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Letter to the Editor

Comments on 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, northeast Siberia and implications for the presence of an East Siberian ice sheet."

Brigham-Grette et al. (2003) and Gualtieri et al. (2003) aimed at strengthening the concept of the Pleistocene Bering land bridge, a broad ice-free corridor open for Asian migrations to the Americas during the last glacial maximum (LGM). They add to numerous supporting papers that appeared in the wake of the "Bering Land Bridge" by Hopkins (1967), including a special issue of *Quaternary Science Reviews* (Vol. 20, 2001). We wish to broaden the discussion.

Our first point is that a consensus is growing among Quaternary geologists that many scores of ^{14}C dates in tightly controlled and mapped stratigraphic succession are necessary before firm conclusions can be drawn regarding the glacial history of a region. That kind of control does not exist even in Alaska, let alone in northeast Siberia. Wrangel Island, discussed in one of the two papers we wish to address, is on the Arctic continental shelf, so if evidence abounds that it had been extensively glaciated, a marine ice sheet would have covered the island. The "gold standard" for mapping and dating a former marine ice sheet was established by Denton and Marchant (2000) and Hall and Denton (2000) for the West Antarctic ice sheet in the Ross Sea embayment. They provided the dated control that guided Denton and Hughes (2000, 2002) in their reconstruction of the ice sheet at the LGM. Another example of this kind of control has documented the extent of a marine ice sheet in the Barents Sea at the LGM (Svendsen et al., 1999). Without such control, a case can be made that both Scandinavia and Britain were unglaciated at the LGM, as Vasil'chuk and Kotlyakov (2000) have argued on the basis of early and scattered radiocarbon dates.

We accept the ^{14}C and cosmogenic isotope ages of Brigham-Grette et al. (2003) for glaciogenic formations from the Pekulney Mountains and the lower Tanyurer River valley, central Chukchi Peninsula. Their work leaves little doubt that there were valley-type glaciers there during the LGM. However, Brigham-Grette and her co-authors (the Russian–American Group, or simply the Group) generalize from that Pekulney evidence that the LGM Chukchi glaciation was restricted to highlands. This conclusion is incompatible with our evidence that an extensive marine ice sheet crossed the Beringian lowlands from the north (Grosswald and Hughes, 1995, 2002).

Our main point of disagreement with these authors and the Group is their focus on mountain glaciers, while ignoring marine ice sheets. They look to highlands for the source of glaciation. We look to the sea. Members of the Group consider only glaciation that was *local* and *terrestrial*. The Group members invariably consider the Beringian glaciers, irrespective of their size (Hopkins, 1967, 1972; Glushkova, 1984, 2001), as centered on uplands and mountains. Finding that these glaciers were small, they assume that all surrounding lowlands and the land bridge were unglaciated.

In contrast, we distinguish between terrestrial and *marine* glaciations of the Chukchi Peninsula. We agree that the Chukchi uplands, including the Pekulney Mountains, supported their own glaciers, but we see that an enormous marine ice sheet originating in the Arctic Ocean had invaded the rest of the peninsula and the adjacent continental shelf (Grosswald and Hughes, 2002). In our interpretation of aerial photographs, marine ice moved in a N to S direction, parallel to and independent of the Pekulney Mountains; it covered and crossed, on a broad front, the latitudinal valley of the Anadyr River. Farther south, it invaded the basin of Lake Krasnoye and pushed water across the mountain ridge that partly circled the lake. In the north, this ice rode over the 1100-km-long latitudinal Chukchi Range, breaching it by a score of through valleys (Figs. 14, 16, Grosswald and Hughes, 2002). A fragment of southward-flowing ice was identified by Heiser and Roush (2001) near the Chukchi Range on SAR imagery, but their view was too narrow to follow ice flow further south. The largest of the breaches was through the Bering Strait, which could not accommodate the entire volume of the passing ice because ice also pushed sideways and intruded landward into the Senyavino fjords, crossed a prominent corner of the Chukchi Peninsula, and exited by way of Provideniya Fjord into the Gulf of Anadyr (Fig. 17 of the same paper). The nature, extent, and age of this marine ice sheet are independent of glaciers in the Pekulney Mountains.

If we take a broader view of the East Arctic glacial system, and include not only Beringia and NE Siberia, but also the adjacent Arctic Ocean, we realize that such an invasion of Beringia by marine ice was inevitable. Indeed, the Arctic Ocean was covered by a kilometer-thick floating ice shelf (Grosswald and Hughes, 1995, 1999; Polyak et al., 2001), which moved poleward from the Queen Elizabeth Islands,

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Fig. 1. An oblique air photograph of central Wrangel Island, looking north. Note the typical Lapland-style glacial geomorphology of the Island. Photo by Roman Zlotin, Institute of Geography RAS, Moscow, Russia.

northern Greenland, and Barents and Kara Seas, crossed the submarine Lomonosov Ridge, and invaded East Siberia, Beringia, and North Alaska. This became indisputably clear from the orientation of drumlins and flutes on a glaciated crest of Lomonosov Ridge, as well as from the position of an accumulation prism on its Amerasian slope (Polyak et al., 2001). This floating mass of ice was a part of the Arctic "white hole" because its mass balance was pronouncedly positive (Grosswald, 2003; Grosswald and Hughes, 1995; Hughes, 1998). Thus it inevitably pushed against the Arctic coast of Beringia, forcing its way through Bering Strait, as seen from scour of its banks and bottom (Creager and McManus, 1967; Grosswald et al., 1999), and thrusting up the continental margins, as an adjustment to ice pressure from the north. Traces of this thrusting are ubiquitous; they include glacial boulders pushed up the north slopes of Alaska (Leffingwell, 1919) and the Chukchi Peninsula (Grosswald et al., 1999), glaciotectonic features of New Siberian Islands and the Kolyma Delta (Grosswald, 1990), and other dated evidence (e.g., Grosswald et al., 1992).

This marine ice sheet, having been a complex dynamic system, reacted nonlinearly, often cataclysmically, to external forcing, in particular to gradual increase of its mass. Thus the chronology of the marine ice advances upon East Siberia, Beringia, and Alaska was controlled not only by climate change but also by the life cycles of the system. So the ages of local terrestrial glaciers, even if obtained by the most sophisticated techniques, allow no conclusions regarding glaciation produced by a marine ice transgression (Hughes, 1986, 1998) of the same or other ages. Brigham-Grette et al. (2001) dated a major glacial advance on the Chukchi Peninsula to a cold episode within marine oxygen isotope stage 5, not to stage 2. They hypothesized that this was a time when seas were warm but summer insolation was low, so a general pan-Arctic glaciation was initiated, beginning in the highlands. We, by contrast, think that this chronology, if it is correct, reflects not a peculiar climate of the eastern Arctic, but major changes of the Arctic glacial system due to its nonlinear response to external forcing.

Our Arctic ice sheet reconstruction at the LGM is based on our interpretation of glacial geology. We are not alone. Practically all modeling experiments based on the past glacier mass balance and CCMs also generate circum-Arctic ice sheets at the LGM, including a Beringian ice sheet (e.g., Bintanja et al., 2002; Budd et al., 1998; Greve et al., 1999; Lindstrom, 1990). In addition, some Alaskan archaeologists find the Beringian ice sheet more consistent with their evidence that human migration across the land bridge was delayed until 12,000 yr ago (e.g., Bonnichsen and Turnmire, 1998), even though a hazardous marine crossing to Australia was accomplished >60,000 yr ago. We think a marine ice lobe blocked the land bridge until 12,000 yr ago (Hughes, 1998; Hughes and Hughes, 1994; Hughes et al., 1991).

Finally, without a marine Beringian ice sheet, as well as the adjacent marine ice sheet in the Sea of Okhotsk (Grosswald and Hughes, 1998), where could one find the sources of vast iceberg armadas that totally modified the sedimentary environment of the North Pacific, including the coastal zone of Japan, between 2.6 myr ago and the Holocene (Kotilainen and Shackleton, 1995; Leg 145 Scientific Party, 1993; Okada, 1980)?

We think that Gualtieri et al. (2003) pose more questions than they answer. One of the raised marine features they describe on Wrangel Island is older than 0.5 myr. How could it survive for so long a time? This "age" highlights the faulty nature of the Group's dating techniques and makes us doubt whether the landforms in question are genuine marine shorelines. The second set of *raised* features and its eustatic origin are inconsistent with their age. This suggests (if the Arctic was connected with the World Ocean, as they believe) that sea level was then some 60–80 m below the present. Our explanation would be glacial-isostatic depression of Wrangel Island by a marine ice sheet.

An ice-free Wrangel Island is totally inconsistent with its Lapland-style geomorphology (Fig. 1), which is ubiquitous wherever one looks in regions not covered by solifluction aprons, in particular the broad trough valleys, alpine peaks

Fig. 2. A typical erratic boulder from Wrangel Island: a glacially sculptured, faceted, and scratched pink quartzite, 70 cm long, from the upper reaches of the Nasha River through near center of landscape presented in Figure 1. Photo by M. Grosswald.

of island mountains, and fields of big scratched and faceted erratics of quartzose and granite (Fig. 2) in the upper reaches of the Nasha River. In Fig. 11 of Grosswald et al. (1999), one can see fresh washboard moraines and other glacial forms produced by ice push southward from Wrangel Island, and Polyak et al. (2001) have identified morainic ridges on the submarine Chukchi Cap north of Wrangel Island.

As a concluding point, we call attention to the growing evidence that global sea level was up to 140 m lower 22,000 to 20,000 cal yr B.P. than today (Lambeck and Chappell, 2001). Where were the ice sheets that provided the additional 20 m of sea-level lowering below the traditional value of −120 m at the LGM? We argued that the only location for additional LGM ice was the continental shelf and adjacent mainland of Arctic Siberia, the Bering Sea, and in the Sea of Okhotsk (Grosswald and Hughes, 2002). Those who disagree need to propose a more likely location for the additional LGM ice and provide arguments to support their assertion. They also need to square their view that a stable dry climate has always existed in northeast Siberia, keeping it largely unglaciated, with the growing evidence for extreme climate variability, marked by iceberg outbursts, in the North Pacific (Kotilainen and Shackleton, 1995; Mix et al., 1999).

A possible reconciliation of the two views may lie in the hypothesis that the high Arctic in general and the Siberian arctic in particular are climatically unstable regions in which small perturbations in climate and other forcing may produce large changes in the extent of glaciation (Hughes, 1995). The whole region is a “white hole” that collects the bulk of precipitation over not only the Arctic, but also within the watersheds of rivers that empty into the Arctic (Hughes, 1998). Fluctuations around the margins of a Pleistocene Arctic ice sheet centered on a thick ice shelf floating in the Arctic Basin would occur mainly when discharge of ice and water from these watersheds found outlets through spillways that opened and closed, creating catastrophic responses to gradual forcing such as glacioisostatic changes and slow changes in sea level and climate (Hughes, 1998; Grosswald, 1999). Highland glaciation of the kind reported by Brigham-Grette et al. (2003) would be “blind” to these changes at lower elevations.

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