**Title:** Distribution and pattern of moraines in Far NE Russia reveal former glacial extent

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**Abstract**

Here we present a series of six maps illustrating the distribution of end moraines in Far NE Russia. The maps are the first to systematically document the distribution of moraines across this region from the Verkhoyansk Mountains at the westernmost limit of our study area to the Chukchi Peninsula in the NE and to Kamchatka in the south, covering an area of almost 4 million $km^2$. Moraines were identified and mapped from analysis of satellite images and digital elevation model (DEM) data. A total of 2173 moraines are identified, and we highlight some 197 more speculative features (perhaps moraines) that require further investigation. The distribution of moraines indicates that much of the region, now largely ice-free, was formerly occupied by glaciers centred upon the region's uplands and that glacier outlets were typically < 200 km in length. The maps demonstrate the usefulness of remote sensing to derive an improved understanding of the glacial history of this vast and isolated region, and we present them to stimulate further work and act as a systematic framework for targeted geochronometric dating.

## Introduction

In terms of its glacial history, Far NE Russia is one of the least understood regions on Earth. There are those, for example, who believe that during the Last Glacial Maximum (referred to in Russian literature as the Sartan; c.21 ka), the region was occupied by a series of vast and coalescing ice-sheets (e.g. Grosswald, 1998; Grosswald and Hughes, 2002, 2004, 2005), while others regard glaciers to have been restricted to only the highest mountains, extending little more than 20 km in length (e.g. Velichko et al., 1984; Arkhipov et al., 1986; Sher, 1995; Glushkova, 2001; Gualtieri et al., 2000; Brigham-Grette et al., 2003; Leonov and Kobrenkov, 2003; Zamoruyev, 2004; Stauch and Gualtieri, 2008). See Stauch and Gualtieri (2008) for a more detailed review of these contrasting theories. Much uncertainty regarding former ice extent in this region stems from a lack of detailed investigation (due to difficult fieldwork access), with reconstructions sometimes generated without being underpinned by comprehensive geomorphological maps. Publications illustrating evidence of former ice extent are very few in number, spatially fragmented and often focus upon individual ranges or regions (e.g. Glushkova, 2001; Grosswald, 1998; Gualtieri et al., 2000; Heiser and Roush, 2001; Grosswald and Hughes, 2002; Laukhin et al., 2006; Stauch et al., 2007; Bigg et al., 2008). In an effort to better understand the glacial history of this large and remote region, moraine maps, covering all of Far NE Russia, are here presented.

## Methods

Moraines were mapped through on-screen digitisation from Landsat ETM+ satellite images (15 and 30 m resolution), and Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) data (90 m resolution). The satellite imagery was the primary basis for mapping, as it provided coverage of the entire study area, whilst the SRTM DEM only covers latitudes of 60°N to 56˚S, a zone within which less than 20 % of the

study area lies. For regions outside this zone, 30 arc-second resolution (approximately 1 km), GTOPO30 DEM data were used to provide a generalised view of regional topography but, because of low resolution, were not used for mapping. In total, 205 satellite images (each covering 185 by 185 km) were viewed in the panchromatic band (band 8), and as false colour composites using a variety of band combinations (typically bands 5, 4 and 2). Moraines were visually identified and then digitised as polygons, with mapping performed using a repeat-pass procedure, whereby each region was viewed on four separate occasions, at a range of scales.

**Moraine description and distribution**

A total of 2370 features were mapped, and classified as either end- or speculative-moraines. End moraines are ridge-like formations of typically unsorted sediment, deposited along the frontal margins of stationary or slowly retreating glaciers. When viewed planimetrically (e.g. in satellite images or DEM data), they often appear arcuate, with their general orientation transverse to glacier flow direction (Fig 1). In total, 2173 end moraines are identified, some up to 110 km in length, and 22 km wide. They cluster in, and around, the region's uplands, though their highest concentrations are upon the Anadyr Lowland of the Chukchi Peninsula (where 62 moraines are mapped within an area of roughly 40,000 $km^2$; map D), and upon the western and southern slopes of the Verkhoyansk Mountains (where 128 moraines are mapped; map A).

The speculative moraines were considered to resemble end moraines in some respects, but with shapes or topographic-contexts which make their origin uncertain (Fig 2), with 197 such features mapped in total. We include these as they might be important moraines but require further investigation, most usefully by fieldwork.

## Completeness

Given that a repeat-pass approach was adopted, we regard the maps to represent a near-complete record of end moraines in Far NE Russia, as revealed in Landsat ETM+ imagery and SRTM data, i.e. we have not just 'cherry picked' the best examples, but have made a systematic survey, and so an absence on the map has some meaning. Comparison with published material (e.g. Glushkova, 2001; Grosswald, 1998; Gualtieri et al., 2000; Heiser and Roush, 2001; Grosswald and Hughes, 2002; Laukhin et al., 2006; Stauch et al., 2007) reinforces our belief that the features truly reflect the broad pattern of moraine distribution, and in the Kamchatka and Koryak region the moraines are consistent with the reconstructions of ice extent reported in Bigg et al. (2008). It is recognised, however, that the use of Landsat imagery limits mapped features to those with scales significantly greater than 15 m (i.e. the resolution of the satellite imagery), and smaller moraines will not have been mapped.

## Implications and conclusions

The maps reveal a large number of previously unidentified moraines, and cover an area an order of magnitude larger than existing maps of glacial landforms in Far NE Russia. The distribution of moraines appears to indicate that much of the region, now largely ice-free, was formerly occupied by glaciers, ice fields, and/or ice caps, centred upon the region's uplands (Fig 3), and provides little evidence to suggest the former presence of vast ice sheets, though this possibility cannot be ruled-out, as the absence of moraines is not necessarily indicative of the former absence of ice. For example, glaciation by cold-based ice-masses or post depositional modification (removal, burial, submergence) are likely to obscure the moraine record.

The distribution of moraines also testifies to distinctly different glacial histories across Far NE Russia. In the Verkhoyansk Mountains, multiple, spatially distinct, moraines are identifiable within, or emanating from, most south and west trending valleys (typically between two and seven, but up to ten in places; map A). In the in the Suntar-Khayata, Chersky, Moma (map B), Kolyma and Anyuy (map C) mountains, the number of moraines per valley is typically below three, and often as low as one, whereas in regions bordering the Pacific Coast (i.e. the Chukchi Peninsula, Koryak Highlands and Kamchatka Peninsula; maps D, F and F, respectively) at least two or three moraines typically lie within, or emanate from, most valleys. This pattern may indicate that central regions experienced fewer phases of glaciation than those to the east and west, that ice-masses in central regions were less dynamic and, therefore, left little identifiable evidence of their former extent, or that moraines in central regions have been destroyed by fluvial or periglacial processes. It is also possible that in some central regions, the most recent phase of glaciation was also the most extensive, thereby destroying any evidence of earlier advances.

In addition to regional differences in the number of moraines, there are notable variations over comparatively small distances. In the Verkhoyansk Mountains (map A), for example, of the 161 moraines mapped, 128 are located to the south and west of the Range, and only 33 to the north and east. A similar trend is identifiable in the Koryak Highlands (map E), where of 336 end and 22 *speculative* moraines mapped, 141 are located within the NE Koryak Mountains, 132 on the southern macroslopes of the central highland, and only 22 on its western slopes. It is possible that these regional differences reflect variations in the prevalence of palaeo ice masses, likely caused by severe palaeo-precipitation gradients from west to east across the Verkhoyansk Mountains (see Stauch and Gualtieri, 2008), and from east to west across the Koryak. However, it is,

again, possible that the absence of moraines reflects differences in glacier dynamics and/or moraine preservation across comparatively small regions, in some cases even adjacent valleys.

The maps are of value in allowing the broad distribution of moraines, in this vast and isolated region, to be assessed, enabling general styles of former glaciation to be inferred, and in facilitating the judicious selection of sites for future field and remote sensing investigations. Analysis of the distribution of moraines, reconstruction of ice extents and assessment of equilibrium line altitudes and climatic inferences are explored in Barr (2009) and should be reported in subsequent papers by the same authors.

## Software

Image geocorrection and on-screen mapping (digitising moraines as polygons) were performed in ERDAS Imagine 8.7. DEM data were processed in ESRI ArcMap 9.2. Polygon shapefiles and processed DEM data were then exported to Adobe Illustrator CS, where the final maps were produced.

## Acknowledgements

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## Map Design

As the mapped region is large (almost 4 million $km^2$), the decision was made (following email correspondence with the Journal of Maps editor) to divide it into six sectors, and present separate maps for each of these. The divisions between sectors are largely defined on the basis of topography, though the distribution of moraines is also taken into consideration.

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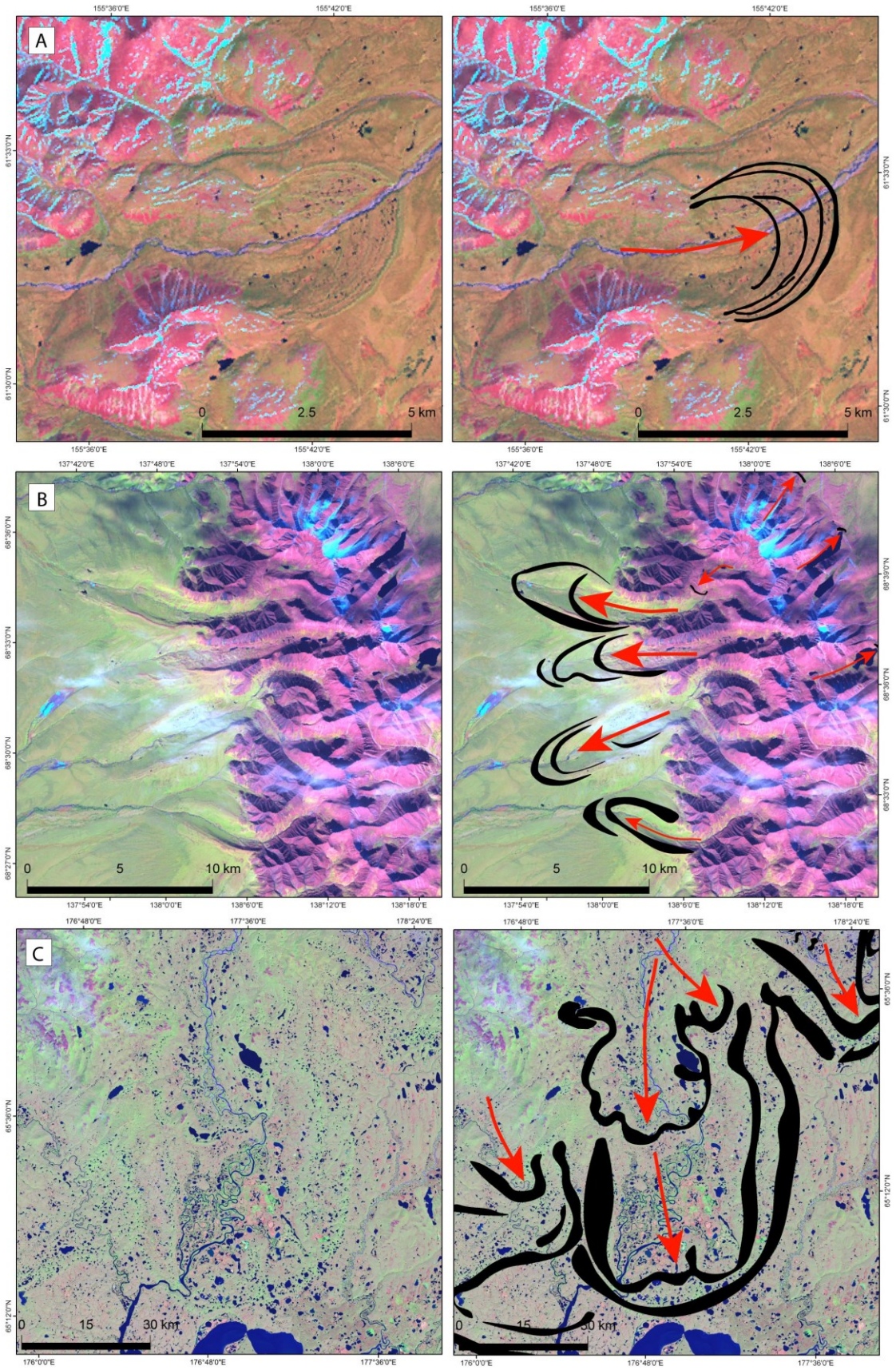
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Figure 1. Examples of mapped end moraines in Far NE Russia, illustrating how their arcuate form often allows palaeo ice-flow directions to be inferred. (A) Within the southern Kolyma Highlands. (B) Within the northern Hadaran'ja Mountains. (C) Upon the Anadyr Lowland. In each figure, the background image is a Landsat ETM+ colour composite of bands 5, 4 and 2. Black polygons are mapped moraines, and red arrows are inferred palaeo ice-flow directions.

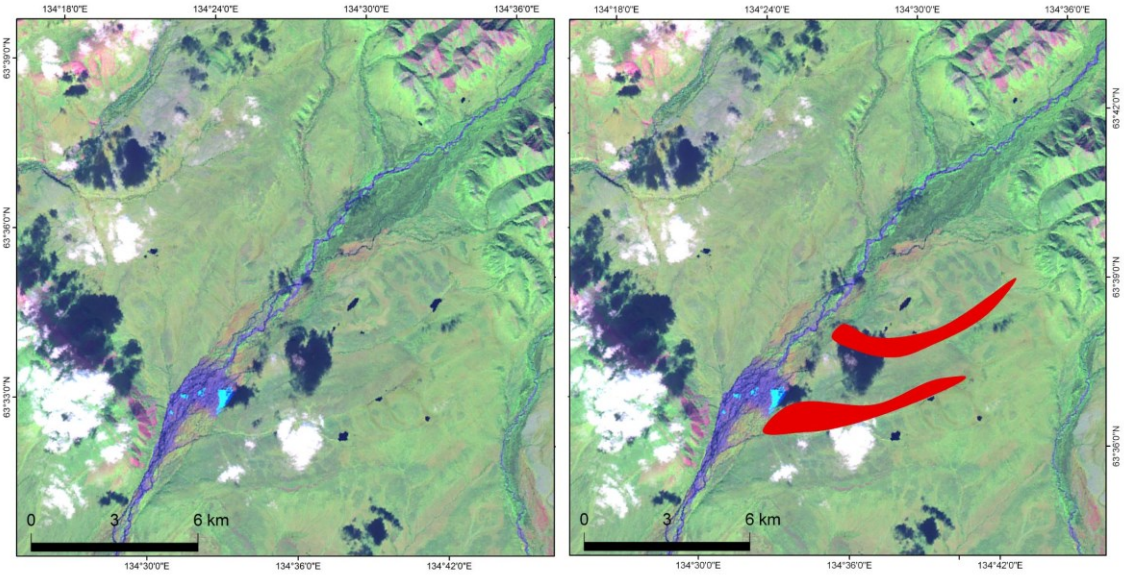
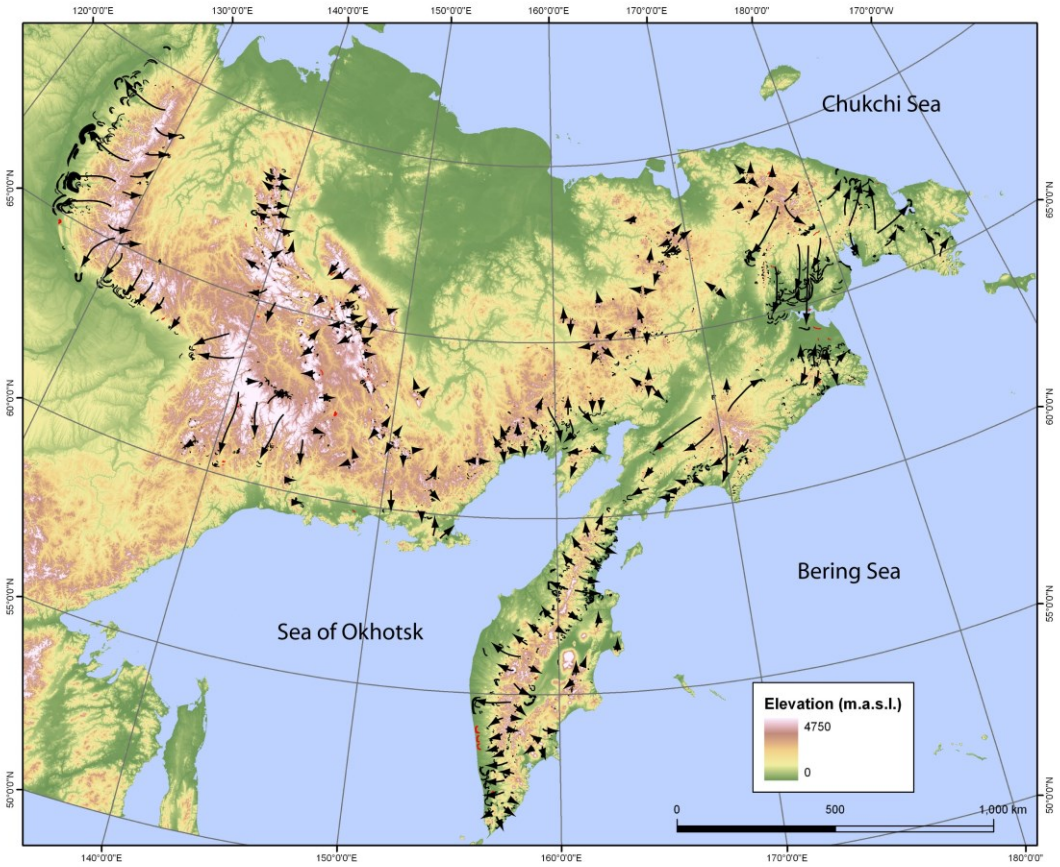



Figure 2. Examples of mapped speculative moraines in the Verkhoyansk Mountains. The topographic context and arcuate form of these features suggests they may be moraines. However, in terms of their relief they appear subdued, it is difficult to distinguish any clear geo-botanical contrast between them and the surrounding landscape, and it is unclear whether the apparent arcuate form is a results from deposition by a glacier, or is an artefact of fluvial erosion (i.e. the eye is drawn to the curve of the streams which act as tributaries to the main river), and it is for these reasons that they are classified as speculative, rather than end moraines. The background image is a Landsat ETM+ colour composite of bands 5, 4 and 2.

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290 Figure 3. Palaeo ice-flow directions as inferred on the basis of moraine orientation (i.e.
291 the direction of Arc). Arrow length reflects moraine distance from mountain divides. In
292 general, inferred flowlines appear to indicate radial-flow from mountain highlands, and
293 provide little support to the view that the region was formerly occupied by a series of
294 extensive and coalescing ice sheets, for example emanating from the Arctic Basin.