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SCIENCE

Glacial geomorphology of the Maidika region, Tibetan Plateau

Miranda S. Lindholm* and Jakob Heyman

Department of Physical Geography, Stockholm University, Stockholm 10691, Sweden

ABSTRACT
We present a glacial geomorphological map at a scale of 1:200,000 of the Maidika region in the southeastern part of the central Tibetan Plateau covering 13,600 km^2. Based on the 90 m resolution SRTM elevation model, the 30 m resolution ASTER GDEM elevation model, and the Landsat ETM+ satellite imagery of 30/15 m resolution, we have mapped glacial valleys, marginal moraines, glacial lineations, and hummocky terrain. Glacial landforms occur frequently and indicate extensive past glaciation with alpine style valley glaciers as well as more extensive ice fields. Of particular interest is the presence of glacial lineation swarms, which is unusual for the Tibetan Plateau glacial landform record. Based on the distribution of glacial landforms, we present a generalized maximum glacial extent reconstruction covering 6045 km^2 or 44% of the map.

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1. Introduction

The Tibetan Plateau has experienced multiple Quaternary glaciations with expanded valley glaciers, ice fields, and ice caps. While Kuhle (2004, and references therein) has argued for an extensive ice sheet during the global last glacial maximum in the late part of the last glacial cycle, a large and growing data set based on geomorphological observations (Derbyshire et al., 1991; Heyman et al., 2009; Lehmkuhl & Owen, 2005) and cosmogenic exposure dating of glacial landforms (Heyman, 2014; Owen & Dortch, 2014) has shown that at least during the last few glacial cycles there has been no plateau-wide Tibetan ice sheet. The mapping of glacial landforms on the Tibetan Plateau has long been hampered by the inaccessibility of vast regions, leaving a fragmented glacial geological record open for speculative reconstructions (cf. Owen & Dortch, 2014: figure 5). The facilitated access to digital elevation and satellite image data has, however, enabled detailed glacial landform mapping of extensive regions based on remote sensing. In a series of maps and papers, the glacial geomorphology of the northeastern, central, and southeastern Tibetan Plateau, as well as the Tian Shan mountains has been presented (Fu, Heyman, Hättestrand, Stroeven, & Harbor, 2012; Heyman, Hättestrand, & Stroeven, 2008; Morén, Heyman, & Stroeven, 2011; Stroeven, Hättestrand, Heyman, Kleman, & Morén, 2013). The glacial landform record in these regions is dominated by glacially eroded valleys and marginal moraines formed by valley glaciers in an alpine topography. One exception is the Haizi Shan on the southeastern Tibetan Plateau where a low-relief plateau surface with glacial lineation swarms and sinuous moraine ridges indicates past ice cap glaciation (Fu et al., 2012, 2013). Swarms of glacial lineations on a low-relief surface and ice cap glaciation have also been reported for the Maidika region in the central Nyainqêntanglha (Derbyshire et al., 1991; Zheng, 2005), making this an interesting region for investigating ice field and ice cap glaciation of the Tibetan Plateau in contrast to alpine valley glaciation.

Here we present a glacial geomorphological map of the Maidika region based on mapping from satellite imagery and elevation models. The aim is to expand the record of detailed glacial landform maps from the Tibetan Plateau to enable spatial reconstructions of past glaciations. Based on the glacial geomorphology, we further present a generalized maximum glacial extent reconstruction.

2. Study area

The Maidika region is located in central Nyainqêntanglha in the southeastern part of the central Tibetan Plateau south of the Tanggula Mountains and east of the Nam Co Lake (Figure 1(a)). The map stretches from 30.6° to 31.5°N and 92.2° to 93.7°E and covers an area of 13,600 km^2 (Figure 1(b)). The Maidika region is dominated by an extensive (c. 50 × 20 km) basin at 4800–5100 m a.s.l. sloping gently toward the southwest surrounded by mountainous terrain with the highest peaks reaching 5500–6000 m a.s.l. In the northeastern and the southeastern corners of the map, tributaries to the Salween and the Yigong Tsangpo Rivers have valley floors just above 4000 m a.s.l. Contemporary glaciers are present on the highest mountains in the eastern part of the study area. Previous studies of the glacial landform record include

*Corresponding author. Email: miranda_lindholm@hotmail.com

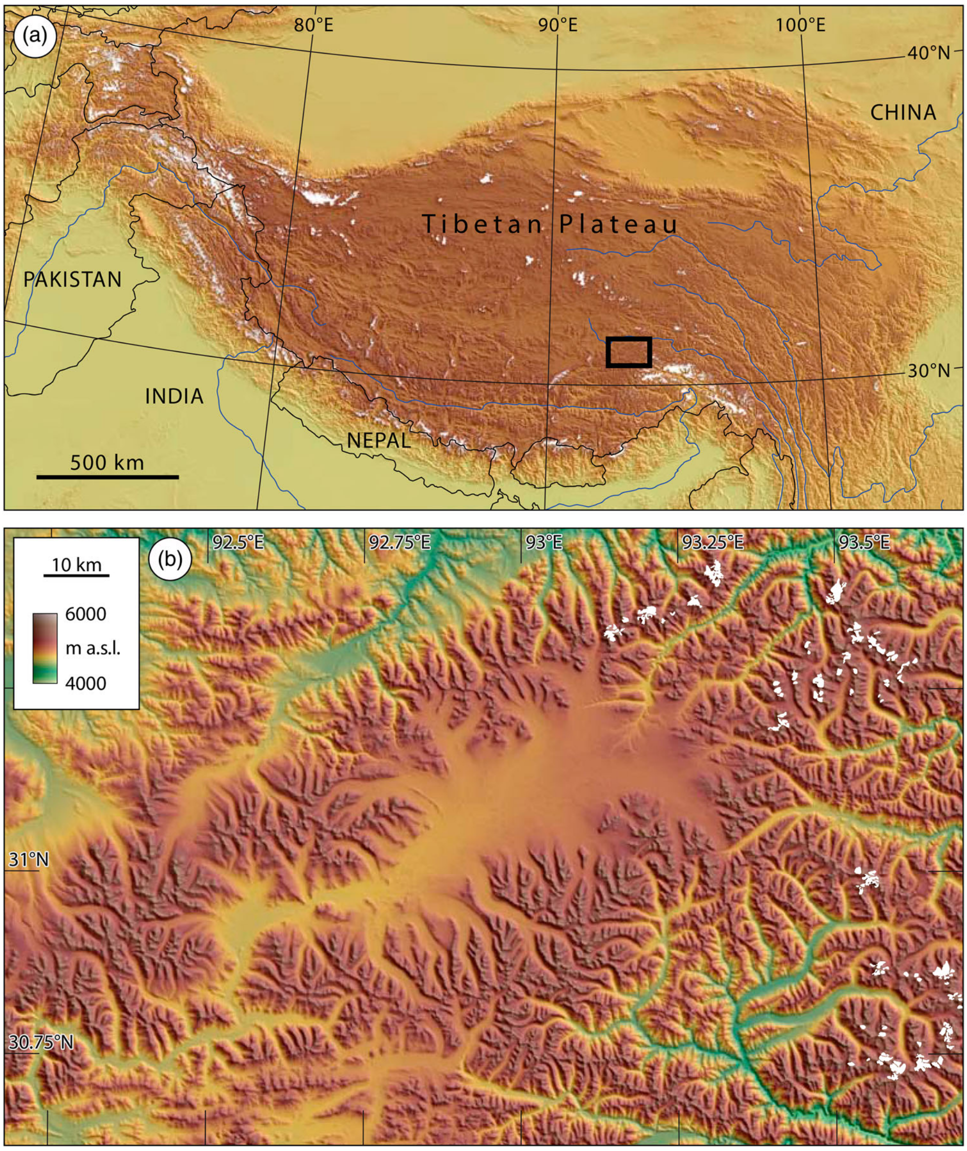

Figure 1. (a) Overview map of the Tibetan Plateau showing the location of the Maidika region in the southeastern part of the central Tibetan Plateau. The glaciers (white) are based on Arendt et al. (2012) with minor updates. (b) Shaded relief elevation model over the Maidika study area. The glaciers (white) are mapped from the Landsat ETM+ imagery.

notes of drumlins in the Maidika basin, a geomorphological map of the northeastern part of the basin, and a reconstructed paleo-ice cap over the basin and the surrounding mountains (Derbyshire et al., 1991; Zheng, 2005).

3. Methods

The glacial geomorphology of the Maidika region was mapped based on visual interpretation of and on-screen digitizing from digital elevation models and satellite images (Blomdin et al., in press; Fu et al., 2012; Heyman et al., 2008; Morén et al., 2011; Stroeven et al., 2013). For elevation model-based mapping, both the 30 m resolution ASTER GDEM and the 90 m resolution SRTM (Jarvis, Reuter, Nelson, & Guevara, 2008) were used. Semi-transparent slope images were produced from and draped over the elevation models to enhance topographic gradients without introducing an orientation bias (Smith & Clark, 2005). For satellite imagery mapping, Landsat 7 ETM + images (Table 1; GLCF, 2014) were used with the RGB band combination 5,4,2 (30 m resolution), pan-sharpened with a semi-transparent image of band 8

Table 1. Landsat ETM+ images (GLCF, 2014) used for mapping the glacial geomorphology.

Path	Row	Acquisition date
137	38	28 December 2000
137	39	28 December 2000
136	38	21 October 2001
136	39	21 October 2001

(15 m resolution). In addition to mapping from elevation models and satellite imagery, Google Earth was used primarily for 3D visualization.

3.1. *Mapped landforms*

The mapped landforms include glacial valleys, marginal moraines, glacial lineations, and hummocky terrain (Figure 2; Main Map) and the mapping approach follow previous Tibetan Plateau/Altai glacial geomorphology maps (Blomdin et al., in press; Fu et al., 2012; Heyman et al., 2008; Morén et al., 2011; Stroeven et al., 2013). In addition to these glacial landforms, contemporary glaciers were mapped from the Landsat ETM+ imagery. Below, the glacial landforms are described with regard to formation and characteristics.

3.1.1. *Glacial valleys*

Glacial valleys are valleys shaped by glacial erosion. They are characterized by relatively flat valley floors and steeper sides, yielding a characteristic U-shape (Figure 2(a)). An important characteristic of glacial valleys is the smoother valley sides compared to fluvial valleys with more frequent and sharper valley spurs. Glacial cirques are included as glacial valleys as they are formed by glacial erosion and commonly transform down-valley into glacial valleys. Glacial valleys have been mapped from the elevation models with additional usage of Google Earth to view the topography in 3D. The upper boundaries of the glacial valleys in the inner parts of mountain regions follow the break in slope between the steep valley walls and the gentler ridge crests. The outer/lowermost parts of the glacial valleys commonly transition gradually into non-glacial valleys (Blomdin et al., in press), and the lowermost boundaries mark the lower end of the valleys with a clear signature of glacial erosion.

3.1.2. *Marginal moraines*

Marginal moraines are depositional ridges formed along glacier margins (Figure 2(b)), and they therefore enable snapshot reconstructions of former glacier outlines. Marginal moraines are commonly outlined in an arcuate shape across valley floors or outside valley mouths (Figure 2(b)), but they can also form extended ridges on low-relief surfaces (cf. Fu et al., 2012, 2013). Marginal moraines have been mapped from both the satellite imagery and the elevation models with additional usage of Google Earth for 3D visualization.

3.1.3. *Glacial lineations*

Glacial lineations are elongated landforms formed subglacially by glacial streamlining (Figure 2(c)), potentially including both erosion and deposition, and the lineations therefore enable reconstruction of ice flow direction (Benn & Evans, 2010). Glacial lineations can include landforms ranging from small flutings to large mega-scale glacial lineations. At the Tibetan Plateau, previously mapped glacial lineations have typically been 0.5–3 km long (Fu et al., 2012; Heyman et al., 2008; Morén et al., 2011) with gentle topographic relief. Glacial lineations in the Maidika study area are characterized by elongated shapes located on low-relief surfaces or on valley floors. (Figure 2(c)). They have been mapped from Landsat ETM+ imagery and care has been taken not to map tectonic bedrock lineations characterized by sharper ridges as glacial lineations.

3.1.4. *Hummocky terrain*

Hummocky terrain consists of undulating sedimentary hills and intermediate depressions (Figure 2(d)). The hills vary from circular to elongated and irregular forms, and the depressions are commonly occupied by water bodies. Hummocky terrain can form by multiple processes, including supraglacial, subglacial, as well as non-glacial processes. Hummocky terrain is here used as a descriptive non-genetic term. The association with glacial landforms such as glacial valleys, marginal moraines, and glacial lineations in the Maidika region give some confidence to an interpretation of the hummocky terrain as glacially formed. Mapping of hummocky terrain has been carried out from the Landsat ETM+ imagery.

3.2. *Completeness, accuracy, and limitations of the map*

The map presents a detailed record of some major glacial landforms with a minimum size of 100–200 m, and for these particular landforms, we consider the landform record to be complete and accurate. Two main limitations for the map are the spatial resolution of the employed elevation models and satellite imagery, and the lack of field investigations of the mapped landforms. The resolution of the elevation models (90 and 30 m) is good enough to accurately map glacial valleys and large marginal moraines but it is too coarse for mapping smaller moraines, glacial lineations, and hummocky terrain. The resolution of the Landsat satellite imagery (30/15 m) is good enough to accurately map marginal moraines, glacial lineations, and hummocky terrain regions with individual forms larger than 100–200 m but it is too coarse for mapping smaller glacial landforms. Similar to the resolution-associated limitation, the absence of field investigations implies a lack of data on smaller glacial landforms and deposits such as glacial boulders and sediments that could potentially be located outside/below the outer-lowermost glacial landforms (cf. Heyman et al., 2009). In summary, the map represents a remote-sensing record of glacial landforms with an accurate and complete record of larger alpine style glaciation

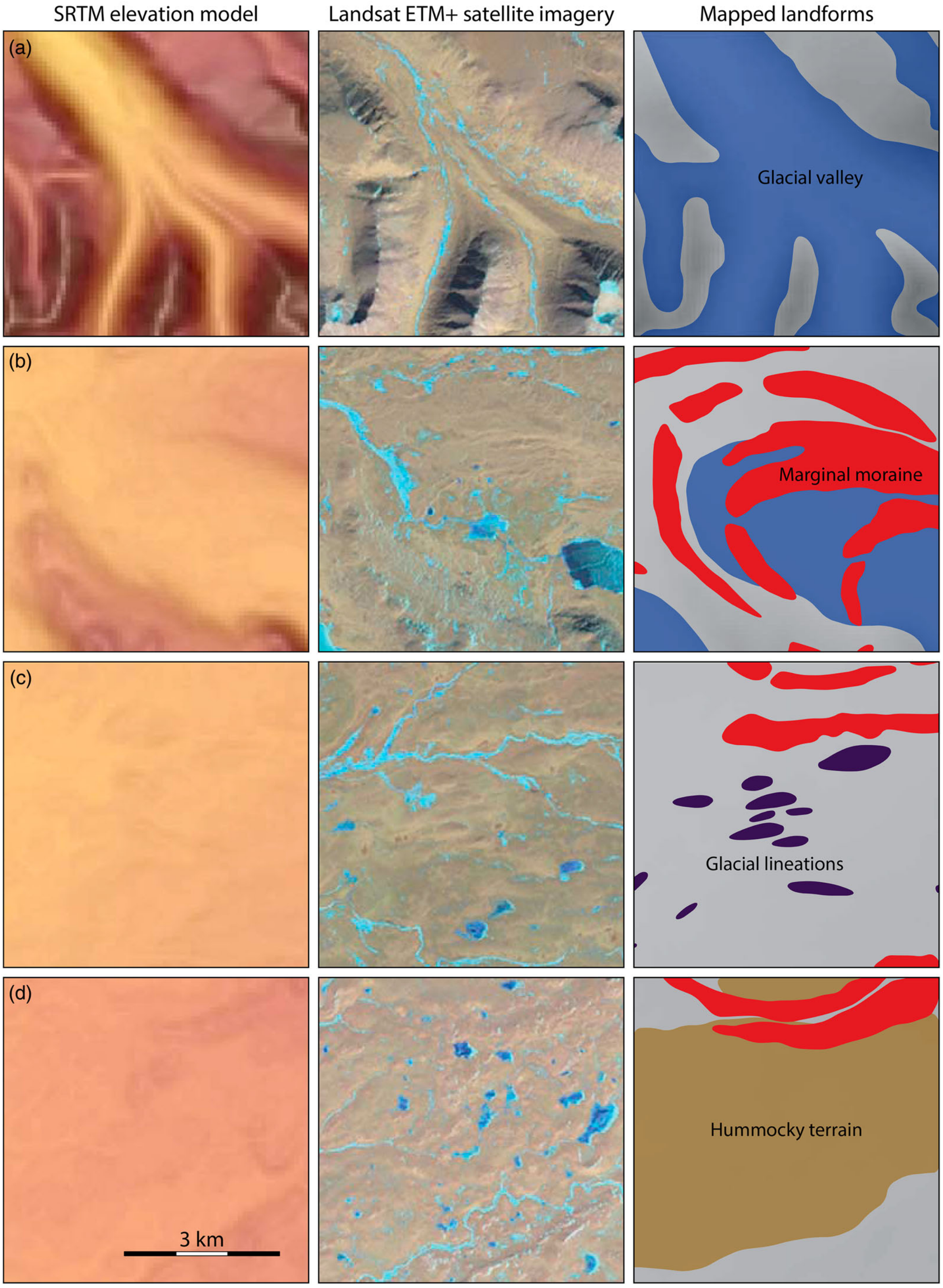

Figure 2. Examples of glacial landforms with SRTM elevation model data (left panels), Landsat ETM+ imagery (middle panels), and mapped glacial landforms (right panels). The SRTM elevation models are draped with a semi-transparent slope model. The Landsat ETM+ images are color composites of bands 5,4,2 draped with a semi-transparent panchromatic image of band 8. North is toward the top of the panels. See Figure 3(a) for the location of each map. (a) Glacial valleys reaching out from a mountain region. (b) Marginal moraines in the outer part of a glacial valley. (c) Glacial lineations. (d) Hummocky terrain in the outer part of a glacial valley.

landforms but it lacks detail at zoomed-in scales below 100–200 m.

3.3. *Generalized maximum glacial extent reconstruction*

The mapped glacial landforms have been used to reconstruct a generalized maximum glacial extent. The reconstruction is outlined to include all glacial landforms and mark a minimum extent of the maximum glaciation (cf. Blomdin et al., in press; Morén et al., 2011). The outer/lower margin of the reconstructed glacial extent is mostly based on the outer-lowermost parts of the glacial valleys and the marginal moraines and taking account of the topography and the outline of glacial landforms for interpolating in-between mapped landforms. The reconstruction is generalized with larger areas

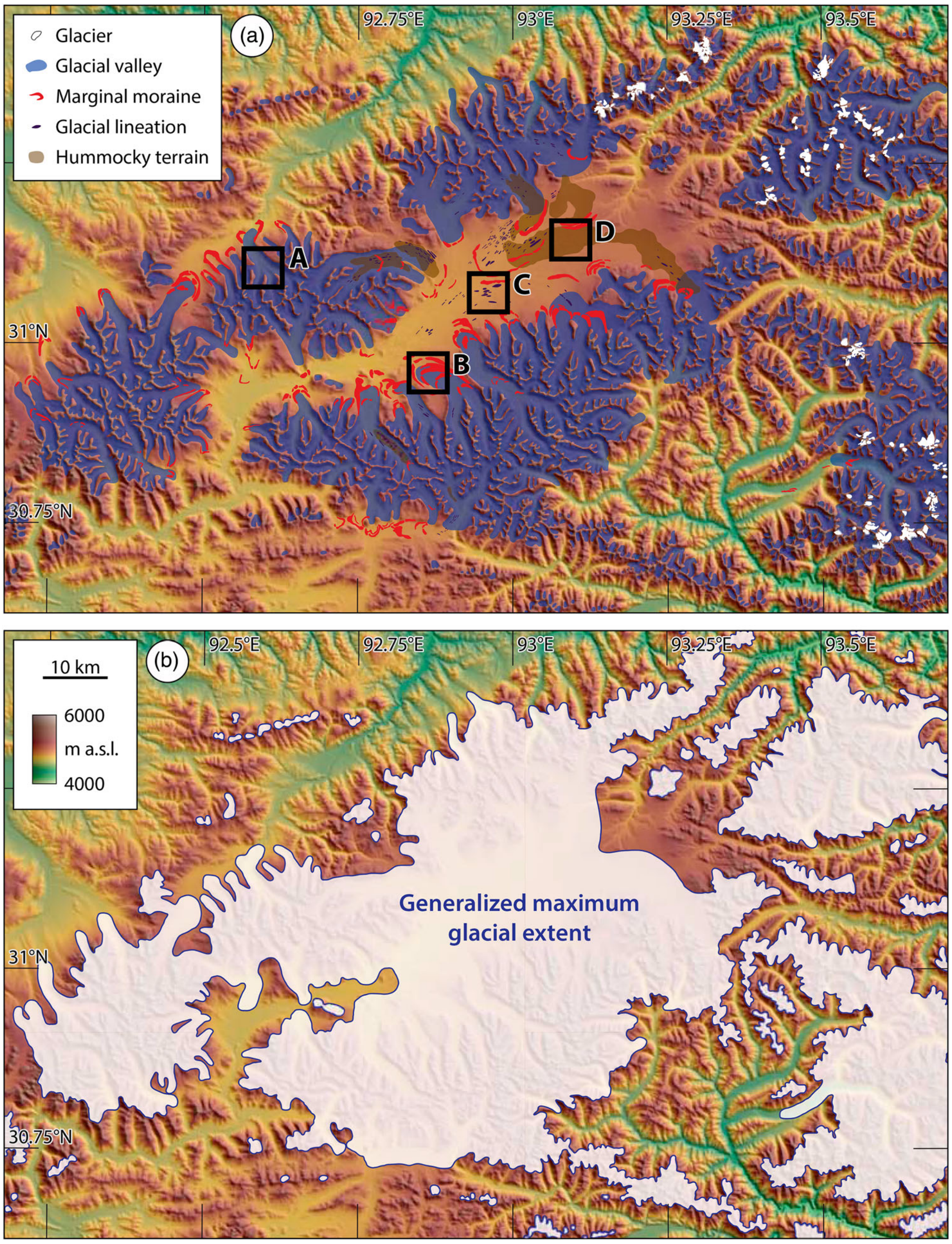

Figure 3. (a) Glacial landform record of the Maidika study area. The black squares show the location of the landform example maps in Figure 2. (b) Generalized maximum glacial extent reconstruction based on the mapped glacial landforms covering 6045 km^2 or 44% of the map.

shown as completely ice covered although some high parts of the reconstruction might have been ice-free ridges or nunataks.

4. Results

Glacial valleys cover 3734 km^2 or 27% of the map. They occur primarily in the mountain regions around the Maidika basin and in the high mountains in the eastern part of the study region. The glacial valleys range from cirques (a few hundred meters in size across) to large valleys (more than 20 km long and 5 km wide). They occur at altitudes between 4520 and 5770 m a.s.l. with 85% of the area between 4900 and 5350 m a.s.l.

A total of 205 marginal moraine polygons (several moraines are split in multiple polygons and some moraines are merged into single polygons; cf. Figure 2(b)) have been mapped, covering an area of 160 km^2. They occur mainly in the outer/lower parts of the glacial valleys with a few moraines located higher up in the glacial valleys and some moraines located outside the glacial valleys. The majority of the marginal moraines are located in the central and western part of the study area, with the highest moraine concentration in the outer parts or outside the glacial valleys reaching out into the Maidika basin. In many locations, multiple marginal moraine ridges form series of latero-frontal moraine complexes. The marginal moraines range from moraine ridge parts less than 0.5 km long to ridges more than 10 km long and 1 km wide. They occur at altitudes between 4580 and 5290 m a.s.l. with 91% of the area between 4800 and 5100 m a.s.l.

A total of 229 glacial lineations have been mapped, covering an area of 14 km^2. Almost all of the glacial lineations are located in the Maidika basin or the glacial valleys leading down to the Maidika basin with a few additional glacial lineations mapped in a glacial valley in the south-central part of the study area. Most of the glacial lineations occur in swarms of multiple lineations although there are also a few singular lineations. The glacial lineations range in size from less than 300 m long and 50 m wide to more than 2000 m long and 500 m wide. They occur at altitudes between 4840 and 5070 m a.s.l.

A total of 8 hummocky terrain areas have been mapped, covering 210 km^2. They are located primarily in the northeastern region of the Maidika basin and in the glacial valleys leading down to the Maidika basin. One additional small hummocky terrain area has been mapped in the south-central part of the map. The individual hummocks are typically 0.1–1 km across. There are round and irregular hummocks as well as some hummocky terrain, including linear elements. The hummocky terrain areas occur at altitudes between 4850 and 5090 m a.s.l.

The generalized maximum glacial extent reconstruction covers 6044 km^2 (44% of the study area), of which 4412 km^2 is one continuous area over the Maidika basin and the surrounding mountains (Figure 3). The previously glaciated areas occur at elevations of 4450–5990 m a.s.l. The reconstruction is more extensive than the glaciers creating most of the marginal moraines in the Maidika basin, as indicated by glacial lineations and hummocky terrain areas. In the southern and western regions, the outer-lowermost moraines commonly mark the maximum glacial extent.

5. Discussion and conclusions

The glacial landforms of the Maidika region show that the area has been extensively glaciated at some point in the past. The glacial valleys and marginal moraines show that alpine style valley glaciers have existed in the mountain regions. The glacial lineations, hummocky terrain, and extended marginal moraines in the Maidika basin indicate that most of, and possibly all of, the Maidika basin was once covered by ice. The orientation of the glacial lineations, being similar to the glacial valleys where they are located and oriented downhill in a NE–SW direction in the Maidika basin, indicates formation under outlet glaciers or under an ice field with glacier flow controlled by underlying topography.

The generalized maximum glacial extent reconstruction generally corresponds well with the Maidika ice cap of Derbyshire et al. (1991) and Zheng (2005) although the maximum glaciation presented here (Figure 3) lacks some outlet glaciers mapped for the Maidika ice cap. Because glacial landforms may have been eroded or degraded, the maximum Quaternary glaciation may exceed the reconstruction. The timing of the maximum glaciation is unknown and it could be asynchronous with different ages of the maximum glacier expansion for different regions of the map. In the eastern part of the study region, there are hardly any glacial landforms other than glacial valleys and this is likely a result of fluvial incision creating a landscape of more pronounced topographic relief (Stroeven et al., 2009).

Of particular interest are the glacial lineations as they represent an uncommon landform on the Tibetan Plateau. Swarms of glacial lineations have previously only been mapped on the Haizi Shan plateau in the southeastern part of the Tibetan Plateau (Fu et al., 2012, 2013), where they are interpreted as formed under an ice cap located on the low-relief plateau surface. The Maidika glacial lineations are similar in size and number to the Haizi Shan glacial lineations but they differ in the topographic setting. While the Haizi Shan lineations are located on a low-relief plateau surface formerly covered by an ice cap, the Maidika lineations are located in a low-relief basin and the glacial valleys leading out to the basin. It is further worth noting that some of the Maidika glacial lineations are located in hummocky terrain areas, indicating that the hummocky terrain has either been formed subglacially or that the hummocks have been subglacially reshaped during the last glaciation (Eyles, Boyce, & Barendregt, 1999).

The age of the Maidika glaciations are yet to be defined as there is no chronological data from the study region. A generally subtle character of the marginal moraines and the glacial lineations indicates that significant post-glacial degradation may have occurred. Considering the exposure ages from the western Nyainqêntanglha (Chevalier et al., 2011; Owen et al., 2005) and the Tanggula Mountains (Colgan, Munroe, & Zhou, 2006; Owen et al., 2005; Schäfer et al., 2002) that to a large part predate the global last glacial maximum around 20 ka, it seems likely that the glacial landforms of the Maidika region to a large degree predate the global last glacial maximum.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Software

Elevation models and satellite images were processed using Esri ArcGIS 10, which was also used for glacial landform mapping. Google Earth was used for 3D visualization. Vector and raster data were exported to

Adobe Illustrator, which was used for producing the map.

Data

Shape files of the glacial landforms are available as Supplementary Materials.

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