REPORT

ARCHAEOLOGY

# Permanent human occupation of the central Tibetan Plateau in the early Holocene

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**Current models of the peopling of the higher-elevation zones of the Tibetan Plateau postulate that permanent occupation could only have been facilitated by an agricultural lifeway at ~3.6 thousand calibrated carbon-14 years before present. Here we report a reanalysis of the chronology of the Chusang site, located on the central Tibetan Plateau at an elevation of ~4270 meters above sea level. The minimum age of the site is fixed at ~7.4 thousand years (thorium-230/uranium dating), with a maximum age between ~8.20 and 12.67 thousand calibrated carbon-14 years before present (carbon-14 assays). Travel cost modeling and archaeological data suggest that the site was part of an annual, permanent, preagricultural occupation of the central plateau. These findings challenge current models of the occupation of the Tibetan Plateau.**

The nature and timing of a permanent human settlement on the Tibetan Plateau and the accompanying cultural and physiological responses, including genetic adaptations, that facilitate life at high altitude are subject to ongoing debate (*1*–*5*). Tibet forms the high-altitude core of Asia (Fig. 1), and although access to the northeastern fringes of the plateau from the adjacent north Asian lowlands via the Yellow River and the Qinghai basin is relatively easy, venturing into the core of the plateau—with elevations well above 4000 m above sea level (masl) and cold, arid, and periglacial conditions—is considerably more challenging. Permanent human occupation of the Tibetan Plateau was thus impeded by the combined effects of remoteness, low primary productivity, and topography, as well as by the physiological constraints of cold stress and hypoxia (*6*). The climatic and paleoenvironmental constraints on this colonization process are poorly understood (*7*–*9*). The number of chronometrically dated archaeological sites remains small, and most of them are located on the northeastern margin of the plateau (*1*, *7*, *10*). Ranging in date from ~9 to 15 thousand calibrated $^{14}C$ years before present (thousand years cal. B.P.), these sites typically are at medium to low elevations (≤3300 masl) and are believed to have been short-term, seasonal occupations monitored from lower-elevation base camps (*7*, *10*).

Current archaeological models that address the timing of a permanent occupation on the high-elevation step of the plateau postulate that it could only have been facilitated by the advent of an agropastoral economy, perhaps as early as ~5.2 thousand years cal. B.P., and more certainly, with the establishment of permanent villages fully reliant on agriculture, by ~3.6 thousand years cal. B.P. (*1*, *4*, *5*). The presence of securely dated sites older than 5.2 thousand years from the interior, high-elevation step of the plateau would challenge these models and would be consistent with research on the genetics of modern Tibetan Plateau peoples, which suggests the presence of a permanent population on the high central plateau dating to at least 8.0 to 8.4 thousand years ago, and possibly as early as the Late Paleolithic (*11*–*15*).

Here we report the results of an extensive reanalysis of the geochronology, paleoenvironment, and archaeology of the Chusang site, which is located on the central plateau ~80 km northwest of Lhasa at an elevation of ~4270 masl, near Chusang, a village known for its hydrothermal springs and extensive travertine formations (spring carbonates deposited by hydrothermal waters) (Fig. 1). The site, discovered in 1998, consists of 19 human hand- and footprints found on the surface of a fossil travertine that formed when hot spring discharge was much higher than it is today (*16*–*18*) (supplementary text and fig. S1). Size variation in the prints suggests that up to six individuals, including possibly two children, created them. Optically stimulated luminescence (OSL) dating of quartz grains extracted from the travertine has indicated that the imprints were created ~20 thousand years ago, making Chusang the only archaeological site from the interior of the plateau for which a Paleolithic age assignment is based on a chronometric date (*16*). However, the complex sedimentological and dosimetric setting at Chusang raises the possibility that the luminescence chronology is severely flawed (*7*, *8*).

Although there are other archaeological sites on the interior of the plateau of reputed Paleolithic age, all are stone tool assemblages of

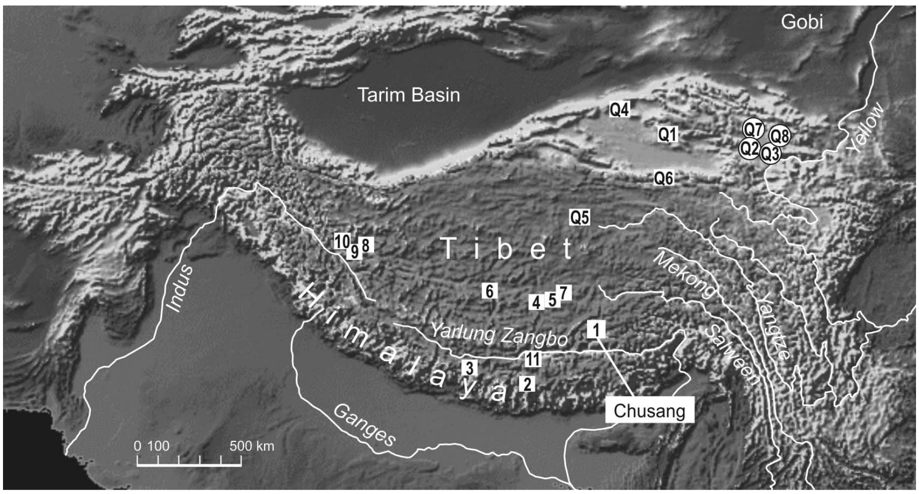


**Fig. 1. Paleolithic sites on the Tibetan Plateau.** Shown are sites with absolute age control (>10 thousand years cal. B.P.; circles) or a tentative Paleolithic age association (rectangles) based on typological cross-dating of lithic artifacts with sites of known age. A Q indicates a Qinghai site. 1, Chusang; 2, Su-re; 3, Ha-dong-tang and Que-de-tang; 4, Zhu-luo-le; 5, Siling-co; 6, Duo-ge-ze; 7, Ge-ting; 8, Zha-bu; 9, Xia-da Co; 10, Re-jiao; 11, Gong-ben; Q1, Xiao Qaidam; Q2, Heimahe 1; Q3, Jiangxigou 1; Q4, Lenghu 1; Q5, Wulanwula Lake; Q6, Yeniugou; Q7, Bronze Wine Canyon; Q8, Ten Hearths.

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surface finds (*7*, *10*), and none has been directly chronometrically dated. The lack of securely dated early sites on the central plateau makes a reanalysis of the chronology of Chusang relevant to a reassessment of current models of the peopling of the Tibetan Plateau (Fig. 1).

The hand- and footprints are scattered over an area ~20 by 30 m and occur at the surface of a single sheet of travertine (*16*) (fig. S1). This sheet is up to 1 m thick, extends for several tens of meters further to the east, and is underlain by colluvium (Fig. 2 and figs. S2 and S3). The imprints are between 2 and 7 mm deep, and the anatomical details of human hands and feet are well preserved (Fig. 3). The imprints were not engraved into the travertine, given that evidence for pecking, scratching, or carving is absent, but must have formed at a very early stage of hydrothermal carbonate formation (probably within a few months after calcite precipitation), when the top layer of the travertine was still soft and deformable under the weight of a human body. This mechanism is supported by petrographic evidence showing that the annual travertine layers directly below these imprints are continuous but bended (*17*) (Fig. 3C and supplementary text). A chronometric age for the travertine that carries the imprints will therefore constrain the time of human presence at these hydrothermal springs.

A thorough understanding of the sedimentology and petrology of the Chusang travertine, in tandem with the application of multiple dating techniques, is key to developing an accurate chronology for the travertine and the embedded hand- and footprints and also important for explaining the formation and preservation of the prints (*18*). The travertine is a fossil spring deposit with a total thickness of ~24 m. The upper ~11 m of the section are characterized by porous, detrital-rich travertine sheets that are up to 2 m thick and laterally extensive (Fig. 2 and and fig. S2). Numerous layers of colluvium [debris flows that originated from the adjacent hill slopes; labeled as diamict massive stratified (Dms) 1 to 4 in Fig. 2 and fig. S2] are intercalated into this upper travertine section. The colluvial layers are typically 0.5 to 2 m thick and can contain (mostly microscopic) organic material. Sedimentology and thin-section microscopy (supplementary text and figs. S4 and S5) show that the travertine sheets (including the imprinted travertine) (i) are annually layered on the centimeter scale (porous summer and dense winter layers), (ii) often have clastic microfabrics (e.g., clasts of redeposited travertine), (iii) have microfabrics that are typical for hydrothermal spring carbonates (dendritic crystals), and (iv) precipitated synchronously with clastic sediment input (debris flows) from the hill slopes. Many of the fabrics show evidence for recrystallization. In contrast to this detrital-rich travertine-colluvium succession, relatively dense and clean cements are encountered in the pore spaces of the imprinted travertine (Fig. 3C).

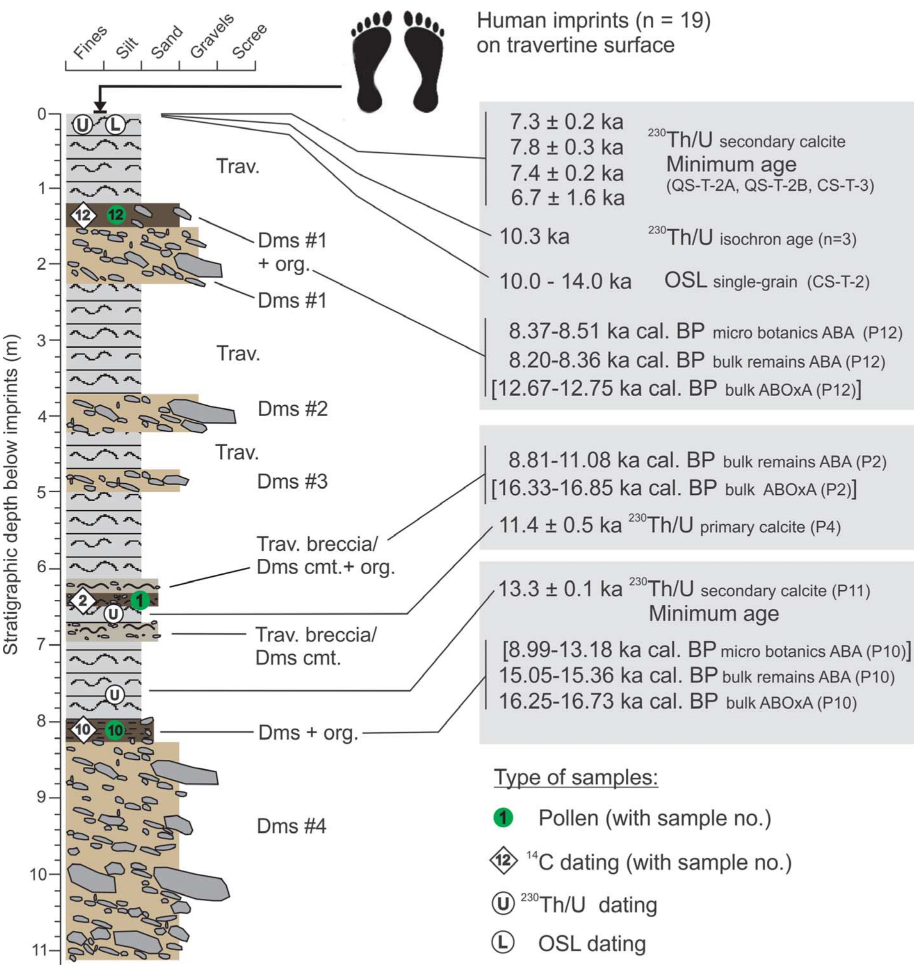


**Fig. 2. Stratigraphic profile of the Chusang travertine with embedded human hand- and footprints, shown with absolute age control data.** The horizontal axis indicates grain size. Radiocarbon ages in square brackets are further discussed in (*19*). Trav., travertine; Dms, diamict massive stratified (colluvium composed of debris flows); cmt., carbonate-cemented; + org., containing organic matter; ABA, acid-base-acid pretreatment; ABOxA, acid-base–wet oxidation–acid pretreatment; ka, thousand years.

A total of 11 samples (nine travertine and two colluvium) were collected from the upper travertine section for $^{230}$Th/U, OSL, and radiocarbon dating, as well as for palynological analysis (fig. S1). Of the nine travertine samples, three were retrieved directly adjacent to imprints, two from the same stratigraphic horizon as the imprints, and the remaining four samples from deeper stratigraphic levels. The two colluvium samples were collected from stratigraphic positions directly below and 8.2 m below the imprinted travertine sheet (fig. S1 shows the sampling locations). The details of each dating method are discussed in the supplementary materials and methods (*19*) and summarized into one chronology (Fig. 2).

Travertine is in principle amenable to $^{230}$Th/U dating, but the high detrital content and diagenetic alteration (recrystallization) of the Chusang travertine impede routine dating. Hence, we followed a modified dating protocol and mapped and subsampled individual (preferentially primary and dense) microfabrics to minimize the risk of sampling altered, potentially recrystallized carbonate (*19*). We used an isochron approach to account for considerable and variable detrital contamination. Multiple subsamples can also help to identify potential problems arising from open system behavior. Where thick enough, clean and dense pore cements were targeted for $^{230}$Th/U dating as well. The three $^{230}$Th/U isochron ages from the travertine sheet that carries the human imprints have very low precision (typically 50% relative error and larger), and the isochron plots indicate more than two isotopic end members (table S1). We conclude that, despite our attempt to sample single mineral phases, the intergrowth of different crystal microfabrics and/or recrystallization (potentially entailing open system behavior) have had severe impacts on the isotopic system and thus have hampered our ability to retrieve $^{230}$Th/U ages of acceptable precision. Nevertheless, all isochron plots (i) broadly confirm bulk Earth values for the initial $^{238}$U/$^{232}$Th activity ratio and (ii) return early Holocene ages (average of 10.3 thousand years), pointing toward a certain degree of consistency in the $^{230}$Th/U isochron data (*19*). The $^{230}$Th/U ages of different

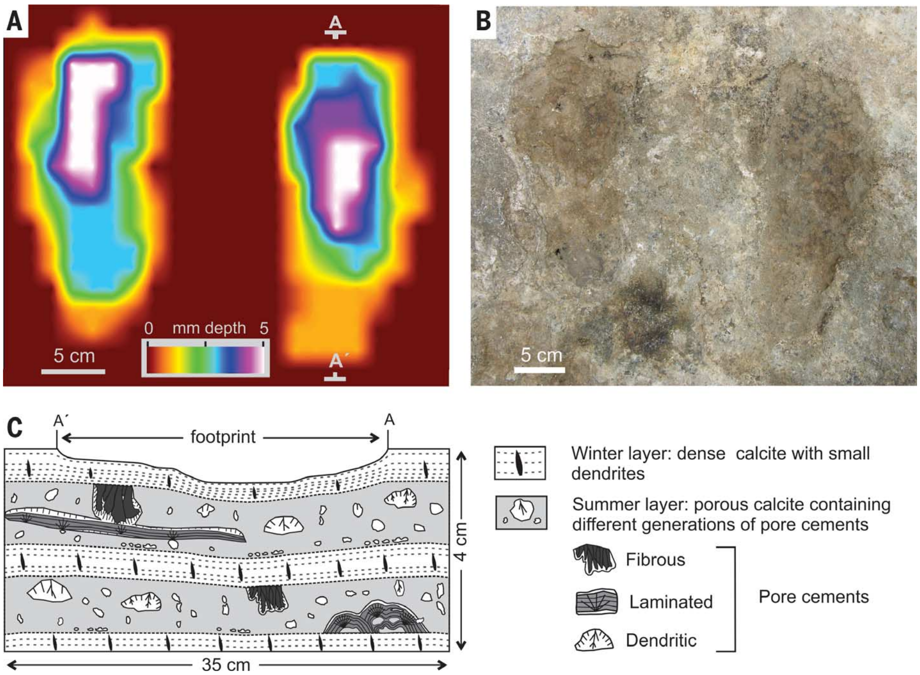


**Fig. 3. Well-preserved human footprints at Chusang.** The footprints are visualized with (**A**) a three-dimensional model and (**B**) a corresponding field image. (**C**) The annual travertine layers below the imprints are bended, suggestive of human presence during travertine formation. The porous summer layers contain numerous cement generations that precipitated shortly after travertine deposition. For the laminated pore cement, a $^{230}$Th/U age of 7.4 thousand years was obtained, providing a robust minimum age for the imprints.

types of pore cements obtained from the same samples are typically more precise and vary from ~5.3 to 7 thousand years (table S1). Most important for assigning a minimum age to the human hand- and footprints is the oldest generation of pore cements—a dense, clean, and laminated calcite for which four subsamples from three travertine samples (all adjacent to the imprints) yielded a weighted mean age of 7.4 ± 0.1 thousand years (Fig. 2). $^{230}$Th/U ages from samples obtained further down-section (a dense travertine sample from 6.6 m and a flowstone sample that precipitated in a fracture at 7.6 m below the imprints; Fig. 2) increase with depth and are thus in stratigraphic order.

For OSL dating, sand-sized quartz grains were extracted from the three travertine samples collected from the imprinted travertine sheet. Only one sample (CS-T-2) yielded enough quartz for dating. A single-grain approach was used for paleodose (De) estimation to investigate partial bleaching (*19*). Determination of the environmental dose rate was aided by modeling to handle disequilibria in the radioisotope decay chains and to constrain the effect of different burial scenarios on the OSL age (*19*) (fig. S6 and tables S2 and S3). The single-grain De distribution is 37% overdispersed (fig. S6), and petrographic thin-section analysis revealed a clastic microfabric in sample CS-T-2 (rounded to subangular travertine clasts that are suggestive of short transport distances; fig. S5). Both observations suggest that the OSL signals of these quartz grains were incompletely reset during transport (i.e., partially bleached) and that a minimum age model is appropriate for De calculation (*20*). Combining the minimum De value of sample CS-T-2 with the minimum and maximum dose rate scenarios constrains the age of the imprinted travertine sheet to ~10 to 14 thousand years (Fig. 2).

Radiocarbon dating was conducted on both the bulk sediment and on microscopic plant remains of two colluvial sediment samples and one clastic but organically rich travertine sample. For the bulk sediment dating fractions, radiocarbon ages were obtained using both the ABA (acid-base-acid) and ABOxA (acid-base–wet oxidation–acid) pretreatment techniques, whereas the microbotanic dating fractions were ABA-pretreated only (*19*). The organically rich colluvium layer from a stratigraphic position directly below the imprints (Dms 1, Fig. 2) yielded ages of ~8.20 to 8.36 and 8.37 to 8.51 thousand years cal. B.P. for the ABA-pretreated bulk and microbotanic fractions, respectively (table S4 and fig. S7). The age yielded for the ABOxA-pretreated bulk fraction of the same colluvium layer is significantly older (~12.67 to 12.75 thousand years cal. B.P.), but for methodological reasons, it may not be accurate (*19*). Radiocarbon ages increase down-section and broadly confirm the $^{230}$Th/U ages from 7.4 m depth (11.4 ± 0.5 thousand years) and 8.1 m depth (> 13.3 ± 0.14 thousand years), thus constraining the depositional history of the lower part of the travertine-colluvium succession to the latest Pleistocene (Fig. 2 and table S4).

The palynological data were obtained discontinuously along the stratigraphic profile and are best understood as paleoecological snapshots providing insights into three discrete time slices at ~15, 11, and 8.4 thousand years ago, respectively (*19*). In each, nonarboreal pollen predominates, suggesting that the landscape during the latest Pleistocene and early Holocene was an alpine steppe dominated by wormwood (*Artemisia*) and grasses (Poaceae; fig. S8). The palynological data do not support the presence of regional tree resources but indicate the presence of local shrubs [*Hippophae* (sea buckthorns)] and megaherbivores.

No artifacts were found near the travertine sheet with the embedded prints. An extensive pedestrian survey of the area surrounding the hot springs located two low-density concentrations of reduction by-products, localities A and B (fig. S9, A and O). The lithics at these localities reflect core-flake and blade-core technologies that are consistent with materials found in assemblages thought to date to the Late Paleolithic or early Holocene on the northeastern margin of the plateau (*10*, *21*, *22*). No microlithic tools or ceramics, which are generally indicative of mid-to-late Holocene occupations (*6*), were found at Chusang.

Although the geochronology of the site is complex, these lines of evidence show that the minimum age of the Chusang site, as dated by a consistent set of $^{230}$Th/U ages taken from a single generation of clean pore cement postdating the prints, is 7.4 ± 0.1 thousand years. Although we cannot state with certainty a maximum age for the site, we can offer two alternatives: (i) a maximum age of the prints of ~8.20 to 8.51 thousand years cal. B.P., constrained by $^{14}$C assays (ABA ages) of the colluvium immediately below the travertine sheet, or (ii) a maximum age of the prints of ~12.7 thousand years cal. B.P. (ABOxA age from the same colluvium), which is consistent with the OSL dates on travertine that range from 10.0 to 14.0 thousand years ago. For either scenario, these ages make Chusang the oldest reliably dated archaeological site on the high-elevation step of the Tibetan Plateau.

This finding has important implications for evaluating current models of the peopling of the Tibetan Plateau. For Chusang to be a station (*23*) or task-specific site monitored seasonally from a base camp at a lower elevation (<3300 masl), travel costs would have been considerable. Travel cost modeling shows that round-trip travel times from such a base camp would have minimally required 28 to 47 days (*19*) (fig. S11A). However, this route would have had to cross the eastern Himalayan range and would have been impassable for much of the year, especially during the early Holocene, because of the closure of high passes by heavy snowfall and expansion of valley glaciers in response to increased precipitation from the Indian summer monsoon (*9*, *24*). A more plausible route (fig. S11B) from the southeast shows a round-trip travel time of

41 to 70 days. Such travel is unlikely to have been undertaken for seasonal, short-term task pursuits in rugged, mountainous terrain, particularly by age-variable groups that may have included children, as is suggested by the presence of small footprints at Chusang (*17*, *25*). These estimates also exceed annual travel distances for most ethnographically known foraging peoples (*26*, *27*). Instead, the data from Chusang support a model of an annual settlement pattern focused on the high interior plateau that likely used adjacent valleys of the major river courses at elevations above 3600 masl. Although we cannot entirely rule out the possibility of the logistical use of Chusang by low-elevation foragers, our analyses of archaeological, geographic, demographic, environmental, and ethnographic evidence converge to suggest that this type of use was highly improbable.

The data from Chusang support the presence of an early, pre-agropastoral population on the high-elevation step of the Tibetan Plateau ~7.4 to 8.4 thousand years ago, although an earlier presence ~12 to 13 thousand years ago cannot be fully discounted. These dates are consistent with what is known of the ancestral genetics of modern Tibetans (*11*–*15*) and coincide with wet and humid climate conditions on the Tibetan Plateau that lasted from ~11.5 until 4.2 thousand years ago because of an enhanced Indian summer monsoon (*28*–*30*). Although an agropastoral lifeway may have enabled substantial population growth after 5 thousand years B.P., it by no means was required for the early, likely permanent, occupation of the high central valleys of the Tibetan Plateau.

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## SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/355/6320/64/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S16
Tables S1 to S5
References (*31*–*110*)

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# Permanent human occupation of the central Tibetan Plateau in the early Holocene

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**The peopling of Tibet**

The date of the first permanent human occupation of the high Tibetan Plateau has been estimated at about 3600 years ago, when agriculture became established. Meyer *et al.* used several dating techniques to analyze sediments at a high-altitude site (4270 m) where human handprints and footprints have been found. Their analysis indicates occupation of the plateau 7400 years ago and possibly earlier. These dates are consistent with the genetic history of Tibetans and suggest that a permanent preagricultural peopling of the plateau was enabled by the wetter regional climate at that time.

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