Science Advances

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Supplementary Materials for

Early isotopic evidence for maize as a staple grain in the Americas

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The PDF file includes:

Sections S1 and S2
Figs. S1 to S10

Other Supplementary Material for this manuscript includes the following:

(available at advances.sciencemag.org/cgi/content/full/6/23/eaba3245/DC1)

Tables S1 and S2

Section S1. Burial context descriptions

Mayahak Cab Pek:

MHCP.98.28.1 (PSUAMS-3775)
Individual MHCP.98.28.1 is a Native American juvenile estimated to be 2–2.3 years of age at death. Approximately 50% of the skeleton is present, with the lower half of the body poorly preserved. This individual was oriented in a prone, flexed position, with the head in the east, facing north.

MHCP.98.28.1b (PSUAMS-2148)
Individual MHCP.98.28.1b consists of several long bones from an Native American infant found in association with MHCP.98.28.1. Originally thought to be in association with MHCP.14.1.1, direct dating demonstrates that they are a separate individual.

MHCP.98.28.1c (UCIAMS-186361)
Individual MHCP.98.28.1c is the temporal bone of an Native American adult recovered from near the pelvis of MHCP.98.28.1.

MHCP.98.28.2 (PSUAMS-2145)
Individual MHCP.98.28.2 consists of the remains of a Native American young adult (approximately 20–30 years at death) of unknown sex. More than 75% of the skeleton is present. Differential preservation has rendered the bones of the lower extremity to be very fragmentary, while the upper body is well-preserved. This individual was buried in an extended, prone position with the head to the south, facing down. Arms were flexed with the hands resting near the sternum.

MHCP.98.34.3a (PSUAMS-4292)
Individual MHCP.98.34.3a is remains of an Native American infant (approximately 10.5 months of age at death), based on dental development. Skeletal remains are fragmentary and represent less than 25% of the skeleton. This individual is associated with MHCP.98.34.3b, which is a second infant represented by a left temporal bone, and MHCP.98.34.4a, an adult. Individual 3a was found in a flexed position, with the head to the north, and the body curving to the west.

MHCP.98.34.3b (UCIAMS-228019)
This individual is represented by a solitary left temporal of an Native American infant. It was recovered in the same context as MHCP.98.34.3a and MHCP.98.34.4. Burial position is unknown.

MHCP.98.34.4a (PSUAMS-3774)
Individual MHCP.98.34.4a consists of the partial remains of a Native American middle adult possible female. Skeletal remains are fragmentary and heavily degraded. The adult appears to have been buried in a flexed position with the head in the north, facing west. The burial feature also contained the remains of three infants, MHCP.98.34.3a and 3b and 4b (UCIAMS-228032). The latter is a Native American infant represented by a left temporal bone and is distinct from MHCP.98.34.3a based on AMS ^{14}C dating.

MHCP.98.3AN.5 (UCIAMS-228032)
This is the left femur of a Native American individual female in her late teens - early twenties (age. 16-24) based on fusing medial clavicle and iliac crest, barely fused thoracic vertebral annular epiphyses. The burial was disturbed, but primary and flexed, oriented with the head roughly to the north.

MHCP.98.3AN.7 (PSUAMS-2149)
Individual MHCP.98.3AN.7 is the poorly preserved remains of a Native American infant (approximately 0.5–2.5 years old at death). Less than 25% of the skeleton is present with only fragments of the cranium, ribs, and upper extremities recovered. This individual was oriented with the head in the north, flexed on its left side, facing east.

MHCP.97.0093 (PSUAMS-5899)
Individual MHCP.97.0093 consists of a Native American adult cranium that was excavated in 1997 when the shelter was first discovered by a previous project. The cranium was part of a larger disarticulated cluster of human remains of at least one adult and one child.

MHCP.14.1.1 (PSUAMS-2333)
Individual MHCP.14.1.1 consists of a Native American middle to late adult female. Preservation condition is poor, and less than 25% of the skeleton is present. The individual was tightly flexed in a supine position, with the knees and arms flexed over the chest; burial position was with the head oriented to the north, facing east/southeast. MHCP.14.1.1 was recovered with several infant bones that may be associated with MHCP.98.28.1.

MHCP.14.1.2a (PSUAMS-1401)
Individual MHCP.14.1.2a consists of the remains of a Native American subadult male (approximately 16–20 years old at death). Preservation is poor; bones are highly fragmented, and less than 25% of the skeleton is present. This individual was buried in a very tightly flexed seated position, with the head oriented to the north, facing south. The burial feature also contains comingled remains of individual MHCP.14.1.2b.

MHCP.14.1.3 (UCIAMS-156914 and PSUAMS-1400)
Individual MHCP.14.1.3 is a Native American older female adult (over 50 years old at time of death). Preservation is excellent and over 75% of the skeleton is present. This individual was buried in a tightly flexed position on their left side, head oriented to the north, facing east.

MHCP.14.1.5a (PSUAMS-1402)
Individual MHCP.14.1.5a is a Native American male subadult (approximately 11–15 years old at death). Approximately 75% of the skeleton is present, with preservation condition ranging from fair to very good. This individual was buried in a flexed position on their right side; the head was in the north facing east. Comingled elements of a second individual were found in the burial fill and are designated as individual MHCP.14.1.5b.

MHCP.14.1.5b (UCIAMS-151853)
Individual MHCP.14.1.5b is the comingled remains of a second Native American individual associated with MHCP.14.1.5a. At least one adult individual is present. Extensive taphonomic damage to these elements relative to those in MHCP.14.15a suggests that the burial feature containing MHCP.14.1.5b, which has a slightly older date may have been intruded into by MHCP.14.15a.

MHCP.14.1.6 (UCIAMS-151854 and UCIAMS-151855)
Individual MHCP.14.1.6 consists is a Native American middle to old adult female. Approximately 75% of the skeleton was recovered and is in fair condition. Within the burial feature the majority of the remains were disarticulated and placed in a tight cluster, though several instances of anatomical articulation were observed.

MHCP.14.2.4a (UCIAMS-186360)
Individual MHCP.14.2.4a is a Native American adult male. Condition of the remains is poor, and most recovered elements are highly fragmented. This individual was buried in an extended supine position, with the head oriented to the north. This burial is associated with a perinate (MHCP14.2.4c) recovered from around the pelvic region. This

burial feature also contained the comingled remains of a duplicate right radius representing individual MHCP.14.2.4b and an infant individual MHCP.12.2c.

MHCP.14.2.4b (PSUAMS-2332)
Individual MHCP.14.2.4b is a Native American adult based on size and morphology and consists of a right radius recovered in the burial feature of individual MHCP.14.2.4a.

MHCP.14.2.4c (PSUAMS-2681)
Individual MHCP.14.2.4c This burial consists of the partial skeleton of a Native American infant male, likely under 6 months of age based on the overall size of the present elements. MHCP.14.2.4c was recovered with the interment of MHCP.14.2.4a but burial position could not be determined, and preservation condition was poor.

MHCP.14.2.4d (PSUAMS-2533)
Individual MHCP.14.2.4d is represented by crania fragments from a Native American juvenile and a long bone found above MHCP.14.2.4b.

MHCP.17.1.c1 (PSUAMS-4800)
Individual MHCP.17.1.c1 is represented by a Native American adult right temporal bone found within a deposit of disarticulated human remains representing at least seven individuals: three adults ranging in age from approximately 29 to approximately 88 years old at death, and four subadults ranging in age from approximately 8 months to approximately 20 years old at death.

MHCP.17.1.7 (PSUAMS-3607 and UCIAMS-228026)
Individual MHCP.17.1.7 is a young female Native American (approximately 17.5–18.5 years old at death), buried in a tightly flexed, supine position, slightly turned on the right side. Approximately 30% of the skeleton is present and in poor condition.

MHCP.17.1.8 (PSUAMS-4290)
Individual MHCP.17.1.8 is a Native American adult male (approximately 30–50 years old at death). More than 75% of the skeleton is present and it is in good condition. This individual was buried with the head oriented to the east, facing south, in a semi-flexed position. The legs and left arm of this individual were flexed and the right arm was extended.

MHCP.17.1.9 (UCIAMS-228025 and UCIAMS-228033)
Individual MHCP.17.1.9 is a Native American 6–7 year old juvenile of unknown sex; age was estimated from dental development. Approximately 75% of the skeleton is present and is in good condition. This individual was buried oriented east, with the head facing north in a tightly flexed position on the left side.

MHCP.17.2.10a (PSUAMS-4581)
Individual MHCP.17.2.10a is a Native American old adult (over 70 years old at death) of unknown sex. Less than 25% of the skeleton is present and is highly fragmented. They were excavated below MHCP.14.2.4 and above MHCP.17.2.11. Burials MHCP.17.10a-10c were part of a burial feature of long bones stacked as part of a bundle.

MHCP.17.2.10b (PSUAMS-5125)
Individual MHCP.17.2.10b is a Native American adult individual of unknown sex or age. Elements were distinguished from MHCP.17.2.10a by a lack of osteophytic lipping and denser bone. Less than 10% of this individual is present.

MHCP.17.2.10c (PSUAMS-5126)
Individual MHCP.17.2.10c is a Native American juvenile (approximately 1.5–3 years old at death). Age was estimated from long bone length. Less than 10% of the skeleton is present. These remains were recovered from the same burial context as MHCP.17.2.10a and 10a.

MHCP.17.2.11 (PSUAMS-3772 and PSUAMS-4582)
Individual MHCP.17.2.11 is a Native American adult male (approximately 35–50 years old at death). Approximately 30% of the skeleton is present and is in poor condition. Due to taphonomic damage and so little present material, burial position could not be determined. Dating of this burial is ambiguous, with different elements yielding results of 5280–4880 cal BP and 4970–4840 cal BP. Combination of the two dates using the R_Combine function in OxCal did not yield statistically significant results. However the reasonable possibility of this being a second individual resulted in assignment of individual MHCP.17.2.11a.

Saki Tzul:

ST.16.1.1 (PSUAMS-1403)
Individual ST.16.1.1 is a Native American female juvenile (approximately 2–3 years old at death). More than 75% of the skeleton was recovered and preservation condition is excellent. ST.16.1.1 was buried in a tightly flexed and positioned on the right side with the head oriented towards the east and facing north.

ST.16.1.2 (PSUAMS-3205)
Individual ST.16.1.2 is a Native American adult male (approximately 35–45 years old at death). Approximately 90% of the skeleton is present and is well-preserved. Individual ST.16.1.2 was buried in the same burial feature with individual ST.16.1.3. This individual was buried in a flexed position on the left side, with the head in the north/northeast, facing east. The right arm was extended with the cranium resting upon it and the right arm was flexed with the right hand resting, palm-down, on the left forearm.

ST.16.1.3 (PSUAMS-3206)
Individual ST.16.1.3 is the remains of a Native American adult male (approximately 35–55 years old at death). Approximately 90% of the skeleton is present; preservation condition is excellent. This individual was buried just east in the same burial feature as individual ST.16.1.2. He was in a flexed position on the right side, the head was oriented to the northeast and the neck was tightly flexed. Legs were tightly flexed. The left arm was extended such that the forearm was resting over the lower torso of individual 2. The right arm was flexed with the right hand under the pelvis, and directly on top of the tibia of individual ST.16.1.2.

ST.16.1.b3 (PSUAMS-3715)
Individual ST.16.1.b3 is a Native American isolated femur fragment. This was recovered from level fill and are not associated with any complete burial.

ST.16.2.a1 (PSUAMS-2146)
Individual ST.16.2.a1 consists of a Native American adult right fibula diaphysis. It is associated with other adult skeletal remains in this context including: a right temporal bone, a cervical vertebra, rib fragments, two metacarpals, and two carpals. These elements are part of the level fill and not a burial feature.

ST.16.2.b1 UCIAMS-228021
This individual Native American adult is represented by the right temporal bone found in association with ST.16.2.a1

ST.16.2.a2 (PSUAMS-2147)
Individual ST.16.2.a2 is represented by a Native American infant petrous. Other skeletal remains from this context include infant ribs and unfused epiphyses though they are not associated with a burial feature.

ST.17.5.4 (PSUAMS-5124)
Individual ST.17.5.4 is a secondary burial of a Native American old adult (66–72 years) female. Approximately 90% of the skeleton is present and in good condition. This burial is considered secondary due to the conspicuous absence of the cranium despite the entire mandible and atlas being present. This individual was buried in a flexed, supine position with the feet to the west. The body was turned slightly to the right side, facing north.

ST.17.6.5 (UCIAMS-228027)
Individual ST.17.6.5 consists of a Native American primary interment of a 30-35-year-old Native American female. The burial was disturbed by the cut of ST.17.6.7a-b which was over the legs, presumably causing pedal phalanges and metatarsals to be missing. More than 90% of the skeleton is present and is in excellent condition. The individual was in an extended position, lying east-west, with the head in the west. The left shoulder was rolled inward against the grave cut. Hips and legs were extended, feet were together.

ST.17.6.7a (PSUAMS-3608, PSUAMS-4577, PSUAMS-4580, and UCIAMS-228029)
Individual ST.17.6.7a is a Native American old adult female (over 60 years old at death). Approximately 95% of the skeleton is present and in excellent condition. Burial position was flexed with the head in the east, facing north. This individual is in the same burial context as ST.17.6.7b.

ST.17.6.7b (PSUAMS-4578)
Individual ST.17.6.7b is a Native American secondary burial of a young adult female (approximately 25–30 years old at death) that consists of disarticulated elements scattered throughout the burial feature. Approximately 75% of the skeleton is present and fragmented. The majority of the skeleton was directly north of ST.17.6.7a.

ST. 17.6.7c (PSUAMS-4579)
Individual ST. 17.6.7c is a Native American scatter of skeletal elements that are slightly older than ST.17.6.7a and ST.17.6.7b but found in the same context. Less than 25% of the skeleton is present. The excavators noted the possibility that this individual intruded into a slightly older context.

ST.17.6.9a (PSUAMS-5128)
Individual ST.17.6.9a consists of a Native American 1.5-2.5 year-old Native American infant comingled with adult remains from ST.17.6.7a-c found in the matrix fill. For this reason, burial position is unknown. Less than 25% of the skeleton is present, but bones are in good condition. This individual is also in the same burial context as ST.17.6.9b.

ST.17.6.9b (UCIAMS-228031)
This individual is represented by a single fragment of a Native American left petrous pyramid. Individual is a juvenile based on bone morphology and was originally associated with ST.17.6.9a, but radiocarbon dating indicates this is a separate individual. Age, sex, and burial position are unknown.

ST.17.7.14 (PSUAMS-5127)
Individual ST.17.7.14 is a Native American infant (approximately 4.5–7.5 months old at death). Approximately 70% of the skeleton is present and in good condition. The individual was buried in a tightly flexed position, but orientation could not be determined in the field.

ST.18.11.5 (PSUAMS-5895)
Individual ST.18.11.5 is a Native American old adult female (over 60+ years old at death). More than 75% of the skeleton is present and well-preserved. Individual ST.18.11.5 was buried in a prone position with the head oriented to the east, facing south. The knees were tightly flexed so that the feet were on top of the pelvis, hips were extended. The left arm was also extended, but the right arm was flexed so that the hand was under the jaw.

ST.18.14.9a (UCIAMS-228028)
Individual ST.18.14.9a consists of the primary interment of a Native American middle adult female. Approximately 60% of the skeleton is present and preservation condition is poor. This individual was placed in a flexed position on the left side, with the knees to the chest, ankles near the pelvis, and arms were slightly flexed. This individual was buried with the head in the north, facing east. A ceramic fragment was found covering the cranial vault, over the occipital.

ST.18.14.4 (PSUAMS-5898)
Individual ST.18.14.4 is a primary interment of a Native American extended adult possible male, buried prone with the head oriented to the north, facing down. The left arm was flexed, with the left hand under the face. The right arm was extended under the head. Legs are slightly flexed, with the left leg flexed at approximately a right angle, with distal left tibia crossing above the midshaft of the right tibia.

ST.18.11.8 (PSUAMS-5896)
Individual ST.18.11.8 is a Native American old adult female (over 60+ years old at death). More than 75% of the skeleton is present and was in good condition, although fragmented. This individual was buried in a flexed position, with the head oriented to the south, facing east.

ST.18.11.9 (PSUAMS-5897)
Individual ST.18.11.9 is a Native American adult of unknown age found slightly below and predating ST.18.11.8. The feet of ST.18.11.9 are missing, with the cranium of ST.18.11.8 in their expected location. It appears that ST.18.11.8 intruded into the cut for ST.18.11.9. The burial is in a flexed position with the head oriented to the south, facing east. The long bones of this individual are broken at mid-shaft.

Section S2. AMS ^{14}C chronology

The radiocarbon chronology developed for this project was derived from 18 AMS dates processed by the WM Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at UC Irvine (UCIAMS) and 41 AMS dates from Pennsylvania State University (PSUAMS). All of these dates were taken directly from documented burial contexts and represent 52 distinct individuals.

Dates were assigned phases based on isotopic determinations of diet and inserted into a simple three-phase Bayesian sequence (refer to Supplementary Data Sheet 2). Agreement indices in OxCal measure how well the model expectations—in this case, our three dietary phases—agree with the observed chronometric data. The high agreement index we received (99.2%) supports the notion of a phased transition to maize dependence over a long period of time. These phases can be generalized as a ~5600-year period prior to maize adoption, a ~700-year transitional period during the Late Archaic, and a period of staple maize consumption from the Terminal Archaic to the Classic Period. When multiple dates originate from the same individual, modeled results were determined using the R_Combine command. Radiocarbon dates are grouped into three phases with minimal constraints, so modeled dates do not differ greatly from unmodeled distributions.

This model may be replicated by running the following CQL2 code in OxCal:

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  {
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    R_Date("UCIAMS-151855, MHCP.14.1.6, PM", 8270, 35);
   };
   R_Date("PSUAMS-4800, MHCP.17.1.c1, PM", 7900, 35);
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   R_Date("PSUAMS-4582, MHCP.17.2.11a, PM", 4330, 20);
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{
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 R_Date("PSUAMS-2148, MHCP.98.28.1b,  TM", 3990, 25);
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 };
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 R_Date("PSUAMS-2681, MHCP.14.2.4c, TM", 3735, 20);
};
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{
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};
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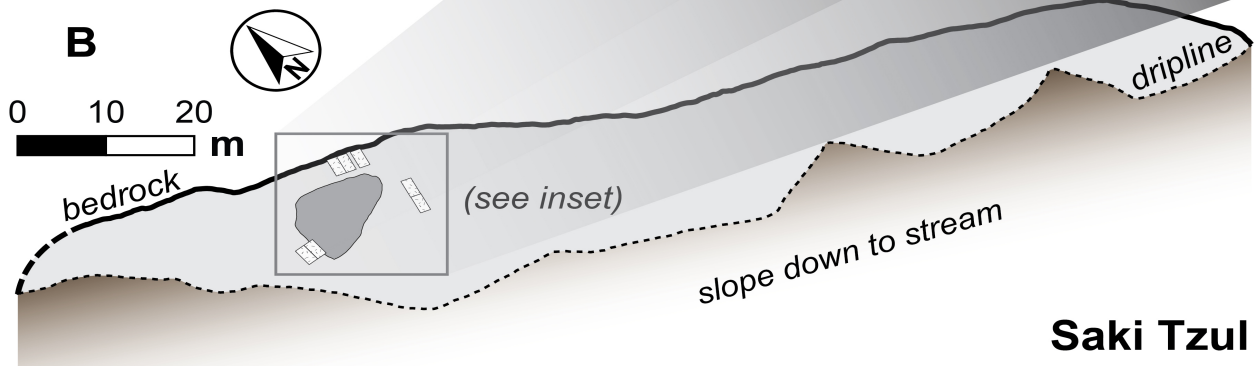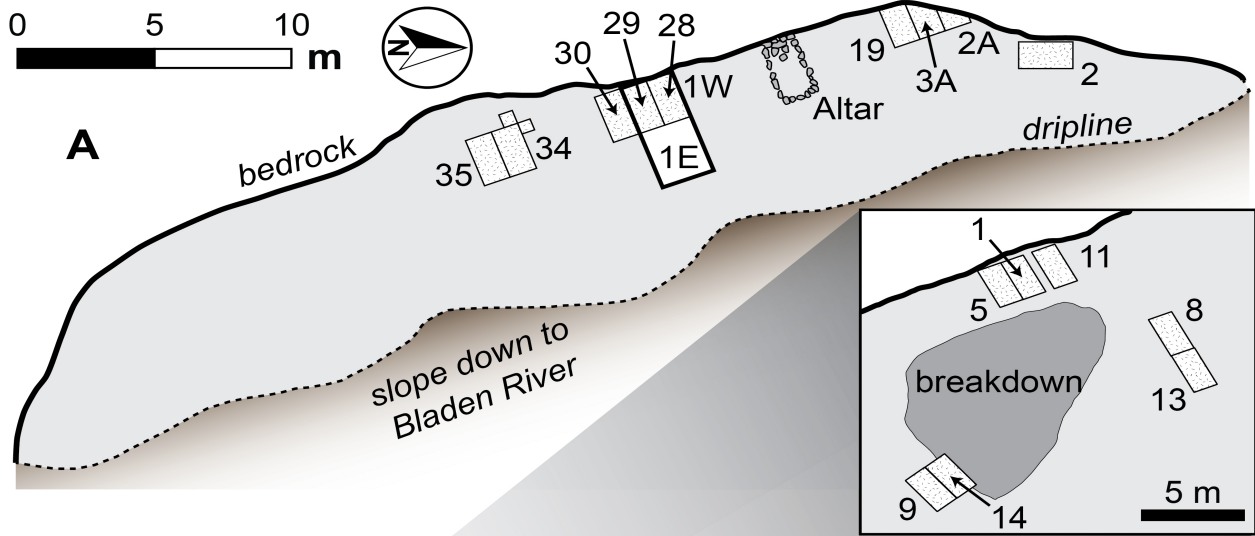
Fig. S1. Site plans of Mayahak Cab Pek (A) and Saki Tzul (B) rockshelters. Major surface features and excavation units from which skeletal samples were recovered are labeled.

Fig. S2. Mayahak Cab Pek Unit 1 profile, with relevant burial contexts plotted.

Legend:
- Pre-maize diet
- Transitional maize diet
- Staple maize diet
- Not sampled

Unit 6 burial cut

ST.16.2.a1
1180–1060 cal BP

ST.16.2.a2
1410–1310 cal BP

ST.17.6.7c

ST.17.5.4
1530–1350 cal BP

Unit 7
burial cut

ST.17.6.7b1
1600–1520 cal BP

ST.17.6.7b2
1530–1350 cal BP

ST.16.1.1
4570–4420 cal BP

ST.17.5.14

ST.16.1.2
7430–7310 cal BP

ST.16.1.3
7460–7320 cal BP

**Saki Tzul
Unit 5 (6+7) profile, 2016–2017**

0   50   100   200
cm
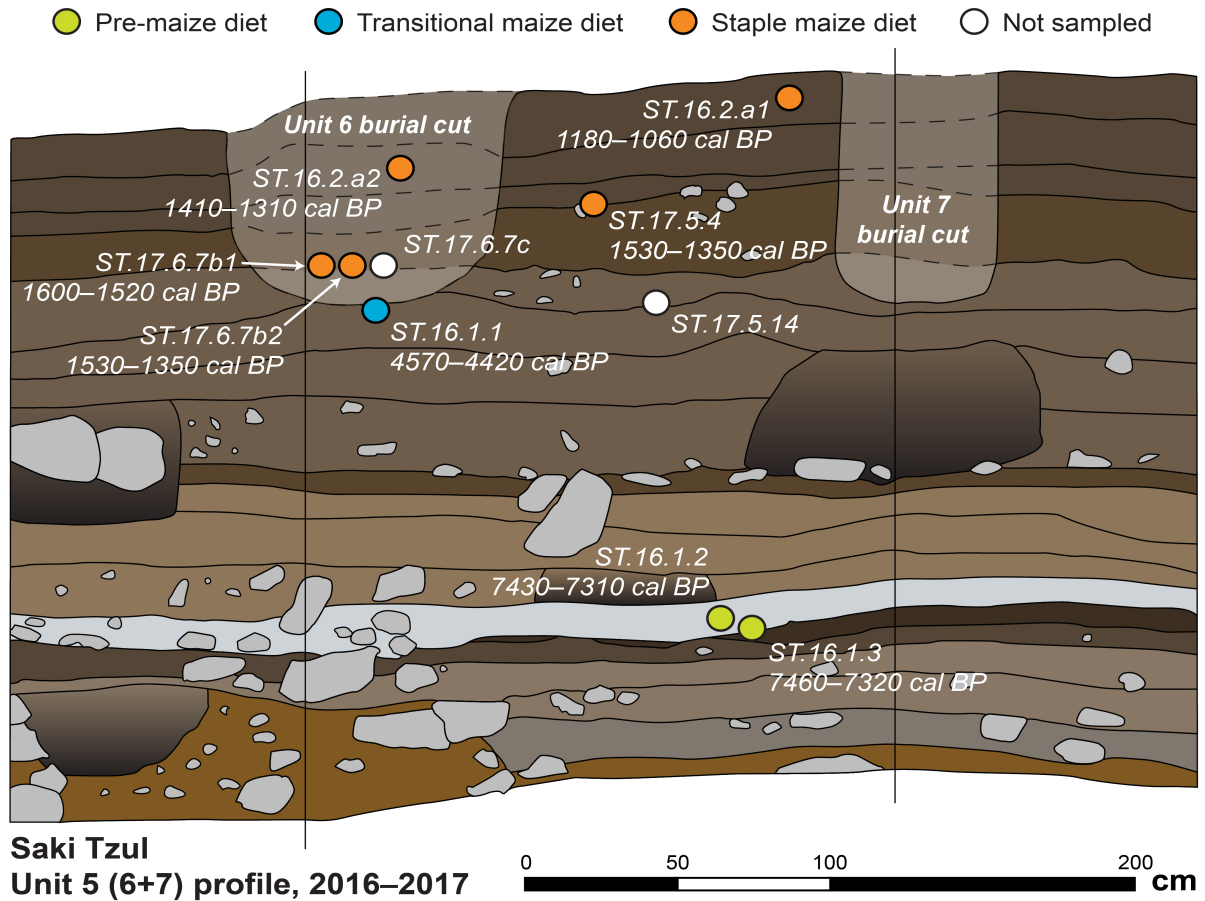
Fig. S3. Saki Tzul Unit 5 east profile, with relevant burial contexts plotted.
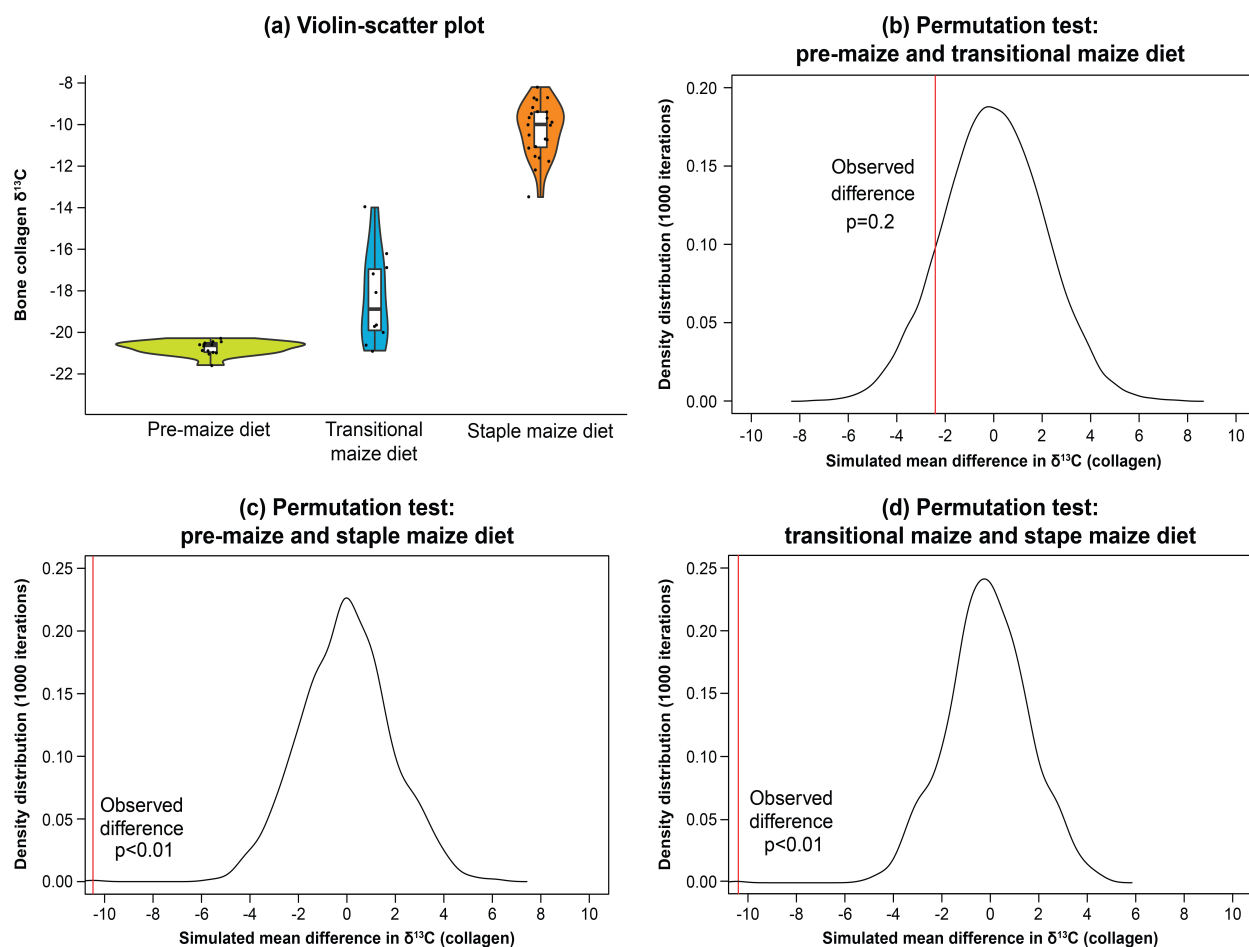
Fig. S4. Variation between $\delta^{13}C_{collagen}$ values in each group and two-sample permutation test results. (a) Violin-scatter plot depicts the distribution $\delta^{13}C_{collagen}$ values in each group. Width shape corresponds to the probability density of each distribution. Black bars represent the median value, white rectangle lengths indicate the 1st and 3rd interquartile ranges, and whiskers designate the minimum and maximum interquartile range. Two-sample permutation analyses with resampling were performed to assess the internal reproducibility and repeatability of the observed mean differences between each group (red lines): (b) Pre-maize diet vs. Transitional diet; (c) Pre-maize diet vs. Staple maize diet; (d) Transitional diet vs. Staple maize diet. Simulated differences were generated from pooled sample groups, randomized, split into a new simulated set based on the size of the original groups. This procedure was repeated 999 times with replacement to determine the probability that the simulated mean difference was greater than or equal to the observed mean difference.
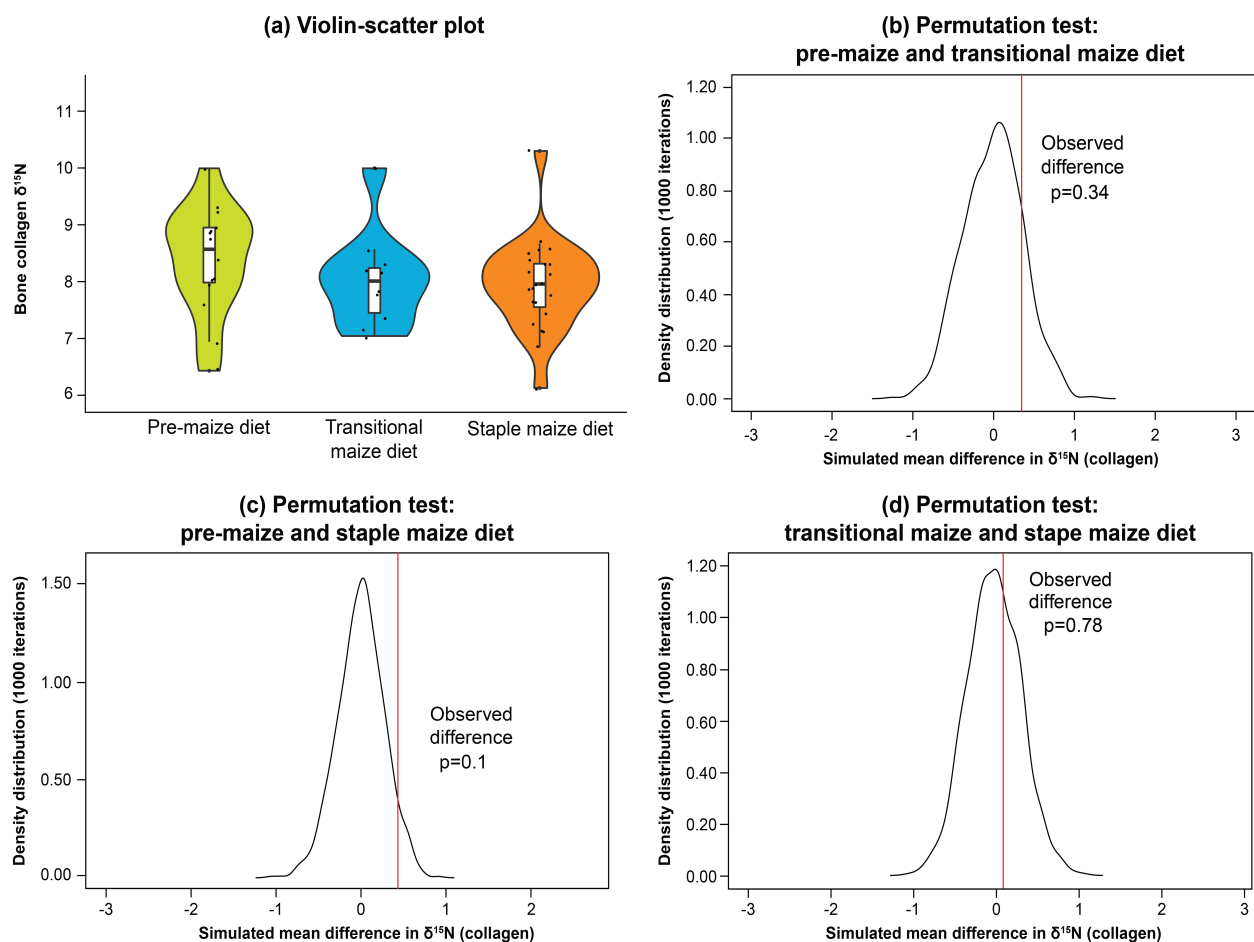
(a) Violin-scatter plot

(b) Permutation test: pre-maize and transitional maize diet

(c) Permutation test: pre-maize and staple maize diet

(d) Permutation test: transitional maize and stape maize diet

Fig. S5. Variation between $\delta^{15}N_{collagen}$ values in each group and two-sample permutation test results. (a) Violin-scatter plot depicts the distribution $\delta^{15}N_{collagen}$ values in each group. Width shape corresponds to the probability density of each distribution. Black bars represent the median value, white rectangle lengths indicate the 1st and 3rd interquartile ranges, and whiskers designate the minimum and maximum interquartile range. Two-sample permutation analyses with resampling were performed to assess the internal reproducibility and repeatability of the observed mean differences between each group (red lines): (b) Pre-maize diet vs. Transitional diet; (c) Pre-maize diet vs. Staple maize diet; (d) Transitional diet vs. Staple maize diet. Simulated differences were generated from pooled sample groups, randomized, split into a new simulated set based on the size of the original groups. This procedure was repeated 999 time with replacement to determine the probability that the simulated mean difference was greater than or equal to the observed mean difference.
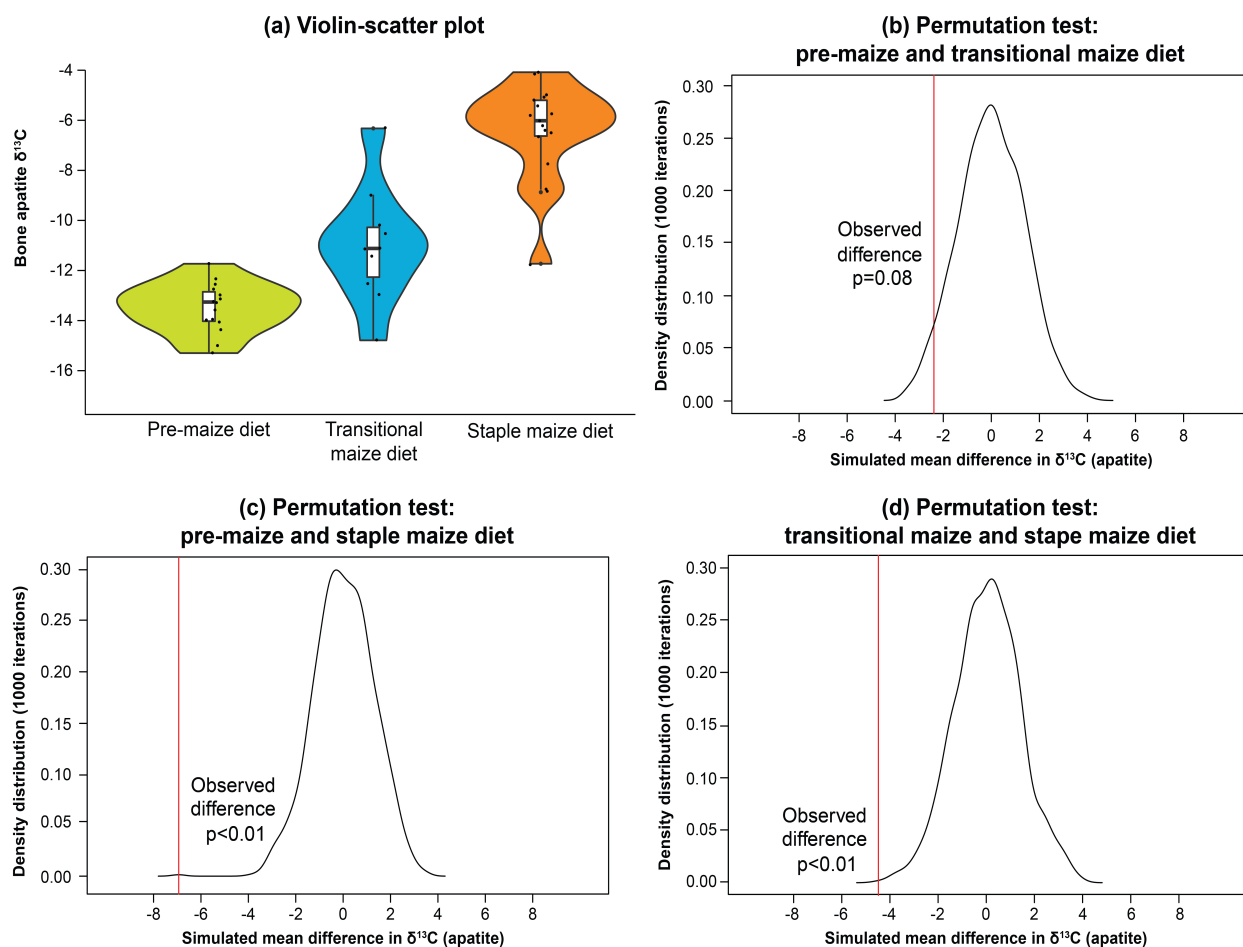
Fig. S6. Variation between δ¹³C$_{apatite}$ values in each group and two-sample permutation test results. (a) Violin-scatter plot depicts the distribution δ¹³C$_{apatite}$ values in each group. Width shape corresponds to the probability density of each distribution. Black bars represent the median value, white rectangle lengths indicate the 1st and 3rd interquartile ranges, and whiskers designate the minimum and maximum interquartile range. Two-sample permutation analyses with resampling were performed to assess the internal reproducibility and repeatability of the observed mean differences between each group (red lines): (b) Pre-maize diet vs. Transitional diet; (c) Pre-maize diet vs. Staple maize diet; (d) Transitional diet vs. Staple maize diet. Simulated differences were generated from pooled sample groups, randomized, split into a new simulated set based on the size of the original groups. This procedure was repeated 999 time with replacement to determine the probability that the simulated mean difference was greater than or equal to the observed mean difference.
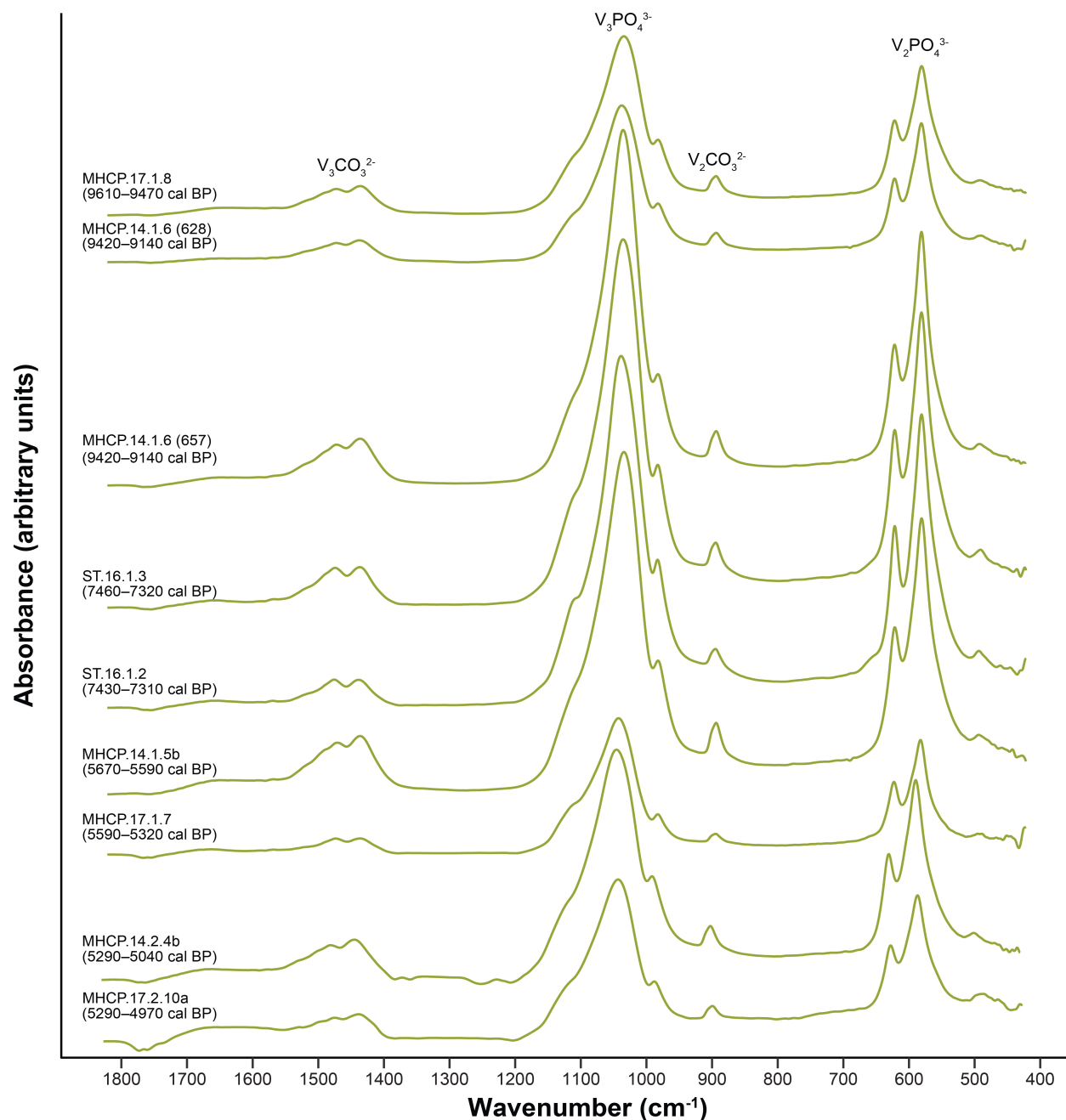
Fig. S7. FTIR spectra of ancient bone apatite samples, expanded on the 400–1800 cm^{-1} domain (part 1). Data are displayed by radiocarbon date (cal BP) and pre-maize diet (green), transitional diet (blue), and staple maize diet (orange) groups. Carbonate (V$_2$ and V$_{3)}$) and phosphate (V$_2$ and V$_{3)}$) absorbance domains are reference at the top of the figure. FTIR spectra are displayed in arbitrary units relative to the infrared absorbance on the wavenumber.
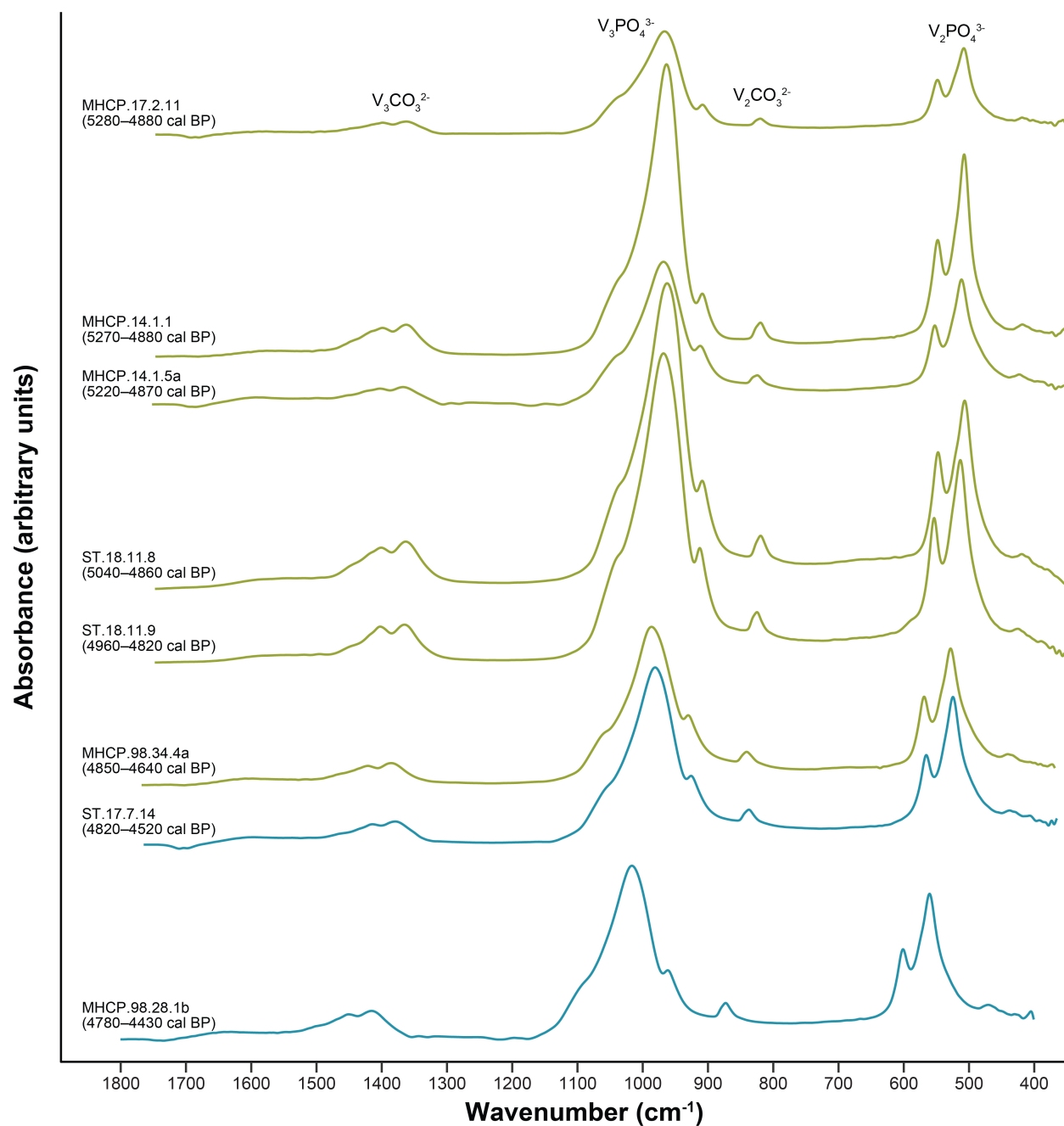
Fig. S8. FTIR spectra of ancient bone apatite samples, expanded on the 400–1800 cm^{-1} domain (part 2). Data are displayed by radiocarbon date (cal BP) and pre-maize diet (green), transitional diet (blue), and staple maize diet (orange) groups. Carbonate (V$_2$ and V$_3$) and phosphate (V$_2$ and V$_3$) absorbance domains are reference at the top of the figure. FTIR spectra are displayed in arbitrary units relative to the infrared absorbance on the wavenumber.
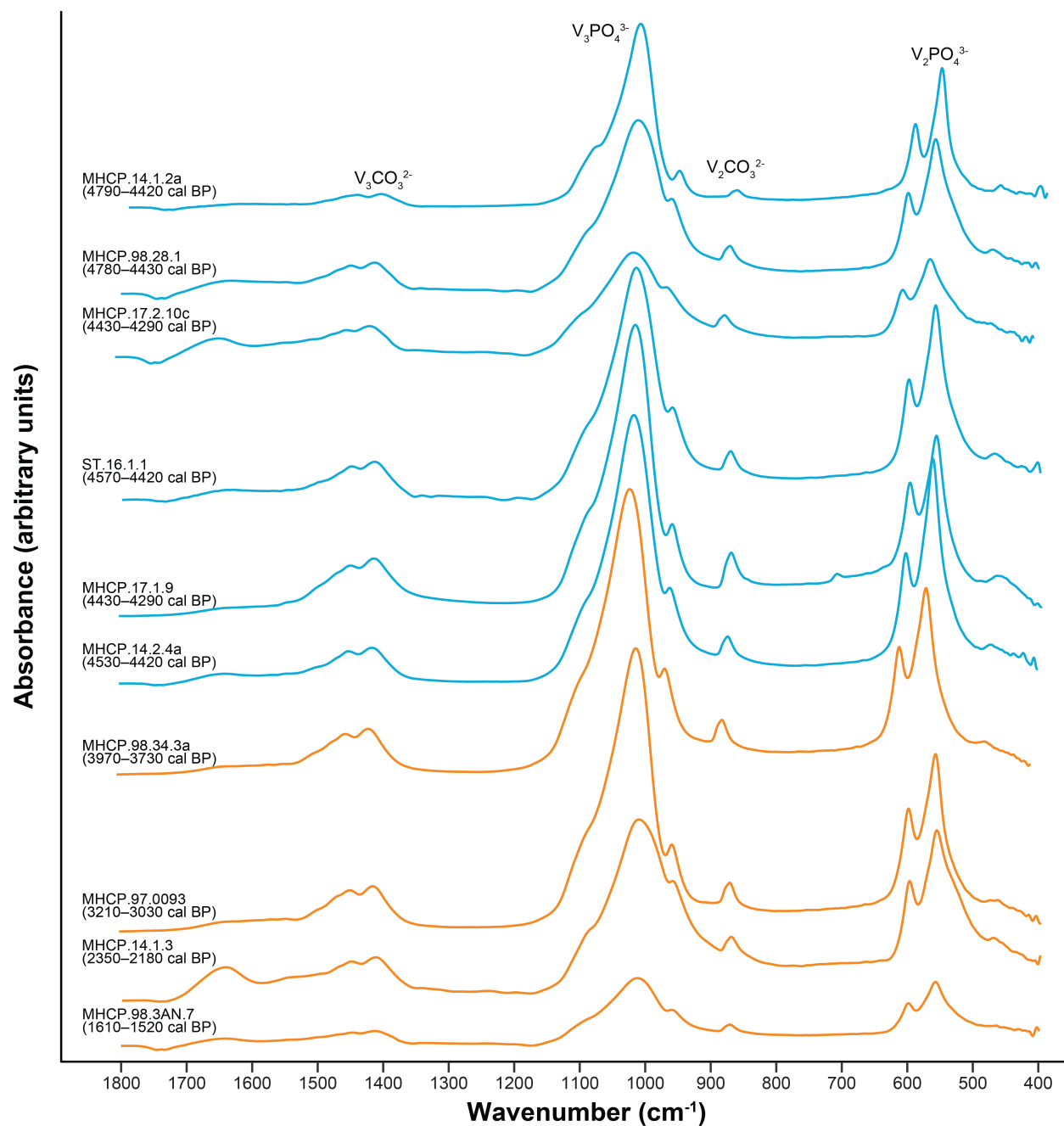
Fig. S9. FTIR spectra of ancient bone apatite samples, expanded on the 400–1800 cm^{-1} domain (part 3). Data are displayed by radiocarbon date (cal BP) and pre-maize diet (green), transitional diet (blue), and staple maize diet (orange) groups. Carbonate (V$_2$ and V$_3$) and phosphate (V$_2$ and V$_3$) absorbance domains are reference at the top of the figure. FTIR spectra are displayed in arbitrary units relative to the infrared absorbance on the wavenumber.
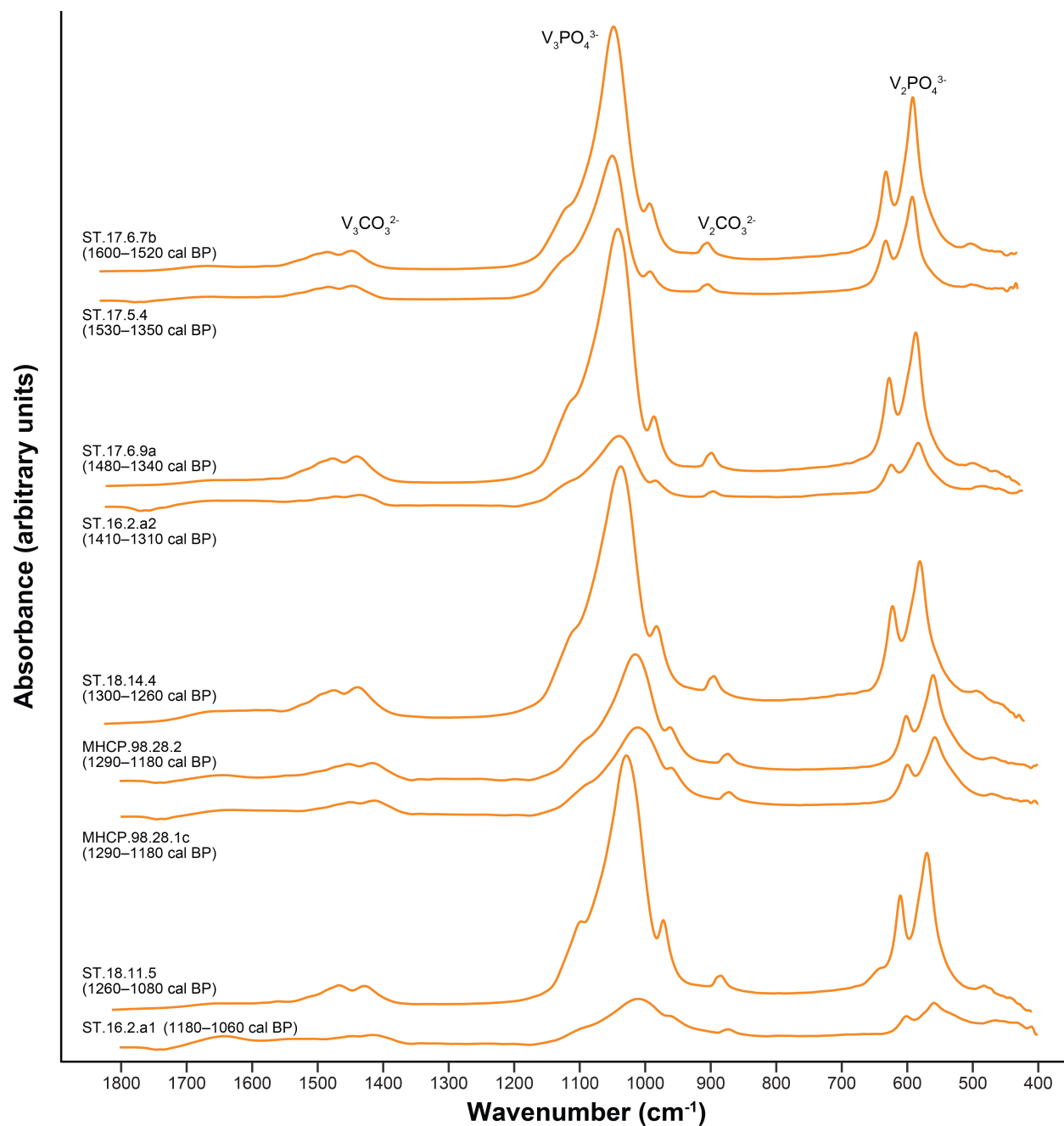
Fig. S10. FTIR spectra of ancient bone apatite samples, expanded on the 400–1800 cm^{-1} domain (part 4). Data are displayed by radiocarbon date (cal BP) and pre-maize diet (green), transitional diet (blue), and staple maize diet (orange) groups. Carbonate (V_2 and V_3) and phosphate (V_2 and V_3) absorbance domains are reference at the top of the figure. FTIR spectra are displayed in arbitrary units relative to the infrared absorbance on the wavenumber.