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An updated moraine map of Far NE Russia

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Barr and Clark published a series of maps depicting the distribution of end moraines across Far NE Russia. These moraines outlined the former distribution and dimensions of glaciers, and were identified through the analysis of Landsat ETM+ satellite images (15- and 30-m resolution). Now, a number of freely available digital elevation model (DEM) datasets are available, which cover the entire ~4 million km^2 of Far NE Russia. These include the 30-m resolution ASTER GDEM and the 90-m resolution Viewfinder Panorama DEM. Here we use these datasets, in conjunction with Landsat ETM+ images, to complete the process of systematically and comprehensively mapping end moraines. With the aid of the DEMs described above, here we present a total dataset of 8414 moraines, which almost quadruples the inventory of Barr and Clark. This increase in the number of moraines is considered to reflect the utility of the DEMs for mapping glacial landforms. In terms of moraine distribution, the Barr and Clark map and the one presented here are comparable, with moraines found to cluster in highland regions and upon adjacent lowlands, attesting to the former occupation of the region by mountain-centred ice masses. This record is considered to reflect palaeoclimatic and topographic controls upon the extent and dynamics of palaeoglaciers, as well as spatial variability in moraine preservation.

Keywords: moraine; NE Russia; geomorphology; palaeoglaciology

1. Introduction

Over recent years, the extent of former glaciation in Far NE Russia (Figure 1) has been a matter of considerable uncertainty, with some arguing that the region was formerly occupied by extensive ice sheets as recently as the global Last Glacial Maximum (gLGM, ~21 ka), whilst others consider the region to have undergone limited glaciation during at least the past 140 ka. These contrasting views are outlined in detail elsewhere (see Brigham-Grette, Gualtieri, Glushkova, Hamilton, & Kotov, 2003; Grosswald and Hughes, 2002; Rutter, 1995; Stauch & Gualtieri, 2008), and were the driving force behind our decision to produce a series of maps depicting end-moraine distribution across the region (Barr & Clark, 2009). However, since, our understanding of the region's glacial history has advanced, as dating of glacial landforms has continued (Zech et al., 2011), chronologically and geomorphologically constrained glacier reconstructions have been generated (Barr & Clark, 2011, 2012), and numerical-model simulations have been used to analyse palaeoclimatic controls upon glaciation in the region (Krinner, Diekmann, Colleoni, & Stauch, 2011). At present, the prevailing view is that Far NE Russia has been occupied by mountain-centred ice masses at various periods during the past 140 ka, but that large ice sheets have been entirely absent during this time (Glushkova, 2011; Krinner et al., 2011; Nurnberg, Dethleff, Tiedemann, Kaiser, & Gorbarenko, 2011; Stauch & Lehmkuhl, 2010, 2011; Zech et al., 2011). There is strong evidence to suggest that the timing of former glaciation across Far NE Russia has been regionally asynchronous during the past 140 ka (Krinner et al., 2011; Stauch & Gualtieri, 2008), and out-of-phase with glaciations in Eurasia and North America (i.e. glaciers in Far NE Russia attained their Late Quaternary maxima sometime prior to the gLGM). In order to continue this progress in our understanding, it is important that the region's glacial geomorphology be studied in detail, and used to constrain (geomorphological and numerical-model)

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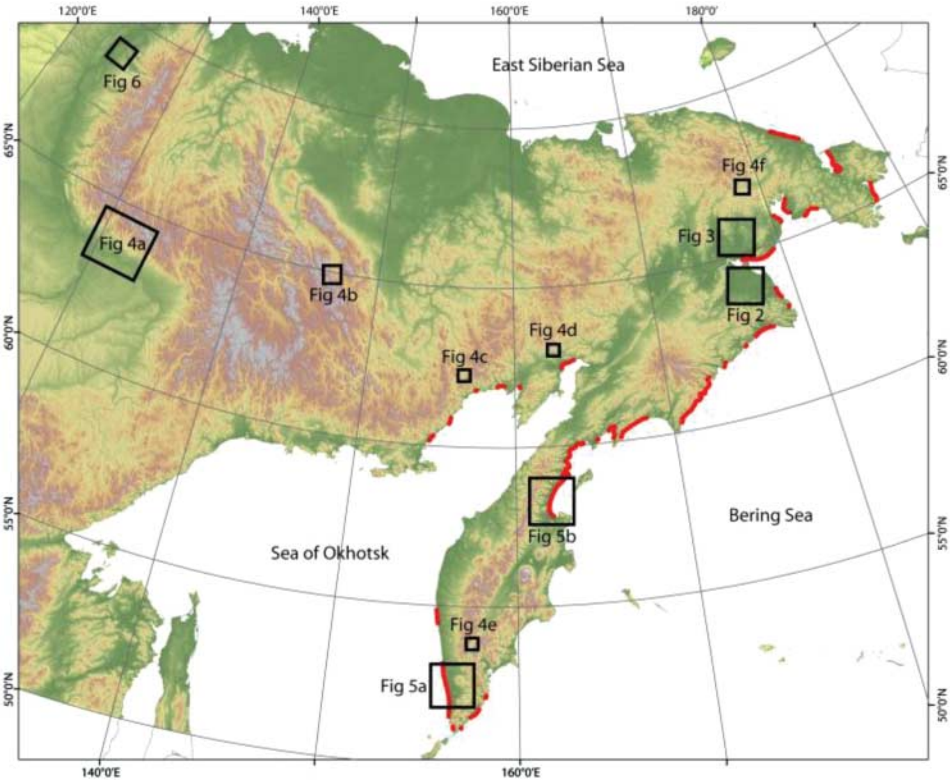

Figure 1. Overview of Far NE Russia. Boxed areas refer to figures shown in this paper. Red areas are where moraines lie within 1 km of the modern coastline.

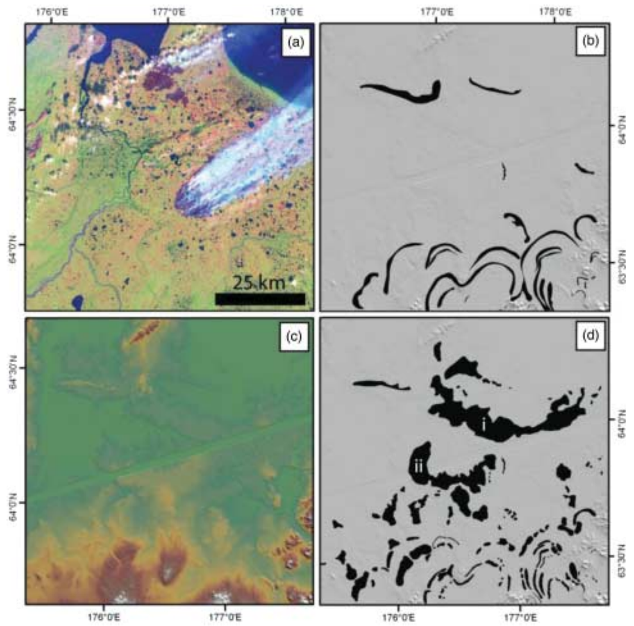

Figure 2. The NE Koryak Highlands and Lower Anadyr depression. (a) Landsat ETM+ satellite image (path 092, row 015, acquisition date 16/08/2002), false-colour composite of bands 5, 4 and 2. The land surface in this image is partly obscured by cloud and smoke from a wild-fire. (b) Moraines (black) as mapped by Barr and Clark (2009). (c) Semi-transparent shaded VFP DEM data (NE solar azimuth) draped over the raw (as downloaded from www.viewfinderpanoramas.org) VFP DEM. (d) Moraines (black) mapped in the present study. Features labelled 'i' and 'ii' are examples of moraines (amongst many others) that were unidentified from the satellite image alone. See Figure 1 for site location.

reconstructions of former glaciation. As a step to achieving this, here we present an updated comprehensive and detailed map of end moraines across Far NE Russia. This paper builds upon the maps of Barr and Clark (2009) (which were primarily produced through the analysis of satellite images), in that moderate resolution digital elevation model (DEM) data are used to conduct detailed and comprehensive mapping across the entire region.

2. Methods

In this study, end moraines were mapped from a combination of the following remotely sensed data sources: (i) version 2 of the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM2, http://www.gdem.aster.ersdac.or.jp/), with a cell size of 30 m; (ii) the ViewFinder Panorama (VFP) DEM (see de Ferranti, 2010), with a cell size of 90 m; and (iii) Landsat ETM+ satellite images, with cell sizes of 15 and 30 m. DEMs (ASTER and VFP) were displayed as semi-transparent shaded relief-images (with solar illumination from the NE, and a 45° solar elevation), draped over a sink-filled version of the datasets. Landsat images were displayed as false colour composites of bands 5, 4 and 2 and panchromatic band 8. End moraines were identified from these sources on the basis of feature plan-morphology, topographic-context, surface vegetation, association with other landforms, and relation to modern hydrological drainage. Moraines were digitised directly on-screen (in ArcGIS), and were mapped as polygon shapefiles, with emphasis placed upon mapping the break-of-slope around feature margins (see Smith, Rose, & Booth, 2006). Mapping was based upon a repeat-pass procedure (see Greenwood & Clark, 2008), whereby each region was viewed at a range of scales, using various combinations of the three datasets. Field-based ground-truthing was not performed, but mapping was partly verified through

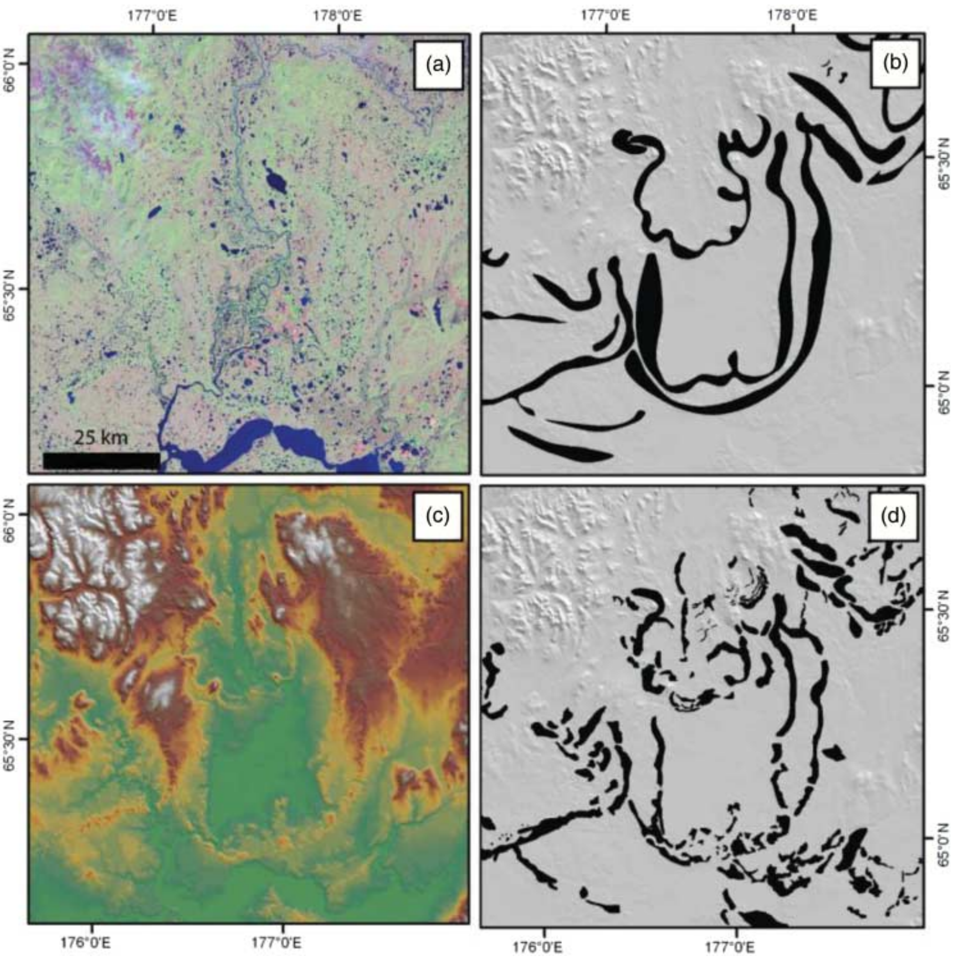

Figure 3. The Anadyr Lowlands. (a) Landsat ETM+ satellite image (path 092, row 014, acquisition date 25/07/2000), false-colour composite of bands 5, 4 and 2. (b) Moraines (black) as mapped by Barr and Clark (2009). (c) Semi-transparent shaded VFP DEM data (NE solar azimuth) draped over the raw VFP DEM. (d) Moraines (black) mapped in the present study. See Figure 1 for site location.

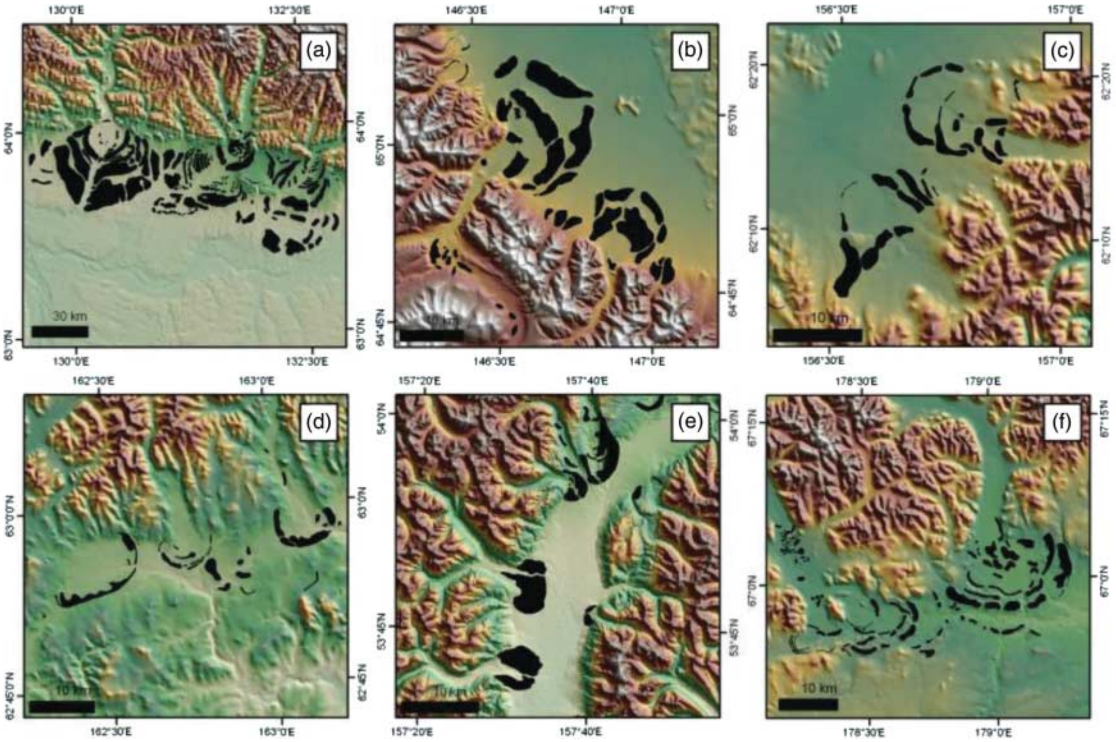

Figure 4. Examples of ‘piedmont moraines’ (black) clustering upon lowland regions adjacent to mountain ranges. In (a) the southern Verkhoyansk Mountains; (b) the Ulachan-Chistai Range of the Chersky Mountains; (c) the Southern Kolyma Highlands; (d) the SE Kolyma Highlands; (e) the SE Sredinny Mountains, Kamchatka; and (f) the Ekityki Mountains, Chukotka. See Figure 1 for site locations.

comparison with published sources (e.g. Glushkova, 2001; Gualtieri, Glushkova, & Brigham-Grette, 2000; Heiser & Roush, 2001; Laukhin, 1997; Laukhin, Zhimin, Pushkar, & Cherepanova, 2006).

3. Moraine morphology and distribution

In total, 8414 end moraines were identified and mapped across Far NE Russia; in comparison to the 2173 moraines mapped by Barr and Clark (2009). This increase is partly due to mapping previously unidentified

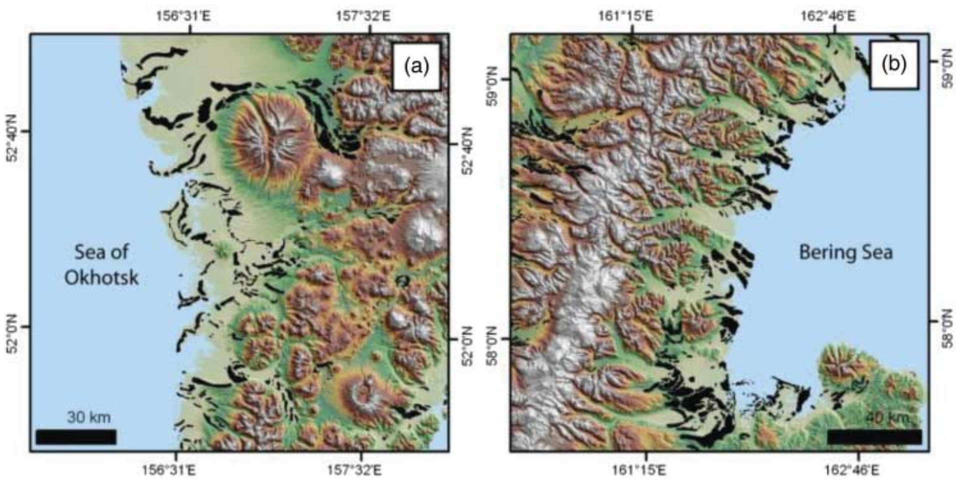

Figure 5. Moraines (black) found at the modern coastline. (a) SW Kamchatka, bordering the Sea of Okhotsk. (b) NE Kamchatka, bordering the Bering Sea. See Figure 1 for site locations.

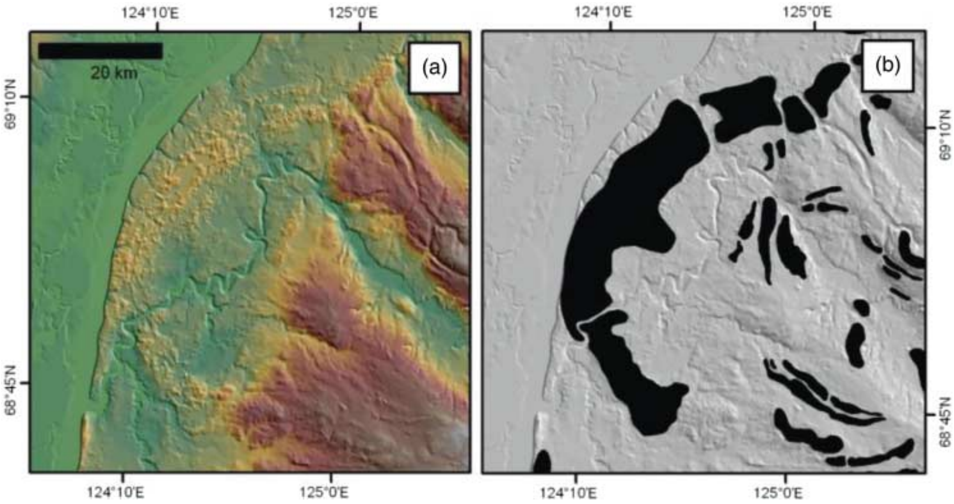

Figure 6. Large arcuate moraines in the northern Verkhoyansk Mountains. (a) Semi-transparent shaded VFP DEM data (NE solar azimuth) draped over the raw VFP DEM. (b) Moraines (black) mapped in the present study. See Figure 1 for site location.

moraines (see moraines 'i' and 'ii' in Figure 2), but is also a function of the detailed and intricate mapping the DEMs enable (Figure 3). Generally, moraines are found in, and around, uplands and appear to cluster upon surrounding lowlands (Figure 4). Many valleys contain numerous moraine sequences (Figures 2–5), and, in places, moraines extend to the modern coastline (Figures 1, 5), where they appear to extend out onto the continental shelf. Moraines typically appear arcuate in plan-from (Figures 2–5), and often consist of segments that were presumably interconnected prior to post-depositional erosion (Figures 3d and 4f). Some of the largest moraines, often found upon lowlands, are up to 53 km in length, 10 km in width, and cover a surface area of up to 428 km^2 (see example in Figure 6). A small number of the region's moraines have been dated, and appear to preserve a record of glaciation spanning at least the past 140 ka (see Stauch & Gualtieri, 2008).

4. Implications and conclusions

The distribution of moraines, presented in this paper, likely reflects palaeoclimatic and topographic controls upon the former distribution and dimensions of glaciers, and also a spatial variability in moraine preservation. When considered as a record of former ice-extent, the moraines reveal that much of Far NE Russia ($\sim$1,092,427 km^2) was formerly glaciated (i.e. the region within the limits of mapped moraines). In places, former ice-masses extended from mountain uplands to the modern coastline, and presumably terminated offshore, supplying debris to the North Pacific and Sea of Okhotsk (see Bigg, Clark, & Hughes, 2008; Nurnberg et al., 2011). Despite the considerable dimensions of such glaciers, the distribution of moraines around mountain centres provides evidence to suggest that former ice masses extended from these upland regions, and fails to support the view that large ice sheets formerly occupied the region (as suggested by Grosswald, 1998; Grosswald & Hughes, 2002). In many areas, moraines are found to cluster upon lowland plains adjacent to these upland valleys (Figure 4), and this is considered not only to indicate that former glaciers were mountain-centred, but also that topographic-controls upon moraine deposition and preservation are significant. Overall, the moraine record presented in this paper builds upon the work of Barr and Clark (2009), and emphasises the usefulness of moderate resolution DEM datasets in mapping glacial landforms. It is anticipated that the data presented here be used by those wishing to constrain former ice extent in Far NE Russia, whether using numerical-model or geomorphological approaches.

Software

Data processing and mapping were performed using ESRI ArcMap version 10.0. Data were exported to Adobe illustrator CS3, where the final map was produced.

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