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Letter to the Editor

Response to Grosswald and Hughes (2004), Brigham-Grette et al. (2003). "Chlorine-36 and ^{14}C chronology support a limited last glacial maximum across central Chukotka, northeastern Siberia, and no Beringian ice sheet," and, Gualtieri et al. (2003), "Pleistocene raised marine deposits on Wrangel Island, northeastern Siberia: implications for Arctic ice sheet history."

Introduction

Grosswald and Hughes continue to question the notion that the Bering Land Bridge was largely an ice-free landscape during the last glacial maximum (LGM). We welcome the opportunity to clarify our findings, which stand in the context of work across this region by scores of Russian and American geologists over the past several decades. The Bering land bridge is not an old concept, as they suggest; rather it is a fundamental bathymetric feature resulting from glacioeustatic sea level change across the wide continental shelves of the Bering and Chukchi Seas. Our work builds upon a large body of literature founded in field-based stratigraphic and geomorphic analysis complemented by the study of marine cores (e.g., Sancetta et al., 1985; Keigwin, 1998; Gorborenko et al., 2004). Especially for the LGM, radiocarbon dating provides the strongest control we have for determining the context and paleogeography of valley glacier complexes over local mountain ranges as well as the continuous deposition of sediments and organic materials in many nonglaciated regions. Grosswald and Hughes suggest that the LGM ice extent in Alaska and northeast Chukotka is not constrained by careful radiocarbon dating, yet their papers (e.g., Grosswald, 1988, 1998; Grosswald and Hughes, 1995, 2002) do not thoroughly cite or even attempt to reinterpret the physical evidence found in countless publications that document this control. Some of the older work has most recently been reviewed by Hamilton (1994) and Kaufman et al. (2003) and is found in papers included in edited volumes (Elias and Brigham-Grette, 2001; Anderson and Lozhkin, 2002, and others).

Tanyurer River Valley

We are delighted that Grosswald and Hughes agree that the extent of ice in the Pekulney Mountains and Tanyurer Valley north of the Anadyr River was very limited during the LGM (Brigham-Grette et al., 2003). The Tanyurer River valley is especially relevant to the question of ice extent across all of western Beringia because in several papers (most recently Grosswald and Hughes, 2002), Grosswald and Hughes present LGM ice sheet maps that suggest extensive ice across this region. We, along with most Russian field workers (e.g., Anatoly Lozhkin, Anatoly Kotov, personal communication, 2004) consider the moraines Grosswald and Hughes identify in the southern Tanyurer Valley to be middle Pleistocene in age (Fig. 2, area C in Brigham-Grette et al., 2003). When these moraines were occupied in the middle Pleistocene they likely did dam a proglacial lake in the vicinity of Krasnoye Lake, as Grosswald and Hughes describe, but these moraines are not LGM in age. Instead, they are covered by a thick blanket of extensive loess, have slope angles that are only a few percent, and are cross-cut by fluvial terraces radiocarbon-dated to more than 36 ka BP. Pat Anderson and Anatoly Lozhkin (personal communication) have cored Melkoye Lake and a smaller lake (Malyii Krechet) and found in shallow depressions on top of these moraines. In addition, marine and fluvial terraces along the Anadyr River at the south edge of theses moraines are middle Pleistocene to middle Holocene in age (Svitoch, 1976); that is, the moraines are older than the terraces.

Style of Regional Glaciation

We strongly disagree with the interpretation that all of the valleys across Chukotka form clear north–south trending glacial troughs created by a Beringian ice sheet. Throughout much of Chukotka, the valleys are more irregular in distribution than they describe; Heiser and Roush (2001) show this based on their mapping of the *entire peninsula* with SAR imagery. Glushkova's (2001, and references therein) surficial mapping/remote sensing work and Ivanov's (1986) stratigraphic work clearly show that alpine glaciation emanated radially from these mountain centers. Moreover, we have dated undisturbed marine sequences around the coast to more than 40 ka (Brigham-Grette et al., 2001). Submerged moraines suggest that through several glacial cycles, Lavrentiya Bay was occupied by ice flowing from west to east out of the Tenyanniyy Range that terminated some 10–20 km offshore (Fig. 1). Several different workers have mapped these moraines using seismic data and bathymetric maps (see Fig. 6 in Brigham-Grette et al., 2001).

Glaciers in the mountainous regions of Seward Peninsula, Alaska, also emanated radially from centers of

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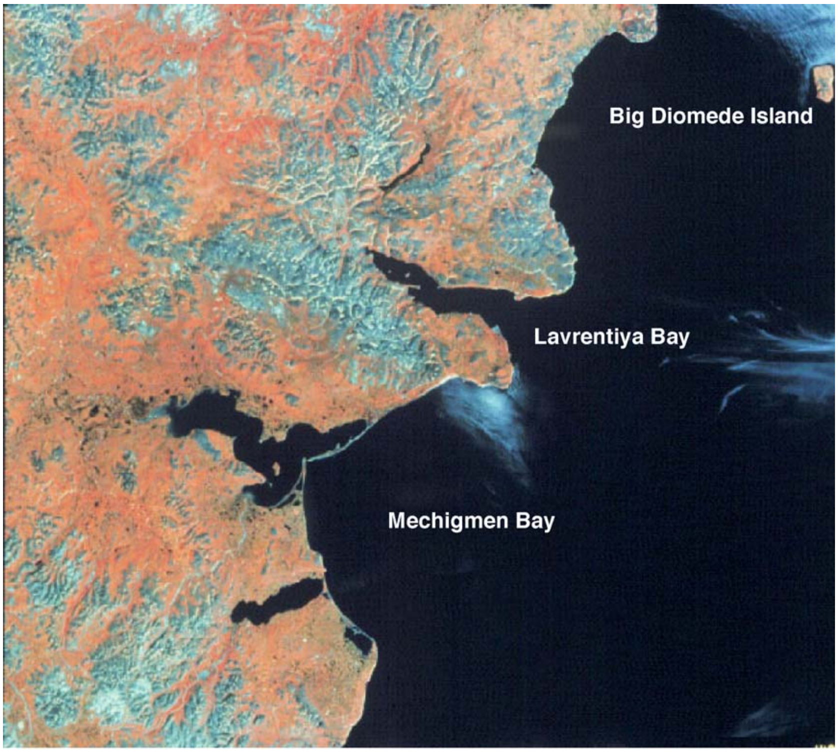

Fig. 1. Land-Sat image (1991) of easternmost Chukotka Peninsula in the middle of the Bering Strait. Lavrentyia Bay contained ice moving from local mountain centers eastsoutheastward down the bay toward the Bering Strait. The large lake south of Mechigmen Bay is dammed by a moraine constructed by ice flowing from southwest to northeast toward the bay.

accumulation (see http://instaar.colorado.edu/QGISL/ak_paleoglacier_atlas/). Numerous lakes found across the northern half of the Seward Peninsula enclose sediments that were deposited continuously throughout the LGM, the most well-known of which is Imuruk Lake, a basin that contains a dated, continuous record back through the last interglaciation (Colinvaux, 1967; Shackleton, 1982). Most remarkable about this terrain is the preservation of the LGM landscape across the northern Seward Peninsula found buried beneath a thick tephra from the eruption of the Devil Mountain Maars, radiocarbon-dated to 18 ka yrs ago (Goetcheus and Birks, 2001). The widespread dispersal of this tephra could *not* have occurred under a Beringian ice sheet and it is even harder to imagine how a marine-based ice sheet could have skirted around the edge of western and northwestern Alaska without leaving evidence, given that the Bering Strait is not a narrow confining deep trough. In the Bering Strait itself, structural deformation of a narrow band of beach deposits and tills on northern and western St. Lawrence Island clearly indicate that glacial ice encroached onto the coast from the northwest, not the north, before the LGM (Brigham-Grette and Hopkins, 1995). Minimum surface exposure ages of 36 to 254 ka BP on Little Diomede Island, north of St. Lawrence Island, indicate that it has not been recently covered by ice (Gualtieri and Brigham-Grette, 2001).

Lack of Glacioisotatic Uplift

Some of the strongest evidence against a Beringian ice sheet, or even an ice stream through Bering Strait, as Grosswald and Hughes suggest, is the complete lack of support for any postglacial rebound from such an ice mass. Heiser (1997) showed that had such an ice sheet actually existed, it would have left shorelines displaced by up to tens of meters around the coasts of Chukotka and Seward Peninsula and northward along the northwest coast of Alaska. She suggests that near the center of the ice sheet, relative sea level should have dropped some 15–20 m due to glacial isostasy in the past 5 ka; near the margin of the ice sheet (e.g., Cape Espenberg) sea level would have risen 6 to 13 m over the past 5 ka as a consequence of forebulge collapse. However, studies around these coasts have failed to find shorelines of the right postglacial age and altitude (Brigham-Grette et al., 2001; Ivanov, 1986). In fact, more than 200 ^{14}C dates have been published documenting the late Holocene age of nearly 13 major beach ridge complexes found between the mouth of the Yukon River and Barrow, all found at elevations of 3 m or less, the same as modern storm beaches (Mason and Jordan, 2002). Coastal stratigraphy and archeological investigations around eastern Chukotka indicate that sea level 7 ka ago was still some 10 m below the present and terrestrial peats near sea level have been accumulating continuously since at least that time (Dinesman et al., 1999). Consistent with the lack of any regional glacioisotatic adjustment are relative postglacial sea level records for the Laptev Sea shelf (Bauch et al., 2001) and records from the Chukchi Shelf (Elias et al., 1992; Brigham-Grette and Lundeen, new unpublished data).

Megafauna during the LGM

Consistent with the evidence for limited LGM ice are scores of radiocarbon ages ranging from older than 40 ka to as young as 3800 yr on mammoth tusks, bones, and tooth enamel from Wrangel Island and areas around the East Siberian Sea (Long et al., 1994; Sher, 1995; Sulerzhitsky and Romanenko, 1999; Vartanyan et al., 1993). The numerical age distribution demonstrates, without a doubt, that mammoths thrived and died both on Wrangel Island and in nearby regions continuously through the last full glacial cycle. These mammoths did not live beneath a Beringian ice sheet; rather, their survival indicates that the emergent Chukchi shelf—the northern edge of the Bering Land Bridge—supported vegetation rich enough in grasses and forbs (the great "mammoth steppe") to have sustained these populations. Mammoths also inhabited the arctic on the Taymyr Peninsula and the northern Siberian lowlands west of Wrangel Island, along with populations of horse, steppe bison, moose, and wolf dating almost continuously from 9600 ka to 46 ka ^{14}C yrs BP (MacPhee et al., 2002).

Wrangel Island

Evidence for the lack of glacial ice on Wrangel Island during the LGM is central to the issue of a Beringian ice sheet. Gualtieri et al. (2003) specifically targeted the low-lying northern coast of Wrangel Island for fieldwork to test the hypothesis that marine sediments on this landscape might contain the postglacial rebound history of a possible Beringian ice sheet. Having spent two field seasons on the island with Sergey Vartanyan, a geologist who has worked there for 15 summers, we are convinced that the island was not glaciated during the LGM; instead, we found evidence for one or two small cirque glaciers less than a few kilometers long. The island contains no evidence for postglacial isostatic rebound; marine deposits covering the northern half of the island, dated by a variety of methods (amino acids, radiocarbon, ESR, micropaleotological assemblages, etc.), are nearly all last interglacial in age or older; and weathered tors on the island provide minimum exposure ages of 65 ka or older from a variety of elevations (Karhu et al., 2001; Gualtieri et al., submitted for publication). We do agree that Wrangel Island experienced widespread glaciation in the past. In fact, similarly to Grosswald and Hughes' Fig. 2, we also saw striated rocks frost-churned to the surface on broad uplands, but this ice cover occurred *long before the LGM* and more likely during the middle Pleistocene and/or earlier. Even so, if such widespread glaciation of Wrangel Island occurred in the distant past, no evidence of a raised marine record is known.

Fig. 2. Hundreds of tors more than 6 m high litter the low hills of northern Chukotka for more than 150 km of the coastal mainland south of Wrangel Island (photo: JBG).

The valleys of Wrangel Island, like those shown in Grosswald and Hughes's Fig. 1, are all structurally controlled by bedrock with glacial modification. We located arcuate bedrock hogbacks that could easily be misinterpreted as small moraines if viewed only in air photos. While we agree that the island probably experienced widespread glaciation in the past, perhaps before the middle Pleistocene, we *did not* find evidence such as fields of striated "quartzose" erratics in the Nasha Valley. Devonian quartzite and Upper Proterozoic rocks of the Wrangel Complex do contain granite and are exposed on Wrangel Island (Kos'ko et al., 1993), so they are not necessarily erratics from off the island. On the coast of northern Chukotka just south of the island we observed literally hundreds of thin pillar-shaped tors 6–10 m high across a distance of more than 150 km, and we think it is highly unlikely that these tors would have all survived being overrun by a Beringian ice sheet (Fig. 2) despite the cautions of Briner et al. (2003).

An Arctic Ocean ice sheet exiting Bering Strait?

Lomonosov Ridge ice scours are now shown by Jakobsson et al. (2003) to be older than the last interglaciation and probably marine isotope Stage 6 in age. It remains to be tested if this is true of the Chukchi cap scours documented by Polyak et al. (2001). The likelihood of thick ice shelves or over-thickened sea ice over the Arctic Ocean during the LGM appears to be the current best explanation for the sterility and low sedimentation rates seen in many Arctic Ocean cores (Jakobsson et al., 2003, and references therein). However, this does *not* mean that a floating ice mass or arctic "white hole" a kilometer thick forced its way across the Chukchi shelf, up the north slope of Alaska, and through Bering Strait. The Alaskan North Slope up to an elevation of nearly 60 m above sea level is blanketed by the Pliocene/Pleistocene Gubik Formation, a marine sequence recording repeated intervals of high sea level during warm interglacials (Dinter et al., 1990; Brigham-Grette and Carter, 1992). Glacial boulders with striations observed and mapped by Leffingwell (1919, p. 147) up to 7 m above sea level *are not LGM in age* but are known to be part of the Flaxman formation. The deposit is glaciomarine in origin, containing large ice-rafted erratics from the collapse via the Admunsen Gulf of an early Laurentide ice sheet during MIS 5a, about 75 ka yrs BP (Brigham-Grette and Hopkins, 1995). The Russian arctic coasts of the East Siberian Sea and the Laptev Sea were also not glaciated from the north (cf. Svendsen et al., 1999). Sher et al. (2003) document hundreds of ^{14}C-dated mammoth bones, showing that during the LGM, mammoths inhabited the Laptev Sea shelf lands. Past evidence for widespread nonglacial LGM environments is well documented on the Lena Delta, the Yana Delta, and parts of the Taymyr Peninsula and Severnaya Zemlya (review Hubberten et al., 2004).

Field evidence and model validation

While Grosswald and Hughes suggest that some ice sheet models and CCMs can generate circumarctic ice sheets, we argue that none of these models generate ice sheets entirely compatible with the physical stratigraphy (cf. articles in Quaternary International 95/96, 2002). While coupled GCM–ice sheet models provide important information about "process," many models generate ice sheets in the wrong places because they fail to simulate atmospheric circulation and precipitation accurately. Marshall et al. (2002) show with modeling experiments how synoptic circulation and precipitation patterns during glacial build up play a critical role in modeled ice extent. Working with field geologists, Siegert and Marsait (2000) suggested that the increased height and size of the LGM Scandinavian and Barents Sea ice sheets precluded the penetration of warm moist air into the Russian far north, creating cold, dry, polar desert conditions from the Kara Sea eastward to Beringia consistent with the modeling implications of Felzer (2001). Moreover, we differ with Grosswald and Hughes' generalization that some Alaskan archeologists favor the notion that human migrations into North America were delayed until after 12 ka due to an ice sheet barrier in Bering Strait. We instead point them to Madsen (2004), focused on the notion that humans may have migrated before or even during the LGM. From our perspective, there was little in the way of habitat restrictions or ice sheets to block human migrations in western and central Beringia (Brigham-Grette et al., 2004).

We disagree with the notion of Grosswald and Hughes, who advocate the presence of a Beringian ice sheet to explain the occurrence of LGM ice-rafted debris in marine cores from the North Pacific. Glaciers reached tidewater in a number of regions around the North Pacific during the LGM, including most of the mountainous southern coasts of Alaska, the Aleutian Islands, and the Kamchatka Peninsula (review by Mann and Hamilton, 1995). We know from field work in the Koryak Mountains bordering the western Bering Sea that LGM ice likely reached tidewater along this coast and was likely a source of IRD, but ice was limited in extent on the north side of the mountains (Gualtieri et al., 2000). The continuous deposition of marine sediments for more than 350,000 yr in the Sea of Okhotsk (Nürnberg et al., 2003; Nürnberg and Tiedemann, in press) precludes that this region was ever covered by a large ice sheet during the late Pleistocene, and consequently it was not itself a source of IRD; rather IRD could come from Kamchatka (see also Grosswald and Hughes, 2002, pp. 133–134).

Discrepancies between global ice volume estimates and observed eustatic sea level lowering at the LGM do not require that the missing ice volume be found "on the continental shelf and adjacent mainland of Arctic Siberia, the Bering Sea and in the Sea of Okhotsk" as Grosswald and Hughes suggest (see also Grosswald and Hughes, 2002). Clark and Mix (2002) make it clear there is more to be learned about the global extent and thickness of past ice sheets. There is no implicit reason to suggest that the “missing ice” was in NE Siberia.

Summary

The Bering Land Bridge in the heart of Beringia was a vast ice-free landscape that stretched for more than 1000 km north–south between the Arctic Ocean and the deeper Bering Sea during the LGM. Field-based observations and stratigraphy backed by hundreds of radiocarbon dates document the surficial processes that acted on this landscape as well as the megafauna that grazed there. We argue that if Grosswald and Hughes would examine the physical evidence, as we have only begun to outline here, and perhaps attempt to reinterpret that evidence rather than just dismiss it, they would realize that the late Pleistocene history of Beringia has its own “gold standard.”

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