

Season of death of domestic horses deposited in a ritual complex from Bronze Age Mongolia Insights from oxygen isotope time-series in tooth enamel

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Abstract

Since its introduction in the eastern steppes of Eurasia, the horse has had a strong impact on the construction of cultures and the organisation of ancient societies by enabling people to move faster and transport goods and people more efficiently. The evolution of this mobility was accompanied by profound changes in the expression of ritual practices, and horses are very present in funerary monuments of the Late Bronze Age. While recent research has made progress on the question of the frequency of these horse deposits, little is known yet about the season in which the animals were slaughtered and the time of year when the funerary and ritual sites were visited. This work proposes to use oxygen isotope variations (δ18O) recorded by developing molars of horses to estimate their season of slaughter. The analysis of a modern reference set consisting of five horses from the Burgast region (Bayan-Ulgii province, western Mongolia) shows that it is possible to date the time of death with a resolution of the order of+ the season. Isotopic analysis of two juvenile horses deposited around a Bronze Age khirgisuur then made it possible to establish that the season of death centred on the winter season for these two individuals. The geochemical and zooarchaeological study reveals that the first horse died in early winter (November) and was deposited shortly after death, while the second horse died during late winter (February) and was deposited several months after death. Two calendars are therefore involved: a technical calendar, which favours a winter slaughter, and a ritual calendar, which is linked to funerals and commemoration. These results show the importance of this approach for the study of ritual practices in the Bronze Age, and they suggest that more complex scenarios need to be considered than those involving a multiple-horse sacrifice at the time and place of the funeral.

Keywords	Khirigsuur; geochemistry; nomadism; funerary practices; archaeozoology; Altai

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Paris, 28th December 2019

Dear Editor,

Please find attached our manuscript titled "**Season of death of domestic horses deposited in a ritual complex from Bronze Age Mongolia: insights from oxygen isotope time-series in tooth enamel**", by Lazzerini et al., for publication in *Journal of Archaeological Science: Reports*.

The determination of the date of death (DOD) of animals found in archaeological contexts provides important information for reconstructing the exploitation of the environment of past mobile or sedentary societies. In this paper, we determine the DOD of ancient horses based on the oxygen isotopic variation of developing molars. To this end, we gathered a reference set of five modern horses from Mongolia with known DOD. We found a good relationship between the last $\delta^{18}O$ value and the known DOD and applied the method to determine the DOD of horse remains found in a Bronze Age khirigsuur at the site of Burgast, western Mongolia. We show that the two Bronze Age horses died at different time periods during winter and that they were thus not slaughtered during a single ceremony. These results show the importance of isotope geochemistry for the study of ritual practices, and they suggest that more complex scenarios need to be considered than those involving a multiple-horse sacrifice at the time and place of the funeral.

We warrant that this manuscript represents original work and is not being considered for publication, in whole or in part, in another journal, book, conference proceedings, or government publication with a substantial circulation. We also warrant that all previously published work cited in the manuscript has been fully acknowledged. We warrant that the manuscript is one of a kind and that all of the authors have contributed substantially to the manuscript and approved the final submission. There is no real or perceived conflict of interest. No colleagues other than the co-authors have reviewed the manuscript in the final stage.

We look forward to hearing from you.
Yours sincerely,

Antoine Zazzo
On behalf of the authors

Season of death of domestic horses deposited in a ritual complex from Bronze Age Mongolia: Insights from oxygen isotope time-series in tooth enamel

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Abstract

Since its introduction in the eastern steppes of Eurasia, the horse has had a strong impact on the construction of cultures and the organisation of ancient societies by enabling people to move faster and transport goods and people more efficiently. The evolution of this mobility was accompanied by profound changes in the expression of ritual practices, and horses are

very present in funerary monuments of the Late Bronze Age. While recent research has made progress on the question of the frequency of these horse deposits, little is known yet about the season in which the animals were slaughtered and the time of year when the funerary and ritual sites were visited. This work proposes to use oxygen isotope variations ($\delta^{18}O$) recorded by developing molars of horses to estimate their season of slaughter. The analysis of a modern reference set consisting of five horses from the Burgast region (Bayan-Ulgii province, western Mongolia) shows that it is possible to date the time of death with a resolution of the order of+ the season. Isotopic analysis of two juvenile horses deposited around a Bronze Age khirgisuur then made it possible to establish that the season of death centred on the winter season for these two individuals. The geochemical and zooarchaeological study reveals that the first horse died in early winter (November) and was deposited shortly after death, while the second horse died during late winter (February) and was deposited several months after death. Two calendars are therefore involved: a technical calendar, which favours a winter slaughter, and a ritual calendar, which is linked to funerals and commemoration. These results show the importance of this approach for the study of ritual practices in the Bronze Age, and they suggest that more complex scenarios need to be considered than those involving a multiple-horse sacrifice at the time and place of the funeral.

Keywords

khirgisuur; geochemistry; nomadism; funerary practices; archaeozoology; Altai

Highlights

- O isotopic analyses were performed on developing molars of modern and ancient horses from Mongolia
- Isotope profiles in modern horses allow the time of death to be distinguished
- Horses deposited in a Bronze Age (BA) monument died at different time periods during winter
- Unlike previously assumed in the literature BA horses were not slaughtered during a single ceremony

1. Introduction

Since its introduction into the eastern steppes of Eurasia as a domestic animal, the horse has had a strong impact on the construction of cultures and the organisation of ancient societies (Anthony, 2007; de Barros Damgaard et al., 2018; Gaunitz et al., 2018; Outram et al., 2009). It has been a source of meat, dairy products, leather, and hair, but above all, it has allowed people to move faster and to transport goods and people more efficiently. In Mongolia, horses were used for riding or pulling carts from the end of the 2nd millennium BCE on (Taylor, 2017). Although the details of these modalities still need to be clarified, it is argued that the emergence of horse riding and chariotry may have encouraged the adoption of nomadic pastoralism. The evolution of this mobility was accompanied by profound changes in the expression of ritual practices. The final Bronze Age witnessed the appearance of the khirgisuurs and deer stones and (KDS) culture, characterised by its funerary complexes. The KDS complexes are abundant in central Mongolia but can also be found as far away from there as the foothills of the Altai. They are characterised by stone monuments (tombs or deer stones) and are usually surrounded by circular or rectangular enclosures, which are, in turn, surrounded by stone circles and stone mounds (Allard and Erdenebaatar, 2005; Fitzhugh, 2009; Lepetz et al., 2019; Wright, 2007). The stone circles often contain charred bones of domestic animals, most often caprines. The stone mounds cover horse skulls, which are sometimes associated with neck and hoof components (Allard and Erdenebaatar, 2005; Broderick et al., 2014, 2016; Fitzhugh, 2009; Zazzo et al., 2019). These deposits can include hundreds of heads, and in some cases more than a thousand. The size of the monuments is probably a function of the social importance of the deceased or the size of the community attached to that person. This importance is perceptible through the height and diameter of the central mound, the quality and number of the deer stones, the size of the enclosure, and, above all, the number of mounds and circles, and thus the quantity of animals involved in the ceremonies. While the gestures leading to these accumulations have been interpreted as marks of homage to ancestors, whether real or mythical, as well as to deities (Fitzhugh, 2009; Lepetz et al., 2019), the arrangement of the heads around the grave and the direction toward which they are oriented evoke the image of horses pulling the khirgisuur, and thus echo the Altai rock art representations of a cart used to transport the deceased (Jacobson-Tepfer, 2012; Lepetz et al., 2019).

Recent advances in research have improved our knowledge on the frequency of these deposits. At the scale of the structure, radiocarbon dating of the horse remains indicates that the deposits were not made simultaneously and may taken place spread over several decades in the case of large khirgisuurs (Zazzo et al., 2019). At the scale of the deposit, the remains of horses do not appear to come from animals that were all killed on site and immediately covered with stones. Indeed, while some of the horse parts were deposited fresh, shortly after slaughter, other parts were probably deposited at least several months later (Lepetz et al., 2019). This possible disconnection between the date of slaughter and the date of deposition also raises the question of the season of site frequentation and the ritual calendar, which remains totally unknown today. It is not known, for example, whether these visits were carried out throughout the year or whether they were confined to a particular time of the year.

Oxygen isotope analysis ($\delta^{18}O$) of tooth enamel can be used to address the question of the season of death of animals (El Adli et al., 2017; Fisher et al., 2003; Julien et al., 2015; Knipper et al., 2008; Koch et al., 1989; Lazzerini et al., *minor revisions*). During its growth, tooth enamel records the isotopic composition of ingested water (drinking water and plant water), which is itself under environmental control. In middle and high latitudes, there is seasonal variation in the $\delta^{18}O$ value of meteoric water, with high values during the warm season and low values during the cold season. Sequential sampling along the growth axis of tooth enamel provides a chronological record of climatic conditions (Balasse, 2003; Fricke et al., 1998; Pederzani and Britton, 2019; Zazzo et al., 2002). If the teeth were still developing at the time of death, stable isotope analysis can be used to determine the date of death. In Mongolia, this approach allowed researchers to estimate that caprines deposited in two tombs in the Xiongnu necropolis of Egiin Gol were slaughtered during the warm season (Lazzerini et al., *minor revisions*).

In 2016, excavations at the site of Burgast (Bayan-Ulgii province, western Mongolia) yielded remains of several horses belonging to a khirgisuur. Two of these horses had teeth that would still have been growing at the time of death, providing an opportunity to determine their slaughter season. Applying this approach, however, requires establishing a reference set constituted of animals slaughtered on a known date. This reference set must be built using the species of interest, because the timing and duration of tooth mineralisation varies from one species to another (Kohn, 1996; 2004; Kohn et al., 1996; Balasse, 2002; Kohn and Cerling, 2002; Passey and Cerling, 2002; Zazzo et al., 2005, 2010, 2012). For this reason, we built a reference set with molars from modern juvenile horses with a known date of death that had lived in the same area. Comparing the results of the isotope analysis and the archaeozoological observations lays the foundation from which to discuss the season of site visits and the ritual calendar during the Bronze Age.

2. Materials

2.1 The archaeological site of Burgast and the Bronze Age horses

The site of Burgast is located in the Aimag of Bayan-Ulgii (Sum of Nogoonnuur), about 100 km north-east from Ulgii as the crow flies, about 15 km from the border with the Republic of Tuva and about 20 km south of the Republic of Altai (Fig. 1). This area is located on the eastern fringes of the Altai mountain range, in its Mongolian part. Bordered to the south by a river and to the north by a rocky massif, the site has the shape of a triangular terrace of ca. 20 ha, at an altitude of 1900 m. Archaeological remains from several periods (Late Bronze Age, Hun Sarmate, Türk) are scattered along the terrace, and these were excavated in 2015 and 2016 by the French-Mongolian Joint Archaeological Expedition. Among the different structures, a khirgisuur was excavated in 2016, and it is the subject of this article (Fig. 2). This Late Bronze Age khirgisuur is composed of a 15.5 × 14 m central mound (ST 60) made up of large blocks. This mound is inscribed in a rectangular area of 20 × 18 m covered with stones laid on the ancient ground and presenting small mounds at the four corners. The central mound contains the remains of a human body (oriented west–east) in

dorsal decubitus position. Excavation of the stones revealed the existence of a casing made of large rocks. No grave good is associated with the deceased. To the west, the complex is flanked by four stone circles, aligned over a length of 14 metres (ST 68 to 71). Their diameter varies from 1.6 to 2 m. Although stone circles generally yield burnt bones and teeth of caprines (Broderick et al., 2014, 2016; Lepetz et al., 2019), these four were empty. To the east, and aligned over a length of 30 m, are seven mounds (ST 61 to 67) of 1.7 to 2 m in diameter, each delimiting a central space of about 1.3 to 1.5 m and each yielding horse remains. The horse remains are fairly well preserved, but bone displacements, breakage and missing parts seem to indicate that taphonomic disturbances (possibly by burrowing animals) have occurred, although it is not always possible to precisely define their extent. The remains comprise elements of heads (skull or mandibles), sometimes accompanied by connected cervical vertebrae and terminal phalanges. The heads are oriented towards the south-east (between 80° and 135°). Two males and one female have been identified. Individual ages range from 1 to 18–20 years old.

Two of the seven mounds (ST 61 and ST 66) contained juvenile individuals that were radiocarbon dated to the very end of the second millennium BCE (Table 1). The remains of structure ST 61 are in the form of a head (skull and mandible) associated with two terminal phalanges and five cervical vertebrae (C2 to C6). The head was placed upside down and rested on its frontal and nasal bones. The stage of dental eruption indicates that this animal was approximately 1 year old at death (Cornevin and Lesbre, 1894). There is an overlap in the formation calendar of M1 and M2 (Figure 3). Because the M1 and M2 of the right mandible were in the process of mineralisation, and because the lower part of M1 was broken, both teeth were selected for analysis in order to be able to obtain as much information as possible. Structure ST 66 yielded the skull (i.e., without mandible) of a young male. The skull had been deposited on its right side. No vertebrae or phalange were present. The stage of dental eruption and wear of the incisors (very little wear on the third incisor), allows us to estimate that the animal was about 5 years old at death. The M3 was still in the process of mineralisation and was therefore sampled.

2.2 The modern horses

The reference dataset consists of five young individuals whose teeth were still growing at the time of death (Fig. 4). These animals come from different herds belonging to Kazakh nomadic herders living around the site of Burgast (Table 2). The horses were not slaughtered specifically for the study, but either succumbed to injuries caused by accidents or predators, or were slaughtered by the herders themselves for consumption. We were not on site when the horses died, and the date of death was provided to us by the herders with a precision equal to or better than 1 month. The date of death of the sampled animals covers the entire calendar year, from the beginning (2018-59a, January) to the end of the year (2017-104b, end of November), providing the opportunity to observe the seasonal recording of the isotopic oxygen composition of the tooth enamel during its formation. Due to the age of the animal at death, which differs between individuals, we had to sample M1 (n = 1), M2 (n = 2) or M3 (n

= 2). Field constraints and the availability of skeletal remains meant that we had to sample either the upper (n = 3) or lower (n = 2) molar.

3. Methods

Tooth sampling was carried out on the mesial side, both for practical convenience (this side has a flat surface with a narrow cementum layer) and also because it should mineralise faster (Zazzo et al., 2012). The outer surface of the tooth was first cleaned with a tungsten burr to remove the cementum. Tooth enamel was then removed by abrasion with a diamond burr. Each sample consists of a horizontal sample of about 1 mm, spanning the entire thickness of the enamel layer and parallel to the growth axis of the tooth. The enamel powder thus recovered (~6–7 mg) was chemically treated following the procedure described in Balasse et al. (2002). The organic matter was removed with a NaOCl solution (2–3%, 0.1 ml solution/mg enamel, for 24 hours). The samples were then rinsed several times with distilled water. Each sample was then reacted with 0.1 M acetic acid (0.1 ml solution/mg enamel, for 4h) to remove exogenous carbonates, rinsed with distilled water and oven dried at 80°C for 12h.

The purified enamel samples were weighed (~ 600 µg) and analysed using a Kiel IV automatic device coupled to a Delta V Advantage Isotope Mass Spectrometer (IRMS) at the Service de Spectrométrie de Masse Isotopique of the Muséum national d'Histoire naturelle (SSMIM) in Paris. The accuracy of the data was checked by repeated analysis of the laboratory's internal carbonate standard (LM Marble) standardised against the international standard NBS 19. The analytical accuracy, estimated by the repeated analysis (n = 80) of LM Marble, was 0.04‰, and the correction applied to bioapatite samples ranged from +0.16‰ to +0.25‰. The isotopic data are presented in δ notation [$\delta = (R_{sample}/R_{standard}) - 1$], with R being the isotopic ratio ($^{18}O/^{16}O$) of the sample to that of the international standard in V-PDB (Vienna PeeDee Belemnite) and expressed in per thousand (‰). The average $\delta^{18}O$ values between individuals and time periods were compared using the One-way ANOVA statistical test coupled with Tukey's post-hoc test using R software version 3.4.4 with a significance threshold at p-value < 0.05.

4. Results

The isotopic values of the 173 modern and archaeological samples are presented in Tables 3 and 4. Summary statistics are presented in Table 5.

4.1 The modern horses

The average $\delta^{18}O$ value of the modern individuals is −10.7 ± 1.0‰ (1σ). The $\delta^{18}O$ values range from −16.1 to −5.0‰, with an average maximum of −6.4 ± 1.1‰ and minimum of −14.6 ± 1.0‰. The average amplitude is 8.2 ± 1.9‰, and the amplitude varies from 6.5 to 9.5‰ (Table 5). With the exception of two individuals (2017-104-M2 and 2018-59A-M1, p <

0.05), the samples from the modern horses are not statistically different from each other ($p > 0.05$). For each individual, the intra-tooth isotope variations follow a sinusoidal signal (Fig. 5). The minimum values correspond to the portion of mineralised enamel during mid-winter (temperature minimum), while the maximum values correspond to the portion of mineralised enamel during mid-summer (temperature maximum). The values recorded at the base of the crown during mineralisation correspond to the environmental conditions prevailing during the last weeks or months of the animal's life (Fig. 5). The last values recorded by the two individuals who died in January and February plot along a decreasing curve, but have not quite reached the winter minimum yet. It is not possible to visually distinguish between these two individuals (Fig. 5). The individual that died at the end of April (2018-58B) has recorded the winter minimum and is a little more advanced in the seasonal cycle. The last values recorded by the individual who died in early July (2018-17B) plot along a strongly rising curve and are nearing the summer maximum. Finally, the last values recorded by the M2 of the individual who died in November 2016 (2017-104) has already recorded the summer maximum and reached a plateau.

4.2 The Bronze Age horses

The average $\delta^{18}O$ value of Bronze Age horse tooth enamel is $-11.3 \pm 2.8‰$ (1σ). The isotopic composition of the enamel samples ranges from -16.1 to $-5.7‰$ (Table 5), with an average maximum value of $-7.6 \pm 2.3‰$ and an average minimum value of $-13.0 \pm 3.5‰$. The seasonal isotopic amplitude recorded by tooth enamel is 8.0‰ for individual ST 61 and 5.9‰ for individual ST 66. The isotope profile of the lower part of the M1 overlaps with that of the M2 (Fig. 6). The last values recorded by the two teeth of the ST 61 individual are placed along an ascending curve to reach a plateau around −6‰. The M3 of individual ST 66 is much more advanced in its formation and recorded a full seasonal signal. The lower part of the tooth records a decrease in $\delta^{18}O$ values but has not reached a plateau yet.

5. Discussion

5.1 The oxygen isotope record of the season of death of the modern horses

Our results indicate that the isotopic value of the last mineralised tooth enamel samples is clearly related to the date of death of the modern horses. The terminal isotope values of the animals that died in late winter are close to the minima, whereas a plateau is reached in the lower part of the tooth of the animal that died in spring. The individual who died in summer approaches a maximum value, and a plateau is reached in the animal that died in early winter. These results differ slightly from those obtained on modern caprine molars from Mongolia (Lazzerini et al., *minor revisions*). Indeed, it can be noted that for animals slaughtered at the same time of year, the patterns of variation in $\delta^{18}O$ are more advanced in caprines than in horses. For example, the values for caprines slaughtered in July have already reached a plateau of high values, while the values for the horse which died at the same period are still rising. Similarly, the terminal values of $\delta^{18}O$ of caprines slaughtered in November

follow a decreasing curve, while those of the horse slaughtered at the same period have not yet started to decrease. This probably corresponds to the fact that horses' tooth development spreads over a longer period of time and that enamel mineralisation lasts longer in horses than in caprines (Bendrey et al., 2015; Hoppe et al., 2004). These findings emphasizes the importance of building a reference set based on the species of interest.

Our results also suggest that the temporal resolution provided by the modern reference set seems variable. Indeed, there is little difference between the terminal isotope values recorded by the individual that died in July (2018-17B) and the one that died four months later, in early November (2017-104) (Fig. 5). Conversely, it is easy to distinguish between two individuals that died 2–3 months apart in spring (2018-58B) and summer (2018-17B). In addition, some inter-individual variability seems to exist. The tooth belonging to the individual that died in January (2018-59A) seems slightly ahead of the tooth from the one that died at the end of February (2018-57A). This variable resolution can be explained by the fact that we are comparing different molars (M1 vs. M3) that do not have the same growth rate. M3 grows more slowly than M1 and M2, and this could lower the temporal resolution of the isotope signal recording in this tooth (Bendrey et al., 2015; Hoppe et al., 2004). In addition, this dataset is made up of teeth that are not all at the same stage of growth: some have almost completed their growth, while others are less advanced. However, the growth rate of horse molars decreases exponentially: 1 cm of enamel taken near the apex corresponds to a growth time period twice as short as a 1 cm taken near the enamel–dentin junction (Bendrey et al., 2015). Not all portions of enamel are equivalent, and therefore not all enamel samples taken incorporate the same amount of time. It can therefore be assumed that the isotope signal of the M1 of individual 2018-59A-M1 is better resolved chronologically than that of the M3 of individual 2018-57A-M3, which grew more slowly. This may explain the fact that the seasonal cycle recorded in the tooth of the animal that died in January appears to be at the same point as, or even slightly ahead of, the one that died at the end of February (Fig. 5). Therefore, we recommend favouring teeth that form first (M1 and M2), and whose crown has not finished growing in length, for estimating the period of death, as they will provide a better temporal resolution. Although preliminary, the reference dataset presented here is consistent and therefore allows us to distinguish between different seasons of death in ancient horses.

5.2. Season of death of the Bronze Age horses

Two developing teeth (M1 and M2) were analysed for the individual from ST 61 (Fig. 6). While the terminal values of the two teeth follow an ascending curve, those of M1 have not yet reached a plateau, unlike those of M2. This difference can be explained by the fact that it was not possible to sample the last 10 mm of M1 because the tooth was broken. On the other hand, due to the exponential decrease in the growth rate of horse teeth, it is possible that the temporal resolution was better for M2 which, unlike M1, had not yet completed its growth in length. For these two reasons, we believe that the slaughter date is better approximated by the isotope profile recorded in M2. This profile is very similar to that observed on the modern horse that died in early November (sample 2017-104). In the case of the ST66 horse, the tooth sampled (M3) had almost completed its growth in length and recorded a decrease in isotope

values, but had not reached a plateau. This profile is very similar to that observed on the M3 of individual 2018-57A, which died in late February, and therefore suggests that death occurred in mid- to late winter. It is interesting to note the presence of a hypoplasia located 11–15 mm from the base of the dental crown of this individual (Fig. 6). Such an anomaly in enamel mineralisation is potentially caused by ecological or climatic factors, such as water or dietary stress, but may also be due to stress related to infections or injuries (Dobney et al., 2004; Upex and Dobney, 2012). This cessation of growth influences the isotope record, which rapidly shifts from a phase of decreasing values of $\delta^{18}O$ to a phase of increasing values. It can be seen that this enamel growth defect occurred at the same time as the $\delta^{18}O$ values were decreasing, and therefore corresponds to the winter period. It is reasonable to assume that the harsh climatic conditions reigning in winter were somehow at the origin of this hypoplasia.

Our results therefore indicate that the two Late Bronze Age horses died at two different periods during the cold season: in early winter (November) for one (ST 61) and during the second half of winter (late February) for the other (ST 66). Today, horses are slaughtered at the beginning of the winter season (November to December), to be consumed until spring. The winter temperatures make it possible to preserve the large amount of meat for at least four months. In addition, this animal is considered by the Mongols to be a "warm snout" (*khaluun khoshuutai*, in the Mongol language), meaning that the energy characteristics of its meat adapt well to the cold season (Marchina et al., 2017). It would be unwise to transpose directly the cultural justifications put forward by modern herders to the Bronze Age. But we can reasonably assume that the pragmatic reasons for meat preservation may had led to the slaughter of horses being organised according to the same seasonal calendar. Although based on a reduced corpus that would benefit from being expanded, the Burgast dataset attests for the first time to the practice of winter slaughter of horses in the Bronze Age.

The data highlight another important fact: these two horses were not killed during a single ceremony. It is therefore necessary to abandon the idea that is implicit in discussions in the literature that the horses deposited in khirgisuurs were all sacrificed on the day of the funeral of the deceased person. This conclusion had already been proposed on the basis of radiometric arguments for large khirgisuurs comprising several hundred individuals (Zazzo et al., 2019). It therefore seems that this conclusion can be extended to smaller monuments. However, the data do not suggest that the individuals were deposited at two different time periods. ST 61 yielded the remains of a skull and associated mandibles in anatomical connection with part of the animal's neck and together with parts of its feet, suggesting that the bones were deposited fresh. This therefore suggests that these elements were placed under the mound shortly after the animal's death. In contrast, ST 66 yielded a single skull, with no mandible and no other bones. This can be interpreted as the deposition of dry skeletal parts, indicating that the slaughter and deposition were not necessarily synchronous (Lepetz et al., 2019). At the large khirgisuur (B10) of Tsatsiin Ereg (central Mongolia) the presence of isolated skeletal elements under the mounds, including skulls without mandibles, and the association of skulls and mandibles belonging to different individuals, indicate that in some cases the remains must have come from horses killed several months before deposition (Lepetz et al., 2019). It is unclear whether this delay is related to a practical reason that would have prevented immediate deposition (which would be the case, for example, if the animal

had been slaughtered several days' travel away from the kirighsuur) or whether there was a ritualistic desire to expose the skeletonised head, similar to the practices observed today among modern herders (Marchina et al., 2017). The slaughter itself may have been sacrificial or purely domestic. It is also possible that some individuals died naturally. At Burgast, based on the archaeozoological and isotopic data, two scenarios are possible. One could argue for a synchronous deposit (at the time of the funeral, for example, but not necessarily) of animals slaughtered at different time periods, which could include horses consumed during the previous year. But one could also argue for successive deposits of fresh and non-fresh animals.

6. Conclusions

Sequential oxygen isotopic analysis of developing molars allows researchers to distinguish between different periods of death for horse remains in an archaeological context. The establishment of a modern reference has allowed us to obtain a temporal resolution of the order of the season and thus to propose a date of death centred on the winter season for two Bronze Age horses deposited in a khirgisuur in western Mongolia. In order to improve the accuracy of the dates of death reconstructed by this approach, it would be desirable to expand the modern reference set and include a larger number of animals of known date of death to better document the impact of tooth type, advance in the mineralisation process, or rate of tooth growth. Our preliminary results are already enriching our understanding of ritual practices in the Bronze Age. Our results indicate that archaeologists need to take into account more complex scenarios than one involving the sacrifice, at the site, of multiple horses on the day of the funeral. In practice, the location of slaughter cannot be determined. These slaughtering events may have been conceived solely in a domestic setting, and therefore related to the practical necessities of acquiring and preserving the meat. Therefore, it is important to keep in mind that both a technical calendar (governing the slaughter of horses, with a focus on winter) and a ritual calendar (governing the deposition of animal remains) are involved.

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Credit roles:

Conceptualisation (AZ, AC, SL); Data curation (NL, SL, CM, BN, VB, DJ, MC, NB, TT, AZ); Formal analysis (NL, DF); Funding acquisition (AC, SL, AZ); Investigation (NL, AC, SL, AZ); Methodology (NL, AZ); Project administration (AZ); Resources (NL, SL, CM, NB, TT, AZ); Software (NL, AC); Supervision (AZ, AC, SL); Validation (NL, AZ, DF); Visualisation (NL, SL); Roles/Writing - original draft (NL, AC, SL, AZ); Writing - review & editing (CM, MC, TT).

BIBLIOGRAPHY

Allard, F., Erdenebaatar, D., 2005. Khirigsuurs, ritual and mobility in the Bronze Age of Mongolia. Antiquity 79, 547–563. https://doi.org/10.1017/S0003598X00114498

Anthony, D.W., 2007. The Horse, The Wheel, and Language: How Bronze-Age Riders from the Eurasian Steppes Shaped the World. Princeton University Press, Princeton.

Balasse, M., 2003. Potential biases in sampling design and interpretation of intra-tooth isotope analysis. Int. J. Osteoarchaeol. 13, 3–10. https://doi.org/10.1002/oa.656

Balasse, M., 2002. Reconstructing dietary and environmental history from enamel isotopic analysis: time resolution of intra-tooth sequential sampling. Int. J. Osteoarchaeol. 12, 155–165. https://doi.org/10.1002/oa.601

Balasse, M., Ambrose, S.H., Smith, A.B., Price, T.D., 2002. The Seasonal Mobility Model for Prehistoric Herders in the South-western Cape of South Africa Assessed by Isotopic Analysis of Sheep Tooth Enamel. Journal of Archaeological Science 29, 917–932. https://doi.org/10.1006/jasc.2001.0787

Bendrey, R., Vella, D., Zazzo, A., Balasse, M., Lepetz, S., 2015. Exponentially decreasing tooth growth rate in horse teeth: implications for isotopic analyses. Archaeometry 57, 1104–1124. https://doi.org/10.1111/arcm.12151

Broderick, L., Houle, J.-L., Bayarsaikhan, Jamsranjav, Seitsonen, O., Bayarsaikhan, J, 2014. The mystery of the missing caprines: Stone circles at the great khirigsuur in the Khanuy Valley, in: Arkheologiin Suudal. Mongolian Academy of Sciences., Ulaanbaatar, pp. 164–174.

Broderick, L.G., Seitsonen, O., Bayarsaikhan, J., Houle, J.-L., 2016. Lambs to the Slaughter: A Zooarchaeological Investigation of Stone Circles in Mongolia. International Journal of Osteoarchaeology 26, 537–543. https://doi.org/10.1002/oa.2425

Cornevin, C., Lesbre, F.-X., 1894. Traité de l'âge des animaux domestiques d'après les dents et les productions épidermiques. J.-B. Baillière et fils, Paris.

de Barros Damgaard, P., Martiniano, R., Kamm, J., Moreno-Mayar, J.V., Kroonen, G., Peyrot, M., Barjamovic, G., Rasmussen, S., Zacho, C., Baimukhanov, N., others, 2018. The first horse herders and the impact of early Bronze Age steppe expansions into Asia. Science 360, eaar7711.

Dobney, K., Ervynck, A., Albarella, U., Rowley-Conwy, P., 2004. The chronology and frequency of a stress marker (linear enamel hypoplasia) in recent and archaeological populations of Sus scrofa in north-west Europe, and the effects of early domestication. Journal of Zoology 264, 197–208. https://doi.org/10.1017/S0952836904005679

El Adli, J.J., Fisher, D.C., Vartanyan, S.L., Tikhonov, A.N., 2017. Final years of life and seasons of death of woolly mammoths from Wrangel Island and mainland Chukotka, Russian Federation. Quaternary International, VIth International Conference on Mammoths and their Relatives, Part 3 445, 135–145. https://doi.org/10.1016/j.quaint.2016.07.017

Fisher, D.C., Fox, D.L., Laub, R.S., 2003. Season of death and terminal growth histories of Hiscock mastodons. The Hiscock Site: late Pleistocene and Holocene paleoecology and archaeology of western New York state. Bulletin of the Buffalo Society of Natural History 37, 83–101.

Fitzhugh, W., 2009. The Mongolian deer stone-khirigsuur complex: dating and organisation of a late bronze age Menagerie, in: Current Archaeological Research in Mongolia, Department of Anthropology Staff Publications. pp. 183–199.

Fricke, H.C., Clyde, W.C., O'Neil, J.R., 1998. Intra-tooth variations in $\delta^{18}O$ (PO_4) of mammalian tooth enamel as a record of seasonal variations in continental climate variables. Geochimica et Cosmochimica Acta 62, 1839–1850. https://doi.org/10.1016/S0016-7037(98)00114-8

Gaunitz, C., Fages, A., Hanghøj, K., Albrechtsen, A., Khan, N., Schubert, M., Seguin-Orlando, A., Owens, I.J., Felkel, S., Bignon-Lau, O., others, 2018. Ancient genomes revisit the ancestry of domestic and Przewalski's horses. Science 360, 111–114.

Hoppe, K.A., Stover, S.M., Pascoe, J.R., Amundson, R., 2004. Tooth enamel biomineralization in extant horses: implications for isotopic microsampling. Palaeogeography, Palaeoclimatology, Palaeoecology, Incremental Growth in Vertebrate Skeletal Tissues: Paleobiological and Paleoenvironmental Implications 206, 355–365. https://doi.org/10.1016/j.palaeo.2004.01.012

Jacobson-Tepfer, E., 2012. The image of the wheeled vehicle in the Mongolian Altai: Instability and ambiguity. The Silk Road 10, 1–28.

Julien, M.-A., Rivals, F., Serangeli, J., Bocherens, H., Conard, N.J., 2015. A new approach for deciphering between single and multiple accumulation events using intra-tooth isotopic variations: Application to the Middle Pleistocene bone bed of Schöningen 13 II-4. Journal of Human Evolution, Special Issue: Excavations at Schöningen: New Insights into Middle Pleistocene Lifeways in Northern Europe 89, 114–128. https://doi.org/10.1016/j.jhevol.2015.02.012

Knipper, C., Paulus, S., Uerpmann, M., Uerpmann, H.-P., 2008. Seasonality and land use in Bronze and Iron Age Kakhetia (Georgia). Oxygen and strontium isotope analyses on horse and cattle teeth. Archäologische Mitteilungen aus Iran und Turan 40, 149–168.

Koch, P.L., Fisher, D.C., Dettman, D., 1989. Oxygen isotope variation in the tusks of extinct proboscideans: A measure of season of death and seasonality. Geology 17, 515–519. https://doi.org/10.1130/0091-7613(1989)017<0515:OIVITT>2.3.CO;2

Kohn, M.J., 2004. Comment: tooth enamel mineralization in ungulates: implications for recovering a primary isotopic time-series, by BH Passey and TE Cerling (2002). Geochimica et Cosmochimica Acta 68, 403–405.

Kohn, M.J., 1996. Predicting animal $\delta^{18}O$: accounting for diet and physiological adaptation. Geochimica et Cosmochimica Acta 60, 4811–4829.

Kohn, M.J., Cerling, T.E., 2002. Stable Isotope Compositions of Biological Apatite. Reviews in Mineralogy and Geochemistry 48, 455–488. https://doi.org/10.2138/rmg.2002.48.12

Kohn, M.J., Schoeninger, M.J., Valley, J.W., 1996. Herbivore tooth oxygen isotope compositions: effects of diet and physiology. Geochimica et Cosmochimica Acta 60, 3889–3896.

Lazzerini, N., Zazzo, A., Coulon, A., Turbat, T., Marchina, C., Lepetz, S., (in review, minor revisions). Date of death of domestic caprines assessed by oxygen isotopic analysis of developing molars: implications for deciphering the calendar of pastoral activities in prehistory. Journal of Archaeological Science.

Lepetz, S., Zazzo, A., Bernard, V., de Larminat, S., Magail, J., Gantulga, J.-O., 2019. Customs, rites, and sacrifices relating to a mortuary complex in Late Bronze Age Mongolia (Tsatsyn Ereg, Arkhangai). Anthropozoologica 54, 151–177.

Marchina, C., Lepetz, S., Salicis, C., Magail, J., 2017. The skull on the hill. Anthropological and osteological investigation of contemporary horse skull ritual practices in central Mongolia (Arkhangai province). Anthropozoologica 52, 171–184. https://doi.org/10.5252/az2017n2a3

Outram, A.K., Stear, N.A., Bendrey, R., Olsen, S., Kasparov, A., Zaibert, V., Thorpe, N., Evershed, R.P., 2009. The earliest horse harnessing and milking. Science 323, 1332–1335.

Passey, B.H., Cerling, T.E., 2002. Tooth enamel mineralization in ungulates: implications for recovering a primary isotopic time-series. Geochimica et Cosmochimica Acta 66, 3225–3234. https://doi.org/10.1016/S0016-7037(02)00933-X

Pederzani, S., Britton, K., 2019. Oxygen isotopes in bioarchaeology: Principles and applications, challenges and opportunities. Earth-Science Reviews 188, 77–107. https://doi.org/10.1016/j.earscirev.2018.11.005

Taylor, W., 2017. Horse demography and use in Bronze Age Mongolia. Quaternary International 436, 270–282. https://doi.org/10.1016/j.quaint.2015.09.085

Upex, B., Dobney, K., 2012. Dental enamel hypoplasia as indicators of seasonal environmental and physiological impacts in modern sheep populations: a model for interpreting the zooarchaeological record. Journal of Zoology 287, 259–268.

Wright, J., 2007. Organizational principles of khirigsuur monuments in the lower Egiin Gol valley, Mongolia. Journal of Anthropological Archaeology 26, 350–365. https://doi.org/10.1016/j.jaa.2007.04.001

Zazzo, A., Balasse, M., Patterson, W.P., 2005. High-resolution $\delta^{13}C$ intratooth profiles in bovine enamel: Implications for mineralization pattern and isotopic attenuation. Geochimica et Cosmochimica Acta 69, 3631–3642. https://doi.org/10.1016/j.gca.2005.02.031

Zazzo, A., Bendrey, R., Vella, D., Moloney, A.P., Monahan, F.J., Schmidt, O., 2012. A refined sampling strategy for intra-tooth stable isotope analysis of mammalian enamel. Geochimica et Cosmochimica Acta 84, 1–13. https://doi.org/10.1016/j.gca.2012.01.012

Zazzo, A., Lepetz, S., Magail, J., Gantulga, J.-O., 2019. High-precision dating of ceremonial activity around a large ritual complex in Late Bronze Age Mongolia. Antiquity 93, 80–98. https://doi.org/10.15184/aqy.2018.175

Zazzo, A., Mariotti, A., Lécuyer, C., Heintz, E., 2002. Intra-tooth isotope variations in late Miocene bovid enamel from Afghanistan: paleobiological, taphonomic, and climatic implications. Palaeogeography, Palaeoclimatology, Palaeoecology 186, 145–161.



Figure 1: Map of Mongolia showing the location of the study site.

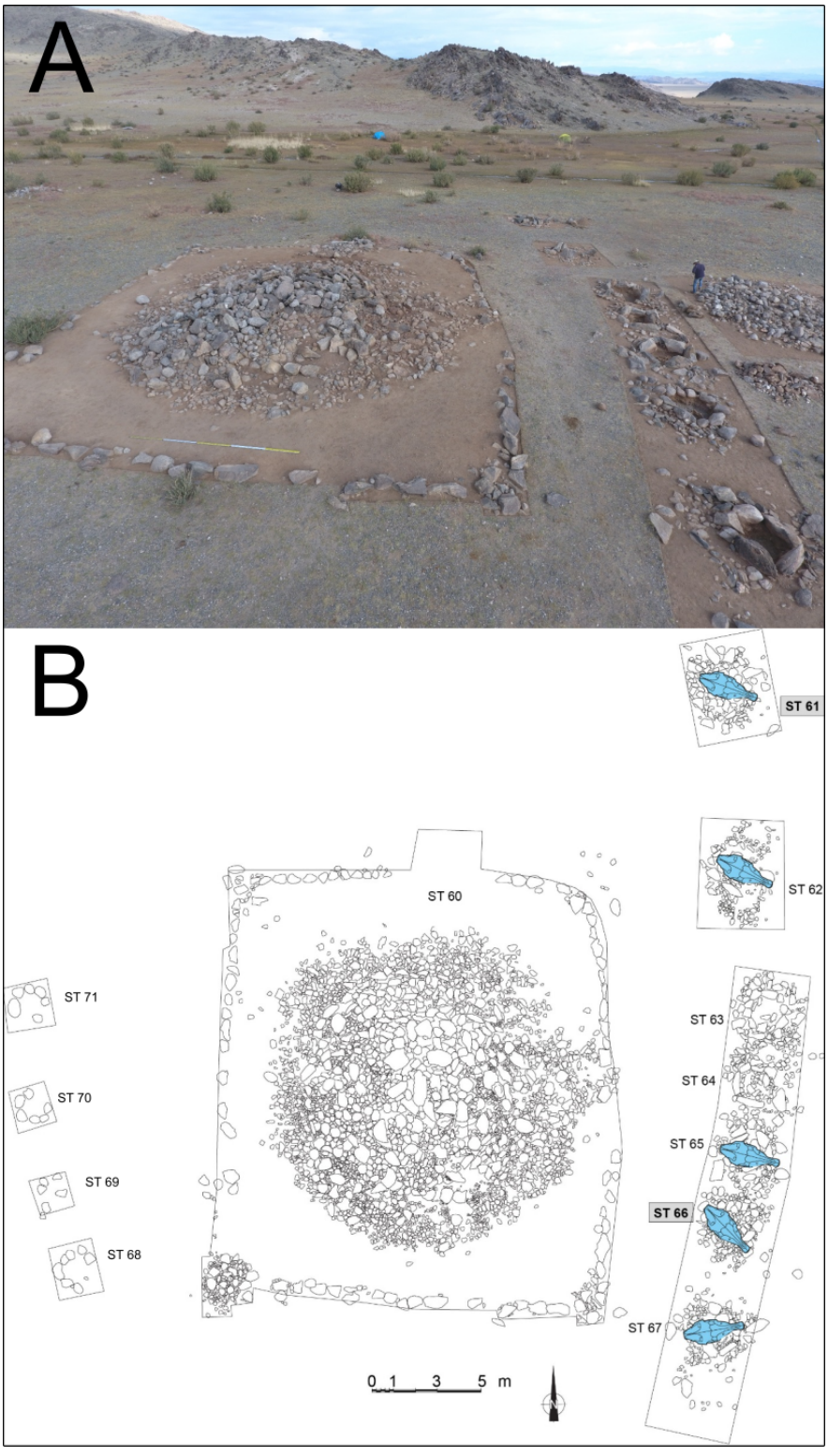


Figure 2: (A) view and (B) plan of khirgisuur ST 60 and its peripheral structures, including the four stone circles (ST 68-71) and seven stone mounds (ST 62-67), located west and east of the central mound, respectively, some of which contained the remains of horses. The stone mounds that contained the individuals analysed in this study are highlighted in grey. Photograph: S. Lepetz.

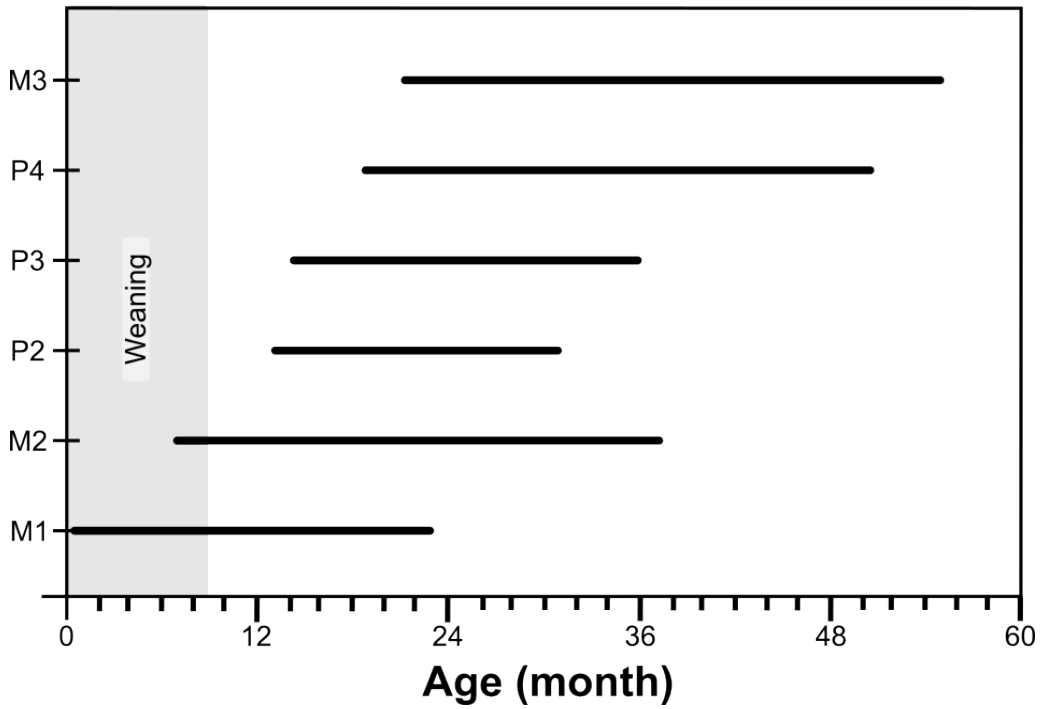


Figure 3: Calendar of horse tooth mineralisation, modified after Hoppe et al. (2004). P2-P4 (premolars) and M1-M3 (molars) refer to tooth from either the upper or the lower jaw.

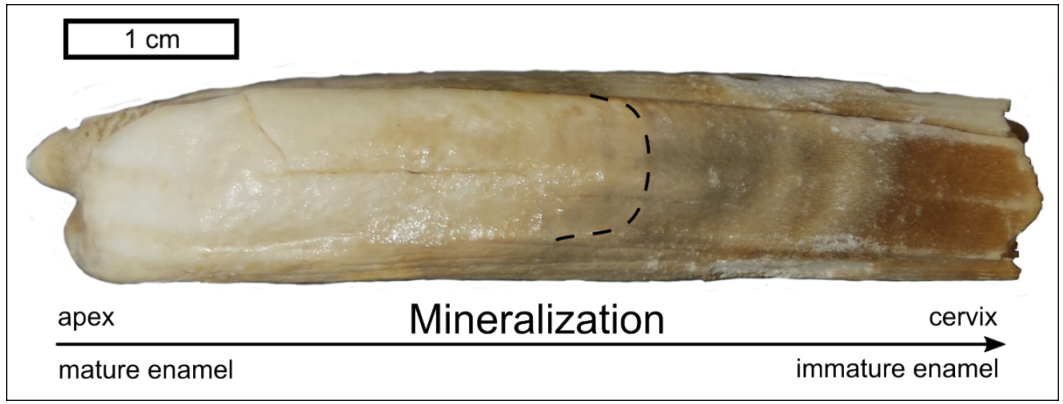


Figure 4: First molar from individual 2018-59a (view from the mesial side). The tooth was still growing at the time of death, and immature enamel (brown in colour) is clearly visible in the lower part of the tooth. The dotted black line indicates the limit between mature and immature enamel. Photograph: N. Lazzerini.

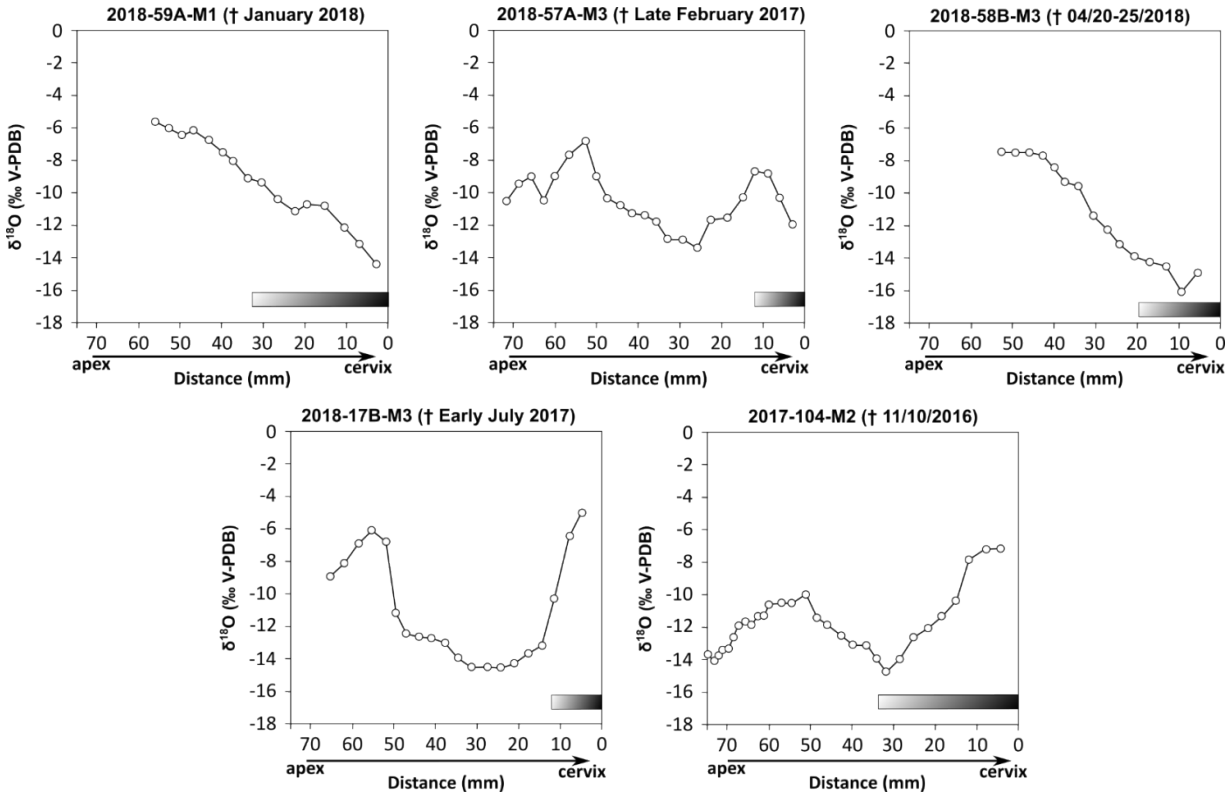


Figure 5: Oxygen isotope ($\delta^{18}O$ ‰) variations recorded along the tooth enamel of the molars from the five modern horses. The position of the sample is expressed as the distance between the sample and the base of the tooth crown, with the oldest enamel on the left and the youngest enamel on the right. The white circles represent the measured data. The period of death of the animal is indicated after the sample label. The results are presented according to the season of death, from January (top left) to November (bottom right). The grey shaded area represents the immature enamel zone.

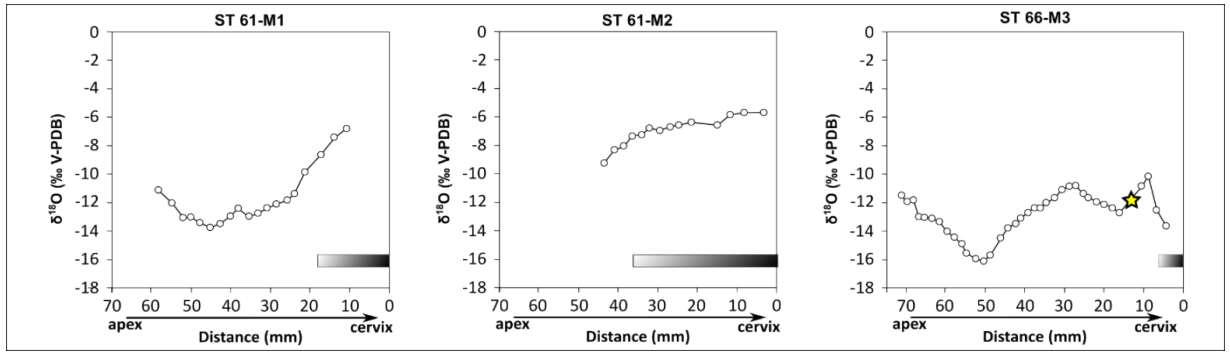


Figure 6: Oxygen isotope ($\delta^{18}O$ ‰) variations recorded along the tooth enamel of the molars from the two Bronze Age horses. The position of the sample is expressed as the distance between the sample and the base of the tooth crown, with the oldest enamel on the left and the youngest enamel on the right. The white circles represent the measured data. The grey shaded area represents the immature enamel zone. The yellow star indicates the position of the hypoplasia.

Table 1: Characteristics of the Bronze Age samples analysed in this study. Subscript and superscript indicate that the molar was taken from the lower or upper jaw, respectively.

Sample	Species	Sex	Estimated age (years)	^{14}C date ± error (1σ)	Target #	Calibrated date (BCE)		Sampled tooth
						from	to	
ST 61 M1 ST 61 M2	*Equus caballus*	?	1	2814 ± 28	ECHo 1507	−1052	−898	M_1 right M_2 right
ST 66 M3	*Equus caballus*	M	~ 5	2887 ± 25	ECHo 1513	−1190	−979	M^3 right

Table 2: Characteristics of the modern reference set analysed in this study. Subscript and superscript indicate that the molar was taken from the lower or upper jaw, respectively.

Sample	Species	Sex	Birth	Death	Season	Sampled tooth
2017-104 M2	*Equus caballus*	F	April–May 2013	10 November 2016	winter	M_2 right
2018-17B M3	*Equus caballus*	M	2013–2014?	early July 2017	summer	M^3 right
2018-57A M3	*Equus caballus*	M	2003?	late February 2007	winter	M^3 left
2018-58B M3	*Equus caballus*	M	2015?	20–25 April 2018	spring	M^3 right
2018-59A M1	*Equus caballus*	F	2016?	January 2018	winter	M_1 right

Table 3: Stable isotope analysis of enamel bioapatite ($\delta^{18}O$‰ V-PDB) from the molars (M1, M2, and M3) of the modern horses. Subscript and superscript indicate that the molar was taken from the lower or upper jaw, respectively. Sample position is indicated as the distance from the base of the tooth crown.

2017-104b M_2		**2018-17b M^3**		**2018-57a M^3**		**2018-58b M^3**		**2018-59a M_1**	
† November		† July		† February		† April		† January	
distance (mm)	$\delta^{18}O$ (‰)	distance (mm)	$\delta^{18}O$ (‰)	distance (mm)	$\delta^{18}O$ (‰)	distance (mm)	$\delta^{18}O$ (‰)	distance (mm)	$\delta^{18}O$ (‰)
74.8	−13.7	65.2	−8.9	71.9	−10.6	67.6		56.2	−5.6
73.1	−14.1	61.8	−8.1	68.7	−9.4	64.6		52.7	−6.0
72.2	−13.8	58.6	−6.9	65.7	−9.0	61.7		49.8	−6.4
71.0	−13.4	55.3	−6.1	62.7	−10.4	58.8		46.9	−6.2
69.8	−13.3	51.9	−6.8	59.9	−8.9	55.4		43.3	−6.7
68.5	−12.6	49.5	−11.2	56.5	−7.6	52.7		39.8	−7.5
67.3	−11.9	46.8	−12.4	52.8	−6.8	49.4	−7.5	37.2	−8.0
65.6	−11.7	43.9	−12.6	50.2	−9.0	46.1	−7.5	33.9	−9.1
64.2	−11.9	41.0	−12.7	47.4	−10.3	42.7	−7.5	30.4	−9.3
62.8	−11.4	37.6	−13.0	44.2	−10.8	39.9	−7.7	26.6	−10.4
61.1	−11.3	34.5	−13.9	41.4	−11.2	37.2	−8.5	22.5	−11.1
59.8	−10.6	31.3	−14.5	38.5	−11.3	34.2	−9.3	19.6	−10.7
57.0	−10.5	27.5	−14.5	35.7	−11.7	30.4	−9.6	15.2	−10.8
54.4	−10.5	24.3	−14.5	32.9	−12.8	27.1	−11.4	10.5	−12.1
51.3	−10.0	21.0	−14.3	29.2	−12.9	24.1	−12.3	6.8	−13.1
48.3	−11.4	17.7	−13.6	25.7	−13.3	20.6	−13.2	2.9	−14.4
45.9	−11.9	14.5	−13.1	22.5	−11.8	17.1	−13.9		
42.8	−12.5	11.4	−10.3	18.5	−11.5	13.0	−14.2		
39.7	−13.1	7.8	−6.5	14.8	−10.3	9.4	−14.5		
36.5	−13.1	4.9	−4.9	11.9	−8.7	5.4	−16.1		
34.0	−14.0			8.7	−8.8				
31.8	−14.7			6.1	−10.3				
28.6	−13.9			2.9	−11.9				
25.1	−12.7								
21.7	−12.1								
18.4	−11.4								
15.0	−10.4								

11.8	−7.9				
7.9	−7.3				
4.2	−7.2				

Table 4: Stable isotopes analysis of enamel bioapatite ($\delta^{18}O$‰ V-PDB) from the molars (M1, M2, and M3) of the Bronze Age horses. Subscript and superscript indicate that the molar was taken from the lower or upper jaw, respectively. Sample position is indicated as the distance from the base of the tooth crown.

ST61 M_1		**ST 61 M_2**		**ST66 M^3**	
distance (mm)	$\delta^{18}O$ (‰)	distance (mm)	$\delta^{18}O$ (‰)	distance (mm)	$\delta^{18}O$ (‰)
13.9	−11.1	3.7	−9.2	71.0	−11.5
17.3	−12.0	6.2	−8.3	69.6	−12.0
20.1	−13.0	8.6	−8.0	68.2	−11.8
22.1	−13.0	10.8	−7.3	66.8	−13.0
24.4	−13.4	13.1	−7.2	65.3	−13.0
27.0	−13.7	15.0	−6.8	63.4	−13.1
29.5	−13.5	17.8	−6.9	61.5	−13.4
31.9	−13.0	20.4	−6.7	59.6	−14.1
34.0	−12.4	22.7	−6.6	57.8	−14.5
36.8	−13.0	25.7	−6.4	55.9	−14.9
39.1	−12.8	32.2	−6.5	54.7	−15.6
41.2	−12.4	35.5	−5.9	52.4	−16.0
43.7	−12.1	39.0	−5.7	50.3	−16.1
46.5	−11.8	44.1	−5.7	48.6	−15.7
48.2	−11.4			46.2	−14.6
51.0	−9.9			44.3	−13.8
54.9	−8.7			42.2	−13.5
58.3	−7.5			40.9	−13.1
61.3	−6.8			39.2	−12.8
				37.5	−12.4
				36.1	−12.4
				34.5	−12.1
				32.5	−11.7
				30.6	−11.1
				28.6	−10.9
				27.3	−10.9
				25.2	−11.5
				23.8	−11.7
				21.8	−12.0
				20.0	−12.1
				17.8	−12.4
				16.0	−12.7
				10.5	−10.9
				8.8	−10.2
				6.8	−12.5
				4.3	−13.7

Table 5: Summary statistics of the oxygen isotopic values ($\delta^{18}O$) of tooth enamel in the modern and Bronze Age (†) horses. Subscript and superscript indicate that the molar was taken from the lower or upper jaw, respectively. N = number of samples per tooth. SD = standard deviation.

Samples	N	$\delta^{18}O$ (‰ V-PDB)			
		Mean ± SD	Max.	Min.	Amplitude
2017-104b-M_2	25	−11.8 ± 1.9	−7.2	−14.7	7.5
2018-17b-M^3	20	−10.9 ± 3.3	−5.0	−14.5	9.5
2018-57a-M^3	23	−10.4 ± 1.7	−6.8	−13.3	6.5
2018-58b-M^3	16	−11.2 ± 3.1	−7.5	−16.1	8.7
2018-59a-M_1	16	−9.2 ± 2.7	−5.6	−14.4	8.8
ST 61 M_1 †	19	−11.7 ± 2.0	−6.8	−13.7	6.9
ST 61 M_2 †	14	−6.9 ± 1.0	−5.7	−9.2	3.5
ST 66 M^3 †	36	−12.9 ± 1.5	−10.2	−16.1	5.9