REPORTS

ASIAN ARCHAEOLOGY

Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 B.P.

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Our understanding of when and how humans adapted to living on the Tibetan Plateau at altitudes above 2000 to 3000 meters has been constrained by a paucity of archaeological data. Here we report data sets from the northeastern Tibetan Plateau indicating that the first villages were established only by 5200 calendar years before the present (cal yr B.P.). Using these data, we tested the hypothesis that a novel agropastoral economy facilitated year-round living at higher altitudes since 3600 cal yr B.P. This successful subsistence strategy facilitated the adaptation of farmers-herders to the challenges of global temperature decline during the late Holocene.

The Tibetan Plateau retains traces of an intermittent human presence from at least 20,000 years ago. Much of this comes in the form of surface finds of worked stone (*1*), but among them are a series of finds with a secure scientific date. Handprints and footprints from this date have been found in the southern plateau (Quesang site) at 4200 m above sea level (masl) (*2*). Archaeological traces are found from 14,600 calendar years before the present (cal yr B.P.). at Jiangxigou 1 (~3200 masl) and 13,100 cal yr B.P. at Heimahe 1 (~3200 masl) (*3*), 9200 cal yr B.P. at Xidatan 2 (~4300 masl) (*4*), and 7500 cal yr B.P. at Yeniugou (3800 masl) in the northeastern part of the plateau (*5*). The evidence in each case comprises animal bones, stone artefacts, and small-scale hearths. Humans clearly reached those altitudes, plausibly in pursuit of game. Although various potential models for human activity in this early episode have been considered (*1*), evidence securely dated to this period at these altitudes reflects the use of stone tools, the lighting of fires, and the processing of hunted carcasses. It may be equated with hunting camps, in most cases used for a single episode. Evidence for sustained agricultural and artisanal activity is lacking.

From the 6th millennium B.P. onward, the northeastern Tibetan Plateau (hereafter NETP) became the principal region of human settlement on the Tibetan Plateau, accounting for 72.4% of its known prehistoric sites (Fig. 1) (*6*–*9*). These are primarily the sites of farming settlements, associated with the reaches of the Yellow River and its tributaries. The NETP constitutes an altitudinal entry point into the higher plateau from the adjacent Loess Plateau (Fig. 1), with which it shares a series of Neolithic and Bronze Age material cultures (*10*). These include the late Yangshao (5500 to 5000 cal yr B.P.), Majiayao (5300 to 4000 cal yr B.P.), Qijia (4100 to 3600 cal yr B.P.), Xindian (3400 to 2700 cal yr B.P.), Kayue (3600 to 2600 cal yr B.P.), and Nuomuhong (3400 to 2800 cal yr B.P.) cultures (text S1). In order to ascertain during what period, and at what altitude, sustained food production first enabled an enduring human presence, we collected artefacts, animal bones, and plant remains from a selection of sites within these cultures. Fifty-three NETP sites (text S2) were thus selected to provide an optimal chronological and geographical range. To establish a secure chronology, 63 charred grains were collected for accelerator mass spectrometry (AMS) radiocarbon dating (*11*) (table S1).

We identified charred cereal grains from all 53 sites (foxtail millet, broomcorn millet, barley, and wheat) and animal bones and teeth from 10 sites (sheep, cattle, and pig) (table S1). Among the 53 sites, an earlier group of 25 sites dates to 5200 to 3600 cal yr B.P. (Fig. 2C and table S1) and reaches a maximum elevation of 2527 masl. A later group of 29 sites dating to 3600 to 2300 cal yr B.P. approaches an elevation of 3400 masl, among which 12 sites lie between 2500 to 1700 masl, 9 sites between 3000 to 2500 masl, and 8 sites between 3400 to 3000 masl.

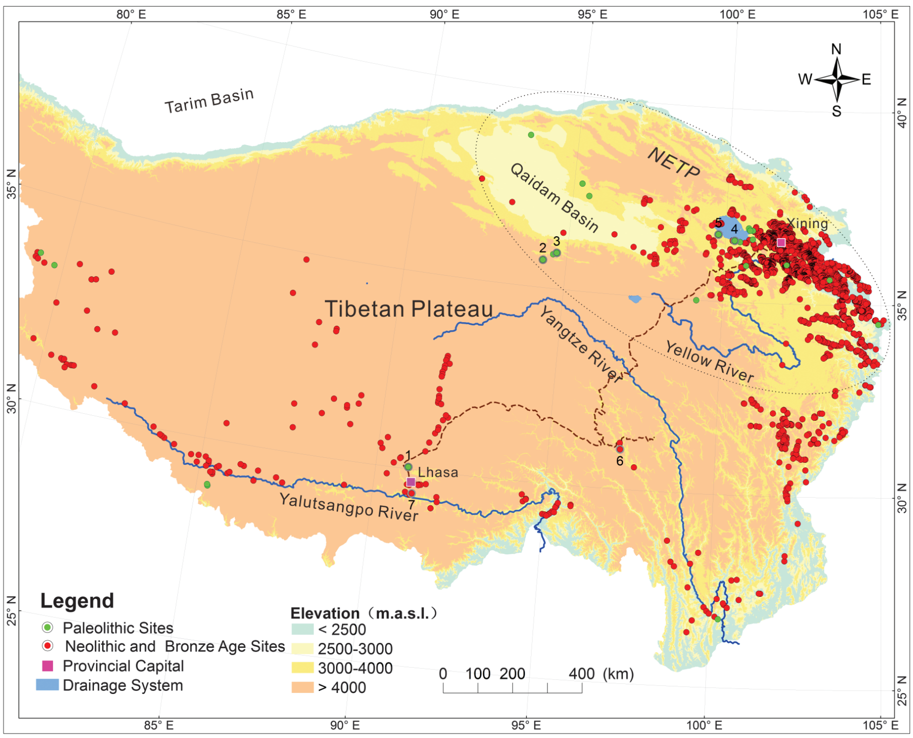

Fig. 1. Distribution of prehistoric sites on the Tibetan Plateau (*2*–*10*). The brown dashed line indicates the Tang-Tibetan routeway in use over the past 2000 years. Solid green circles with numbers indicate dated Paleolithic sites in the Tibetan Plateau mentioned in the text: 1, Quesang; 2, Xidatan 2; 3, Yeniugou; 4, Jiangxigou 1; 5, Heimahe 1. Solid red circles with numbers indicate Neolithic and Bronze Age sites mentioned in the text: 6, Karuo; 7, Changguogou.

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The earlier group reflects the widespread settlement within the NETP of farming communities along the Yellow River and its tributaries at elevations below ~2500 masl. Foxtail millet and broomcorn millet account for 98.1% of the recovered charred cereal grains (table S1), indicating that millets constituted the primary crops during this period, a conclusion also supported by stable carbon isotope studies (text S3 and fig. S5). Taken together with the material culture evidence, we can view this occupation of the higher reaches of the Yellow River as an extension of the expansion of millet agriculture across the middle and lower reaches in preceding millennia (*12*). The apparent limits of farming settlement around 2500 masl in NETP before 3600 cal yr B.P. may in turn be related to the frost sensitivity of millet crops (*13*, *14*), as has been shown for the southwestern Tibetan Plateau (*15*).

The later groups of sites do not share the same altitudinal constraint. Among the selected samples are sites reaching 3400 masl, and in the wider landscape are contemporary sites with a similar material culture reaching 4700 masl (*6*). These higher-altitude sites moreover display a shift in the balance of crops among the charred grains. Although the same suite of crops may be found at both lower and higher altitudes, the lower-altitude assemblages are dominated by millet but the higher-altitude assemblages by barley, with an occasional record of wheat and broomcorn millet. Sites located above 3000 masl are also marked by the presence of sheep bones.

The presence of crops and livestock in itself indicates a more sustained human presence than what is needed to hunt game at high altitudes. Although more frost-hardy than millets, barley has a longer growing season, typically requiring 6 months between sowing and harvest (*16*). Other evidence [for example, of house and tomb construction (*10*)] further endorses the notion of a sustained and probably year-round human presence.

On the basis of the above evidence, the prehistoric human occupation of the NETP can be subdivided into three phases. During the first phase (pre–5200 cal yr B.P.), hunter-gatherers made occasional forays to altitudes reaching above 4300 masl, presumably tracking game. During the second phase (5200 to 3600 cal yr B.P.), a longstanding tradition of millet farming that had become widely established along the middle and lower reaches of the Yellow River extended upstream into the NETP. Millet farming had spread across the Loess Plateau after 5900 cal yr B.P. (*17*) and subsequently spread across these lower reaches of the NETP from 5200 cal yr B.P. Toward the end of the second phase (4000 and 3600 cal yr B.P.), two significant additions are observed in the crop repertoire (text S4 and fig. S6). The North Chinese crops of broomcorn and foxtail millet were joined or displaced on some sites by the principal cereals of the Fertile Crescent, barley and wheat. There has been much interest in the chronology and consequences of the meeting of east and west staple crops in prehistory (*18*–*20*). Here, its notable consequence was to facilitate the sustained settlement of the Tibetan Plateau's higher altitudes. The importation of wheat and barley enabled human communities to adapt to the harsher conditions of higher altitudes in the Tibetan Plateau, a possibility raised in previous studies (*15*, *21*).

The key addition was barley. During phase three, from around 3600 cal yr B.P., sites can be divided into those that lie above or below 2500 masl. In the lower-altitude group, the longstanding crops, broomcorn and foxtail millet, are joined by barley as a third component in an otherwise traditional dietary repertoire. In the higher-altitude group, however, the frost-sensitive millet is absent, and the cold-tolerant barley has moved to a primary position (Fig. 2D). Alongside the presence of wheat (also relatively cold-tolerant) and sheep, the diet at these high altitudes has clearly been transformed, but in a manner that enabled sustained settlement at unprecedented altitudes.

Fewer sites have been investigated in detail in areas beyond our study area on the plateau; the evidence they yield is consistent with the pattern that has been noted here and in (*22*). Ecological niche modeling on the southeastern Tibetan Plateau has shown that the warmer condition of more southerly latitudes raised the altitude that millets were able to reach at Karuo between 4700 and 4300 cal BP to 3100 masl (*15*, *22*, *23*). During our phase three, agriculture reached even higher elevations in the south-central Tibetan Plateau. For example, Changguogou (Fig. 1) was occupied after 3500 cal yr B.P. at an elevation of 3600 masl, growing a range of Fertile Crescent crops, including naked barley, wheat, oat, rye, and pea alongside foxtail millet (*24*).

Turning to the climatic context, during the early and middle Holocene the summer monsoon was strong in north China and the climate was generally warm in the Northern Hemisphere (Fig. 2, A and B) (*25*, *26*). These relatively favorable conditions provided a context both for the earlier forays of hunter-gatherers into higher altitudes and the broader expansion of millet agriculture in northern China. The Northern Hemisphere temperature curve displays a significant temperature drop throughout our second phase, reaching a minimum at the start of our third phase (*26*). In other words, the human expansion into the higher, colder altitudes took place as the continental temperatures had themselves become colder.

In our third phase, the evidence displays two aspects of the human response to this cooling of climatic change. The established farming landscapes of the lower altitudes retained their

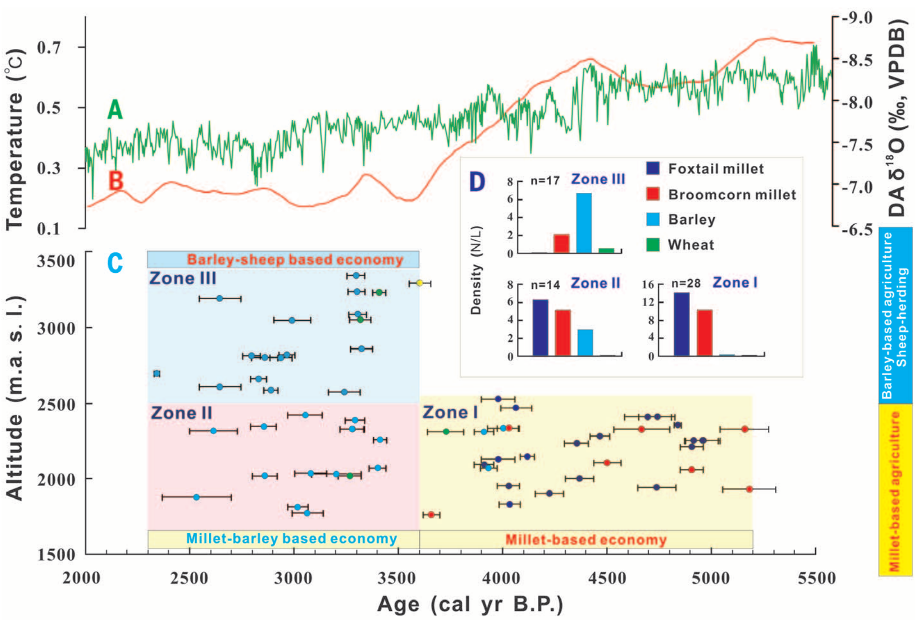

Fig. 2. Climatic records, radiocarbon dates, and charred cereal grain records from 53 investigated sites on the NETP. (**A**) Asian summer monsoon changes indicated by Dongge Cave speleothem oxygen isotopes (*25*). (**B**) Northern Hemisphere (30° to 90°N) temperature record compared to 1961–1990 instrumental mean temperature (*26*). (**C**) Calibrated AMS radiocarbon dates of charred grains (solid symbols with 2σ error bar) from 53 investigated sites of different archaeological cultures on the NETP and their altitudes (table S1). Zone I includes 25 sites dated between 5200 and 3600 cal yr B.P., and zones II and III include 12 sites and 17 sites dated between 3600 and 2300 cal yr B.P., below and above 2500 m.a.s.l., respectively. Circle colors indicate crops as in (D), with the addition of capers indicated in yellow. (**D**) Density variation of crop remains from flotation samples from zones I, II and III. *N* = number of charred grains, *n* = number of flotation samples.

essential crop repertoire, buffered against temperature change with the significant addition of cold-hardy barley. That same combination of crops additionally enabled the establishment of farms at altitudes hitherto uncultivated, taking farming in some places to elevations above 4000 masl.

Several features of this high-altitude farming prompt further questions about adaptive response. As indicated at the outset, these may include genetic resistance in humans to altitude sickness (*27*); genetic response in crop plants that is observable in the genetics of barley, in relation to such attributes as grain vernalization, flowering time response, and ultraviolet radiation tolerance (*28*); and the identity, genetic and ethnic, of the human communities themselves (*1*, *29*). Such genetic outcomes are all consequent upon the ecological trajectories of cross-continental crop movement. Elsewhere in Europe, Asia, and Africa, that movement has been seen to have a wide variety of outcomes. In the NETP, the data presented here document its facilitation of cultivating the "roof of the world."

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S6
Tables S1 to S3
References (*30*–*44*)

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ANIMAL PHYSIOLOGY

The roller coaster flight strategy of bar-headed geese conserves energy during Himalayan migrations

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The physiological and biomechanical requirements of flight at high altitude have been the subject of much interest. Here, we uncover a steep relation between heart rate and wingbeat frequency (raised to the exponent 3.5) and estimated metabolic power and wingbeat frequency (exponent 7) of migratory bar-headed geese. Flight costs increase more rapidly than anticipated as air density declines, which overturns prevailing expectations that this species should maintain high-altitude flight when traversing the Himalayas. Instead, a "roller coaster" strategy, of tracking the underlying terrain and discarding large altitude gains only to recoup them later in the flight with occasional benefits from orographic lift, is shown to be energetically advantageous for flights over the Himalayas.

Migrating birds must overcome many challenging environmental obstacles, such as arid deserts (*1*, *2*) and featureless oceans (*3*–*5*), but few are capable of negotiating the formidably high mountains separating the Indian subcontinent from central Asia. Famously, one species that manages this feat is the bar-headed goose (*Anser indicus*), which biannually traverses the high passes of the Tibetan massif and snow-capped Himalayan mountains (*6*–*8*). Over the years, there has been much debate as to how high these birds might fly and what physiological mechanisms could be involved at the highest altitudes (*8*–*12*), but, although one goose has been directly tracked as high as 7290 m for a brief period (*12*), no measurements of their physiological or biomechanical flight performance have been made in the wild.

To investigate the flight dynamics and energetics of migratory bar-headed geese, we used custom-designed implantable instruments (*13*) to measure abdominal temperature and pressure (every 30 s), tri-axial acceleration (100 Hz in 18-s bursts every 2 min), and electrocardiography (180 Hz in the same 18-s period) from seven birds, collecting data totaling 391 hours of migratory flight (Fig. 1). The data loggers weighed 32 g and were housed in biocompatible tubing (dimensions 7 × 2 cm) capped by titanium electrodes.

Abdominal body temperature during flight (40.2°C ± 1.2 SD) tended to increase in tandem with flight activity, especially during times of

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Science

Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 B.P.

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Colonizing the roof of the world
Humans only settled permanently on the Tibetan plateau about 3600 years ago. Chen *et al.* examined archaeological crop remains unearthed in northeastern Tibet, which elucidate the timing of agricultural settlement. Although much earlier traces of humans in Tibet have been dated to 20,000 years ago, year-round presence at the highest altitudes appears to have been impossible until the advent of suitable crops, such as barley. Surprisingly, these prehistoric farming communities expanded onto the plateau at the same time as climate was cooling.
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