;

4 nearly horizontal isochrons across the source catchment.

Given these constraints, which we discuss below, changes in the age range of detrital mineral grains record changes in the relief of the source catchment (Fig. 4). Each of the preceding four requirements is testable in a modern setting of known age gradient by dating detrital minerals in the modern sediment, a test which should precede any attempt to invert palaeorelief from older sediments.

First requirement: high single-grain precision

Of the techniques available for dating single mineral grains, only single-grain, laser microprobe ^{40}Ar/^{39}Ar fusion satisfies the requirement that the grain's age be invertible for a discrete elevation. The high intrasample variability of fission-track ages violates this requirement because detrital grains disaggregated from the bedrock cannot be assigned to a unique elevation range within the source catchment. This is because any whole rock sample has grains with a wide distribution of fission-track ages whose mean is the age of the sample. Working before the advent of single grain ^{40}Ar/^{39}Ar dating methods, Wagner *et al.* (1979) briefly discussed the possibility of inverting the range of fission-track ages of boulders (i.e. the average age from many grains within the boulder) to estimate relief. This approach provides a minimum palaeorelief estimate because the probability of sampling the elevation extrema of a large basin from boulders is low. In contrast, ^{40}Ar/^{39}Ar dating of individual mineral grains has low intrasample variability as long as the diffusion domain sizes are small (McDougall & Harrison, 1988) rather than large (e.g.

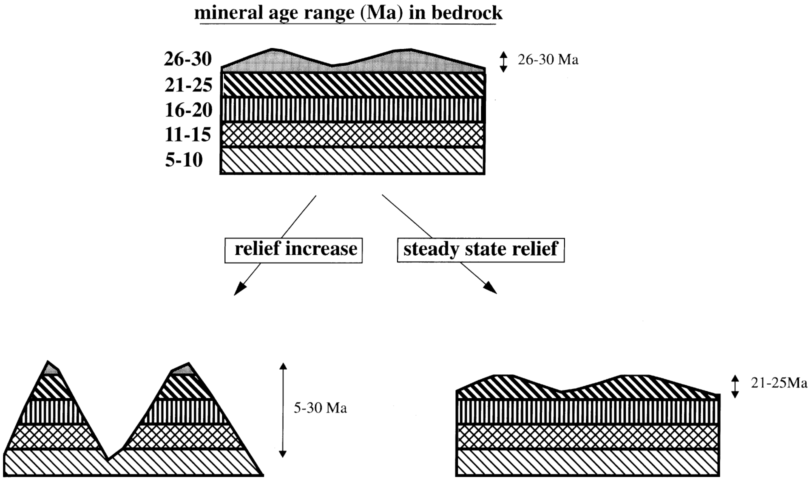

Fig. 4. Illustration of the influence of changes in relief on the distribution of mineral ages available for erosion at the ground surface. The example in the lower left illustrates the case for an increase in relief, that on the right illustrates the case for steady-state relief.

Hames & Hodges, 1993) relative to grain size. Diffusion domains can be thought of as the dimensions over which the concentration of the daughter product in the crystal varies spatially; only when they are small relative to grain size will detrital grains yield a consistent age.

Second requirement: no change in mineral age

To fulfil the second requirement, grains must retain their isotopic ages during transport and deposition in order to invert their original elevation from their age. Biotite isotopic ages seem to be susceptible to alteration after exhumation (Clauer, 1981; Mitchell & Taka, 1984). In contrast, white micas (e.g. muscovite) demonstrably retain their isotopic age, even after extreme weathering (Clauer, 1981). They have been used in detrital provenance studies (e.g. Heller *et al.,* 1985, 1992) and appear to be the most reliable candidate for relief inversion. K-feldspar may retain isotopic signals from the original catchment (e.g. Copeland & Harrison, 1990; Harrison *et al.,* 1993) but there is evidence of isotopic alteration under extreme lateritic weathering (Clauer, 1981). Where such advanced weathering is absent (e.g. most high-gradient landscapes), K-feldspar could be used to invert for relief. There is an additional incentive to use K-feldspar because its closure temperatures (150–360°C; Lovera *et al.,* 1989) span fission-track closure temperatures of apatite (100 ± 20°C; Wagner & Van den haute, 1992) and zircon (210 ± 40°C; Wagner & Van den haute, 1992). Hence K-feldspar-bearing rocks with apatite or zircon fission-track age–elevation trends are likely to contain the same dependence in their K-feldspar grains. Unless field studies demonstrate that the isotopic age of K-feldspar is alterable under temperate erosion regimes, we suggest it is a candidate for palaeorelief inversion. Hornblende is also a potential mineral for relief-inversion, although we are not aware of any data on its susceptibility to isotopic alteration.

A further caveat of the second requirement is that minerals used for relief-inversion upstream of the sampling point must not have sources other than those with the documented age–elevation dependence (or unequivocal age differences must exist between the mineral extraneous to the area with the age–elevation dependence and that from within it used for relief reconstruction). These conditions necessitate sampling close enough to the source that minerals from other terrains with similar cooling ages do not contaminate a potential relief signal. For this reason, the age range of detrital minerals in the Bengal fan (Copeland & Harrison, 1990) does not allow quantitative assessments of Himalayan palaeorelief because the huge source area contains many provenances for minerals of similar ages.

Third requirement: sediment is well mixed

Sediment eroding from the bedrock must be sufficiently mixed by hillslope, glacial and fluvial processes so that the age distribution of minerals in sampled sediment reflects the elevation extrema of the catchment bedrock. Geochemical and provenance studies (Wolfenden & Lewin, 1978; Stott, 1986; Takeuchi, 1989; Cruikshank *et al.,* 1993) suggest that mixing from hillslope and fluvial processes homogenizes sand and coarse silt fractions of sediment over relatively short distances (i.e. 5–10 km). If sediment is thoroughly homogenized, the number of samples needed to sample the elevation extrema can be simulated using Monte Carlo modelling techniques. Assuming a spatially uniform detrital mineral production rate (mineral concentration and erosion rate are spatially uniform), a sample size of 40 grains provides a 90% probability of capturing 90% of the relief of a sample catchment (Fig. 5). In general, this threshold sample size will be inversely proportional to the standard deviation of the elevation histogram, and proportional to the total relief because these control the probability of sampling an elevation. This sample size is a lower bound because the degree of sediment mixing and spatial variations in mineral concentration and (or) erosion rate will also weight the age distribution in the sediment. We are unaware of well-constrained data that directly address the question of mixing length or spatial variation in mineral production rate, and sample size should be evaluated using modern sediments to estimate the relief in a modern field site, prior to palaeorelief inversion.

There must be minimal storage time between erosion and final deposition because long storage times (> 1 Ma) could preserve and mix grains eroded at different times, yielding an artificially large palaeorelief. We suggest that long-term storage is unlikely in high-gradient areas (e.g. < 5 Ma lag times in the Himalayan detrital data sets), although storage may be important if there are

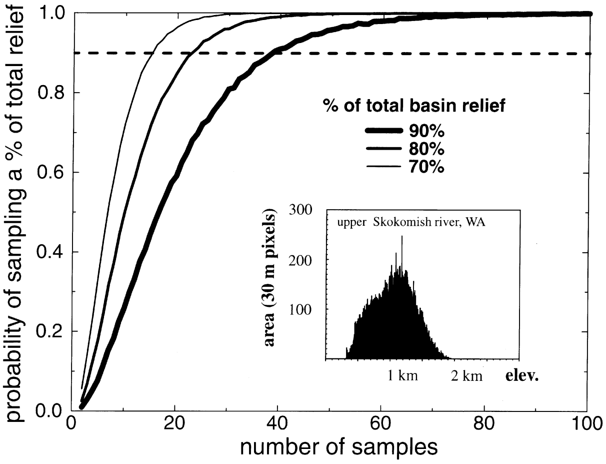

Fig. 5. Plot of the number of samples needed to achieve a specified probability of sampling a given percentage of total catchment relief. Curves represent the results of 15 000 realizations of Monte Carlo simulations for different percentages of relief. Samples are drawn randomly from a normal distribution simulating the elevation distribution of the Skokomish River, Washington (inset).

intermontane basins between the source and the sediment sampling site.

Fourth requirement: near-horizontal isochrons

Isochrons in the source catchment must be sufficiently horizontal for a required relief precision. The condition of horizontal isochrons is the most restrictive of the four requirements. Many deeply exhumed areas have nonhorizontal isochrons due to differential rock uplift and exhumation during isotopic setting (Spear & Harrison, 1989), or faulting and doming thereafter (Fig. 6). There are, however, areas whose distributions of mineral ages are consistent with horizontal isochrons (Fig. 2).

ADDITIONAL REQUIREMENTS FOR PALAEORELIEF INVERSION

In addition to these four requirements for relief inversion in the modern case, we add a caveat for palaeorelief inversion from ancient sediment. Using the measured age gradients in the modern landscape to invert relief from Eq. (1b) is problematic in areas where the erosion of mountain peaks has removed evidence for possible changes in isotopic age gradients driven by changes in exhumation rate and/or geothermal gradient. Many age–elevation profiles show such a change, and Fig. 7 illustrates how a hypothetical change in age gradient could simulate an apparent palaeorelief change. Hence, relief inversion is best constrained in areas with minimal peak-lowering, as demonstrated by an old erosion surface, or the retreating margin of an escarpment or graben. In these places, age gradients at the highest elevations have not changed since the creation of the erosion surface.

We can estimate the mineral age gradient in eroded landscapes using the age gradients in modern outcrops of minerals with higher closure temperatures. To calculate eroded age gradients we assume a known, steady-state geotherm (dT/dz). Apparent exhumation rates recorded at shallow depths in minerals with low closure temperatures are simultaneously recorded at deeper depths in

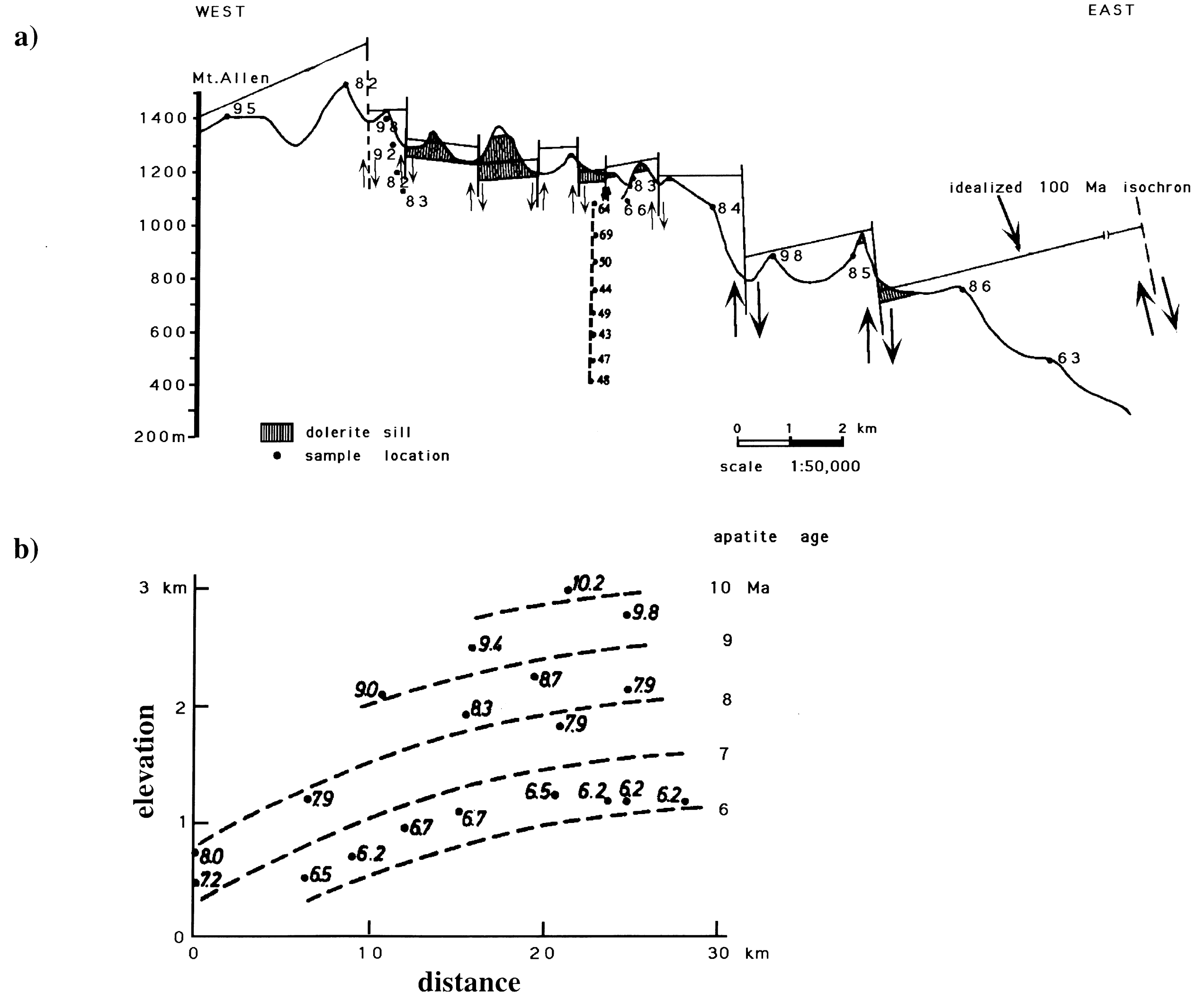

Fig. 6. Sites with a nonunique age–elevation relation. (a) Topographic cross-section showing faulted 100 Ma isochron in Southern Victoria Land, Antarctica (after Fitzgerald & Gleadow, 1990). (b) Plot of elevation vs. distance illustrating doming of apatite fission-track age isochrons in the Gotthard massif, Switzerland (after Wagner & van den Haute, 1992).

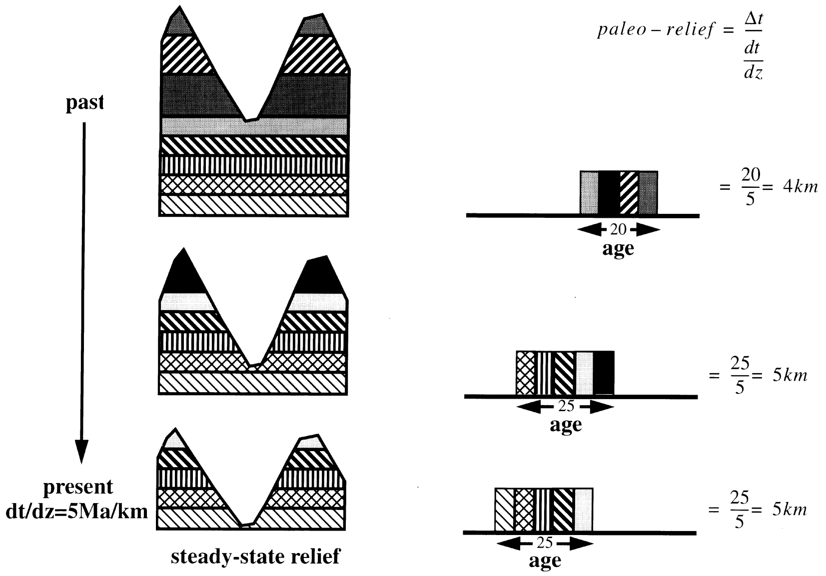

Fig. 7. Illustration of the potential for changes in age gradient to simulate relief change. Left column shows steady-state relief during a doubling of the age gradient. Right column shows the age range of the detrital mineral increasing by 5 Ma, leading to the inference (based on the modern age gradient) that relief has increased by 1 km.

minerals with higher closure temperatures. For a mineral with a closure temperature (T_1) less than that of a higher closure temperature (T_2) mineral,

$$Z^* = Z_s + (T_2 - T_1)/(dT/dz) \tag{5}$$

where Z^* is the elevation relative to the sample elevation (Z_s) at which the age gradient of the relief-inversion mineral is equal to that of the higher closure temperature mineral for a steady-state geotherm dT/dz. Hence for landscapes where significant peak-lowering is probable, age gradients for more than one mineral are required. For K-feldspar, the mineral with the potentially lowest ^{40}Ar/^{39}Ar closure temperature (as low as 150°C for the smallest diffusion domains; Lovera *et al.*, 1989), eroded age gradients are largely constrainable where zircon fission-track data are available, because Z^* is of the order of several kilometres. For example, curves in Fig. 8 show Z^* as a function of geotherm for an assumed K-feldspar closure temperature of 150°C. Higher closure temperatures (corresponding to larger diffusion domains) will lower all curves, flattening their curvature at lower geotherms. Similarly, if the source rock for sediments eroded from above the current peaks had the same age gradient as modern surface bedrock, then the cooling rate of bulk grains from cobbles in the sediment [as deduced from their age spectra via step-heating (e.g. Lovera *et al.*, 1989)] will be equal. The possibility of using this technique on single grains with the laser probe is also under investigation (e.g. York *et al.*, 1981; Layer *et al.*, 1987; Lee *et al.*, 1990), although single-grain step heating analysis in a nonlaser, very-low blank furnace may provide an attractive alternative. If this approach proves feasible, we can directly test the assumption of constant age gradient, as grains from eroded horizons should have similar cooling rates to their cousins eroded from elevations of known age gradient.

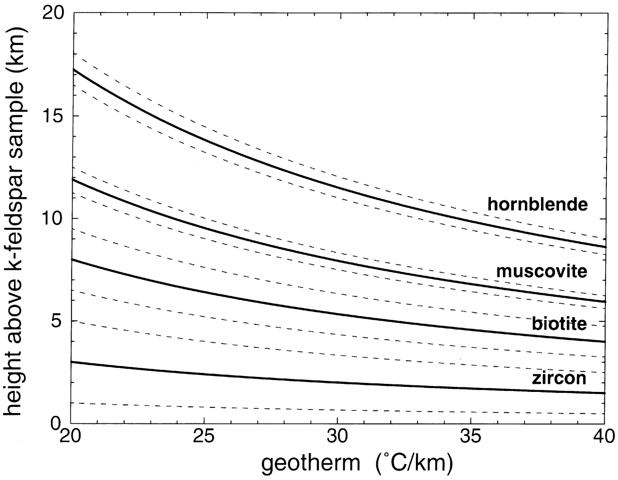

Fig. 8. Plot of the geotherm vs. the elevation offset at which different minerals give palaeoage gradients for K-feldspar (assumed closure temperature of 150°C). Closure temperatures for minerals not mentioned in text are: biotite, 280–340°C (McDougall & Harrison, 1988); muscovite, 375–400°C (Keppie *et al.*, 1993); and hornblende, 480–510°C (McDougall & Harrison, 1988; for cooling rates from 1 to 10°C Ma^{-1}). Dashed lines indicate minimum uncertainty due to the range of closure temperatures.

EXAMPLES

Previous detrital mineral dating studies address either regional provenance issues or the time lag between mineral cooling age and depositional age as a measure of exhumation rates. These studies were not designed with relief-inversion in mind, so the potential topographic signal in their data sets is difficult to assess, primarily because the source regions are either concealed (Kelley & Bluck, 1992) or lack well-constrained age–elevation relations (Copeland & Harrison, 1990; Harrison *et al.*, 1993). Nevertheless, the large number of samples in

Harrison *et al.* (1993) and Heller *et al.* (1992) make these attractive data sets to examine in light of our model.

Siwalik Group, Himalaya

Harrison *et al.* (1993) used ^{40}Ar/^{39}Ar to date the minimum age of detrital K-feldspars from Miocene–Pliocene deposits of the Siwalik Group, fluvial deposits from the Himalayas whose depositional ages are locally constrained by magnetostratigraphy (Fig. 9). We selected the three horizons with the densest sampling at 2.8, 5.2 and 8 Ma, defining the age range of actively eroding rock from depositional age to the first significant gap in detrital age. We reasoned that detrital mineral ages eroding from recently set isochrons (those with a lag time <5 Ma) are more-or-less continuous and that the first significant gap in detrital age greater than 5 Ma marks a transition to relict ages from stable or reworked source areas. We use 5 Ma because it is an upper limit to lag time for the existing detrital mineral studies in the Himalayas (e.g. Cerveny *et al.,* 1988; Copeland & Harrison, 1990; Harrison *et al.,* 1993). In Fig. 9, the age range (circled number) remains constant at 23 Ma between stratigraphic ages 8 and 5.2 Ma, but decreases by 5 Ma between stratigraphic ages 5.2 and 2.8 Ma. We can interpret this age-range change as: (1) not significant because the number of samples is insufficient to capture the age extrema in the sediment; (2) an artefact of structural deformation of pre-existing isochrons; (3) a result of a decrease in relief; or (4) a result of a decrease in the exposed age gradient. This example highlights the ambiguity of the relief-inversion technique if there are no constraints on the source area's present isochrons or their eroded age gradients. Although the first assumption is a valid explanation for the observed change in age range, we can calculate the results of assumptions 3 and 4. Assuming the observed change in age-range $[(\mathrm{d}/\mathrm{d}t)(\Delta t)$ is -5 Ma/2.4 Ma, or approximately $-2]$ is due entirely to a change in relief, Eq. (2) becomes

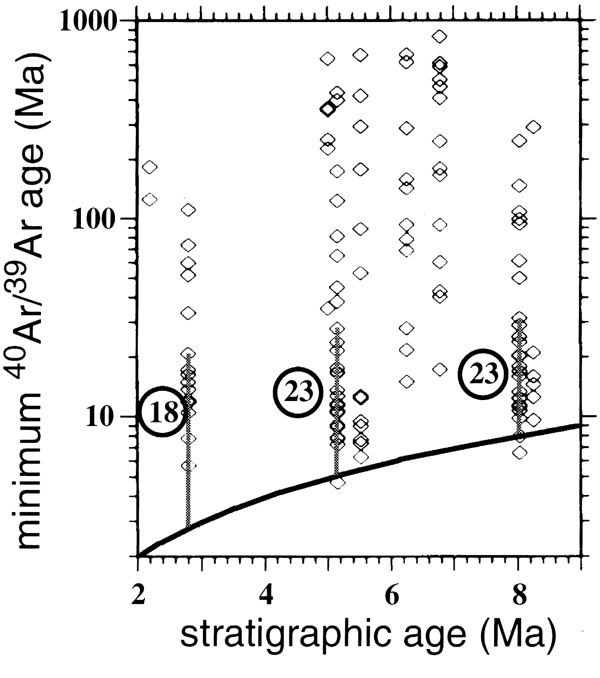

Fig. 9. Minimum detrital K-feldspar dates vs. stratigraphic age for the Bakiya sandstones, Siwalik Group (after Harrison *et al.,* 1993). Curve is the depositional age determined by magnetostratigraphy, vertical lines are our estimates of detrital age range for the three most densely sampled horizons with the age range circled (see text for discussion of how these ranges were established).

$$\frac{\mathrm{d}}{\mathrm{d}t}(\Delta z) = \left[1 \Big/ \left(\frac{\mathrm{d}t}{\mathrm{d}z}\right)\right] \cdot -2$$

which yields a 0.2–2.0 km Ma^{-1} decrease in relief over the Pliocene for apparent exhumation rates of 0.1–1.0 km Ma^{-1}. Given that total age ranges of 18–23 Ma suggest either impossibly large relief or extreme age gradients, it is apparent that the source areas did not have a unique age–elevation dependence. However, there are no steady-state age gradient geometries that would yield a decrease in age range with an increase in relief, so Eq. (2) indicates that the change in age range is due to something besides a change in relief. Accordingly, we could interpret the change solely as a result of a decreased age gradient at the surface, and solve Eq. (3) for $(\mathrm{d}/\mathrm{d}t)(\mathrm{d}t/\mathrm{d}z)$:

$$(\mathrm{d}/\mathrm{d}t)(\mathrm{d}t/\mathrm{d}z) = -2/\Delta z.$$

For relief of 1–8 km, the age gradient at the surface is changing at a rate of -0.25 to -2.0 km^{-1}, respectively. At the midrange of relief, an age gradient changing by -0.50 km^{-1} will explain the observed change in age range in the sediment. This decrease in the age gradient would reflect an increase in the apparent exhumation rate of 2 km Ma^{-1}, equivalent to the minimum exhumation rate Harrison *et al.* (1993) calculate for these samples.

Our intuition that relief could not have decreased over the Pliocene in the source area suggests that the change in the age range of detrital K-feldspars in Harrison *et al.* (1993) is probably explained by incomplete sampling, deformation of isochrons, or an increase in regional exhumation rate over the Pliocene. If the change is a sampling artefact, the constant age range from the late Miocene to Pliocene suggests little change in relief or surface distribution of age gradient in the source area.

Idaho batholith

Heller *et al.* (1992) studied the age range of detrital white micas from Eocene sedimentary units in the western US, concluding that the Idaho batholith was the likely source. Criss *et al.* (1982) document doming and faulting of originally horizontal biotite isochrons (apparent exhumation rates $=0.10$–0.14 km Ma^{-1}) in the batholith during emplacement of the Challis volcanics at *c.* 40 Ma. Hence the Idaho batholith fails the third criterion for relief inversion–that the source has a unique, well-defined age–elevation dependence. Nonetheless, assuming that white mica age gradients are equal to those for biotite, and that all the detrital micas are from the batholith, the detrital age range of ≈34 Ma measured in the Eocene fluvial deposits of the Montgomery Creek Formation (Renne *et al.,* 1990) implies a relief of 3.0–4.2 km in the source area of the Idaho batholith. Given that the isochrons were probably domed with an amplitude of ≈1 km by the time these sediments were deposited, this provides an estimate of 2–3 km of late Eocene palaeorelief in the Idaho batholith. While this suggests relief comparable to the modern landscape, this estimate is speculative until both the provenance and the age gradient of the white micas are better constrained.

DISCUSSION

The requirements that a field site must meet in order to estimate relief from the age range of a detrital mineral are quite restrictive, so we do not envisage this technique to be applicable to all sites within a mountain belt. Rather, palaeorelief estimates may be feasible for a few carefully chosen field sites, where estimating palaeorelief is important enough to justify ^{40}Ar/^{39}Ar dating of many detrital grains. For instance, sites within many mountain belts should show an increase in the age range of detrital sediments to be consistent with Molnar & England's (1990) hypothesis of a late Cenozoic increase in relief driven by climate change. One could also potentially compare palaeorelief and contemporaneous exhumation rates, testing the hypothesis that erosion rate is related to local relief over large time-scales (Ahnert, 1970; Ohmori, 1983).

There are a number of areas with documented age–elevation relations that may contain a relief record in their shed sediment (e.g. Fig. 2), and probably more that have yet to be identified. In the broadest sense, tectonic setting constrains the probable location of structural environments with undisrupted isochrons. For instance, rift or extensional styles of deformation with large normal faults or escarpments may lack fault disruption of isochrons in the footwalls (Fig. 2c) and are ideal field sites from that perspective. Although convergent mountain chains often have severely disrupted isochrons, local structural units or late-stage batholiths can remain apparently intact following cooling (e.g. Fig. 2d; Hess *et al.,* 1993).

In addition to the potential field sites discussed above, a well-defined muscovite age–elevation relationship (Fig. 2b) makes Mt Washington, New Hampshire, an ideal place to test the inversion of modern relief from modern sediments. This area provides an opportunity to test both the persistence of the biotite isotopic ages during erosion and transport and the mixing length necessary to sample elevation extrema. However, Pleistocene glaciers have probably removed any pre-Holocene deposits that would allow us to invert for palaeorelief, so the site would only be a test of relief inversion from modern sediment.

Another field site with the potential to investigate palaeorelief is along the Wasatch fault in the western US, where zircon fission-track ages increase with elevation in the Cottonwood Stock (Fig. 2c). The age range of minerals eroding at any time from the stock is controlled by the topographic relief above the local basin. The relief history of the stock ought to be invertible from the age range of detrital K-feldspars in dated sediments in the adjacent basin. In areas like this, bio- or magnetostratigraphies can control the temporal precision of palaeorelief inversions. Again we emphasize that the accuracy of relief estimates depends on the certainty with which an advantageous cooling-age architecture at the time of stripping can be known, information typically dependent on isochrons from multiple minerals.

CONCLUSIONS

We suggest a way in which an elevation-dependent order in the landscape (in this case mineral age) can be used to measure a fundamental property of Earth's surface over geological time: relief. Given appropriate constraints on regional provenance and geology, detrital mineral dating techniques can be used to define quantitatively the evolution of relief over geological time. This relief inversion method can yield palaeorelief records only for mountain ranges where deformation has not severely disrupted isochron structure, so a critical problem is that of constraining cooling-age architecture in eroded bedrock source areas. In landscapes with horizontal isochrons, it is reasonable to expect that now-eroded adjacent and overlying isochrons were horizontal as well. The technique cannot be used, however, where structural deformation changes isochron geometry in an unpredictable way. Properly selected field sites should allow use of detrital age ranges in ancient sediments to reconstruct the evolution of relief in mountain ranges over orogenic time-scales. With such a record, we can begin to evaluate quantitatively the role of relief as a forcing mechanism for both geological and biological change.

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