17 March 1961, Volume 133, Number 3455 SCIENCE

Frozen Mammoths and Modern Geology

The death of the giants can be explained as a hazard of tundra life, without evoking catastrophic events.

William R. Farrand

Frozen woolly mammoths have perplexed both scientists and laymen during the several centuries since the first direct description of a frozen mammoth was recorded, in 1692. In the words of Digby (*1*), a well-known manmoth hunter, "the gods must have enjoyed many a hearty laugh over humanity's attempt to account for the remains of mammoths." One of the biggest obstacles to complete interpretation of the frozen mammoths was, and to a lesser degree is still, the lack of detailed knowledge of the distribution, geologic context, and age of the beasts. Tolmachoff (*2*) wrote a very complete summary of the information available in 1929, but no comprehensive paper has appeared since that time, although many more geological data are now at hand.

In contrast to scientific efforts, a number of popular and quasi-scientific articles (*3*, *4*) have appeared in recent years, in which fragmentary knowledge, folk tales, and science fiction are combined under the guise of verity—much to the chagrin of scientists and the confusion of the public. The most recent of such articles is that of Sanderson (*3*), who comes to the conclusion that the "frozen giants" must have become deep-frozen within only a few hours' time. Such a thesis, however, consistently disregards the actual observations of scientists and explorers (discussed below). Adding insult to injury, Sanderson proceeds to fashion a fantastic climatic catastrophe to explain his conclusions.

Information from diverse, mostly European, sources (*5*) is summarized in this article to bring the subject of frozen mammoths up to date and at the same time to supply to scientists in general the information with which to refute the current quasi-scientific theories. Although the general ecology and range of the woolly mammoths is included, this article centers on the frozen representatives of the species and the special problems they present. All other species of mammoths, such as the Columbian, Imperial, and Jefferson mammoths, are entirely excluded from this discussion.

The subject of extinction is not discussed here because it is not a problem peculiar to frozen mammoths but one that concerns other species of mammoths and many other large Pleistocene mammals as well. Let me say only that climate apparently did not play a direct role in the demise of the Siberian mammoths. Woolly mammoths were well adapted to extreme cold and to tundra vegetation—conditions which still characterize the area where frozen cadavers have been found. Furthermore, woolly mammoths lived in pre-Wisconsin and late-Wisconsin time, and this shows their ability to survive a glacial onslaught.

Description and Ecology

The taxonomic position of the woolly mammoth is rather well defined (*6*), although some controversy surrounds its generic name. *Elephas primigenius* Blumenbach 1799 has withstood many competitors throughout the years; it is found in much of the older literature and is still used in Europe. Currently, however, *Mammuthus primigenius* (Blumenbach) (*7*, p. 415; *8*) is used in North America and, accordingly, is used in this article, without any attempt to resolve the difference. However, histological examination of frozen mammoth bone from Alaska favors retention of the genus name *Elephas* (*9*).

Mammuthus primigenius (Blumenbach) was an imposing creature (Fig. 1), standing as tall as modern elephants but with slightly different proportions (*10*, p. 806; *11*, p. 129). The Siberian mammoths—2.8 meters tall at the shoulders—were somewhat smaller than the average European woolly mammoths (3.2 to 3.9 meters tall); modern Indian elephants are 2.7 to 3.2 meters tall, and African elephants average 3.4 meters. The woolly mammoth differed from modern elephants in the following important features: (i) the mammoth's head had a conspicuous topknot formed by large sinuses (*7*, Fig. 311) and possibly lumps of excess fat (it is well shown in prehistoric cave drawings in western Europe); (ii) the mammoth had only four skeletal toes as compared to pentadactylism in other elephants; (iii) its body was covered, or nearly covered, with long coarse hair and thick underfur; under its epidermis, which was identical with that of a modern elephant, was a layer of fat up to 9 centimeters thick; (iv) the mammoth's tusks were larger and more

The author is a research associate in Pleistocene geology at Lamont Geological Observatory, Palisades, N.Y., and a member of the geology department of Columbia University, New York.

curved than those of modern elephants, although not as curved as they are often depicted; Digby (*1*, p. 171) found in a collection of more than 1000 tusks that "not one tusk in ten forms a third of a circle, not one in twenty even a semi-circle"; and (iv) the slope of the back from shoulder to hip was greater in the mammoth than in modern elephants, and this was especially pronounced in the Siberian population.

The evolutionary development of Pleistocene elephants is rather well known; it is based mainly on dental characters (decrease in the size of dental plates and the thickness of enamel layers and increase in the height of teeth). The main line of mammoth development leads from *Mammuthus* (*Elephas*) *planifrons* and *M.* (*Elephas, Archidiskodon*) *meridionalis*, which were warm-latitude forest dwellers of early Pleistocene time, through *M.* (*Elephas, Archidiskodon*) *trogontherii*, a cool steppe dweller of the middle Pleistocene (Günz-Mindel interglacial into Riss glacial), into *M.* (*Elephas*) *primigenius*, a cold steppe and tundra dweller of later Pleistocene times [late Mindel(?) into late Würm] (*12*, pp. 457, 470; *13*).

The straight-tusked elephants (*Loxodonta*) were evolving during this same time in more southerly regions of Europe and Africa. Serological tests of the Berezovka mammoth (*10*, p. 794) and histological examination of Alaskan mammoth bone (*9*) indicate close relationship between the woolly mammoths and modern *Elephas* (Indian elephants). *Mammuthus* (*Elephas*) *primigenius* appears to have been a species adapted for extreme cold and tundra conditions, as shown by its smaller size and broad four-toed feet for marshy terrain and by a further decrease in the size of dental plates and the thickness of enamel layers. It seems, furthermore, to represent a dead-end evolutionary development.

The habitat of the woolly mammoth is indicated clearly by it physical appearance and food habits, as determined from the frozen carcasses and associated fossils. Long hair, thick wool, and a heavy layer of fat definitely indicate a cold climate. Stomach contents (*1, 2, 6, 14*) reveal an abundance of grasses, sedges, and other boreal meadow and tundra plants, along with a few twigs, cones, and pollen of high-boreal and tundra trees. In general, this floral assemblage is "richer . . . , somewhat warmer and probably also moister" than the present flora of the tundra in which frozen mammoth carcasses are now found (*14*). Quackenbush (*15*) found "large trees" associated with fossil mammoth in a now-treeless part of Alaska and also came to the conclusion that the climate was somewhat milder when the mammoths lived. The flora of deposits enclosing frozen mammoth carcasses is similar to that of the stomach contents (Table 1). Furthermore, the healthy and robust condition of the frozen cadavers (*2*, p. 49) indicates that the mammoths fared well on such a diet.

The fauna of which the woolly mammoth formed a part was composed mainly of boreal and arctic steppe- and tundra-dwelling animals, although a few problematical warmer-latitude types

Fig. 1. "Stuffed mammoth found in the permafrost zone." This is the Berezovka mammoth displayed in the Zoological Museum, Leningrad, in the position in which it was discovered. The skin of the face and trunk were missing. [Zoological Museum, Leningrad, courtesy of J. H. Zumberge]

appear in some European deposits. The more complex character of this fauna, as compared to the flora, is easily understood in terms of (i) the migratory nature of the large mammals involved (*16*) and (ii) the fact that most of the faunal assemblages were found in western Europe, which in glacial times was a transition area between glacial and tundra conditions on the one hand and steppe and boreal forest on the other. Soergel strongly emphasizes the effect of seasonal migrations on the faunal assemblages of central Europe, and he points out (*17*) that woolly mammoths occur only in glacial or transitional (glacial/interglacial) faunas and not in *high*-interglacial assemblages.

Distribution

Whereas *Mammuthus primigenius* was widely distributed throughout most of northern Eurasia and northern North America (*6, 10, 18*), *frozen* remains of woolly mammoths have been found only north of latitude 60°N (mostly north of the Arctic Circle) and distributed around the Arctic Ocean, from the Yenisei River in Siberia to the interior of Alaska (*2; 10; 15; 19; 20*, p. 259). Such a distribution shows the relative abundance of the woolly mammoth in certain parts of the high latitudes and coincides with the present-day extent of frozen ground. Even *bones* of the woolly mammoth are rare in Scandinavia, and they are lacking entirely in most of the Canadian archipelago. Other than two very fragmentary carcasses from Alaska, all of the frozen cadavers have come from northern Siberia (Fig. 2). There have been at least 39 discoveries of frozen mammoth remains, with some soft parts preserved, but only four of these were nearly complete: Adam's mammoth from the Lena delta (recovered in 1806), Herz's mammoth from the Berezovka River (1899), Stenbock-Fermor's mammoth from Great Lyakhov Island (1906), and Vollosovich's mammoth from the Sanga-Yurakh River (1907).

The woolly mammoth that has been most intensively studied is that from the Berezovka River. The woolly mammoth most recently discovered, also well studied although by no means a complete carcass, was unearthed on the Mamontova River in the Taimyr Peninsula in 1948 (*20*, p. 259; *21*). On the other hand, fossil tusks of woolly mammoth are very abundant and have been collected by ivory hunters for centuries. Digby (*1*, p. 169) describes a single cache of more than 1000 tusks which he examined in Yakutsk, and Flint (*12*, p. 470) mentions some 50,000 tusks from Siberia alone. The obvious conclusion is that the frozen mammoths were members of a populous race located in Siberia (and elsewhere) and not occasional strays who happened to migrate beyond their normal range. And, contrary to some popular accounts, the figures cited above do not support the conclusion (*3*, p. 82) that "absolutely countless numbers" of woolly mammoths were frozen and that "many of these animals were perfectly fresh, whole, and undamaged. . . ."

The types of deposits that enclose frozen remains of woolly mammoths help us to reconstruct their habitat, but unfortunately, complete descriptions are not available for some of the early discoveries. "Mammoth-bearing drift" is described by Tolmachoff (*2*, p. 51) as usually constituting the locally high portions of the tundra and lying above sediments of the "last Arctic transgression" [the "Boreal transgression" of

Table 1. Plants found in the stomach of the Berezovka mammoth (*2, 6, 14*) and in deposits enclosing the Mamontova mammoth (*21*).

Plant	Berezovka	Mamontova
Trees and shrubs		
Abies (*sibirica?*)	+	
Alnus hirsuta	+	
Betula alba	+	
B. nana	+	+
Betula sp.	+	
Cassiope tetragona		+
Larix (*sibirica?*)	+	
Picea (*obovata?*)	+	
Pinus pumila		+
P. sibirica	+	+
Salix polaris	+	+
Salix sp.	+	
Vaccinium vitis idaea	+	
Herbs, grasses, and mosses		
Caryophyllaceae		
Arenaria Minuartia cf. *arctica*		+
Cerastium sp.	+	
Dianthus sp.	+	
Melandrium sp.	+	
Sagina nivans		+
S. (*nodosa?*)	+	
Chenopodiaceae		
Atriplex (*patulum?*)	+	
Compositae		
Artemisia borealis		+
A. dracunculus	+	
A. sacrorum	+	
A. vulgaris	+	
Aster sp.	+	
Erigeron cf. *criocephalus*		+
Gnaphalium uliginosum	+	
Lactuca [*Mulgedium*] *sibiricum*	+	
Senecio cf. *resedifolius*		+
Tanacetum vulgare	+	
Sp. indeterminate	+	
Cruciferae		
Draba sp.		+
Sp. indeterminate	+	
Cyperaceae		
Carex glareosa	+	
C. hyperborea		+
C. incurva	+	
C. lagopina [*lachenalii?*]	+	
C. cf. *maximum*		+
Eriophorum angustifolium		+
Sp. indeterminate (*N*-2)	+	
Gentianaceae		
Gentiana sp.	+	
Gramineae		
Agropyron cristatum	+	
Agrostis borealis	+	
Alopecurus alpinus	+	
Beckmannia cruciformis	+	
Bromus sibiricus	+	
Herbs, grasses, and mosses (cont.)		
Gramineae (Cont.)		
Elymus sp.	+	
Hordeum jubatum	+	
H. violaceum	+	
Phragmites communis	+	
Puccinellia [*Atropis?*] *distans*	+	
Sp. indeterminate (*N*-8)	+	
Labiatae		
Thymus serpyllum	+	
Leguminosae		
Caragana jubata	+	
Oxytropis campestris	+	
O. sordida	+	
Sp. indeterminate		+
Papaveraceae		
Papaver alpinum	+	
P. lapponicum		+
P. cf. *radicatum*		+
Plantaginaceae		
Plantago media	+	
Polemoniaceae		
Polemonium cf. *boreale*		+
Polygonaceae		
Oxyria digyna?	+	
Polygonum cf. *viviparum*		+
Rumex acetosella	+	
Primulaceae		
Androsace sp.		+
Ranunculaceae		
Caltha palustris	+	
Ranunculus acris	+	
R. Gmelini		+
R. pygmaeus		+
Thalictrum sp.		+
Rosaceae		
Potentilla sp.	+	
Rosa sp.	+	
Sanguisorba officinalis	+	
Saxifragaceae		
Saxifraga cf. *hirculus*		+
Scrophulariaceae		
Pedicularis cf. *sudetica*		+
Umbelliferae		
Aegopodium podagraria?	+	
Angelica (*decurrens?*)	+	
Lycopodiaceae		
Sp. indeterminate		+
Polypodiaceae		
Dryopteris sp.		+
Sp. indeterminate (*N*-2)	+	
Bryophytes		
Aulacomnium turgidum	+	
Cladonia rangiferina	+	
Drepanocladus [*Hypnum*] *fluitans*	+	
Sphagnum sp.		+

current Russian (22) terminology]. Marine fossils have never been discovered in deposits containing frozen mammoths (2). The Mamontova specimen (20, p. 259) was found in floodplain deposits postdating the Boreal transgression, and Digby (1, p. 55) said that "practically all cold-storage mammoths and woolly rhinos are found on the sides of cliffs sloping down to rivers —a lake in one or two cases." The frozen mammoth found in a bluff facing Eschscholtz Bay, Alaska, was buried in floodplain deposits, which also included a beaver dam (15).

Geological Age

Much discussion has centered around the age of frozen mammoths, but several lines of evidence now point toward a solution of this question. To begin with broad categories, we know that woolly mammoths do not exist at the present and that they originated no earlier than the Mindel (second) and probably as late as the Riss (third) glacial stage; therefore, the species occurred in the last half of the Pleistocene epoch.

Flint (12) judged the fauna of the Alaskan frozen muck, which includes woolly mammoth, to be an interglacial fauna, on the basis of some warmer-latitude species which occur there and a series of infinite radiocarbon dates (the oldest being "greater than 30,000 years"). But some finite dates have also come from the Alasken muck: *Bison crassicornis* horn sheaths (M-38) were dated 16,000 ± 2000 years before the present (23), and skin and flesh of a baby elephant, possibly a woolly mammoth (L-601), were recently dated by the Lamont radiocarbon laboratory at 21,300 ± 1300 years (24). These dates show the complex nature of the muck (silt) deposits and point to the possibility that several, temporally separated faunas may be mixed together.

The area in northern Siberia in which frozen woolly mammoths are found can be subdivided with respect to the extent of Pleistocene glaciation, as defined by recent Russian work (22), and thereby can aid in dating some of the carcasses (Fig. 2). Almost all of northern Siberia north of the Arctic Circle and west of the Lena River was covered by glacier ice of the Last glaciation, the Zyryansky stage in Russian terminology (Fig. 3). East of the Lena only the uplands were glaciated, the arctic coastal plain in that area being left free of ice (25). In the latter area mammoth cadavers are found outside the area of glaciation, but they overlie marine sediments of the Boreal transgression. In the former

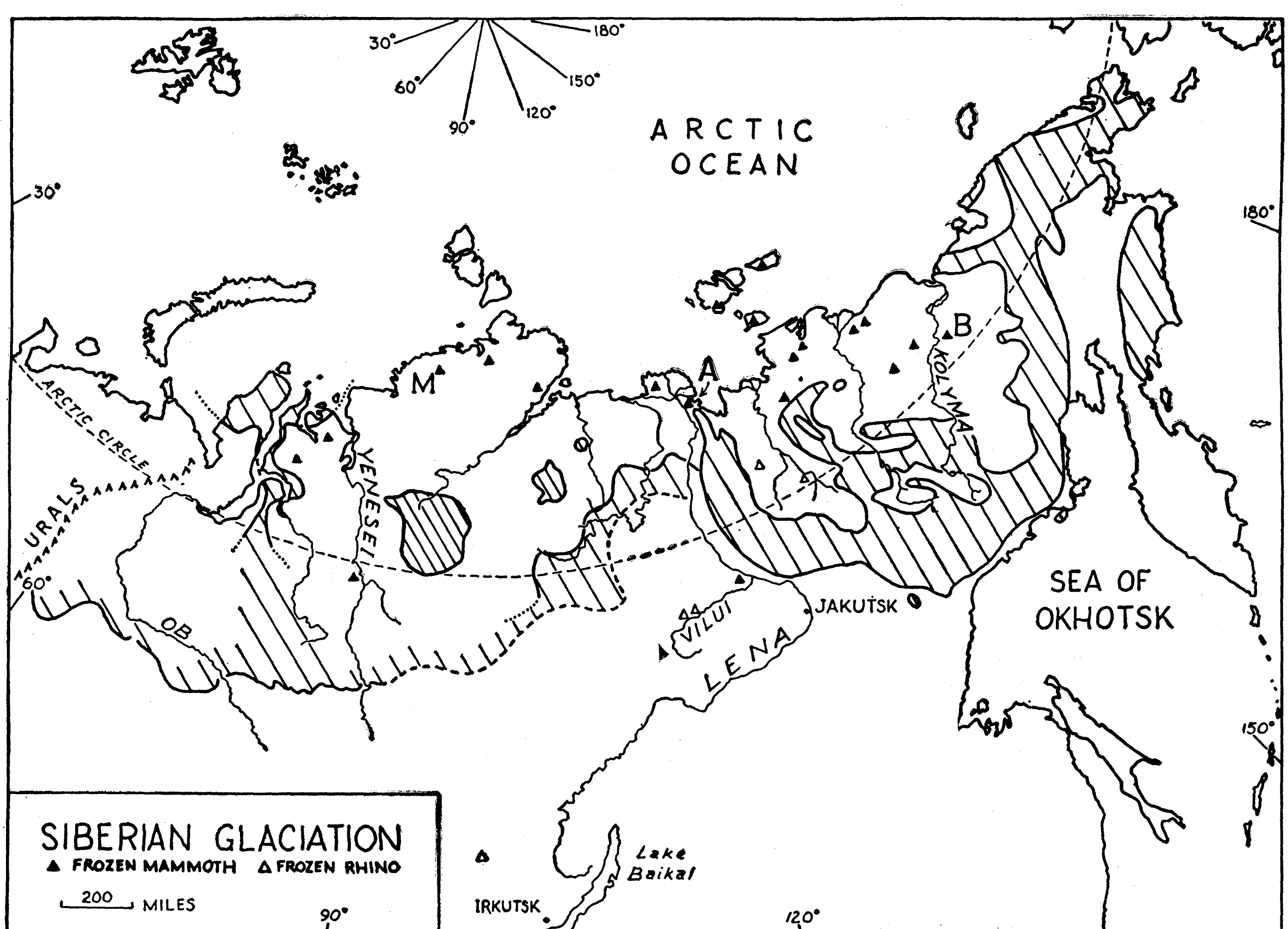

Fig. 2. Extent of glaciation in northern Siberia and location of frozen carcasses of the mammoth and the woolly rhinoceros (10). East of the Lena River only the maximum extent of glaciation is shown; this was alpine-type glaciation, not a continuous ice sheet. West of the Lena the maximum glaciation is shown by broad hatching; the Zyryansky stage (not hatched) and the Sartansky stage (closer hatching) are shown in so far as they are known. (*A*) The Adam's mammoth (dated > 30,000 years); (*B*) Berezovka mammoth; (*M*) the Mamontova mammoth. The extent of glaciation of the arctic islands is not shown.

area—that is, west of the Lena—mammoths are found above deposits of the Last glaciation which, in turn, overlie sediments of the Boreal transgression.

Russian geologists assign most of the mammoth remains to the Karginsky warm period, an interstadial which followed the maximum extent of the Zyryansky glaciation but preceded the final (Sartansky) expansion of now extinct glaciers of the northern Siberian highlands. It has been suggested (*22*) that this final expansion was equivalent to the Salpausselka moraines of northern Europe (Valders substage in North America), which formed about 10,500 years ago. Therefore, the mammoths *west of the Lena River* apparently lived in a relatively warm period prior to the close of the Last glaciation, probably the Allerød or Two Creeks interstadial, of Europe and North America, respectively—a period in which the climate was less warm than at present.

On the other hand, the flora associated with the Berezovka and Mamontova mammoths (Table 1) indicates a climate slightly warmer than the present, and the Lena delta mammoth (Y-633) was dated by radiocarbon as more than 30,000 years old (*26*). Both of these facts point to an interglacial age *prior* to the Last glaciation, a conclusion which is compatible with the occurrence of all mammoths *east* of the Lena River, including the Lena delta, which appears not to have been glaciated. The Berezovka and Lena-delta mammoths could, therefore, be remnants of the final part of the Last interglacial period.

But the Mamontova mammoth from the Taimyr Peninsula presents a problem: although the associated flora is a warmer-latitude flora than that found at present, the mammoth lay in an area covered by Zyryansky glaciers and apparently must postdate the maximum of the Last glaciation. The only period since the maximum of the Last glaciation in which the climate was warmer than at present was the postglacial Hypsithermal interval (*27*). If Popov (*20*, p. 274) is correct in his determination that this mammoth lived at the time of the second terrace above the present floodplain of the Mamontova River, then it probably predates the Hypsithermal interval. It is conceivable but unlikely that two periods of downcutting have occurred there in post-Hypsithermal time (*25*). Therefore, an apparent paradox remains—that the climate in northern Siberia was warmer than at present at some period in late glacial time when climates elsewhere on the earth were cooler than at present.

It is also argued (*29*) that some of the woolly mammoths lived in northern Siberia during the postglacial Hypsithermal interval (7500 to 4000 years ago), but the data on which such a conclusion is based are also compatible with late Last-interglacial time or an interstadial of the Last glaciation. Furthermore, although woolly mammoths are prominent in prehistoric cave art in late Last-glacial time, they are unknown in postglacial deposits in the much-studied areas of Europe and North America. Also, Griffin (*30*) reports that mammoths were hunted by Siberian Advanced Paleolithic people in the Lake Baikal area as late as 12,000 to 9000 years ago, during the waning stages of the Last glaciation, but that no mammoths of a more recent date are found in these sites.

In summary, Siberian frozen woolly mammoths are found (i) in deposits related in time to the Last glaciation, most of them dating from a major interstadial prior to 10,500 years ago, and (ii) in deposits apparently of late Last-interglacial age (postmaximum Boreal transgression). This time range agrees with that of the distribution of *Mammuthus primigenius* throughout Europe and North America (including Alaska), where it is found from late (?) Last-interglacial through late Last-glacial times.

Death and Preservation

All the evidence now at hand supports the conclusions of previous workers that no catastrophic event was responsible for the death and preservation of the frozen woolly mammoths. The cadavers are unusual only in that they have been preserved by freezing; the demise of the animals, however, accords with uniformitarian concepts. The ratio of frozen specimens (around 39) to the probable total population (more than 50,000) is of the order of magnitude expected among terrestrial mammals on the basis of chance burial. Furthermore, the occurrence of nearly whole carcasses is extremely rare (only four have been found), in spite of the numerous expeditions for fossil ivory and other exploration in northern Siberia.

There is no direct evidence that any woolly mammoth froze to death. In fact, the healthy, robust condition of the cadavers and their full stomachs argue against death by *slow* freezing. On the other hand, the large size of their warm-blooded bodies is not compatible with *sudden* freezing. In addition, all the frozen specimens were rotten and, in most cases, had been somewhat mutilated by predators prior to freezing. This is attested to by many first-hand accounts (*2*, p. 60; *15; 20*, p. 274; *31*). Although some of the flesh recovered from the cadavers was "fibrous and marbled with fat" and looked

	SIBERIA	NORTH EUROPE	ALPS	NORTH AMERICA
RECENT	POST-GLACIAL	POST-GLACIAL		
UPPER	SARTANSKY GLACIATION KARGINSKY INTERSTADIAL ZYRYANSKY GLACIATION KASANTSEVKY MARINE DEPOSITS	WEICHSEL: SALPAUSSELKA ALLERÖD	WÜRM	WISCONSIN: VALDERS TWO CREEKS
	INTERGLACIAL: SANCHUGOVSKY MESSOVKY (BOREAL TRANSGRESSION)	EEMIAN	R/W	SANGAMON
MIDDLE	MAXIMUM GLACIATION INTERGLACIAL	SAALE HOLSTEIN	RISS M/R	ILLINOIAN YARMOUTH
LOWER	GLACIATION PRE-GLACIAL	ELSTER	MINDEL GÜNZ	KANSAN NEBRASKAN

Fig. 3. Siberian glacial chronology [after Saks and Strelkov (*22*)] and suggested correlations with glacial sequences in northern Europe, the Alps, and north-central North America.

"as fresh as well-frozen beef or horse-meat," only dogs showed any appetite for it; "the stench . . . was unbearable" (*1*, pp. 119, 129). Histological examination of fat and flesh of the Berezovka mammoth showed "deep penetrating chemical alteration as a result of the very slow decay," and even the frozen ground surrounding a mammoth had the same putrid odor, implying decay *before* freezing (*2*, p. 60). Furthermore, the stories of a banquet on the flesh of the Berezovka mammoth were "a hundred per cent invention" (*2*, p. 60).

Soft parts of other fossils are not unknown in the geologic record, but sudden or catastrophic changes of climate have not been postulated to explain the preservation of these parts. Skin and hair of Pleistocene ground sloths are known from nonglacial areas. From more remote times we have mummified skin of Mesozoic dinosaurs and muscle fibers of Devonian sharks, still showing individual fibers and cross-striations (*7*). Such fossil evidence implies preservation of these soft parts for a considerable period of time—at least as long as was required for lithification of the enclosing sediments.

The only direct evidence of the mode of death indicates that at least some of the frozen mammoths (and frozen woolly rhinoceroses as well) died of asphyxia, either by drowning or by being buried alive by a cave-in or mudflow. As stated above, sudden death is indicated by the robust condition of the animals and their full stomachs. Asphyxiation is indicated by the erection of the penis in the case of the Berezovka mammoth and by the blood vessels of the head of a woolly rhinoceros from the River Vilyui (Siberia), which were still filled with red, coagulated blood (*1, 2, 32*).

The specific nature of deposits enclosing the mammoths is not known well enough to be very helpful as an indicator of the mode of death or burial. Most of the remains are associated with river valleys and with fluviatile and terrestrial sediments, but whether the mammoths bogged down in marshy places or fell into "riparian gullies" or were mired in and slowly buried by sticky mudflows is not clear. Perhaps all three of these agencies and several others were involved. One point of fact helpful in this problem is the specificity of the frozen animals: in Siberia only mammoths and woolly rhinoceroses have been found frozen and preserved, and the former have been found in much greater numbers than the latter (*1*, p. 40; *33*).

So far no other members of the contemporary Eurasian fauna—stag, horse, reindeer, antelope, musk ox, and so on (*16*)—have been found frozen and well preserved. That only the bulky and awkward "giants" of the fauna are so preserved points to some peculiarity of their physique as a contributing factor. The low-slung rhinoceros would have trouble negotiating marshy ground and snow drifts. Similarly, the mammoth, with his stiff-legged mode of locomotion, would have difficulty on such terrain and, moreover, would probably not be able to cross even small gullies. It would be nearly impossible for him to extricate himself if he had fallen into a snow-filled gully or had been mired into boggy ground. A modern elephant is unable to pass over any trench which barely exceeds his maximum stride because of the pillar-like leg structure which is required to support his vast body (*11*, p. 41). Also, the mere weight of the mammoth's body would have been a dangerous attribute if the animal happened to graze too near the edge of a river bluff which had been softened by the summer sun.

The stomach contents of the frozen mammoths indicates that death occurred in the warm season, probably in late summer or early fall (*2*, p. 49; *18*), when melting and solifluction would have been at a maximum and, accordingly, locomotion would have been difficult.

The several theories of entombment, which have been alluded to above, generally reflect the theorist's particular experiences or impressions in the mammoth-bearing terrain. Digby (*1*) was impressed by "countless riparian gullies" which would have been ideal mammoth traps when filled with snow in the winter. Vollosovich (see *2*, p. 57) was himself trapped in a slowly moving stream of very sticky mud and had to be rescued by his guides. He theorized that an animal so trapped might fall on its side and act as a dam, being slowly buried and suffocated by mud. The Berezovka mammoth is commonly regarded (*12*) as having fallen as a cliff slumped beneath it; its broken bones attest to such a fall. Presumably it then suffocated as it was buried alive by the caving bluff. Popov (*20*) believes the Mamontova mammoth perished in a bog while grazing on the floodplain of the ancient Mamontova River. Quackenbush (*15*) believed that his specimen from Alaska perished on a floodplain and that most of the flesh rotted away before the corpse was naturally buried by floodplain sediments. Another possibility is drowning by breaking through river ice (*2*, p. 63). All of these theories are credible and can be accepted as possibilities. There appears to be no need to assume the occurrence of a catastrophe.

Conclusions

Although some problems concerning the frozen fauna of Siberia and Alaska remain to be solved, recent field work and new techniques have contributed much to our understanding since Tolmachoff's summary account in 1929. Frozen woolly mammoths have now been found in northern and northeastern Siberia and Alaska in deposits attributed to Last interglacial and Last glacial times. They are unknown in postglacial deposits. Only four of the 39 known frozen carcasses are by any means complete, and all of the cadavers were rotten and somewhat mutilated prior to being frozen. More than 50,000 mammoths lived in Siberia during late Pleistocene time.

The woolly mammoths lived in a tundra region similar to that in which they are found today, but the climate was slightly warmer and perhaps moister. They were apparently well adapted to the cold climate; their long hair, warm underwool, and thick layer of subcutaneous fat protected them against the cold air, and their broad, four-toed feet and relatively small size (as compared to that of their fossil European relatives) were advantageous in marshy pastures. The frozen mammoths were healthy and robust when they died.

The well-preserved specimens, with food in their stomachs and between their teeth, must have died suddenly, probably from asphyxia resulting from drowning in a lake or bog or from being buried alive by a mudflow or cave-in of a river bank. Since only the heavy-footed giants of the fauna—the mammoths and woolly rhinoceroses—have been found in a frozen state, it is very unlikely that a catastrophic congelation occurred in Siberia. On the contrary, the frozen giants are indicative of a normal and expected (uniformitarian) circumstance of life on the tundra (*34*).

References and Notes

1. B. Digby, *The Mammoth and Mammoth-hunting in Northeast Siberia* (Appleton, New York, 1926).
2. I. P. Tolmachoff, *Trans. Am. Phil. Soc.* **23** (1929); this paper is the main source of information published prior to 1929.
3. I. T. Sanderson, *Saturday Evening Post* **39** (16 Jan. 1960).
4. I. Velikovsky, *Earth in Upheaval* (Doubleday, New York, 1955), chap. 1; C. H. Hapgood, *Saturday Evening Post* **22** (10 Jan. 1959).
5. Most of the first-hand information on discovery and geology of the mammoths is still available only in Russian.
6. H. F. Osborn, *Proboscidea* (American Museum of Natural History, New York, 1942), pp. 1122–69.
7. A. S. Romer, *Vertebrate Paleontology* (Univ. of Chicago Press, Chicago, ed. 2, 1945), p. 415.
8. C. W. Hibbard, in R. F. Flint, *Glacial and Pleistocene Geology* (Wiley, New York, 1957), p. 464.
9. H. C. Ezra and S. F. Cook, *Science* **129**, 465 (1959).
10. J. K. Charlesworth, *The Quaternary Era* (Arnold, London, 1957).
11. R. Carrington, *Elephants* (Basic Books, New York, 1959).
12. R. F. Flint, *Glacial and Pleistocene Geology* (Wiley, New York, 1957).
13. W. Soergel [*Palaeontol. Z.* **22** (1941)] treats the climatic significance of the *meridionalis-trogontherii-primigenius* line; K. D. Adam, *Geol. Bavarica No. 19* (1953), pp. 357–363.
14. A. Heintz, *Blyttia* **16**, 122 (1958), a paper based on pollen analyses by Kuprijanova; F. Camus, *Compt. rend.* **160**, 842 (1915). H. Gams [in F. Verdoorn, *Manual of Bryology* (Nijhoff, The Hague, 1915), p. 313] comes to the same conclusion on the basis of mosses.
15. L. S. Quackenbush, *Bull. Am. Museum Nat. Hist.* **26**, 107 (1909).
16. Horse, steppe bison, giant deer, woolly rhinoceros, arctic musk ox, and reindeer are open-terrain, cold-latitude animals which often occur with *M. primigenius*; warmer-latitude woodland types such as woodland musk ox, stag, and elk are less common associates (data from numerous sources).
17. W. Soergel, *Palaeontol. Z.* **22**, 33, 40 (1941).
18. E. M. Kindle, *Am. J. Sci.* **208**, 183 (1924) (for Banks Island); J. R. Mackay, *Can. Dept. Mines and Tech. Surveys, Mines Branch Mem. No. 5* (1958), p. 25 (for MacKenzie River delta area).
19. H. E. Anthony, *Natural Hist.* **58**, 299 (1949).
20. A. J. Popov, in *The Ice Age in the European Section of USSR and in Siberia*, K. K. Markov and A. J. Popov, Eds. (State Lomonosov Univ. of Moscow, 1959), p. 259 (in Russian).
21. Y. D. Zaklinskaya, in *ibid.*, p. 276; A. P. Zhuze, in *ibid.*, p. 301; E. N. Pavlovskij, *Proc. Intern Congr. Zool., 14th Congr.* (1956), p. 61.
22. V. N. Saks and S. A. Strelkov, "Quaternary Deposits of the Soviet Arctic," *Trans. Arctic Geol. Research Inst. Moscow* **91**, 221 (1959) (in Russian).
23. H. R. Crane, *Science* **124**, 670 (1956).
24. E. A. Olson (Lamont Geological Observatory), personal communication; this mammoth was first reported by H. E. Anthony [*Natural Hist.* **58**, 299 (1949)].
25. A. P. Vaskovsky, in *Ice Age in the European Section of USSR and in Siberia*, K. K. Markov and A. J. Popov, Eds. (State Lomonosov Univ. of Moscow, 1959), p. 512, Fig. 1.
26. M. Stuiver, E. S. Deevey, L. S. Gralenski, *Am. J. Sci. Radiocarbon Suppl.* **2**, 53 (1960).
27. E. S. Deevey and R. F. Flint, *Science* **125**, 182 (1957).
28. V. D. Dibner, in V. N. Saks and S. A. Strelkov [*Trans. Arctic Geol. Research Inst. Moscow* **91**, 98, Fig. 8 (1959)] also assigns the Mamontova fauna to the Karginsky interstadial, and therefore prior to the end of the last glaciation.
29. L. A. Kuprijanova, in A. Heintz, *Blyttia* **16**, 139 (1958); see Heintz's counterarguments in the same paper.
30. J. B. Griffin, *Science* **131**, 802 (1960).
31. Benkendorf and Hertz, cited in B. Digby, *The Mammoth and Mammoth-hunting in Northeast Siberia* (Appleton, New York, 1926), pp. 102, 118–19.
32. E. W. Pfizenmayer, *Mammutleichen und Urwaldmenschen in Nordost-Siberien* (Brockhaus, Leipzig, 1926), p. 167.
33. Three of the four known frozen rhinoceroses were found south of the Arctic Circle, and the animals did not cross the Bering Strait. They were probably animals of warmer climate than the mammoths.

34. This article is Lamont Geological Observatory contribution No. 480. It was supported by a grant from the U.S. Steel Foundation. The subject was suggested and valuable advice was offered by M. Ewing and W. L. Donn of Lamont Geological Observatory. C. W. Hibbard and W. S. Benninghoff of the University of Michigan gave a great deal of help with biological details. H. E. Anthony and R. G. Van Gelder of the American Museum of Natural History were very helpful in supplying parts of the frozen baby mammoth for radiocarbon dating.

Debris from Tests of Nuclear Weapons

Activities roughly proportional to volume are found in particles examined by autoradiography and microscopy.

Jan Sisefsky

Since the summer of 1955, airborne debris from nuclear-weapon tests has been collected and examined at the Research Institute of National Defence, Stockholm. The debris has been collected on glass-fiber paper (30 by 60 cm) with a sampling device carried by aircraft (*1*) at altitudes up to about 13 kilometers. Usually two samples have been taken at the same time, one above and one below the tropopause. Debris has also been collected on glass-fiber paper at ground level.

Routinely, one-fourth of the filter paper is used for spectrometric determination of the contents of a number of gamma-ray-emitting nuclides, from which an age determination can be made (*2*). The remainder is autoradiographed on photographic film of the type most sensitive to beta rays—that is, no-screen x-ray film (*3*, p. 220) (Ilford "Ilfex"). The exposure time is usually 7 days, and the films are developed according to the recommended procedure (ID 42; 4 minutes, 20°C). The autoradiographs show black, dense, circular spots with diffuse edges, varying in diameter from a few millimeters down to about 10 microns (see Fig. 1); spots of 10-micron diameter are the smallest that can be distinguished. The largest spots appear only when there is fresh radioactivity; usually only a few of them appear per square decimeter of filter area. The smaller spots are more frequent, the smallest ones being sometimes so numerous that they merge to a black haze, reproducing the structure of the filter. Although, as a rule, samples taken above the tropopause are of higher activity than the corresponding ones taken below it, the ratio of big spots to small ones is usually larger for samples taken below the tropopause.

From the autoradiographs it is possible to determine the activity of the individual particles and to locate their position on the filter (see *4*).

The author is affiliated with the Research Institute of National Defence, Stockholm.

Radioactive Particle Measurement

The simplest method of measuring the size of an autoradiograph spot is to determine its "diameter" under the microscope with a low-power objective (for example, × 4; ocular, × 12.5) and an ocular scale. The totally black center of a spot is surrounded by an area where the unexposed parts lie like islands in the blackening area. Further out from the center the black grains lie isolated, surrounded by unexposed film (Fig. 1). The edge of a spot can be defined as the zone where these two types of blacken-