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Strontium Isotope Analysis, the Neonatal Line, and Archaeological Caribou Herd Identity in Northwest Alaska

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ABSTRACT. *Rangifer tarandus* is a keystone species in the Arctic and has shaped human land use in this region for tens of thousands of years. The migratory ecotype requires large landscapes and long migrations between summer and winter ranges to meet their nutritional needs. The extent to which these ranges have remained the same has been controversial and uncertain. Archaeological caribou herd identity is usually ascribed based on modern caribou herd distribution. However, no study has assessed the validity of the implicit assumption of multi-thousand years of range stasis. Given that a caribou herd's distribution and landscape use may change in response to ecological or climatic changes, it is important to assess whether past and present calving ground locations may have shifted. In this study, we applied strontium isotope analysis to identify calving grounds of archaeological caribou from the pre-contact/historic Lake Kaiyak site (MIS-00032) near the calving grounds of the modern Western Arctic caribou herd (WAH). We found that the $^{87}Sr/^{86}Sr$ values of the molars were consistent with those predicted for WAH ranges. The dental enamel from the neonatal line (NNL), a pathological marker of birth, was consistent with the modern WAH calving grounds and early summer range. These results suggest that the archaeological specimens were WAH animals. Broadly, this supports the use of strontium isotope analysis of permanent molars with an emphasis on the NNL to determine the herd identity of ungulates in the archaeological record, which has important implications for archaeology and modern wild ungulate herd management.

Keywords: Archaeological caribou herd; strontium; neonatal line; isotope analysis; isoscape; LA-MC-ICP-MS

RÉSUMÉ. Dans l'Arctique, le *Rangifer tarandus* est une espèce clé. Depuis des dizaines de milliers d'années, cette espèce façonne l'utilisation des terres de l'Arctique par l'être humain. Afin de répondre à ses besoins alimentaires, l'écotype migratoire a besoin de vastes paysages et de longues migrations entre les aires d'estivage et les aires d'hivernage. La mesure dans laquelle ces aires sont demeurées inchangées fait l'objet de controverses et d'incertitudes. En général, l'identité d'un troupeau de caribou archéologique est déterminée en fonction de la répartition d'un troupeau de caribou moderne. Cependant, aucune étude n'a évalué la validité de l'hypothèse implicite de la stase des aires de répartition sur plusieurs milliers d'années. Puisque la répartition d'un troupeau de caribou et l'utilisation du paysage peuvent changer en réponse aux changements écologiques ou climatiques, il est important d'évaluer si les lieux de mise bas, anciens et actuels, peuvent avoir changé. Dans le cadre de cette étude, nous avons utilisé l'analyse isotopique du strontium pour déterminer les aires de mise bas du caribou archéologique au site historique et préeuropéen de Lake Kaiyak (MIS-00032), près des aires de mise bas du troupeau de caribou moderne de l'Arctique de l'Ouest (WAH). Nous avons constaté que les valeurs $^{87}Sr/^{86}Sr$ des molaires coïncidaient avec celles prévues pour les aires du troupeau de l'Arctique de l'Ouest. L'émail dentaire de la ligne néonatale, un marqueur pathologique de la naissance, correspondait aux aires de mise bas et à l'aire estivale initiale du troupeau de caribou moderne de l'Arctique de l'Ouest. Ces résultats suggèrent que les spécimens archéologiques provenaient de bêtes du troupeau de l'Arctique de l'Ouest. De manière générale, ces données viennent appuyer l'utilisation de l'analyse isotopique du strontium des molaires permanentes mettant l'accent sur la ligne néonatale pour déterminer l'identité du troupeau d'ongulés des données archéologiques, ce qui a d'importantes implications pour la gestion du troupeau sauvage d'ongulés archéologiques et modernes.

Mots-clés : troupeau de caribou archéologique; strontium; ligne néonatale; analyse isotypique; paysage isotopique; LA-MC-ICP-MS

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АННОТАЦИЯ. Северный олень (лат. *Rangifer tarandus*) – ключевой вид арктической фауны, на протяжении десятков тысяч лет определяющий землепользование человека в Арктике. Этой мигрирующей популяции нужен простор и большие расстояния для миграции между летним и зимним ареалами для удовлетворения своих потребностей в питании. Однако спорным остается вопрос насколько эти ареалы сохранились. Археологическая идентичность стада северных оленей обычно определяется на основе нынешнего распределения стада. Однако не проводились исследования, оценивающие обоснованность предположения о стазисе ареала, длившегося много тысяч лет. Учитывая, что распределение и использование ландшафта стадом может измениться в ответ на климатические изменения, важно оценить, могли ли измениться места отела в прошлом и в настоящее время. В этом исследовании мы использовали анализ изотопов стронция для археологического определения мест отела северных оленей из доконтактного/исторического участка на озере Кайяк (MIS-00032) недалеко от мест отела современного западно-арктического стада (WAH). Для анализа использовались образцы со стоянки на озере Каяк (MIS-00032) и стоянки возле мест отела современного Западного арктического стада (англ. Western Arctic caribou herd, WAH). Мы обнаружили, что соотношения изотопов стронция $^{87}Sr/^{86}Sr$ в коренных зубах соответствуют прогнозам для диапазонов WAH. Зубная эмаль неонатальной линии, патологический маркер рождения, соответствует современным местам отела WAH и раннему летнему ареалу. Исходя из этого, можно предположить, что археологические образцы являются животными WAH. В целом, это обосновывает использование анализа содержания стронция в постоянных коренных зубах с акцентом на зубную эмаль неонатальной линии для определения идентичности стада из археологических свидетельств, что имеет большое значение для археологии и современного управления стадом диких оленей.

Ключевые слова: Археологическое исследование стада северных оленей; стронций; неонатальная линия; анализ изотопов; LA-MC-ICP-MS

INTRODUCTION

Rangifer tarandus, caribou in North America and reindeer in Europe and Asia, is a keystone species of the Arctic and subarctic regions that is receiving considerable attention regarding population dynamics and longevity (Joly et al., 2021). The species is a cornerstone of Alaska Native communities' subsistence lifestyles and ecosystem function (Fauchald et al., 2017). Recent studies have indicated more than 70% of herds across the Arctic are declining in population at a time when forage appears to be more abundant and herds should be expanding (Ju and Masek, 2016; Myers-Smith et al., 2019). Changes in modern caribou herd migratory routes and range size have been documented (Hinkes et al., 2005; Bergerud et al., 2008; Couturier et al., 2010; Joly et al., 2021). The ethnographic record suggests that migratory herds can disband (Burch, 2012). A significant question raised by these changes is if caribou herds have shifted their habitats of use, including their calving grounds, and summer, migratory, or winter ranges. If so, other significant questions are opened such as have those shifts happened in the recent or distant past and under what conditions?

Caribou have long been central to human survival strategies in the Arctic (Burch, 2012; Friesen, 2013); they were the primary source of hides for the clothing necessary to endure the deep cold of high latitudes (Burch, 2012). Historically they have been the main source of animal protein for people in the far north (Gubser, 1965). Today, caribou remain the primary source of some vital nutrients, such as iron, zinc, and vitamin B12, and a major source of protein for some northern communities (Kenny et al., 2018). For thousands of years, cooperative large-scale harvests of migrating caribou were done using drive lines combined with corrals or water features (Friesen, 2013). In a good year, a community could harvest hundreds of caribou in a single day (Burch, 2012), and thousands in a single season (Dall, 1870). This implies that a herd of hundreds of thousands of animals with an annual range of hundreds of thousands of square kilometers would have been subject to the harvest of many thousands of animals per annum. Today, decades after mass harvest methods have ceased (Gubser, 1965; Binford, 1978), humans remain the second most significant caribou predator after wolves *(Canis lupus)* (Bergerud, 2000; Burch, 2012). An understanding of the historical and archaeological patterns of caribou herd landscape use and how it has changed in response to dynamics in human exploitation, climatic shifts, and ecological change is important for anthropology, archaeology, and modern wildlife management.

Archaeologists seeking to understand past northern peoples, need to understand the land-use patterns of the caribou herds upon which these peoples depended. Changes in caribou herd land use dictate changes in human land use in these high latitudes (Bergerud et al., 2008; Burch, 2012). Without a scientific method to identify a herd and its movements in an archaeological context, herd identity is assumed based on a site's proximity to extant herds or, as is more often the case, not addressed. Ascribing herd identity based on modern herd distribution assumes that herd ranges are static and that herds have not died out or disbanded. This is not the case (Hinkes et al., 2005; Burch, 2012). As a result, there are gaps in archaeological site location models for caribou harvesting sites.

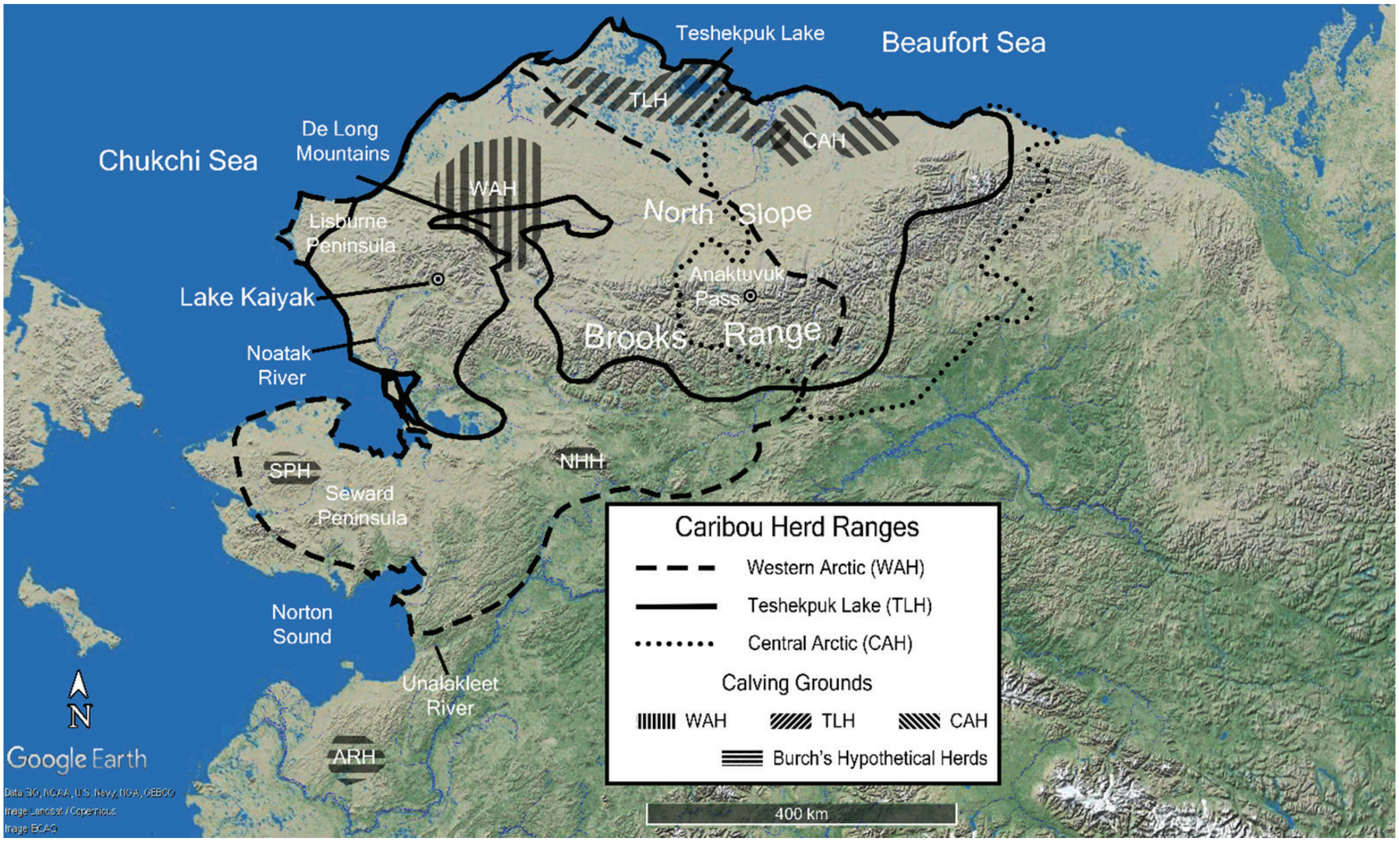


FIG. 1. Caribou herds of northwestern Alaska and locations mentioned in the text, except those specific to the lithology. Extant herd ranges and calving grounds based on Prichard et al. (2020: Fig. 1). Hypothetical herd (SPH = Seward Peninsula caribou herd, NHH = Nulato Hills caribou herd, ARH = Andreafsky River caribou herd) calving grounds based on Burch (2012:Fig 7.1) Map is a combination of Google Earth, a USGS topographic map quadrangle layer created for Google Earth by Earth Point (2020), and the major Alaska rivers are highlighted by a Google Earth layer created by the Alaska Department of Natural Resources (2020).

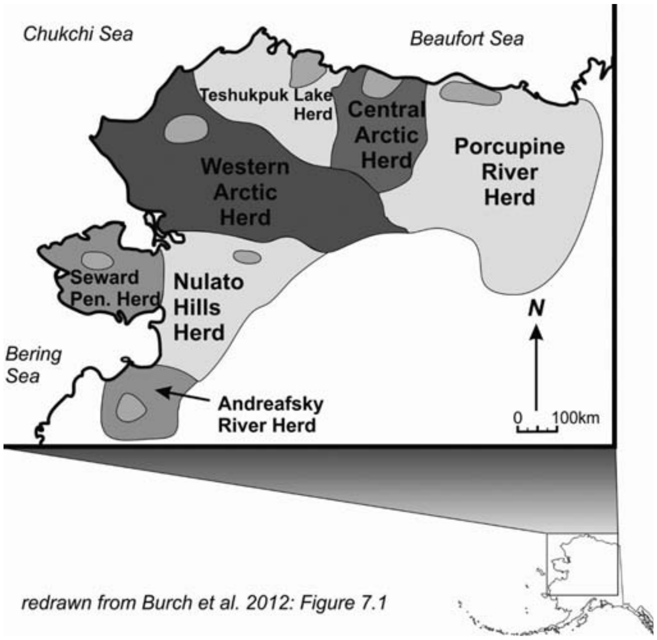
BACKGROUND

Known and Hypothesized Caribou Herds of Northwest Alaska

Modern radio collar data demonstrates that northwestern Alaska is currently occupied in whole or in part by three caribou herds: the Western Arctic caribou herd (WAH), the Teshekpuk Lake caribou herd (TLH; also known as Teshekpuk caribou herd), and the Central Arctic caribou herd (CAH) (Prichard et al., 2020; see Fig. 1). The modern WAH range covers northwestern Alaska from the Arctic Ocean to the Unalakleet River drainage and from the eastern two-thirds of the Seward Peninsula to Anaktuvuk Pass in the middle of the Brooks Range (Dau, 2011; Fig. 1). The WAH calves in the De Long Mountains, Utukok Hills, and adjacent areas north of the Brooks Range, summers on the western North Slope, and winters on the Seward Peninsula (Dau, 2015; Prichard et al., 2020). The TLH range consists of the central North Slope and Brooks Range, sharing significant parts of the eastern portion of the WAH range. The TLH calves near Teshekpuk Lake and summers between Teshekpuk Lake and the Beaufort Sea coast. Most of the TLH winters on the coastal plain, while some winter in the central or western Brooks Range (Person et al., 2007; Prichard et al., 2020). TLH animals have been documented in all parts of the WAH range, except for the Seward Peninsula (Parrett, 2015). The CAH range consists of the central and eastern North Slope and Brooks Range (Lenart, 2015; Pedersen et al., 2021), overlapping only with the eastern most parts of the WAH. The CAH calves in two locations on the central coastal plain (see Fig. 1), summer along the Beaufort Sea coast, and winter in and around the east-central Brooks Range (Lenart, 2015; Prichard et al., 2020). Based solely on documented extant herds, a caribou recovered from the archaeological record in northwestern Alaska could be from any one of these three herds. The ethnographic record, however, indicates an even more complex situation.

Burch (2012) uses ethnographic and historic records to hypothesize that at the start of the nineteenth century there were three more caribou herds in northwest Alaska (Fig. 2). They argue that prior to a devastating caribou population crash in the mid to late nineteenth century three now disbanded herds were south of the Brooks Range; the Seward Peninsula caribou herd (SPH) on the Seward Peninsula, the Nulato Hills caribou herd (NHH) east of the Seward Peninsula, and the Andreafsky River caribou herd (ARH) east and south of Norton Sound.

If these herds did not exist and the WAH, TLH, and CAH had the same ranges before the late nineteenth-century caribou crash (Fig. 1) as they do today, then these herds endured the many ecological difficulties of the nineteenth century, simply retracting their ranges in response to their declining populations during the late nineteenth century crash and then expanding again as they recovered. In this situation archaeological human land-use models in northwest Alaska may safely be based on WAH, TLH, and CAH migration patterns. If, however, the three herds proposed by Burch (2012) did exist and died out during the late nineteenth-century caribou crash, then we have a multi-decadal example of how migratory caribou herds respond to the disbanding of a neighboring herd or herds. Documentation of such an event would be valuable for archaeologists and wildlife managers alike. The existence of these herds would require a reevaluation of archaeological land-use models for the entire region. It would also provide a real-world example of where, when, and how migratory caribou herds colonize suitable habitat. Before these and other questions can be addressed, a scientific method to identify an archaeological caribou herd is necessary.



redrawn from Burch et al. 2012: Figure 7.1

FIG. 2. Reconstruction of mid-nineteenth century caribou herd calving grounds (dark areas) and ranges for northwest Alaska from Burch (2012:Map 7.1). Figure drawn by Diane Hanson.

Caribou Herd Identity

Caribou herds are defined by the habitual use of discreet calving grounds by pregnant cows over a period of years (Skoog, 1968; Geist, 1998; Bergerud et al., 2008; Dau, 2011). Calving grounds are one of the most consistently used areas of a herd's range from year to year (Skoog, 1968; Gunn and Miller, 1986; Hinkes et al., 2005) and the focal point of the annual migration for pregnant cows (Bergerud, 2000). The Alaska Department of Fish and Game (ADF&G) delineates a herd's calving grounds by combining annually determined "99% fixed kernel utilization distribution of radio collared parturient cows" (Arthur and Del Vecchio, 2009:3) during peak calving into multiyear 95% fixed or adaptive kernel of calving areas (Carroll, 2007; Dau, 2007, 2015; Parrett, 2015). These cumulative maps often depict a core 50% or 75% utilization area within the larger 95% kernel calving distribution. Hinkes et al. (2005) however, only require that >50% of pregnant cows express range fidelity annually for an area to be defined as the herd's calving grounds. This paper uses the cumulative (2003 to 2015) calving grounds and herd ranges delineated by the 75% kernel utilization distribution provided in Prichard et al. (2020:Fig. 1).

Defining a herd on discreet and habitual calving ground use does not address all situations. Some herds have multiple calving grounds, such as the CAH, which has regularly used two since it was initially surveyed in 1978 (Lawhead and Cameron, 1988; Lenart, 2015). Other herds have intermittently used satellite calving areas concurrent with their main calving ground, such as the Mulchatna caribou herd (Hinkes et al., 2005; Barten, 2015). The Mulchatna caribou herd is located in southwest Alaska near the head of the Alaska Peninsula along the Mulchatna River. Multiple herds can also use overlapping calving grounds while remaining behaviorally and genetically distinct, such as the Fortymile caribou herd (also referred to as the Fortymile River herd) and the White Mountain caribou herd, which are of the migratory and sedentary ecotypes respectively (Mager et al., 2014; Ehlers et al., 2021). The Fortymile caribou herd and the White Mountain caribou herd are located in central eastern Alaska along the Fortymile River and in the White Mountains respectively. The migratory ecotype is characterized by long migrations, calving grounds above the treeline, and calving saturation (i.e., calves are dropped in a limited space and time). The sedentary ecotype has shorter migrations, may spend the whole year above or below the treeline, and practices calving dispersion (i.e., calving is more spread out in both space and time; Bergerud, 2000; Hinkes et al., 2005). Pregnant cows occasionally calve with a neighboring herd then return to calving with their original herd. Of observed parturient cows (OPC) most return to their original herd after a year, though Prichard et al. (2020) observed three which calved with other herds for two or more years before returning to their original herd. From 2003 to 2015 Prichard et al. (2020) documented that 3.5% and 3.9% of TLH OPCs (n = 257) calved with the WAH and CAH respectively. For the CAH, 2.8% of OPCs (n = 240) calved with other herds; 0.8% with the WAH, 0.8% with the TLH, and the remaining 1.2% with the Porcupine River caribou herd (PRH; also referred to as the Porcupine caribou herd). However, this appears to be a behavior of smaller herds. Only 0.5% of the PRH OPCs (n = 192) calved with another herd, the CAH. None of the WAH OPCs (n = 520) calved with another herd. Of the OPCs which calved in the WAH calving range between 2003 and 2015 (n = 531), 0.02% were from other herds (Prichard et al., 2020). Then there are the herds which have overlapping calving grounds and cannot be genetically distinguished, such as the TLH and CAH

(Mager et al., 2013). TLH and CAH have been regarded as separate herds since 1978; the inclusion of parts of the CAH's calving grounds within a cumulative 95% kernel utilization distribution of TLH OCPs during peak calving was only observed after 2006 (Carroll, 2007; Person et al., 2007; Parrett, 2009; Prichard et al., 2020).

The development of a more nuanced definition of caribou herd than that provided above is beyond the scope of this paper. The habitual use of discreet calving grounds definition of a herd, along with radio tracking, has provided the basis for herd management since the 1970s. Furthermore, finding a calving ground will still produce useful data all on its own by locating a focal point of the annual movements of caribou in a given area and the peoples who exploited them. Human control of areas adjacent to calving ground locations has previously been correlated to subsistence self-sufficiency; during the last 200 years, peoples who controlled hunting grounds closest to the calving grounds of the George River caribou herd on the Ungava Peninsula, Canada, were more self-sufficient during periods of famine coincident with low caribou populations than other Indigenous peoples on the Ungava Peninsula (Bergerud et al., 2008). Therefore, the provided definition with its focus on calving grounds will be used here.

Burch (2012) and Britton et al. (2009) proposed that past caribou herds can be identified if their calving grounds could be located. In their results and discussion, Britton et al. (2009) proposed that European Paleolithic caribou herd calving grounds could be identified through an analysis of archaeological/paleontological caribou tooth enamel for the geospecific radiogenic isotope of strontium (Sr).

Radiogenic Strontium

Mass spectrometry analysis of the isotopic ratio ^{87}Sr/^{86}Sr in calcified tissues has been used to reconstruct human and animal movements for decades (Hoppe et al., 1999; Koch, 2007; Copeland et al., 2008, 2016; Hobson et al., 2009; Wooller et al., 2021). To date there have been three published studies on ^{87}Sr/^{86}Sr from dental enamel of Alaskan caribou (Britton et al., 2009; Gigleux et al., 2019; Le Corre et al., 2023) and two on Pleistocene reindeer in France (Britton, 2010; Britton et al., 2011) in which the migratory behavior and range were identified. ^{87}Sr/^{86}Sr is ideal for migration studies due to its spatial geological variation, low temporal variability, and the incorporation of Sr (which has a similar atomic radius and is chemically similar to calcium, (Ca); Faure and Powell, 1972) into calcified tissues with no significant biotic fractionation (Flockhart et al., 2015). The relatively high molecular mass of both ^{87}Sr and ^{86}Sr and the small difference in mass between them makes any biofractionation negligible as the isotopes move through the trophic levels (Flockhart et al., 2015).

The ^{87}Sr/^{86}Sr signature in local bedrock is determined by the original ^{87}Sr/^{86}Sr, the relative amounts of ^{87}Rb (the parent element that decomposes to ^{87}Sr through beta decay) to Sr, and the bedrock's age (Faure and Powell, 1972; Faure, 1977). Minerals in the bedrock with higher content of Rb, such as potassium feldspars, typically contain the highest (more radiogenic) ^{87}Sr/^{86}Sr values. Several processes contribute to the ^{87}Sr/^{86}Sr ratios available in the biosphere: weathering of bedrock from groundwater (Stueber et al., 1972); plant root uptake from soil (Maurer et al., 2012; Flockhart et al., 2015) and bedrock (Perakis and Pett-Ridge, 2019); precipitation containing marine aerosols (Miller et al., 1993); dust transport (Beard and Johnson, 2000; Miller et al., 2014); and ecosystem recycling (Perakis and Pett-Ridge, 2019). In many cases, the ^{87}Sr/^{86}Sr range observed in the ecosystem reflects the weathering of the local bedrock, however, when allochthonous sediments (e.g., glacial or eolian deposits) are the main soil parent material, the ^{87}Sr/^{86}Sr can be very different from the bedrock (Widga et al., 2017). The local ^{87}Sr/^{86}Sr is best known from bioavailable Sr contained in plants or small-range mammal teeth (Maurer et al., 2012). The Sr of local bedrock is a reasonable proxy when a bioavailable ^{87}Sr/^{86}Sr isoscape—defined as a predictive model for the distribution of an element's isotope ratios across a geographic space—is not available (Bataille and Bowen, 2012).

Once within an animal's body, Sr is readily substituted for Ca during calcification of tissues including bone, cartilage, cementum, dentine, and enamel (Boskey, 1988; Erben, 2003). However, the ^{87}Sr/^{86}Sr signature found in a given tissue is not a one-to-one equivalent with the place an animal occupied at any given moment. In mature animals, the signature reflects an averaging of the Sr incorporated into a tissue during development and any subsequent tissue turnover. There are multiple sources or pools from which the incorporated Sr isotopes may come, some or all of which may have distinct ratios. Among these pools are food, water, and the Sr cycling within the animal's body (Montgomery et al., 2010; Shagina et al., 2015a, 2015b; Weber et al., 2020). The interpretation of Sr ratios is further complicated in tissues developed in prenatal and nursing animals by the addition of another pool, the mother's body, which is itself impacted by all the above factors. While in utero all the Sr introduced to an animal's body is passed through the mother. Following birth, the mother's body remains the primary source of new Sr via lactation and nursing until a greater amount of Sr is ingested through nonmaternal sources than through the maternal one and ends when the young are fully weaned (Shagina et al., 2015a, b). The primary source of Sr introduced to offspring in these life stages remains the mother's diet; however, the demands of gestation and lactation outpace what diet alone can provide. To meet these deficits the mother's body draws on materials stored within its own tissues (Shagina et al., 2015a, b). Models of maternal Sr metabolism in human beings (*Homo sapiens*) put forward by Shagina et al. (2015a, b) posit that a pregnant or lactating mother's isotopic signal is influenced by a variety of factors among which are: diet, isotopes already present in the tissues, metabolism, where she is in the progression of her pregnancy or lactation, excretion, and a complex system of isotope exchange and recycling within her body. In this way the unborn animal and the mother's milk carry a signal that is dominated by but not identical to the Sr available on the landscape (Shagina et al., 2015a, b).

The direct maternal influence on the offspring begins to decrease as the offspring starts to ingest Sr from nonmaternal sources but continues until the offspring is fully weaned. Caribou calves start grazing on the day they are born (de Vos, 1960), start weaning at 20 days postpartum, and are metabolically weaned (the calf is no longer dependent on milk) at 40–45 days postpartum. Weaning is generally completed between 2–6 months, though a calf may be fully weaned prior to this (Lavigueur and Barrette, 1992). This pattern of weaning has been documented in calcified tissues with an isotopic analysis of $\delta^{15}N$ of first permanent mandibular molar (M_1) roots by Drucker et al. (2001). Even after weaning the maternally derived Sr continues to impact the Sr signal within the young animal through the internal exchange and recycling of Sr isotopes. The extent to which the mother's isotopic signal impacts that of the offspring is unclear. It may vary from species to species and individual to individual. In this paper we assume that the maternal influence on the Sr incorporated into an animal's dental enamel is negligible after weaning relative to the Sr available on the landscape. While Sr derived from the mother's tissues makes an important contribution to the Sr values of a neonate's tissues, the nature and degree of that influence in ungulates is not well understood and is not addressed in this paper.

Enamel Formation, the Neonatal Line, and Time Resolution

Of the calcified tissues, dental enamel is the most resistant to ion exchange with the diagenetic environment and thus retains the original $^{87}Sr/^{86}Sr$ signature longer than other calcified tissues (Tuross et al., 1989; Lee-Thorp and van der Merwe, 1991; Ayliffe et al., 1992). Because the Sr signature of a given tissue is an average of the Sr incorporated during tissue development (Bentley, 2006; Montgomery et al., 2010), understanding the nature and timing of development is essential to accurate interpretation of that signature. The formation of dental enamel (amelogenesis) in mammals consists of two stages: secretory and maturation (Smith, 1998). During the secretory stage, the protein matrix in which the enamel will fully mature is accreted. The newly accreted matrix is up to 30% mineralized by weight or approximately 10% by volume (Smith, 1998). While the nonmineralized portion of the matrix will be replaced during the maturation stage, the mineralized portion is not and becomes a permanent fixture of the fully matured enamel. The secretory stage moves along a single axis, beginning at the cusps and moving toward the cervix of the crown. The matrix is accreted in successive laminations at regular intervals known as striae of Retzius. Each stria spans from the enamel-dentine junction (EDJ) to the outer enamel surface (OES) and are visible on the tooth surface under low magnification as perikymata. Except for those on the cusp where many striae fold back in an arc starting and ending at the EDJ. Striae of Retzius are accreted at a consistent rate, though the rate can vary between species and individuals. Ungulates as a group appear to be uniform in this as one stria is equal to a single day (Jordana et al., 2014). This developmental rate is maintained even when an individual experiences metabolic or physiological stress. During periods of stress, the organization of the matrix is reduced and will not be repaired. These pathological striae of Retzius are known as "brown striae of Retzius" or simply "brown striae" (Hillson, 2005:161,163).

The NNL is a brown stria that forms at birth due to the physiological stress a neonate experiences during the birthing process and the move from the controlled in-utero environment to the uncontrolled postpartum environment (Iinuma et al., 2004; Smith and Tafforeau, 2008; Witzel, 2014). NNLs are only found in teeth that were in the secretory stage during birth. In these teeth the NNL is the highest (closest to the occlusal surface) brown stria in the crown. The enamel matrix above the NNL is well organized and uniform, reflecting consistent nourishment and the controlled in utero environment. The enamel matrix following the NNL appears less uniform and features brown stria (Iinuma et al., 2004; Jordana et al., 2014; Fig. 3a) reflecting the inconsistent and stressful nature of the postpartum environment. The only permanent mandibular molar in the secretory stage during birth in caribou is the M_1 (Wu et al., 2012).

The second stage of amelogenesis, the maturation stage, moves along two axes from the cusp toward the cervix and from the EDJ toward the OES (Fig. 3a). Once maturation is complete, minerals will compose 95% of the enamel by weight, or approximately 70% by volume (Smith, 1998). The rate and geometry of tooth mineralization is complex and not wholly understood (Tafforeau et al., 2007; Müller et al., 2019). Maturation lags matrix production and increasingly slows down as the mineralization front moves towards the OES (Tafforeau et al., 2007; Müller et al., 2019). This results in an increasingly reduced time resolution as the enamel approaches the OES from the EDJ, since the minerals incorporated in the tissue may not have been introduced for days, weeks, months, or years after matrix secretion (Passey and Cerling, 2002; Montgomery et al., 2010). However, radiographs and isotope analysis demonstrate that a thin strip of enamel immediately next to the EDJ matures during or shortly after the secretory stage, thus retaining the least attenuated, or dampened, isotopic signature (Tafforeau et al., 2007; Müller et al., 2019). The thickness of this rapidly mineralized layer next to the EDJ varies between species: ≤ 100 µm in humans (Müller et al., 2019) and ≤ 20 µm in rhinoceros (Tafforeau et al., 2007). The thickness of this rapidly mineralized layer in caribou is currently unknown. However, the closer the sample is to the EDJ the higher the time resolution (Tafforeau et al., 2007; Müller et al., 2019).

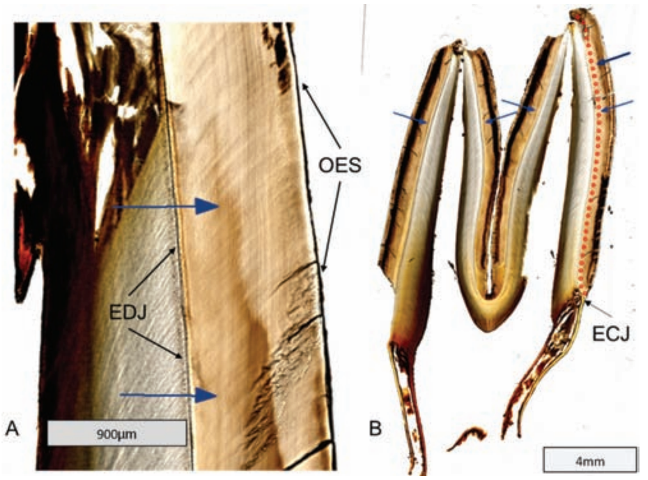


FIG. 3. A) close-up of tooth B cross-section. The enamel-dental junction (EDJ) and the outer enamel surface (OES) are indicated by black arrows. Blue arrows point to the NNL. The NNL separates the pre-birth enamel with muted striae of Retzius from the less uniform post-birth enamel with pronounced striae of Retzius. B) cross-section of tooth A. Circles show the sample track, blue arrows show the NNL in all cusps. The enamel-cementum junction (ECJ) is indicated by a black arrow.

Using traditional solution chemistry on teeth from modern and archaeological *R. tarandus*, Britton et al. (2009, 2011), Britton (2010), and Gigleux et al. (2019) were able to identify the general range of the animals and whether the animals were of the migratory or sedentary ecotypes. Calving grounds were not and could not be specifically identified. The sample size required by traditional solution chemistry for specimen preparation has a maximum temporal resolution of six months (Montgomery et al., 2010). This prohibits the identification of the range where a calf spent less than two weeks. This temporal resolution limitation in traditional solutions chemistry may be further exacerbated by the practice of including enamel near the OES that has taken months or even years to mature.

Incremental tissue sampling via laser ablation (LA) has been suggested as a solution to low geographic precision and large time-averaging of traditional solution chemistry. Gigleux et al. (2019) suggest that LA in conjunction with multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) may be used to sample incremental tissues, which accrete in predictable intervals. The small laser spot needed for LA-MC-ICP-MS, measured in micrometers (µm) rather than mm, could access a much higher temporal and geographic resolution, does not require chemical separation of the specimen, and samples can be taken *in-situ*. Copeland et al. (2008) conclude that LA-MC-ICP-MS, while less accurate than traditional solution chemistry methods for $^{87}Sr/^{86}Sr$ analysis, is within the margin of accuracy sufficient for migration and geographic origin studies (±0.003 ppm). More recently, Lugli (2019) proposed a correction method taking into account the signal measure for ^{88}Sr as a proxy for the Sr content, a method that improves the accuracy of $^{87}Sr/^{86}Sr$ measured by LA-MC-ICP-MS to the thousandths place (±0.001). As such, LA-MC-ICP-MS is sufficient for the needs of this study.

Hypothesis

From the above information, we hypothesize that an archaeological caribou herd's calving grounds, and thus herd identity, can be found by serial sampling archaeological caribou M_1s close to the EDJ via LA-MC-ICP-MS, then comparing the resulting $^{87}Sr/^{86}Sr$ ratios with available strontium isoscapes for an area multiple times the size of the maximum known migratory caribou herd range, centered on the location from which the M_1s were obtained while accounting for geography, and using the samples from the NNL to orient the samples in time and space.

Study Area

Geology of Northwest Alaska: Northwest Alaska has three different ages of bedrock (Colpron et al., 2007; Fig. 7 in Brennan et al., 2014). The Paleozoic bedrock consists of two crust fragments. The Arctic Alaska (AA) fragment includes the northern portion of the Brooks Range, North Slope, and Seward Peninsula (Fig. 4a). The Ruby (RB) fragment forms a chevron immediately south of AA. The RB fragment runs from Kotzebue Sound eastward, dividing the Brooks Range with AA. In eastern Alaska, RB makes a sharp turn to the southeast (Fig. 4a). The Paleozoic bedrock has the highest reaching and broadest range of $^{87}Sr/^{86}Sr$ ratios, 0.707 to 0.800 (Bataille et al., 2014; Brennan et al., 2014), in northwestern Alaska (Fig. 4b). East of Kotzebue Sound is an Oceanic Terrane of unspecified age that forms a chevron of bedrock that hugs the inside of the RB fragment's chevron. The Oceanic Terrane $^{87}Sr/^{86}Sr$ ratios range between 0.707 and 0.740, overlapping slightly with the lower $^{87}Sr/^{86}Sr$ ratios of the Paleozoic bedrock (Bataille et al., 2014; Brennan et al., 2014). The Cretaceous bedrock (K) consists of the Kuskokwim Group and the Yukon-Koyukuk basin. It sits inside the chevron formed by the Oceanic Terrane. K is partially bordered on the west by the Seward Peninsula. South of the Seward Peninsula, K forms the coast of Norton Sound and much of western Alaska. The K $^{87}Sr/^{86}Sr$ ratios range from 0.701 to 0.711. While mostly lower than those of the Paleozoic bedrock, K's $^{87}Sr/^{86}Sr$ ratios overlap with the other two bedrock types between 0.707 and 0.711 (Bataille et al., 2014; Brennan et al., 2014; Figs. 4a and 4b)

Lake Kaiyak Site (MIS-00032): The Lake Kaiyak site (MIS-00032) is a late pre-contact, single-component village of eight house pits in the middle Noatak River Valley (Fig. 1) on the western edge of the nineteenth-century Napaaqtugmiut Iñupiat territory near their border with the Nuataagmiut Iñupiat (Burch, 1998). The site is on the southeastern shore of Lake Kaiyak (alternatively written Lake Kayak or Kayak Lake) approximately 14 km north of the Noatak River. The lake sits in a swale between gentle rolling hills creating a natural catchment for caribou from which they were harvested (Gilbert-Young, 2004). Caribou dominate the zooarchaeological assemblage, with 1666 of the 1681 faunal specimens identified to species

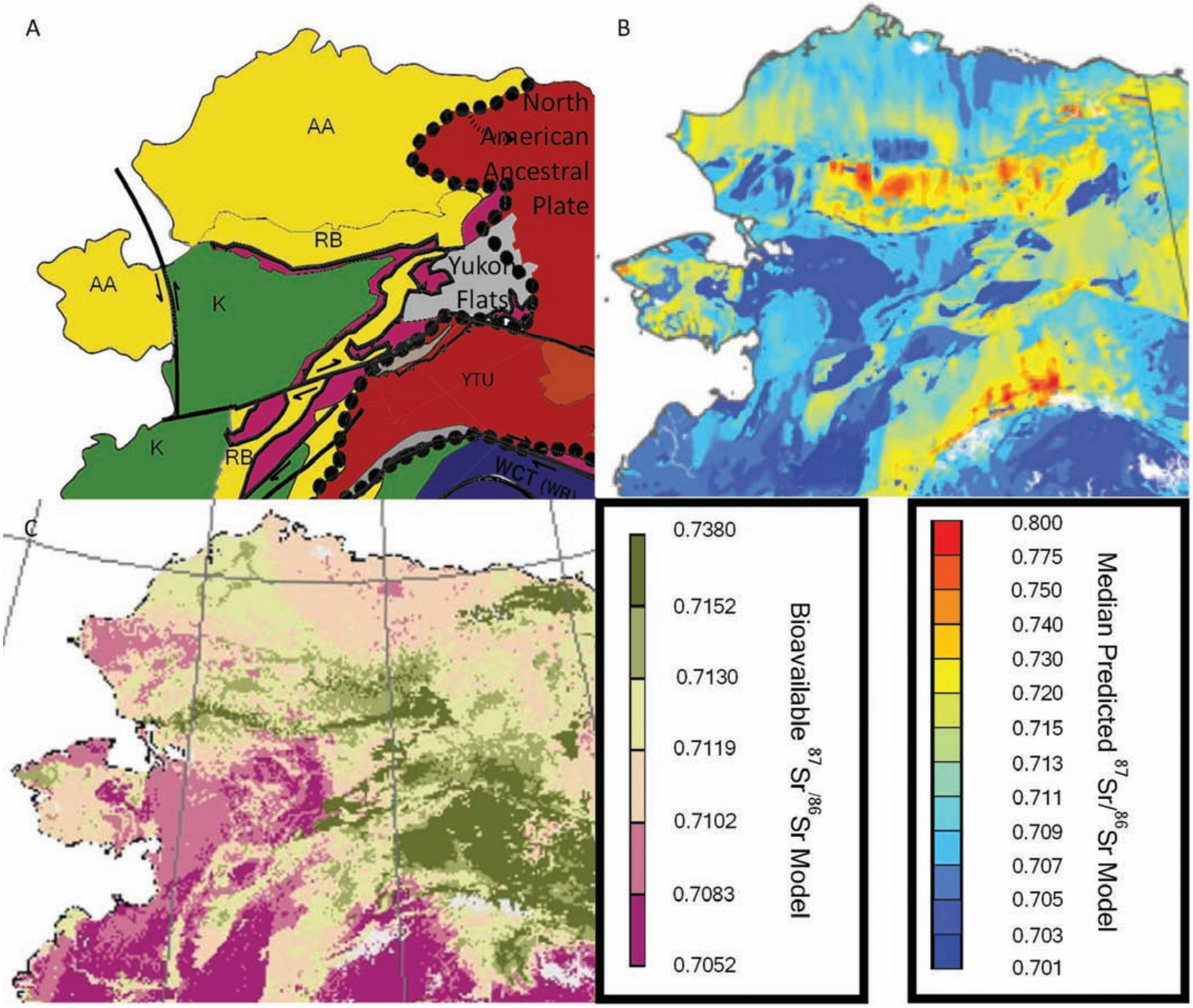


FIG. 4. A) Lithology of northwest Alaska, including the boundary of the North American Ancestral Plate (dashed line) modified from Brennan et al. (2014:Fig.7). Yellow = Precambrian and Paleozoic crust fragments, AA= Arctic Alaska, RB= Ruby, green = Cretaceous, K= Kuskokwim Group and Yukon-Koyukuk basin, pink = unknown age, Oceanic Terranes, red = Precambrian to Mesozoic, YTU = Yukon-Tanana Uplands, grey = unknown age, Yukon Flats, blue = Paleozoic, Jurassic, and Early Cretaceous. B) ^{87}Sr/^{86}Sr isoscape of Northwest Alaska (modified from Bataille et al., 2014:Fig 3b). C) bioavailable ^{87}Sr/^{86}Sr isoscape of Northwest Alaska (modified from Funck et al., (2021:Fig 4).

(Gilbert-Young, 2004). House types and faunal analysis led Gilbert-Young (2004) to the conclusion that the site was occupied in fall/winter, and the inhabitants exploited the fall caribou migration. The two excavated houses appear to have been constructed contemporaneously. House 1 has evidence for two floors, indicating a minimum of two seasons of fall/winter occupations (Gilbert-Young, 2004). Artifact types were almost exclusively endemic to Alaska. The only exception was half of a blue glass trade bead. The artifact and feature types led Gilbert-Young (2004) to estimate house occupation between AD 1578 and AD 1760. Groethe, field supervisor of the 1996 excavation, described what appeared to have been "a post-occupational cache pit excavated into the roof of the tunnel" (Gilbert-Young, 2004:15). This cache pit indicates ongoing use of the site for caching food, presumably caribou, after the houses were abandoned. Radiocarbon dates of unmodified caribou bone taken from the floors of both houses place their occupation between cal AD 1445 – 1631 (Shirar, 2011), these dates, originally published using IntCal09, have been updated here with IntCal20.

METHODS AND MATERIALS

^{87}Sr/^{86}Sr Alaska Isoscapes

The two ^{87}Sr/^{86}Sr isoscapes of Alaska used for data interpretation were the Bataille et al. (2014) bedrock model and the Funck et al. (2021) bioavailable ^{87}Sr/^{86}Sr model. The

Bataille et al. (2014) $^{87}Sr/^{86}Sr$ bedrock model is a refinement of the model from Bataille and Bowen (2012). The Bataille et al. (2014) model provides an account of total $^{87}Sr/^{86}Sr$ isotope ratios but is not based on bioavailable Sr isotope ratios. The individual data points within the Bataille et al. (2014) model were interpolated through a series of equations using thousands of geological samples to produce a predictive map for Alaska. Our geographic predictions are limited by the resolution of these interpolations. The Bataille et al. (2014) model uses a global lithological map (GLiM) developed by Hartmann and Moosdorf (2012) to divide Alaska into three sub-models: igneous rock, siliciclastic sedimentary rock, and carbonate rock. Each sub-model has a unique equation or set of equations by which the $^{87}Sr/^{86}Sr$ is predicted. These equations incorporate a variety of factors including, among others, the $^{87}Rb/^{86}Sr$ of the parent material, material age, rate of weathering, $^{87}Sr/^{86}Sr$ of major waterways, and $^{87}Sr/^{86}Sr$ of thousands of modern rock, and yield a predicted $^{87}Sr/^{86}Sr$ range for a given location in Alaska at 1 km^2 resolution. The models were calibrated with published data sets from global, North American, and Alaskan datasets, then validated against Alaskan data sets, except the carbonate rock sub-model which was previously validated in Bataille and Bowen (2012). For Bataille et al. (2014), only Alaskan samples were used to calibrate the carbonate rock sub-model.

The igneous sub-model was calibrated using 31,421 samples from a global data set from www.earthchem.org and 18,706 samples from the Alaska Geochemical Database then validated using 788 samples from Alaska (Bataille et al., 2014). The siliciclastic sedimentary rock sub-model was calibrated using 17,727 samples from the Alaska Geochemical Database (AGD) and then validated using 97 rocks from Alaska (Bataille et al., 2014). The carbonate rock sub-model was carried over from Bataille and Bowen (2012) in which it was calibrated with 9130 igneous and 207 sedimentary samples from a global GEOROC dataset and validated with 246 samples from across the contiguous United States, available from the Precambrian Marine Carbonate Isotope Database (PMCI) and GEOROC (Bataille and Bowen, 2012). For Bataille et al. (2014), the carbonate sub-model was calibrated with 358 samples from the AGD. The igneous, siliciclastic sedimentary, and carbonate sub-models are capable of explaining 72%, 51%, and 52% of the $^{87}Sr/^{86}Sr$ bedrock variability respectively and were applied within the study area at a scale of 1 km^2 (Bataille and Bowen, 2012; Bataille et al., 2014).

The individual data points of the Funck et al. (2021) bioavailable $^{87}Sr/^{86}Sr$ model were also interpolated through a series of equations, including those of the Bataille et al. (2014) model, and 162 samples of terrestrial rodents from across Alaska, particularly north of latitude 65° N. Areas of high geological variation, such as the Seward Peninsula and the western Brooks Range, were emphasized. Whenever possible, specimens with high geographic provenience were preferred. $^{87}Sr/^{86}Sr$ sampling followed a solution method published in Mackey and Fernandez (2011). Funck et al. (2021) developed the 87Sr/86Sr isoscape model using the method published in Bataille et al. (2018) and went on to develop a multivariant regression model using geological, environmental, and climatological conditions of each specimens' collection location, the bedrock isoscape model developed in Bataille et al. (2014) as a covariant, and calibrated using the rodent teeth $^{87}Sr/^{86}Sr$ as a response variable. Predictors of $^{87}Sr/^{86}Sr$ variations were selected using the VSURF algorithm then "a multivariate random forest regression was applied and validated using an n-fold cross-validation. The resulting model was used in combination with selected predictors to predict the mean and interquartile range of $^{87}Sr/^{86}Sr$ variations across eastern Beringia" (Funck et al., 2021:79).

Specimen Description

Since the sampling method presented in this paper is destructive and was untested at the time of analyses, the authors elected to use specimens with limited provenience. Using specimens of limited provenience for destructive or novel analysis is preferable to using specimens with more complete provenience, as the latter specimens have greater potential interpretive information that could be lost during analysis. Eight isolated caribou teeth, three for radiocarbon dating and five for Sr isotope analysis, were selected from the Lake Kaiyak site collection curated by the National Park Service. All the specimens were recovered from the backfill of a disturbed midden at the Lake Kaiyak site. Their archaeologically significant provenience beyond this is unknown.

Since the archaeological samples were not extracted directly from individual animals, our dataset was designed to limit the probability that any two teeth intended for $^{87}Sr/^{86}Sr$ analysis represent the same individual. First, all these teeth are from the left side. Second, they are all mandibular. Third, teeth were limited to M_1s and second molars (M_2s). The risk that any supernumerary molars were sampled is small as all documented supernumerary molars in caribou morphologically resemble the third molar (M_3) (Miller and Tessier, 1971), possessing a third set of cusps on the distal side. Any two left M_1s are not likely to be from the same individual; the same applies to any two M_2s. But a particular left M_1 and a particular left M_2 could represent the same individual animal and thus be interdependent.

The five specimens (A–E) selected for $^{87}Sr/^{86}Sr$ analysis had well-preserved crowns with minimal cracking or chipping. Their roots ranged from nearly whole to almost completely missing. Specimens with the least degree of occlusal tooth wear were preferred. Due to the constraints of the available material, there was a range of tooth wear among the specimens selected. Crown heights were greater than 12 mm. M_1s were most desired as they are the only permanent molars to have a NNL in caribou. Macroscopically, a caribou M_1 cannot be morphologically differentiated from a M_2 when they are isolated, consequently, there were equal odds that any tooth chosen would be one or the other.

Due to limited material suitable for testing, age estimations were not considered during the selection process but were noted afterwards. To estimate the animal's age, the degree of wear on the occlusal surface of each specimen was compared with Miller (1974). The more accurate cementum layer-based method (Pike-Tay, 1995) was not an option since the tooth roots were incomplete (A, C, D, and E) or missing (B). Tooth wear age estimation is based on the premise that tooth wear and age are positively correlated. While there are many variables, including individual and regional diet, dental morphology and defects, and individual proclivities for tooth use that prevent the application of any one formula of wear rate to a given species, the method is useful for general estimations of age and is widely used in archaeological and wildlife studies (Taber, 1963; Miller, 1974; Loison et al., 2001).

Aging the Midden

To determine the age of the midden from which the specimens were taken, three teeth were selected for radiocarbon dating and sent to Beta-Analytic (Miami, Florida) without any modification or preparation. These teeth were well preserved, fully mature, maxillary, permanent molars. Due to the constraints of the available materials, the same precautions against tooth interdependence were not an option, and one right and two left maxillary molars of unknown tooth position were selected. The resulting data were then compared with the four radiocarbon dates published in Shirar (2011) after their adjustment to the IntCal20 calibration curve. These dates were then compared in OxCal online (version 4.4.4) (Ramsey, 2009) using the R_Combine analysis to establish the probable groupings among the seven dates. These groupings were then run through the three models for the occupation phase or phases of the site: contiguous, sequential with gaps, and sequential overlapping.

Methods for Embedding Specimens

We embedded the five specimens for strontium isotope analysis in polymethyl methacrylate (PMMA) as per Harmston et al. (2019) with the exception that specimens were placed under vacuum pressure for two minutes at the beginning of each bath. This forced the solutions deeper into the many microscopic cracks and fissures within the tissues and helped extract gas bubbles that might expand and damage the teeth during polymerization. Once polymerized, PMMA supports fragile teeth during the mechanical processing that follows. Because PMMA is a carbon-rich polymer, $[CH_2C(CH_3)(CO_2CH_3)]_n$, embedding dental tissues in PMMA alters the carbon concentration within the dental tissues (Harmston et al., 2019). As the introduced carbon may affect radiocarbon dating, the authors opted not to radiocarbon date the teeth being analyzed for Sr.

We radially sectioned, buccal-lingually, the embedded teeth into 2 mm thick sections and then sent them to Wax-it Histology Services, Inc. (Vancouver, BC) for thin sectioning, grinding, polishing, and imaging. A thorough description of the process and materials used is available in the supplementary material.

Striae of Retzius

The specimens were sectioned at 135 μm then ground in 10 μm increments and photographed using a transmission light microscope. At 135 μm, striae of Retzius, including brown striae and the NNL, were visible across much, but not all, of the cross-sections. Fewer striae were visible after the specimens were ground to 125 μm. The optimal thickness for striae of Retzius examination and NNL identification in archaeological caribou is greater than 125 μm and possibly above 135 μm. The average thickness of the striae of Retzius proved to be variable, becoming thinner from cusp to cervix. This variation affects the time resolution of the sampling method (Table 1) and should be considered when interpreting these and other results from serial sampled dental tissues.

Neonatal Line Identification

In specimens A and B, the highest brown stria intersected the EDJ roughly halfway up the crown on the buccal side, at 7.2 mm and 6 mm above the enamel-cementum junction (ECJ) (Fig. 3B) respectively. In both specimens, the enamel above the highest brown stria was well organized and uniform. Below the first brown stria, the enamel was coarser, organizationally more varied, and featured multiple brown striae (Fig. 3A). The brown stria that marked this transition in matrix quality is the NNL. Since the M_1 is the only permanent mandibular molar in development at birth (Wu et al., 2012), the presence of a NNL distinguishes these teeth as M_1s. Specimens C, D, and E displayed no transition point from well organized to less organized enamel and had brown striae from the cusp to the cervix, demonstrating that they began formation after birth. This and the lack of a third set of cusps, a characteristic of M_3s, identified specimens C, D, and E as M_2s. Knowing the tooth positions, and thus developmental time, is vital to interpreting the strontium signatures and to producing age estimations for each tooth.

According to the tooth wear analysis there is an eight-month difference between the oldest M_1 and the youngest M_2. Occlusal tooth wear for each specimen was most consistent with the following ages in months: A (15), B (17), C (25), D (27), and E (> 40) (Miller, 1974; Table 2). Based on the age estimates and the tooth positioning in the tooth row and lower left quadrant of the mouth, tooth independence is established; each tooth was from a distinct individual animal.

TABLE 1. Averaged striae of Retzius thickness, and the average number of days within and between samples.

Specimen	A (M_1)	B (M_1)	C (M_2)	D (M_2)	E (M_2)	Jordana et al. (2014)
Striae of Retzius Average Thickness (µm) ± one SD	16.11 ± 2.30	17.66 ± 2.46	14.94 ± 2.19	13.12 ± 2.79	15.28 ± 2.54	14.17 ± 0.81
Averaged days per sample	9	8	10	11	10	11
Averaged day between samples	12	11	13	15	13	14

^{87}Sr/^{86}Sr Sampling and Determination

Sampling sites were centered 125 µm from the EDJ to avoid accidental sampling of the EDJ or dentine. The laser spot was a 150 µm circle (Fig. 3B). There were 196 µm between sample sites. The size of the sample site and the distance between the sample sites were based on the average thickness for striae of Retzius (14.17 ± 0.81 µm) as reported in Jordana et al. (2014). If the measurements from Jordana et al. (2014: Table 2) were applicable, then each sample would equal approximately 11 days of the secretory stage, with approximately 14 days of the secretory stage between samples.

Samples were taken at the ICP-MS Metals and Strontium Isotope Facility at the University of Utah using the Excimer laser ablation system (Teledyne CETAC Excite) with a HelEx II cell connected to a MC-ICP-MS (Neptune Plus, Thermo-Fisher Scientific). The accuracy of the system was monitored using a marine shell, which was also used for tuning and peak shape optimization at the beginning of each session or when the measured ^{87}Sr/^{86}Sr value was outside the accepted range. The ^{87}Sr/^{86}Sr average for over 100 marine shell tests done during the five sessions needed to measure the five caribou teeth was 0.70920 ± 0.00006 (1 SD). These values agree with the long-term (8 years) average of the marine shell tests done in lab. Accuracy was considered appropriate when at least five marine shells in a row produced an average <1 SD. Traditional data processing to obtain ^{87}Sr/^{86}Sr was used (Brennan et al., 2015).

Ablated bioapatite includes major elements of phosphorous (P), Ca, and oxygen (O), which produce the molecular interference ^{40}Ca^{31}P^{16}O on mass 87 and then biasing ^{87}Sr/^{86}Sr towards more radiogenic values (Lewis et al., 2014; Irrgeher et al., 2016). The magnitude of the bias is related to the Sr concentration in the bioapatite. The lower the Sr concentration, the larger the impact of the interference and therefore the larger the bias. The correction method used to account for the effect of the molecular interference, based on Lugli (2019), is provided in the supplementary file.

Because each tooth contained different amounts of Sr, the correction was, on average, different for each tooth: A (−0.0018), B (−0.0024), C (−0.0041), D (−0.0042), and E (−0.0051). The uncertainty in the corrected ^{87}Sr/^{86}Sr is estimated as 0.0015. In general, ^{31}P and ^{88}Sr intensities were relatively constant within each tooth, although ^{88}Sr sometimes displayed a well-defined trend changing uniformly with the age of the enamel. For some ablation spots ^{31}P intensity was significantly lower than the tooth average, in which case the corresponding ^{87}Sr/^{86}Sr value strongly deviated from the trend observed in the tooth. Less often, ^{88}Sr intensity was significantly higher than average, and the corresponding ^{87}Sr/^{86}Sr also deviated from the trend observed in the tooth. We interpret these intensity anomalies as indications of altered or contaminated enamel, and those values were rejected. The number of rejected spots from total (Rejected/Total) were as follows: A (1/37), B (0/41), C (9/39), D (0/34), and E (5/35).

TABLE 2. ^{87}Sr/^{86}Sr specimen characteristics. All specimens were mandibular and from the left side. None of the specimens possessed a third cusp.

Specimen	NNL Present	Tooth Position[1]	Age estimate in months[2]
A	Yes	M_1	15
B	Yes	M_1	17
C	No	M_2	25
D	No	M_2	27
E	No	M_2	>40

[1] (based on presence/absence of 3rd cusp or NNL).

[2] (based on Miller, 1974).

Because of the angle at which the striae of Retzius lay relative to the EDJ and the size of the sample sites, the NNL, when present, passed through four samples. The NNL ran near the center of the second and third of these sample sites. The ^{87}Sr/^{86}Sr ratios from the second and third samples were used to interpret the NNL-calving grounds ^{87}Sr/^{86}Sr relationship. The ^{87}Sr/^{86}Sr ratios from the first and fourth sample sites that included the NNL were not used in the interpretation since the NNL was on the margins of these samples.

RESULTS AND DISCUSSION

Strontium and Herd Identity

The ^{87}Sr/^{86}Sr results for each of the five sampled teeth (Table 3; Fig. 5) demonstrate movements across geological formations with distinct ^{87}Sr/^{86}Sr ratios. This is consistent with the migratory ecotype. Figure 5a displays the two M_1s: A and B. The time period for these specimens includes up to three months prior to birth and three months postpartum (Wu et al., 2012). This includes late winter (March and April), parturient cow spring migration (May and early June), calving (mid-June), and summer (late June through August) (Dau, 2009). The expected pattern is one of near-constant mobility, which is born out in the graph (Fig. 5). Figure 5b displays the M_2s: C, D, and E. These specimens

TABLE 3. ^{87}Sr/^{86}Sr results*, samples of the NNLs**, samples used to interpret NNL signature. Cells with dashes represent samples that were unacceptable, and cells that are blank represent samples not taken.

Specimen			A (M_1) Sr^{87}/Sr^{86} ± 0.0015	B (M_1) Sr^{87}/Sr^{86} ± 0.0015	C (M_2) Sr^{87}/Sr^{86} ± 0.0015	D (M_2) Sr^{87}/Sr^{86} ± 0.0015	E (M_2) Sr^{87}/Sr^{86} ± 0.0015
Sample:	Relative to Cusp	Relative to NNL (A/B)					
	1	23/19	0.7116	0.7145	0.7175	0.7112	–
	2	22/18	0.7117	0.7144	0.7178	0.7123	0.7175
	3	21/17	0.7117	0.7145	0.7183	0.7127	0.7181
	4	20/16	0.7120	0.7143	0.7165	0.7131	0.7175
	5	19/15	0.7120	0.7149	0.7165	0.7134	–
	6	18/14	0.7119	0.7152	0.7148	0.7139	0.7177
	7	17/13	0.7120	0.7152	0.7165	0.7137	0.7183
	8	16/12	0.7118	0.7152	0.7155	0.7144	–
	9	15/11	0.7117	0.7152	0.7163	0.7144	0.7174
	10	14/10	0.7123	0.7156	0.7172	0.7135	0.7174
	11	13/9	0.7122	0.7155	0.7173	0.7144	0.7172
	12	12/8	0.7120	0.7159	0.7178	0.7141	0.7177
	13	11/7	0.7121	0.7158	0.7182	0.7147	0.7165
	14	10/6	0.7120	0.7163	0.7186	0.7145	0.7170
	15	9/5	0.7121	0.7165	0.7194	0.7144	0.7164
	16	8/4	0.7119	0.7160	–	0.7143	0.7165
	17	7/3	0.7118	0.7164	–	0.7141	0.7171
	18	6/2	0.7124	0.7163 *	0.7189	0.7142	0.7171
	19	5/1	0.7133	0.7159 **	–	0.7138	–
	20	4/−1	0.7131	0.7158 **	–	0.7134	0.7174
	21	3/−2	0.7131	0.7146 *	–	0.7129	0.7175
	22	2/−3	0.7132 *	0.7147	–	0.7128	0.7178
	23	1/−4	0.7134 **	0.7147	0.7159	0.7127	0.7188
	24	−1/−5	0.7131 **	0.7146	0.7153	0.7130	0.7183
	25	−2/−6	0.7127 *	0.7145	0.7143	0.7133	0.7185
	26	−3/−7	0.7134	0.7142	0.7145	0.7132	0.7185
	27	−4/−8	0.7132	0.7140	0.7148	0.7131	0.7186
	28	−5/−9	0.7129	0.7147	0.7148	0.7133	0.7187
	29	−6/−10	0.7131	0.7144	0.7145	0.7136	0.7188
	30	−7/−11	0.7133	0.7143	0.7148	0.7137	0.7185
	31	−8/−12	0.7136	0.7148	0.7151	0.7136	0.7178
	32	−9/−13	0.7136	0.7151	0.7150	0.7134	0.7181
	33	−10/−14	0.7138	0.7158	0.7151	0.7138	0.7179
	34	−11/−15	0.7137	0.7159	0.7143	0.7145	0.7177
	35	−12/−16	0.7139	0.7160	0.7151		
	36	−13/−17	–	0.7160	0.7156		
	37	−14/−18	0.7137	0.7156	–		
	38	−/−19		0.7151	–		
	39	−/−20		0.7143	–		
	40	−/−21		0.7142			
	41	−/−22		0.7140			

developed from the third to twelfth months postpartum, nine months total. This includes weaning, fall migration (mid-/late September to early November), and winter (mid-November to early May) (Wu et al., 2012). Reproductively immature animals usually join bulls and non-pregnant cows for their spring migration, which moves straight to the summer grounds, and may bypass the calving grounds. This migration often lags that of the parturient cows by days or weeks (Dau, 2009) and may not be included in the developmental period. The expected pattern of a complete M_2 is high mobility followed by lower to low mobility. Specimens C and E appear to conform to this, D however does not, it is possible that animal D overwintered in an area with a higher degree of isotopic variation per unit area.

Comparing the data to the two available isoscapes of northwestern Alaska, Bataille et al. (2014) and Funck et al. (2021) produced two similar but distinct interpretations (Figs. 6, 7, and 8). Both models agree that these animals used parts of the Brooks Range and North Slope and did not utilize the area south of Kotzebue Sound and east of the Seward Peninsula, a significant part of the modern WAH wintering grounds. Both models also agree that the teeth could have come from the Seward Peninsula. The parts of the Seward Peninsula potentially used by these animals, with the exception of D’, are comparatively small and fractured, suggesting varying degrees of sedentary behavior rather than migratory behavior. However, larger more continuous areas highlighted on other parts of both isoscapes and the apparent non-use of the land between the Seward Peninsula to the Brooks Range make the Seward Peninsula an unlikely place for these animals to have lived.

The ^{87}Sr/^{86}Sr results from the NNLs are highlighted in Figure 6. The geographic areas represented in Figures 6a and 6b, derived from Bataille et al. (2014:Fig 3b), are largely consistent with 1987 to 2008 cumulative WAH seasonal movement maps presented in Dau (2009), particularly for the calving and summer periods. Importantly, there is no overlap in the NNL values and those of the calving grounds

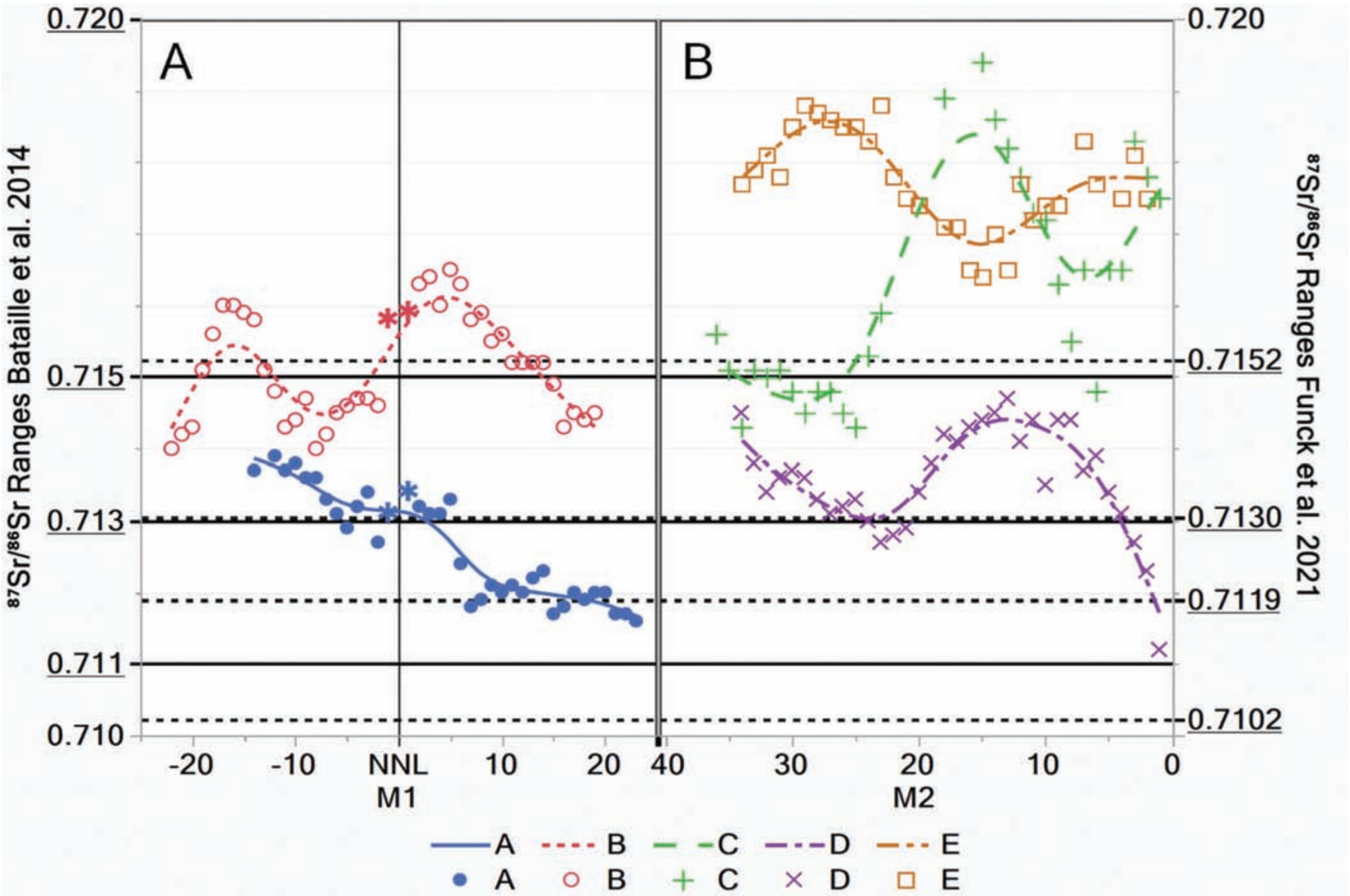


FIG. 5. Fluctuations in the ^{87}Sr/^{86}Sr ratios for the Lake Kaiyak animals. The ^{87}Sr/^{86}S ranges presented in Bataille et al. (2014) are listed on the left x axis and marked by horizontal solid lines. The ^{87}Sr/^{86}S ranges presented (Funck et al., 2021) are listed on the right x axis and marked by dashed horizontal lines. Each specimen has its own symbol and line style; these are in the legend immediately beneath the graph. Each specimen's symbol is linked with a smoothed line, $\lambda = 0.050$. The graph is divided into M$_1$ specimens on the left, and M$_2$ specimens on the right. On both sides time runs left to right with the oldest enamel, that closest to the cusp, for each tooth on the left and the youngest enamel, that closest to the cervix, on the right. The M$_1$ side is divided into in utero and postpartum based on the position of the NNLs. The M$_1$ side may represent as much as six months of enamel development, three months in utero and three months postpartum, March to September (Wu et al., 2012). Asterisks mark the samples that were used to interpret the NNLs from specimens A and B. The M$_2$ side may represent as much as nine months, from three to 12 months postpartum, September to May (Wu et al., 2012).

of the TLH or the CAH. There is some overlap with the location where Burch (2012) places the calving grounds for the hypothetical SPH. For reasons expressed in the preceding paragraph, the SPH is not considered a likely candidate for the herd identity of these animals. Figures 6A' and 6B', derived from Funck et al. (2021:Fig 4), tell a different story with the NNL of specimen A overlapping with the WAH and the western most part of the TLH. The pixel count of the illuminated area within the WAH calving grounds is slightly more than five times that of the TLH calving grounds. This suggests that A is a WAH animal but is inconclusive. B' shows no overlap with the three extent or any of the hypothetical herds in Northwest Alaska. It does however overlap extensively with the calving grounds of the PRH which are in the northeastern most part of the map. The modern PRH range extends west into the central Brooks Range but does not reach Anaktuvuk Pass (Prichard et al., 2020), let alone Lake Kaiyak, some 400 km farther west. For this and other reasons expressed further on, PRH is not considered probable for herd identity.

Figure 7 displays the combine ^{87}Sr/^{86}Sr results for the M$_1$s, A and B, and Figures 7a and 7b results are consistent with 1987 to 2008 cumulative WAH seasonal movement maps established by Dau (2009), particularly for the calving and summer periods. The coloured area highlighted in Figure 7a' is too broad to exclude any North Slope herd. Figure 7a' suggests a highly mobile animal that is consistent with the migratory ecotype. Figure 7b' suggests the low mobility characteristic of the sedentary ecotype. Figure 7b' is dominated by areas in the central to central eastern and southern side of the Brooks Range, areas consistent with winter ranges of the three extant herds. There are discontinuous areas on the North Slope which are affiliated with the TLH and WAH summer range, and the PRH calving grounds. Being disconnected from other larger spaces makes them less likely candidates for the five or six months of enamel development specimen B represents. It is possible that the mother of animal B remained in her herd's traditional winter grounds to calve and rear B to independence. B then joined a migrating herd later in life. Britton et al. (2009) observed this phenomenon in one of

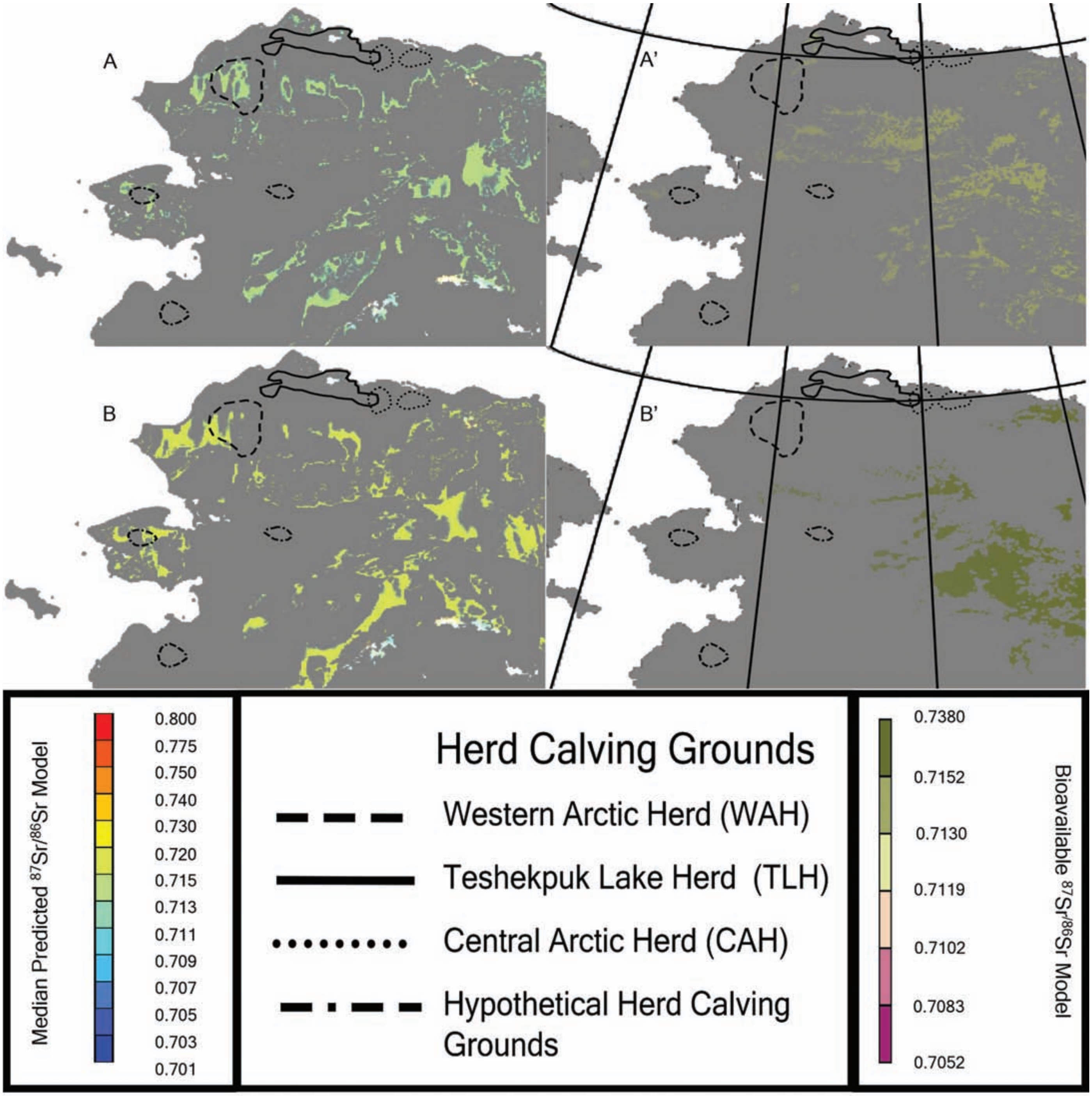


FIG. 6. Lake Kaiyak specimen NNL $^{87}Sr/^{86}Sr$ isoscapes of Northwest Alaska. The calving grounds for the modern WAH, TLH, and CAH, and the hypothetical SPH, NHH, and ARH are marked. A and A' display the NNL $^{87}Sr/^{86}Sr$ value range distribution for specimen A on isoscapes modified from Bataille et al. (2014:Fig 3b) and Funck et al. (2021:Fig 4) respectively. B and B' display the NNL $^{87}Sr/^{86}Sr$ value range distribution for specimen B on isoscapes modified from Bataille et al. (2014:Fig 3b) and Funck et al. (2021:Fig 4) respectively.

the five modern migratory animals they sampled. They speculate that the sedentary individual may have been a cross between a feral reindeer and wild caribou. If B is a reindeer-caribou cross then the specimens post-date 1892; the year domestic reindeer were introduced to Alaska (Burch, 2012).

Figure 8 displays the combined results for the M_2s, C, D, and E. Figures 8C, 8D, and 8E suggest low mobility, especially E, which was the most worn of the M_2s. All three support overwintering north of the Brooks Range, in areas consistent with the modern WAH summer grounds. This is not unexpected as some WAH animals routinely forgo the fall migration and overwinter in the summer range (Dau, 2011, 2015). This also agrees with an assertion made by Burch (2012) that the nineteenth century WAH range was restricted to the Brooks Range and North Slope (Fig. 2).

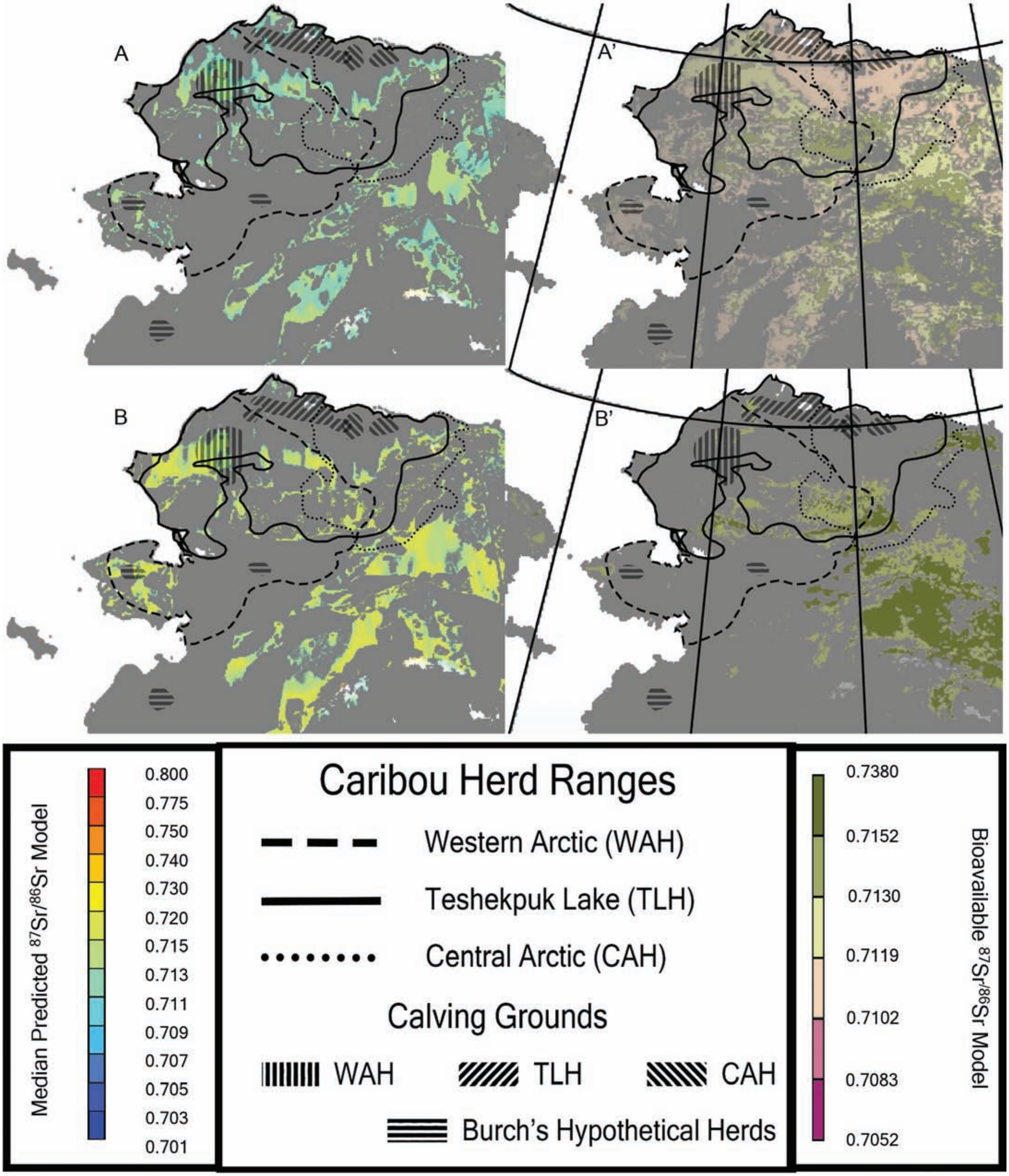


FIG. 7. Lake Kaiyak specimen M$_1$ ^{87}Sr/^{86}Sr isoscapes of Northwest Alaska. The calving grounds and ranges for the modern WAH, TLH, and CAH, and the purported calving grounds of the hypothetical SPH, NHH, and ARH are marked. A and A’ display the complete ^{87}Sr/^{86}Sr value range distribution for specimen A on isoscapes modified from Bataille et al. (2014:Fig 3B) and Funck et al. (2021:Fig 4) respectively. B and B’ display the complete ^{87}Sr/^{86}Sr value range distribution for specimen B on isoscapes modified from Bataille et al. (2014:Fig 3B) and Funck et al. (2021:Fig 4) respectively.

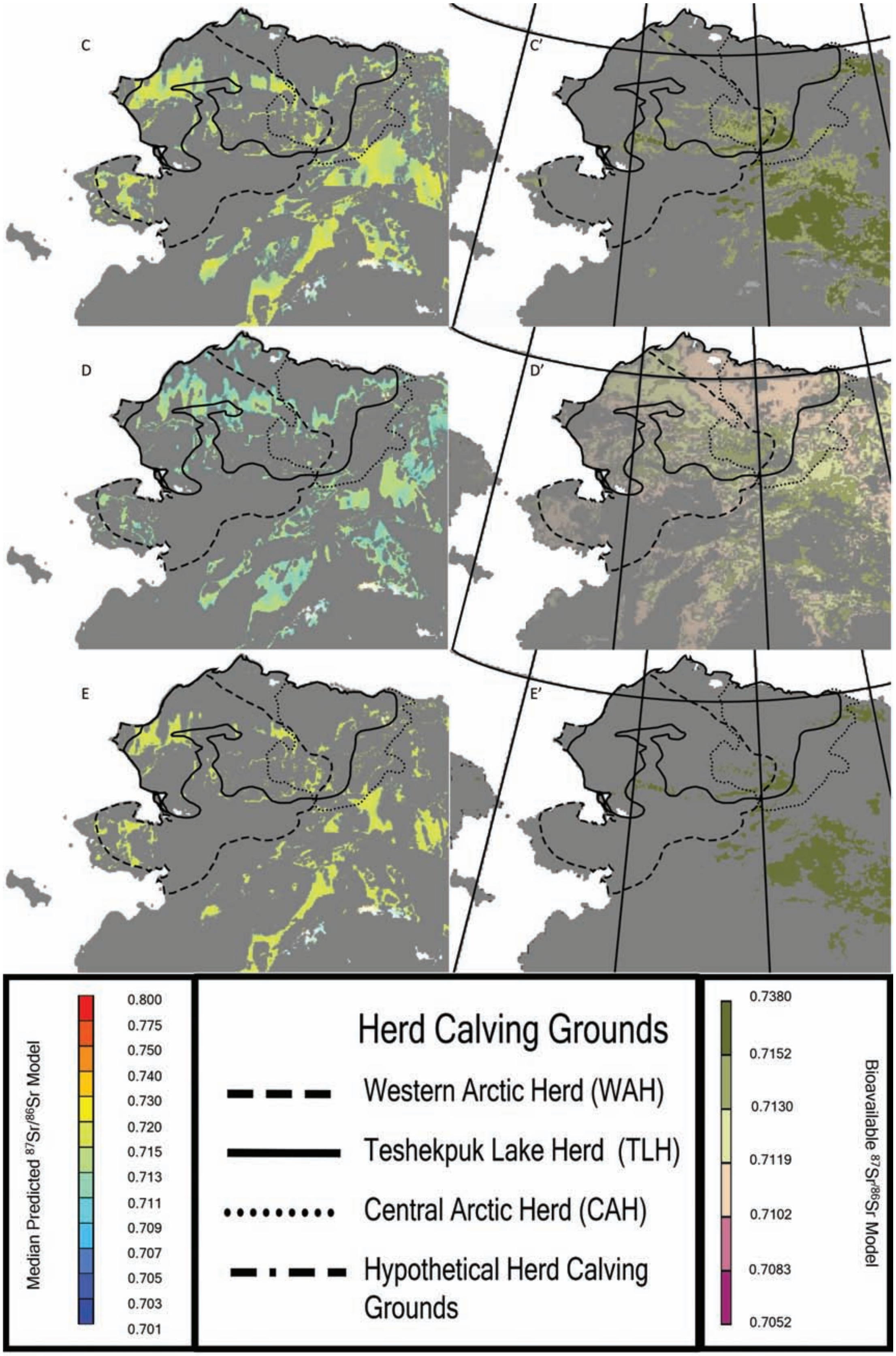


FIG. 8. Lake Kaiyak specimen M_2 ^{87}Sr/^{86}Sr isoscapes of Northwest Alaska. The ranges for the modern WAH, TLH, and CAH are marked. C and C' display the complete ^{87}Sr/^{86}Sr value range distribution for specimen C on isoscapes modified from Bataille et al. (2014:Fig 3b) and Funck et al. (2021:Fig 4) respectively. D and D' display the complete ^{87}Sr/^{86}Sr value range distribution for specimen D on isoscapes modified from Bataille et al. (2014:Fig 3B) and Funck et al. (2021: Fig 4) respectively. E and E' display the complete ^{87}Sr/^{86}Sr value range distribution for specimen E on isoscapes modified from Bataille et al. (2014:Fig 3b) and Funck et al. (2021:Fig 4) respectively.

TABLE 4 The radiocarbon dates and associated information for the Lake Kaiyak Site

Lab #	Catalog	Short ID	Material	$\delta^{13}C$	Conventional 14C age	2σ Calibrated age ranges
Beta-508593	NOAT 5164-2019-S1	DM-1	Tooth	−17.9 ‰	150 ± 30 BP	cal AD 1667 – 1783 (42.7%) cal AD 1796 – 1894 (33.9%) cal AD 1903 – post-1950 (18.9%)
Beta-624453	NOAT 5164-2022-S1	DM-2	Tooth	−18.2 ‰	200 ± 30 BP	cal AD 1726 – 1811 (53.2%) cal AD 1644 – 1694 (25.5%) cal AD 1917 – post-1950 (16.7%)
Beta-624454	NOAT 5164-2022-S2	DM-3	Tooth	−16.9 ‰	150 ± 30 BP	cal AD 1666 – 1783 (42.8%) cal AD 1796 – 1894 (33.8%) cal AD 1903 – post-1950 (18.8%)
Cams-141635	NOAT 5118	HP1-1	Caribou bone	−19.1‰	385 ± 30 14C BP	cal AD 1445 – 1525 (63.1%) cal AD 1559 – 1566 (1.2%) cal AD 1571 – 1631 (31.2%)
Cams-141638	NOAT 5719	HP1-2	Caribou bone	−19.0‰	400 ± 30 14C BP	cal AD 1437 – 1523 (74.1%) cal AD 1575 – 1625 (21.3%)
Cams-141636	NOAT 5214-2	HP2-1	Caribou bone	−19.2‰	245 ± 30 14C BP	cal AD 1523 – 1572 (11.0%) cal AD 1630 – 1683 (53.5%) cal AD 1737 – 1755 (3.0%) cal AD 1761 – 1802 (26.4%) cal AD 1937 – post-1950 (1.6%)
Cams-141637	NOAT 5214-95	HP2-2	Caribou bone	−20.0‰	405 ± 30 14C BP	cal AD 1436 – 1521 (77.6%) cal AD 1580 – 1624 (17.8%)

With so small a sample size it is not possible to identify which is the case. Figures 8C' and 8E' also suggest low mobility, but in areas that are more consistent with the winter ranges of the modern TLH, WAH, and, to a lesser extent, the CAH. D' is too broad for ready interpretation. As with 8C, 8D, and 8E, an interpretation consistent with Burch (2012) is possible but cannot be verified with this sample size.

When the five Lake Kaiyak specimens are considered together, as though they are from a single herd, the model presented in Bataille et al. (2014:Fig. 3b), strongly supports a WAH identity. The Funck et al. (2021) model suggests that the animals are from the WAH but cannot rule out the TLH as the herd of origin. Neither model suggests that they are from the CAH or one of Burch's hypothetical herds. Considering both models together, the Lake Kaiyak specimens probably came from WAH animals.

Dating the Lake Kaiyak Site

Identifying the antiquity of a population permits the various ecological and environmental conditions it has endured to be determined and how they have affected that population. This information can then be used for wildlife management decisions. The data from the three radiocarbon-dated teeth from the midden, DM-1 (Beta-508593; caribou tooth; $\delta^{13}C = -17.9$ ‰), DM-2 (Beta-624453; caribou tooth; $\delta^{13}C = -18.2$ ‰), and DM-3 (Beta-624454; caribou tooth; $\delta^{13}C = -16.9$ ‰), are presented in Table 4 with the four radiocarbon dates published in Shirar (2011). All dates have been calibrated using IntCal20.

The online version of OxCal was used to calibrate and analyze the radiocarbon dates from the midden and the house pits to determine the number of phases represented using R_Combine analysis. The results are in Table 5. The three midden dates passed the R_Combine analysis, as did three of the house pit dates. One house pit date, NOAT 5214-2 (HP2-1), was found to be an outlier from the other house pit dates. The midden dates combined with HP2-1 passed the R_Combine analysis (Table 5).

From these tests the Lake Kaiyak site appears to have at least two phases and is a multicomponent site. The midden was used well after the two excavated house pits. With midden dates that are correlated and with no mention of stratification within the midden, it is interpreted as a single component. It appears that HP2-1 comes from the same phase as the midden, how it came to be in the floor of House 2 is unknown. It may be that HP2-1 is an intrusion from a higher stratum or that the house floor was dug into the stratum from which the other three caribou bones originate.

Following the establishment of two phases of site use, the probable nature of those phases was tested using contiguous, sequential with gaps ranging from 25 to 100 years with a standard ±30-year uncertainty value, and sequential overlapping models were run to determine which of these models best fit the data. Of the models run the two-phase overlapping model had the highest agreement indices ($A_{model} = 121.2$, $A_{overall} = 117.3$; Table 5). Under the two-phase overlapping model, Phase 1, represented by the house pit material, dates to cal AD 1345 – 1666 as 95.4% confidence interval (CI). Phase 2, represented by the midden specimens and HP2-1, dates to cal AD 1525 – post-1950 at 95.4% CI.

This broad date range is the result of the radiocarbon calibration curve passing through the same radiocarbon determination value range as the teeth several times between AD 1600 and AD 1950, with a sizable plateau through much of the nineteenth century. Because of this, more dates from the midden or from the six remaining unexcavated house pits may not sufficiently tighten the time range for useful interpretation. This range is far

TABLE 5. Statistical tests and results for the radiocarbon-dated Lake Kaiyak specimens.

Short ID	R_Combine analysis 1	R_Combine analysis 2	R_Combine analysis 3	Contiguous model	Two-phase sequential model	Two-phase overlapping model
DM-1	Failed X2-Test: df = 6 T = 91.6 (5% 12.6)	Passed X2-Test: df = 2 T = 1.9 (5% 6.0)	Passed X2-Test: df = 3 T = 7.0 (5% 7.8)	$A_{model} = 100.9$, $A_{overall} = 94.8$ (Worst Fit)	$A_{model} = 116.9$, $A_{overall} = 109.6$	$A_{model} = 121.2$, $A_{overall} = 117.3$ (Best Fit)
DM-2						
DM-3						
HP2-1		Failed X2-Test: df = 3 T = 19.231(5% 7.8)				
HP2-2			Passed X2-Test: df = 2 T = 0.2 (5% 6.0)			
HP1-1						
HP1-2						

too broad to be of concrete use for interpreting which climatic, ecological, or anthropogenic challenges a herd has experienced. An alternative absolute dating method to radiocarbon dating may be more useful.

The broad time frame offered by radiocarbon dating in this case can be narrowed by the relative dating technique of artifact typology. The artifacts recovered from the houses are consistent with those of the Kangiguksuk and Sapun Creek sites in the Noatak River Valley. Based on artifact typology and a single dendrochronology sample from the Kangiguksuk site, both sites are believed to have been occupied in the sixteenth century, the seventeenth century, or both (Gilbert-Young, 2004; Shirar, 2011). Of particular significance for the Lake Kaiyak Site is the partial blue glass trade bead mentioned previously. The half bead is consistent with beads which first arrived in Alaska in AD 1741 with the Vitus Bering expedition (Gilbert-Young, 2004). The two-phase overlapping model pushes the house occupations back to sometime between the mid-fourteenth and mid seventeenth century, AD 1666 at the latest. This orphans the bead from the three house pit dates by 75 years, but not from the Phase 2 dates. The arrival of the half bead at the Lake Kaiyak site in or after AD 1741 places the bead within the 95.4% probability range for all four specimens. Through these dates, the half bead becomes affiliated with the midden and sets an oldest date for Phase 2 at AD 1741. The absence of artifact types can be just as telling as their presence, particularly with types of artifacts that become nearly ubiquitous. A youngest date determination may rest in what is not at the Lake Kaiyak site.

European and American trade goods trickled into Iñupiat territory throughout much of the nineteenth century. Starting in the early 1880s, these goods increased dramatically as American whalers began to pay Iñupiat men for work with American trade goods (Gubser, 1965; Burch, 1984). This led to a major disruption in traditional Iñupiat economy and culture as the Iñupiat became increasingly reliant on these foreign goods. The complete absence of European or American trade goods from the Kaiyak Lake Site artifact collection, excepting the partial blue glass trade bead, strongly suggests that the second phase occurred between AD 1741 and AD 1900. Furthermore, historic and ethnographic records provide circumstantial support for a pre-1900 date for the Lake Kaiyak site.

Burch (1998) describes two Iñupiat nations or peoples in the Noatak River valley during the nineteenth century, the Napaaqtugmiut of the lower Noatak River and the Nuataagmiut of the upper. Both nations exploited the fall caribou migration for crucial winter clothing materials and food (Burch, 1998). Their existence along the Noatak River valley is evidence of preestablished and reliable caribou migration routes in the area. During the early nineteenth century, their populations are estimated to have been 536 and 264 – 336 respectively (Burch, 1998). The population of both peoples was severely reduced during the latter half of the nineteenth century because of diseases, famine, and increased physical stress from a caribou crash that resulted in winter clothing shortages. The 1900 US census reports only 75 permanent occupants in the Napaaqtugmiut territory, and 45 in the Nuataagmiut territory (Burch, 1998). Except for a few families who overwintered a year or two in the upper Noatak River Basin in the 1920s and 1930s, the resident human population of the middle and upper Noatak River Basin never rebounded (Burch, 1998). Such low numbers make large-scale caribou harvesting in the traditional way impossible. Not that there were many caribou in Northwest Alaska during the late nineteenth and early twentieth century to harvest. Historic and ethnographic accounts report that caribou were almost absent from Northwest Alaska from the 1880s until the 1920s (Nelson et al., 1887; Nelson, 1900; Gubser, 1965; Burch, 2012). With nearly no people and next to no caribou in the western Brooks Range in 1900, the mass harvest approach used at the Lake Kaiyak site is untenable. The absence of American trade goods does not support a post-1900 interpretation. The second phase of the Lake Kaiyak site was most likely ended prior to the twentieth century.

Apparent WAH Range Fidelity

At the extreme ends of the Lake Kaiyak site midden radiocarbon date range, animals may be from the mid-sixteenth or post mid-twentieth centuries. The post mid-twentieth century posterior age does not offer much interpretive value. When each tooth is considered individually within the two-phase overlapping model, the youngest date within a tooth's 95.4% CI is cal AD 1948 (DM-2). If these teeth represent animals from the mid-twentieth century, then the scientifically established age of the WAH is pushed back from the mid-1970s (Dau, 2001) to 1948; a gain of approximately twenty-five or thirty years.

When artifact typology, historic records, and ethnohistoric accounts are considered, that time range is reduced by approximately 250 years, becoming mid-eighteenth century to 1900 AD. If these teeth represent animals from the mid-eighteenth century, which would be consistent with the ethnographic record (Burch, 2012), then the WAH has been using the same range for three hundred years, a gain of nearly three centuries. This means that the WAH endured the turmoil of the nineteenth century including, a staggering decline in human predatory pressure due to recuring epidemics starting in the 1830s (Burch, 1998), a dramatic climate shift following the end of the Little Ice Age (Crawford, 2014), a profound caribou population crash that ended multiple Iñupiat nations in the 1860s or 1870s (Burch, 1998), the wide spread introduction of repeating rifles in the 1880s (Foote, 1964), and competition with domestic reindeer imported from Siberia in the 1890s (Burch, 2012). Whether domestic reindeer also introduced disease or aided in the premature recovery of the wolf population, which suffered a significant reduction following the crash in the 1860s or 1870s (Nelson et al., 1887), is unknown. Ethnographic and anecdotal evidence suggest that the WAH did not begin to rebound until the 1910s or 1920s (Burch, 2012). The WAH crested in the early 1970s making an approximate hundred-year half population cycle from crash to crest. The WAH then crashed again, bottoming out in 1976 and cresting again in 2003, completing a half population cycle in twenty-seven years (Dau, 2011, 2015). This suggests that the circumstances surrounding the crash in the 1860s or 1870s and subsequent recovery were substantially worse than those of the 1970s crash. The severity of the late mid-nineteenth century crash notwithstanding, the WAH has recovered to become one of the largest caribou herds in the world and a vital source of subsistence for more than 40 communities (Western Arctic Caribou Herd Working Group, 2019). This testifies to the resilience that is possible for a migratory caribou herd.

CONCLUSIONS

This study is the first time that isotope analysis has been used to identify the calving grounds of archaeological caribou. This was accomplished by orienting tooth samples in developmental time and geographic space. Developmental time was calibrated by identifying the NNL, tooth position, and using known dental development timing and rates. Position in geographic space was determined by serially sampling the first two permanent molars via LA-MC-ICP-MS for Sr isotopes near the EDJ at the level of weeks or days of developmental time. The samples from the NNL oriented the animal in both space, at the calving grounds, and developmental time, during the calving period in early to mid-June. The ^{87}Sr/^{86}Sr results were then compared with two isoscapes of Alaska (Bataille et al., 2014; Funck et al., 2021) and caribou herd ranges, extant (Prichard et al., 2020) and hypothesized (Burch, 2012), in Northwest Alaska. The Bataille et al. (2014) bedrock model supports Lake Kaiyak animals as part of the WAH. The Funck et al. (2021) bioavailable model is less supportive, suggesting that the Lake Kaiyak animals are most likely part of the WAH, but could also be of the TLH.

Though the sample size is small, it is sufficient to demonstrate the potential of this method to identify migratory caribou herds in the archaeological record. However, further refinement is needed to identify the limitations and capabilities of this approach more fully. Similar studies with more specimens from modern and archaeological caribou representing diverse herds, preferably from two or more neighboring herds of migratory caribou will be necessary. Studies on captive or wild herds that have calving grounds with more homogenous strontium signatures are also recommended, the PRH is an ideal wild candidate for a study of this kind. Wu et al. (2012) is the only radiographic study of caribou tooth development of which the authors are aware and was indispensable to the interpretations presented in this paper. However, of the 42 animals examined by Wu et al. (2012), only two were fetuses. More radiological and tooth mineralization studies on the timing, rate, and pattern of dental development in caribou, particularly fetal and young of the year, are necessary for a more accurate interpretation of the results. Future studies should sample as close to the EDJ as can be done without including dentin and keep the laser spots as small as practically possible. Of particular importance is a more solid understanding of mother-offspring isotope exchange, especially considering the rapid weaning caribou, and ungulates in general, undergo compared to human beings. The interpretation of the results would be aided by higher resolution strontium isoscapes than used in this study, particularly between ^{87}Sr/^{86}Sr 0.711 and 0.720. With these and other refinements Sr isotope analysis via serial sampling using LA-MC-ICP-MS specifically targeting the NNL may prove to be the archaeological equivalent of a tracking collar for large migratory land mammals.

The radiocarbon dates from this study are too broad to establish whether these animals are from the seventeenth, eighteenth, nineteenth, or twentieth century or centuries. They do reveal that the Lake Kaiyak site is a multi-component site consisting of at least two occupational phases rather than a single component site with only one period of occupation as was previously described (Gilbert-Young, 2004). The archaeological context supports an eighteenth or nineteenth century interpretation of the animals. The ethnographic and historic contexts suggest mid-nineteenth century or earlier interpretation. If this is true, then the WAH has been using the same calving and summer range for at least the last two to three hundred years through the ecological and climatological upheavals concurrent with that time, including a sharp and significant reduction in a major predator (human beings) and the end of the Little Ice Age during the mid-nineteenth century. Nevertheless, absolute dating approaches other than radiocarbon will increase the utility of this method for wildlife management by tightening the possible age range, especially for specimens from the last three centuries.

The data provided by this method will aid archaeologists in developing human land-use models relative to seasonal caribou ranges contemporary with the people or peoples being studied. The ability to identify and track archaeological/paleontological caribou herds will provide modern wildlife managers with a deeper time perspective on herd dynamics, granting insight into which ecological or climatological factors have the most significant impact on a population than is currently available. Such information will prove valuable in management design for large ungulates and the local ecological systems of which they are a part in the present and future.

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