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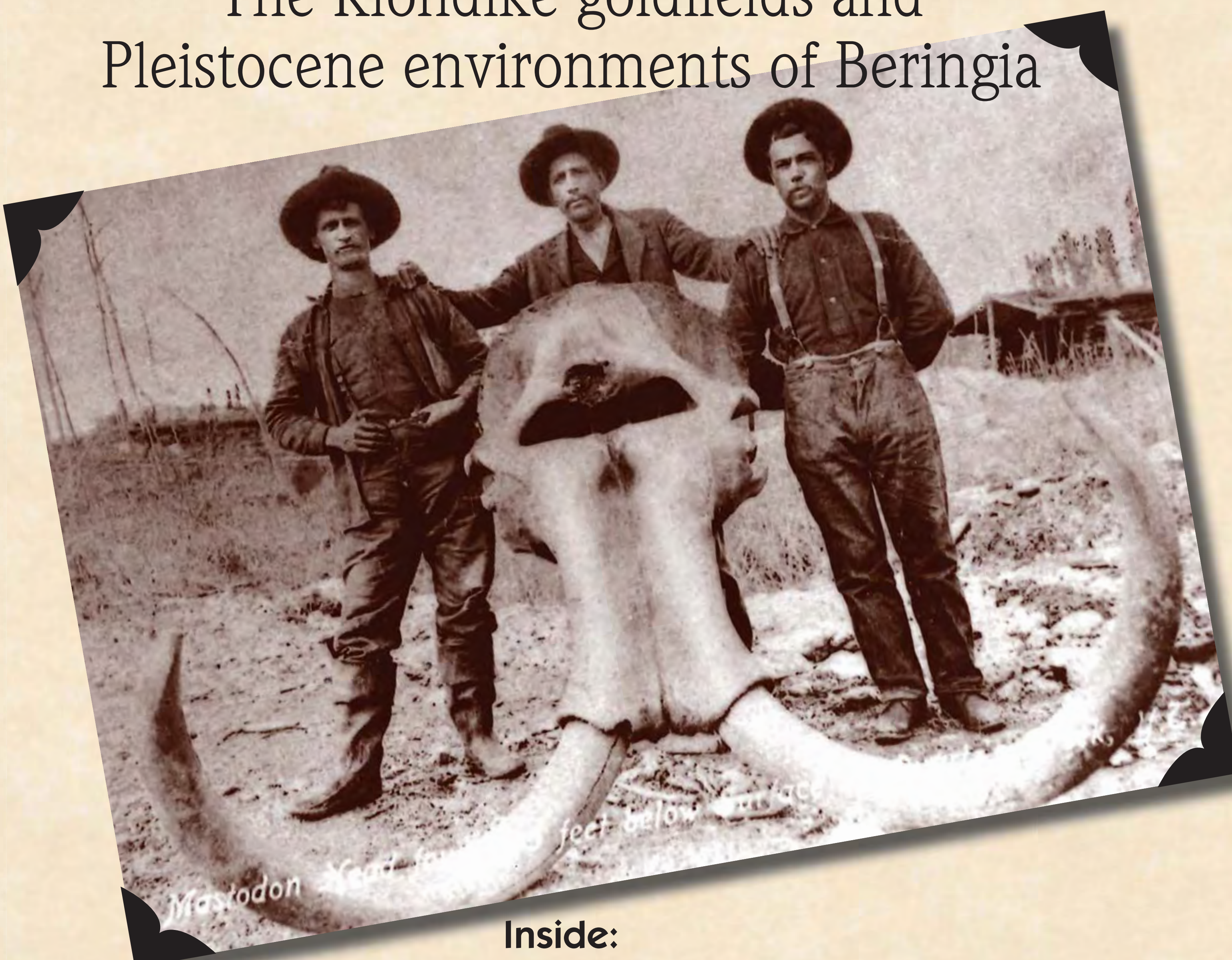

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SCIENCE ARTICLE

Cover: Following the footsteps of stampeders to the Klondike creeks, scientists from across Canada and abroad were lured to the area by reports of spectacular ice-age fossils from the permafrost, including this mammoth skull (not mastodon as written) recovered from Quartz Creek following the Gold Rush. Photo courtesy Dawson City Museum Archives. See "The Klondike goldfields and Pleistocene environments of Beringia" by D.G. Froese et al., p. 4–10.

The Klondike goldfields and Pleistocene environments of Beringia

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ABSTRACT
The Klondike goldfields of Yukon, Canada, contain a key record of Pleistocene Beringia, the region of Alaska, Siberia, and Yukon that remained largely unglaciated during the late Cenozoic. A concentration of mining exposures, with relict permafrost that is locally more than 700,000 years old, provides exceptional preservation of paleoenvironmental archives and a new perspective on the nature of paleoenvironments during the Pleistocene. A critical feature is the stratigraphic association of distal tephra beds with these paleoenvironmental archives, which facilitates their regional correlation and, in many cases, provides independent ages for the paleoenvironmental assemblages. Paleoenvironmental analyses of fossil arctic ground-squirrel middens and buried vegetation indicate the presence of cryoxerophilous ("steppe-tundra") vegetation growing on well-drained substrates with deep active layers (seasonal thaw depths) during cold intervals of the Pleistocene. Studies of full-glacial paleosols and cryostratigraphic relations of associated ground ice indicate the importance of active loess deposition and surface vegetation cover in maintaining the functionally distinct mammoth-steppe biome, which supported grazing mega-fauna populations, including mammoth, horse, and bison.

INTRODUCTION
Swedish biogeographer Eric Hultén introduced the concept of Beringia to explain the distribution of arctic and boreal plants around the Bering Strait. He proposed that a continuous Holarctic refugium beyond the continental ice sheets of North America existed during the Quaternary (Hultén, 1937). Hultén originally considered Beringia as the region of the continental shelf exposed when lowered sea level connected eastern Asia with North America, but we now consider it more broadly to

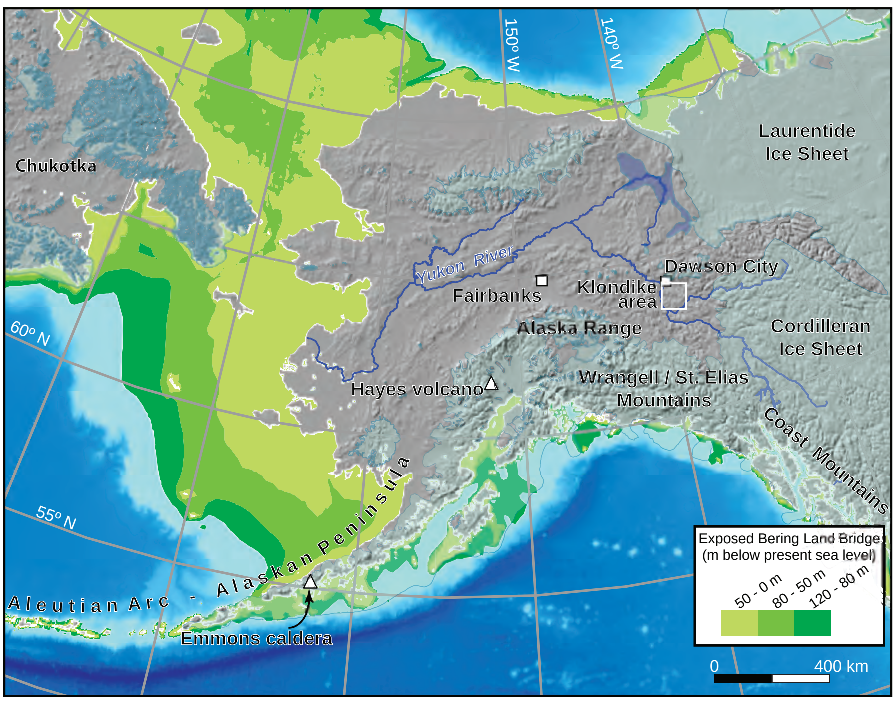

Figure 1. Eastern Beringia during the last glacial maximum with eustatic sea level lowering of 120 m. The region was largely unglaciated with the exception of local uplands that supported alpine glaciers (glacier limits from Ehlers and Gibbard, 2004).

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include the unglaciated landmass from the Kolyma River in Siberia to Yukon, Canada. This area extends ~3000 km across, and includes the Klondike region toward the eastern edge of that boundary (Fig. 1).

Beringia represents the largest contiguous Arctic expanse to remain unglaciated during the Pliocene and Pleistocene and preserves an exceptional sedimentary archive spanning the past several million years. Relict permafrost (Kotler and Burn, 2000; Froese et al., 2008) in Beringia has preserved a diversity of exceptional paleoenvironmental archives, including mammals (Guthrie, 1990), paleobotanical remains (Goetcheus and Birks, 2001; Zazula et al., 2003), and ancient DNA (Shapiro et al., 2004). Critical to stratigraphic integrity, and to understanding the paleoenvironmental significance of these archives, is the presence of widespread (>10^6 km^2) and numerous distal volcanic ash layers or tephra beds (Westgate et al., 2001). These tephra beds are datable by a variety of methods, including glass fission-track (Westgate et al., 2001) and associated radiocarbon ages (Froese et al., 2002), but they also provide correlative timelines between sites based on their unique geochemistry. The presence of these tephra beds within the perennially frozen late Cenozoic sediments of eastern Beringia is unique to this area of the northern hemisphere. Similar permafrost-preserved records are found in Siberia (e.g., Sher et al., 2005), but the lack of readily datable materials there, namely a rich tephrostratigraphy, is a challenge to developing chronologies beyond the range of radiocarbon dating (~50,000 years).

Substantial progress has been made since Hultén's time in documenting the biogeographic significance of Beringia (Hopkins et al., 1982; Brigham-Grette, 2001), including its role as an evolutionary center (Sher, 1997) and as the crossroads for faunal exchanges between Asia and North America (e.g., Sher, 1999; Repenning and Brouwers, 1992; Shapiro et al., 2004). However, considerable debate has focused on how Beringia could support a diverse grazing megafauna under Pleistocene glacial climates (Guthrie, 1990). Discussion is based largely on interpretations of lacustrine paleoecological records that differ from those derived from river bluff exposures and, especially, exposures in the Fairbanks placer mining region (Hopkins et al., 1982; Guthrie, 1990). Until recently, however, the Klondike region has received comparatively little attention beyond the analysis of late Pleistocene vertebrate fossils (Harington, 2003). Here, we highlight recent study of the tephrostratigraphy and associated paleoenvironmental archives in the Klondike region, which has led to new understanding of late Pleistocene environments of Beringia.

REGIONAL SETTING

The interior of Yukon and Alaska has a strongly continental climate due to the pronounced rain shadow of the Coast and St. Elias Mountains of western Canada and the Alaska Range and Wrangell Mountains of southern Alaska (Fig. 1). This aridity was likely established by the Pliocene (White et al., 1997; Froese et al., 2000), such that during Plio-Pleistocene glacial intervals, the interior of Yukon and Alaska was cold enough to support ice sheets but too dry for extensive glaciation. The Klondike region lies at the eastern edge of this unglaciated area, within 150 km of the last glacial maximum Cordilleran Ice Sheet (Fig. 1).

Figure 2. *Bison priscus* skull recovered from sediments associated with the late Pleistocene Dawson tephra on a tributary to Dominion Creek. Pleistocene fossils are still actively recovered from perennially frozen placer mining exposures in the Klondike, particularly in narrow valleys and near hillslopes where loessal "muck" deposits have aggraded.

Since the discovery of placer gold in the Klondike in 1896 and the subsequent gold rush, mining has produced tremendous exposures of surficial sediments within the Klondike goldfields, along with the recognition of abundant Pleistocene fossil bones (e.g., Harington and Clulow, 1973). Prior to the gold rush, G.M. Dawson and R.G. McConnell of the Geological Survey of Canada (Dawson, 1894) had collected fossils from the area, and the Muséum d'histoire naturelle de Paris, the U.S. Biological Survey, and the American Museum of Natural History sent researchers to collect ice-age fossils in the early 1900s. Perhaps the most noteworthy of all paleontologists to have worked in the Klondike is C.R. Harington, who made sizable vertebrate collections for the Canadian Museum of Nature during the 1960s–1990s. Hundreds to thousands of fossils are still produced every year from placer gold mining and provide an invaluable research resource (Fig. 2).

Nearly all drainages of King Solomon Dome (Fig. 3) have produced gold, with total production estimated at ~15,000,000 oz; active mining produces >50,000 oz annually, largely from small, independently owned mines. Development of radiating drainage from King Solomon Dome (Fig. 3) during the Cenozoic released gold from bedrock sources, and, coupled with slow rates of uplift, produced prominent terraces in major valleys dating to the Pliocene and early Pleistocene (McConnell, 1907; Froese et al., 2000). In the valley bottoms, local creek gravels are associated with ice-rich loess, or "muck" deposits (Fig. 4).

TEPHROSTRATIGRAPHIC FRAMEWORK

The presence of numerous distal silicic tephra beds has been instrumental in the development and interpretation of the late Cenozoic sedimentary and paleoenvironmental record in the Klondike region (Preece et al., 2000; Westgate et al., 2001).

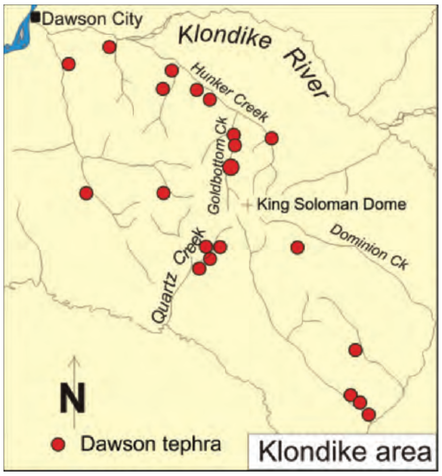

Figure 3. Klondike area map of late Pleistocene Dawson tephra locations (after Froese et al., 2006).

Figure 4. Ice-rich loessal deposits, or "muck," of the Klondike goldfields. Aggradation of loess with permafrost has led to exceptional preservation of paleoenvironmental archives in the Klondike area. Paleoenvironmental reconstruction from these muck deposits, sometimes called "Pleistocene in a blender," was largely avoided because of their complexity. Detailed tephrostratigraphy has led to new understanding of their significance for reconstructing Pleistocene environments of eastern Beringia.

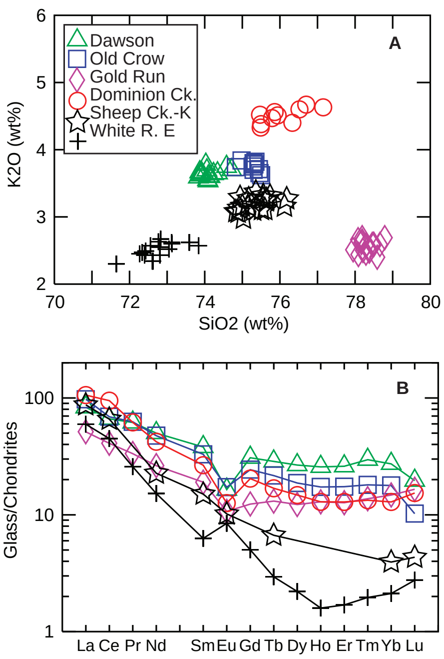

Figure 5. (A) Bivariate plot of SiO_2-K_2O in glass shards illustrating differences in geochemistry for some Klondike area tephra beds. (B) Rare earth element profiles for tephra beds shown in A. Data are normalized to chondrites using the values of Sun and McDonough (1989). Dawson, Old Crow, and Dominion Creek tephra beds have Type I characteristics, while Sheep Creek-K and White River Ash–east lobe (White R. E) have Type II characteristics. Gold Run tephra has a distinctive mix of characteristics, with glass trace-element compositions similar to Type I and mineralogy similar to Type II (data sources and analytical methods: Preece et al., 2000; Westgate et al., 2001, 2008; Pearce et al., 2004; this paper).

The glass morphology, mineral content, and geochemistry of each tephra bed help to reveal its provenance and suggest two broad volcanic source areas (Fig. 5; Preece et al., 2000). Tephra beds from the Aleutian arc–Alaska Peninsula, or Type I beds, have few crystals, mainly bubble-wall glass shards, abundant pyroxene, and rare earth element (REE) profiles with a well-developed negative Eu anomaly (Fig. 5). In contrast, Type II beds, derived from the Wrangell Volcanic Field (and Hayes volcano), have abundant crystals and glass that is mainly in the form of highly inflated pumice; hornblende is abundant, and REE profiles are steep, with a weakly developed Eu anomaly (Fig. 5). Physical and chemical properties, together with stratigraphic and paleoecological context, allow identification of tephra beds and their correlation between sites (Fig. 5). At least seven Type I beds are known in the Klondike, including Dawson (25.3 ^{14}C ka B.P.), Dominion Creek (82 ± 9 ka), and Old Crow (131 ± 11 ka); the 26 known Type II beds include White River Ash (1.2 and 1.7 ka) and Sheep Creek-K (ca. 80 ka). Six "other" beds are also present in the Klondike; these are either too mafic for classification or, like the Gold Run tephra (740 ± 60 ka), have characteristics of both Type I and II tephra beds.

The most commonly observed bed is the late Pleistocene Dawson tephra, one of the largest Quaternary eruptions in eastern Beringia, likely exceeding 50 km^3 (Fig. 6; Froese et al., 2002, 2006; Mangan et al., 2003). Dawson tephra has been identified at more than 20 sites in the area (Fig. 3), where it typically occurs as a 30–80-cm-thick bed in "muck" deposits (Fig. 7). Bracketing radiocarbon ages on plant macrofossils provide a mean age of ca. 25,300 ^{14}C yr B.P. and a calendar year estimate of ca. 30,000 yr B.P. (Froese et al., 2006; Demuro et al., 2008); Dawson tephra marks the onset of glacial conditions of Marine Isotope Stage (MIS) 2 in central Yukon (Zazula et al., 2006). Other beds provide similar time markers in the Klondike: Old Crow tephra for late MIS 6 (131 ± 11 ka; Péwé et al., 2009), directly below the last interglacial (MIS 5e) thaw unconformity; Sheep Creek-C tephra (ca. 90 ka) for late MIS 5 interglacial conditions; and Sheep Creek-K tephra (ca. 80 ka) for the MIS 5–4 transition (Westgate et al., 2008). Collectively, these and other beds provide key marker horizons for discrete timeslices between sites in the Klondike, allowing integration of diverse paleoenvironmental archives from relict permafrost, plant and insect macrofossils, pollen, and vertebrate remains.

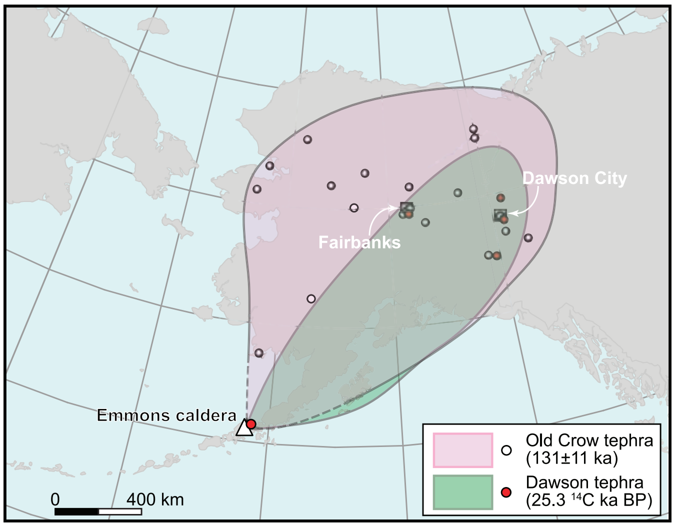

Figure 6. Dawson and Old Crow tephra distribution (after Froese et al., 2002).

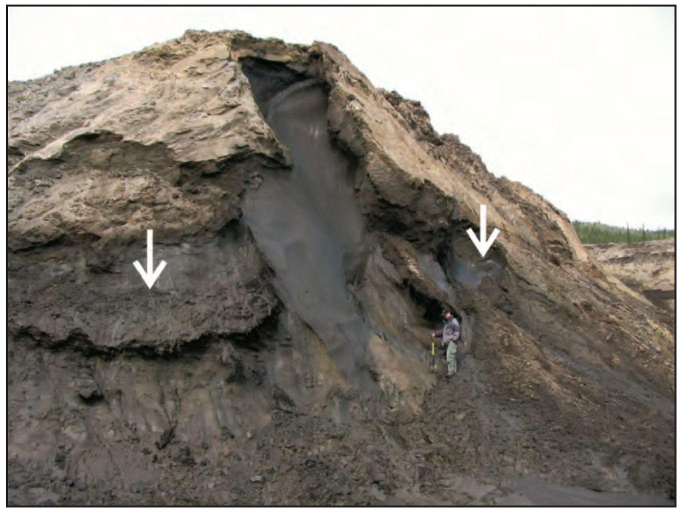

Figure 8. Ice wedge cross-cutting late MIS 5 forest bed at head level of person in photo along Dominion Creek. Sheep Creek tephra-K (ca. 80 ka) is present about midway through the silts (arrow), marking the late MIS 5–4 transition in central Yukon.

Figure 7. Late Pleistocene Dawson tephra (25,300 ^{14}C yr B.P.) overlying syngenetic ice wedge at Quartz Creek. Depression of tephra into the wedge top (upper right) marks the former depression of the polygonal ground network, indicating the ice wedge was active when the tephra was deposited. Arrows mark arctic ground squirrel middens; tephra thickness is ~40 cm.

Figure 9. Graminoid-rich paleosol with roots overlying ice wedge, marking the paleo-active layer when the soil was formed. The paleosol is cross-cut by secondary ice wedge growth (vertical arrow at left) and includes beds of Dominion Creek tephra (82 ± 9 ka; horizontal arrow), marking early MIS 4 glacial conditions. Ice axe: 80 cm.

"MUCK": BERINGIA'S ICE AGE FREEZER

Muck deposits in the Klondike are part of a broader complex of silts that blanket much of Beringia and are usually considered to be loess and locally re-transported loess from creeks and river valleys that aggraded with permafrost (Péwé, 1975; Fraser and Burn, 1997; Muhs et al., 2003; Fig. 8). In the discontinuous permafrost zone (50%–90% frozen ground), which includes the Klondike and Fairbanks regions, these ice-rich loessal deposits are found on north- and east-facing slopes and within narrow valleys along hillslopes. The frozen deposits have high organic carbon content (Fraser and Burn, 1997; Sanborn et al., 2006), reflecting aggradation of the permafrost table with silt deposition, and may reach tens of meters in thickness. These combined processes buried soils before their associated root detritus and other plant material could decompose (Fig. 9), preserving Pleistocene organic remains in permafrost at some sites for more than 700,000 years (Froese et al., 2008). Similar Pleistocene deposits are present in Siberia, where they are termed Yedoma, though it is not well accepted that these are, sensu stricto, eolian deposits (Sher, 1997; Schirrmeister et al., 2008).

The influence of surface vegetation cover on permafrost reveals important functional differences between the reconstructed Pleistocene glacial steppe-tundra environment (Zazula et al., 2003) and the modern boreal forest environment of interior Yukon and Alaska. Most sites with mucks present are north- and east-facing or in narrow valleys with black spruce (*Picea mariana*) forests and are characterized by thick covers of moss and partially humified vegetation litter. The thermal properties of this groundcover promote deep winter cooling and insulate the ground from summer heat, resulting in poorly drained substrates with permafrost and shallow active layer depths. Recovery of MIS 2 and 4 arctic ground-squirrel middens and paleosols from muck deposits at these sites reveals that substrates were better drained during Pleistocene glacial intervals than they are at present (Zazula et al., 2005; Sanborn et al., 2006). In fact, arctic ground squirrels are absent from the Klondike region today, suggesting important expansion of their ranges during Pleistocene glacial intervals (Zazula et al., 2005). Present-day ground squirrels, in southern Yukon and the north slope of Alaska, require well-drained soils with active layer depths of ~1 m for burrowing and successful hibernation. The translocation of paleosol A-horizon material in the paleo-active layer and truncation of underlying ice bodies provide additional evidence for deeper active layers (Sanborn et al., 2006; Fig. 9). Thus, despite summer air temperature depression of several degrees Celsius during the glacial intervals (e.g., Elias, 2001), soils were better drained with deeper active layers due to the presence of graminoid vegetation cover, which lacked the insulating properties of modern soils in the region. Well-drained soils with deeper active layers and additions of soil nutrients from loess deposition would have enabled greater nutrient turnover, essential for a herbaceous steppe-tundra habitat that supported herbivores, such as woolly mammoths and horses (Laxton et al., 1996).

QUATERNARY MAMMAL FOSSILS

The Klondike is one of North America's most productive localities for the recovery of late Pleistocene mammal fossils (Harington, 2003). Most Klondike faunas are dominated by the "big-three" of Beringia—steppe bison (Fig. 2; *Bison priscus*), woolly mammoth (*Mammuthus primigenius*), and Yukon horse (*Equus lambei*). Fossils of less common species are recovered occasionally, including the western camel (*Camelops hesternus*), American mastodon (*Mammut americanum*), American lion (*Panthera leo atrox*), short-faced bear (*Arctodus simus*), and helmeted muskox (*Bootherium bombifrons*). Mummified or freeze-dried partial carcasses recovered from the Klondike highlight the role of permafrost in the preservation of the late Pleistocene paleontological record. Impressive mummified carcasses include black-footed ferret (*Mustela nigripes*) and Yukon horse (*Equus lambei*), whose stomach contents have provided important dietary information (Harington, 2007). The exceptional preservation of Klondike vertebrate bones has led to recent ancient biomolecule studies using mitochondrial DNA sequencing and radiocarbon dating to establish phylogenetic histories for bison (Shapiro et al., 2004), horse (Weinstock et al., 2005), and mammoth (Debruyne et al., 2008).

PALEOENVIRONMENTAL ARCHIVES

Questions concerning the nature of terrestrial ecosystems in Beringia have been a major research focus for Quaternary paleoecologists for decades (Hopkins et al., 1982; Guthrie, 1990; Birks and Birks, 2000). Although the Klondike region has been well known for Pleistocene mammal fossils for the past century, there has been little systematic paleoecological research in the region until the last decade. The abundance of Pleistocene vertebrate faunas and well-constrained stratigraphic records makes the Klondike a valuable region for resolving questions concerning the relations between mammals, glacial vegetation, and Pleistocene climates.

Recent paleoecological work in the Klondike has focused on detailed analysis of fossil middens (nests, seed caches, and burrows) of arctic ground squirrels (*Spermophilus parryii*) (Zazula et al., 2003, 2007). In the Klondike, over 100 middens have been recovered and analyzed systematically in association with the Sheep Creek-K–Dominion Creek tephras (ca. 80 ka) and Dawson tephra (ca. 25.3 ^{14}C ka), providing paleoenvironmental records for MIS 4 and early MIS 2, respectively. Plant macrofossils (seeds, fruits, leaves) from the middens are dominated by grasses, dryland sedges, sage, and a wide variety of flowering forbs. Together, these plants formed an open, grass- and forb-rich steppe-tundra community that thrived on the well-drained, deeply thawed loessal soils in the Klondike during Pleistocene cold intervals.

CONCLUSIONS

The Klondike goldfields provide an exceptional record of Pleistocene Beringia. The development of a robust tephrostratigraphic and chronologic framework for the perennially frozen deposits has facilitated integration of paleoenvironmental archives from vertebrate remains and paleobotanical, paleosol, and cryostratigraphic observations. This mammoth-steppe environment was characterized by graminoid and forb-rich vegetation with better-drained loessal substrates and deeper active layers despite summer temperature depressions. Collectively, these records support the notion that functional differences between the cryoxeric steppe-tundra and the modern boreal environment provides a means to explain the existence of a rich grazing fauna during Pleistocene glacial intervals.

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LETTERS

Dear Dr. Parrish,

I would like to thank you for your defense of industry, (*GSA Today*, v. 19, no. 6, p. 11–12), especially big industry, in spite of the fact that I, personally, was never particularly happy working for large companies.

I would like to add to your comments that it takes two to tango. We would not have environmental problems associated with mining and energy production on the scale that we do if the demand were not there, and the demand is us, every single last one of us.

We demand low-cost goods and low-cost energy, and we happily buy ever larger houses and cars and ever more things to go in them. We travel more and more. We also have powerful institutions and incentives to keep the population growing and, hence, increasing demand.

These actions lead inevitably to larger and larger holes in the ground in more and more sensitive places. If we each paid as much attention to reducing our footprint on the planet as many of us do to "saving" this and that aspect of nature, nature could take care of itself and our civilization would last a lot longer. Those who criticize industry's environmental damage should look in the mirror.

Thank you,

John Berry, *John Berry Associates, jlbassoc@flash.net*

To the editor of *GSA Today*,

The evident need for the column by President Parrish in the June issue was a surprise and a disappointment to me. I've been one of the evil resource-extraction polluters for more than 50 years. If I ever encountered a fellow geoscientist who took offense at my occupation, I was too dumb to notice. It saddens me that such folks are out there.

The article offered several items in defense of industry people. That shouldn't be necessary, but since it seems to be, I think it is worthwhile to point out two other factors: (1) no governmental or academic employee could possibly survive in this day and age without the benefits of extracted mineral or hydrocarbon resources; and (2) nor could these same people earn their living without benefit of industry. Their funding ultimately derives from taxes on tangible goods that have been created and sold by industry. The truth is, geoscientists in both resource and non-resource arenas need each other. So enough of this holier-than-thou business.

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The Earth Science Literacy Initiative has released its **Earth Science Literacy Principles**—nine "Big Ideas" outlining what every Earth citizen should know about earth science.

The Earth Science Literacy Initiative is funded by the U.S. National Science Foundation and cosponsored by such major geological organizations as GSA, AGU, AGI, and the USGS. The nine principles and 75 supporting concepts were assembled through the cooperation of many hundreds of earth scientists and educators and represent the current state of understanding in the earth-science research community.

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