Radiocarbon Chronologies and Extinction Dynamics of the Late Quaternary Mammalian Megafauna of the Taimyr Peninsula, Russian Federation

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This paper presents 75 new radiocarbon dates based on late Quaternary mammal remains recovered from eastern Taimyr Peninsula and adjacent parts of the northern Siberian lowlands, Russian Federation, including specimens of woolly mammoth (*Mammuthus primigenius*), steppe bison (*Bison priscus*), muskox (*Ovibos moschatus*), moose (*Alces alces*), reindeer (*Rangifer tarandus*), horse (*Equus caballus*) and wolf (*Canis lupus*). New evidence permits reanalysis of megafaunal extinction dynamics in the Asian high Arctic periphery. Increasingly, radiometric records of individual species show evidence of a gap at or near the Pleistocene/Holocene boundary (PHB). In the past, the PHB gap was regarded as significant only when actually terminal, i.e., when it marked the apparent “last” occurrence of a species (e.g., current “last” occurrence date for woolly mammoth in mainland Eurasia is 9600 yr BP). However, for high Arctic populations of horses and muskoxen the gap marks an interruption rather than extinction, because their radiocarbon records resume, nearly simultaneously, much later in the Holocene. Taphonomic effects, ΔC^{14} flux, and biased sampling are unlikely explanations for these hiatuses. A possible explanation is that the gap is the signature of an event, of unknown nature, that prompted the nearly simultaneous crash of many megafaunal populations in the high Arctic and possibly elsewhere in Eurasia.

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Introduction

Radiocarbon chronologies and species histories

At present, the Asian portion of the high Arctic periphery (i.e., mainland north of $\sim 66^\circ\text{N}$, plus the continental shelf and islands in the Arctic Sea) supports only two species of herbivorous megafaunal mammals—reindeer (*Rangifer tarandus*), both wild and domesticated, and muskox (*Ovibos moschatus*) reintroduced from Canada and Alaska in the 1970s (Lent, 1999). It was not always thus. Several thousand years ago, this same zone supported at least a half-dozen large herbivores (Sher, 1974; Vereshchagin & Baryshnikov, 1984; Kahlke, 1994, 1999). Some (e.g., *Mammuthus primigenius*, *Bison priscus*) became extinct on the mainland near the Pleistocene/Holocene boundary (PHB), perhaps as part of the Eurasian equivalent of the end-Pleistocene extinctions which affected the continental New World slightly earlier (for discussion of putative causes, see Graham & Lundelius, 1984; Agenbroad, 1984; MacPhee & Marx, 1997; Martin & Steadman, 1999; Alroy, 2001). Others, like Asian *O. moschatus*, also disappear from the record at about the same time, only to reappear—briefly—thousands of years later. Was there a single, temporally constrained event that provoked the loss of many, but clearly not all, of the Holarctic megafauna? Or was it rather a case of separate responses to separate factors, with some species suffering complete extinction while others were unaffected or experienced local extirpation only? Or are these apparent patterns simply artefacts of an imperfect radiocarbon record?

To answer such questions, presence/absence data on individual species are necessary but not sufficient, because information on populations across time is also needed. Some headway in understanding the population dynamics of now-extinct species in different parts of the globe is being made through an array of novel techniques and applications (e.g., Fisher, 1996; Culver *et al.*, 2000; Greenwood *et al.*, 2001), and there is hope that molecular investigations of continuity and change in gene distributions will eventually offer intriguing insights into species' histories during the last part of the Quaternary (e.g., Vilà *et al.*, 2001). However, it is important not to lose sight of the fact that the scaffolding on which all historical investigations hang is time. Without a dependable chronometric record, process becomes obscured or uninterpretable. In Quaternary studies, it is the radiocarbon record that has played, and will no doubt continue to play, a pivotal role not only in defining in general terms when Quaternary extinctions took place, but also in revealing whether or not individual extinctions were temporally coordinated in those places where large losses occurred (Faunmap Working Group, 1996; Beck, 1996; Martin & Steadman, 1999; MacPhee *et al.*, 1999; Grayson, 2001).

Another aspect of the radiocarbon record is that it may also supply useful diachronic information on

species composition and change in a given area. The causes and consequences of population fluctuation are questions of fundamental importance in animal ecology, but relevant modern studies are usually limited in time depth to a few decades (e.g., Berger *et al.*, 2001; Jackson *et al.*, 2001; Bjørnstad & Grenfell, 2001). Admittedly, techniques for examining population dynamics over much longer intervals, such as the one contemplated here, are crude at present. Nevertheless, any reliable information concerning this topic may help to elucidate why so many megafaunal species have disappeared in geologically recent times (Graham & Lundelius, 1984; MacPhee & Marx, 1997; MacPhee & Flemming, 1999; Martin & Steadman, 1999; Alroy, 2001).

In this paper we are principally concerned with the history of mammalian megafauna on the Taimyr Peninsula and the adjacent northern Siberian lowlands (Figure 1(a)–(b)) during the latest part of the Quaternary, i.e., after the Last Glacial Maximum (LGM). Our primary tool for this purpose is the current radiocarbon record for Taimyr, which we have been able to substantially augment with 75 separate age assessments (67 dates on isolated fossils and eight weighted averages for multiply-dated specimens or individuals; Tables 1–3; Figure 2(a)–(d)). This new date pool is based on samples selected for dating from the extensive fossil collections made by members of the Cerpolex/Mammuthus Expedition (hereafter, CME) in 1999–2000, mostly in the eastern half of Taimyr. Our chief concern here is to place these new dates within the context of similar date pools collated in other recent publications (see, especially, Sulerzhitsky, 1995; Sulerzhitsky & Romanenko, 1997, 1999; Vasil'chuk *et al.*, 1997; Orlova *et al.*, 2000).

The Taimyr Peninsula has long been of interest to Quaternary paleontologists because at least some elements of the now-extinct megafauna appear to have survived there and in nearby regions somewhat longer than they did elsewhere on the mainland (i.e., the Eurasian continent as it exists today, without regard to connections that may have existed at times of lowered sea level). For example, the latest dates for woolly mammoths anywhere in mainland Eurasia are based on specimens from the Taimyr and nearby Yamal peninsulas (Sulerzhitsky, 1995; this paper). (The latest records of all are for Wrangel Island in the East Siberian Sea, where mammoths survived until *c.* 3700 yr BP (Vartanyan *et al.*, 1993, 1995; Lister, 1993; Reumer & Mol, 2001).) Taimyr has also yielded “last” occurrence dates for several other species or distinct populations (*Bison priscus*, north Asian *Equus “lenensis”* [= *E. caballus*], and Asian *Ovibos moschatus*). This suggests that this area is of prime importance for investigating megafaunal extinction dynamics in northern Eurasia. Additional resolution will depend on gathering many more megafaunal dates, especially for species other than *Mammuthus primigenius*.

Figure 1(a).

Figure 1(b).

Figure 1(c).

Figure 1. The Asian high Arctic periphery: (a) North-central section of Russian Federation; (b) Taimyr Peninsula and adjacent regions; and (c) Lake Taimyr and environs. Maps identify localities and basins named in text and [Tables 1–5](#).

Study area: Khatanga and Taimyra basins, Taimyr Peninsula

Historically, most fossil collecting activities in Taimyr have been conducted within the confines of the peninsula's two largest river basins ([Figure 1\(b,c\)](#)), the Khatanga and the Taimyra (latter term used in preference to "Taimyr basin" to avoid confusion with peninsular name). The Khatanga, the major river system of

the central part of the northern Siberian lowlands, arises from major tributaries (e.g., Kheta, Kotuy) that drain the north slopes of the Putorana plateau, and also receives major affluents from the south-east (Popygai) and the north (Bol'shaya Balakhnya). The Taimyra system is composed of two large rivers, the Upper (Verkhnyaya) Taimyra and Lower (Nizhnyaya) Taimyra. The former ends and the latter begins in the

Table 1. AMS ^{14}C ages, late Quaternary megafaunal mammals from eastern Taimyr Peninsula (Russian Federation)

Lab Code ¹	Specimen	Provenance ²	Age (^{14}C yr BP, $\delta^{13}\text{C}$ corrected)
<i>Mammuthus primigenius</i>			
GrA-17350	Mandible	Bikada R	9920 $\pm$ 60
Beta-148640	Tusk	Gol'tsovaya R	10,270 $\pm$ 40
Beta-148663	Ulna	Arilakh L	11,940 $\pm$ 40
Beta-148636	Femur	Near Sopochneya settlement	13,560 $\pm$ 40
Beta-148642	Femur	Sabler C	15,390 $\pm$ 50
Beta-148646	Molar	Bol'shaya Balakhnya R	18,190 $\pm$ 60
GrA-17347 ^{3, 4}	Skull	Upper Taimyra R, internal delta	20,500 $\pm$ 90
Beta-148647 ^{3, 4}	Humerus	Upper Taimyra R, internal delta	20,620 $\pm$ 70
Beta-148633	Mandible	Taimyr P	20,800 $\pm$ 70
GrA-17604	Calcaneus	Baskura P (Taimyr L)	20,950 $\pm$ 190
Beta-148639	Skull	Trautfetter R	24,170 $\pm$ 110
Beta-148651	Skull	Munchirdakh L	24,250 $\pm$ 110
Beta-148634	Thoracic vert.	Near Sopochneya settlement	25,800 $\pm$ 130
Beta-148665	Humerus	Baskura P (Taimyr L)	26,100 $\pm$ 170
Beta-148662	Ulna	Taimyr P	28,270 $\pm$ 210
Beta-148643	Molar	Taimyr L, coast opposite Kupffer Is	28,310 $\pm$ 170
Beta-148635	Humerus	Talalakh L	29,990 $\pm$ 280
Beta-148637	Molar	Talalakh L	30,890 $\pm$ 290
Beta-148644 ³	Skull	Bol'shaya Balakhnya R	31,580 $\pm$ 240
Beta-148631	Tibia	Baikuraturku L	31,580 $\pm$ 330
Beta-148667	Skull	Sabler C	32,530 $\pm$ 270
Beta-148650 ^{3, 5}	Ulna	Novaya R	32,600 $\pm$ 280
Beta-148632	Tibia	Taimyr P	32,750 $\pm$ 280
Beta-148641	Femur	Arilakh L	32,840 $\pm$ 290
Beta-148630	Mandible	Arilakh L	36,950 $\pm$ 450
Beta-148666	Skull	Popygai R	37,080 $\pm$ 460
Beta-148664	Pelvis	Arilakh L	39,050 $\pm$ 580
Beta-148638	Mandible	Trautfetter R	39,560 $\pm$ 910
Beta-148645	Pelvis	Sabler C	40,560 $\pm$ 700
Beta-148648 ^{3, 6}	Tibia	Arilakh L	40,790 $\pm$ 970
GrA-17439 ^{3, 5}	Thoracic vert.	Novaya R	41,580 $\pm$ 1190/ – 1040
Beta-148668 ^{3, 6}	Humerus	Arilakh L	43,160 $\pm$ 1280
GrA-17499 ^{3, 6}	Femur	Arilakh L	43,500 $\pm$ 1000
Beta-148669	Molar	Popygai R	47,660 $\pm$ 1650
Beta-148649 ^{3, 6}	Femur	Arilakh L	>49,210
<i>Ovibos moschatus</i>			
Beta-148653	Skull	Sabler C	15,800 $\pm$ 50
Beta-148628	Horn sheath	Taimyr L, S of Sabler C	18,370 $\pm$ 70
Beta-148627	Atlas vert.	Sabler C	19,310 $\pm$ 80
Beta-148654	Skull	Bol'shaya Balakhnya R	19,710 $\pm$ 70
GrA-17500	Horn sheath	Taimyr L, coast opposite Kupffer Is	20,770 $\pm$ 180
Beta-148629	Skull	Yalutarida R delta, Matuda P	21,190 $\pm$ 90
Beta-148658	Skull	Khatanga townsite	21,330 $\pm$ 70
Beta-148655 ^{3, 7}	Skull	Popygai R	21,500 $\pm$ 100
GrA-17605 ^{3, 7}	Skull	Popygai R	22,530 $\pm$ 220
Beta-156194	Metapodial	Taimyr L, coast opposite Kupffer Is	22,370 $\pm$ 80
Beta-148652	Metapodial	Taimyr L, coast opposite Kupffer Is	22,610 $\pm$ 100
Beta-148657	Femur	Upper Taimyra R	24,660 $\pm$ 110
Beta-148656	Skull	Sabler C	27,440 $\pm$ 150
GrA-17349	Skull	Sabler C	32,540 $\pm$ 210
UtC-10156	Skull	Bikada R	36,700 $\pm$ 700
Beta-148626	Skull	Sabler C	42,680 $\pm$ 1240
<i>Bison priscus</i>			
Beta-148623	Hornsheath	Popygai R	8860 $\pm$ 40
Beta-148624	Metapodial	Sabler C	39,760 $\pm$ 870
Beta-148625	Tibia	Talalakh L	45,320 $\pm$ 1740
<i>Equus caballus</i>			
Beta-148659	Radius-ulna	Taimyr L	17,950 $\pm$ 60
GrA-17351	Skull	Arilakh L	18,090 $\pm$ 80
Beta-148660	Skull	Sabler C	24,690 $\pm$ 110
Beta-148622	Tibia	Talalakh L	36,770 $\pm$ 610

Table 1. Continued

Lab Code ¹	Specimen	Provenance ²	Age (¹⁴ C yr BP, ^{δ13} C corrected)
<i>Alces alces</i>			
Beta-148621	Frontal	Near Sopochnaya settlement	4050 ± 40
GrA-17346	Antler	Novaya R., Ari-Mas	47,900+1000/ – 9000
<i>Canis lupus</i>			
Beta-148620 ³	Skull	Sabler C	16,310 ± 50
GrA-17432 ³	Skull	Sabler C	16,670 ± 70
<i>Rangifer tarandus</i>			
GrA-17497a ³	Lower molar	Taimyr L	8700 ± 45
GrA-17497b ³	Mandible	Taimyr L	8710 ± 60

¹GrA, Groningen AMS, Center for Isotope Research (The Netherlands); Beta, Beta Analytic, Inc. (Florida, U.S.A.). Ages are cited as ^{δ13}C corrected mean age ± 1 sigma (σ).

²Geographical abbreviations: B, bay; C, cape; Is, island(s); L, lake; NNE, north northeast; P, peninsula; R, river; S, south.

³Replicate date for this specimen/individual; see Table 3 for weighted average.

⁴Hook mammoth.

⁵Markel mammoth.

⁶Pilot's Site mammoth.

⁷Specimen from partial muskox skeleton (skull, jaws, and five associated upper cervicals).

western end of the large but shallow Lake Taimyr, situated in the lowest part of the Taimyra basin. The Lower Taimyra, which drains northward to the Kara Sea, has several tributaries of proven paleontological importance (e.g., Shrenk, Mamonta). A third watershed, the Bikada, drains into the lake from the east. Tributaries of the Bikada include the Nyun'karakutari and N'yen'gatiatari, both of which have yielded important fossils.

Other basins in Taimyr (e.g., Leningradsкая, Pyasina) have been less intensively collected but are undoubtedly worth additional prospecting (cf. Sulerzhitsky & Romanenko, 1999). This point also applies to peninsular coastlines and the Severnaya Zemlya islands to the north of Taimyr proper. For completeness we make brief reference to the few dates on fossils from these other areas and include them in certain analyses.

Lake Taimyr is situated on the southern margin of the Byrranga mountains (max. elev., 1146 m), which extend in a narrow arc across the peninsula from southwest to northeast and provide the area's only substantial relief. North of the lake, the landscape is generally rugged and hilly. To the south, it merges with the nearly featureless northern Siberian lowland belt. As a result, the divide between the Khatanga and Taimyra basins is very low (<50 m asl). According to Möller *et al.* (1999), on at least one occasion during the late Quaternary the water level in Lake Taimyr rose far above its current elevation (5 m asl). Overflow from the lake would have drained into the Khatanga basin via the headwaters of the Bol'shaya Balakhnya, with the result that large areas of the lowlands on either side of the river would have been shallowly submerged for a

time. Spillover along the course of the Upper Taimyra may have also affected the western part of the Taimyr Peninsula (P. Möller, pers. commun.).

The 60-km wide Vil'kitskogo Strait that presently separates the Severnaya Zemlya islands from Cape Chelyuskin reaches depths between 100 and 200 m. Whether or not the islands and mainland were actually continuous during the last glaciation, it is probable that megafauna could have crossed (and re-crossed) over sea ice at any time when conditions permitted. Thus it is reasonable to link the faunal history of Severnaya Zemlya with that of the mainland. The current dating record (four dates, *Mammuthus* only) is not dense enough to make useful inferences about the length of megafaunal tenure on these islands, although it is sufficient to establish that mammoths survived on the middle island, Oktyabr'skoy Revolyutsii, until nearly the end of the Pleistocene (Sulerzhitsky & Romanenko, 1999).

Taphonomic considerations

Although the discovery of individual megafaunal carcasses in northern Asia tends to generate considerable interest, such discoveries are chiefly noteworthy because they occur so rarely (see Vereshchagin & Tikhonov, 1999; Mol *et al.*, 2001a,b). Indeed, although megafaunal bone is a common sight in Taimyr, it is rather unusual to encounter skeletons or even associated elements. For example, the beach along the east side of Cape Sabler, Lake Taimyr (Figure 1), is acknowledged to be one of the best collecting areas on the peninsula. From simple positional considerations it is obvious that bones which end up on the cape's beach

Table 2. Conventional ^{14}C ages, late Quaternary megafaunal mammals from eastern Taimyr Peninsula (Russian Federation)

Lab Code ¹	Element	Provenance	Age (^{14}C yr BP, not $\delta^{13}\text{C}$ corrected)
<i>Mammuthus primigenius</i>			
GIN-10508	Tusk	N'yen'gatiatari R (74°50-0'N, 106°10-0'E)	10,070 ± 60
GIN-11138a	Molar	Kupchiktakh L (73°35-9'N, 101°07-8'E)	10,200 ± 40
GIN-10507	Tibia	Nyun'karakutari R (75°21-0'N, 105°30-0'E)	10,270 ± 120
GIN-10552	Molar	Krasnaya R (74°34-0'N, 98°30-0'E)	10,790 ± 100
GIN-10506	Bone (unspecified)	Bikada R (74°50-0'N, 106°00-0'E)	12,050 ± 150
GIN-11127	Tusk	Bol'shaya Balakhnaya R (73°35-7'N, 100°33-4'E)	26,200 ± 150
GIN-11130a ²	Skull	Bol'shaya Balakhnaya R (73°36-2'N, 100°29-7'E)	30,850 ± 200
GIN-11137	Molar	Kupchiktakh L (73°35-9'N, 101°07-8'E)	32,200 ± 800
GIN-11128	Rib	Bol'shaya Balakhnaya R (73°32-1'N, 100°29-2'E)	>38,600
GIN-11127a	Tusk	Bol'shaya Balakhnaya R (73°35-7'N, 100°33-4'E)	39,300 ± 600
GIN-11134	Sacrum	Bol'shaya Balakhnaya R (73°32-1'N, 100°29-2'E)	40,200 ± 600
<i>Ovibos moschatus</i>			
GIN-25529	Skull	Pronchishchev B (no specific coordinates)	2900 ± 60
GIN-11130	Cervical vertebra	Bol'shaya Balakhnaya R (73°36-2'N, 100°29-8'E)	>39,000
<i>Equus caballus</i>			
GIN-10509	Maxilla	Nyun'karakutari R (75°18'N, 105°45'E)	9010 ± 140
GIN-11133	Femur	Bol'shaya Balakhnaya R (73°32-1'N, 100°29-2'E)	17,000 ± 150
GIN-11132	Scapula	Bol'shaya Balakhnaya R (73°31-6'N, 100°29-6'E)	23,900 ± 400
GIN-11129	Tibia	Bol'shaya Balakhnaya R (73°36-7'N, 100°24-8'E)	32,800 ± 900
GIN-11136	Bone	Kupchiktakh L (73°36-4'N, 100°08-9'E)	>30,000
GIN-11135	Femur	Kupchiktakh L (73°36-4'N, 101°08-9'E)	>40,400
<i>Rangifer tarandus</i>			
GIN-11131	Bone	Bol'shaya Balakhnaya R (73°36-2'N, 100°29-8'E)	20,250 ± 90
GIN-11138	Antler	Bol'shaya Balakhnaya R (73°35-0'N, 100°04-5'E)	<38,600

¹GIN, Geological Institute, Russian Academy of Sciences (Russia). For other abbreviations, see Table 1. Ages are cited as measured (raw) mean date ± 1σ.

²Cf. B-148644, Table 1 (same specimen).

must be eroding out of the cliff face that towers above it, which is composed of unconsolidated silts, peats, sands, and gravels at base (for a detailed description, see Möller *et al.*, 1999). However, it is quite uncommon to see bones actually *in situ* in the cliff face before they erode out, and articulated elements are almost never encountered as such. These points suggest that, for the

most part, (a) the bones contained in the Cape Sabler deposits probably occur as isolated elements, not as articulated skeletons, and that (b) they do not regularly occur in concentrations, but are widely dispersed in the sediments. Earlier bouts of collecting activity cannot explain the lack of numerous associated remains at present, as new material is presumably eroding out all

Table 3. Replicate age estimates and weighted average ages for selected specimens noted in Tables 1 and 2¹

Specimen	Lab Code	Element	Age (¹⁴ C yr BP) ²	Weighted Average (¹⁴ C yr BP)
Jarkov mammoth	UtC-8137	Bone	19,920 ± 130	20,200 ± 80
	UtC-8138	Hair	20,380 ± 140	
	UtC-8139	Skin	20,390 ± 160	
Hook mammoth	GrA-17347	Skull	20,500 ± 90	20,560 ± 60
	Beta-148647	Humerus	20,620 ± 70	
Markel mammoth ³	GrA-17439	Vertebra	41,580 + 1190/ – 1040	32,950 ± 250
	Beta-148650	Ulna	32,600 ± 280	
Pilot's Site mammoth ⁴	Beta-148648	Tibia	40,790 ± 970	42,420 ± 500
	Beta-148668	Humerus	43,160 ± 1280	
	GrA-17499	Femur	43,500 ± 1000	
Bol'shaya Balakhnya mammoth	Beta-148644	Skull	31,520 ± 240	31,230 ± 140
	GIN-11130a		30,850 ± 200	
Popigay muskox	Beta-148655	Skull	21,500 ± 100	21,710 ± 90
	GrA-17605		22,530 ± 200	
Lake Taimyr wolf	Beta-148620	Skull	16,310 ± 50	16,430 ± 40
	GrA-17432		16,670 ± 70	
Lake Taimyr reindeer	GrA-17497a	Molar	8700 ± 45	8700 ± 40
	GrA-17497b	Mandible	8710 ± 60	

¹Weighted average method of Long & Rippeteau (1974).

²Assays are $\delta^{13}\text{C}$ corrected except in case of estimates for Bol'shaya Balakhnya skull (Beta-148644 not corrected in order to accord with GIN-11130a, for which there is no $\delta^{13}\text{C}$ estimate). Weighted averages for this specimen is therefore probably 30–70 yr too young.

³Dates for Markel mammoth are not compatible and weighted mean is not judged to be a reliable indicator of age. At least one additional date is needed to resolve problem.

⁴Based on the three finite dates listed in Table 1. The fourth date, which is nonfinite (>49,180, Beta-148649), is significantly older and was not utilized.

the time. We suggest that these observations apply generally to the taphonomy of Taimyr, particularly to the more rugged parts of the peninsula situated north of the lake.

Nevertheless, this situation is somewhat surprising. Among other factors, low mean temperature and apparent scarcity of large meat-eaters in Taimyr during the past several tens of thousands of years should have favoured slow decomposition and even slower derangement of megafaunal skeletal associations. For the vast majority of specimens, human transport is unlikely because there is no evidence that people had reached Taimyr or adjacent regions of northernmost Siberia until the very end of the Pleistocene or early Holocene (Kuzmin & Tankersley, 1996; Orlova *et al.*, 2000; Pitul'ko, 2001). Great concentrations of specimens, like those at Berelekh (Vereschagin & Baryshnikov, 1984), are never encountered in Taimyr. Moreover, no butchering marks were seen on any of the mammoth material collected by the CME, nor have any such alterations been reported previously. Accordingly, by default ice and water must be considered the primary agents of bone dispersal along the high Arctic periphery. Carcasses can be torn apart by moving ice shearing off exposed limbs or other bodily parts, especially during spring breakup when carcasses may only be partly frozen to the ground. This must be why intact limbs, sometimes with soft tissues still attached, can occur in isolation, without any other portions of the

body in the vicinity. Ice can also cause push fractures, breaking up even the largest and thickest elements like mammoth femora and humeri.

Since most fossil finds are made in river valleys, it is logical to think that events like spring breakup must be responsible for moving elements to and fro. But even if the majority of fossil specimens have been subject to repeated redeposition, many have just as clearly not. Indeed, the exquisite condition of many specimens indicates quite the opposite. For example, mammoth skulls with intact molars, tusks, and nasal turbinates are occasionally found at surface without any bones belonging to the same skeleton nearby (Figure 3). This presumably indicates that either the skull or, alternatively, all the rest of the skeleton, had to have been moved at least once—but perhaps only once, which is the important point. Although an intact mammoth skull with tusks may weigh 100–150 kg or more, extensive pneumatization would provide some buoyancy (cf. Shipman, 1981; Todd & Frison, 1986). One might infer that only large volumes of water, moving at high velocity, would be able to move such an object a significant distance, but without proper taphonomic experimentation this can only be considered an inference.

Tusks provide a parallel case. A tusk of a large male woolly mammoth can weigh as much as 80 kg, at least in a water-logged state (D. Mol, pers. obs.). Of the 160 tusks in varying states of completeness collected by

Figure 2(a) and (b).

Figure 2(c).

Figure 2. Scattergram/histogram presentations depicting current radiocarbon dating information on late Quaternary mammalian taxa from Taimyr Peninsula, Russian Federation: (a) 75 AMS and conventional dates reported in this paper (see Tables 1–3); (b) 112 previously-published dates (various sources); (c) combination of datasets in (a) and (b). “Radiocarbon dates” are means of individual radiocarbon assays, whether AMS or conventional; variates are grouped in intervals of 1000 years. “Previously published” dates are ones selected primarily from lists published by Sulerzhitsky (1995), Sulerzhitsky & Romanenko (1997, 1999), and Vasil’chuk *et al.* (1997). Key: BISO, *Bison priscus*; HORS, *Equus caballus*; MAMM, *Mammuthus primigenius*; MOOS, *Alces alces*; MUSK, *Ovibos moschatus*; REIN, *Rangifer tarandus*; WOLF, *Canis lupus*.

For Beta Analytic AMS dates only ($N=50$), grand mean=27,390 yr BP (s.d.=10,780); for previously published dates only, grand mean=28,420 yr BP (s.d.=12,925). Differences in distributions of variates in the two data sets are not significant at the 0.05 level as judged by both parametric and non-parametric tests (unpaired t test, $P=0.47$; Kolmogorov-Smirnov statistic, $P=0.42$; Mann-Whitney statistic, $P=0.36$), nor was Hartley’s F -test for homogeneity of variances comparing Beta Analytic and previously reported GIN subsets (variance ratio $F=1.3818$).

Although dates are scattered over the whole period accessible to radiocarbon dating, some intervals appear to be much more heavily sampled than others (concentrations). There are also some apparent gaps (rarefactions) for which there are few or no dated specimens. See text for discussion.

CME personnel prior to August, 2001, there are only four obvious pairs (i.e., paired tusks belonging to a single individual). Obviously, tusks, like skulls and long bones, do move.

Methods

Collecting methods

Specimen collection was performed by CME personnel as well as by hired collectors who worked in designated drainages in several parts of eastern Taimyr and the Khatanga watershed. Most collected material was brought to the central processing station at Cape Sabler for eventual packing and removal by helicopter to the expedition’s cold storage “ice cave” in Khatanga

(Mol *et al.*, 2001b). A number of other specimens, collected years earlier by other hands, have also been deposited in the Khatanga CME collection.

Fossil hunting in eastern Taimyr is generally conducted along lake margins and river banks, and our collecting effort was no exception. This bias simply recognizes the fact that bones are exposed in riparian settings much more frequently than they are on the tundra. It is also considerably easier to see and collect fossils in areas that lack any vegetation whatsoever. Finally, in eastern Taimyr permafrost begins within a meter of the surface; excavation is therefore indicated only in the case of unusual finds or concentrations of bones.

For most specimens, the only provenance information is the drainage in which the find was made. However, as an experiment (cf. Table 2), some local

Figure 3. Age distribution of substantially complete skeletons (crosses) and isolated skulls (half-filled circles) of *Mammuthus primigenius* having known provenances in Taimyr. Some of the singleton skulls may have been associated with postcranials that were not retrieved (or recognized as such) at the time of discovery. Weighted average ages are given for specimens marked by asterisks (see Table 3). For details, see text. Skeletons: Khatanga, 45,000 ± 200 yr BP (MAG-369); Pilot's Site, 42,420 ± 500 yr BP (Table 3); Markel, 32,950 ± 250 yr BP (Table 3); Hook, 20,560 ± 60 yr BP (Table 3); Jarkov, 20,200 ± 80 yr BP (Table 3); Mamonta River (*Mammuthus primigenius* neotype), 11,450 ± 250 yr BP (T-297). Skulls: Trautfetter, 24,170 ± 110 yr BP (B-148639); Munchirdakh, 24,250 ± 110 yr BP (B-148651); Bol'shaya Balakhnya, 31,230 ± 140 yr BP (see Table 3); Popygai, 37,080 ± 460 yr BP (B-148666). For isotope lab abbreviations see Table 4.

collectors were provided with GPS units to record exact locations (latitude and longitude; altitude was not recorded). Although it might be argued that such

precision is pointless for surface-deposited specimens, in fact it can be very helpful in determining the proximity of specimens to one another, or which parts of a drainage have been well collected.

Specimen selection

The majority of the dates that we report here are derived from teeth and long-bone compactum. Specimens for dating were selected according to overall quality of preservation, taxonomic representativeness, and likelihood of DNA recovery. Intact long bones were preferred over other elements because we have had notable success in extracting DNA from marrow tissues preserved in medullary cavities (Greenwood *et al.*, 2001). (Results of our ancient DNA investigations will be reported elsewhere.)

Another reason for concentrating on well preserved material was our belief that such specimens would, on the whole, turn out to be relatively recent and therefore have a bearing on refining estimates of "last" occurrences of megafaunal species (MacPhee & Marx, 1997; Martin & Steadman, 1999). Our results (Tables 1, 2) show that this belief was misplaced. Although there is of course some correlation between excellence of preservation and relative recency, on the tundra the correlation is not high: generally speaking, appearance is not a good index of antiquity, and well preserved material can be of any age. For most of the late Quaternary, Taimyr's extremely cold winters, combined with short, cool summers and little annual precipitation, have insured that conditions optimal for the preservation of bone have prevailed there for at least the last 50,000 years (and no doubt much longer).

Sampling methods

After photographic recording, specimens selected for dating or molecular studies were sampled (either by coring out material with an electric drill, or detaching pieces with pliers). Samples were immediately placed in separate containers (cone tubes or plastic bags, depending on size), labelled, and stored for later processing. Marrow, if present, was scooped into cone tubes, labelled, and stored at cool temperatures (~5–10°C) until processing.

Coring was accomplished with diamond-edged "hole-saw" drill bits, ~1 and 2 cm in diameter (available from Triatic Inc., 22 Grassmere Ave., West Hartford, CT 06110). The bits worked well on small, relatively thin-walled elements such as muskox cannon bones. However, when drilling very thick material (e.g., mammoth long-bone compactum, muskox basiscrania), a continuous water drip was necessary in order to prevent undue bit wear. Drill bits were washed in water after each sampling procedure, but it was usually difficult to remove all adherent material from the

diamond edge. Small, portable ultrasound baths are recommended for work of this kind in future.

Dating considerations

Although chronometric records based on radiocarbon dating are of central importance to late Quaternary paleontology, it is necessary to keep in mind their limitations (van der Plicht, 1998, 2000). The INTCAL98 calibration curve (Stuiver *et al.*, 1998), the current international standard, is based on several sources. The curve's backbone is provided by tree-ring chronology, which currently yields a continuous record extending back to 10,280 cal yr BP. To this is added a separate, floating chronology, at present based only on German pine tree data, that extends the record back to 11,860 cal yr BP with an acknowledged probable uncertainty of ± 10 cal yr (Kromer & Spurk, 1998). This interval embraces almost all of the period of greatest interest here. Corals with pairwise dates (^{14}C and U-series) provide a third source of calibration and extend the INTCAL98 curve back to 15,585 cal yr BP. However U-series dating is not tree-ring counting, and is therefore not "absolute". Further, because of marine reservoir effects, a factor of 400–500 cal yr must be used to "correct" dates based on coral. Beyond 15,585 cal yr BP there are isolated pair-dated coral datapoints that extend the pertinent record to $\sim 40,000$ cal yr BP. Other cross-checking methods, including varves, are being tested and will no doubt lead to improvements and extensions (see van der Plicht (2000) and related papers published in the journal *Radiocarbon*, vol. 42(3)).

The shape of the calibration curve, which is empirical, is ultimately controlled by secular variation in the amount of atmospheric ^{14}C ($\Delta^{14}\text{C}$). During the last 50,000 years, flux in $\Delta^{14}\text{C}$ has been substantial. During the latest Pleistocene and Holocene the trend has been fairly regularly downward, toward lower atmospheric ^{14}C content. Within this interval, $\Delta^{14}\text{C}$ is now well understood (van der Plicht, 1998, 2000). Much more problematic are the massive excursions that punctuate earlier parts of the radiocarbon record, particularly because different methodologies used to investigate flux do not produce the same results. Thus Beck *et al.* (2001) recently reported the existence of markedly fluctuating $\Delta^{14}\text{C}$ values between 45,000 and 33,000 cal yr BP, amounting at times to more than double the modern atmospheric $^{14}\text{C}/^{12}\text{C}$ ratio. However, this peak, which is based on stalagmite data, is not replicated in the Lake Suigetsu varve record published by Kitagawa & van der Plicht (1998). Conversely, a peak recorded at 31,000 cal yr BP in the varve record is not obvious in the stalagmite data (van der Plicht, 2000, in prep.). The meaning of these huge excursions in $\Delta^{14}\text{C}$ is likely to remain controversial (Yokoyama *et al.*, 2000): at present, they cannot be accounted for by reference to any plausible level of change in the solar and terrestrial magnetic fields.

A final point concerns the comparative reliability of dates based on bone and other hard tissues. Although the propensity of dense connective tissues to uptake contaminants in the form of allochthonous carbon is certainly a consideration, in high-latitude, open-air terrestrial contexts like the Taimyr Peninsula, it is unlikely to be a major concern. In such contexts all processes leading to the release of stored carbon, such as mechanical or chemical erosion of sediments, production of CO_2 by plants, or deposition via meteoric water, are relatively muted and slow. In the absence of carbonate rocks (outcropping rocks on the Taimyr are mostly Devonian shales), substantial reservoir effects are not likely.

Results

This section provides taxon-by-taxon assessment of results in comparison to previous chronometric studies. Radiometric assays are provided in Table 1 (AMS dates) and Table 2 (conventional scintillation dates); weighted averages for replicate datings of the same specimen or individual are given in Table 3. Statistical statements are based primarily on a database of 188 radiocarbon dates on megafaunal skeletal elements from Taimyr, collated from the literature and this paper. (Database available from senior author on request.) The software package Statview 5.0.1 (SAS Institute, Cary, North Carolina), PowerPC version, was used for all statistical tests. Replicates are omitted from computations and tallies unless otherwise indicated.

All radiocarbon dates are cited in radiocarbon years Before Present ("1950"), or "yr BP" AMS dates listed in Table 1 have been corrected for carbon isotope fractionation ($\delta^{13}\text{C}$); dates listed in Table 2 are uncorrected, as are the raw dates under the "Age" column in Table 4. Although it is certainly appropriate to distinguish between corrected and uncorrected dates when possible, in general the effect of $\delta^{13}\text{C}$ on date computation is negligible for bones of terrestrial mammalian herbivores.

Many late Quaternary Asian megafaunal taxa are seriously oversplit. In general, we have tried to utilize the most widely accepted names and species concepts for the taxa of interest here. Reconstructed range maps for various parts of the Pleistocene for the taxa of interest here may be found in Kahlke's (1999) monograph.

Woolly mammoth

Current record and new results. The new radiocarbon dates ($N=46$) for *M. primigenius*, including replicates, range from $>49,180$ to 9920 ± 60 yr BP (Tables 1–3). Despite selection bias toward putatively young material, 30 (65%) of the samples (excluding replicates) proved to be older than 20,000 yr BP. Currently, the youngest date for *M. primigenius* in Taimyr

is 9670 ± 60 yr BP (GIN-1828; Sulerzhitsky & Romanenko, 1997), for a tusk from the Lower Taimyra basin. At 2σ this date virtually overlaps our youngest date (GrA-17350), which raises the possibility that we have sampled the same (presumably terminal) population of woolly mammoths. It is noteworthy that at least a dozen dates $<11,000$ yr BP are now recorded for Taimyr mammoth specimens (Figure 2(c)). We also take this opportunity to formally publish a weighted average date for the Jarkov mammoth (Table 3).

Evaluation. Because mammoths have long been a favourite subject for radiocarbon dating in northern Asia, the new dates by themselves add little that is novel. However, it seems reasonable to infer, on the basis of what is now a rather substantial dating sample (*c.* 130 dates for Taimyr mammoths, including replicates), that *Mammuthus primigenius* was either exceedingly rare or absent in Taimyr by 9500 yr BP. Further treatment of the implications of this climacteric are reserved for a later section (see Discussion).

Of quite separate significance are dates for associated skeletal specimens of mammoths. CME personnel have so far collected or identified four partial skeletons of *Mammuthus primigenius* in eastern Taimyr. These include the well known Jarkov specimen and three others, dubbed the “Hook,” “Markel” and “Pilot’s Site” mammoths (Table 3). There is also a fifth collection of extremely well preserved bones (femur, humerus, and two pelves), recovered from an unspecified place on Cape Sabler many years ago, that are of comparable size, condition, and coloration. Dubbed the “White” mammoth, these remains were thought to constitute a single animal. However, dates on the femur ($15,390 \pm 50$ yr BP) and one pelvis ($40,560 \pm 700$ yr BP) indicate that this material consists of at least two individuals whose component parts cannot now be separated without dating each of them individually.

The discovery and extraction of the Jarkov specimen has been thoroughly documented (Mol *et al.*, 2001a) and details need not be repeated here. Information on the discovery of the Markel and Pilot’s Site specimens is sparse, although it is clear that each was found on surface as a set of apparently associated remains. Hook was probably essentially complete at the time of discovery in 1990 (Mol *et al.*, 2001b). Unfortunately, its excavation—paid for by a Japanese documentary film crew—was poorly conducted. Soft tissues were certainly present in abundance at the time of discovery, although their completeness cannot now be ascertained. At the time the skull, some vertebra, several long bones, and a few other elements were retrieved for the museum of the Taimyr Nature Reserve in Khatanga. The rest of the Hook skeleton, including most of the animal’s hindquarters, was left in the river bank at the spot where the specimen was first encountered. Since then, remains of the carcass have progressively slid down into the river bed. During May, 2001,

a number of the remaining elements, including some with adherent soft tissue, were recovered by CME personnel. It is tragic that so much of this excellent specimen has been lost to science.

The dates for the Jarkov and Hook specimens form tight clusters and raise no interpretative problems (Table 3). By contrast, dates for the Markel and Pilot’s Site individuals are spread out over many thousands of years. This possibly indicates that more than one individual is present in each case. However, it is important to note that the pertinent dates are near, if not beyond, the limit of reliable radiocarbon dating, and have large counting errors. In the case of Pilot’s Site, we discarded the non-finite date ($>49,180$ yr BP) when computing the weighted average. Even so, the average, $42,420 \pm 500$ yr BP, should not be taken too literally; a conservative estimate for the Pilot’s Site skeletal material would simply be that it is $>40,000$ yr BP.

Horse

Current record and new results. The date of 9010 ± 140 yr BP (Table 2) for the Nyun’karakutari cranium establishes that horses were still present in Taimyr immediately after the end of the Pleistocene. The youngest within-Pleistocene record for horses in this region is $14,100 \pm 160$ yr BP (GIN-3823a, Sulerzhitsky & Romanenko, 1997). An appreciable gap exists between these terminal or near-terminal Pleistocene dates and the next oldest— 3250 ± 60 yr BP (GIN-3243, Sulerzhitsky & Romanenko, 1997)—which lies deep within the Holocene (see Discussion).

Evaluation. Eurasian “caballoid” horses have been oversplit at every possible level (cf. Kahlke, 1999). It is quite clear from the molecular evidence that domesticated horses (*=E. caballus*) incorporate a tremendous breadth of genetic diversity (Vilà *et al.*, 2001), and that multiple species-level divisions within the caballoid group are untenable. We resolve the picture for Taimyr by placing late Quaternary horses from this region within *E. caballus*, *sensu lato*. Rusanov (1968) preferred to recognize a different species or subspecies (*lenensis*) for north Asian horses, but we do not make this distinction. Taimyr horses were quite small, and possible connections with extant Central Asian Przewalski’s horse (*E. c. przewalskii*) as well as so-called *E. lambei* from Alaska have been noted by Forstén (1988).

Muskox

Current record and new results. Compared to other parts of the Asian high Arctic (cf. Guthrie, 1990; Stuart, 1991), eastern Taimyr has yielded late Quaternary muskox remains in great abundance. However, little effort has been devoted to developing a good regional chronometric picture for *Ovibos*. Eighteen

Table 4. Calibrations of published ^{14}C assays (N=50) for four megafaunal species from late Quaternary of Taimyr Peninsula and Severnaya Zemlya (Russian Federation)

Lab Code ¹	Sample	Provenance	Age (^{14}C yr BP not $\delta^{13}\text{C}$ corrected)	Cal yr BP intercept	Cal yr BP age range (2 s range, Method B) ^{2, 3}	Source ⁴
<i>Mammuthus primigenius</i>						
GIN-1828	Tusk	Lower Taimyra R	9670 ± 60	11,150	11,200–11,040 @ 50% 10,960–10,760 @ 46%	(3)
GIN-8256	Tusk	NE coast of Taimyr P (Berge Pronchishcheva)	9780 ± 40	11,200	11,230–11,160 @ 100%	(2)
GIN-1495	Molar	Lower Taimyra R	9860 ± 50	11,230	11,300–11,170 @ 90% 11,340–11,320 @ 6%	(3)
GrA-17350	Mandible	Bikada R	9920 ± 60	11,260	11,560–11,460 @ 20% 11,440–11,190 @ 80%	(9)
GIN-10508	Tusk	N'yen'gatiatari R	10,070 ± 60	11,780	12,150–11,540 @ 83% 11,510–11,400 @ 9%	(1)
GIN-1489	Molar	Engel'gardt L	10,100 ± 100	11,670	12,130–11,260 @ 98%	(3)
GIN-11138a	Molar	Kupchiktakh L	10,200 ± 40	12,030	12,380–11,690 @ 96%	(1)
Beta-148640	Tusk	Gol'tsovaya R	10,240 ± 40	12,020	12,380–11,690 @ 97%	(1)
GIN-10507	Tibia	Nyun'karakutari R	10,270 ± 120	12,230	12,820–11,690 @ 99%	(1)
GIN-1828k	Radius	Lower Taimyr R	10,300 ± 100	12,210	12,670–11,630 @ 97%	(3)
GIN-3768	Limb bone	Nganasanskaya R	10,680 ± 70	12,830	12,980–12,600 @ 81% 12,500–12,340 @ 19%	(3)
GIN-10552	Molar	Krasnaya R	10,790 ± 100	12,890	13,130–12,620 @ 96%	(1)
GIN-3067	Molar	Baikura Neru B (Taimyr L)	11,140 ± 180	13,140	13,480–12,830 @ 95% 13,770–13,690 @ 3%	(3)
T-297	Soft tissues	Mamontovaya R	11,450 ± 250	13,440	14,090–12,880 @ 100%	(3)
LU-610	Tusk	Severnaya Zemlya Is (Oktyabr'skoy Revolyutsii Is)	11,500 ± 60	13,460	13,540–13,170 @ 74% 13,810–13,630 @ 26%	(3)
Beta-148663	Ulna	Arilakh L	11,900 ± 40	13,940	14,120–13,790 @ 87% 13,780–13,640 @ 10%	(1)
GIN-10506	Bone	Bikada R	12,050 ± 150	14,080	12,420–11,620 @ 73% 15,320–14,640 @ 27%	(1)
GIN-1783 ⁵	Limb bone	Baskura P (Taimyr L)	12,100 ± 80	14,100	14,360–13,820 @ 67% 15,640–15,320 @ 32%	(2)
GIN-2943r	Bone	Severnaya R	12,260 ± 120	14,260	15,430–14,530 @ 50% 14,460–14,040 @ 46%	(3)
GIN-3242	Bone	Severnaya R	12,450 ± 120	14,720	15,460–14,130 @ 100%	(3)
GIN-2677	Limb bone	Bikada R	12,780 ± 80	15,420	15,790–14,370 @ 100%	(3)
LU-3827	Tusk	Sablera C	13,200 ± 130	15,870	16,450–14,880 @ 100%	(7)
GIN-2758a	Bone	Bol'shaya Balakhnya R	13,340 ± 240	16,030	16,790–14,900 @ 100%	(2)
Beta-148636	Femur	Sopochnaya settlement	13,530 ± 40	16,290	16,770–15,820 @ 100%	(1)
Beta-148642	Femur	Sabler C	15,330 ± 50	18,390	18,970–17,850 @ 100%	(1)
GIN-3130	Bone	Bederbo-Tarida R	16,330 ± 100	19,470	20,130–18,870 @ 100%	(2)
Beta-148646	Molar	Bol'shaya Balakhnya R	18,140 ± 60	21,610	22,300–20,960 @ 100%	(1)
LU-654b	Tusk	Severnaya Zemlya Is (Oktyabr'skoy Revolyutsii Is)	19,270 ± 130	22,850	23,640–22,110 @ 100%	(3)
LU-688	Tusk	Severnaya Zemlya Is (Oktyabr'skoy Revolyutsii Is)	19,970 ± 110	23,660	[24,400]–22,920 @ 100%	(3)
UtC-8137, 8138, 8139	Bone	Bol'shaya Balakhnya R	20,200 ± 80 ⁶	23,920	[24,610]–23,170 @ 100%	(5)
<i>Ovibos moschatus</i>						
GIN-3803	Bone	Logata R	2700 ± 70	2780	3000–2710 @ 97%	(2)
GIN-25529	Skull	Pronchishchev B	2900 ± 60	3040	3260–2850 @ 100%	(1)
GIN-2945	Skull	Chelyuskin C	2920 ± 50	3080	3260–2920 @ 95% 2910–2870 @ 4%	(2)
— — — — ⁷	Skull	Chelyuskin C	3800 ± 200	4190	4650–3690 @ 96%	(8)
GIN-3131	Skull	Bol'shaya Balakhnya R	12,150 ± 40	14,120	15,360–14,620 @ 38% 14,370–14,040 @ 52%	(2)
Beta-148653	Skull	Sabler C	15,710 ± 50	18,850	19,450–18,290 @ 100%	(1)
GIN-3239	Skull	Agapa R	16,080 ± 100	19,180	19,820–19,580 @ 100%	(2)
GIN-1815	Skull	Lower Taimyra R	17,800 ± 300	21,160	22,110–20,250 @ 100%	(2)
GIN-3140v	Skull	Sabler C	17,800 ± 160	21,160	21,910–20,430 @ 100%	(2)
Beta-148628	Horn	Sabler C	18,310 ± 70	21,820	22,510–21,150 @ 100%	(1)
Beta-148627	Atlas	Sabler C	19,230 ± 80	22,900	23,650–22,190 @ 100%	(1)
Beta-148654	Skull	Bol'shaya Balakhnya R	19,640 ± 70	23,360	[24,120]–22,650 @ 100%	(1)

Table 4. Continued

Lab Code ¹	Sample	Provenance	Age (¹⁴ C yr BP not δ^{13} C corrected)	Cal yr BP intercept	Cal yr BP age range (2 s range, Method B) ^{2, 3}	Source ⁴
<i>Equus caballus</i>						
GIN-2744	Bone	Bol'shaya Balakhnya R	2150 $\pm$ 200	2140	2710–1710 @ 100%	(2)
GIN-3243 ⁸	Skull	Agapa R	3250 $\pm$ 60	3470	3640–3340 @ 99%	(2)
GIN-10509	Maxilla	Nyun'karakutari R	9010 $\pm$ 140	10,200	10,500–9680 @ 100%	(1)
GIN-3823a	Bone	Logata R	14,100 $\pm$ 160	16,910	17,510–16,330 @ 100%	(2)
Beta-148659	Radius-ulna	Taimyr L	17,950 $\pm$ 60	21,310	21,980–20,650 @ 100%	(1)
GrA-17351	Skull	Arilakh L	18,090 $\pm$ 80	21,500	22,190–20,850 @ 100%	(1)
GIN-3140b	Bone	Bol'shaya Balkhnya R	18,300 $\pm$ 200	21,740	22,550–20,970 @ 100%	(2)
<i>Bison priscus</i>						
Beta-148623	Horn sheath	Popigay R	8810 $\pm$ 40	10,040	10,160–9710 @ 100%	(1)

¹Reporting laboratory acronyms: Beta, Beta Analytic, Inc. (Florida, U.S.A.); GIN, Geological Institute, Russian Academy of Sciences (Russia); LU, Geographical Research Institute, St Petersburg State University (Russia); GrA, Groningen AMS, Center for Isotope Research (Netherlands); T, Trondheim, Radiological Dating Laboratory (Norway); UtC, Utrecht van de Graff Laboratorium (Netherlands).

²Method B in CALIB v4.3 package (Stuiver *et al.*, 1998) was used for all calibration computations, using assumptions of atmospheric ¹⁴C model; all results rounded to nearest 10 yr Cal BP for each Beta Analytic date was computed from the measured ¹⁴C date using lab-supplied δ^{13} C value. Multiple intercepts have been averaged. Calibration for each GrA and UtC date was calculated directly from lab-supplied date (δ^{13} C corrected). All other dates listed under “Age (¹⁴C yr BP)” in this table are *uncorrected* measured ¹⁴C dates, and therefore differ slightly from listings in Table 1. To convert to cal yr BP, δ^{13} C = –25.0 was assumed unless real value known.

³Probability estimate of true date being within a certain cal yr range, as provided by CALIB v4.3. Estimates of <3% not reported. Dates in square brackets are linear extensions beyond INTCAL98 calibration curve's current terminus (c. 20,265 BP).

⁴Sources: (1) this paper; (2) Sulerzhitsky, 1995; Sulerzhitsky & Romanenko, 1997, 1999; (3) Vasil'chuk *et al.* (1997); (4) Stuart (1991); (5) University of Utrecht/Mammuthus project; (6) Vereshchagin & Tikhonov (1999); (7) Möller *et al.* (1999); (8) Vereshchagin & Baryshnikov (1984); (9) Reumer & Mol (2001).

⁵Stuart (1991) lists Cape Sabler as locality for this specimen.

⁶Weighted average of 3 dates; see Table 3.

⁷Assay number not available.

⁸Incorrectly listed as muskox by Stuart (1991, Table 11, p. 508) (Sulerzhitsky, in litt. 03/04/01).

new dates for muskox are reported in Tables 1 and 2 (including one replicate), and they cover a lengthy interval—42,590 $\pm$ 1240 to 2900 $\pm$ 60 yr BP. Partial or complete muskox skeletons are probably commonly encountered, although rarely collected as such. In any case, the partial skeleton from the Popigay valley (Table 3) is the only one on record with a ¹⁴C date.

Evaluation. The late Pleistocene range of *Ovibos*, at its maximum, extended from North America through northern Asia to western Europe (Kurtén & Anderson, 1984). Eurasian and New World muskoxen are usually considered to constitute one widely distributed species, although one of us (A.T.) prefers to distinguish the Eurasian population at the subspecies level (*O. moschatus pallantis*; see Tikhonov, 1998).

It was previously believed that muskoxen were extirpated in Eurasia around the end of the Pleistocene, and that populations of *O. moschatus* survived in the New World only (cf. Martin & Guilday, 1967). However, it is now clear that the story must be more complex, because there is ample evidence for muskox presence in Taimyr (and, less persuasively, in southern Siberia) during the late Holocene. The first indication of this

was Vereshchagin's (1971; see also Vereshchagin & Baryshnikov, 1984) report of dates of 3800 $\pm$ 200 and 2900 $\pm$ 95 yr BP for two skulls that had been surface-collected on Cape Chelyuskin in 1948. These results were later confirmed by Harington (1970). Recently, another young date—at 2700 $\pm$ 70 yr BP (GIN-3803; Sulerzhitsky & Romanenko, 1997), the youngest so far—was reported for a muskox specimen from the middle channel of the Logata, a tributary of the Upper Taimyra. GIN 255290 (Table 2), based on a CME specimen from Pronchishchev Bay, is statistically indistinguishable from this result. Exclusive of the Taimyr record, the latest date for *Ovibos* in Eurasia is 10,750 $\pm$ 50 yr BP (LU-1666), for a specimen from Kotel'nyy I., New Siberian Islands (Sulerzhitsky & Romanenko, 1997).

Interestingly, Vereshchagin (1971) noted the presence of perfectly circular holes (including an alleged bullet hole) in one of the Chelyuskin skulls. He speculated that the muskox may even have been known to the first Russian trappers and explorers who penetrated the Taimyr region in the early 1600s (Belov, 1956). There is, however, no reliable evidence to this effect. (But see Spassov, 1991 and Lent, 1996, on intriguing but ambiguous archeological evidence

of muskox survival at the beginning of the first millennium AD.) At present, it is possible only to say that the cause of the final disappearance of muskoxen in Asia is not known, and that there is a substantial gap between the last Pleistocene records for Asian *O. moschatus* and the much later records for Taimyr (see Discussion).

Bison priscus

Current record and new results. In contrast to penecontemporaneous Alaskan sites (cf. Kurtén & Anderson, 1984; Guthrie, 1990), fossils of steppe bison are not common in Taimyr. Thus any new data on the temporal distribution of *Bison priscus* in this part of northern Asia are welcome. The three dates reported here are distributed over a lengthy interval (Table 1). The earlier two, $39,760 \pm 870$ and $45,320 \pm 1740$ yr BP, are the oldest finite dates that have been reported for Taimyr bison. The third date, 8860 ± 40 yr BP, which is based on a partial horn sheath, is currently the latest published record for *B. priscus* anywhere in continental Eurasia. It is also substantially younger than the eight other published dates for Taimyr bison, all of which are $>27,000$ yr BP.

Although the sheath is well preserved it is quite incomplete, measuring only 40 cm along its centreline parallel to the arc of curvature. This value suggests an animal of moderate rather than large size.

Evaluation. Our new evidence establishes that *B. priscus* still existed in the Khatanga catchment at the beginning of the Holocene. This also appears to be true for southern Siberia (e.g., 8960 ± 60 yr BP (GIN-96) for bison from the archaeological site of Ust' Belaya, Angara basin (Ermolova, 1978; Tikonov, 1999)). Slightly older dates have been recorded for bison specimens from the Lower Kolyma, Indigirka, upper Yenisei, and Selenga drainages (see Stuart, 1991; Tikonov, 1999). The youngest European fossils assigned to *B. priscus*, from southern France, are associated with dates of 11–12,000 yr BP (Stuart, 1991, 1999).

It should be noted that the taxonomic status of the steppe bison is somewhat ambiguous. *Bison priscus* is the usual default taxon used to attribute isolated or incomplete bovin fossils from late Quaternary contexts in north-central Siberia. This species is usually regarded as being distinct from *Bison bison* (the American bison) and *Bison bonasus* (the living European wisent), although all three are very closely related (Guthrie, 1990; Stuart, 1991). Certainly, distinguishing among late Quaternary *Bison priscus*, *B. schoetensacki*, *B. latifrons*, and *B. bison* exclusively on the basis of horn core morphology seems a suspect enterprise. Adding further doubt to the utility of maintaining such an array of names is the assertion that *B. priscus* may have been able to interbreed (!) with these other, allegedly distinct species (cf. Kurtén & Anderson, 1980). Finally, some authors believe that

B. priscus survived as such into very recent times (Vereshchagin & Baryshnikov, 1984), in which case it cannot be considered to be a “prehistoric” extinction. However, in our view the evidentiary grounds for this belief are slim.

Rangifer tarandus

Current record and new results. In the past, reindeer fossils were rarely considered worth dating. Indeed, we were able to find only nine published dates on *Rangifer* material for the entire Asian Arctic periphery, and only one of these concerns a specimen from Taimyr (5090 ± 80 yr BP, GIN-3132; specimen from Bol'shaya Balakhnya basin). Although only three new dates are offered here, they are sufficient to confirm that *R. tarandus* was present in Taimyr at least as early as 36,000 yr BP.

Evaluation. Our single early Holocene record (8710 ± 60 yr BP, weighted average) falls within a crucial period just after the Pleistocene/Holocene transition (see Discussion). Reindeer remains are exceedingly common in Taimyr, and it would not be difficult to fill out the chronometric record for *R. tarandus* if that were considered to be a priority.

Other Taxa

Current record and new results. Species that are extant but rarely encountered in paleontological contexts in northern Asia still merit dating because radiometric information may help with assessing their previous synchronic ranges and other patterns of interest. We report here on AMS dates for moose (*Alces alces*) and wolf (*Canis lupus*) (Table 1).

The date on the Sopochnaya moose frontal, 4050 ± 40 yr BP, is by far the youngest of the very few dates reported for Taimyr *Alces*. The canid specimen was of interest because its comparatively small size and characters of the cheekteeth and skull raised the possibility that it might be a domesticated or semi-domesticated animal. We believe that its replicate dates— $16,310 \pm 50$ and $16,670 \pm 70$ yr BP—render this argument improbable, and we therefore allocate the specimen to *Canis lupus* per se. Although the dating is regarded as reliable, it should be noted that the two age estimates for the wolf skull do not overlap at 2σ .

Evaluation. The radiometric record for moose in Late Pleistocene Asia is sufficient to indicate that it once ranged over a substantial portion of northern Siberia (Kahlke, 1999), presumably during favourable periods when the tree line was situated to the north of its present position. Nevertheless, it is unsurprising that *Alces*, a browser, is rarely encountered palaeontologically in the high Arctic. The presence of moose in Taimyr during the Karginsk interstadial is supported by three dates listed in the Sulerzhitzky & Romanenko

(1997) compendium, all of which are in excess of 30,000 yr BP. A fourth date reported here (47,900 ± 1000/–9000 yr BP, GrA-17346) may also be regarded as supportive of interstadial presence of moose.

No other extinct megafaunal species have been recorded for Taimyr, even though several taxa (e.g., *Saiga tatarica*, *Panthera leo*) are known to have occurred elsewhere in Siberia at roughly similar latitudes. The absence of a record for woolly rhino is unsurprising, given the rarity of this species at all times and places (Kahlke, 1999). Examination of several alleged rhino specimens found by or reported to the CME team in the course of the 2000 expedition failed to reveal any definite cases. A *Coelodonta* skull from the Gydan Peninsula, just to the west of Taimyr, is on display in the museum in Dudinka. However, it has not been described or dated (D. Mol, pers. obs.). Presumably it is just a matter of time—and prospecting—until the presence of *Coelodonta* in Taimyr is confirmed.

A small number of micromammal remains (all extant species), mostly attributable to the collared lemming (*Dicrostonyx torquatus*), Arctic hare (*Lepus arcticus*), and polar fox (*Alopex lagopus*), were collected during 2000 but have not been dated.

Discussion

Distribution of dates in correlation with latitude

Sulerzhitsky & Romanenko (1999) noted that “last” occurrence dates for woolly mammoths are younger in the northern part of Taimyr than in the south, implying that the species managed to persist longer at higher latitudes. The new dates reported here may be said to support this observation, with the proviso that within-interval ranges are substantial (Figure 4; see also Table 4). Of some interest is the fact that virtually all Taimyr mammoth remains having dates younger than 12–13,000 yr BP come from localities north of the 74° parallel.

There is a complementary interbasinal difference in date distributions within the Pleistocene that may also be instructive (cf. relevance of basinal analysis in Agenbroad, 1984). To investigate this difference we compared date pools for the Khatanga and Taimyra basins, using megafaunal dates older than 10,000 yr BP (for sources, see Table 4 and compendia noted therein). Of 163 dates compiled for this purpose, the Khatanga basin is represented by 93 entries (range: 11,200–53,170 yr BP) and the Taimyra basin by 70 (range: 10,070–46,100 yr BP). Although ranges are very similar, means and distributions are not. The mean for the Khatanga sample, 33,460 yr BP, is considerably older than that for the Taimyra sample, which is only 24,260 yr BP. The Mann-Whitney *U* statistic indicates that the two distributions are significantly different ($U=1745.0$; $P<0.0001$). Persistence in the north is also suggested by the tallies in Table 5, which presents a

Figure 4. Box plots, dated specimens of *Mammuthus primigenius* ($N=109$) from Taimyr Peninsula and northern Siberian lowlands north of 70°N (various sources). Specimens grouped according to provenances within intervals of approximately 1° width (e.g., all provenances situated between 74°0′–74°59′ are placed within the 74° bracket). Some intervals combined because of paucity of specimens. Latitudinal position had to be inferred in cases in which provenances were vaguely stated in the original reports. For each 1° interval, box plot summarizes mean (vertical line), 50th percentile limits (grey box), 90th percentile limits (nail lines outside box), and positions of outliers (half-filled circles). Distribution of dates given by histogram (upper right); accuracy of older age estimates (before 30,000 yr BP) should be regarded as doubtful (see text).

As noted by Sulerzhitsky & Romanenko (1999), there is an empirical trend toward younger mean dates per interval as one moves northward in Taimyr, although within-interval ranges are substantial.

slightly different combination of mammoth dates by basin (or island).

On closer inspection, however, it is evident that the mammoth dates control the statistical location of the two distributions. If mammoths and poorly sampled taxa (moose, reindeer, wolf) are removed, within-Pleistocene dates for the remaining megafauna ($N=52$) appear to have very similar distributions and the Mann-Whitney statistic is not significant ($P=0.1288$). Although this test does not explain what happened to mammoth populations in these areas, one possibility is that mammoths became rarer in the southern (Khatangan) part of the Taimyr Peninsula after 20,000 yr BP, but remained more numerous in the northern (Taimyran) part until the time of extinction or “last” occurrence. Perhaps this was because large influxes of meltwater left large parts of the northern Siberian lowlands waterlogged (or perhaps even underwater) for a long period after the end of glaciation.

Radiocarbon dating and timing of extinctions

Radiocarbon dates are routinely used to fix times of extinction during the late Quaternary (e.g., MacPhee *et al.*, 1999; Gonzalez *et al.*, 2000). The governing principle is that, given a sufficiently dense dating record for a now-extinct species, “last” occurrence dates can be meaningfully used to define the interval in which disappearance probably took place (cf. McFarlane, 1999). However, sampling intensity is only the first of

Table 5. *Mammuthus primigenius*, 115 radiocarbon ages for specimens from Taimyr Peninsula and Severnaya Zemlya (Russian Federation)¹

Ages (¹⁴ C yr B.P.) by Region ^{2,3}	Khatanga Basin	Pyasina Basin	Taimyra Basin	Severnaya Zemlya & NE Coast	Statistics for Total Sample
<i>N</i>	61	3	46	5	115
Mean (of <i>N</i> dates)	34,980	26,030	22,860	17,110	29,120
S.D.	10,530	6150	11,450	6340	12,370
Minimum	10,200	20,400	9670	9780	9670
Maximum	53,170	32,600	46,100	25,030	53,170

¹For dating sources, see Table 4.

²Dates rounded to nearest 10 yr.

³Replicate dates on same specimen or individual are averaged (see Table 3).

several issues that must be considered in using radiocarbon dates for this purpose. For example, one important concern is that, from an epistemological standpoint, any given “last” occurrence date is merely a provisional and *minimum* estimate of the true extinction date (MacPhee & Flemming, 2001). Except in the most contrived hypothetical cases, extinction dates can only be presented in the form of probability statements (Signor & Lipps, 1982).

Another concern of special relevance to late Quaternary paleontology and archeology is the problem of “dating plateaus” (e.g., Long *et al.*, 1998; Fiedel, 1999). If, as once believed, the amount of ¹⁴C formed in the upper atmosphere had been effectively constant over time, one radiocarbon year would be approximately equal to one absolute (calendar) year (Geyh & Schleicher, 1991). As much empirical evidence shows, there is no equivalence of this sort across any substantial time period, largely because of considerable flux in the amount of cosmogenic ¹⁴C entering the carbon reservoir (van der Plicht, 2000; Beck *et al.*, 2001). For present purposes the chief complication is that a given radiocarbon age estimate (i.e., mean age ± 1 or 2σ), when graphed against a standardized calibration curve like INTCAL98, may intersect the curve at several points. If that happens, the resulting calibrated range will consist of several apparently equipotential solutions, their number and width depending on the shape of the calibration curve at the point(s) of intersection. In practical terms, this is equivalent to increasing the size of the error term, often to the extent that meaningful interpretation of times series becomes impossible. Thus in the case of the late Quaternary extinctions in the New World (Beck, 1996), most “last” occurrence dates for now-extinct megafauna fall within the upper part of the “Younger Dryas plateau” (hereafter, YD plateau), which is formally defined as persisting from 10,800 to 9800 yr BP (12,500 to 10,000 cal yr BP) when $\Delta^{14}\text{C}$ fell by 80‰ (Kitagawa & van der Plicht, 1998). Any radiocarbon date that falls within the YD plateau will be consistent with a wide span of calendar years (Fiedel, 1999). Thus in the case of North American losses, all that can be reasonably said at present is that the majority of megafaunal extinctions took place

sometime around 13,500–12,500 cal yr BP, but within an additional envelope of uncertainty that is not less than ± 1000 cal yr wide. This is an unhelpful conclusion, as certain explanations of the extinctions depend upon rapid scheduling and close timing in the loss of different species (MacPhee & Marx, 1997; Martin & Steadman, 1999).

Interestingly, the situation in northern Eurasia may be somewhat more promising, depending on when or whether the various species of interest actually became extinct. In contrast to the North American case, a number of reported “last” occurrence dates for mainland Asian megafauna lie within the terminal part of, or just after, the YD plateau. These dates fall within the earliest part of the Holocene, a period that was less affected by abrupt shifts in the value of $\Delta^{14}\text{C}$. In principle, this may help to constrain more narrowly the interval in which the extinctions took place. In Table 4, for example, dates lying between *c.* 9800 and 8800 yr BP have corresponding cal yr BP ranges that are from 25% to 90% smaller (in total span) than those of dates between *c.* 10,250 and 11,250 yr BP with roughly similar sigmas (cf. B-148623 and GIN-8256 vs. B-148640 and GIN-3768). Although these examples are merely illustrative, they raise the hope that some late Quaternary extinctions will not be as difficult to constrain as others.

The significance of “gaps”

In the present sample, six (11%) of the 55 non-replicate AMS dates are older than 40,000 yr BP. The corresponding figure for a pool of 112 previously-reported dates is 22 (20%) (Figure 2(a)–(c)). Such high proportions of “old” dates are not unusual for surface-collected samples from the high Arctic periphery (Sulerzhitsky & Romanenko, 1999). Because bone collagen lasts remarkably well in this region, beautifully preserved specimens frequently register little or no measurable radiocarbon activity, indicating that their true age lies beyond the analytical range of current techniques. Also, the relatively high frequency of radioactively dead (or nearly dead) specimens indicates that contamination of bone collagen by “young” radiocarbon sources, such as humic acids, either

does not occur or is inconsequential (Sulerzhitsky & Romanenko, 1999).

Nevertheless, one cannot be uniformly confident of the meaning of dates from different parts of the radiocarbon range. Radiocarbon dates that are within the range of tree-ring calibration (<11,860 cal yr BP) have a potentially precise solution in cal yr, even if, as discussed above, systematic errors may affect overall accuracy. However, dates that are considerably older than 30,000 yr BP are subject to greater uncertainties. These considerations make a difference to the evaluation of certain features of the Taimyr record, especially with regard to the interpretation of apparent “gaps”.

Gaps are detected empirically: in a good record, they are anomalous intervals for which there are few or no dates. However, their inductive significance increases if (a) the gaps are lengthy, and (b) they occur at the same time in the chronometric records of other regions in which the target species existed, and (c) other plausible reasons for the gaps can be eliminated. This last criterion is always critical, as the following discussion shows.

(a) *36,000–33,000 yr BP gap.* This apparent anomaly, obvious in the combined date pool (Figure 2(c)), has two aspects: (a) near absence of dates falling within the range 36,000–33,000 yr BP, and (b) excess of observations on either side of this period. Only three mean dates in the 188-date database fall within this interval, yielding an incidence of ~ 1 mean date/thousand years for this period. By contrast, the overall incidence for the combined sample is 3.7 mean dates/thousand years (range, *c.* 53,000–2000 yr BP). By itself this difference is of little interest, and the gap effectively disappears if 2σ error bars are taken into account. However, there is the second feature to consider, i.e., the relatively large number of dates falling on either side of the gap: 24 between 33,000–30,000 yr BP and another 22 between 39,000–36,000 yr BP, or twice the average number expected per thousand years. If there were isometry between radiometric and calendrical measures of time, then under conditions of random sampling the gap could be interpreted as a period of real megafaunal absence, sandwiched between periods of greater-than-normal population density. However, the calibration presented by Beck *et al.* (2001) indicates that the apparent anomaly under discussion here falls completely within the period of greatest $\Delta^{14}\text{C}$ fluctuation, *c.* 44,000–40,000 cal yr BP, raising the possibility that the rarefaction is an artifact. Indeed, as graphed by Beck *et al.* (2001), see-sawing in the $\Delta^{14}\text{C}$ trend during this period results in a true chronometric inversion, which throws doubt on the actual value of any date from this period. Possibly, rapid shifts in $\Delta^{14}\text{C}$ values are the root cause of both the rarefaction of variates seen in the mid-part of the range as well as the concentrations at the ends, although we have not modelled this point.

Significantly, this rarefaction/concentration is not detectable interregionally. In a collation of 143 published dates for mammoth fossils from Yamal, Yakutia, and the northeastern part of the Far East (data not shown), we found no clear evidence of a hiatus between 35,000–33,000 yr BP, nor any unusual concentration of dates in the intervals immediately before and after. Nor is rarefaction seen in a similar dataset assembled by Sulerzhitsky & Romanenko (1997, 1999). Kuznetsova *et al.* (2001) report a significant gap in the record (mammoths only) for the New Siberian Islands, but the gap is much longer (44,000–36,000 yr BP) than the one seen in the Taimyr data or elsewhere in the Arctic periphery. While factors local to Taimyr (or, for that matter, the New Siberian Islands) cannot be completely discounted as a cause for the gap, at present there is no reason to regard it as more than a sampling error or possibly a bias produced by rapid $\Delta^{14}\text{C}$.

There are additional apparent gaps in the earliest part of the record, >45,000 yr BP, but we see no reason to consider them in view of the serious doubts attending the reality of the gap at 36,000–33,000 yr BP.

(b) *21,000–19,500 cal yr BP gap.* The second apparent gap is best seen in Figure 5, which plots the calibrated intercepts of 50 dates less than *c.* 20,000 yr BP presented in Table 4. When the extremes of the 2σ ranges are considered, the gap closes noticeably, although the short interval between 19,750 and 20,250 cal yr BP remains patent. Kuznetsova *et al.* (2001) have found a similar gap in the mammoth record for the New Siberian Islands and the Bykovskiy Peninsula south-east of Lena Delta. The paucity of records may be due to environmental conditions at the time. During the LGM, Taimyr may have experienced extreme polar desert conditions (Siegert & Marsiat, 2001), perhaps including some amount of terrestrial-ice cover (but this is debated; cf. Grosswald, 1998; Möller *et al.*, 1999; Grosswald & Hughes, 1999). Other regions along the high Arctic coast are similar, in that there are few dates on fauna which correlate with the period that includes the LGM and its immediate aftermath. Indeed, it is pertinent to note that the entire period between 21,000 and 17,000 cal yr BP is underrepresented in our date compilations (cf. additional small gap in the interval 18,000–17,000 cal yr BP). It should be noted that the calibration curve for this part of the record is derived from paired/U-series dates on corals, and is subject to additional systematic errors that do not apply to the dendrochronological part of the curve (van der Plicht, 2000). Thus, although it is intriguing that Taimyr might have been less frequented by megafauna during the coldest part of the Sartan (=Late Weichselian), the radiocarbon evidence for this is far from conclusive.

(c) *8000–4000 yr BP gap.* This last gap is different from the others in that it appears in all relevant records (including ones outside Taimyr) and falls within the

Figure 5. Distribution of calibrated dates ($N=50$) for selected Taimyr megafauna lying within INTCAL98 (Stuiver *et al.*, 1998) calibration range (to 24,000 cal yr BP). Dates shown as intercepts only, to simplify graphic presentation. See Table 4 for additional information on dates, provenances, and calibrations. Only species or distinct populations that eventually became extinct within the high Arctic periphery are included (*Mammuthus primigenius*, *Bison priscus*, *Ovibos moschatus*, *Equus caballus*). Modern reintroductions not considered. Histogram shows distribution of intercepts grouped in intervals of 2000 years.

Two conspicuous rarefactions in megafaunal presence in Taimyr seem to be present (21,000–19,500 cal yr BP, and 10,000–4,000 cal yr BP). The earlier gap (apparently coeval with the LGM and its immediate aftermath) almost disappears when 2σ ranges of individual dates are considered (Table 4). Its significance is therefore ambiguous at this time, although it is important to note that few megafaunal dates from any part of the high Arctic periphery fall within or immediately after the LGM. The early Holocene gap is more robust and can be correlated with the late Quaternary megafaunal extinctions in Eurasia. See text and Figure 6.

part of the calibration curve controlled by the dendrochronological standard. It therefore is not likely to be a result of biased sampling, taphonomic effects, or heretofore undetected $\Delta^{14}\text{C}$ flux. However, due to the paucity of observations, the gap requires close inspection and interpretation. To increase resolution, multi-regional radiocarbon records were collated for seven megafaunal taxa for the period after 18,000 yr BP (Figure 6). This was necessary because the persistence times of taxa other than *Mammuthus* in specific areas cannot be adequately demonstrated empirically, due to limited sampling. For example, it is known that *Bison* existed in Taimyr around 40,000 yr BP, and a string of later dates confirm that this species was also there at $27,600 \pm 400$ yr BP (Sulerzhitsky & Romanenko, 1999). Thereafter, however, there is no later record for *Bison* in Taimyr until 8810 ± 60 yr BP (B-148623). It is possible but surely unlikely that *Bison* was absent from Taimyr for nearly 20,000 years. Rather, it appears that, by chance, remains of chronometrically more recent bison have not been selected for dating. This seems to be borne out by the limited dating records for northern Yakutia, which establish that *Bison* persisted in high-latitude Siberia until nearly the end of the Pleistocene (Stuart, 1991). Similar arguments apply to the other taxa considered: although regional records are individually very spotty, in combination they indicate that individual species were present along the high Arctic periphery for tens of thousands of years prior to the end of the Pleistocene. The gray boxes (screens) on each species' timeline represent currently undocumented portions of their separate histories (see Figure 6).

It is useful to discuss the Pleistocene/PHB and the later Holocene portions of these collated records separately. For mainland woolly mammoths, steppe bison, and horse, the within-Pleistocene radiocarbon record for northernmost Asia continues up to, or just beyond, the end of the epoch (*c.* 9600–8800 yr BP, corresponding to *c.* 11,000–10,000 cal yr BP, in round figures), although dating is dense only for *Mammuthus*. It is plausible that *Ovibos* and *Coelodonta* might have truly terminal Pleistocene records as well, but if so the relevant specimens have not yet been found and dated. At present, empirical records for muskox and woolly rhino in Asia end in the late 11th and early 15th millennia BP respectively. (Kahlke 1999 notes the existence of an unpublished date of *c.* 11,000 yr BP for a *Coelodonta* specimen from Jilin, China, but this date needs to be verified before being accepted.) The reindeer record is very poor, although there are three dates (each from a different region) that fall into the interval between the mid-10th millennium and the earliest part of the 8th millennium BP (*c.* 11,000–9500 cal yr BP). There are no latest Pleistocene dates for *Alces*. Nevertheless, on the whole one's perception is that all of the megafaunal species present in northernmost Asia at the beginning of the period covered by radiocarbon dating were still there at or very near the end of the Pleistocene.

Figure 6. Chronometric summary of dates for seven megafaunal taxa, high Arctic periphery of Asia, post-18,000 yr BP (dating from various sources; see Table 4). Number of independent dates per area varies greatly. For *Mammuthus primigenius*, the post-18,000 yr BP dating framework is truly dense only for the Taimyr Peninsula and Wrangel Island, and to a lesser degree for the Kolyma, Indigirka, and northern Yakutia region. For all other taxa and regions, the number of records is much smaller. Date representation is not exhaustive, although it is believed that all currently available “last occurrence” dates for listed taxa have been included. To simplify presentation, each symbol has a constant width (representing mean date $\pm 2\sigma$, where σ is normalized to 100 years). With specific regard to Taimyr, all taxa except *Coelodonta antiquitatis* are confirmably present early in the radiocarbon record (>30,000 yr BP).

The regional radiocarbon records of all Asian high Arctic megafauna show significant interruptions, most of which can be ascribed to low sampling effort. However, regional records also show that at least some populations of all megafaunal taxa managed to persist into the last two millennia or so of the Pleistocene. After this, areal records tend either to stop or to enter a lengthy hiatus, only to start again deep with the Holocene.

Grey boxes or screens on each species' time line represents undocumented portions of their histories (dashed if species is completely extinct, solid if still extant in at least part of its range). It should be noted that, although the position of the screens imply that *Mammuthus*, *Bison*, and *Coelodonta* disappeared quasi-simultaneously, as present there is no empirical evidence for this.

Species and populations generally thought to have become extinct close to the PHB: populations of *Mammuthus primigenius* living in areas other than Wrangel Island; *Bison priscus*; and *Coelodonta antiquitatis*. Species and populations that survived into the Holocene, as established by post-PHB records: Wrangel Island mammoths, *Ovibos moschatus*, *Equus caballus*, *Alces alces*, and *Rangifer tarandus*. There are no dating records for *Ovibos moschatus*, *Equus caballus*, or *Alces alces* for most or all of the first half of the Holocene. When late Holocene *O. moschatus* and *E. caballus* became locally extinct in northern Asia is not known, except that it must have occurred after c. 2000 yr BP but before 400 yr BP (time of first Russian penetration; Holland, 1994).

The later Holocene record is quite different: either megafaunal species do not appear at all, or reappear only after a lengthy hiatus. Previously, this point was usually considered of interest only in relation to the extinct megafauna, such as *Mammuthus primigenius*, *Coelodonta antiquitatis*, and *Bison priscus*, which do not, of course, reappear in mainland dating records

after the close of the Pleistocene or earliest Holocene. But total loss is obviously not the only pattern present. This is especially noteworthy in the case of *Ovibos moschatus* and *Equus caballus*. At least according to the existing record, their chronologies enter a hiatus near the PHB that lasts until c. 4000 yr BP, when they restart almost simultaneously. Although insufficient sampling

could be an explanation for the gap, these two species have been the subject of a significant amount of collecting and radiocarbon dating. If there is a sampling bias, it is unexpected that it would take essentially the same form in two quite different species.

In seeking to offer an explanation for the early Holocene gap in megafaunal records, it is useful to turn to the evidence for the best investigated species, *Mammuthus primigenius*. The empirical record for this species ends permanently *c.* 10,000 yr BP in all mainland areas in which mammoths are known to have survived into the end-Pleistocene. In view of the large number of radiocarbon dates for this species, this conclusion may be considered very highly corroborated. The one known regional exception is Wrangel Island, but even here the record is not continuous. As may be seen in Figure 6, mammoths persisted on Wrangel until about 12,000 yr BP; at this point the local record stops. Then, after a substantial hiatus, the chronology begins again *c.* 7700 yr BP and continues to *c.* 3700 yr BP (Vartanyan *et al.*, 1993; Sulerzhitsky & Romanenko, 1999). It needs to be emphasized that the end-Pleistocene gap in the Wrangel mammoth record is one of the best supported in late Quaternary paleontology, thanks to the large number of dates generated by different researchers in order to test the original claim of survival of *Mammuthus* into the Holocene (cf. Martin & Stuart, 1995). Collecting conditions on Wrangel precisely parallel those in Taimyr and are just as stochastic, because virtually all finds are made at surface and can be of any age (R. MacPhee, pers. obs.). Indeed, when looked at from within the Pleistocene, the Wrangel record is very much like that of the New Siberian Islands or Yakutia, with “last” occurrence dates hovering around 12,000 yr BP.

If woolly mammoths locally disappeared on Wrangel for a time, from what source population was the island recolonized? More generally, if the hiatus near the PHB affected mammoths, were the other megafauna affected similarly? If they were, then there is a clear implication: there was probably a common cause, because the probability of several long-established mammalian species disappearing within 1000 years of each other (or less) is otherwise highly improbable. How, then, can these diverse facts and inferences be harmonized?

Widespread megafaunal collapse at the Pleistocene-Holocene boundary?

One explanation, which should be testable through a program of intensive investigations, is that there was an event at the end of the Pleistocene or earliest Holocene that led to the virtual disappearance of large mammals throughout northern Asia. Here we are referring not only to megafaunal extinctions—which have long been notionally linked to the Pleistocene/Holocene transition—but also to extirpations, that is,

to major population crashes among those species that did not become extinct at this time. As to what this event might have entailed, we can offer no resolution here because we disagree among ourselves regarding its probable nature. Marked climate change in western North America during roughly the same timespan eventually induced dramatic faunal changes in that area, as Grayson (2000) has recently detailed. However, the northern Eurasian event could have exerted its main effect within a very short period—probably much less than the broad interval (9500–8000 yr BP) depicted in Figure 6, which is exclusively modelled on “last” occurrence data—and need not have been climatic in nature. (The bibliography provides references to a number of recent papers on the causation of late Quaternary extinctions, to which the reader is referred.)

Central to our hypothesis is the idea that catastrophe was followed by recovery—in some cases. We hypothesize that in one or more refugial areas, the location of which is currently unknown or cannot yet be identified as such, survivors managed to persist after most of their conspecifics died out. These provided the stock for later repopulation of abandoned ranges. The speed and success of recovery evidently varied. This would be consonant with modern experience with differential recovery responses in species and communities that have been affected by extreme population variability (Vucetich *et al.*, 2000; Jackson *et al.*, 2001). Among species known to have survived into the Holocene, mammoths appear to have made the most limited recovery, repopulating Wrangel Island only from some unknown (but presumably mainland) source. The woolly rhino, whose last records are exclusively Pleistocene, evidently did not recover at all. It may or may not be relevant that, alone among the species-level taxa discussed here, *Coelodonta* had no populations or sister species in the New World (and therefore no hope of recolonization from that source). The record for moose is too inconsiderable for comment.

Other species did better. If *Ovibos moschatus* and *Equus caballus* recovered earlier than *c.* 4000 yr BP in northern Asia, they must have done so in areas or during intervals for which there is as yet no radiocarbon coverage. Both were gone soon thereafter, at least from northern Siberia. Whether humans played any direct role in either their reintroduction or their demise is not known.

The extremely late date for *Bison priscus* (8860 ± 40 yr BP) noted in Table 1 is perched on the cusp of the assumed rarefaction event. The plausibility of *B. priscus* having died out later than usually thought is marginally increased by Stuart's (1991, 1999) observation that several “survivor” taxa made it through the end-Pleistocene only to suffer local extirpation or range contraction shortly thereafter (e.g., disappearance of *Equus caballus* from Britain and *Dama dama* from northern and central Europe). Yet another example is offered by the giant Irish deer, *Megaloceros giganteus*, recently shown to

have persisted on the Isle of Man and in Scotland until *c.* 9200 yr BP (Gonzalez *et al.*, 2000).

The one exception to the scenario of PHB faunal collapse may be *Rangifer tarandus*. There is a late record for this species on the Yamal Peninsula at 7990 $\pm$ 70 yr BP (GIN-293), followed by one for the Bol'shaya Balakhnya valley at 5090 $\pm$ 80 yr BP (GIN-3132; Sulerzhitsky & Romanenko, 1997). It may be that the supposed rarefaction event did not affect reindeer, although with so few dates available for this species no conclusion is possible at this time. However, there are other records for *Rangifer*, from Svalbard and Franz Josef Land, that have an indirect bearing on the problem. Van Der Knaap (1989) and Forman *et al.* (2000) have reported dates as old as 6400 cal yr BP on reindeer fecal pellets and shed antlers collected from these islands. Neither area has produced dates that relate to the first half of the Holocene. Seeking to explain this for the Franz Josef Land record, Forman *et al.* (2001) stated that only the best-preserved antlers were selected for dating purposes for their study, and that through happenstance older remains may not have been sampled. We suspect that one's ability to selectively control for age on the basis of preservation alone would be no better in Franz Josef Land than in Taimyr. It is quite plausible that reindeer were simply absent from these islands during the first half of the Holocene, although whether this happened in correlation with mainland events or independently cannot be evaluated at present.

Of additional interest is the fact that the reindeer dates from Franz Josef Land terminate *c.* 1300 cal yr BP, and there are no historical records (i.e., none since the archipelago's generally accepted date of discovery in 1873 (Holland, 1993)). In combination, these data seem to indicate that, not unexpectedly, reindeer were subject to "normal" population crashes/expansions/recolonizations, especially in the more marginal parts of their distributions. But there was always some place where they managed to survive and carry on. Thus the real paradox posed by reindeer and the other remaining high Arctic megafauna is not that they in particular were survivors, but that so few others were.

In conclusion, the possibility that the megafauna of northern Eurasia were affected by an event at or near the PHB, resulting in complete species-level losses in some instances and widespread populational collapses in others, adds an important nuance to the continuing debate concerning the nature and cause of Late Quaternary extinctions. This scenario may be tested by dating programs that not only search for "last" occurrences, but that also compare dating records of different taxa in different affected areas. For falsification purposes, a much larger megafaunal date pool than exists at present may show that populations of different species did not undergo coordinated disappearances across wide areas of northern Asia at or near the PHB, or that the record of presence/absence is too variable to admit any common cause. Although it might be argued

that there could be a geophysical explanation for the pattern of radiocarbon dates around the PHB, the only one proposed to date—radical change in the atmospheric concentration of carbon dioxide in the high Arctic (Sulerzhitsky, 1997)—lacks a plausible mechanism. Molecular evidence may also be marshalled to establish whether or not Holocene populations were genetically continuous with their Pleistocene precursors across the critical period. Clearly, much remains to be learned about the dynamics of megafaunal extinction and persistence in the far north.

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