Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg?

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The high altitudes of most mountain ranges have commonly been ascribed to late Cenozoic uplift, without reference to when crustal thickening and other tectonic processes occurred. Deep incision and recent denudation of these mountain ranges, abundant late Cenozoic coarse sediment near them, and palaeobotanical evidence for warmer climates, where high mountain climates today are relatively cold, have traditionally been interpreted as evidence for recent uplift. An alternative cause of these phenomena is late Cenozoic global climate change: towards lower temperatures, increased alpine glaciation, a stormier climate, and perturbations to humidity, vegetative cover and precipitation.

NOT long after continental glaciation had been recognized, Dana[1] linked it to a late Cenozoic rise of mountain ranges. Over the next 100 years, several eminent Earth scientists[2-7] supported and developed this idea, but in all cases the main logical link remained the temporal correlation of mountain building with the onset of glaciation. Then, when geologists discovered more than one Pleistocene glaciation, the significance of this correlation temporarily lost favour.

Now, with Pleistocene glaciations recognized as a consequence of variations in the Earth's orbit[8] superimposed on a long-term global cooling throughout the Cenozoic era, attention has again been directed to the association of this cooling with regional elevation changes[9,10]. Uplift of large mid-latitude terrains could effect a global cooling by three different physical mechanisms. First, increased elevations at temperate latitudes could extend the duration of winter, and with increased durations of snow cover, the albedo should increase[11]. Second, the increase in elevation of large regions should profoundly affect the circulation of the atmosphere, and experiments with general circulation models suggest that the presence of high terrains in Central Asia and western North America would lead to lower global temperatures than if these areas were low[12]. These experiments also match a number of observed regional climate differences that are not obtained in such experiments on landscapes with little or no high terrain[13]. Finally, chemical weathering, enhanced by the increased exposure of minerals eroded rapidly from cold high altitudes and transported to warmer, moister low elevations, would absorb more carbon dioxide from the atmosphere, thus decreasing the natural 'greenhouse effect'[14]. In view of the simple logic of these physical mechanisms, and the impressive correlations of calculated with existing regional climate differences[13], the weak link in the argument relating climate change to late Cenozoic mountain building becomes the inference that mountain ranges and high plateaux rose in late Cenozoic time.

In what follows, we argue that most of the evidence used to infer late Cenozoic uplift could, in large part, be a consequence of the very climate changes that this supposed uplift is thought to have caused. Undoubtedly, some regions are higher today than they were 2 or 10 Myr ago, but many may simply appear to be higher because the geological effects of late Cenozoic climate change could cause the same changes in the landscape and fossil record as regional uplift would.

The Cenozoic climate record

Both palaeobotanical data[15] and oxygen isotopes[16-18] indicate

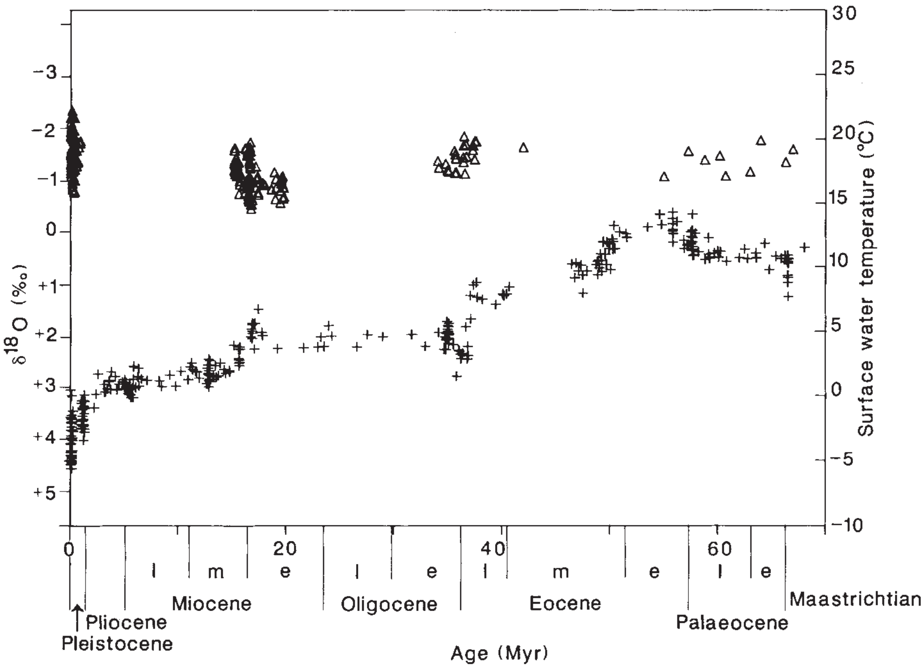

FIG. 1 Oxygen isotope records (and inferred temperatures) for the past 70 Myr from low-latitude surface waters of the Pacific (△) and from ocean deep waters as observed in the South Atlantic (+). Because ocean deep waters are formed at high latitude, the lower curve can be taken as representing the isotope composition of high-latitude surface water. The temperature scale is valid only in the absence of an Antarctic ice sheet—roughly up to mid-Miocene time. Including a correction for the effect of the ice sheet would raise more recent temperatures by ~3 °C. (Figure courtesy of N. J. Shackleton, modified after ref. 17.)

a monotonic, but not steady, cooling of the Earth over the past 50 Myr. Abrupt decreases in temperature occurred near the Eocene/Oligocene boundary[15-21] (~36 Myr ago), at ~15 Myr in the Miocene epoch[16,17,22], and at ~2.5 Myr near the end of the Pliocene epoch[16-18], when continental glaciation in the Northern Hemisphere began[23]. Moreover, the decrease in temperature has been much greater at high than at low latitudes[15,18,24]. For example, oxygen isotopes from planktonic foraminifera deposited at sub-Antarctic latitudes indicate a decrease in surface water temperatures of ~12 °C since late Eocene time[16,17], but those from equatorial latitudes indicate hardly any change in such temperatures[18,24] (see also Fig. 1). Similarly, a comparison of late Quaternary and present-day elevation ranges of plants growing in the equatorial Andes indicates a temperature difference of ~4.5 °C (ref. 25), but oxygen isotopes from cores in Antarctic ice of the same age imply temperatures 11 °C lower than today[26]. The resulting increase in latitudinal temperature gradient is important because it promotes an increased transport of water vapour and latent heat from low to high latitudes[27], and therefore a stormier climate.

Definitions of uplift

The geological literature is much confused by an inconsistent definition of the word uplift[28]. Uplift is a vector opposite to the gravity vector, and a meaningful definition must specify both a reference frame and an object that moves. The most useful reference frames are the geoid (sea level corrected for eustatic changes) and the Earth's surface; the objects that move are either particular rocks or, again, the Earth's surface. In the physical processes linking elevation and climate change[11-13], what matters most is the uplift of the Earth's surface relative to sea level, which is the change in mean elevation. This cannot be measured directly and must be inferred indirectly (see below).

The uplift of rocks relative to the local Earth surface, as measured using geochronology and petrological geobarometers and geothermometers, can be called 'exhumation', and is equal to the thickness of rock removed from the Earth's surface[28,29]. By isostasy (Archimedes' principle applied to light crust overlying heavier mantle), the removal of a layer of crust of thickness ΔT and density ρ_c, compensated by a crustal root in a mantle of density ρ_m, results in a lowering of the surface of $\Delta T\ (\rho_m - \rho_c)/\rho_m \approx \Delta T/6$ (Fig. 2*a*). Thus, the isostatic response to rapid erosion of a region of gentle relief and mean elevation h could transform it into one with peaks at heights of $2h$ (or higher), with valleys near sea level, but with a *lower* mean elevation of only $0.83h$ (Fig. 2*b*).

The uplift of rocks relative to sea level is the sum of the uplift of the Earth's surface and exhumation[28]. As an example, the heights of marine terraces above sea level (corrected for eustatic

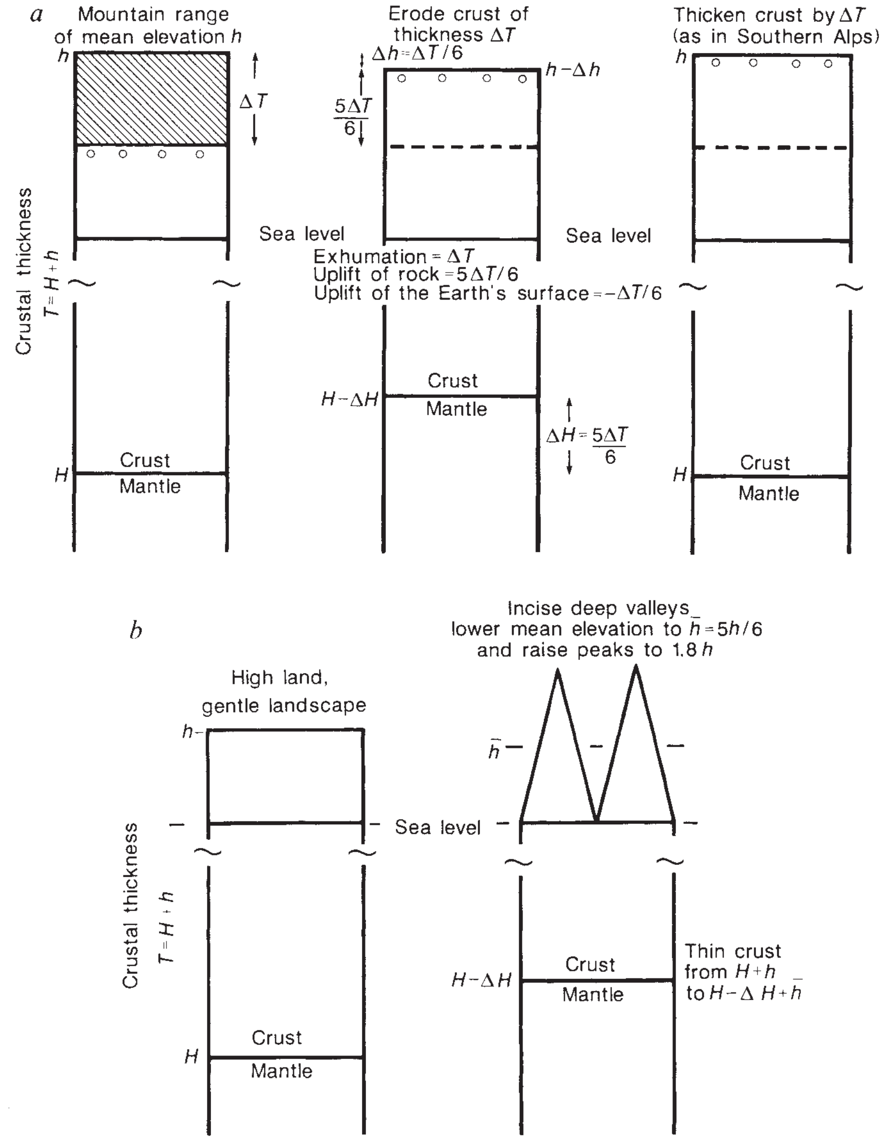

FIG. 2 Simplified crustal sections showing the effects of erosion and crustal thickening on mean elevation, depth of the Moho (the crust/mantle boundary) and uplift of rock. *a*, Imagine a mountain range (left) of mean elevation *h*, depth to the Moho *H* and crustal thickness $T = H + h$, and allow a thickness of crust ΔT to be eroded. By isostasy, the mean elevation should decrease by $\Delta h \approx \Delta T/6$, and the underlying rock, including the Moho, should rise by $5\Delta T/6$ (centre). Hence, an exhumation of ΔT yields uplift of rock of $5\Delta T/6$, but a lowering of mean elevation of $\Delta T/6$. Only if, simultaneously, tectonically caused crustal thickening at depth replaces the thickness of crust, ΔT, lost by erosion, will the mean elevation and the depth to the Moho remain constant (right). This is what seems to be happening in the Southern Alps of New Zealand[50] (see text). *b*, Similarly, if a gentle highland of mean elevation *h* (left) were deeply incised by rivers that eroded valleys nearly to sea level (right), the mean elevation should drop slightly to about $5h/6$, the remaining rock and Moho would rise by an amount equal to *h*, and the highest peaks would be much higher than before. In this way, a climatically induced increase in erosion rate can cause exhumation of rocks, and hence the appearance of uplift, with no increase (in fact, with a decrease) in mean elevation.

changes) provide a direct measure of the uplift of the rocks concerned. But the heights of such terraces would equal the change in mean elevation of the terrain only if no material had been removed by erosion. The uplift of such terraces could be caused entirely by tectonic processes, if there were no erosion, or entirely by isostasy, if the uplift of these rocks were merely the isostatic response of the terrain to the removal of material by erosion.

Evidence used to infer recent uplift

We contend that many inferences of recent uplift of mountain ranges are based not on measures of uplift of the Earth's surface, but on estimates either of uplift of rocks or of exhumation[28]. Furthermore, some of the phenomena used as indicators of uplift could in fact be caused by climate change. An abrupt change in climate, as seems to have occurred at ~15 Myr[22], and as clearly occurred at ~2.5 Myr[23], is likely to affect the rate at which the landscape evolves. An increase in alpine glaciation will incise and denude high terrains, and changes in precipitation are likely to affect erosion rates. We suggest that a change towards a cooler and stormier climate could be responsible for the geomorphological evidence ('youthful landscapes') often used to infer recent uplift. Similarly, increased denudation and exhumation should yield an increase in the rate of coarse terrigenous sedimentation, a phenomenon also often attributed to uplift. Finally, global cooling has contributed to the change in mountain flora from warmth-loving species to those characteristic of cooler environments—palaeobotanical evidence that is commonly taken to indicate recent uplift of the fossil material relative to sea level.

Geomorphology. One of the observations commonly used to infer recent uplift is the sharp incision by streams and rivers into gentle surfaces mantled by late Cenozoic sediment. It is a basic tenet of geomorphology that the uplift of a surface with respect to the base level of the streams provides the streams with increased potential energy and steeper gradients, leading to rapid incision of the surface.

Such observations comprise the primary evidence for de Sitter's[30] postulation of 2,000 m of Pliocene uplift of the Pyrenees and Alps, and 1,000 m for the High Atlas mountains. From incised erosion surfaces at 1,000–2,000 m on the north flank of the Pyrenees and an extrapolation to 3,000 m near the crest of the range, de Sitter inferred 2,000 m of uplift since the beginning of the Pliocene epoch. Similarly, Trümpy[31] reported that the Pliocene Alps were 'not more than a hilly tract', whereas now deep valleys near sea level separate ridges with crests rising to 4,000 m. Because the present mean elevation of the Alps is only ~2,000 m[32], however, de Sitter's[30] inferred uplift of 2,000 m could simply be the isostatic response to the removal of material by the incision of the deep valleys (see Fig. 2*b*). It is easy to imagine that global cooling enabled alpine glaciers to grow and to excavate deep valleys. We do not suggest that the Alps and Pyrenees underwent no erosion for tens of millions of years before 2.5 Myr, but rather that a change in the processes of erosion and an increased erosion rate reshaped the gentle early Pliocene landscape into jagged relief.

Like those in the Alps and Pyrenees, the major structures of the Rocky Mountains of Colorado, Wyoming and Utah formed in late Cretaceous and early Cenozoic time. Partly because a high erosion surface has been deeply dissected in late Cenozoic time, much of the present elevation of the Rockies is nearly unanimously assigned to the Pliocene and/or Pleistocene epochs[33–36]. But, as "glacial erosion was the chief cause of the destruction of the Eocene surface in the higher parts of the mountains" (ref. 35, p. 244), here too, climate change should be considered as a contributor to accelerated erosion rates, and the appearance of recent uplift.

Sedimentation. Widespread rapid denudation manifests itself not only by the exhumation of rock, but also by an increased rate of deposition of sediment, near or far from the exhumed terrain. Thick deposits of late Cenozoic conglomerate surround most steep mountain ranges, and the large cobbles that comprise conglomerate imply transport along steep slopes. Thus, "tectonic activity is commonly held responsible for abrupt coarsening of alluvial fan sequences"[37]. Potter[38] used this argument to infer late Tertiary uplift of the southern Appalachians. Another of the arguments for recent uplift of the Rocky Mountains derives from the presence of thick late Cenozoic conglomerate near them[33,34,39]. Uplift of one block with respect to another can cause steep gradients, but, as Blackstone[33] noted for one basin in the Rockies, climate change also can affect the potential for streams to transport large cobbles. As Frostick and Reid[37] pointed out, infrequent but large storms can produce the abrupt coarsening of fanglomerate stratigraphy that is commonly attributed to tectonic processes.

Accelerated denudation is also revealed by sediment accumulation far from mountain ranges. Accumulation rates of pelagic sediment in the Atlantic, Indian and Pacific oceans in late Cenozoic time exceeded those for the rest of that era[40], with a four- to fivefold increase[41] in the rate of terrigenous deposition since 5 Myr. Like Donnelly[42], we suspect that the rapid increase in sediment accumulation throughout the world is a consequence of climate change.

The deposition rate since 2 Myr in the Gulf of Mexico, and in particular in the Mississippi delta, has been roughly four times that for the previous 60 Myr (see Fig. 3), and Hay *et al.*[43] argued that most of this material has come from the Rocky Mountains. Using constant quantitative relations among elevation differences, rates of sediment transport, base level to erosion, and an assumed history of eustatic sea-level change, they calculated a large late Cenozoic uplift of the Rocky Mountains from this thick Quaternary sediment. Because sediment transport rates also depend on climate[44–46], however, a different relationship between sediment transport and elevation for late Cenozoic and earlier times would yield a different, perhaps negligible, inferred Quaternary uplift of the Rockies.

The rapid denudation of the Southern Alps of New Zealand, where a wealth of observations indicate rapid uplift of rock with respect to sea level[47–49], illustrates the relationship of uplift of rock to both denudation and tectonics. Adams[50] showed that the regional erosion rate, determined both from suspended sediment in streams and from sediment accumulations around the island, is comparable to the rate of uplift of rock. Thus, the isostatic response to the removal of material must be a major cause of the present uplift of the marine terraces. To see this, remember that for each 1 km of material removed from the range, the isostatic response is a lowering of the mean elevation by only ~0.17 km (Fig. 2). Thus, although in the steady state that Adams[50] deduced, tectonic processes seem to maintain a supply of rock to be eroded (by thickening the crust), nevertheless, if tectonic processes stopped, five-sixths of the uplift of rock would still occur. Oblique convergence between the Pacific and Australian plates[51,52] has occurred in the region of the Southern Alps since 10–15 Myr[50], but virtually all of the sediment in the basins surrounding the Southern Alps seems to be younger than 2.5 ± 0.5 Myr. Thus, the recent increase in the rates of sedimentation and erosion correlates well with the onset of 'Pleistocene' glaciation, at least as dated in the Northern Hemisphere[23], but not with any resolvable change in plate motion[51,52].

Palaeobotany. The main cause of the enormous variation in vegetation over the Earth is the variation in climate. Thus, to use palaeobotany as a palaeobarometer, one must first use it as an indicator of palaeoclimate and then relate that climate to an inference of what the climate would have been in the same region at sea level.

One palaeobotanical approach used to infer palaeoclimates exploits qualitative relationships between assemblages of different taxa and the climates that characterize their present environments[53]. One assigns the fossil plants 'nearest living relatives', and then finds a present-day environment that includes

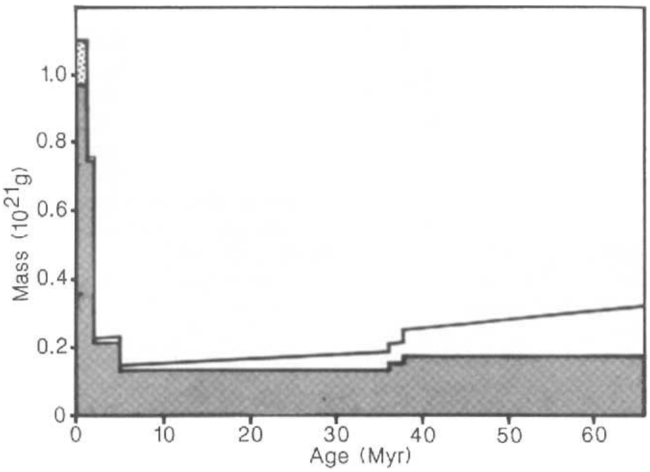

FIG. 3 Mass of Cenozoic sediment in the northwestern Gulf of Mexico and its drainage basin, between the Rocky Mountains and the Appalachians, as a function of the age of the sediment (from ref. 43). The blackened area shows existing sediment, minus an estimate by Hay *et al.* of the sediment transported by the Laurentide ice sheets from the Canadian shield in the past 1–2 Myr and deposited in this drainage basin. The line above shows their estimate of the sediment that was deposited and subsequently removed. Note that the huge increase in sedimentation at ~2 Myr correlates with the abrupt onset of widespread glaciation in the Northern Hemisphere[23].

as many of these relatives as possible. From the characteristics of that environment, one infers a likely palaeoclimate of the region[53]. The assignment of a nearest living relative is likely to be easiest for the most recent geological past; for Miocene and older times, a substantial fraction of the fossil species are extinct, and the conditions in which many of them lived must have been different from those of their descendants. For example, Axelrod[54] found that most of the nearest living relatives of fossil taxa from the Eocene Copper River formation in northeastern Nevada grow in either of two types of forest: coastal redwood forests, where elevations range from sea level to ~150 m, and fir-hemlock forests in the Sierra Nevada, at elevations of 1,400–2,400 m. Clearly, assigning a palaeo-elevation (or palaeoclimate) to such a fossil assemblage from present-day equivalents requires an element of subjectivity that makes the method qualitative at best[55].

Moreover, sometimes the taxonomic classification is based on parts of a plant, such as pollen, that can be relatively insensitive to climate change. Fossil pollen may have fallen from trees whose leaves and wood have since evolved to be adapted to a different climate, while the pollen remains similar. As an extreme analogy, imagine finding late Quaternary tusks in the Siberian Arctic, matching them to the nearest living relative, the elephant, and concluding that because elephants now live in hot, dry savannas at low latitudes, the present North Pole also lay at tropical latitudes in the late Quaternary era. Tusks are not adaptations to climate.

A second palaeobotanical approach to palaeoclimate ignores, insofar as is possible, the taxonomy of the fossil plants and simply uses what is known of how plants adapt to different climates. Using trees from eastern Asia, Wolfe[56] showed that the percentage of species having leaves with smooth, continuous margins ('whole margins') varies linearly with mean annual temperature, with a scatter of only 2 °C. The application of physiognomic characteristics to palaeoclimates is not without limitations[56], but climate changes inferred from the physiognomy of fossil plants have been corroborated. From leaf shapes, Wolfe[15,19,20] deduced an abrupt drop in temperature of several degrees in only a couple of million years near the Eocene/Oligocene boundary. Oxygen isotopes from the sub-Antarctic region near New Zealand later corroborated this rapid decrease in both surface and bottom water temperatures[16,21]. Using nearest living relatives, however, Axelrod and Bailey[57] inferred only a gradual change.

Virtually all attempts to use palaeobotany to infer palaeo-elevations have relied on taxonomy, not physiognomy. Moreover, many studies, such as those reporting recent uplift of the Tibetan plateau or the Himalayas[58-61], have ignored global climate change. Given that most of the Earth cooled during the late Cenozoic era[15-18], it is not surprising that palaeobotanical observations make it seem that mountain ranges have risen recently. For an average lapse rate of ~6 °C km^{-1}, a secular change in temperature of 6–9 °C since 5–15 Myr[16-18] could yield an erroneous inference of 1,000–1,500 m of uplift. Moreover, because environmental lapse rates tend to be lower than free-air lapse rates[62], such a change in mean annual temperature could lead to a larger error in inferred uplift. Thus, although both the Himalayas and Tibet rose in Cenozoic time, the palaeoclimatic inferences of an accelerating rise throughout Cenozoic time[58-61] (see Fig. 4) are likely to be exaggerated, if not simply false[28].

The Rocky Mountains provide another example of exaggerated, palaeobotanically determined, late Cenozoic uplift. MacGinitie[63] noted that many of the species from the early Oligocene Florissant flora in central Colorado could not be matched with present-day equivalents from any single, well defined forest; nevertheless, he inferred a relatively warm mean annual temperature of 18 °C and a palaeo-elevation of less than 915 m. The evidence for warm climates where early Eocene (Laramide) deformation had created mountain ranges is a common argument for low palaeo-elevations[39,64,65], and the palaeo-elevation of Florissant has provided a base level for estimates of subsequent uplift of the whole of the Rockies and the Great Plains[65]. Recall, however, that the late Eocene/early Oligocene climate was very warm—warmer than it has been since then[15-18].

Using the physiognomy of the fossil leaves of the Florissant assemblage, Meyer[66] inferred a mean annual temperature of 14 °C, not greatly different from MacGinitie's 18 °C. By comparing this with the likely warm early Oligocene sea-level temperature at the same latitude, however, and using an appropriate lapse rate and a 200-m difference between early Oligocene and present sea level, Meyer[66] inferred a palaeo-elevation of 2,450 m. Even if a smaller sea-level difference were used, this would be indistinguishable from the present elevation of 2,600 m. He also inferred a high palaeo-elevation of 2,800–3,500 m for the nearby Marshall Pass flora of roughly the same age, presently at 2,835–3,080 m. Moreover, from the physiognomic characteristics of the late Oligocene Creede flora, at 2,680 m in central Colorado, Wolfe and Schorn[67] inferred a mean annual temperature of 0–2.5 °C, which is virtually identical to the present mean annual temperature of 1.9 °C. Ironically, because Wolfe and Schorn[67] were prejudiced by the prevailing opinion that the Rockies rose only in late Cenozoic time, they suggested that the Creede flora were deposited in a basin where cold air could be trapped. Thus, Meyer's[66] and Wolfe and Schorn's[67] analyses, based on physiognomic characteristics of fossil plants and on differences in present and past climates, show that differences between past and present taxa should not be taken as evidence of low elevations in the western United States in mid-Cenozoic time and of a subsequent recent increase in the mean elevation of the Rockies.

Climate change and the appearance of uplift

The arguments above are intended to show that most estimates of late Cenozoic uplift of mountain ranges are exaggerated, at least if changes in mean elevation define uplift, and to suggest that much of the evidence used to infer recent uplift is a consequence of climate change. Most palaeobotanical inferences of recent uplift of the Earth's surface ignore global cooling, which biases these estimates upward. Inferences of changes in mean elevation from elevated geomorphic surfaces, increased denudation or increased sedimentation overlook the parts played by erosion, which depends on climate[44–46], and by isostatic rebound. Isostatic compensation of material removed by erosion will elevate the remaining terrain, but the uplift of ridges and peaks with respect to sea level does not necessarily signify an increase in mean elevation. Our attribution of the rapid erosion of mountain ranges in late Cenozoic time to climate change must remain a hypothesis, given that climate change can be very different in different places[13], that different types of local climate change can increase erosion rates[44–46], and that it is difficult to distinguish a local climate change due to global processes from one due to local uplift. Nevertheless, the same difficulties face the geologist trying to show that the recent rapid incision of a major mountain range is due to uplift, instead of global climate change.

The correlations of global climate change with the phenomena used to infer uplift offer some support for the idea that climate change is responsible for these phenomena. The physiognomy of Oligocene fossil plants from the Rocky Mountains[63,66,67] is consistent with the climates that would be expected at present elevations, if known global climate changes[15–18] are allowed for, but with lower elevations if that global cooling is ignored. Moreover, much of the deep incision of the erosion surface across the Rocky Mountains was due to glaciation[35]. In fact, most major mountain ranges thought to have risen in late Cenozoic time have been glaciated, and glaciation increased greatly as the Earth became cooler. The onset of rapid sedimentation in New Zealand at ~2.5 Myr[50], due to rapid erosion of the Southern Alps, correlates with the onset of late Cenozoic cooling and glaciation[23], but not with any obvious change in tectonics[51,52]. Finally, late Cenozoic uplift has been inferred for mountain ranges throughout the world, yet globally synchronous changes in plate motions, if they have occurred, have been small. Climate change, on the other hand, has been a global phenomenon.

Although the physical mechanisms by which global climate change might affect erosion rates could be different in different regions, several plausible processes are likely to have enhanced erosion. At relatively high altitudes or high latitudes, alpine glaciation is likely to be the dominant process of erosion, and global cooling surely enhanced glaciation. In the absence of glaciation, the principal "agents of erosion and transportation are the impact of raindrops and the surface flow of water"[46], but variations in precipitation can affect erosion in such extreme ways that one cannot assume that more precipitation would lead to more erosion, or vice versa. In some climates, increased precipitation can increase erosion, but in others, a decrease in precipitation can increase erosion, by reducing the amount of protective vegetation[68]. Whether global cooling led to increased or decreased precipitation is difficult to decide (see below) and likely to vary regionally.

The atmosphere is a thermal engine, which absorbs the Sun's energy in the tropics and transports it upwards and polewards as both sensible heat and latent heat in water vapour. Precipitation in middle latitudes is strongly affected by the ability of the atmosphere to transport humid air from the tropics to cooler higher latitudes. This transport is accomplished primarily by large-scale eddies generated by baroclinic instability[27], the same instability that makes the climate stormy. Two aspects of the temperature field affect the rate of transport: the strong temperature dependence of the saturated mixing ratio of vapour and dry air, and the latitudinal temperature gradient. The mixing ratio is proportional to $\exp(-L/RT) = \exp(-5{,}400/T)$, where L is the latent heat of vaporization, R is the dry-air gas constant, and T is temperature in degrees Kelvin[27]. The strong dependence of the mixing ratio on temperature makes cooler air much drier than warm air, implying that global cooling would lead to drier climates and less precipitation. The rate of transport, however, is also proportional to the square of the latitudinal temperature gradient. Thus, the inferred change from ~0.25 to 0.5 K per degree of latitude since early Cenozoic time[15] would yield a fourfold increase in latitudinal transport of moisture, but a decrease in mid-latitude temperature of 10 K would yield only a 1.8-fold decrease in water vapour transported. This kind of calculation, which ignores the reduced evaporation at middle latitudes at lower temperatures, is too imprecise to allow a definitive statement about changes in precipitation during Cenozoic time, but it emphasizes that global cooling would not necessarily reduce precipitation. More importantly, the increased latitudinal temperature gradient should have enhanced baroclinic instability, making the climate stormier. Annual erosion rates in many areas are dominated by a few storms[44,46]; thus, even if global cooling did lead to a drying, as some general circulation model runs suggest[69], the increased storminess could have increased net erosion.

Climate change and uplift: chicken and egg?

The temporal correlation of late Cenozoic glaciation with phenomena commonly ascribed to recent uplift is inescapable, but assigning the ultimate cause of late Cenozoic climate change to late Cenozoic uplift arising from tectonic processes is a hypothesis that we reject. Instead, we have suggested here that

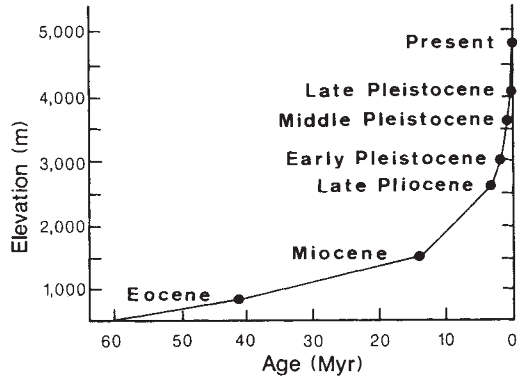

FIG. 4 Inferred history of uplift of the Tibetan Plateau and the Himalayas, based on palaeobotanical data largely from the north slope of the Himalayas. (Redrawn from ref. 60.) Fossil species whose nearest living relatives grow at relatively low elevations and in relatively warm climates were used to infer lower past elevations, but no account was taken of global cooling, as illustrated in Fig. 1. We show this as an example of inferred uplift, but we doubt that it is precise, or that it applies to all of the Tibetan plateau.

the phenomena commonly used to infer recent uplift are a consequence of climate change.

This is not to dismiss entirely the processes linking elevation and climate described by Birchfield, Kutzbach, Raymo, Ruddiman and Weertman[9-14]; indeed, there is evidence for their operation in a longer-term correlation (if only crude) of climate change with the growth of high terrain in the past 50 Myr[10]. There was no Tibetan plateau in late Cretaceous time, when marine limestones were being deposited in the region[70]. Moreover, because the present tectonic activity in Asia seems to be due to the collision of India withEurasia in Cenozoic time, the high mean elevation of much of the rest of eastern Asia was also probably acquired during Cenozoic time. Thus, the gradual cooling over the past 50 Myr might be the consequence of the tectonic processes that built Tibet, the Himalayas and other high terrains in Asia.

It follows that changes in mean elevation, climate change and the phenomena commonly used to infer uplift are coupled to one another. Although the physical mechanisms linking climate change to uplift should apply most strongly to regions where mean elevation has increased, they could also operate where crests of ranges have risen in response to erosion and isostatic rebound. This raises the possibility that climate change, weathering, erosion and isostatic rebound might interact in a system of positive feedback. Suppose increased weathering and erosion could enhance a negative 'greenhouse effect'[14]; then, if climate change accelerated erosion and weathering, the associated withdrawal of carbon dioxide from the atmosphere might cause further global cooling. Increased rates of erosion and isostatic rebound would alter the distribution of elevations by making the crests of ranges higher than before. The prolonged duration of winter and snow cover in such higher areas might lead to further reductions in temperature[11]. In addition, mountain ranges with high crests and deep valleys will perturb atmospheric circulation more strongly than those with the same mean elevation but lower crests. Thus, if the rise of crests of mountain ranges were to perturb the climate in such a way as to enhance erosion, isostatic rebound would cause a further rise, and further perturbations to the climate. By such feedback mechanisms, the gradual regional uplift of the Earth's surface in Asia, due to Cenozoic tectonics, might have led to an accelerating climate change and the illusion of accelerated uplift of mountain ranges throughout the world. □

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