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FRONT MATTER

Title

- **Full title: Qaidam Basin leaf fossils show northeastern Tibet was high, wet and cool in the early Oligocene**
- **Short title: A high, wet and cool Oligocene Qaidam Basin**
- **One sentence summary:** Quantitative analysis of newly discovered early Oligocene leaf fossils characterize the paleoclimate of the Qaidam Basin, northern Tibet as temperate and wet at an elevation close to that of the present day, showing high elevations were present in northern Tibet before the rise of the Himalaya.

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Abstract

The Paleogene environment of today's semi-arid and arid Central Asia is poorly quantified and knowledge of the paleoelevation of northern Tibet remains elusive, yet both are crucially important for understanding inter-relationships between growth of the Tibetan Plateau and Asian monsoon development. Here, using the physiognomy of newly discovered early Oligocene (30.8 Ma) fossil leaves from the Qaidam Basin, we reconstruct quantitatively the paleoclimate and paleoelevation of this critical part of northern Tibet. We find the Qaidam Basin floor was at its present height of ~3.3 km in the early Oligocene, higher than the rising Himalaya at that time, and experienced a temperate, moderately wet climate. Near-freezing (1.4 ± 3.5 °C) winters accompanied cool summers (~23 ± 2.9 °C). Annual precipitation exceeded 1000 mm with

subdued (non-monsoonal) seasonality in which summers were drier than winters. This finding challenges geodynamic models that envisage a Miocene or later uplift of northern Tibet and progressive uplift from the south.

MAIN TEXT

Introduction

Abundant sedimentological evidence indicates that a step-wise drying in Central Asia began in the late Eocene (*1*) and persists today, but the underlying mechanisms for this aridification are poorly understood and contentious. Drying has been linked to Cenozoic global cooling (*2*), uplift of Tibet associated with India-Asia plate collision (*3*), or the retreat of the proto-Paratethys, a broad pre-Miocene epicontinental sea over central Eurasia (*4*, *5*). Existing studies of Paleogene environments in Central Asia are mainly based on sedimentary (*1-4*) or stable isotope records (*5*). To understand fully the links between tectonics and climate change in the region requires quantification of past climate as well as a detailed knowledge of Paleogene topography, but currently both these critical components are poorly constrained.

The Qaidam Basin is a key region for understanding the history and inter-linkages between Central Asia aridification and regional tectonism relating to the topographic development of the Tibetan Plateau because the basin hosts an extremely thick (~12,000 m) continuous Cenozoic sedimentary succession ranging from the Paleocene to Quaternary (*6*, *7*). Palynological data (*8*), as well as fossil fish (*9*), reveal a Neogene step-wise aridification of the Qaidam Basin, but the Paleogene vegetation, climate and surface elevation remain poorly known (*10*). Secular climate change is often invoked at the Eocene-Oligocene transition (EOT) to explain an observed shift in the paleo-environment (*1*), but coeval uplift in the region can also lead to a significant change in the local and regional climate signal, altering the sensitivity of the region to secular climate change at the EOT. Critically, the lack of a quantified uplift history and environment for northern Tibet, especially of the Qaidam Basin, hampers our understanding of the growth of the Tibetan

Plateau both in terms of its pattern of growth and the underlying mechanisms driving its evolution. Most geodynamic models consider the rise of northern Tibet post-dates that of southern and central Tibet (*11*), but the uplift history of the region is obscure with stable isotope-based paleoaltimetry, known to be problematic in continental interiors (*12*), only indicating a major uplift of the Qaidam Basin after the middle Miocene (*13*). Well-dated paleontological evidence required to test this is rare, and as yet has not been applied in a paleoaltimetric context.

Plant fossils are crucial to cross-validate and compare paleoclimatic inferences based on sedimentary evidence with those simulated by models. In addition to reflecting paleovegetation, plant fossil assemblages can also be used to estimate quantitatively the paleoclimate and paleoelevation using taxonomy-independent, leaf physiognomic methods (*14-16*). However, paleobotanical records, especially well-preserved plant megafossils, are rare in the Paleogene of Central Asia, with only western Kazakhstan so far yielding relevant (Oligocene) floras (*17*). Here we report a new well-preserved fossil plant assemblage from the early Oligocene of the northern Qaidam Basin, northeastern Tibet. A high-resolution magnetostratigraphic study (*6*) constrains the age of the flora to be ~30.8 Ma. This fossil assemblage provides an excellent opportunity to evaluate the regional climate and topography at the northern margin of what is now the Tibetan Plateau during the early Oligocene, shortly after permanent ice sheets had formed in Antarctica (*18*) and relatively early in the India-Asia plate collisional process. To quantify the paleoclimate and paleoelevation of the Qaidam Basin floor in the early Oligocene we analyze leaf forms using the Climate-Leaf Analysis Multivariate Program (CLAMP) (*19*) (http://clamp.ibcas.ac.cn) combined with a coupled atmosphere-ocean general circulation climate model (GCM) configured for age-appropriate boundary conditions.

Results

Geological context and age constraints

The Qaidam Basin, with a present elevation ranging between 2.8 km and 3.2 km, is an intermontane non-marine basin bounded by the Altyn Tagh Shan in the northwest, the Qilian Shan in the northeast, and the Kunlun Shan in the south (Fig. 1). Cenozoic strata within the Qaidam Basin have been subdivided into seven lithostratigraphic units (*6*, *7*). From the oldest to youngest these are: the Lulehe Formation (Fm.), the Xiaganchaigou Fm., the Shangganchaigou Fm., the Xiayoushashan Fm., the Shangyoushashan Fm., the Shizigou Fm., and the Qigequan Fm.. High-resolution magnetostratigraphy of a well-studied and documented sedimentary succession, constrained by a variety of paleontological data (ostracodes, pollen, leaves, mammals), defines the entire Dahonggou section (fig. S1). This section ranges in age from ~52 Ma (the base of the Lulehe Fm.) to ~7 Ma (the lower Shizigou Fm.) (*6*) and hosts the plant fossils reported here, Crucially This chronology (*6*) is consistent with most biostratigraphic, magnetostratigraphic, and detrital low-temperature thermochronologic studies on the Qaidam strata, including a recent work based on the nearby Hongliugou section (Fang et al., 2019) in which the age of Shangganchaigou Formation is well constrained by mammal fossils and magnetostratigraphy. The clay minerals and iron oxides records of the Hongliugou section in the Qaidam Basin and the Xiejia section in the Xining Basin both exhibit in-phase change with Paleogene cooling (Fang et al., 2019), suggesting a reliable regional paleoenvironmental correlation, and in turn confirming the regional controls. The Eocene age of the Lulehe Fm. adopted here is also supported by the cooling ages observed from the surrounding mountains, as indicated by independent thermochronological dating (Jian et al., 2018; Du et al., 2018; Zhuang et al., 2018).

A younger age for the base of Lulehe Fm. from a chronology derived from the Honggou section (*20*) is not adopted here because it is in conflict with other chronological results in the region, and also early Cenozoic source-to-sink processes observed throughout the whole Qaidam Basin (Lu et al., 2018; Song et al., 2019). Crucially this younger age relied on fission track ages from only 2%

Commented [RAS1]: Would it be worth adding the comments about the Wang et al FT grains being partially annealed and the age population being only 2 grains out of a hundred. I found this to be a powerful argument in the responses letter. In fact this section could be expanded along the lines of the responses letter.

of detrital appatites and these were likely to have undergone partial annealing. This is evidenced by two samples (D54 and H52) where their respective minimum grain ages of 19.8 and 8.2 Ma are far younger than the supposed deposition ages of 23.7 and 21.3 Ma.

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Plant fossils were collected from the lower member of the ~1500 m-thick Shangganchaigou Formation (Fig. 2) exposed within the Dahonggou anticline at the northern margin of Qaidam Basin, ca. 45 km south of Daqaidam Town, Delingha City, Qinghai Province (Fig. 1). The Shangganchaigou Formation is an Oligocene to lower Miocene lacustrine and deltaic succession (*6*) and the layer that produces the plant fossils corresponds to C12n of the geomagnetic polarity time scale (GPTS) (Fig. 2) (*21*). Linear interpolation between thickness and age yield an age of ~30.8 Ma (Rupelian) for these plant fossils.

Plant fossil assemblage

The fossil locality (37.4675 °N, 95.21639 °E) is at a present elevation of 3246 m above mean sea level (AMSL) and experiences a mean annual temperature of 1.9°C, and a mean annual precipitation of 82.7 mm as recorded at the Daqaidam meteorological station (37.85 °N, 95.37 °E, 3173.2 m AMSL) (Table 1).

A total of 728 plant megafossil specimens, predominantly leaves, were collected and most of them are well preserved with gross morphology and detailed venation being easily observed. Species diversity is low, yielding only 21 morphotypes of woody dicot leaves (Fig. 3), leafy shoots of *Glyptostrobus* (Fig. 3Y), a cupressaceous conifer that is native to South China today, fruits of *Populus* (Salicaceae) (Fig. 3X) and *Cyclocarya* (Juglandaceae) (Fig. 3V), as well as single-seeded pods of *Podocarpium* (Fig. 3W), which is an extinct genus of legume. The leaf fossil assemblage is dominated by *Populus* and *Podocarpium*. The paleoflora most likely represents a temperate deciduous predominantly broad-leaved woodland, and given the overall warmer temperatures in the early Oligocene (*18*) and the relatively low paleolatitude (39° N) (Table 1) this type of vegetation suggests, qualitatively, an elevated landscape.

Paleoclimate estimates

The leaves of woody plants interact with and process the atmosphere and so have to possess adaptations suited to (and thus indicative of) their immediate environment (*19, 22*). These adaptations are reflected in leaf morphological (physiognomic) features that are preserved even when fossils lack organic material. Such features can be interpreted in terms of the predominant climate using multivariate statistical analysis and calibration data derived from modern vegetation growing under known quantified climates (http://clamp.ibcas.ac.cn). Unlike pollen, leaves cannot remain intact after undergoing significant pre-burial downslope transport, and so recognizable leaves must represent conditions altitudinally and spatially close to the burial site. Moreover, unlike geochemical proxies, leaf physiognomic climate signatures are immune to diagenetic alteration.

The early Oligocene Qaidam flora plots within the PhysgAsia2 CLAMP calibration space (fig. S2), meaning that this calibration is valid to derive past environmental conditions from the Qaidam fossil flora. The paleoclimate estimates (Table 1) show that the northern Qaidam Basin experienced a temperate and wet climate during the early Oligocene, with a mean annual air temperature (MAT) of 11.6 ± 2.4 °C, a cold month mean temperature (CMMT) of 1.4 ± 3.5 °C, and growing season precipitation (GSP) of 1229 ± 643 mm. The CMMT was above freezing at 1.4 °C, but the estimate has quite a large uncertainty (standard deviation 3.5 °C) so some short duration periodic frosts were likely. Notably, the fossil flora does not contain any obligate thermophyllic taxa such as palms (not used in the CLAMP analysis) that are intrinsically vulnerable to freezing, which supports the inference that frosts did occur from time to time. The CLAMP results also show a moderate seasonal variation in temperature, with the difference between the warm month mean temperature (WMMT) and CMMT being ~22 °C, notably less the present-day range of ~29 °C.

Apart from the warmer and less seasonal thermal regime, significant differences exist between the northern Qaidam Basin precipitation regime in the early Oligocene and that of the present-day. The growing season (7.4 ± 1.1 months) precipitation (GSP) estimate for the early Oligocene is more than 20 times than that of the present, but the seasonal variation in precipitation was much lower. Based on local climate records (Table 1) the northern Qaidam Basin today experiences a precipitation ratio for the 3 consecutive wettest months (3WET) to that in the 3 consecutive driest months (3DRY) of ~22:1, while in early Oligocene it was just ~3:1, which by any definition is not monsoonal. The precipitation seasonality in the early Oligocene may be lower than estimated since the standard deviation is high (400 mm) and 3WET may be overestimated (*22*), but CLAMP seasonal humidity estimates also show that the Qaidam summer was the driest season (notably so) as measured by both vapor pressure deficit (VPD) and potential evapotranspiration (PET) (Table 1). VPD is is the difference between the amount of moisture in the air at any given moment and how much moisture the air can hold when it is saturated, while PET is a measure of the capacity of the atmosphere to remove water from a surface through evaporation and transpiration and assumes an unlimited water supply. For the Oligocene Qaidam Basin we estimate the mean VPD ratio for the three summer months (VPD.Sum) to that for the three winter months (VPD.Win) was 5:1, while the PET measures indicate evapotranspiration in the warmest month was 6.1 times that of the coldest. Unlike relative humidity both VPD and PET have a linear relationship to plant transpiration.

Paleoelevation

To determine the Qaidam Basin floor elevation we use the moist enthalpy method, which is based on energy conservation principles (*23*), coupled with information from climate model simulations. Put simply, the difference between moist enthalpy at sea level ($H_{sea\ level}$) and that at an unknown elevation (H_{high}) divided by the acceleration due to gravity (g) yields the elevation difference (Z).

$$Z = (H_{sea\ level} - H_{high})/g \qquad (1)$$

The early Oligocene flora from the northern Qaidam Basin yields a CLAMP-derived moist enthalpy value of 307.5 ± 84 kJ/kg, but because during the early Oligocene the Qaidam Basin was in a continental interior setting there are no proximal sea level floras to obtain contemporaneous sea level enthalpy measures. To overcome this lack of a local sea level datum a paleo-sea surface moist enthalpy value for the northern Qaidam Basin was derived from a GCM simulation configured with Rupelian paleogeography (fig. S3) and boundary conditions, and adjusted using paleo-spatial trends in coastal coeval CLAMP-derived sea level moist enthalpy values (see Material and Methods section). Using Equation (1) this model-mediated sea level moist enthalpy value (340 kJ/kg) yielded a Qaidam Basin floor paleoelevation of ~3.3km ± 1.3 km, which is indistinguishable from that of the present-day. The uncertainty combines values arising from the scatter about the regression model in CLAMP and that arising from the latitudinal scatter in the model sea level moist enthalpies used in the paleopositional correction.

The geological data used to construct the paleotopography used in the GCM simulation suggest surface height in the Qaidam area of ~ 3km. To test that this did not induce an element of circularity in our analysis we also ran experiments where the Qaidam region was given ‘artificial’ elevations ranging from 0km (sea level) to 4 km in 1 km increments. Differences in modelled sea level enthalpy from these experiments were remarkably small and well within model and proxy uncertainties. When the basin floor was set at 4 km as against 3 km this resulted in a simulated sea level moist enthalpy change of only 0.5 kJ/kg, or 52 m elevation difference, and when set to 2 km the difference was 0.67 kJ/kg (68 m). This uncertainty rose by just 3.1 kJ/kg (318m) when a 1 km elevation was used instead of 3 km.

Discussion

Temperate climate with notable thermal seasonality

This similarity in elevation between the northern Qaidam Basin at 30.8 Ma and that of today makes comparisons between the Rupelian and modern climate intriguing. The Qaidam fossil plant assemblage yields a temperate climate, with MAT, WMMT and CMMTs significantly higher than those of the present-day; temperature estimates that are consistent with the taxonomic composition of the fossil flora, which is dominated by typical temperate species, e.g. *Populus* and *Cyclocarya*. Quantitative reconstruction of paleoclimate elsewhere in the Qaidam Basin and neighboring regions is lacking, but a recent CLAMP study of an early Oligocene flora in southeastern Tibet also reveals a warmer-than-present thermal regime despite being at a similar elevation (*16*). The early Oligocene floras in western Kazakhstan represent even warmer warm-temperate vegetation (*17*) with some subtropical elements, and as such likely grew at an elevation significantly below 3 km.

A warmer Qaidam Basin, even at a similar elevation to today, is consistent with greater overall global warmth in the early Oligocene. By 30.8 Ma the mean global temperature as estimated from marine data had increased after cooling across the Eocene-Oligocene transition (*18*). The CLAMP estimates for the early Oligocene Qaidam flora highlight a marked temperature seasonality, with some winter freezing likely, although the thermal range was smaller than that of the present-day. The difference between the WMMT and CMMT was ~21.5 °C and consistent with a continental climate. It is not surprising that the northern Qaidam Basin had a continental climate during the early Oligocene since it was distant from the retreated proto-Paratethys sea. In the early Eocene the proto-Paratethys sea attained its maximum area extending from the Mediterranean to the Tarim basin, but subsequently retreated westward after the early Eocene and by the Eocene-Oligocene transition (~34 Ma) had shrunk to the present position of the Caspian Sea (fig. S3) (*24*). While the thermal influence of the proto-Paratethys was limited, this did not apply to moisture transported by westerlies.

High precipitation with low seasonal variation

In striking contrast to the arid regime in Qaidam Basin today, which is characterized by minimal but highly seasonal (summer ~58 mm, winter ~3 mm) precipitation and evaporation (Table 1), the estimated GSP in early Oligocene was 1229 ± 643 mm with low precipitation seasonality. Although the standard deviation of GSP estimates is high, even the minimum value of GSP (~590 mm) is more than 10 times than that of the present-day (57.6 mm). This pattern of precipitation suggests that during late Paleogene moisture in Central Asia was derived by a westerly flux of humid air from the retreated proto-Paratethys (*25*). Our GCM simulation suggests that this effect was particularly evident in winter.

Today's Asian monsoons are characterized by summer precipitation while the mid-latitude westerlies are associated with winter precipitation (*26*). The contemporaneous early Oligocene Mangkang flora from southeastern Tibetan Plateau also yields a similar 3WET/3DRY ratio of ~3:1 using the CLAMP proxy (*16*). Physiognomic trait spectra of Eocene leaves from South China also suggest that a strong monsoon, with modern characteristics that is dominated by a 'sea-breeze' monsoon circulation, developed much later across southern Asia (*15*).

The high precipitation estimates in northern Qaidam indicate that the present-day high-standing topography of Tian Shan, Altai Shan, Pamir and Altun Tagh ranges that tend to block westerly moisture did not have this effect in the early Oligocene and may suggest they had yet to achieve their current heights. This inference is supported by regional tectonics studies, which suggest the Tian Shan (*27*), Altai Shan (*28*) and Pamir (*29*) ranges exhibited limited relief before the Miocene. During most of the Oligocene, although retreated, the proto-Paratethys sea still covered a large area of central Eurasia (fig. S3), and could have been the source of moisture evident in the seasonal cycle (*25*). A western source for the high precipitation is also supported by the presence of well-developed early Oligocene vegetation in Kazakhstan (*17*) and evapotranspiration from these thermophyllic broad-leaved forests could have further enhanced regional moisture recycling in Central Asia.

A high Qaidam Basin during the early Oligocene

The elevation of the northern Qaidam Basin at ~31 Ma is reconstructed to have been comparable to its present-day altitude of ~3,200 m. Palynological assemblages also suggest that the Xining Basin of northeastern Tibet had been surrounded by mountains as high as those of the present day since ~38 Ma (*30*).

Although stable isotope-based paleoaltimetry points to a middle-late Miocene surface uplift of the Qaidam Basin (*13*), this is not in conflict with our findings. Stable isotope compositions are likely biased to where predominant fractionation takes place and in the case of meteoric waters this is inevitably at high elevation where rainout occurs as moisture-laden air is forced over topographic highs. Thus, the middle-late Miocene uplift may not have been that of the Qaidam Basin floor but that of the surrounding mountains. By contrast leaf fossils must indicate conditions and surface heights close to their burial site, i.e. in lowland sites of sediment accumulation within basins.

Geologic evidence shows that the northern boundary of the Tibetan orogen was set in the Eocene following the initial India-Asia collision, although whether a high topography was built simultaneously in this region is unknown (*31*). Here we show that in northern Tibet a close-to-present elevation of ~ 3 km for at least one basin floor had been achieved by the early Oligocene, a time when the central Himalaya were at an elevation of < 2.3 km (*32*). Moreover, by using the same moist enthalpy method as we use here, analysis of fossil leaf assemblages also shows that the southern Lhasa terrane (*14*, *32*) and the southeastern margin (*16*) of the Tibet had reached their present-day elevations by the middle Miocene and early Oligocene respectively. Thus, a combination of stable isotope and phytopaleoaltimetry (*10, 16, 32*) is demonstrating that complex, and in places high, relief existed in Tibet before the rise of the Himalaya and that the modern high

Tibet is not solely the product of the India-Asia collision. This has implications for the amount of subducted greater India that contributed to the building of Tibet.

Although we can say with confidence that parts of northern Tibet such as the Qaidam Basin were at ~ 3 km in the Paleogene, we cannot yet fully reconstruct the elevation history of the region and so understand Tibet-wide tectonic processes with any confidence. It could be that the Qaidam uplift long pre-dated the arrival of India and resulted from earlier terrane collisions. Alternatively, it may be that compressional forces from India were transmitted through southern and central Tibet so that the Qaidam region exhibited far-field deformation very early in the India-Asia collision process. It is also possible that the Qaidam Basin was high at 52 Ma, the start of Lulehe deposition, and underwent subsidence brought about by topographic loading during the simultaneous early Eocene deformation within the Qilian Shan and Altyn Tagh Shan (*33*). Future paleoaltimetric studies using well-dated fossil assemblages may yet answer these questions.

Materials and Methods

Fossil preparation

The studied plant fossils are preserved as impressions with gross morphology and gross venation in finely laminated lacustrine grey-green mudstone and marlstone. Fossil specimens were prepared manually with a fine engraver knife to remove extraneous matrix, and photographed using a Nikon D810 digital camera with 60 mm Nikkor macrolens under oblique illumination. The studied fossil leaves were divided into morphotypes based on their leaf architecture, and only well-preserved specimens were identified at family or generic level.

CLAMP

To decode the environmental signals preserved in the early Oligocene Qaidam woody dicot leaf assemblage we used the Climate-Leaf Analysis Multivariate Program (CLAMP) proxy with the PhysgAsia2 leaf physiognomy training set as used in previous Tibetan and Himalayan studies (*32*, *34*). However here we use a new climate calibration based on high spatial resolution (~1 km^2) WorldClim2 climate data (*35*) to obtain a broader suite of well-quantified environmental variables. The results are presented in Table 1.

CLAMP is a widely used taxonomy-independent, multivariate statistic technique based on canonical correspondence analysis (CCA), which correlates the leaf physiognomy of modern vegetation with climate data (*19*), and using these correlations determines the conditions prevailing during growth of the ancient vegetation as represented by fossil assemblages. The scoring of leaf physiognomic characters (data file S1) follows the standard protocols on the CLAMP website (http://clamp.ibcas.ac.cn). The studied specimens, typical examples of which are shown in Fig. 3, are housed in the Institute of Geological Survey, China University of Geosciences, Wuhan (S27-135-1~S27-135-728).

The database used in CLAMP codes 31 leaf characters averaged over a minimum of 20 taxa. For calibration we used modern leaves comprising the PhysgAsia2 dataset (data file S2), which contains leaf data from both monsoon and non-monsoon exposed vegetation (*34*). The accompanying climate calibration used here is based on gridded ~1 km resolution Worldclim2 data observed at the same locations as in the PhysgAsia2 dataset (data file S3). Using regression models in four-dimensional space (see "http://clamp.ibcas.ac.cn" for details) traditionally CLAMP has returned 11 climate variables shown in red and by an asterisk in Table 1, but here we added 15 more variables that show good correlations with leaf physiognomy to better explore the overall thermal and seasonal moisture regime.

Paleoelevation estimates

We applied the moist enthalpy method (*23*) to estimate the paleoaltitude of the northern Qaidam Basin during the early Oligocene. This technique derives from the observation that moist static energy is conserved as a parcel of air rises over topographic highs (*23*). Moist static energy is the product of moist enthalpy and potential energy, so differences in moist enthalpy between two elevations can be resolved to elevation differences by dividing by the constant acceleration due to gravity (*g*) (Equation 1). Moist enthalpy is a climatic parameter related to both air temperature and moisture, and is well correlated with leaf physiognomy (*19*).

Paleopositional adjustments

Because moist enthalpy varies with latitude, and model and proxy values are unlikely to be identical, any systematic model and proxy-derived mean sea level moist enthalpy differences need accounted for in order to properly use a combination of model and proxy values to derive the paleoelevation for the Qaidam Basin. Any approach to achieve model-proxy parity should also accommodate, as far as possible, uncertainties in both proxy retrodictions and model simulations. Inevitably differences arise between moist enthalpy estimates derived from proxies and those predicted by climate models. These differences occur because models attempt to represent typical conditions for a given time slice that can span several million years. Moreover, the model values give the average climate over the area of the model grid cell (~3.75° longitude × 2.5° latitude) rather than at the exact location of the plant fossil assemblage and are subject to imprecisely known model boundary conditions (e.g. paleogeography and atmospheric composition), as well as uncertain model parameters. By contrast proxy estimates represent conditions averaged over much shorter time intervals and spatial spread, but are also subject to methodological uncertainties.

Moist enthalpy tends to vary zonally (*23*) and GCMs tend to produce steeper latitudinal moist enthalpy trends than the proxy data (REF). To obtain a model-derived sea level moist enthalpy for the early Oligocene Qaidam Basin that can legitimately be compared to that derived from the fossil assemblage requires the model value to be adjusted consistent with the observed moist enthalpy at the paleosurface. To make this adjustment we selected from our pre-existing CLAMP archive roughly coeval Oligocene leaf assemblages thought to represent near sea level conditions across a 20°N to 50°N paleolatitudinal range (table S1). By comparing them with paleo-sea level moist enthalpy values predicted by the Rupelian GCM we derived a simple linear regression of the differences to obtain a latitude-dependent adjustment value at the Qaidam paleolocation. The scatter in the model-proxy differences also allowed us to accommodate proxy model uncertainties, plus any variation in the proxy values due to the fossil assemblages not properly representing mean paleo sea level moist enthalpy. The derived regression equation:

$$y = -0.2622x + 3.645 \qquad (2)$$

shows that at the Qaidam Basin palaeolocation the model underestimates moist enthalpy with respect to the proxy by 6.46 kJ/kg. Applying this the model-derived moist enthalpy rose from 333.1 kJ/kg to 339.5 kJ/kg.

Using equation (1) the paleoelevation of the early Oligocene Qaidam Basin (Z) was given by:

$$Z = (339.5-308.2)/9.81 = 3.19 \text{ km}.$$

Combining the CLAMP uncertainty (1 sigma) of 8 kJ/kg (Table 1) and that of the adjustment regression (10.9 kJ/kg) yielded a combined uncertainty of ±1.38 km.

Climate Model

The climate model used is HadCM3L, a fully coupled atmosphere-ocean GCM with a resolution of 3.75° longitude × 2.5° latitude, 19 vertical atmosphere levels and 20 ocean depth levels, and incorporates a dynamic vegetation model, TRIFFID. The simulation was run for > 6000 model years until ocean circulation equilibrated fully with no trend in the integrated ocean temperature. HadAM3, the atmospheric sub-model of HadCM3L using the equilibrated sea surface temperatures from the HadCM3L simulation, was used to determine paleo moist enthalpy at sea level. The paleogeography in the model was appropriate for the Rupelian (fig. S3), based on Getech Plc. reconstructions (0.5° x 0.5° longitude x latitude) (*36*) upscaled to the HadCM3L resolution (*37*). The HadCM3 family has seen extensive use in the Intergovernmental Panel on Climate Change (IPCC) 3rd to 5th Assessment reports (AR3-5), and importantly in this context shows skill in representing both mean climate state compared to observations globally (*38*), as well as the Asian monsoon climate (*36*) where it out-performs most other contemporaneous models.

H2: Supplementary Materials

Fig. S1. Stratigraphic column of the Dahonggou section. The Dahonggou section studied here is measured on the southern limb of the Dahonggou anticline, northern Qaidam Basin. It is well exposed, more than 5 km thick, and consists of Lulehe Formation, Xia Ganchaigou Formation, Shang Ganchaigou Formation, Xia Youshashan Formation, Shang Youshashan Formation and Shizigou Formation from bottom upwards. The section is further subdivided into 584 beds. Dip direction varies southward from 20°–30° in the anticline core, to 45°–55° in the middle part, and becomes shallower toward the top.

Fig. S2. CLAMP plots showing the position of the early Oligocene Qaidam fossil leaf assemblage in PhysgASia2 calibration space. The fossil leaf assemblage is shown as a red dot, the modern vegetation samples as open black circles. Climate vectors are shown in blue. **(a)** canonical correspondence analysis (CCA) plot of axes 1 v 2. **(b)** CCA plot of axes 1 v 3. **(c)** CCA plot showing axes 2 v 3. The fossil assemblage lies within the PhysgAsia2 physiognomic space showing the calibration is appropriate for this assemblage.

Fig. S3. Rupelian GCM paleogeography (a), moist enthalpy (kJ/kg) at sea level (b), precipitation (mm/day) in December-February (c) and precipitation (mm/day) in June-August (d). The paleogeography is based on that developed by Getech Plc.

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References and Notes

1. G. Dupont-Nivet, W. Krijgsman, C. G. Langereis, H. A. Abels, S. Dai, X. Fang, Tibetan plateau aridification linked to global cooling at the Eocene–Oligocene transition. *Nature* **445**, 635–638 (2007).
2. J. X. Li, L. P. Yue, A. P. Roberts, A. M. Hirt, F. Pan, L. Guo, Y. Xu, R. G. Xi, L. Guo, X. K. Qiang, C. C. Gai, Z. X. Jiang, Z. M. Sun, Q. S. Liu, Global cooling and enhanced Eocene Asian mid-latitude interior aridity. *Nature Communications* **9**, 3026 (2018).

3. Z. An, J. E. Kutzbach, W. L. Prell, S. C. Porter, Evolution of Asian monsoons and phased uplift of the Himalaya–Tibetan plateau since Late Miocene times. *Nature* **411**, 62–66 (2001).
4. L. Bougeois, G. Dupont-Nivet, M. de Rafélis, J. C. Tindall, J.-N. Proust, G.-J. Reichart, L. J. de Nooijer, Z. Guo, C. Ormukov, Asian monsoons and aridification response to Paleogene sea retreat and Neogene westerly shielding indicated by seasonality in Paratethys oysters. *Earth and Planetary Science Letters* **485**, 99–110 (2018).
5. J. K. Caves, M. J. Winnick, S. A. Graham, D. J. Sjostrom, A. Mulch, C. P. Chamberlain, Role of the westerlies in Central Asia climate over the Cenozoic. *Earth and Planetary Science Letters* **428**, 33–43 (2015).
6. J. Ji, K. Zhang, P. D. Clift, G. Zhuang, B. Song, X. Ke, Y. Xu, High-resolution magnetostratigraphic study of the Paleogene-Neogene strata in the Northern Qaidam Basin: Implications for the growth of the Northeastern Tibetan Plateau. *Gondwana Research* **46**, 141–155 (2017).
7. X. Wang, Z. Qiu, Q. Li, B. Wang, Z. Qiu, W. R. Downs, G. Xie, J. Xie, T. Deng, G. T. Takeuchi, Z. J. Tseng, M. Chang, J. Liu, Y. Wang, D. Biasatti, Z. Sun, X. Fang, Q. Meng, Vertebrate paleontology, biostratigraphy, geochronology, and paleoenvironment of Qaidam Basin in northern Tibetan Plateau. *Palaeogeography, Palaeoclimatology, Palaeoecology* **254**, 363–385 (2007).
8. Y. Miao, X. Fang, F. Wu, M. Cai, C. Song, Q. Meng, L. Xu, Late Cenozoic continuous aridification in the western Qaidam Basin: evidence from sporopollen records. *Climate of the Past* **9**, 1863–1877 (2013).
9. M. Chang, X. Wang, H. Liu, D. Miao, Q. Zhao, G. Wu, J. Liu, Q. Li, Z. Sun, N. Wang, Extraordinarily thick-boned fish linked to the aridification of the Qaidam Basin (northern

Tibetan Plateau). *Proceedings of the National Academy of Sciences* **105**, 13246–13251 (2008).

10. T. Deng, L. Ding, Paleoaltimetry reconstructions of the Tibetan Plateau: progress and contradictions. *National Science Review* **2**, 417–437 (2015).
11. P. Tapponnier, X. Zhiqin, F. Roger, B. Meyer, N. Arnaud, G. Wittlinger, Y. Jingsui, Oblique stepwise rise and growth of the Tibet Plateau. *Science* **294**, 1671–1677 (2001).
12. A. Mulch, C. P. Chamberlain, in *Mountains, Climate and Biodiversity*, C. Hoorn, A. Perrigo, A. Antonelli, Eds. (Wiley-Blackwell, 2018), pp. 81–93.
13. G. Zhuang, M. T. Brandon, M. Pagani, S. Krishnan, Leaf wax stable isotopes from Northern Tibetan Plateau: Implications for uplift and climate since 15 Ma. *Earth and Planetary Science Letters* **390**, 186–198 (2014).
14. R. A. Spicer, N. B. Harris, M. Widdowson, A. B. Herman, S. Guo, P. J. Valdes, J. A. Wolfe, S. P. Kelley, Constant elevation of southern Tibet over the past 15 million years. *Nature* **421**, 622–624 (2003).
15. R. A. Spicer, J. Yang, A. B. Herman, T. Kodrul, N. Maslova, T. E. V. Spicer, G. Aleksandrova, J. Jin, Asian Eocene monsoons as revealed by leaf architectural signatures. *Earth and Planetary Science Letters* **449**, 61–68 (2016).
16. T. Su, R. A. Spicer, S.-H. Li, H. Xu, J. Huang, S. Sherlock, Y.-J. Huang, S.-F. Li, L. Wang, L.-B. Jia, W.-Y.-D. Deng, J. Liu, C.-L. Deng, S.-T. Zhang, P. J. Valdes, Z.-K. Zhou, Uplift, climate and biotic changes at the Eocene–Oligocene transition in south-eastern Tibet. *National Science Review*, nwy062 (2018).
17. S. G. Zhilin, History of the development of the temperate forest flora in Kazakhstan, U.S.S.R. from the Oligocene to the Early Miocene. *The Botanical Review* **55**, 205–330 (1989).

18. J. Zachos, M. Pagani, L. Sloan, E. Thomas, K. Billups, Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* **292**, 686–693 (2001).

19. J. Yang, R. A. Spicer, T. E. V. Spicer, C.-S. Li, ‘CLAMP Online’: a new web-based palaeoclimate tool and its application to the terrestrial Paleogene and Neogene of North America. *Palaeobiodiversity and Palaeoenvironments* **91**, 163–183 (2011).

20. W. Wang, W. Zheng, P. Zhang, Q. Li, E. Kirby, D. Yuan, D. Zheng, C. Liu, Z. Wang, H. Zhang, J. Pang, Expansion of the Tibetan Plateau during the Neogene. *Nature Communications* **8**, 15887 (2017).

21. J. G. Ogg, in *The Geological Time Scale 2012*, F. M. Gradstein, J. G. Ogg, M. Schmitz, G. Ogg, Eds. (Elsevier, Amsterdam, 2012), pp. 5–113.

22. R. A. Spicer, S. Bera, S. De Bera, T. E. V. Spicer, G. Srivastava, R. Mehrotra, N. Mehrotra, J. Yang, Why do foliar physiognomic climate estimates sometimes differ from those observed? Insights from taphonomic information loss and a CLAMP case study from the Ganges Delta. *Palaeogeography, Palaeoclimatology, Palaeoecology* **302**, 381–395 (2011).

23. C. E. Forest, P. Molnar, K. A. Emanuel, Palaeoaltimetry from energy conservation principles. *Nature* **374**, 347–350 (1995).

24. R. E. Bosboom, G. Dupont-Nivet, A. J. P. Houben, H. Brinkhuis, G. Villa, O. Mandic, M. Stoica, W. J. Zachariasse, Z. Guo, C. Li, Late Eocene sea retreat from the Tarim Basin (west China) and concomitant Asian paleoenvironmental change. *Palaeogeography, Palaeoclimatology, Palaeoecology* **299**, 385–398 (2011).

25. N. Meijer, G. Dupont-Nivet, H. A. Abels, M. Y. Kaya, A. Licht, M. Xiao, Y. Zhang, P. Roperch, M. Poujol, Z. Lai, Z. Guo, Central Asian moisture modulated by proto-Paratethys Sea incursions since the early Eocene. *Earth and Planetary Science Letters* **510**, 73–84 (2019).

26. L. Araguás-Araguás, K. Froehlich, K. Rozanski, Stable isotope composition of precipitation over southeast Asia. *Journal of Geophysical Research Atmospheres* **103**, 28721–28742 (1998).

27. M. Jolivet, L. Barrier, O. Dauteuil, A. Laborde, Q. Li, B. Reichenbacher, S.-M. Popescu, J. Sha, Z. Guo, Late Cretaceous–Palaeogene topography of the Chinese Tian Shan: New insights from geomorphology and sedimentology. *Earth and Planetary Science Letters* **499**, 95–106 (2018).

28. J. K. Caves, D. J. Sjostrom, H. T. Mix, M. J. Winnick, C. P. Chamberlain, Aridification of Central Asia and uplift of the Altai and Hangay Mountains, Mongolia: Stable isotope evidence. *American Journal of Science* **314**, 1171–1201 (2014).

29. W. H. Amidon, S. A. Hynek, Exhumational history of the north central Pamir. *Tectonics* **29**, TC5017 (2010).

30. G. Dupont-Nivet, C. Hoorn, M. Konert, Tibetan uplift prior to the Eocene-Oligocene climate transition: Evidence from pollen analysis of the Xining Basin. *Geology* **36**, 987–990 (2008).

31. M. K. Clark, K. A. Farley, D. Zheng, Z. Wang, A. R. Duvall, Early Cenozoic faulting of the northern Tibetan Plateau margin from apatite (U–Th)/He ages. *Earth and Planetary Science Letters* **296**, 78–88 (2010).

32. L. Ding, R. A. Spicer, J. Yang, Q. Xu, F. Cai, S. Li, Q. Lai, H. Wang, T. E. V. Spicer, Y. Yue, A. Shukla, G. Srivastava, M. A. Khan, S. Bera, R. Mehrotra, Quantifying the rise of the Himalaya orogen and implications for the South Asian monsoon. *Geology* **45**, 215–218 (2017).

33. F. Cheng, C. N. Garzione, M. Jolivet, Z. Guo, D. Zhang, C. Zhang, Q. Zhang, Initial Deformation of the Northern Tibetan Plateau: Insights From Deposition of the Lulehe

Formation in the Qaidam Basin. *Tectonics* **38**, https://doi.org/10.1029/2018TC005214 (2019).

34. M. A. Khan, R. A. Spicer, S. Bera, R. Ghosh, J. Yang, T. E. V. Spicer, S. Guo, T. Su, F. Jacques, P. J. Grote, Miocene to Pleistocene floras and climate of the Eastern Himalayan Siwaliks, and new palaeoelevation estimates for the Namling–Oiyug Basin, Tibet. *Global and Planetary Change* **113**, 1–10 (2014).
35. S. E. Fick, R. J. Hijmans, WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* **37**, 4302–4315 (2017).
36. K. R. Sperber, H. Annamalai, I. S. Kang, A. Kitoh, A. Moise, A. Turner, B. Wang, T. Zhou, The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. *Climate Dynamics* **41**, 2711–2744 (2013).
37. D. J. Lunt, A. Farnsworth, C. Loptson, G. L. Foster, P. Markwick, C. L. O'Brien, R. D. Pancost, S. A. Robinson, N. Wrobel, Palaeogeographic controls on climate and proxy interpretation. *Climate of the Past* **12**, 1181–1198 (2016).
38. P. J. Valdes, E. Armstrong, M. P. S. Badger, C. D. Bradshaw, F. Bragg, T. Davies-Barnard, J. J. Day, A. Farnsworth, P. O. Hopcroft, A. T. Kennedy, N. S. Lord, D. J. Lunt, A. Marzocchi, L. M. Parry, W. H. G. Roberts, E. J. Stone, G. J. L. Tourte, J. H. T. Williams, The BRIDGE HadCM3 family of climate models: HadCM3@Bristol v1.0. *Geoscientific Model Development* **10**, 3715–3743 (2017).

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Competing interests: The authors declare that they have no competing interests.

Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or Supplementary Materials. Additional data related to this paper may be requested from the authors.

Figures and Tables

Fig. 1. Landform map of the Qaidam Basin. The fossil locality is indicated by a trifoliate leaf symbol.

Fig. 2. Middle part of the Dahonggou section that preserves the studied plant fossils. (A) Stratigraphic column of the studied section. This is located in the lower member of

Shangganchaigou Formation, the northern Qaidam Basin. Shown is the magnetostratigraphic correlation, the chronology and the lithology of the studied section, as well as the chronologic and stratigraphic position of the plant fossil locality (indicated by a simple leaf). (**B**) Satellite image of the studied section showing the position of the plant fossil locality (indicated by a simple leaf).

Fig. 3. Early Oligocene Qaidam plant fossils. Material recovered from the lower member of Shangganchaigou Formation in the Dahonggou section, northern Qaidam Basin. All scale bars = 1 cm. (**A to U**) Representative specimens of the 21 morphotypes of woody dicot leaves. (**C, G, H**) *Populus*. (**O, R**) *Podocarpium*. (**V**) Fruit of *Cyclocarya*. (**W**) Single-seeded pod of *Podocarpium*. (**X**) Fruit of *Populus*. (**Y**) Leafy shoot of *Glyptostrobus*. (**T**) *Cercidiphyllum*.

Table 1. The modern and paleoclimate of the northern Qaidam Basin during early Oligocene estimated using CLAMP WC2Asia2 Calibration dataset. Modern values are from the Daqaidam meteorological station (37.85° N, 95.37° E, 3173.2 m a.m.s.l.). The paleolatitude and longitude are derived from Getech Plc. Rupelian plate rotations used in the GCM. Climatic parameters are: mean annual temperature (MAT), warm month mean temperature (WMMT), cold month mean temperature (CMMT), length of growing season (LGS), growing season precipitation (GSP), mean monthly growing season precipitation (MMGSP), three wettest months precipitation (3WET), three driest months precipitation (3DRY), relative humidity (RH), specific humidity (SH), enthalpy (ENTH), annual mean vapor pressure deficit (VPD.ANN), mean vapor pressure during the three summer months (VPD.SUM), mean vapor pressure deficit during the three winter months (VPD.WIN), mean vapor pressure during the spring months (VPD.SPR), mean vapor pressure during the three fall months (VPD.AUT), mean annual potential evapotranspiration (PET.ANN), mean potential evapotranspiration during the warmest month (PET.WRM), mean

potential evapotranspiration during the coldest month (PET.CLD), mean minimum temperature during the warmest month (MINT.W), and the mean maximum temperature during the coldest month (MAXT.C). The growing season is defined as the period measured in months during which the mean temperature is ≥ 10°C.

VARIABLE	UNITS	QAIDAM (Modern)	QAIDAM (Fossil)	UNCERTAINTY (□)
Age	Ma	0	30.8	-
Latitude	Decimal °	37.85	37.47	-
Longitude	Decimal °	95.37	95.22	-
Paleolatitude	Decimal °	-	38.55	-
Paleolongitude	Decimal °	-	88.19	-
MAT*	°C	1.9	11.6	2.4
WMMT*	°C	15.5	23	2.9
CMMT*	°C	-13.4	1.4	3.5
LGS*	months	3	7.4	1.1
GSP*	cm	5.76	122.9	64.3
MMGSP*	cm	1.92	14	6.5
3WET*	cm	5.76	64.10	40
3DRY*	cm	0.26	22.5	9.8
RH.ANN*	%	35	62.9	10.2
SH.ANN*	g/kg	-	5.8	1.8
ENTH*	kJ/kg	-	307.5	8
VPD.ANN	hPa	-	5.5	2.4
VPD.SUM	hPa	-	10.0	3.5
VPD.WIN	hPa	-	2	1.5
VPD.SPR	hPa	-	3.3	4
VPD.AUT	hPa	-	6.8	2
PET.ANN	cm	-	989	162
PET.WRM	mm	-	143	24.4
PET.CLD	mm	-	23.4	13.9
MINT.W	°C	-	17.6	2.9
MAXT.C	°C	-	6.3	3.5

Supplementary Materials

Fig. S1. Stratigraphic column of the Dahonggou section. The Dahonggou section studied here is measured on the southern limb of the Dahonggou anticline, northern Qaidam Basin. It is well exposed, more than 5 km thick, and consists of Lulehe Formation, Xia Ganchaigou Formation, Shang Ganchaigou Formation, Xia Youshashan Formation, Shang Youshashan Formation and Shizigou Formation from bottom upwards. The section is further subdivided into 584 beds. Dip direction varies southward from 20°–30° in the anticline core, to 45°–55° in the middle part, and becomes shallower toward the top.

Fig. S2. CLAMP plots showing the position of the early Oligocene Qaidam fossil leaf assemblage in PhysgASia2 calibration space. The fossil leaf assemblage is shown as a red dot, the modern vegetation samples as open black circles. Climate vectors are shown in blue. **(a)** canonical correspondence analysis (CCA) plot of axes 1 v 2. **(b)** CCA plot of axes 1 v 3. **(c)** CCA plot showing axes 2 v 3. The fossil assemblage lies within the PhysgAsia2 physiognomic space showing the calibration is appropriate for this assemblage.

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