Constant elevation of southern Tibet over the past 15 million years

Robert A. Spicer*, Nigel B. W. Harris*, Mike Widdowson*, Alexei B. Herman†, Shuangxing Guo‡, Paul J. Valdes§, Jack A. Wolfe|| & Simon P. Kelley*

* *Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK*
† *Geological Institute, Russian Academy of Science, 7 Pyzhevskii Pereulok, 119017 Moscow, Russia*
‡ *Nanjing Institute of Geology & Palaeontology, Academica Sinica, Nanjing 210008, China*
§ *Department of Meteorology, Reading University, Earley Gate, PO Box 243, Reading RG6 6BB, UK*
|| *Desert Laboratory, Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA*

The uplift of the Tibetan plateau, an area that is 2,000 km wide, to an altitude of about 5,000 m has been shown to modify global climate[1–3] and to influence monsoon intensity[4–8]. Mechanical and thermal models for homogeneous thickening of the lithosphere make specific predictions about uplift rates of the Tibetan plateau[9,10], but the precise history of the uplift of the plateau has yet to be confirmed by observations. Here we present well-preserved fossil leaf assemblages from the Namling basin, southern Tibet, dated to ~15 Myr ago, which allow us to reconstruct the temperatures within the basin at that time. Using a numerical general circulation model to estimate moist static energy at the location of the fossil leaves, we reconstruct the elevation of the Namling basin 15 Myr ago to be 4,689 ± 895 m or 4,638 ± 847 m, depending on the reference data used. This is comparable to the present-day altitude of 4,600 m. We conclude that the elevation of the southern Tibetan plateau probably has remained unchanged for the past 15 Myr.

Our present understanding of the uplift history of the Tibetan plateau is limited by the absence of a technique that can measure surface elevation directly because, unlike exhumation and erosion rates, which can be inferred from a range of well-calibrated techniques, palaeoaltitudes can be deduced only from proxy observations. In particular, there remains great uncertainty concerning the altitude of the Tibetan plateau during Neogene times, a critical period in the development of the monsoon[11,12], with consequent implications for Cenozoic global cooling. Elevation changes of the Tibetan plateau are driven ultimately by the Eocene collision[13] and the continued convergence between the Indian and Eurasian plates. It has been argued from structural studies that the pre-collision surface of the southern plateau may have already achieved significant altitudes[14].

A synthesis of Cenozoic deformation, magmatism and seismic structure suggests that the plateau of southern Tibet may have been uplifted during the Eocene[15]. The presence of high-K magmatism sourced from the subcontinental lithospheric mantle[6] has been ascribed to delamination triggered by mantle convection[3,9]. Extensional deformation, which is evident from north–south normal faults and regarded as indication of sufficient plateau uplift to result in east–west spreading[3], has been dated at 7–9 Myr ago[5], coeval with changes in foraminiferal populations in the Indian Ocean[12] and in the $\delta^{13}C$ signature and sediment production of Himalayan molasse[4,11], all of which have been cited as proxies for the intensity of the monsoon.

Other normal faults have yielded older ages (>13 Myr ago), however, which suggests that the southern and central Tibetan plateau has been an established geomorphological feature since at least the Middle Miocene[16,17], a conclusion supported by stable-isotope palaeoaltimetry of Late Miocene (~10 Myr ago) north Himalayan carbonates[18]. It is also supported by a study of a north–south dyke swarm in southern Tibet, which established that east–west extension followed the generation of shoshonitic magmatism 18.3 ± 2.7 Myr ago (ref. 19). It is argued that by this time the southern Tibetan plateau had reached sufficient elevation to have attained excess potential energy after the convective removal of part of the subcontinental lithospheric mantle. But these proxies for altitude are strongly dependent on tectonic models of plateau formation.

Here we exploit the empirical relationship between leaf physiognomy and properties of the atmosphere related to altitude by using the climate leaf analysis multivariate program (CLAMP)[20,21]. Although empirical, this relationship seems to be robust throughout the Tertiary[21], 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. By applying the CLAMP methodology to Neogene Tibetan floras, we obtain the first estimate of palaeoaltitude for the Tibet plateau that is dependent on neither tectonic models nor stable-isotope systematics.

The Namling basin of southern Tibet (Fig. 1) comprises Neogene lava flows and shales with abundant plant-rich horizons interbedded with tuffaceous material unconformably overlying an Upper Cretaceous/Eocene volcanic basement. The western side of the basin has a series of steeply dipping, ash-rich, lacustrine sediments, within which two fossil leaf sites have been sampled.

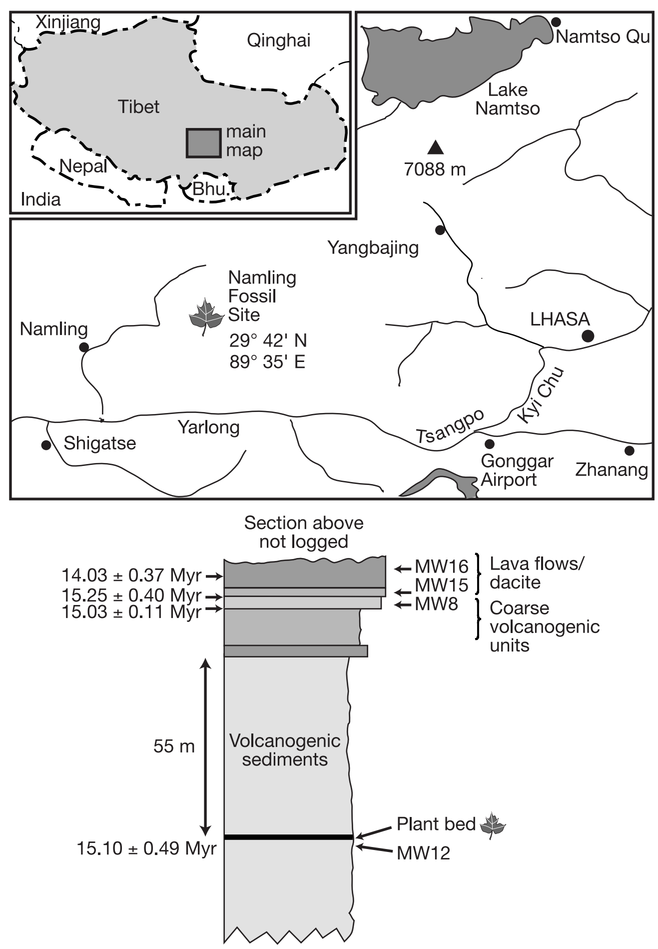

Figure 1 Upper part of the ~300-m logged section from Namling, indicating the stratigraphical position and ages of key dated samples. Inset shows location of Namling basin. MW indicates samples used in ^{40}Ar–^{39}Ar analyses.

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The lower site (locality A) lies at 4,300 m and the upper site at 4,600 m beneath capping lava flows at >4,800 m. At both localities abundant impressions in fine-grained water-lain grey tuffs represent leaves showing minimal mechanical fragmentation and no size sorting. We infer that the leaves were derived from trees growing proximal to the lake margins rather than from elevated sources on the distal edges of the basin.

Both localities yielded assemblages with similar floral composition. Taxa that normally rot quickly (*Alnus*, *Salix*) showed no sign of biodegradation, which suggests that the overall species composition is not biased because of preferential species decay. The age of flora from locality A (15.10 ± 0.49 Myr) was constrained by ^{40}Ar–^{39}Ar dating of sanidine feldspar in a volcanogenic sediment lying immediately below it, and by phlogopite micas extracted from a potassic lava succession that overlies it (15.03 ± 0.11 Myr ago). Because both ages are within error, it is probable that the plant-bearing succession was deposited about 15 Myr ago.

The antiquity of the Namling flora precludes palaeoclimate, and the derived palaeoaltitude, being estimated from the modern climatic tolerances of the nearest living relatives (NLRs) of the ancient plants. This NLR technique is only useful for assemblages in which it is reasonable to expect modern species to occur. For 15-Myr floras, the constituent species are all extinct and can be compared only with their presumed modern descendants at genus level at best. Because the spread of environmental tolerances of species within a given genus is often large (for example, the genus *Salix* contains both tropical and Arctic species) the application of the NLR methodology in this instance involves large uncertainties. Alternative methods of better constrained precision need to be used to determine the palaeoaltitude of the Namling flora.

The only palaeobotanical technique that offers rigorous quantitative estimates of palaeoclimate and palaeoaltitude for leaf assemblages of this antiquity, and with quantifiable uncertainties, is one based on leaf physiognomy. The foliar physiognomy of woody dicots is demonstrably correlated with climate and, because this correlation is the product of the physical laws of gas diffusion, fluid flow and radiation balance, it is assumed to be stable over time[20,21]. More than 400 collected specimens were categorized into 35 morphotypes using leaf architecture and venation characteristics and were subjected to a CLAMP analysis. CLAMP values for the Namling fossils yield a mean annual temperature (MAT) of 6.8 ± 3.4 °C and a cold month mean temperature (CMMT) of −6.2 ± 5 °C using a data set containing the so-called 'alpine nest' samples (Physg3ar). An alternative data set (Physg3br) that lacks samples from cold environments gave an MAT of 8.1 ± 2.3 °C with a CMMT of −4.19 ± 3.7 °C. The modest CMMTs suggest that either data set is appropriate for analysing the Namling fossils.

Although height can be calculated from lapse rates, in mountainous regions lapse rates are notoriously variable and dependent on local topography[22]. Because the ancient topography at the scale of individual depositional basins is unknown, we have used instead the more reliable approach of determining enthalpy, which is related to moist static energy (MSE). This thermodynamically conserved parameter of the atmosphere, which is related to both temperature and humidity, quantifies the total energy content of a parcel of air excluding the negligible kinetic energy[21,23]. MSE is roughly conserved following an air parcel trajectory and, thus, in mid-latitudes it is roughly invariant with longitude[23]. In lower latitudes, the longitudinal gradients can be larger. Because enthalpy is a function of temperature and moisture—two parameters that are crucial to plant growth—enthalpy can be decoded from foliar physiognomy using CLAMP[21,23] (Fig. 2).

Analysis of the Namling assemblages using the Physg3ar data set yielded an enthalpy value of 289 ± 7 kJ kg^{-1}, and the Physg3br set gave 290 ± 6.4 kJ kg^{-1}. To determine altitude, the method requires an estimate of MSE at a known elevation. Normally this is based on one or more proximal and coeval sea-level floras from similar latitudes; however, such floras have not yet been recovered. To overcome this problem we calculated the Miocene MSE using the Hadley Centre numerical climate model. The advantage of this approach is that MSE can be calculated at the location of the fossil leaves and thus does not require any assumptions about the trajectories of the air parcels. Assuming longitudinal invariance was one of the largest sources of uncertainites[23] in previous North American studies, and such uncertainties increase for tropical latitudes.

The weakness of using the climate modelling approach lies in the uncertainties related to the modelling process. Although MSE is a relatively robust model variable, there are uncertainties arising from the representation of the physics in the model, and from our lack of knowledge of the detailed boundary conditions for the Miocene. Table 1 lists the potential sources of errors from this approach.

An estimate of the magnitude of errors associated with the model's internal physics of can be obtained from a comparison between the model-simulated modern climate and observations. Typical errors in tropical regions are of the order of 2 kJ kg^{-1}. This is a conservative estimate, however, because most climate models have been 'tuned' towards the observations. The effect of uncertainties in the Miocene boundary conditions can be estimated by performing sensitivity simulations. Changes to the height of Tibet do not significantly influence the model estimates (as expected from the theory[23]). Errors related to palaeolongitude and palaeolatitude are relatively unimportant because we use the model predictions at the fossil sites (this would be the principal source of uncertainty if we were using sea-level fossil assemblages). The biggest uncertainty arises from lack of knowledge of the sea surface temperatures. We

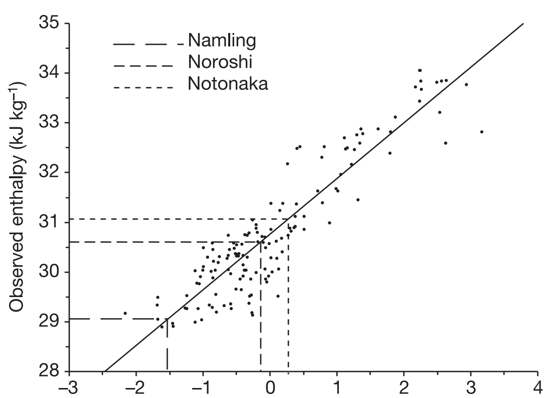

Figure 2 CLAMP enthalpy vector score against observed enthalpy regression for the Physg3br data set. Broken lines show the vector score and corresponding enthalpy predictions for the Namling flora and those from two coeval Miocene locations in Japan.

Table 1 **Potential sources of errors in model simulations of moist static energy**

Source of uncertainty	MSE uncertainty
Inaccuracies in simulating present-day distribution (calculated as the root mean square difference between the observations and the model in the region of Tibet)	2.3 kJ kg^{-1}
Palaeolongitude and palaeolatitude uncertainties	0.4 kJ kg^{-1}
Model sensitivity to variations in Tibetan elevation	Maximum of 0.6 kJ kg^{-1}
Changes in sea surface temperature	5.3 kJ kg^{-1} in the vicinity of Tibet; maximum of 8.2 kJ kg^{-1} over the globe

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evaluated this uncertainty by performing sensitivity tests by prescribing a range of different sea surface temperatures, or ocean heat transports (when using a slab ocean model). Lack of a detailed palaeobathymetry precluded fully coupled ocean–atmosphere simulations.

To validate further the Miocene model simulations, we compared them with MAT and enthalpy values derived from the 15-Myr Notonakajima and Noroshi floras[24,25] from Japan (mean MAT, 15 °C; mean enthalpy, 308 kJ kg^{-1}). The model sea surface temperatures were adjusted to ensure a good match to these sea level data (model-simulated MAT, 11 °C; mean enthalpy, 306 kJ kg^{-1}).

The model simulated Namling moist static energy is 335.5 kJ kg^{-1} (see Supplementary Information). Changes in sea surface temperature typically gave variations of 5.3 kJ kg^{-1} (in the Tibetan region, and we use this as our estimate of uncertainty) but elsewhere the variations could be as much as 8.2 kJ kg^{-1}. Overall, the height estimate for the Namling basin floor 15 Myr ago using the Physg3ar data set is given by:

$$Z = [(335.5 \pm 5.3) - (289.5 \pm 7.0)]/g = 46.0 \pm 8.78/9.81$$

$$= 4,689 \pm 895\,\mathrm{m}$$

Using the Physg3br set, the palaeoelevation estimate is 4,638 ± 847 m. Including a worse-case modelling uncertainty of 8.2 kJ kg^{-1} would give an uncertainty of 1,099 m. It should also be noted that there is a large seasonal cycle in enthalpy in the monsoon regions but all analyses have used the annual mean estimates.

These results have two important implications. First, the elevation of the valley floor has not changed significantly over the past 15 Myr. Any marked change in uplift rates that resulted from lithospheric delamination, as predicted by homogeneous thickening models, would have occurred before that time beneath southern Tibet. Second, if the plateau elevation had been stabilized at a threshold elevation above which it could not be supported by marginal stresses during the Early to Middle Miocene[17,19], then by 15 Myr ago the relief between plateau surface (~5,000 m) and intermontane basins was similar to the contemporary topography.

Our data provide a quantitative estimate of the altitude of southern Tibet 15 Myr ago; however, we caution against simple links being drawn between increases in the monsoon intensity (for example, at 8 Myr ago[5] or 2.6 Myr ago[7]) and plateau uplift. Until a similar floral analysis is repeated for northern Tibet, no conclusions can be drawn about uplift of the whole plateau. Indeed, our results are consistent with geological arguments for a three-phase model of diachronous uplift with initial Eocene uplift in the south, uplift of central Tibet during the Oligo-Miocene and finally uplift of northern Tibet during the Plio-Quaternary[15]. The monsoon is driven, in part, by summertime sensible and latent heating effects of an uplifted plateau on the troposphere, and both plateau elevation and surface area determine the extent of these effects on atmospheric circulation[1,3]. The complex interplay between elevation history and monsoon intensity can therefore be unravelled only once the increasing area of uplifted plateau throughout the Neogene is charted. Numerical climate-model experiments[8] that assume uplift of the plateau evolved from small uplifted areas at moderate elevations (1,000–2,700 m) to large uplifted areas at high elevations (1,000–5,700 m) may therefore be unrealistic. The consequences of high elevations being achieved by progressively larger areas extending from south to north through time should now be examined. □

Methods

Dating

^{40}Ar–^{39}Ar analyses were done on mineral separates using the laser step-heating technique at the Open University.

CLAMP

Each morphotype was scored for 31 character states and evaluated by CLAMP using canonical correspondence analysis (CANOCO v.4.0) and Physg3ar and Physg3br reference data sets for Northern Hemisphere (including Asia) temperate vegetation and climate (see Supplementary Information). Regression equations for CLAMP vector scores against observed climatic parameters were calculated in Axes 1–4 space. Uncertainties are here quoted as 2 s.d. of the residuals about the mean.

Enthalpy

We used the following moist static energy equation:

$$h = c_p T + L_v q + gZ = H + gZ$$

where h is moist static energy, c_p is the specific heat capacity of moist air at a constant pressure, T is temperature (in kelvin), L_v is the latent heat of vaporization, q is the specific humidity, g is gravitational acceleration and Z is the altitude. Enthalpy is given by $H = c_p T + L_v q$. The difference between two estimates of enthalpy for a given location yield an estimate of their difference in potential energy and hence height separation.

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Correspondence and requests for materials should be addressed to R.A.S. (e-mail: R.A.Spicer@open.ac.uk).

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