Evidence for restricted ice extent during the last glacial maximum in the Koryak Mountains of Chukotka, far eastern Russia

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ABSTRACT

Field evidence in the Koryak Mountains–Lake Mainitz region of far eastern Russia supports three Pleistocene glacial advances. The early Wisconsinan and pre-Wisconsinan glaciations are represented by broad lobate moraines extending as much as 30 km north of the Koryak Mountains. Field evidence demonstrates that the terminal, lateral, and medial moraines, as well as meltwater channels, dead ice topography, kettles, and outwash plains mark the extent of ice during the last glacial maximum (LGM), during which glaciers reached no more than 20 km beyond their present limits. Those emanating from the southern Koryak Mountains may have reached the Bering Sea. Numerical and relative dating techniques support these results and test the theoretical models of the LGM in western Beringia. Erratics on moraines and glaciofluvial terraces, common to all valleys at 13–13.8 m above river level, yield 36Cl exposure ages ranging from 10.08 to 25.78 ka. The Koryak Mountains–Lake Mainitz record of glaciation is spatially and temporally consistent with the glaciation pattern across central Beringia found in other terrestrial and marine records. Glacier growth in the Koryak Mountains was sustained by possible increased summer sea surface temperatures and precipitation in the northwest Pacific region. Evidence from the northern Koryak Mountains (lat 64°N, long 177°E) indicates that the extent of ice in western Beringia was limited to mountain and valley glaciers during the LGM. This field-based research contradicts M.G. Grosswald’s theoretical Beringian ice sheet hypothesis.

Keywords: Beringia, Chukotka, cosmogenic elements, erratics, glaciation, northwest Pacific.

INTRODUCTION

The distribution of past glacial ice in Chukotka (Fig. 1) is poorly known and controversial. One hypothesis is that during the last glacial maximum (LGM, ca. 20 ka) a single ice sheet covered the entire Arctic Ocean and coalesced with ice caps on Chukotka and other circum-Arctic landmasses (Grosswald and Vozovik, 1984; Grosswald, 1988, 1998; Hughes and Hughes, 1994; Grosswald and Hughes, 1995). This so called maximum model of Arctic ice is unsupported by field evidence, yet variations are commonly used in climate models to illustrate global ice distribution during the last glaciation (Peltier, 1994; cf. Kotilainen and Shackleton, 1995; Hughes, 1996; Grosswald, 1998). Another hypothesis for the LGM in circum-Arctic areas is that ice was limited in extent to mountain and valley glaciers, the Arctic Ocean had a cover of sea ice, and glaciers extended a minimal amount (to 20 km) beyond their present margins (Hamilton, 1986; Kaufman and Hopkins, 1986; England, 1992; Brigham-Grette et al., unpub. data). The latter theory is supported by field-based studies and, in most cases, this research is chronologically constrained by detailed stratigraphic work.

In order to test the two competing hypotheses, our studies focused on the Koryak Mountains (1062 m) as well as the Nahodka, Nychekveem, Gitgivem, Rocamaha, and Lake Mainitz valleys (Fig. 2). In addition, the stratigraphy along the Cape Dionysia coastline (Fig. 2) was investigated. Field work was undertaken during the summers of 1995 and 1996.

The purpose of this paper is to describe the glacial history of the Koryak Mountains (lat 64°N, long 177°E) using modern chronological tools to supplement existing Russian work. This paper also presents field evidence opposing a Beringian Ice Sheet as proposed by Grosswald (1998) and argues that the extent of ice during the LGM in Chukotka was restricted.

PREVIOUS WORK

The Bering Strait region has had a significant influence on past Arctic climate change, especially with respect to changes in paleoceano-graphic and atmospheric currents and the migration of flora and fauna. Throughout the late Pliocene and early Pleistocene, the Bering-Chukchi platform was alternatively submerged and emergent due to fluctuations in sea level. The last time the land bridge linked Asia to North America was ca. 11 ka (Hopkins, 1959; Dyke et al., 1996; Elias et al., 1996, 1997).

Although much field work has been done in Alaska and other parts of eastern Beringia (Fig. 1), western Beringia has remained unstudied in terms of modern, field-based, glacial geology. Previous work by Russian scientists (Arkhipov et al., 1986a, 1986b; Bespaly, 1984; Ivanov, 1986; Glushkova, 1992) was based on air photo interpretation and stratigraphic studies with limited field work in scattered locations. Most previous studies lack numerical age control of the glacial history, with the exception of radiocarbon age estimates on deposits associated with deglaciation.

Maps by Arkhipov et al. (1986b) that summarized the morphological type of late Pleistocene glaciation illustrated the Koryak Mountains as areas typical of valley- and cirque-type glaciers. Bespaly (1984) concluded that the Sartan glaciation (late Wisconsin equivalent) in Chukotka was only half the size of the Zyryan (early Wisconsin equivalent) and that Sartan glaciers never extended beyond the foothills of the Koryak Mountains. Glushkova (1992) suggested that the maximum extent of glaciation in Beringia found in other terrestrial and marine records.
undertaken independent of the inland glacial on sites scattered throughout Chukotka and were throughout Chukotka. (SAR) to distinguish among glacial advances during the last glacial maximum and that an<br>pedogenic study confirmed that ice was limited by seismic transects across the Chukchi Sea and<br>continental shelf during the last glaciation. Mostoller’s (1997) moraine morphometric and<br>ers, and that these glaciers did not reach the Chukotka supported valley and piedmont glaci-<br>Glushkova (p. 339, 1992) concluded that the snowline in Chukotka was 150–300 m higher during the Sartan than the Zyryan glaciation, although “there is still no prevailing idea on the number of glacial epochs, character and scale of glaciation, glacial geography, and age boundaries.” Glushkova also interpreted the Koryak Mountains–Lake Mainitz region as characterized by valley glaciers (Glushkova, un-pub. map).<br>The absence of glacial sediment as interpreted by seismic transects across the Chukchi Sea and northern Bering Sea (Fig. 1) by Biryukov et al. (1988) indicate that the mountainous regions of Chukotka supported valley and piedmont glaciers, and that these glaciers did not reach the continental shelf during the last glaciation. Mostoller’s (1997) moraine morphometric and pedogenic study confirmed that ice was limited during the last glacial maximum and that an older, more extensive (mid-Pleistocene) ice cover existed in the Tanyurer River valley (Fig. 2) to the north of the Koryak Mountains. This work is also supported by Heiser (1997) who used satellite synthetic aperture radar (SAR) to distinguish among glacial advances throughout Chukotka.<br>Studies of the coastal stratigraphy were based on sites scattered throughout Chukotka and were undertaken independent of the inland glacial<br>Glushkova (1988) indicate that the mountainous regions of the northern Bering Sea (Fig. 1) by Biryukov et al., 1993). Lozhkin and Anderson (1995) concluded that the previous work by Russian scientists is incomplete in terms of the sequence and timing of marine deposits. Studies by Brigham-Grette et al. (un-pub. data) on the coastal stratigraphy to the north of the field area, along the outer Chukotka Peninsula, indicate that the previous work by Russian scientists is incomplete in terms of the sequence and timing of marine deposits. Palynological studies indicate that significant differences in the timing of vegetation and possibly climate change across Beringia occurred throughout the late Quaternary (Lozhkin et al., 1993). Lozhkin and Anderson (1995) concluded from paleovegetation patterns in northeastern Russia that seasonal precipitation was slightly greater and mean January temperatures were as much as 12 °C higher than present during the last interglaciation. This conclusion may help to explain why some ice advances throughout the Pleistocene were significantly more extensive than others. For example, the increase in moisture availability at the end of the last interglaciation may be a significant factor affecting the size and duration of Wisconsi-nan glacial advances and episodes. During the transitional period between the LGM and the Holocene interglaciation conditions, Betula was dominant in eastern and central Beringia, but was possibly absent from western Beringia (Lozhkin et al., 1993). Although we know that these changes occurred, we do not know why they existed. What was the difference in climate between western and eastern Beringia throughout the Pleistocene?<br><br>REGIONAL SETTING<br>Weather patterns in Chukotka are relatively erratic due to the influence of the Arctic anticyclone, as well as the confluence of the Siberian anticyclone and Pacific cyclone, particularly in the Koryak Mountain region. The presence of the Aleutian Low to the southeast also plays an important role in delivering moist air to the region. Climatic records spanning 55 yr from two

### Figure 1. Map of Beringia with place names. Core locations are marked in the Sea of Okhotsk, Bering Sea, and Pacific Ocean. BS—Bering Strait; BG—Bering Gyre; CB—Cold Bay; AP—Alaska Peninsula; AK—Ahklun Mountains; and C—Cook Inlet. Study area and Figure 2 location are shown in the box. The area in gray is the Meiji drift. Heavy black arrows indicate dominant ocean circulation.
World Meteorological Stations near the study area (Anadyr, 64.8°N, 177.6°E, and Markova 64.7°N, 170.4°E) provide mean annual temperature and precipitation data for the region. Mean annual temperatures are –8 °C and –10 °C, respectively, and mean annual precipitation for the two areas is 279 and 331 mm, respectively. Present snowline elevations on the northern and southern flanks of the Koryak Mountains are ~600 and 380 m, respectively.

The study area is in a zone of continuous permafrost with abundant ice wedges in river bluffs. The range of typical mean annual ground temperatures is –1 to –5 °C (Brown et al., 1997). In the Koryak uplands, the permafrost is as much as 100 m thick (Gasanov, S.S., 1969), but in northern Chukotka thicknesses can be between 230 and 700 m (Brown et al., 1997). Two soil pits at the top of the Cape Dionysia bluffs indicate active layer depths of 27 and 32 cm overlain by 18–32-cm-thick organic mats.

**METHODOLOGY**

**Surficial Mapping**

Study of Landsat images from 1972 and 1973 allowed the choice of field areas showing well-defined glacial landforms. Field areas were also selected on the basis of accessibility by helicopter, boat, tracked vehicle, and/or on foot (Fig. 2). Terrace heights were determined by hand-leveling. Equilibrium line altitudes (ELA) were determined for comparison by three different methods: area accumulation ratio (AAR) of 0.55–0.58, toe-to-headwall area ratio (THAR), and maximum elevation of lateral moraines (MELM).

**Amino Acid Analysis**

Amino acid geochronology was used to determine the relative age of marine mollusks in glacio-marine sediment with focus on whole valves of the genera *Astarte*, following the rationale outlined by Miller and Brigham-Grette (1989). Although *Astarte* are susceptible to the leaching of amino acids (Roof, 1997), this was the most ubiquitous and well-preserved species present in all samples. There were 75 analyses completed on *Astarte* from 16 samples along the Cape Dionysia shoreline. Preparation of shells for amino acid analyses followed standard techniques used in many labs (Kriausakul and Mitterer, 1978; Schroeder and Bada, 1976; Miller and Hare, 1980; Miller and Brigham-Grette, 1989; Mitterer and Kriausakul, 1989).

**Moraine Morphometry**

Moraine morphometric studies, following the methodology of Kaufman and Calkin (1988) and Peck et al. (1990), were carried out on all terminal and lateral moraines. Measurements included distal and proximal slope angles, and crest width at two or three sites per moraine. Kaufman and Calkin (1988) concluded that average slope angle is the best single distinguishing criterion and that with just a few measurements, moraines can be subdivided by relative age.

**Soil Pedogenesis**

Two soil pits, located on the crest and mid-slope, were dug on each moraine to compare soil development from each slope position as well as among moraines and terraces. Soil profiles were described and samples from each horizon were collected for particle size analysis. Soil age relationships were suggested by Tedrow (1977) and Catt (1986).

**Cosmogenic Nuclide Analysis (36Cl)**

The premise in using cosmogenic isotopes in the context of this paper is that glaciers erode, transport, and deposit erratics that had previously been shielded from cosmic rays. When the deposited rocks are uncovered, nuclides such as 36Cl are formed during spallation reactions between cosmic rays and major elements in the rock. We took 16 samples for 36Cl cosmo-
LAST GLACIAL MAXIMUM IN THE KORYAK MOUNTAINS OF FAR EASTERN RUSSIA

EVIDENCE FOR MULTIPLE PLEISTOCENE GLACIATIONS

Kankaren Range

The northern side of the Kankaren Range (Fig. 3) is marked by drift sheets from glaciers emanating from major north-south–trending valleys. Erratics of green and gray quartzite and granite occur on top of a 201 m basalt high (Fig. 4B). Broad lobate moraines extending to 30 km beyond (north of) the eastern Kankaren Range are visible on both SAR images and Landsat photos.

Lake Mainitz

Lake Mainitz is ~130 m deep, 16 km long, and is in a graben to the south of the Kankaren Range (Figs. 3 and 4B). The lake’s north-flowing outlet is the Gitgiveem River, which drains into the Nygechevkeem River. The major inlets to the lake are the Gitgipokeetkinveem and the Vorchin Rivers (Fig. 4).

Geomorphology. Prominent landforms near the lake include drift sheets from major tributaries (Fig. 4). The surface of one drift sheet, on the east side of the lake, is composed of an 11-cm-thick organic mat underlain by 24 cm of loam. The drift sheets enter the lake and culminate at points where modern spits exist. These spits are interpreted to be remnants of former deltas that drained meltwater runoff and other major glacial inflows into the lake. The spits to the north and south of Toomani Island were likely once connected to the island and have since been eroded and reworked by modern processes. Conglomerate and sandstone erratics, as well as till veneer, are present on the 268 m basalt high at the northern end of the lake (Fig. 4B). Southnorth–trending meltwater channels on Toomani Island and similar channels are cut into a lateral moraine on the west margin of the lake. Ice thickness in the Lake Mainitz basin was between 377 and 540 m, on the basis of ice modeling using the maximum elevation of glacial landforms. The paleo-ELA of the glacier in this valley was 305 m, determined by the THAR (0.5) methodology and, more realistically, 500 m, based on AAR (0.55) methodology.

Terraces. Two prominent terraces, 13.8 m and 6.9 m above the present lake level, occur around the perimeter of Lake Mainitz (Fig. 4B). The terraces are composed of silt and subangular to subrounded cobbles with varying lithologies. No soil development occurs on the terraces. The continuous surfaces are dissected by channels and kettle ponds in some places around the lake. Cosmogenic (36Cl) isotope analysis of rounded cobbles on the 13.8 m terrace yields ages of 10.08 ± 0.85 (96LM52) and 19.51 ± 2.27 ka (96LM53). Shells, or other dateable material, are not preserved around the lake.

Chronology and Interpretation. The drift sheets, remnants, deltas, erratics, and meltwater

<table>
<thead>
<tr>
<th>Sample</th>
<th>NR/S (E-15)</th>
<th>Error (%)</th>
<th>RICH age (ka)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cape Dionysia</td>
<td>303.5 ± 11.9</td>
<td>3.9</td>
<td>25.78</td>
<td>7.755</td>
</tr>
<tr>
<td>96CD13</td>
<td>298 ± 14</td>
<td>4.7</td>
<td>52.99</td>
<td>9.285</td>
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<tr>
<td>Nygechevkeem River Valley</td>
<td>96NK19</td>
<td>93.0 ± 5.5</td>
<td>5.9</td>
<td>13.52</td>
</tr>
<tr>
<td>96NK21</td>
<td>98.7 ± 5.7</td>
<td>5.8</td>
<td>15.51</td>
<td>7.768</td>
</tr>
<tr>
<td>96NK25</td>
<td>73 ± 10</td>
<td>14</td>
<td>21.65</td>
<td>15.54</td>
</tr>
<tr>
<td>96NK28</td>
<td>46 ± 6</td>
<td>13</td>
<td>19.76</td>
<td>14.39</td>
</tr>
<tr>
<td>96NK29</td>
<td>69.1 ± 4.7</td>
<td>6.8</td>
<td>11.59</td>
<td>9.533</td>
</tr>
<tr>
<td>96NK50</td>
<td>42.7 ± 2.8</td>
<td>6.6</td>
<td>10.62</td>
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<tr>
<td>Nahodka Valley</td>
<td>96CD38</td>
<td>70.8 ± 4.5</td>
<td>6.4</td>
<td>14.72</td>
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<tr>
<td>96CD39</td>
<td>90.1 ± 5.2</td>
<td>5.8</td>
<td>15.87</td>
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<tr>
<td>96CD40</td>
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<td>4.9</td>
<td>16.65</td>
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<tr>
<td>96CD41</td>
<td>87.3 ± 4.9</td>
<td>5.6</td>
<td>14.71</td>
<td>7.632</td>
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<tr>
<td>96CD46</td>
<td>80.5 ± 4.1</td>
<td>5.1</td>
<td>15.99</td>
<td>7.2</td>
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<tr>
<td>Lake Mainitz</td>
<td>96LM52</td>
<td>57.5 ± 3.3</td>
<td>5.7</td>
<td>10.08</td>
</tr>
<tr>
<td>96LM53</td>
<td>51.7 ± 5.3</td>
<td>10</td>
<td>19.51</td>
<td>11.61</td>
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<tr>
<td>Lake Rocamaha</td>
<td>96RM54</td>
<td>91 ± 7</td>
<td>7.7</td>
<td>10.85</td>
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Notes: NR/S—the normalized radionuclide/stable nuclide ratio and reported absolute error; RICH—rock in situ produced cosmogenic-nuclide history.
channels suggest that the structurally controlled Lake Mainitz basin was glaciated during the LGM by a glacier flowing from south to north and from the mountains on the east and west sides of the valley. The terraces, formed during a higher lake level, are cut into till. The till at the northern end of the lake marks the extent of ice. We envisage glaciers spilling over from the two main valleys feeding into the lake from the east and west. The west valley ice was probably an extension of the ice in the Nygchekeveem Valley. Although these valleys were not visited, the kettled landscape is similar to the kettled landscape to the north of the lake and suggests that it has been glaciated. This hypothesis is supported by the location of the spits, or remnant proglacial deltas draining the ice tongues. The ice tongues from the east and west either calved into a 13.8 m higher Lake Mainitz, or converged with ice flowing over the lake basin from south to north. This ice reconstruction is based on lateral meltwater channels, the south-north trough on Toomani Island, and the conglomerate and sandstone erratics on the 268 m plateau on the northwest side of the lake. This ice configuration fits with reconstructed ice elevations of ~500 m in the Nygchekeveem Valley and 500–530 m in the Lake Mainitz basin. The undated 18.4 and 27.5 m terraces of the Gitgiveem River valley are interpreted to be glaciofluvial, and composed of reworked till or outwash material originally deposited at the terminus of the glacier.

The chronology of the last glacial maximum in this basin is based on two \(^{36}\)Cl ages on cobbles from the 13.8 m lake terrace. The ages are minimums; however, the 10.08 ka \(^{36}\)Cl date may more accurately represent the age of the 13.8 m terrace. The 19.51 ka date probably represents inherited \(^{36}\)Cl in the rock. The younger date of 10.08 ka can be interpreted two ways. The first interpretation is that the 13.8 m terrace level was occupied for 9.4 k.y. and that the two dates represent different phases of terrace growth. If this is the case, the lake level would be 13.8 m higher until ca. 10 ka, when the lake level then dropped to 6.9 m above its present level. The absence of the 13.8 m terrace and the presence of a continuous 6.9 m terrace surrounding the Little Mainitz basin suggests that ice may have occupied that basin during the 13.8 m highstand, or between 19.5 and 10.0 ka. The two modern spits separating the Big and Little Mainitz basins are till or moraine remnants that previously dammed the lake, as ice was occupying the Little Mainitz basin. As the ice retreated, the lake level dropped to 6.9 m above present. Coring the lake would help answer some questions regarding the chronology of the lake levels. Work is presently being done by P. Anderson and A. Lozhkin on two nearby lakes, Lake Gitgikau and Patricia Lake.

The second interpretation of the \(^{36}\)Cl 10.08 ka date is that it is anomalously young, and that the cobbles had recently rolled, been frost-heaved ~10 k.y. ago from its original position, spalled, or weathered. Large, datable cobbles were difficult to find on the terrace surface, and some of the rock fragments from the best samples came from the sides of the rock that have been recently exposed to surface deflation. Relatively recent exposure of the sides of the rock, shielding of the lateral rock surface, or the edge effect would explain an anomalously young age (Zreda and Phillips, 1994; Dunne et al., 1999).
If this were the case, the duration of the 13.8 m lake highstand is unknown, as is the time of the lake lowering to the 6.9 m stand.

Whether the ice advance from the south is isochronous with the ice advances from the east and the west of Lake Mainitz is uncertain. Detailed studies in the intervening valleys, the Plaksivaya River (Fig. 4B), and the surrounding mountains, as well as coring of the lakes, would yield more definitive information. An investigation of the lowlands surrounding Lake Pekulneyskoye would also yield clues as to the glacier and/or marine interaction and sea-level fluctuations along this coastline.

**Rocamaha Lake**

Rocamaha Lake (Figs. 2 and 4A) is in a broad, U-shaped, tributary valley of the Gitgipokeetkinveem River, the major inflow into Lake Mainitz. Cirque floor elevations of four glaciers in the Lake Rocamaha region range from 380 to 500 m. Proximal and distal slope angles on an unconsolidated, fresh, cirque terminal moraine in this valley are 22° and 24°, respectively. The 36Cl cosmogenic isotope analysis of the largest and most stable boulder on the moraine yielded an age of 10.85 ± 1 ka (96RM54). Rock-glacierized moraines and young cirques are present in the southern Rocamaha Valley, and three modern cirque glaciers are actively calving into lakes within the valley. Paleocirque glaciers on the southern side of the Koryak Mountains (Fig. 2) most likely coalesced in the broad Rocamaha Valley and flowed south toward Lake Pekulneyskoye and the Bering Sea (Fig. 2). The ELAs for four modern cirque glaciers in the basin range from 450 to 700 m, using the THAR methodology. Paleo-ELAs are difficult to determine and may not be useful on tidewater glaciers, such as those on the south side of the Koryak Mountains that calve into the Bering Sea (e.g., Paterson, 1994). At least one terrace occurs in the broad valley to the northwest of Lake Pekulneyskoye. Bedrock-controlled terraces, which give way to steep-sided scree slopes, surround the lake in the northern part of the valley.

**Chronology and Interpretation.** The relatively fresh-looking landscape in the valley is indicative of Holocene glacier advance on the northern and southern sides of the Koryak Mountains. The modern, low-elevation cirques in this valley indicate that during the Sartan and older glaciations, ELAs were lower than ~400 m, and glaciers on the south side of the Koryak Mountains probably reached the Bering Sea. The relatively steep moraine slope angles and young 36Cl cosmogenic isotope age of 10.85 ka serve as a minimum age on deglaciation and moraine stabilization. Sartan ice most likely advanced out of the Rocamaha Valley into the structurally controlled Gitgipokeetkinveem River and north into Lake Mainitz. This date is consistent with the 36Cl 10.08 ka date at Lake Mainitz.

**Nahodka Valley**

The Nahodka Valley (330 m) is a U-shaped tributary valley at the southern end of the Nygchekveem Valley and close to the source of 600-m-high modern cirque glaciers (Figs. 2 and 5). The U-shaped valley is 1.0 km wide and surrounded by mountains that rise to 961 m on its west side. Hanging valleys at 600 m elevation connect with the main Nygchekveem Valley. Lateral moraines and meltwater channels in this valley occur at an elevation of 560 m, and former ice thickness is estimated to have been 250 m. Paleo-ELA, derived from cirques at the head of the valley, is estimated to be 664–695 m asl.

The most prominent landform in the valley is a 14.3 m arl (above river level) terrace that grades to 13.8 m in the central part of the Nygchekveem Valley (Fig. 6). Upvalley, the terrace measures 17...
from the Nygchekveem Valley. The 1.9 ka deglaciation of valley glaciers retreating south minimum age for the Sartan (late Wisconsinan) erratics at the head of the valley. A reasonable age for erratic boulders and the presence of modern glac- shown by the abundance, angularity, and size of glaciofluvial and close to the ice source, as channel. A prominent boundary occurs between ice during a later glaciation or a lateral meltwater wash surface that was subsequently overrun by largest, most stable, erratic boulders were dated and vegetated with Pinus pumila. Six of the erratic samples from the two moraines are 36Cl cosmogenic isotope analysis as 21.65 ± 3.4 ka (96NK25). The average slope angle on this moraine is 7°–7.5°.

A terminal moraine with a distal slope angle of 6° accessible from the Nygchekveem River occurs 17 km south of Gladkoye Lake. A 2-km-wide terminal moraine belt can be clearly seen 28 km downvalley from Gladkoye Lake (Fig. 7B) on Landsat images, air photos, and 1:25,000 topographic Russian maps. The moraine crest is 158 m in elevation and is marked by kettle lakes, and meltwater channels. Nearly 100% of the moraine is covered by Pinus pumila, and erratics on the surface were absent. A minimum 36Cl age on one small (1.27 m) frost-heaved boulder is 10.62 ± 0.87 ka (96NK50). This boulder is interpreted as being frost heaved due to its low position in the ground and unstable position.

Terraces. Four terraces occur in the Nyg- chekveem Valley (Fig. 6). The lowest two ter- races, at 1 and 4.5 m arl, are in the modern flood plain and are composed of rounded cobbles, pebbles, and sand. The 13–13.8 m arl terrace is most likely Sartan in age, based on one 36Cl date of 15.99 ± 1.15 ka (96HD46) as well as continuity in Nygchekveem and adjacent valleys (Fig. 6). On the west side of the Nygchekveem Valley a minimum height was obtained on a prominent 15.4 m terrace consisting of a fining-upward sequence of angular to subangular cobbles, gravel, coarse sand, and silty mud. We be-

Nygchekveem Valley

Geomorphology. The Nygchekveem Valley is one of the main meridional valleys in the north- ern Koryak Mountains and is adjacent to Lake Mainitz (Figs. 2 and 7). The valley contains nu- merous lateral and medial moraines (Figs. 6 and 7), the surfaces of which are dissected by meltwater channels, churned up by frost boils, and vegetated with Pinus pumila. Six of the largest, most stable, erratic boulders were dated using 36Cl cosmogenic isotope analysis and yielded ages ranging from 11.59 to 21.65 ka (Table 1 and Fig. 7A). Slope angles for all moraines average 6°. The uppermost elevation of the moraines in the main valley is 350 m and to 460 m in the Temnay Valley, a west tributary val- ley. The elevation of the lateral moraines de- creases steadily downvalley (south to north) to 90 m. Based on moraine height and glacier profiling, a minimum estimate of ice thickness during the LGM in the central Nygchekveem Valley was 200 m and as much as 230 m in the tributary val- leys. The landscape in the Temnay tributary val- ley is dominated by kames, kettles, oxbow lakes, meltwater channels, and an extensive outwash plain. The paleo-ELA for the Nygchekveem Val-
lieve this is correlative with the 13–13.8 m terrace. Due to the proximity of the terraces to the ice source, most are composed of glaciofluvial sediment and no material datable by radiocarbon was found.

**Soils.** Nine soil pits were dug on moraines and terraces in the Nygchekveem V alley. Five pits were dug on the crests of moraines, three on the midsection of moraines, and one on a terrace. In general, the five soil pits on moraine crests contain a 4–9-cm-thick Oi horizon, a 10–22-cm-thick Bw horizon composed of sandy loam, silt loam, or loamy sand, and a BC or Cd horizon composed of sand and/or cobbles to a maximum depth of 53 cm. Although permafrost was not encountered in any of the crest soil profiles, organic pods in the Bw horizon, variegated colors in the BC horizon, and larger cobbles at the surface were recognized. The cobbles at the surface are believed to be due to frost heave, and in general, the abundance and size of the cobbles decreased with depth down to the C horizon.

The soil profiles on the midslope (5°–15°) of the moraines are characterized by an 8–18-cm-thick Oi horizon underlain by a Bw or BC horizon composed of loam, silt loam, or loamy sand to 40 cm in depth. More cobbles were encountered in two of the midslope pits than on the crest pits; however, one midslope pit did not contain cobbles. The one soil pit in a terrace yielded a 5-cm-thick Oi horizon and BC1 and BC2 horizons of silt loam and medium to coarse sand, respectively. The soil pit in the lower Nygchekveem Valley terminal moraine (28 km downvalley) contained fewer boulders and cobbles than the other Nygchekveem Valley pits, and also had a redder (5YR 5/6) and more well-developed B horizon. The increased reddening and decrease in boulder content in the soil is due to the advanced stages of soil development on this older, pre-Sartan surface. As noted here, erratics were absent on the surface of the moraine as well, indicating prolonged exposure of this surface to weathering, erosion, and reworking.

**Chronology and Interpretation.** The numerical chronology of deglaciation in the Nygchekveem Valley is constrained by the five $^{36}$Cl cosmogenic dates (11.59–21.65 ka) on erratics on moraines, and one date (15.99 ka) from the 13.8 m terrace upvalley. The relatively young and anomalous $^{36}$Cl date of 10.62 ka on a frost-heaved boulder on the moraine 28 km downvalley from Gladkoye Lake does not represent the age of the moraine, but simply the age of the frost heaving that exposed the boulder. We propose that the moraine’s soil profile, absence of boulders, abundance of vegetation, subdued topography, size, and distance from the ice source are evidence for greater antiquity than the moraines surrounding Gladkoye Lake. The moraine 28 km downvalley is interpreted to be of pre-Sartan and most likely of Zyryan age. Although we have no numerical control on the age of this moraine, the moraine morphometry is similar to terminal moraines in the Tanyurer River valley to the north, which indicate Zyryan or older ages based on $^{36}$Cl cosmogenic isotope data (Gualtieri et al., 1997).

The Gladkoye Lake moraines and lower Nygchekveem V alley moraine mark the maximum extent of the Sartan ice advance. The Sartan maximum extent most likely took place >15 ka. However, although the cosmogenic ages are usually interpreted to be minimum dates on deglaciation, they can be too old due to an inheritance of older
36Cl (Briner and Swanson, 1998) inherited from an earlier time in the rock’s exposure history. One of the many assumptions inherent in using in situ accumulation of 36Cl to determine exposure ages of rocks is that the erratic has been “zeroed” of its former 36Cl accumulation during transport in the glacier. If a sufficient portion of the rock has not been eroded, or stripped of ~0.5–1.0 m of its outside surface during transport within the glacier, then some of the older, or inherited, 36Cl will still be present. For more discussion on the inheritance problem see Briner and Swanson (1998).

Because these erratics have not traveled far from the ice source they may not have been sufficiently eroded during glacier transport, and therefore the oldest age may be too old to estimate the true age of deglaciation. These ages correlate with ages of the Sartan ice advance of the Tanyurer River valley (Fig. 2), which is based on both cosmogenic and radiocarbon age estimates (Brigham-Grette et al, 1997; Gualtieri, 1997; Gualtieri et al., 1997; Mostoller, 1997).

The central Nygchekveem Valley moraine morphology contrasts with that of Holocene and modern moraines in the Rocamaha and Nahodka Valleys. This, in conjunction with the cosmogenic analyses, supports the pre-Holocene age of the Nygchekveem Valley landforms.

The 15.99 ka 13–13.8 m arl continuous terrace is interpreted to be a glaciofluvial outwash surface. The age of this landform further supports the 15 ka age for the Sartan deglaciation.

The soil data collected from the midslope and crest pits differ in Oi and Bw thickness. In general, profiles on the midslopes had thicker horizons, as would be expected, due to aggradation of crest material on the slope. The contrast between the soil profiles, in general, from the Sartan-age central Nygchekveem Valley moraines with the Zyryan Nygchekveem Valley moraine 28 km downvalley is supplementary to the morphometric data and further supports the restricted extent of the Sartan glaciers.

Lower Anadyr Depression and Cape Dionysia

The lower Anadyr depression (Fig. 2) is composed of numerous small lakes and rivers that drain either into the Velikaya River or directly into the Anadyr Estuary. The highest point in the area is Mount Dionysia (577 m). Erratics are present in a stream on the western side of the mountain, and till, composed of subrounded quartzite boulders in sandy silt, is present on the east face of the 150-m-high Little Dionysia Mountain (informal name), which is a smaller peak a few kilometers east of Mount Dionysia.

Gullies in coastal bluffs south of Cape Dionysia are dominated by till, which includes striated clasts to 35 cm in length. In addition, erratics to 1 m in length occur on the modern beach at the mouths of the gullies. Stratigraphically below the till, shell fragments and whole valves are found up to 11 m asl in massive fine-grained silt interbedded with sand and containing two pebbly layers. About 2 km north of the cape, striped (170°–190° orientation) and gouged basaltic bedrock is exposed on shore, but shells are absent in the bluff sediments. Terraces at 50–60, 20–30, and 5–7 m asl are not easily discernable; however, we measured 70, 22, 11, and 6.5 m terraces using a digital altimeter (±1 m). Two samples were taken for cosmogenic isotope analysis from basaltic bedrock between the mountain and the bluffs. These yielded 36Cl ages of 25.78 ± 2 (95CD1) and 52.99 ± 5.2 ka (96CD13).

A. Gasanov (1969) described glaciomarine units to 16 m thick with mollusks, gravel layers,
ice wedges, and laminated sand and silt to the north and south of Cape Dionysia; however, no chronological control is available for measured sections. We revisited the area in 1995 and 1996, logged sections, and collected mollusk samples for radiocarbon age determination and amino acid geochronology: 75 analyses were completed on Asterita from 16 samples along the Cape Dionysia shoreline (Fig. 2). Average total ratios of alle/Ile are 0.042 ± 0.017, indicating a realistic age range between 71.7 and 96.3 ka, based on modern permafrost temperatures in Anadyr. Radiocarbon age estimates on the two individual shell samples with the lowest alle/Ile ratios (0.026 and 0.020 total) yielded infinite ages of >49.9 ka and >45.2 ka (AA25668 and AA25669). This chronology is consistent with Svitoch’s (1976) TL date of 66.7 (AA25668 and AA25669). This chronology is consistent with Svitoch’s (1976) TL date of 66.7 ka on a 50–60 m terrace south of Cape Dionysia.

**Chronology and Interpretations.** The 36Cl cosmogenic data from bedrock on the Anadyr lowland suggest that this area has been exposed, or ice free, since at least 52.99 ka, and most likely longer. Pre-Sartan (pre–late Wisconsinan) ice crossing this peninsula probably came from the 1012-m-high Zolotay Mountains (Fig. 2) and flowed south-southwest across the peninsula. The age of the glaciomarine unit on the Cape Dionysia shoreline as inferred from amino acid and radiocarbon data suggests that since 71.7–96.3 ka this coastline has remained free of glacial overriding, glacially derived sediment, and raised marine deposits. The numerical age for the glaciomarine unit places it in the Valkatlen interglaciation (stage 5 or Kazantsevo interglaciation as defined in Siberia). The absence of raised marine deposits due to glacioisostatic loading of the crust on this and other Chukotkan or Bering Strait Island coastlines (Gualtieri, unpub. data; Brigham-Grette et al., unpub. data; Brigham-Grette and Hopkins, 1995) precludes the existence of a marine-based ice sheet in the East Siberian Sea, the Arctic Ocean, Bering Sea, or Bering Strait during the last glacial maximum. Theoretical calculations and arguments for abandonment of a marine-based ice sheet model were discussed in Heiser (1997).

Data and field observations from the Cape Dionysia coastline, coupled with the geomorphology of the northern Kankaren Range, indicate that ice from the south, or Koryak uplands, did not inundate the lower Anadyr depression or the Cape Dionysia coastline during the last glacial maximum. The Kankaren Range drift sheets extending 1.0 km beyond the present mountain front, as well as the presence of till on the local basalt high, represent the extent of the LGM (Sartan). The moraines visible on the SAR and Landsat photos mark the extent of a pre-Sartan glacia tion. The presence of thick permafrost close to the surface in the lower Anadyr depression is consistent with the hypothesis that this area has remained ice free throughout the Sartan interval.

**CORRELATION WITH THE LGM IN ALASKA AND OTHER PARTS OF RUSSIA**

The restricted ice extent and age span of the LGM in the Koryak Mountains–Lake Mainitz region is compatible with the regional climatological regime for Beringia. Ages for deglaciation and ELA estimates for areas that share the same primary moisture source as the Koryak Mountains are shown in Table 2 and Figure 8. The only other 36Cl-based chronology in the region is that of Briner et al. (1998) for the western Akhklun Mountains, Alaska. The other numerical chronologies are mainly based on 14C ages from fluvial or glaciofluvial terraces associated with the LGM. The methodology of ELA determination is not consistent among researchers; therefore, if a method other than area accumulation ratio (0.6–0.65) was used, that is indicated in Table 2.

The chronology of the LGM and deglaciation in the Koryak Mountains is regionally consistent. However, local variations within mountain ranges (north vs. south) could have been very large, as shown by the variation in ELA lowering or absolute elevation. The style of glaciation during the LGM was also similar in western and southwestern Alaska and far eastern Russia. In general, glaciers were cirque, valley, or montane in character and reached no more than 20 km beyond mountain fronts. No evidence was found for land or marine-based ice sheets coalescing with terrestrial domes, as proposed by some (e.g., Grosswald and Vozovik, 1984; Grosswald, 1988, 1998; Hughes and Hughes, 1994). The minimum model of ice extent is consistent with anthropological and vegetation interpretations for the Bering land bridge during the LGM (Ager, 1982; Elias et al., 1997). Diatom assemblages (core RC14-121, Fig. 1) suggest year-round sea ice cover in the Bering Sea during the LGM, thereby precluding it as a viable moisture source to feed large ice sheets (Sancetta et al., 1985).

In order to determine a robust chronology of regional paleoclimatic change, a numerical chronology must be established at smaller spatial intervals. Only two terrestrial numerical chronologies for glaciation exist in central Beringia (Briner et al., 1998; this study), however, as the number of marine and lacustrine records in this region expands, higher resolution correlation with the glacial geology is needed.

**SPECULATION ON CORRELATION WITH THE REGIONAL MARINE RECORD**

Scholl and Stevenson (1997) suggested that the climate regime in Beringia is determined by temperature, salinity, and the volume of surface water exchanged between the Pacific Ocean and Bering Sea. Therefore, the terrestrial and marine paleoenvironmental records should be consistent, and changes in terrestrial ice extent should be reflected in marine records. The proximity of the Koryak Mountains to the 100 m Bering Sea isobath affords the op-
portunity of preservation of the terrestrial ice extent changes in the regional marine record. Other glaciated mountain ranges in Beringia are adjacent to the continental shelf or the exposed Bering Land Bridge, and therefore, their ice fluctuations are less likely to be reflected in the marine record. Marine records from the far northwest Pacific, the southern Bering Sea, and the Sea of Okhotsk (Fig. 1) show evidence for cooling during the LGM. Calving icebergs from southern Koryak Mountain tidewater glaciers emptying into the Bering Sea could have been carried south by the counterclockwise-rotating Bering Gyre surface current (Fig. 1) and may provide a source for ice-rafted debris (IRD) found in some of the marine cores described in the following. Sea surface temperatures during the LGM in the Japan Sea, the northwest Pacific, and the Sea of Okhotsk also provide clues as to the timing of large-scale climatic interactions and fluctuations among the atmosphere, oceans, and continents.

Keigwin et al. (1992) identified an IRD (terrigenous sediment >150 μm) peak older than 15 ka in core RAMA44PC (Fig. 1) as discussed in Gorbarenko (1996). The ice rafted debris (IRD) data are from Keigwin et al. (1992) and Gorbarenko (1996). Core locations are given for each data set and are shown in Figure 1. The lower and italicized IRD scale is from Gorbarenko’s data, which were determined by visual estimation of the terrigenous concentration in the >100 μm fraction, where 1—few; 2—rare; 3—common; 4—abundant. Keigwin et al.’s (1992) IRD data are based on the >150 μm fraction. Summer sea surface temperatures (SSTs) are from core V20-120 (Fig. 1) and are based on foraminiferal variations using transfer functions (Morley et al., 1987; Heusser and Morley, 1997). The modern summer SST at site location V20-120 (12.5 °C, Heusser and Morley, 1997) is shown for reference and is indicated by the dashed line. The average summer SST for this site during the LGM is 13–14 °C (Heusser and Morley, 1997). This trend continues to the late glacial, as shown by Elias et al. (1997), who reported higher than modern summer temperatures (11.5–13 °C) on the Bering land bridge 11 ka. The two parallel, horizontal dotted lines indicate times when summer SST in the North Pacific was higher than modern, at the height of the LGM in the Koryak Mountains as well as other central Beringian locations. It is concluded that higher than modern summer SSTs and increased precipitation sustained glacier growth in the North Pacific region during the LGM.
Last Glacial Maximum in the Koryak Mountains of Far Eastern Russia

Table 2. Comparison of the LGM, ELA, and Deglaciation for Central Beringia

<table>
<thead>
<tr>
<th>Location</th>
<th>LGM (ka)</th>
<th>ELA (m, asl)</th>
<th>Deglaciation (ka)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Lawrence Island</td>
<td>&lt;25</td>
<td>150*</td>
<td>&gt;11</td>
<td>Heiser (1997)</td>
</tr>
<tr>
<td>Aleutian Islands</td>
<td></td>
<td></td>
<td></td>
<td>Thorson and Hamilton (1986)</td>
</tr>
<tr>
<td>Cold Bay</td>
<td></td>
<td></td>
<td></td>
<td>Dochat (1997)</td>
</tr>
<tr>
<td>Alaska Peninsula</td>
<td></td>
<td></td>
<td></td>
<td>Dettman (1998)</td>
</tr>
<tr>
<td>Western Akhulgin Mountains</td>
<td>26–24</td>
<td>300*</td>
<td>&gt;16.9</td>
<td>Briner et al. (1998)</td>
</tr>
<tr>
<td></td>
<td>20–17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cook Inlet</td>
<td>25–14</td>
<td></td>
<td>18–12.2</td>
<td>Schmoll and Vehie (1986); Hamilton (1994)</td>
</tr>
<tr>
<td>Gulf of Alaska</td>
<td>15–12</td>
<td></td>
<td></td>
<td>Molnia (1986)</td>
</tr>
<tr>
<td>West-central Alaska</td>
<td>&lt;34</td>
<td>300–400*</td>
<td>&gt;11</td>
<td>Kline and Bundtzen (1986); Péwé (1975)</td>
</tr>
<tr>
<td>Western Brooks Range</td>
<td>24–15</td>
<td></td>
<td></td>
<td>Hamilton (1986)</td>
</tr>
<tr>
<td>Seward Peninsula</td>
<td>&gt; 11.5</td>
<td>200–400*</td>
<td></td>
<td>Kaufman and Hopkins (1986); Kaufman et al. (1988, 1989); Peck et al. (1990)</td>
</tr>
<tr>
<td>Kuvevem River, central Chukotka, Russia</td>
<td>270</td>
<td></td>
<td></td>
<td>Mostoller (1997)</td>
</tr>
<tr>
<td>Northeastern Russia</td>
<td>26–11</td>
<td>600</td>
<td></td>
<td>Bespaly et al. (1984); Savoskul and Zech (1997)</td>
</tr>
<tr>
<td>Southern Kamchatka, Russia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Koryak Mountains, Chukotka, Russia</td>
<td>&gt; 5</td>
<td>460–500, 400–550, 450–600</td>
<td>15</td>
<td>This study; Glushkova (1992); Heiser (1997)</td>
</tr>
</tbody>
</table>

Notes: LGM—last glacial maximum; ELA—equilibrium line altitudes. ELA determination methods other than area accumulation ratio (AAR) (0.6–0.65); Dettman: cirque floor elevation; Kaufman and Hopkins: toe-to-headwall (0.4); Savoskul and Zech: mean elevation of lateral moraine and AAR; Glushkova: Geopher’s formula and cirques; this study: AAR (0.55 and 0.58), asi—above sea level. *Indicates amount ELA lowered from modern.

Water source, the Koryak Mountain glaciers could have contributed to the IRD record.

Field evidence exists for three Pleistocene glacial advances in the Koryak Mountains–Lake Mainitz region. This conclusion is consistent with Heiser’s (1997) work based on SAR imagery for the Chukotka Peninsula. The Zyryan glaciation is represented in the Nygechevveem Valley only by the downvalley moraine. A pre-Zyryan glaciation is postulated for the age of the broad lobate moraines extending as much as 30 km north of the eastern Kankaren Range. The most well-preserved evidence for glaciation in the Nygechevveem and Lake Mainitz Valleys is of the Sartan glaciation, with a maximum ice advance in both valley systems >15 ka. This is based on geomorphology and numerical data. Reconstructed ELAs for the LGM are 460 m in the Nygechevveem Valley and 300 in the Lake Mainitz basin based on AAR. A continuous terrace, 13–13.8 m arl and dated using 36Cl cosmogenic isotopes, is correlated between valleys, and clearly relates to the Sartan deglaciation. The higher terrace in the Nahodka Valley (57 m) although undated, is evidence for an older glaciation in this region.

The Koryak Mountains–Lake Mainitz record of glaciation is spatially and temporally consistent with the glaciation pattern across central Beringia. Higher than present sea surface temperatures and increased precipitation in the northwest Pacific region during the LGM may have provided the moisture necessary to build and sustain Koryak Mountain glaciers. This study provides direct field evidence against Grosswald’s (1998) Beringian ice sheet hypothesis.

Acknowledgments

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References Cited


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