Glacial geomorphology of the Bayan Har sector of the NE Tibetan Plateau

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Abstract: We here present a detailed glacial geomorphological map covering 136,500 km^2 of the Bayan Har sector of the northeastern Tibetan Plateau - an area previously suggested to have nourished the most extensive Quaternary glaciers of the Tibetan Plateau. The map, presented at a scale of 1:650,000, is based on remote sensing of a 90 m SRTM digital elevation model and 15/30 m Landsat ETM+ satellite imagery. Seven landform types have been mapped; glacial valleys, glacial troughs, glacial lineations, marginal moraines, marginal moraine remnants, meltwater channels and hummocky terrain. A large number of glacial landforms exist, concentrated around mountain blocks protruding above the surrounding plateau area, testifying to former glacial activity. In contrast, large plateau areas of lower altitude lack glacial landforms. The mapped glacial geomorphology indicates multiple former glacial advances primarily by valley and piedmont glaciers, but lends no support to the hypothesis of ice sheet scale glaciation in the area. The presented glacial geomorphological map demonstrates the usefulness of remote sensing techniques for mapping the glacial geomorphology of the Tibetan Plateau, and it will be used for reconstructing the paleoglaciology of the Bayan Har sector of the northeastern Tibetan Plateau.

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1. Introduction

Glacial reconstructions exist for the entire Tibetan Plateau (Frenzel, 1960; Li et al., 1991; 2005; Pu, 1991; Kuhle, 2004), but there appears to be an absence of glacial geomorphological maps to underpin reconstructions at a plateau-wide scale. Comprehensive glacial geomorphological maps with individual landforms, such as marginal moraines, glacial valleys, and cirques, have been presented for individual mountain areas only (e.g. Derbyshire et al., 1991; Lehmkuhl and Liu, 1994; Zheng and Rutter, 1998; Klinge and Lehmkuhl, 2004; Zhou et al., 2004). However, none of these cover an area larger than 13,500 km^2, and for most of the Tibetan Plateau (c. 3 million km^2) such maps are absent (Figure 1). In an effort to help understand the paleoglaciology of the Tibetan Plateau, we here present a detailed glacial geomorphological map covering 136,500 km^2 of its northeastern sector.

The extent of glaciations in the Bayan Har sector of the northeastern Tibetan Plateau has not been robustly resolved. Tafel (1914) first noted the presence of glacial traces in the presently unglaciated Bayan Har area. Subsequent glacial reconstructions range from glaciers, restricted to valleys radiating from the highest mountain areas, to regional or plateau-wide ice sheets (Li et al., 1991; Lehmkuhl et al., 1998; Zheng and Rutter, 1998; Zhou and Li, 1998; Kuhle, 2003). For the last glaciation the leading inference is one of restricted valley glaciers (Li et al., 1991; Lehmkuhl et al., 1998; Zheng and Rutter, 1998; Zhou and Li, 1998). Particularly for older glaciations, however, there remains the possibility for significantly larger glacial extent. Li et al. (1991), for example, presented a reconstruction for a regional ice sheet of 95,000 km^2 in our study area - the Huang He ice sheet. The notion of a regional ice sheet in the Bayan Har sector has subsequently gained considerable recognition (e.g. Derbyshire et al., 1991; Shi, 1992; Shi et al., 1992; Hövermann et al., 1993; Rutter, 1995; Zhou et al., 2004; Ehlers and Gibbard, 2007). Based on studies of inferred glacial landforms and sediments (Zhou et al., 1994; Zhou, 1995), Zhou and Li (1998) presented a paleoglaciological reconstruction of the Bayan Har sector comprising four glacial configurations, two restricted to valleys, of proposed Marine oxygen Isotope Stage (MIS) 2 and 4 ages, and two also inundating parts of the surrounding plateau surface, of proposed MIS 6 and 12 ages. Except for the proposed plateau-scale ice sheet (Kuhle, 2004), the Huang He ice sheet is the most extensive Quaternary ice sheet proposed for the Tibetan Plateau.

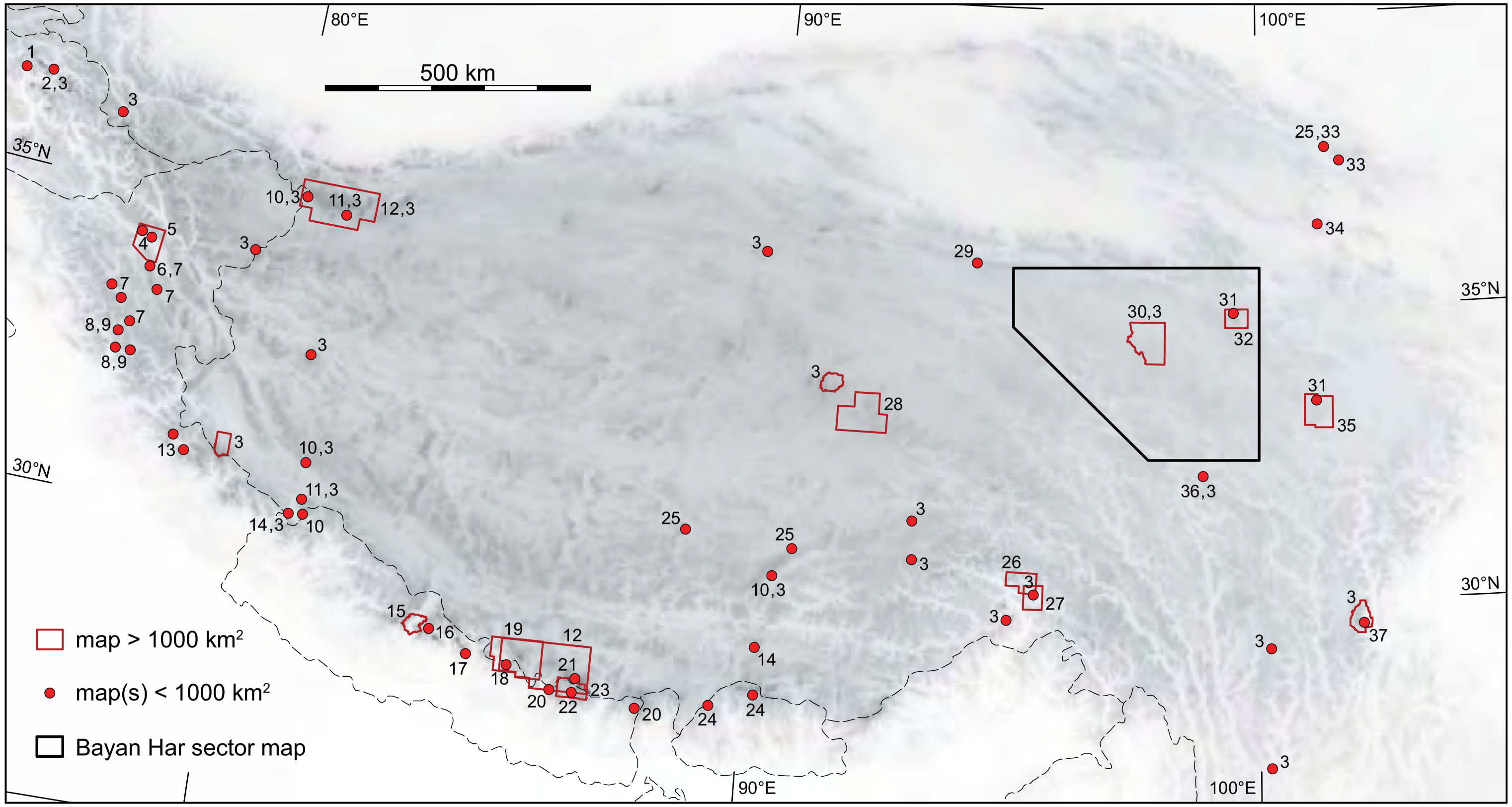

Figure 1 (previous page) Occurrences of glacial geomorphological maps with individual glacial landforms on the Tibetan Plateau. Key to the numbers is as follows: 1. Meiners (2005); 2. Owen et al. (2002); 3. Shi et al. (2005); 4. Owen et al. (2006a); 5. Burbank and Fort (1985); 6. Damm (2006); 7. Taylor and Mitchell (2000); 8. Owen et al. (1996); 9. Owen et al. (1997); 10. Zhou et al. (2004); 11. Derbyshire et al. (1991); 12. Zheng and Rutter (1998); 13. Sharma and Owen (1996); 14. Zheng (1989); 15. Fort (2000); 16. Owen et al. (1998); 17. Zech et al. (2003); 18. Shiraiwa and Watanabe (1991); 19. Zheng (1988); 20. Meiners (1999); 21. Burbank and Kang (1991); 22. Richards et al. (2000); 23. Kuhle (2005); 24. Iwata et al. (2002); 25. Lehmkuhl et al. (2002); 26. Li et al. (2005); 27. Klinge and Lehmkuhl (2004); 28. Colgan et al. (2006); 29. Owen et al. (2006b); 30. Zheng and Wang (1996); 31. Owen et al. (2003a); 32. Wang (1987); 33. Rose et al. (1998); 34. Owen et al. (2003b); 35. Lehmkuhl and Liu (1994); 36. Lehmkuhl (1998); 37. Owen et al. (2005).

The Huang He ice sheet reconstruction is based on scarce field data and, as a consequence, this reconstruction has endured criticism (Zheng and Wang, 1996; Lehmkuhl, 1998; Zheng and Rutter, 1998). There are glacial geomorphological overview maps which cover large parts of our study area (Zhou and Li, 1998; Kuhle, 2003) but detailed glacial geomorphological maps containing individual landforms only exist for the north-central part of Bayan Har Shan (Zheng and Wang, 1996, 4400 km^2) and for the Anyemaqen Shan (Wang, 1987, 1500 km^2; Figure 1). In addition, there are almost no radiometric constraints. The only dated glacial deposits are located northeast of the Anyemaqen ice field, where cosmogenic exposure and optically stimulated luminescence dates were interpreted to represent advances of alpine glaciers during MIS 3 and 2 and the early Holocene (Owen et al., 2003a).

With the glacial geomorphological map presented in this paper, and fieldwork in conjunction with the larger-scale project of which this is an important part (Stroeven et al., In press), we aim to take a significant step forward in understanding the paleoglaciology of the Tibetan Plateau. We can now start to evaluate the merits of the Huang He ice sheet on the basis of glacial geomorphological traces identified in Landsat imagery and digital topography, and we can evaluate whether our methodology would be apt for further extension to the mapping of the glacial geomorphology of the entire Tibetan Plateau.

2. Physiography of the Bayan Har area

Our study region is centered on the Huang He (Yellow River) source area and the Bayan Har Shan (Shan = Mountain), and is restricted in the southwest by the Chang Jiang (Yangtze River) valley gorge. Elevations primarily range between 4000 and 5000 m above sea level (a.s.l.), although mountain peaks generally summit above 5000 m a.s.l. and fluvial valleys along the margins are incised to lower elevation (the Huang He floors at c. 2800 m a.s.l. in the northeastern corner and the Chang Jiang floors at c. 3300 m a.s.l. in the southwestern corner). The main physiographic units are the NW-SE trending Bayan Har Shan (5267 m a.s.l.; centrally-located and presently non-glaciated), the eastern part of Burhan Budai Shan (5445 m a.s.l.; northern edge and presently non-glaciated) and the Anyemaqen Shan (6282 m a.s.l.; northeastern edge with the contemporary Anyemaqen ice-field) (Figure 2). The bedrock lithology consists mainly of sandstones and shales with granite intrusions (Liu et al., 1988), and the bedrock structure is dominated by WNW-ESE strike-slip faults (Fu and Awata, 2007).

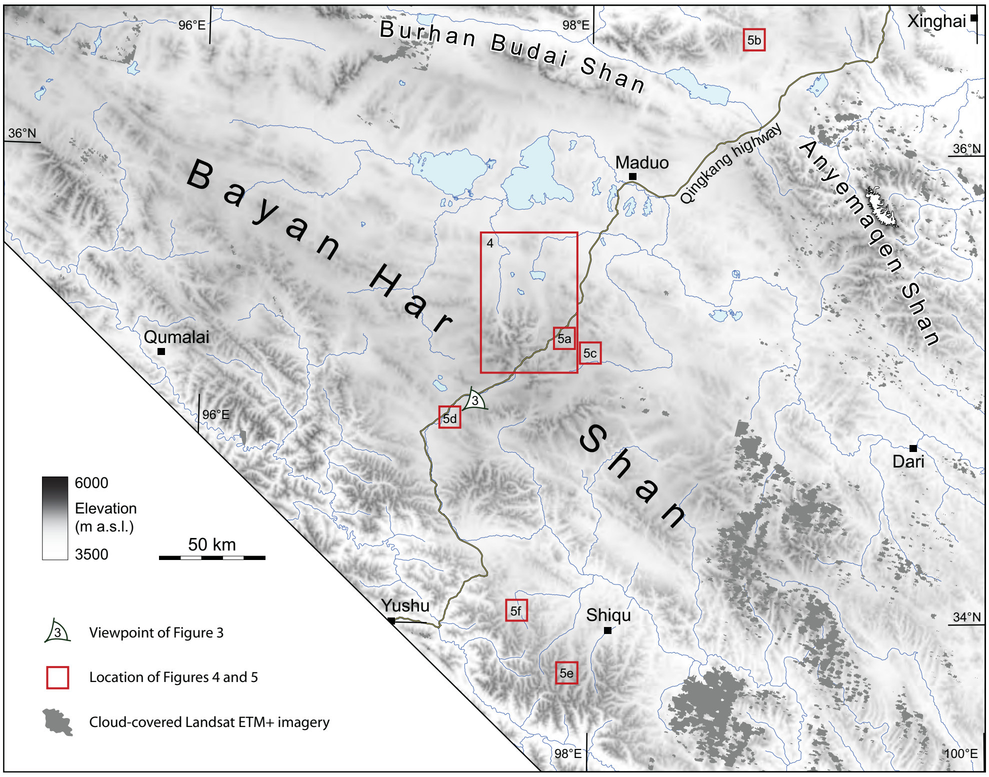

Figure 2 Map of the study area, including the viewpoint of Figure 3 and the locations of Figures 4 and 5, and showing areas covered by clouds in Landsat ETM+ imagery.

3. Methods

The glacial geomorphology has been mapped from a digital elevation model (DEM) and satellite imagery. We used the Shuttle Radar Topography Mission (SRTM) DEM of 90 m horizontal resolution (USGS, 2004; Jarvis et al., 2006). To enhance the visual impression of the topography, semi-transparent grey-scale images of shaded relief and slope were produced from and draped across the DEM. Orthorectified Landsat ETM+ imagery was the primary source of satellite data. RGB colour composite images of bands 5, 4, 2 and 4, 3, 2 (30 m resolution) were draped by a semi-transparent grey-scale image of the panchromatic band 8 (15 m resolution) to improve viewer resolution. Where significant parts of the Landsat ETM+ imagery were cloud-covered (Figure 2), orthorectified Landsat TM colour composite images (30 m resolution) were employed. A total of 16 satellite scenes acquired from the Global Land Cover Facility (GLCF, 2007) were utilized (Table 1).

The mapping was principally performed at a consistent scale of 1:75,000. Google Earth TM imagery was frequently employed for 3-D visualization and the identification of all landform types (Figure 3). Seven categories of glacial landforms were identified and mapped: glacial valleys, glacial troughs, glacial lineations, marginal moraines, marginal moraine remnants, meltwater channels, and hummocky terrain. Examples of mapped glacial landforms are presented in Figures 4 and 5. The mapped geomorphology was field-checked during 2005, 2006 and 2007. Lakes, rivers and contemporary glaciers were mapped from satellite imagery.

GLCF-ID	Type	Path	Row	Acquisition date
039-445	ETM+	136	036	2000-08-31
039-406	ETM+	135	036	1999-09-23
039-407	ETM+	135	036	2000-08-08
039-359	ETM+	134	036	2001-07-03
039-316	ETM+	133	036	2001-08-13
039-317	ETM+	133	036	2002-07-31
039-408	ETM+	135	037	1999-09-23
039-360	ETM+	134	037	2000-10-04
039-361	ETM+	134	037	2001-07-03
039-318	ETM+	133	037	2002-07-15
039-444	ETM+	136	035	1999-09-14
039-405	ETM+	135	035	1999-07-21
039-358	ETM+	134	035	2001-07-03
039-315	ETM+	133	035	2001-07-12
011-038	TM	133	037	1994-05-14
011-037	TM	133	036	1995-07-20

Table 1 Landsat satellite imagery GLCF (2007) used for mapping.

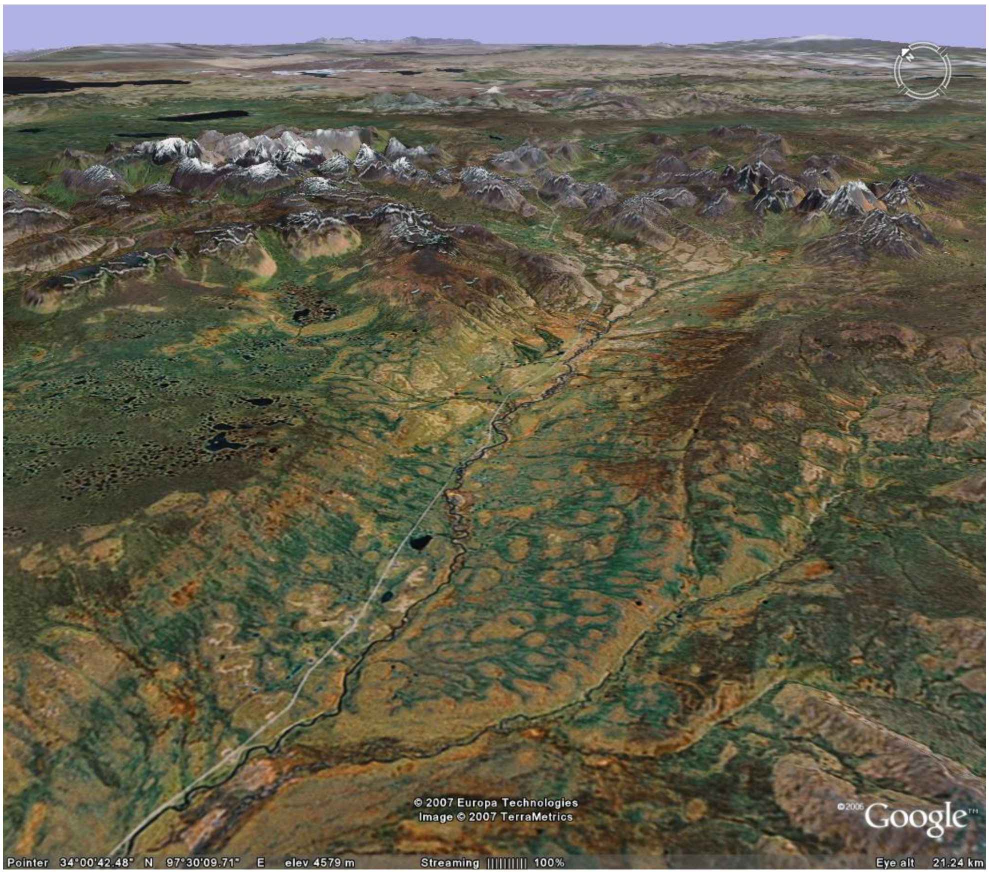

Figure 3 Oblique Google Earth^{TM} imagery displaying a glacial trough crossed by marginal moraines southwest of the central Bayan Har Shan. The base of the image spans approximately 9 km. For image location see Figure 2. Permission for publication was granted by Google Earth Brand Permissions (2007-06-12).

4. Landform definitions and descriptions

Glacial valleys are valleys with a clear U-shaped cross-section constrained by steep valley sides (Figure 4). The glacial valleys, with smooth surfaces, differ distinctly from the sharp, non-glacial valleys formed by tectonic action and fluvial incision. The glacial valleys are generally <2.5 km wide, <15 km long, and 100-400 m deep with depth/width ratios of 0.07-0.20. Cirques, with bowl-formed valley heads, are also included in the glacial valley category. Glacial valleys are distributed around the highest mountain areas with a slight decrease of glacial valleys towards the west of the map. Glacial valleys have primarily been identified from the DEM and in Google

Earth^{TM} imagery.

Glacial troughs are U-shaped valleys of more gentle relief, with moderate slopes towards surrounding higher relief, and have larger dimensions than the glacial valleys (Figure 4). The glacial troughs are up to 9 km wide and 50 km long and are generally shallow, with depths of 30-300 m and depth/width ratios of 0.01-0.10. Glacial troughs are generally located around high mountain areas, typically in locations where several glacial valleys merge. Glacial troughs have primarily been identified from the DEM and in Google Earth^{TM} imagery.

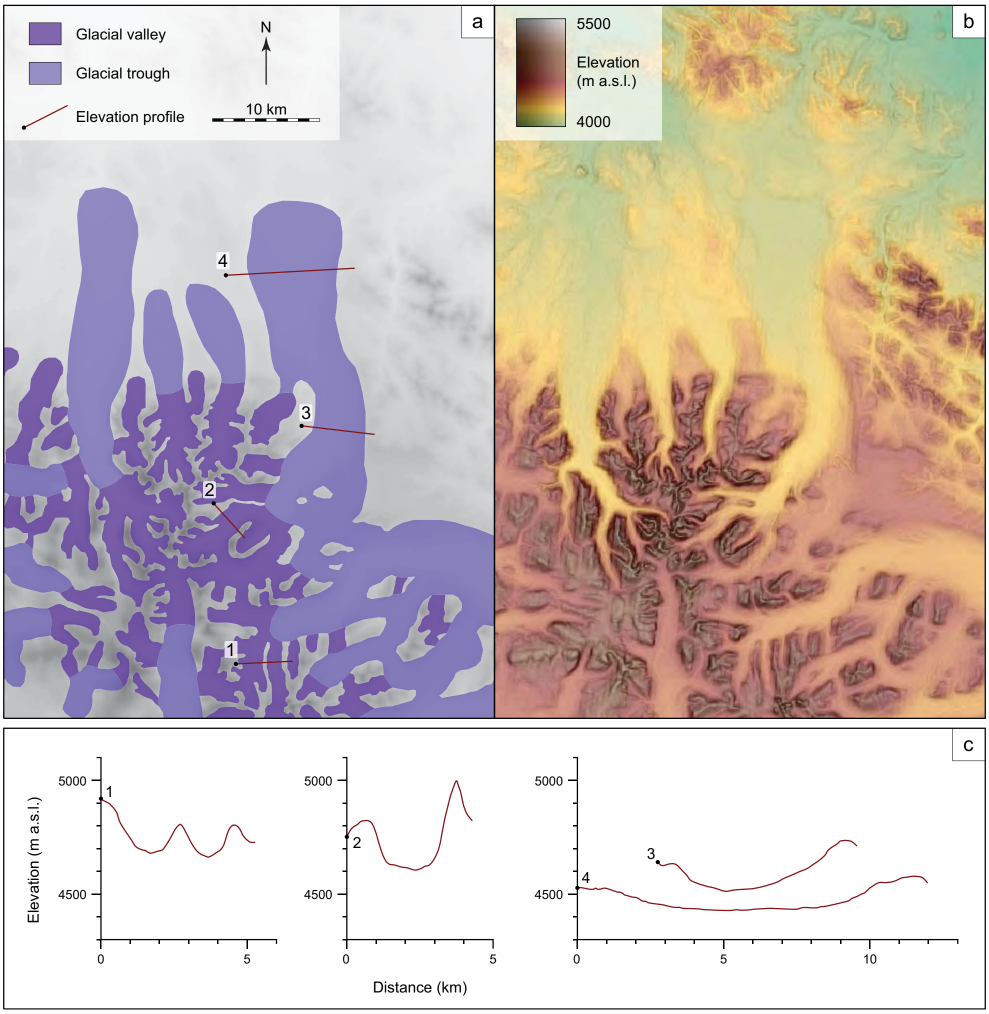

Figure 4 Mapped glacial valleys and troughs (a) in the central Bayan Har Shan with a coloured DEM draped by a semi-transparent grey-scale slope image (b) giving flat slopes a bright hue and steep slopes a darker hue. Elevation profiles (c) illustrate the U-shape of the valleys and the more gentle topography of the glacial troughs.

Glacial lineations are elongated features formed by subglacial streamlining. We have been careful to distinguish tectonic imprints from glacial lineations and all mapped glacial lineations are aligned with glacial valley/trough floors and are oriented independent of tectonic lineations (Figure 5a). The glacial lineations are 0.5-3.2 km long, <500 m wide and <30 m high. The majority of the glacial lineations are crag-and-tails or are interpreted to have a bedrock core, although some lineations may be composed entirely of sediments. Glacial lineations are located mainly in the upper parts of large glacial valleys of the central and southeastern Bayan Har Shan. Glacial lineations have primarily been identified from satellite images but also from the DEM and in Google Earth^{TM} imagery.

Marginal moraines are ridge-like features formed along a glacier margin (Figures 5b, c). Such ridges can be located along the valley sides (lateral moraines) or curving across valleys (frontal moraines). The marginal moraines range in size from 0.1 to 2 km wide and 0.5 to 15 km long. The ridges are generally rather subdued, having gentle slopes of less than 5° and up to 15 m high ridge crests. Marginal moraines are located in and around high mountain areas and often occur outside glacial valleys and troughs. The highest concentration of moraines is found in the central Bayan Har Shan. All marginal moraines are visible in the DEM although identification of the moraines has been aided by the use of satellite images and Google Earth^{TM} imagery.

Marginal moraine remnants are ridge-like landforms similar to the marginal moraines but with a less distinct appearance in DEM and satellite images (Figure 5c). The marginal moraine remnants are, similar to the marginal moraines, located across valleys or along valley sides, again indicating former ice-marginal positions, but they have a faint topography and/or a diffuse outline. The marginal moraine remnants are generally located in the same areas as the marginal moraines. Identification of the marginal moraine remnants has been done from satellite images, the DEM and Google Earth^{TM} imagery.

Meltwater channels are water eroded channels with a location, outline and size indicative of a formation along or close to an ice margin (Figures 5d-f). Glacial meltwater channels of two genetic types have been mapped. First, lateral and latero-frontal meltwater channels formed along the margins of glacier tongues are located on the slopes of glacial valleys and troughs and slope down-valley at an oblique angle to the contour lines before curving down towards the valley floor (Figure 5e). The lateral channels commonly occur in series of parallel channels and are often winding. Second, proglacial meltwater channels are formed by meltwater running off a glacier margin, or possibly through glacial lake drainage, as indicated by the size and location of the channel (e.g., a large channel running straight off a marginal moraine) (Figure 5f). The meltwater channels are 0.5-4 km long and <10 m (lateral channels) or <100 m (proglacial channels) deep. Meltwater channels are located primarily in and outside glacial troughs of the central, southern and southeastern Bayan Har Shan. Meltwater channels have been identified from satellite images and Google Earth™ imagery (lateral channels) and the DEM (proglacial channels).

Hummocky terrain is an irregularly-shaped sedimentary deposit of adjoining hills and depressions (Figures 5c, d). Hills are rounded, irregular or elongated in plan-form and can be 100 m to 1 km across. Hummocky terrain generally has a gentle relief with hummocks protruding <10 m above the surrounding ground. Hummocky terrain covers in total 1900 km^2 with individual areas covering up to 450 km^2. Hummocky terrain is distributed mainly in a band along the NW-SE trending Bayan Har Shan with major hummocky terrain areas located around the central Bayan Har Shan. A number of glacial processes have been proposed for the formation of hummocky terrain (Benn and Evans, 1998) although they may also be formed by non-glacial processes, and they may contain both till and water-lain deposits. Hummocky terrain is here used as a descriptive, non-genetic term. However, because the location and outline of hummocky terrain areas strongly correlate to the locations of glacial troughs and marginal moraines, there appears to be some evidence for a glacial origin of our unit. Field checks of hummocky terrain areas in central and western Bayan Har also confirm a glacial origin, with abundant glacial deposits at all investigated hummocky terrain areas. Identification of hummocky terrain has been done from satellite images and Google Earth ™ imagery only since the DEM is of insufficient resolution to show the hummocky topography clearly.

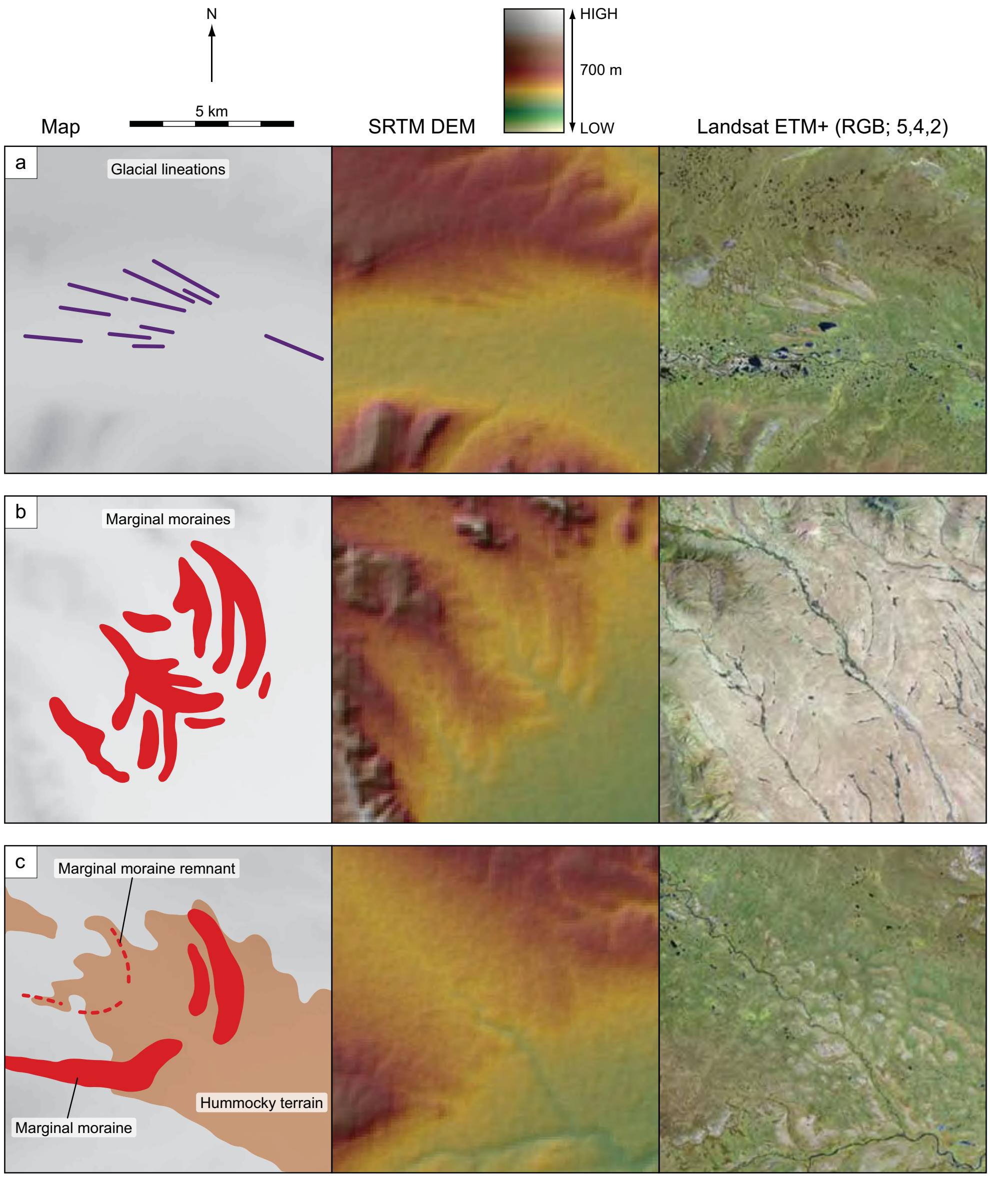

Figure 5 Examples of mapped landforms and their appearance in the DEM and satellite imagery. Mapped landforms (left panel; note that not all mapped landforms are displayed here), coloured digital elevation models draped by a semi-transparent grey-scale shaded relief (middle panel), and Landsat ETM+ RGB colour composite images of band 5,4,2 draped by a semi-transparent grey-scale image of band 8 (right panel). (a) Glacial lineations in the central Bayan Har Shan. (b) Marginal moraines in the northeastern part of the study area. (c) Hummocky terrain, marginal moraines and marginal moraine remnants east of the central Bayan Har Shan. For image locations, see Figure 2.

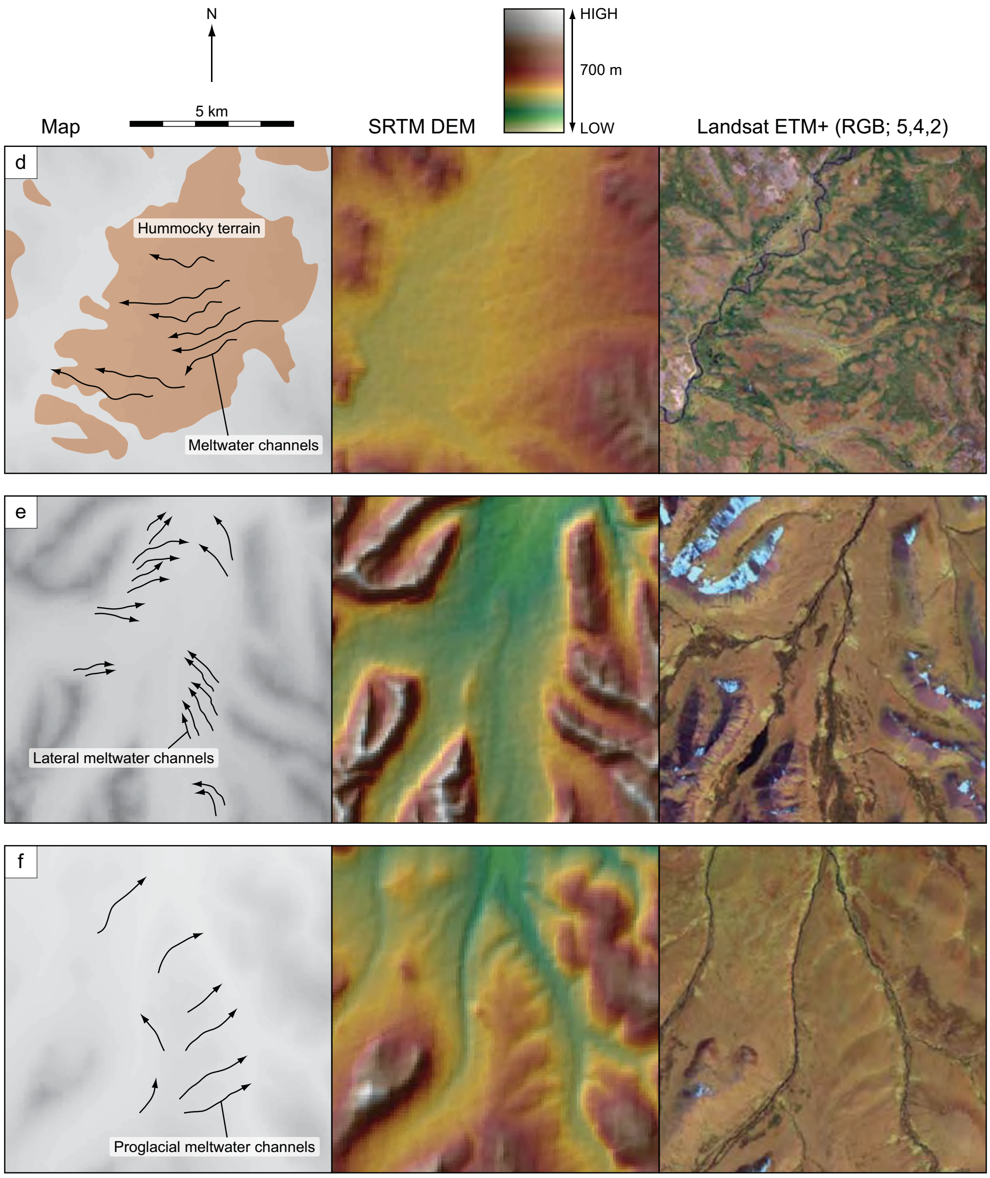

Figure 5 (continuation). Examples of mapped landforms and their appearance in the DEM and satellite imagery. Mapped landforms (left panel; note that not all mapped landforms are displayed here), coloured digital elevation models draped by a semi-transparent grey-scale shaded relief (middle panel), and Landsat ETM+ RGB colour composite images of band 5,4,2 draped by a semi-transparent grey-scale image of band 8 (right panel). (d) Hummocky terrain and meltwater channels southwest of the central Bayan Har Shan. (e) Series of lateral meltwater channels in the southern part of the study area. (f) Proglacial meltwater channels in the southern part of the study area. For image locations, see Figure 2.

5. Completeness and accuracy of the map

We consider the map to present a complete and accurate picture of glacial landforms that are larger than 100-200 m in the study area of the northeastern Tibetan plateau. The DEM and satellite images have been interpreted multiple times to attain cartographic consistency across the entire study area, and field checks confirm the remote sensing interpretations. Naturally, the remote sensing technique limits the ability to identify landforms of scales approaching pixel resolution, and small glacial landforms (e.g., small roche moutonnées and narrow moraine ridges), if present, may not be revealed. Glacial valleys, glacial troughs, glacial lineations and hummocky terrain, on the one hand, are landforms of a size far exceeding the resolution of the DEM and satellite imagery, and the mapped landforms are considered to represent the complete set of landforms in the study area. The mapped marginal moraines, marginal moraine remnants and meltwater channels, on the other hand, are constrained to landforms larger than 100-200 m and there may be a presence of smaller glacial landforms that remain unmapped. However, during field checks we have been unable to detect such small glacial landforms, suggesting that they may be uncommon or non-existing.

The map presents the main glacial imprint on the landscape. This may not be used to imply that the landform imprint also yields a complete reflection of paleoglaciological extent, as non-erosive cold-based ice coverage may be difficult to detect in landscape morphology and complicates the glacial imprint (Kleman, 1994) and fluvial incision with landscape rejuvenation may destroy the glacial imprint (Stroeven et al., In press).

Landforms in the northern part of the study area, previously suggested to be marginal moraine features (Kuhle, 1989) and glacial valleys (Zhou and Li, 1998) are absent on our map. This is because we agree with interpretations of Lehmkuhl et al. (1998) and Stroeven et al. (In press), respectively, that these are non-glacial landforms related to tectonic processes.

6. Conclusions

A large number of glacial landforms in the Bayan Har sector of the northeastern Tibetan plateau can be used for paleoglaciological reconstructions. From these, it is evident that much of the predominantly ice free uplands were formerly covered by extensive valley glacier networks. Glacial advances of varying extent are indicated by the location of marginal moraines, meltwater channels and glacial lineations. There is a strong correlation between the presence of glacial landforms and altitude, with mapped landforms clustering in and around the high mountain blocks that protrude above the surrounding plateau. Extensive areas of the plateau below these mountain blocks, especially around the Huang He source area north of Bayan Har Shan, completely lack glacial landforms. Ice sheet-scale landform assemblages are notably absent, such as plateau-scale glacial lineation swarms, ribbed moraines or eskers. Hence, the mapped landforms testify to former alpine style glaciations but lend no support to the presence of former plateau-scale or even regional ice sheets.

The mapped glacial geomorphology will be used in further studies, including field studies of glacial deposits and radiometric dating, aiming towards a detailed paleoglaciological reconstruction of the Bayan Har sector of the northeastern Tibetan plateau. The presented map reveals a large number of previously unmapped landforms from an area at least an order of magnitude larger than in previous attempts to map the glacial geomorphology of the Tibetan Plateau (Figure 1). Furthermore, the level of detail and the large coverage of the map manifest the adequacy of remote sensing techniques - being time effective and inexpensive - for mapping the still concealed glacial geomorphology of other sectors of the Tibetan plateau.

Data

The author has supplied data (as a series of shapefiles) used in the production of the accompanying map. This PDF has a ZIP archive embedded within it (stored as a .ZI file extension) containing the data and can be accessed by right-clicking on the “paperclip” icon at the beginning of this section (you will need to save the file and edit the file extension to .ZIP). Whilst the contents of the ZIP file are the sole responsiblity of the author, the journal has screened them for appropriateness.

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Software

The DEMs were processed in ERDAS Imagine 9.1 and the satellite imagery in ENVI 3.4/4.3 to produce images that were imported into ArcGIS 9.1/9.2 in which all mapping was performed. Google Earth™ software was used for 3D visualization. To produce the map and figures, DEMs modified in Adobe Photoshop CS2 and vector data exported from ArcGIS were imported into Adobe Illustrator CS2/CS3 in which the final layout was performed.

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