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The elevation history of the Tibetan Plateau and its implications for the Asian monsoon

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Abstract

The determination of the evolving palaeoaltitude of the Tibetan Plateau since the India–Eurasia collision underpins our understanding of how orography in central Asia affects the intensity of the monsoon and hence global climate change. Palaeoaltitudes, however, cannot be measured directly and need to be inferred from proxy observations that are usually model-dependent. Differing tectonic models for the behaviour of the lithosphere during continental collision have contrasting implications for the elevation of the plateau. However, two techniques recently employed for determining palaeo-elevation are independent of tectonic models, the first involving the variation with altitude of oxygen isotopes in precipitation and the second involving the change of leaf morphology with moist static energy of the atmosphere.

Elevation studies have focused on southern Tibet, largely due to the relative ease of access to the region. There is a remarkable unanimity amongst the diverse techniques applied that the altitude of the southern plateau has not significantly changed since at least the mid Miocene (*ca.* 15 Ma) arguing for an onset of the monsoon system during or before the early Miocene. A range of tectonic studies suggest that the northern and eastern parts of the plateau are younger geomorphological features, but there are few quantitative constraints of the timing of elevation from these regions of Tibet. Since both the elevation and the surface area of the plateau impact on atmospheric circulation, palaeoaltitude studies need to be extended to chart the increasing areas of elevated land surface through time.

Keywords: Tibetan Plateau; Monsoon; Palaeoaltitude; Climate change

1. Introduction

The Tibetan Plateau, with an area of over 2.5 million km^2 at an average elevation of over 5 km, is the largest and highest mountain plateau on Earth. Its global significance does not lie simply in its physical parameters, but more importantly in the recognition that the plateau constitutes a significant forcing factor on the intensity of the Asian monsoons (Kutzbach et al., 1989; An et al., 2001; Liu and Yin, 2002).

Uplift of a large mountain plateau has both physical and chemical effects. A broad uplifted Tibetan Plateau provides a source of heating in the lower atmosphere during the summer, that creates a vast, low-pressure system over central Asia, drawing in warm and humid air from the Indian Ocean towards the plateau (Webster, 1987). Because of the geometry of normal Hadley circulation, this effect is particularly marked for an elevated heat source at 30–35° N, the latitude of Tibet (Molnar et al., 1993). Airflow is forced upwards when it impinges

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on the physical barrier of the Himalaya along the southern edge of the plateau, causing intense monsoon precipitation on the southern slopes.

The resulting run-off feeds large Asian rivers such as the Ganges, Indus, Sutlej and Brahmaputra that rise on the Tibetan Plateau and flow south through the Himalaya (Fig. 1). The monsoon system also feeds the rivers of southeast Asia, such as the Salween, that descend off the eastern margin of Tibet. The enormous flux of detrital material carried by these rivers is represented by the huge volumes of sediments deposited in the submarine fans of the Bay of Bengal and the Arabian Sea; the Bengal Fan alone constitutes the world's largest submarine fan system covering an area of 200,000 km^2 (Alama et al., 2003). Other rivers that rise in eastern Tibet, such as the Mekong, the Changjiang and the Huanghe, flow eastwards to debouch into the East and South China seas. An important consequence of the combined mechanical weathering from these vast river systems is the burial of large masses of organic carbon, sequestering carbon from the reservoir available for recycling between atmosphere and surface, and so forcing a cooling trend on global climate (France Lanord and Derry, 1997).

Mechanical erosion resulting from monsoon precipitation is accompanied by chemical dissolution, and causes large chemical fluxes from Tibet and the Himalaya to the oceans. Despite the fact that the Tibetan Plateau makes up less than 5% of global land area, rivers that rise in this region contribute a quarter of all the dissolved matter transported to the oceans by rivers worldwide (Palmer and Edmond, 1992). Consequently these rivers are responsible for extremely high silicate weathering fluxes (Gaillardet et al., 1999). Chemical weathering of silicate rocks is a major sink for atmospheric CO_2 and hence uplift of Tibet, if linked to enhanced silicate weathering fluxes, provides a possible explanation for long-term global cooling during the Cenozoic (Ruddiman and Kutzbach, 1989; Raymo and Ruddiman, 1992). However, the temperature dependence of dissolution reactions moderates the effects of mountain uplift on reduction of CO_2 from the atmosphere. The efficacy of this feedback mechanism is supported by the limited range of surface temperatures maintained over geological history (Berner et al., 1983; Caldeira et al., 1993). Although there is continuing debate concerning quantitative estimates of CO_2 fluxes resulting from the uplift of Tibet and the Himalaya, some current models suggest that average temperatures in a world without a large elevated plateau in Central Asia would probably be warmer by about 1–6 °C (Bickle, 2002).

This paper presents a review of the diverse methods that have been employed to determine the elevation history of the plateau, and a discussion of how the uncertainties inherent in such methods affect our understanding of the linkage between surface uplift and climate.

2. Tibet and the monsoon

In order to understand the nature of the coupling between climate and tectonics it is necessary to establish the history of the Asian monsoons in some detail. This is particularly true given the distinction between the effects of plateau uplift on the East Asian and on the Indian monsoon systems (Liu and Yin, 2002). However, there is no simple direct method for measuring past monsoon intensity whether this is defined as differences in winter and summer average wind direction, as differences in winter and summer average temperatures or in terms of summer precipitation. Consequently there remains much debate concerning the timing of the onset of the monsoon and its subsequent variations in strength.

Ramstein et al. (1997) have linked the drying up of shallow seas north of present-day Tibet during the Oligocene to the onset of the monsoon system. Dating of loess deposits in China attests the strength of winter monsoon winds as far back as 22 Ma (Guo et al., 2002). Sedimentation rates deduced from seismic profiles from the South China Sea (Clift et al., 2002) suggest an active monsoon by the early-mid Miocene (11–16 Ma) and stable-isotope studies also from the South China Sea indicate changes in terrestrial ecosystems at this time that can be related to the evolution of East Asian monsoon (Jia et al., 2003). Using isotopic compositions of shells from sediments deposited in the Himalayan foreland basin, Dettman et al. (2001) suggested a strong Indian monsoon before 10.7 Ma and that after 7.5 Ma the climate became significantly more arid. In contrast, other studies argue the Indian and East Asian monsoons were initiated as recently as 8–9 Ma (An et al., 2001). Despite these different interpretations, there is general consensus for a dramatic change in the character of the monsoon system about 6–8 Ma, as indicated by faunal evidence for increased upwelling in the Arabian Sea (Kroon et al., 1991), by an increase in chemical weathering intensity as inferred from clay mineral fractions recovered from the Bengal Fan (Derry and France Lanord, 1996) and by an ecological shift observed in northern Pakistan (Quade et al., 1989), although the significance of the last study for the monsoon has been questioned (Cerling et al., 1997). Renewed strengthening of the East Asian monsoon has been suggested during the Pliocene, 2.6–3.6 Ma ago (An et al., 2001).

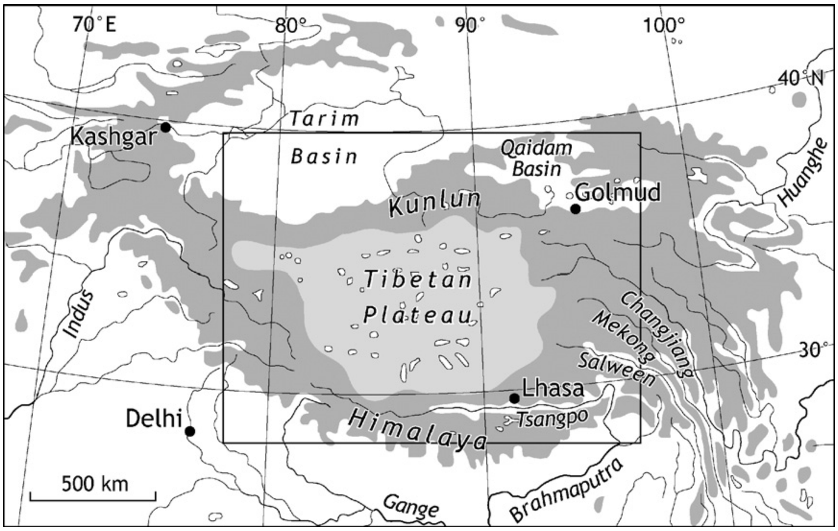

Fig. 1. Topography and drainage of the Tibetan Plateau. Shaded region indicates altitude over 3000 m; pale shading indicates extent of internal drainage basin. Rectangle shows location of Fig. 2.

Despite the complexities of unravelling the history of the monsoon, several studies have sought to correlate episodes of plateau uplift with changes in the strength of the monsoon. For example, evidence for the late Miocene strengthening of the Indian monsoon (6–8 Ma) has been linked to tectonic activity in southern Tibet (Harrison et al., 1995) and Pliocene strengthening of the East Asian monsoon (2.6–3.6 Ma) has been associated with uplift of the northern plateau (Zheng et al., 2000). However, Tibetan tectonics is not the only forcing factor on the monsoon intensity. It has been argued that the apparent late Miocene increase in monsoon intensity is not linked to the uplifted plateau but reflects strengthening wind regimes in response to global cooling and the consequent increase in the polar ice volumes (Gupta et al., 2004). These authors argued that this hypothesis is supported by the disparity between differing estimates of the timing of Tibetan uplift.

3. Pre-collision Tibet

Elevation changes of the Tibetan Plateau are ultimately driven by the Eocene collision between the Indian and Asian plates (*ca.* 50 Ma) and their continued convergence. One goal of research into Tibetan tectonics is to chart the elevation of the plateau through time from collision to present day. Unfortunately, the only certain point in this trajectory remains the present-day altitude. Indeed, it can not even be assumed that Tibet had negligible relief prior to collision since structural studies suggest that the surface of the southern plateau had already achieved significant altitudes prior to collision (England and Searle, 1986; Murphy et al., 1997). The presence of Late Cretaceous-Palaeogene marine deposits in southern Tibet suggests that at least some of the region was at sea level around the time of collision (Zhang et al., 1998). Given that the Transhimalayan arc is indicative of considerable relief prior to collision along the active continental margin of Asia (see G_3, Fig. 3), it seems unlikely that uplift of Tibet to form a large plateau, with relatively minor internal relief (Fielding, 1996), occurred as a single event. This review will focus on the uplift history of southern Tibet, the site of the majority of relevant studies on Tibetan uplift (Fig. 2), and return, in a later section, to the question of diachroneity during the elevation of the plateau.

4. Elevation of southern Tibet

There are three lines of enquiry that have been invoked to assess palaeo-elevations in southern Tibet; those derived from modelling the physical behaviour of the deforming lithosphere, those that link the unroofing rates to changes in surface elevation and those that exploit physical properties that are directly related to altitude.

4.1. Geodynamic models

Geodynamic models for lithospheric thickening and the uplift of Tibet can provide a basis for evaluating elevation histories. During the 1980s, a commonly held assumption was that all shortening between India and Asia had been accommodated by crustal thickening (e.g.

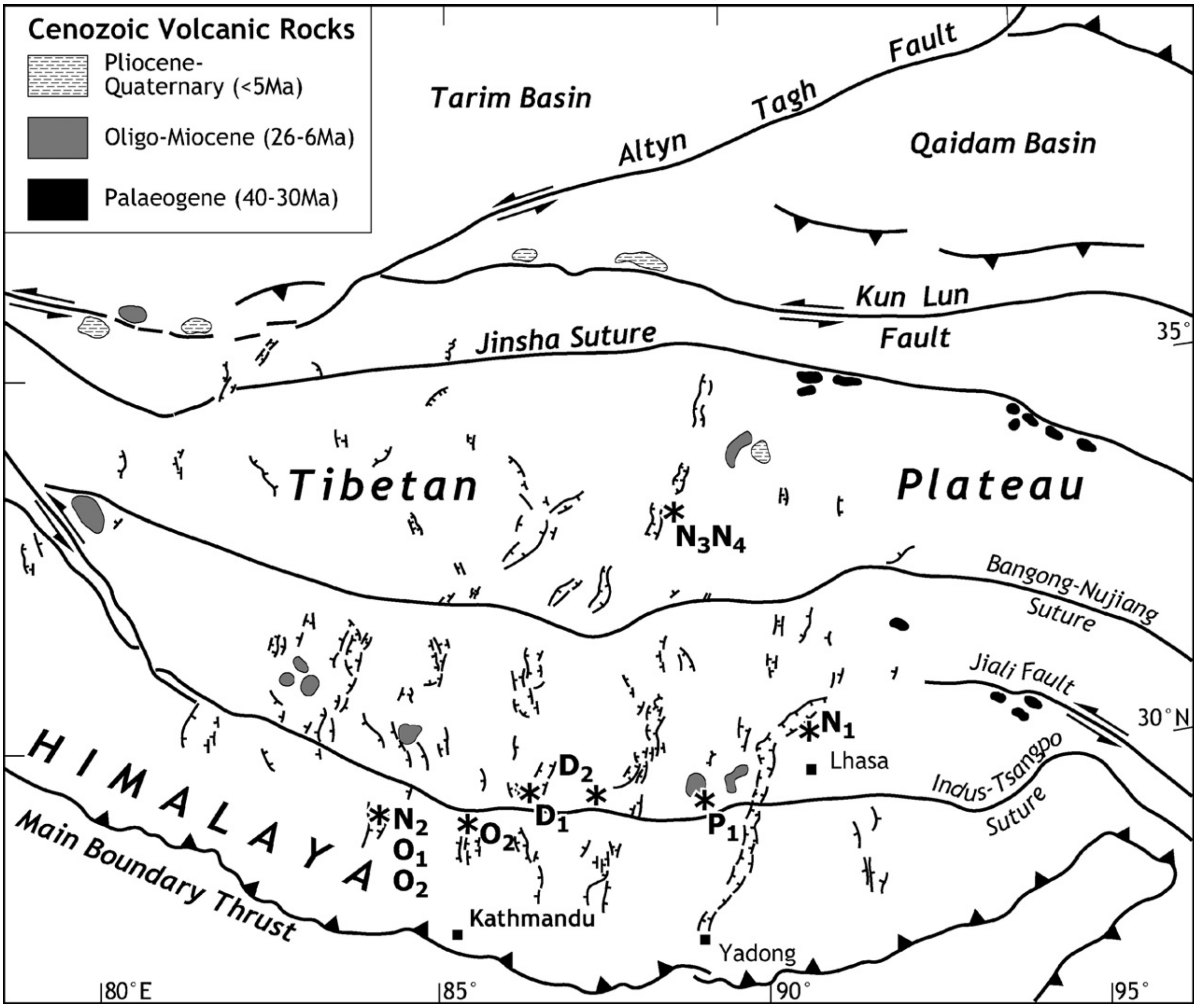

Fig. 2. Tectonic map of the Tibetan Plateau, indicating localities of site-specific palaeoaltitude studies discussed in the text. Distribution of Cenozoic magmatism for which dates are available are shown as fields; sources from Chung et al. (1998), Williams et al. (2003) and references therein. Sources of palaeoaltitude studies as follows. Normal faults; N_1 = Harrison et al. (1995), N_2 = Coleman and Hodges (1995), N_3 = Yin et al. (1999), N_4 = Blisniuk et al. (2001). Dykes, D_1 = Williams et al. (2001). Oxygen isotope studies; O_1 = Rowley et al. (2001), O_2 = Garzione et al. (2000a,b). Palaeobotany site; P_1 = Spicer et al. (2003).

Zhao and Morgan, 1985). Such an approach, coupled with additional assumptions regarding the proportion of crust removed by erosion, allowed the uplift history to be modelled from available plate tectonic reconstructions (see G_1, Fig. 3). However, this method takes no account of the possibility of lateral spreading of the crust, of escape tectonics along the strike-slip system of northern and eastern Tibet (Leloup et al., 1995), nor of the possibility that the base of the lithosphere has been modified by mantle processes (Molnar et al., 1993).

A more sophisticated geodynamic model resulted from the recognition that lithospheric thickening results largely from continuous thickening and widespread viscous flow of crust and mantle (England and Houseman, 1988). The model predicted that following a period of gradual thickening and isostatic uplift, mantle convection will trigger convective thinning of the base of thickened lithosphere (England and Houseman, 1989; Platt and England, 1994). The isostatic response to this event is rapid uplift until the plateau reaches an elevation that cannot be supported by marginal stresses. A transition from compressional to extensional deformation is predicted, in response to the dissipation of potential energy following plateau uplift (Molnar et al., 1993). Linkage between uplift and E–W extension is supported by the observation that seismicity with normal fault-

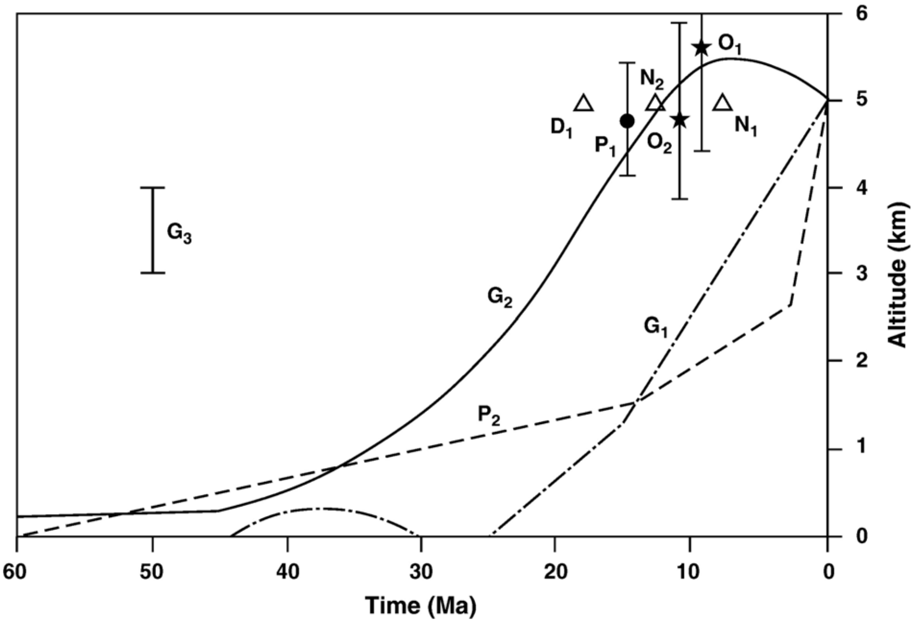

Fig. 3. Estimates of the altitude of the surface of the southern Tibetan Plateau deduced from studies discussed in the text. Filled symbols indicate quantitative palaeo-elevation estimates (with uncertainties). Other proxies assume a present-day altitude of 5 km. Lines trace proposed elevation histories from indicated source. G_1 = Zhao and Morgan (1985), G_2 = Fielding (1996), G_3 = Murphy et al. (1997), P_2 = Xu (1981). Other sources as for Fig. 2.

plane solutions is characterised by epicentre elevations that are greater than 4000 m above sea level (Molnar et al., 1993). This extensional phase is marked by north-striking normal faulting (Fig. 2). Based on such a model for the uplift of Tibet, and constrained by a range of geological data available at the time, Fielding (1996) proposed an uplift history that traces an increasing rate of elevation from collision until about 8 Ma, followed by plateau collapse to its present altitude (see G_2, Fig. 3). The mechanics of collapse has recently been examined by 3D finite-element modelling of stress and faulting patterns using a viscoelastic rheology; results predict E–W extension would be initiated when the plateau achieved about 75% of its present elevation (Liu and Yang, 2003).

If normal faults result from the plateau elevation exceeding that which can be supported by marginal stresses, then dating the time of initiation of these faults should provide the time by which that part of the plateau reached the threshold elevation. Extensional deformation, as evidenced by a system of N–S normal faults, has been dated at 7–9 Ma (Harrison et al., 1995; see N_1, Fig. 3). However, other normal faults (Fig. 2) have yielded older ages (>13 Ma, see N_2, Fig. 3) suggesting that the southern and central Tibetan Plateau has been an established geomorphological feature at least since the mid-Miocene (Coleman and Hodges, 1995; Blisniuk et al., 2001). There is also evidence for continued E–W extension during the Pliocene in central Tibet (Yin et al., 1999). It should be noted that E–W extension in southern Tibet has also been accredited to basal shear caused by India underthrusting southern Tibet (McCaffrey and Nabalek, 1998) and to collisional stresses localised along the southern part of the Himalayan arc (Kapp and Guynn, 2004). In either case, elevation of the plateau would be decoupled from extension. Indeed increasing elevation may be concomitant with extension as the Indian indenter progresses northwards.

Convective thinning of the mantle lithosphere will have thermal as well as mechanical consequences, resulting in the melting of the sub-continental lithospheric mantle and consequent shoshonitic magmatism (Turner et al., 1996). If the local eruptions of Neogene magmatism on the high Tibetan Plateau (Fig. 2) are a response to lithospheric thinning that in turn triggered the most recent phase of uplift, then the earliest period of such magmatism should date the event that is a direct cause of present-day elevation. A review of Neogene magmatism in Tibet placed this time at *ca.* 13 Ma in the southern part of the plateau (Turner et al., 1996). A subsequent study of a N–S dyke swarm in southern Tibet established that E–W extension followed the generation of shoshonitic magmatism derived from melting of the sub-continental lithospheric mantle

(Williams et al., 2001), consistent with plateau uplift resulting from convective removal of the base of the lithosphere. This implies that the crust was undergoing extension by the age of the dyke swarm (18.3±2.7 Ma) by which time, it was argued, the plateau of southern Tibet had reached sufficient elevation to have attained excess potential energy (see D_1, Fig. 3). Since these dykes were emplaced *ca.* 8 m.y. after the earliest dated shoshonitic lava flows in southern Tibet (Miller et al., 1999), it is possible that this phase of plateau uplift was initiated even earlier, perhaps by 25 Ma. A review of the Tertiary magmatism of Tibet (Williams et al., 2003) concludes that in both northern and southern Tibet melts are sourced from the sub-continental lithospheric mantle. In the south, earliest magmatism at *ca.* 25 Ma, precedes east-west extension by 7 m.y., whereas in the north earliest magmatism at *ca.* 19 Ma, precedes east-west extension by 5 m.y. (Williams et al., 2003). The tentative conclusion drawn from these data is that convective thinning resulted in melting of the sub-continental lithospheric mantle, initially beneath southern Tibet, and more recently beneath northern Tibet. Magmatism was followed, over a timescale of 5–7 m.y., by elevation of the plateau and consequent E–W extension. However, the proposed links between magmatism and tectonics are model-dependent, and an alternative view argues that break-off of the subducted Indian lithosphere may be responsible for Neogene magmatism in southern (though presumably not northern) Tibet (Mahéo et al., 2002). If true, then magmatism and surface uplift are decoupled, undermining this approach for predicting the elevation history of the plateau.

The simple correlation of high-K magmatism with uplift is particularly hazardous if not linked to an understanding of both the associated stress regime and the specific source region for the melt. One study has concluded that the southeastern margin of Tibet was uplifted 30–40 Ma, before uplift of the rest of the plateau (Chung et al., 1998), on the basis of the distribution of Palaeogene, high-K magmatism. Without detailed geochemical modelling of their source it could equally be argued that such melts are controlled by deep crustal fractures that have been reactivated during the development of pull-apart basins on the southeastern margin of the plateau (Leloup et al., 1995), hence the spatial association between Palaeogene magmatism and major strike-slip faulting (Fig. 2).

The tectonic and igneous proxies for elevation change described above are underpinned by the thin viscous sheet model for the behaviour of continental lithosphere during thickening. However this remains controversial, and a competing model argues that the elevation of the plateau resulted from time-dependent localised shear between coherent lithospheric blocks (Tapponnier et al., 2001). The thin viscous sheet model has also been criticised for ignoring changes in mechanical behaviour of crustal material at depth (Royden et al., 1997). A recent thermo-mechanical model for the evolution of the Himalaya–Tibetan orogen considers the effect of a decreased viscosity in the mid-crust through internal heating, resulting in the gravity-driven southward extrusion of an orogenic channel (Beaumont et al., 2001). This model predicts that the topographic rise of Tibet will develop initially by elevation of the surface proximal to the suture. This linear elevated region, which was modelled to rise to the present elevation of the plateau within 12 m.y. of the collision, is predicted to propagate outwards, both northwards across Tibet, and southward towards the Himalaya, as the mid-crust becomes hot and weak.

4.2. Unroofing and uplift

Uplift is a term that is employed rather loosely in different contexts, but whether inferred from sediment erosion, isotopic cooling ages, fission track dating or cosmogenic isotope, it is the exhumation (or unroofing) rate that is obtained, not the surface uplift. The controls on exhumation of the crust are complex, involving topography, active tectonics and precipitation. None of these is necessarily directly related to surface uplift. These variables are related by the relationship:

$$\text{Surface uplift} = \text{uplift of rock} - \text{exhumation}$$

as discussed by England and Molnar (1990). Hence without some knowledge of the uplift rate of the rock, exhumation rates yield no quantitative information on surface uplift rates.

An absence of significant erosion across most of the plateau has inhibited the use of mineral thermochronometers in charting the cooling history of the exposed rocks on the plateau surface. However, deeper crustal levels are exposed within the Transhimalayan batholith along the southern margin of the plateau, and it has been inferred from Ar–Ar mineral cooling ages that the rocks of the southern plateau experienced rapid exhumation during the early Miocene (Copeland et al., 1987; Harrison et al., 1992). This however does not constrain the change in surface elevation.

The nature and volume of detritus being deposited within the Indian foreland basin, or offshore in submarine fans, are directly related to the unroofing rate of the orogenic belt from which they are derived. The sedimentary records preserved in both the foreland basin of northern India and in the Indus and Bengal fans have been recovered back to the early Miocene (France Lanord et al., 1993; Clift et al., 2001). In both depositional environments there is an increase in sediment-accumulation rates at 15–20 Ma (Clift et al., 2004) and a subsequent decrease after 7–8 Ma (Burbank et al., 1993; Einsele et al., 1996). However, as discussed above, unroofing rates can not be simply correlated with surface elevation. It is unsafe to assume that climate is unchanging during uplift, not least because plateau elevation will have a direct effect on precipitation, flora and on surface temperature. For example, the late Miocene decrease in mechanical weathering could result from decreased glaciation in southern Tibet, or from slope stabilisation from dense plant cover (Burbank et al., 1993).

Whilst eastern Tibet is subject to erosion by the great rivers of east Asia, the sediment fluxes observed south of the Himalaya will be dominated by Himalayan sources rather than erosion of the Tibetan Plateau (France Lanord et al., 1993; Galy et al., 1999) and so are not likely to yield useful information on the surface elevation of southern Tibet that lies to the north of the Himalaya. Indeed, cosmogenic ^{10}Be exposure histories of *in-situ* bedrock surfaces from the large area of internal drainage that forms the interior of the Tibetan Plateau (Fig. 1) indicate particularly low erosion rates of <30 mm/ka in southern and central Tibet over the past 150 ka (Lal et al., 2003), a reflection of the extreme aridity of the climate during this period.

4.3. Altitude proxies

Quantitative palaeoaltimetry requires the exploitation of a physical variable that is directly dependant on the elevation of the surface on which it is measured. One such property is the change in oxygen isotope composition (δ^{18}O) of precipitation. This approach has been calibrated both empirically (Garzione et al., 2000a) and by assuming that equilibrium isotope fractionation during Rayleigh distillation is linked to the thermodynamics of atmospheric ascent and water vapour condensation (Rowley et al., 2001). An empirical oxygen-isotope study concluded that by *ca.* 11 Ma the southern edge of the Tibetan Plateau had reached present-day elevations (O_2, Fig. 3, Garzione et al., 2000b). By applying an isotope-elevation calibration to δ^{18}O analyses of upper Miocene carbonates from southern Tibet it was concluded that present altitudes had been achieved, to within an uncertainty of about 1400 m, by about 10 Ma (O_1, Fig. 3, Rowley et al., 2001). This technique was criticised by Shuguia et al. (2003) on the grounds that Rayleigh distillation provides an idealised model that assumes the immediate removal of precipitation. They argued that convective conditions are more appropriate, particularly for the monsoon system, and these yield weaker isotope-elevation gradients which would lower the predicted altitude. In order to apply this technique over a wider range of environments, more refined calibrations are required, as acknowledged by the reply of Rowley et al. (2003), but this approach clearly has great potential for future palaeoaltitude studies.

Palaeobotany provides an alternative potential proxy with both species and leaf morphology varying in response to altitude. Since the 1980s Chinese palaeobotanists have been estimating altitudes from fossilised leaf fragments, largely by correlations with the nearest-living relative of the species concerned. For example Xu (1981) charted a gradual elevation rise in the elevation of southern Tibet until the Late Pliocene, followed by a rapid increase. According to this study, by 10 Ma southern Tibet lay at a height of only *ca.* 2000 m (P_2, Fig. 3), a conclusion at variance with every recent published study on Tibetan elevation. The apparent precipitously steep rise is probably a consequence of ignoring the effect of global climate change. A decrease in precipitation and temperature in southern Tibet over this timescale should lead to changes in plant species at specific altitudes.

Rapid developments in palaeobotanical studies have revolutionised the accuracy and the precision of estimates derived from leaf fossils, exploiting the relationship between leaf physiognomy and properties of the atmosphere related to altitude using the Climate Leaf Analysis Multivariate Program (CLAMP). The technique rests on a strong correlation between leaf morphology and moist static energy (MSE), a thermodynamically conserved parameter of the atmosphere that incorporates temperature and humidity, both critical variables for plant growth (Wolfe, 1993). Although empirical, this relationship appears to be robust throughout the Tertiary (Wolfe, 1973), in part because leaf physiognomy has a basis in convergent evolution constrained by the laws of physics and in part because the relationship between leaf morphology and climate is not subject to diagenetic modification. To convert estimated values of MSE into palaeoaltitudes it is necessary to invoke a global climate model to estimate the MSE at known altitudes during the Miocene. By applying the CLAMP methodology to Neogene floras from southern Tibet, Spicer et al. (2003) obtained altitude constraints (4689 ± 795 m and 4638 ± 744 m) that were derived from well-preserved, precisely dated (15.10±0.49 Ma to 15.03±0.11 Ma), leaf assemblages recovered from the Namling Basin, southern Tibet (P_1, Fig. 3). These data imply that the elevation of the southern plateau has remained unchanged (within 800 m) over the past 15 m.y. They also imply that at 15 Ma the plateau of southern Tibet was thickly forested which would itself have impacted on the mid Miocene climate.

Samples of pedogenic carbonates have now been recovered from the same section as provided the Namling flora (Currie et al., 2005). Model results from $\delta^{18}O_{cc}$ data, using the method of Rowley et al. (2001), indicate an elevation of 5200+1370/− 605 m at 15 Ma, identical, within the quoted uncertainties, with the value determined from fossil leaf physiognomy.

Recently it has been suggested that plants could provide a direct indicator of altitude through the correlation between stomatal density in leaves and CO_2 partial pressure (McElwain, 2004). Although this approach has the advantage of being independent of global climate models, it is unclear how useful the technique will be in interpreting the fossil record given that the correlation is strongly species specific and so its application would be restricted to fossil floras comprising extant species.

5. Diachronous uplift

Sudden climate changes imposed by orographic evolution are probably triggered by threshold conditions being reached (Molnar et al., 1993), but it remains uncertain that it was the *altitude* of southern Tibet that provided a threshold for monsoon intensification. There is now considerable evidence that by the mid Miocene the plateau, at least in the south, had already been stabilised near present elevations for several million years, yet this period marks a phase of marked change in the monsoon system. Because the monsoon is driven by the effects of summer heating imposed by the uplifted surface on the troposphere, both elevation and the surface area of the plateau are significant for the intensity of the effect on atmospheric circulation. This poses a new question; prior to 15 Ma, what *area* of the plateau had been uplifted to present elevations? If uplift was diachronous, either in an E–W or a N–S sense, this would have a critical effect on the heating effect of the troposphere and therefore on the monsoon.

5.1. East–West diachroneity

It cannot be assumed that the India–Asia collision was a strictly orthogonal impact, acting simultaneously along the entire length of the Himalayan arc. Sedimentological and structural data suggest that suturing of the collision zone decreased in age eastwards from *ca.* 52 Ma to *ca.* 41 Ma (Rowley, 1996). Indeed across the Himalaya from Zanskar (NW India) eastwards to Bhutan (a distance of 1500 Ma) there is a progressive decrease in $^{40}Ar/^{39}Ar$ cooling ages from 22–18 Ma to 13–11 Ma suggesting that exhumation of the Himalaya may have propagated from west to east (Guillot et al., 1999). If this reflects oblique collision, resulting in the anticlockwise rotation of India following initial impact, then it is reasonable to infer that early uplift relating to collision may have initiated in the south-west of the plateau propagating eastwards as convergence continued. However, a study of detrital zircons across the southern Himalaya limits any such diachroneity between Zanskar and western Nepal to less than 2 m.y. (DeCelles et al., 2004).

Detailed geomorphological observations on river capture and reversal are linked to surface uplift, although linking such observations with quantitative constraints on uplift rates is more problematical. South-eastern Tibet is characterised by a low-gradient margin across which an elevation rise of 5 km is distributed over 1500 km. Rivers such as the Changjiang (Yangtze) that flow eastwards off the plateau do not cut through the Himalaya but drain into the East China Sea (Fig. 1). Geomorphic observations on these fluvial systems, coupled with U–Th/He and fission-track dating of river gorges, constrain incision rates that arguably provide a proxy for uplift of the eastern side of the plateau (Schoenbohm et al., 2004; Clark et al., 2004) although climatic variation must also contribute. Using this approach it was concluded that the margins of eastern Tibet were being actively incised, and by implication uplifted, between 7 and 13 Ma (Clark et al., 2003) and that *ca.* 2 km of surface uplift of the eastern plateau took place within the past 10–30 Ma. The greater part of this uplift (*ca.* 1.5 km) occurred since Pliocene times (Schoenbohm et al., 2004). If true, then the geomorphology of the southern plateau appears to have been growing eastwards from a central nucleus since the mid Miocene. It has been suggested that the large-scale morphology of eastern Tibet is a response to eastward fluid flow in the lower crust (Clark and Royden, 2000).

5.2. North–South diachroneity

The elevation history deduced for southern Tibet probably does not apply further north. Nearly all geodynamic models of the Tibetan orogen predict that initial elevation close to the suture will propagate northwards through time. There is a difference though between models that see this as a continuous process (e.g. Clark and Royden, 2000; Beaumont et al., 2004; Zhang et al., 2004) and those that consider the Tibetan crust to have behaved as a composite, rather than a unified structure (e.g. Tapponnier et al., 2001). The latter study provides a review of Cenozoic deformation, magmatism and seismicity and concludes that the Tibetan lithosphere has been uplifted as three time-dependent blocks; south Tibet was elevated during the Eocene, central Tibet in the Oligo-Miocene and northern Tibet in the Plio-Quaternary. A differing time frame has been obtained from finite-element modelling of deformation in the Tarim Basin, constrained by the sedimentary record. This concluded that the western Kunlun (northern Tibet) was initially uplifted during the Oligocene and was subjected to accelerating uplift since the Late Miocene, *ca.* 10 Ma (Yang and Liu, 2002). A northward younging in E–W extension across the plateau has been noted by Williams et al. (2003). Indeed several lines of evidence indicate that the post-Miocene tectonic history of northern Tibet is more active than those found in the south of the plateau, including (i) SCLM-derived Quaternary shoshonitic volcanism (Fig. 2) that is restricted to the northern edge of the plateau (Turner et al., 1996; Williams et al., 2003); (ii) sedimentological evidence for major uplift during the Pliocene (<4.5 Ma), possibly driven by climate change (Zheng et al., 2000); and (iii) magnetostratigraphic records from eolian clay deposited in northern China that identify Pliocene uplift surges in the Kunlun (Qiang et al., 2001). A recent oxygen-isotope study of carbonates from the NE margin of the Tibetan Plateau concluded that there is an increase in δ^{18}O values from $-10.5‰$ to $-9‰$ at *ca.* 12 Ma (Dettman et al., 2003). The authors interpret these data as evidence that the plateau had achieved sufficient elevation to block humid air-flow from the Indian Ocean to northern Tibet. The data do not, however, constrain the uplift of the northern plateau itself. Rather they suggest that a sufficient area of the plateau (or the Himalaya) had achieved a threshold altitude to effect the re-organisation of airflow. Overall, the scant observations from northern Tibet do suggest that uplift of the northern plateau may have been particularly rapid since at least the Pliocene. This inference clearly requires testing by quantitative palaeoaltitude proxies.

6. Conclusions

Present knowledge of palaeo-elevation histories is in its infancy. Further studies are clearly needed, particularly of central and northern Tibet, using more direct elevation proxies such as leaf morphology from dated, well-preserved and morphologically varied assemblages, or oxygen-isotope systematics from dated carbonate lithologies, in order to chart the distribution and area of uplifted plateau at a range of elevations throughout the Neogene. Only then may it prove fruitful to seek linkages between monsoon development and plateau uplift.

The conclusion that at least southern Tibet reached its present elevation by *ca.* 15 Ma is indicated by much of the proxy elevation data reviewed above (Fig. 3). The finding is consistent with (i) the inference from estimates of the past pH of surface-layer sea water that atmospheric CO_2 concentrations were significantly reduced during the Palaeogene, but have remained fairly constant over the past 20–25 m.y. (Pearson and Palmer, 2000), and (ii) the absence of evidence for major changes in pCO2 during the late Miocene based on the alkenone record (Pagani et al., 1999).

A pre-mid Miocene date for uplift of southern Tibet implies that ages on the initiation of individual normal faults may not necessarily record the time at which that part of the plateau reached maximum elevation. Indeed, given the structural complexity of the upper crust and the evolving stress field across the plateau through time it is likely that some faults were initiated long after maximum elevations were reached.

Present palaeoaltitude constraints do not support a specific link between the significant change in the character of the late Miocene monsoon at 6–8 Ma (Kroon et al., 1991; An et al., 2001) and elevation of the southern plateau. These results do however argue for the onset of the monsoon system prior to the mid Miocene as proposed by Ramstein et al. (1997), Clift et al. (2002), Guo et al. (2002) and Jia et al. (2003).

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