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Landscape analysis of the Huang He headwaters, NE Tibetan Plateau — Patterns of glacial and fluvial erosion

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ABSTRACT

The large-scale geomorphology of the Huang He (Yellow River) headwaters, centered around the Bayan Har Shan (5267 m asl) in the northeastern part of the Tibetan Plateau, is dominated by an uplifted remnant of a low-relief relict plateau with several mountain ranges. We have performed geomorphological mapping using SRTM topographic data and Landsat 7 ETM+ satellite imagery to evaluate landscape characteristics and patterns, and to investigate the relative importance of different erosional processes in the dissection of this plateau remnant. The distribution of valley morphologies indicates that the eastern and southern margins of the plateau remnant have been extensively dissected by the Huang He and Chang Jiang (Yangtze) rivers and associated tributaries, while the mountain ranges have valley morphologies with U-shaped cross-sections that indicate large impacts from glacial erosion during Quaternary glaciations.

An east-west decrease in the abundance of glacial valleys in mountains above 4800 m asl suggests that the diminishing size of the mountain blocks, coupled with increased continentality, resulted in more restricted glaciations to the west. Glacial valleys in mountain blocks on the plateau remnant are wider and deeper than adjacent fluvial valleys. This indicates that, integrated over time, the glacial system has been more effective in eroding the mountains of the relict upland surface than the fluvial system. This erosion relationship is reversed, however, on the plateau margin where dramatic fluvial rejuvenation in valleys that are part of the Huang He and Chang Jiang watersheds has consumed whatever glacial morphology existed. A remarkable correspondence exists between the outline of the relict plateau remnant and the outline that has been proposed for the Huang He Ice Sheet. This coincidence could mean that the Huang He Ice Sheet was larger than originally proposed, but that evidence for this has been consumed by fluvial incision at the plateau margin. Alternatively, this coincidence could indicate that what has been described as an ice sheet border is merely the outline of a relict plateau landscape.

In apparent support of the latter, the absence of large-scale glacial geomorphological evidence on the plains of the relict plateau surface is not consistent with the hypothesis of a Huang He Ice Sheet.
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1. Introduction

As the highest and youngest plateau in the world, the Tibetan Plateau (Fig. 1) is a key global topographic feature with inferred regional and global climatic significance (Ruddiman and Kutzbach, 1989; Molnar and England, 1990; Prell and Kutzbach, 1992; Raymo and Ruddiman, 1992; An et al., 2001). Uplift of the plateau resulted in drier and colder conditions, thereby dictating the initiation, timing, and extent of Quaternary glaciations on the plateau (e.g., Clark et al., 2004; Lehmkuhl and Owen, 2005). The Tibetan Plateau uplift also forced large-scale and profound environmental changes in surrounding areas, including the formation of deserts in northwestern China (e.g., the Taklamakan Desert and the Badain Jirin Desert; Wu, 1981; Wang, 1990).

Uplift of the Tibetan Plateau accelerated fluvial incision and rates of mass movement at its margin, as indicated by increased river transport and off-shore deposition (Clift et al., 2002). Recent studies have highlighted the importance of fluvial incision into the plateau margin in response to tectonic forcing as a mechanism for isolating remnants of the original plateau surface (Clark et al., 2004, 2005, 2006;

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Fig. 1. Index map of southeastern Asia. The study area is in the headwaters of the Huang He (Yellow) and Chang Jiang (Yangtze) rivers. The outlines of Fig. 2 and the study area are highlighted by the boxes. (This figure is available in colour in the online version of this article.)

Schoebohm et al., 2004, 2006). These remnants of the plateau surface can be used as reference surfaces against which to evaluate the impact of lateral erosion since uplift. These relict surfaces, however, also provide information on the long-term topographic evolution of the Tibetan Plateau itself, as distinct from effects caused by marginal incision.

Crucial questions in the debate over the long-term evolution of topographic relief on the Tibetan Plateau and its role in global and regional climate change include the relative impacts of glacial and non-glacial erosion and the timing and extent of Quaternary glaciation on the plateau. Despite intensified research into this topic during the last two decades, the history and style of Tibetan glaciation and the relationship between Tibetan Plateau glaciation and global climate change are still not well understood (Brozovic et al., 1997; Molnar, 2005; Owen et al., 2005).

As part of a larger investigation into the possible existence of a regional-scale ice sheet in the headwaters of the Huang He (Yellow River), centered around the Bayan Har Shan (Figs. 1 and 2), we undertook large-scale geomorphological mapping with the following objectives:

1. to map, visualise and analyse the spatial distribution of glacial erosional morphology
2. to compare overall glacial impact with fluvial impact on the relict plateau surface and on the plateau margin
3. to analyse the implications of such observations and comparisons for the glacial history of the region.

1.1. Glacial history of the northeastern Tibetan Plateau

The glacial history of the Tibetan Plateau has been the subject of much debate, and remains controversial despite an intensified pace of chronological research following the introduction of terrestrial cosmogenic nuclide (TCN) techniques (e.g., Derbyshire et al., 1991; Lehmkuhl, 1998; Owen et al., 2005). One particularly critical issue is whether the entire Tibetan Plateau was covered by a large ice sheet during the global last glacial maximum (LGM) (Kuhle, 1985, 1988, 1998, 2004) or if the local mountain ranges had independent ice covers (Zheng, 1989a,b; Derbyshire et al., 1991; Rutter, 1995; Lehmkuhl, 1998; Zheng and Rutter, 1998). Three widely different past glacial configurations have been proposed for the Huang He headwaters region of the Tibetan Plateau:

(i) inundation by a plateau-scale ice sheet
(ii) expansion of valley glaciers in the mountains on the plateau
(iii) inundation by expanded and amalgamated mountain ice fields to form a regional ice sheet (Huang He Ice Sheet).

The first two configurations are end-member interpretations of the field evidence for LGM glaciation and are mutually exclusive. The third configuration may have predated the LGM.

The case for an ice sheet on the scale of the entire Tibetan Plateau is principally based on the argument that its equilibrium line altitude (ELA), inferred from the altitudes of glacial features, was below the average elevation of the Tibetan Plateau, and that this would have led to plateau-scale ice sheet glaciation (Kuhle, 1985, 1988, 1998, 2004; Gupta et al., 1992; cf. the concept of instantaneous glacierization, Barry et al., 1975). For the headwaters of the Huang He, Kuhle (2003) also presents data on deposits proposed to originate from a plateau-scale ice sheet. Contrary to the plateau-scale ice sheet hypothesis, however, extensive geomorphological, sedimentological, and chronological data, and ice core, lake sediment, and climatological arguments indicate that only a limited expansion of ice from the mountains occurred during the LGM (e.g., Derbyshire et al., 1991; Shi et al., 1992; Hövermann et al., 1993; Lehmkuhl and Liu, 1994; Rutter, 1995; Sharma and Owen, 1996; Feng, 1998; Lehmkuhl, 1998; Lehmkuhl et al., 1998; Zheng and Rutter, 1998; Schäfer et al., 2002; Wang et al., 2002; Yi et al., 2002; Zhou et al., 2002; Owen et al., 2003a, b,c, 2005; Lehmkuhl and Owen, 2005). From these studies, it appears that if a Tibetan ice sheet covered the entire plateau, it did not occur during the last few hundred thousand years, a conclusion that is in broad agreement with the Li et al. (1991) map of the extent of Quaternary glaciers on the Tibetan Plateau.

Relatively few publications exist concerning the glacial history of the Huang He headwaters in the northeastern part of the Tibetan Plateau. Uplands in the source area of the Huang He, which are defined by the Chang Jiang (Yangtze River) in the southwest, are thought to have supported mountain glaciers during the LGM and a regional-scale ice sheet, the Huang He Ice Sheet by Li et al. (1991) and Zhou and

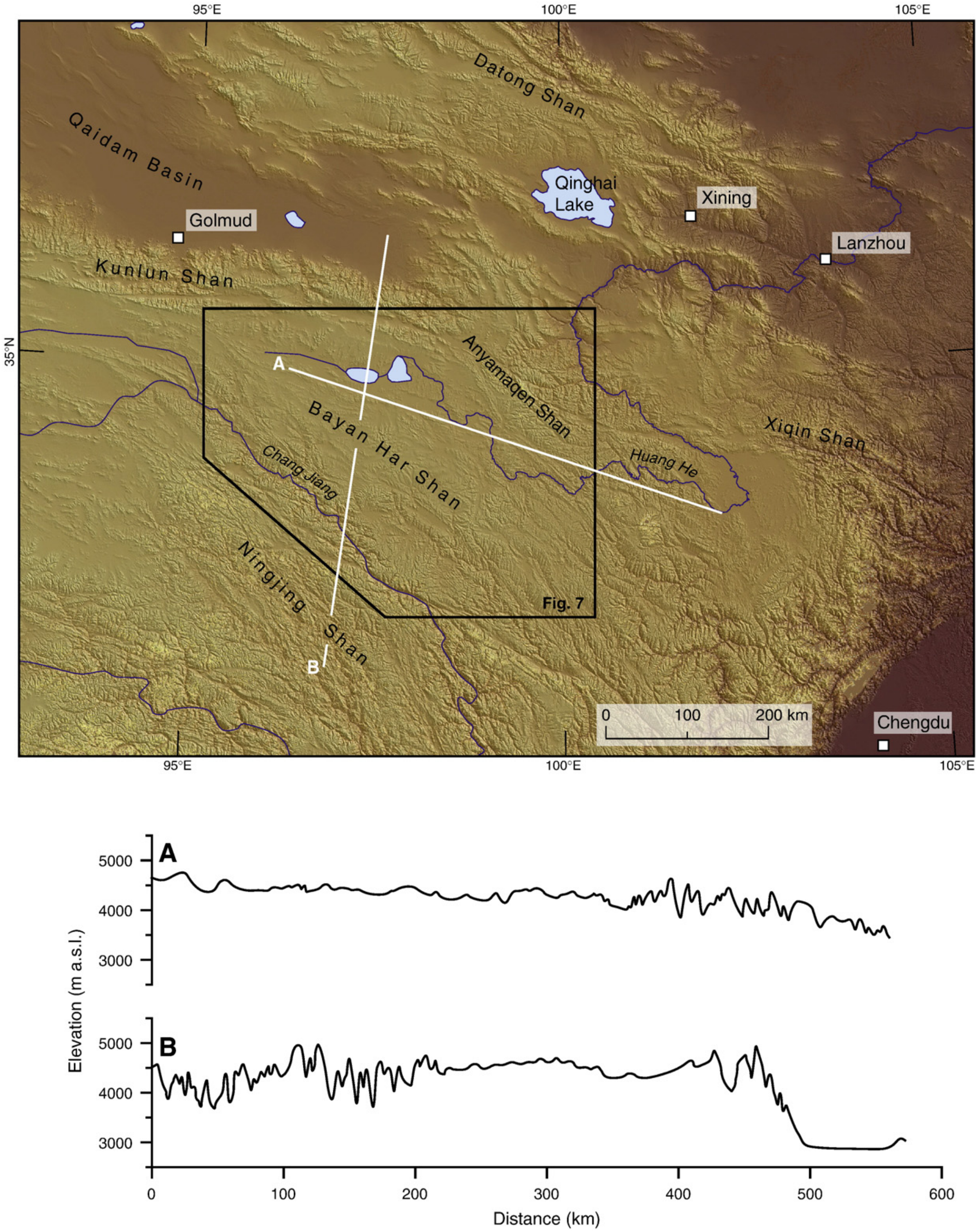

Fig. 2. Physiography of the northeastern Tibetan Plateau. Moderate and high relief mountains stand out above a low-gradient plateau surface that has steep marginal slopes as shown by WNW-ESE and SSW-NNE elevation profiles. The box denotes the outline of the study area (see Fig. 7). (This figure is available in colour in the online version of this article.)

Li (1998), during some earlier phase of glaciation. An independent ice sheet of this scale would have been the most extensive Quaternary ice mass on the Tibetan Plateau (Zhou and Li, 1998). Based on field observations and interpretations of satellite images, Li et al. (1991) proposed a roughly triangular outline for the ~80,000 km^2 Huang He Ice Sheet.

Following geomorphological and stratigraphical studies (Zhou, 1995; Zhou et al., 1994), Zhou and Li (1998) presented a paleoglaciological reconstruction for the Huang He headwaters that suggested two stages of mountain centered valley glaciation and two stages of ice sheet glaciation — the maximum of which corresponds to the Huang He Ice Sheet of Li et al. (1991). The four glacial stages were tentatively correlated to marine oxygen isotope stages (MIS) 12, 6, 4 and 2, with a decreasing extent of ice during each subsequent glaciation. Evidence for the Huang He Ice Sheet included the presence of glacial valleys, erratics, and tills, mainly from the northern part of the hypothesized ice sheet area. Although the scarcity of data underlying this reconstruction has left it vulnerable to criticism (Zheng and Wang, 1996; Lehmkuhl et al., 1998; Zheng and Rutter, 1998), the concept of a Huang He Ice Sheet has been cited in numerous studies (Derbyshire et al., 1991; Shi, 1992; Shi et al., 1992; Hövermann et al., 1993; Lehmkuhl and Liu, 1994; Rutter, 1995; Lehmkuhl, 1998; Zhou et al., 2004; Ehlers and Gibbard, 2007).

Owen et al. (2003a) present the only absolute numerical dates available for the glacial history of this part of the northeastern region of the Tibetan Plateau. TCN and optically stimulated luminescence dates from moraines outside the contemporary glaciers on Anyemaqen Shan (Fig. 2) suggested to them that three glacial advances of diminishing extent occurred during MIS 3, 2 and 1 (early Holocene). This is consistent with dated sequences elsewhere on the Tibetan Plateau (Owen et al., 2005). A paucity of data from the northeastern region of the Tibetan Plateau, concerning the extent and chronology of former glaciations, requires further paleoglaciological studies before any conclusions can be reached regarding the scale and timing of Quaternary glaciers and ice sheets in this area (Zheng and Rutter, 1998; Klinge and Lehmkuhl, 2004; Lehmkuhl and Owen, 2005).

1.2. Fluvial degradation of the Tibetan margin

The most dynamic geomorphological region is the margin of the Tibetan Plateau, mostly because of the remarkable increase in local relief (Fielding et al., 1994). A number of the largest rivers on Earth drain this margin, and the high loads of sediment indicate rapid rates of denudation in the catchments. This rapid fluvial incision and concurrent slope processes (Ouimet et al., 2007) have resulted in upland surfaces becoming isolated from the main plateau, with a sharp contrast between the palimpsest, low-relief upland morphologies and the steep fluvial systems.

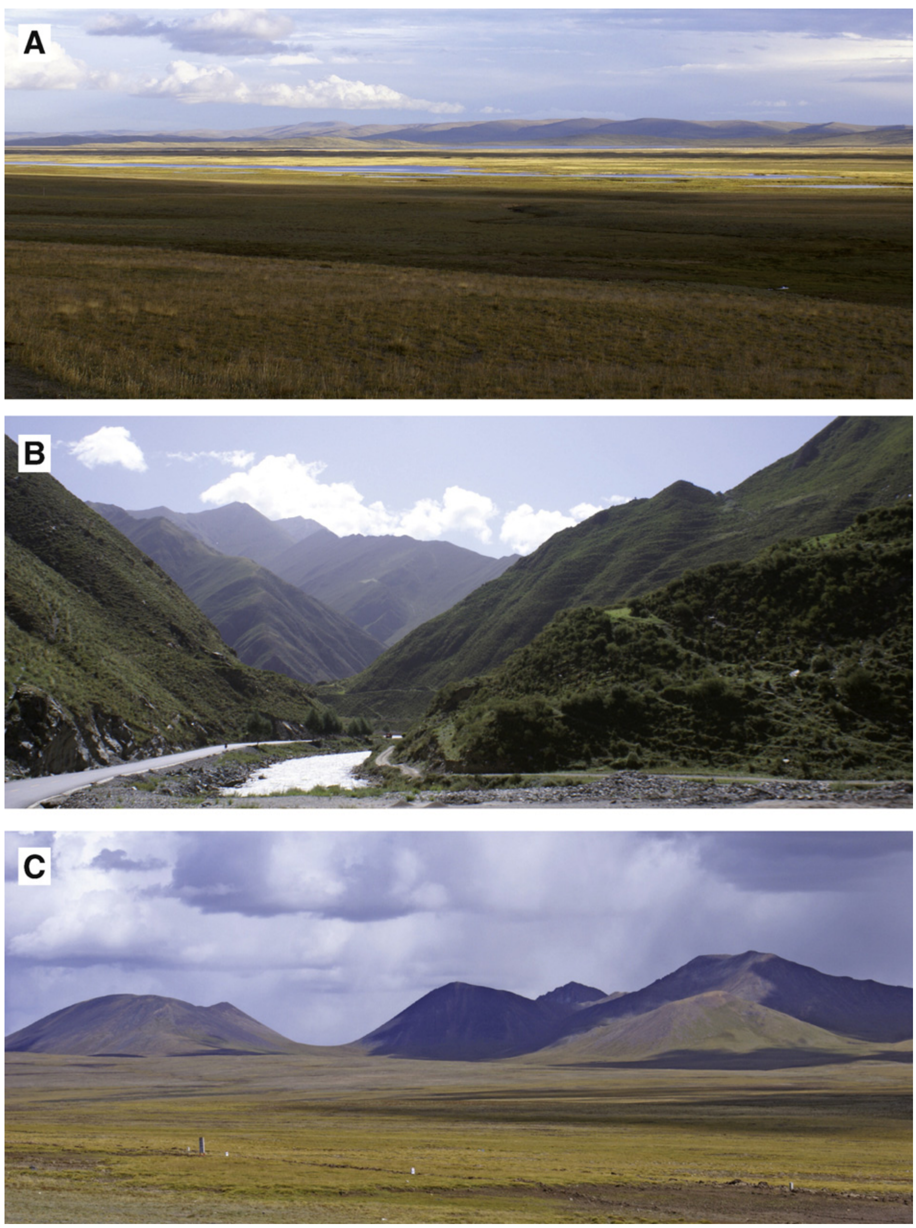

Fig. 3. Typical landscapes of the study area from a field perspective: (A) relict upland surfaces, characterized by sediment basins and mountain blocks with rounded interfluves. (B) Fluvial landscapes, with deeply-cut fluvial valleys which have steep and straight walls (tributary to Chang Jiang). (C) Glacial landscapes, with marked U-shaped valleys and arêtes, here cut into the relict upland surface of the Bayan Har Shan. (This figure is available in colour in the online version of this article.)

Most studies interpret that the upland surfaces have similar altitudes as indicating that fluvial erosion has incised into the margins of large, regionally-uplifted blocks. For example, rapid fluvial incision into bedrock has been interpreted to reflect a tectonic uplift of similar magnitude on the southern Tibetan Plateau margin (Burbank et al., 1996; Lavé and Avouac, 2001), thereby sustaining topographic equilibrium. Kirby et al. (2003) measured longitudinal river profiles along incising rivers and similarly suggested that anomalously steep channels at the eastern margin of the Tibetan Plateau reflect active plateau uplift. High elevation, low-relief plateau surfaces of postulated pre-uplift age, heavily dissected by actively incising rivers in steep fluvial valleys on the south-eastern margin (Clark et al., 2004, 2005, 2006; Schoebohm et al., 2004, 2006), have also been interpreted as indicating fluvial incision triggered by lower base levels following uplift. Finally, Lehmkuhl (1994) interpreted relict surfaces across the northeastern Tibetan Plateau as an uplifted surface that has been dissected by fluvial incision by the Huang He and its tributaries.

In this research we compared the fluvial landscape of the Huang He headwaters with the large-scale geomorphology of the relict upland. We also examined the patterns and impact of large scale glacial erosion in this area, and its relation to the fluvial and mass movement destruction of the relict upland and its margins.

2. Physiography

The study area covers 150,000 km^2 and consists of a relatively flat plateau surface at ~4300 m asl (Figs. 2, 3A and 4A), with parallel sets of mountain ranges rising ~1–2 km above the plateau surface, and deeply incised (1–2 km) NW-SE trending river valleys (Figs. 2, 3B and 4B). The Huang He headwaters study area is centered on the Bayan Har Shan upland, which has a maximum summit elevation of 5267 m asl. The bulk of the plateau consists of Triassic-age sandstones and shales, and the mountain blocks are primarily oriented parallel to major NW-SE trending faults. Many of the higher peaks are developed in areas of Mesozoic granite intrusions (Fig. 5).

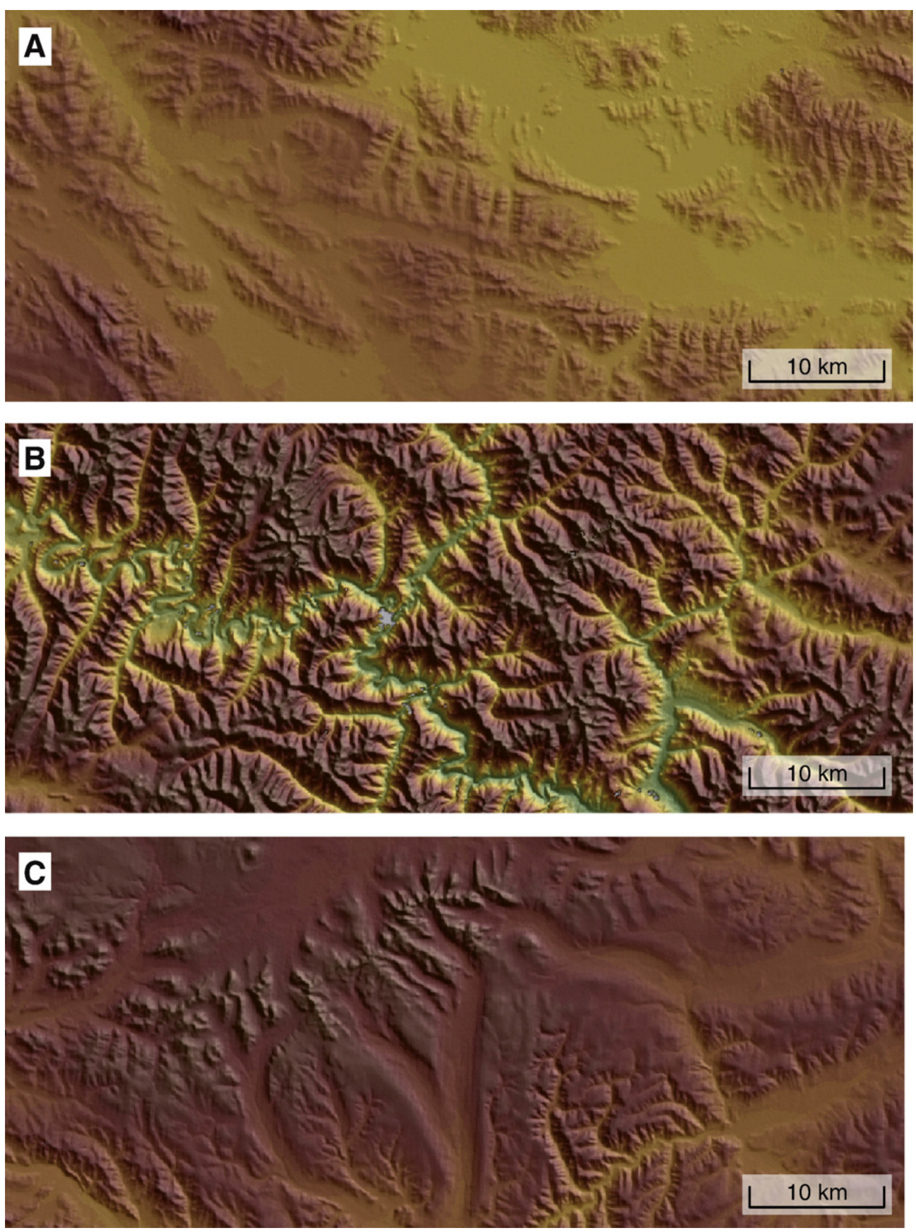

Fig. 4. Typical landscapes of the study area from a DEM perspective: (A) relict upland surfaces. (B) Fluvial landscapes. (C) Glacial landscapes. For location, see Fig. 7. (This figure is available in colour in the online version of this article.)

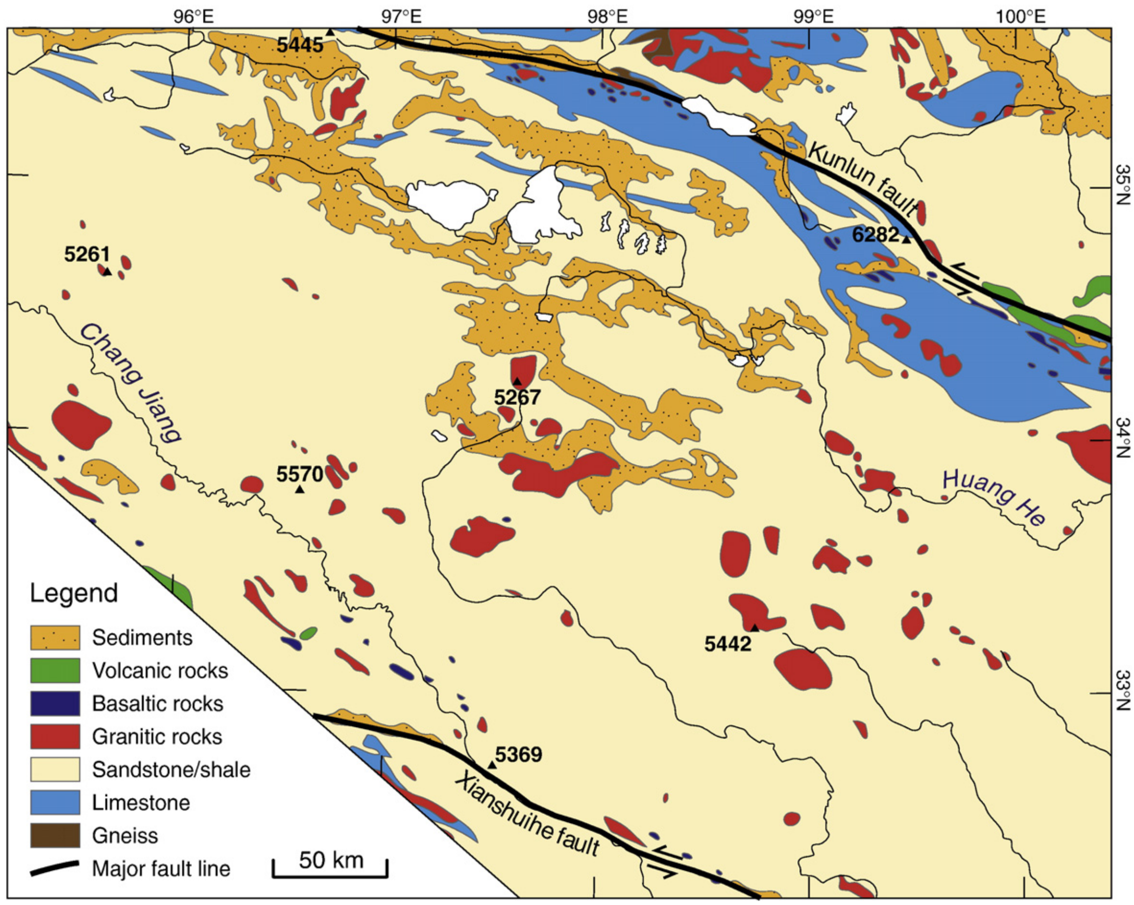

Fig. 5. Bedrock geology of the study area (based on Liu et al., 1988). (This figure is available in colour in the online version of this article.)

Three major mountain chains in the study area, from which ice could have emanated to inundate the surrounding plateau surface to form a Huang He Ice Sheet, are the presently unglaciated eastern extremity of the Kunlun Shan (northern boundary) and the Bayan Har Shan, and the presently glaciated Anyemaqen Shan on the north-eastern border of the region. The Anyemaqen Shan is closer to the edge of the plateau, and is higher and wetter (Lehmkuhl, 1998). The primary drainage of the region is provided by the Huang He, which is low gradient in its headwaters until it reaches the edge of the uplifted plateau. The southern margin of the plateau block is defined by the Chang Jiang. The tributaries of the Chang Jiang that drain the study area flow in a generally southwest direction, and are high gradient streams in steep V-shaped valleys (Fig. 3B).

3. Methods

3.1. Landform mapping

Large-scale landforms were mapped using remote sensing data from various sources. The principle dataset was the Shuttle Radar Topography Mission (SRTM) digital elevation model (USGS, 2004), with a horizontal resolution of 90 m. This data set was analysed in ArcGIS 9.1, which was also used to create shaded relief and hillslope models. The ArcGIS 9.1 profile graph tool and Google Earth™ imagery were also employed. The geomorphology was further mapped in 10 Landsat 7 ETM+ satellite images in various combinations of false colour composites of bands 2, 3, 4, and 5 (30 m resolution), and the panchromatic band 8 (15 m resolution). Complementary information, such as lakes and rivers, was also mapped from satellite images. Field observations and verifications were conducted in 2005, 2006 and 2007.

We mapped three main types of landscape morphology; relict upland surfaces, fluvial landscapes, and glacial landscapes (Fig. 4). We define relict upland surfaces as plains and rolling landscapes with gentle slopes, having a low relative relief (typically <500 m) and characterised by convex-concave hillslopes (Figs. 3A and 4A). In contrast, young fluvial landscapes are composed of distinctly V-shaped valleys with steep straight slopes where the relative relief often exceeds 500 m (Figs. 3B and 4B). Glacial landscapes are composed of U-shaped valleys and troughs, and in contrast to relict surfaces, glacial valleys are separated from each other by arêtes, or have valley benches high up on the valley sides that mark the incision into older surface generations (Figs. 3C and 4C). The glacial valleys are typically up to 2 km wide and 10 km long and are mostly found clustered around the higher massifs, although they sometimes also extend beyond the foothills of individual mountain blocks.

To distinguish relict landscapes, where we postulate that little landscape modification is going on at present, from young fluvial landscapes, which are highly geomorphologically active today, we produced a slope map (where darker areas signify steeper slopes) which, as a semitransparent layer, was draped over a coloured elevation map. The resultant image displays areas lacking steep slopes (relict upland landscape) with a characteristic “hazy” appearance, whereas the steeper slopes of the younger fluvial landscape have a clear and dark hue (Fig. 6). Because of the striking difference between these two landscape classes, the on-screen mapping of the border across the study area was mostly a straightforward operation. Valleys that have upper reaches in the relict upland and extend into the fluvial landscape, however, were analysed with longitudinal profiles, where nickpoints were used as the boundary between relict and rejuvenated fluvial valley systems.

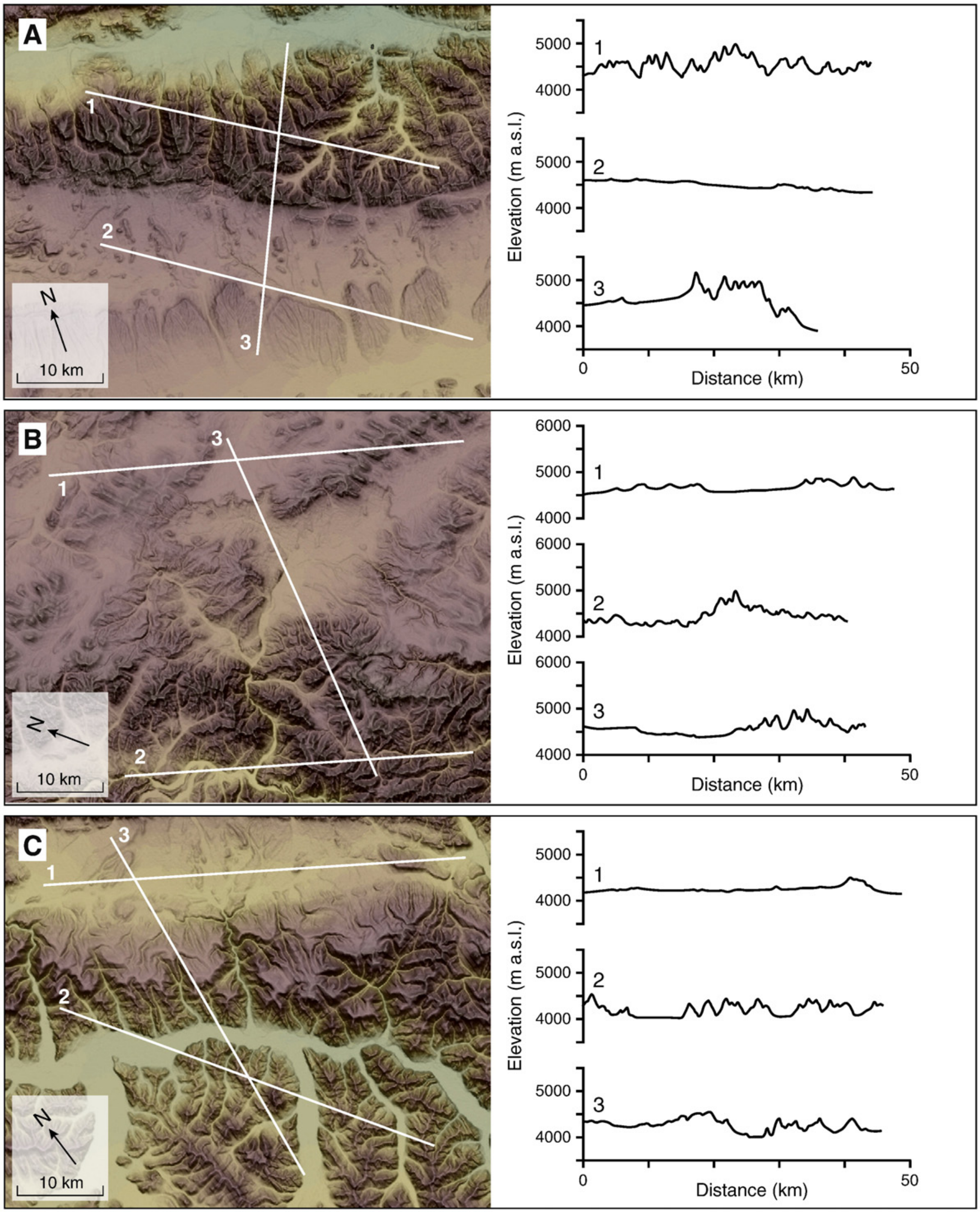

Fig. 6. The relict upland surface margin as shown by DEM maps and elevation profiles. The maps display a semitransparent grey-scale slope image draped over a colour DEM. Low relief terrain has a bright and "hazy" appearance whereas steep slopes have a darker and clearer hue. For location of the maps, see Fig. 7. (This figure is available in colour in the online version of this article.)

The resulting map has three landscape classes (Fig. 7), each with a specific morphometric signature (Fig. 8). Fig. 8 shows that relict surfaces and fluvial surfaces are characterised by a dominance of low (<4°) and high (15–20°) slope angles, respectively. The glacial landscape shows a more even distribution of slope angles (predictably given the characteristic U-shape shape of glacial valleys) with a discernable but small maximum for low slope angles (1–2°). The latter would be expected for the unusually shallow and wide glacial valleys of our study area (Heyman et al., 2008).

A spatial analysis of the distribution of low and high slope angles is shown in Fig. 9, where areas with slopes <4° and >15° are highlighted. The vast majority of the areas with low slope angles (<4°) are found on the plateau, showing that plains are its most characteristic feature. Where low slopes are present in the fluvial and glacial landscapes, they are restricted to valley floors. In contrast, steep slopes dominate the fluvial landscape class. Restricted areas with steep slopes (>15°) also occur outside the fluvial landscape class, and they have formed dominantly in mountain blocks affected by glacial erosion (cf. Fig. 7).

3.2. Mapping consistency

Because all mapping was performed by on-screen digitising and was based solely on DEM and satellite data, the mapped landforms

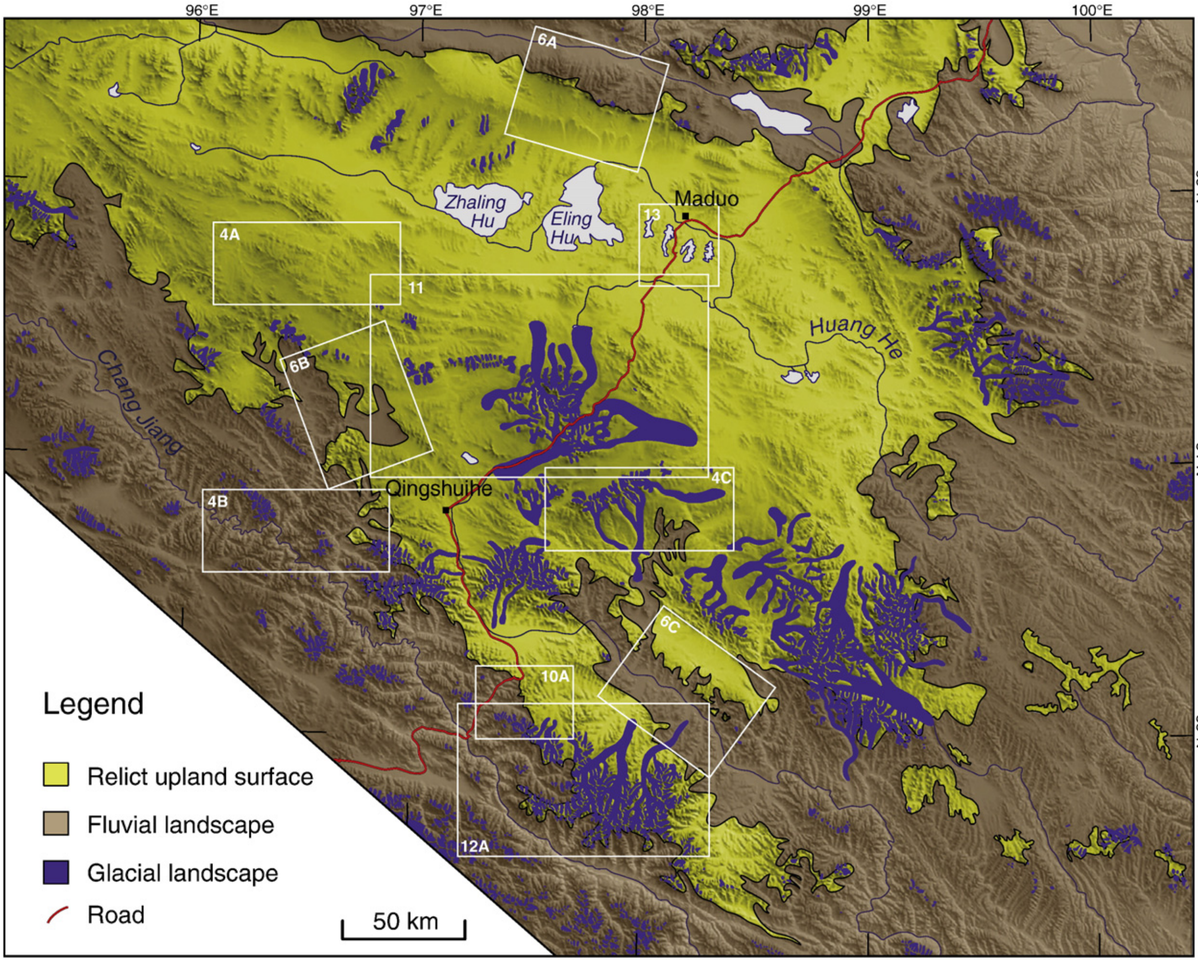

Fig. 7. Major landscape units in the headwaters of the Huang He. Shown are a relict upland surface, young fluvial landscapes at and below the margin of the relict surface, and a glacial landscape which predominantly consists of large glacial valleys and troughs. The white boxes depict the locations of Figs. 4A–C, 6A–C, and 10–13. (This figure is available in colour in the online version of this article.)

necessarily represent a subjective analysis of the landscape. Our interpretations were guided, however, by objective geomorphological criteria (mostly hillslope characteristics). To attain cartographic consistency across the entire study area and to tackle the problem of boundary delineation, the topographic and satellite data were interpreted multiple times by multiple interpreters.

4. Results

The largest-scale pattern apparent from the DEM and remote sensing is the contrast between the primarily low gradient plateau surface, with extensive areas with slopes <4°, and the high gradient areas of fluvial rejuvenation on the plateau margins, with extensive areas with slopes >15° (Fig. 9). Landscape elements on the plains, such as rolling topography, meandering rivers, wide floodplains, and sediment basins (Figs. 3A, 4A, 10D and F) contrast dramatically with steep fluvial landscape elements, with sharp V-shaped valleys and limited floodplains (Figs. 3B, 4B, 10C and E). The junction between these two types of landscapes consists of a sharp contrast in gradient for both hillslopes (Fig. 6) and river channel long-profiles (Fig. 10A and B).

Areas in and adjacent to the higher mountain blocks display widespread morphological evidence of alpine-style glacial erosion and deposition (Figs. 7 and 11; Heyman et al., 2008), although no active glaciers occur in these specific mountain blocks at present, except for the Anyemaqen Shan. Erosional landforms include U-shaped glacial valleys (Figs. 3C, 4C and 7), occasional lake basins, and small-scale lateral meltwater channels. Depositional landforms

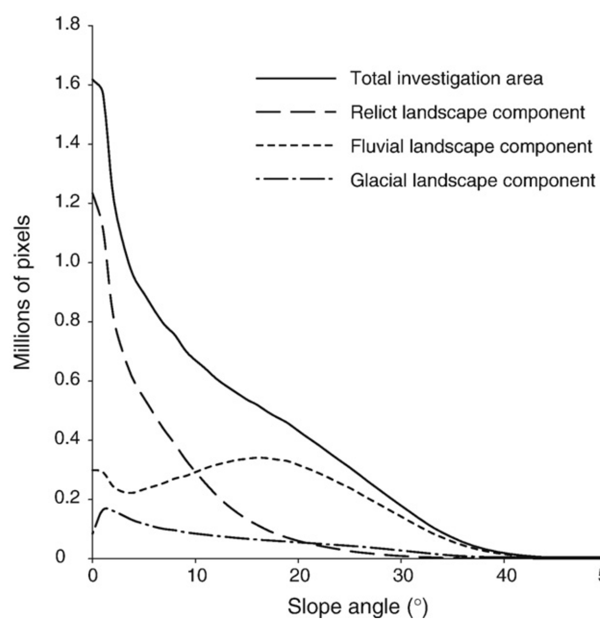

Fig. 8. Distribution of slope angles in the investigation area (solid curve) and its three landscape components.

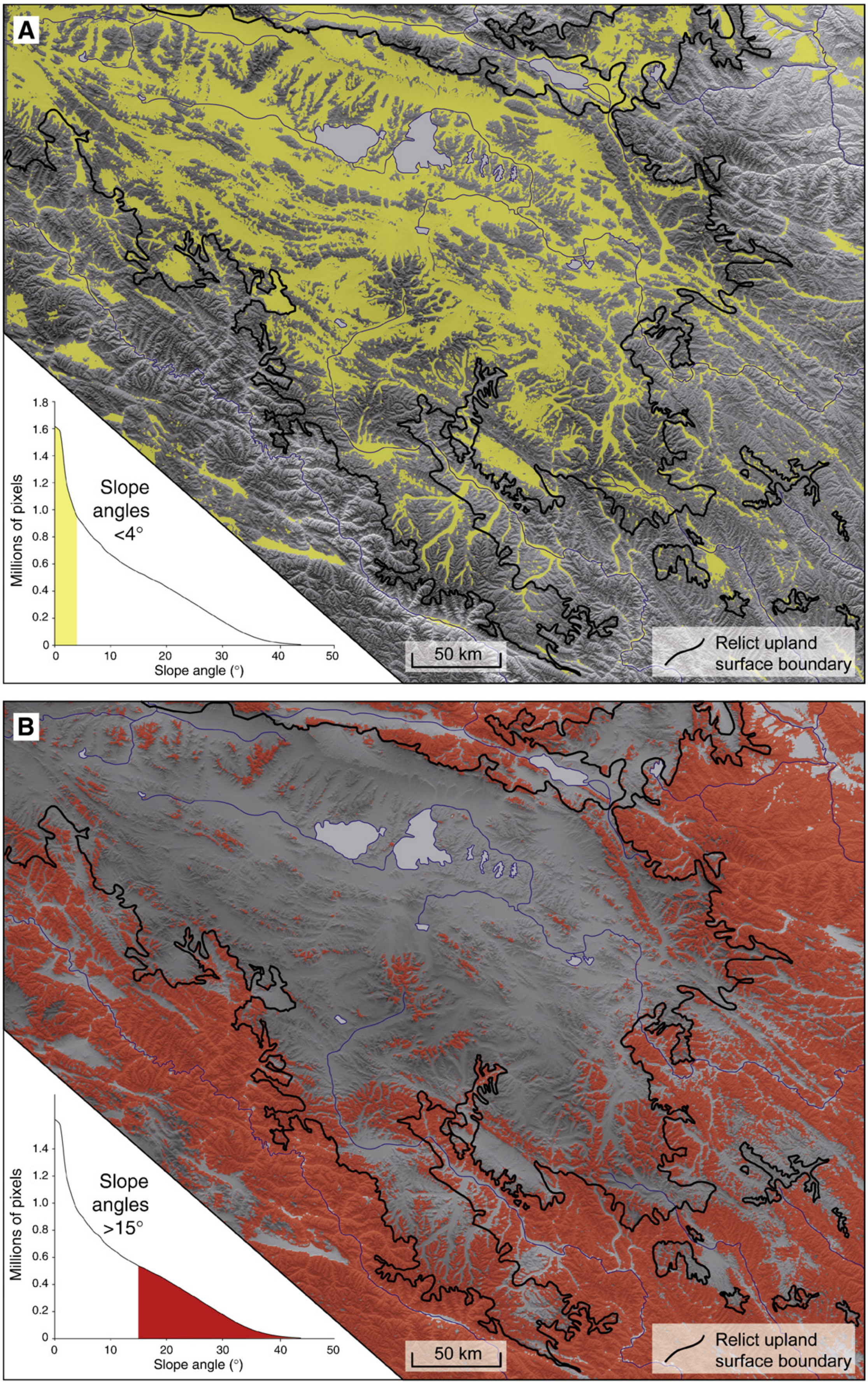

Fig. 9. Spatial patterns of with the occurrence of (A) low (<4°) and (B) high (>15°) slope angles in the study area. The black solid line denotes the limit of the relict upland surface. Insert from Fig. 8.

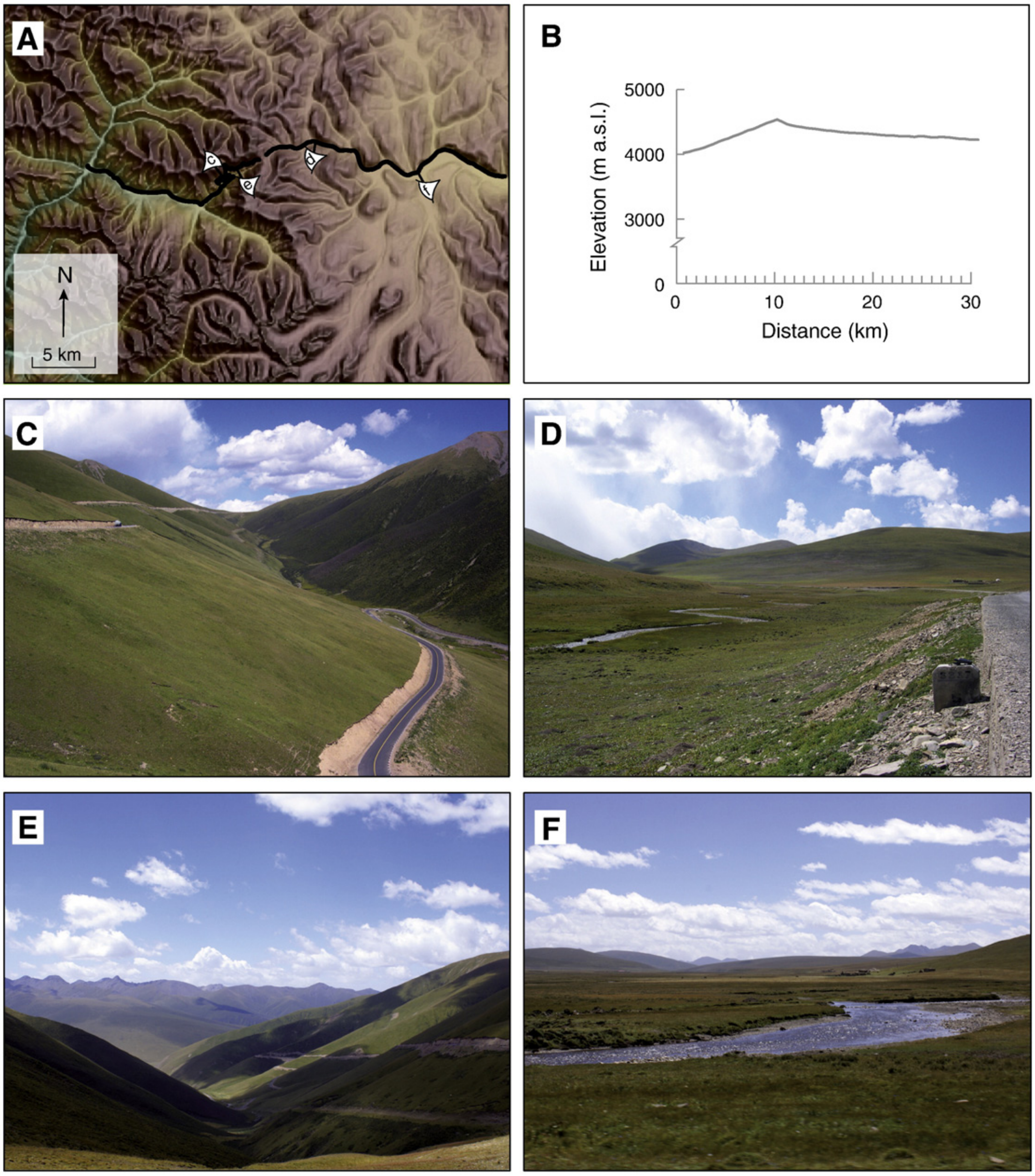

Fig. 10. Comparison of the relict upland surface (east) versus the rejuvenated fluvial landscape (west). (A) DEM map with black line marking the location of the elevation profile in Fig. 10B (for location of the depicted area, see Fig. 7). (B) Elevation profile. (C–F) Photographs of the relict upland surface (D and F) and the rejuvenated fluvial landscape (C and E) demonstrate significant differences between the landscapes. (This figure is available in colour in the online version of this article.)

primarily consist of lateral moraines and end-moraines (Fig. 11), but also include hummocky moraines and drumlins. Taken together, these traces comprise an impressive record of glaciation. The presence of suites of end-moraines and associated meltwater traces indicate that some of these glacial advances terminated on the lower mountain slopes and plateau surface (Figs. 7 and 11). North-trending glacial valleys north of the central Bayan Har Shan are incised deeper than and cross-cut non-glacial E-W trending valleys (Fig. 11).

5. Discussion

The decrease of the size and number of glacial valleys from east to west (Fig. 7) indicates that less glacial erosion occurred towards the west. We interpret this as a consequence of fewer and smaller upland areas and an increased continental climate towards the interior, western part of the plateau. The lower precipitation regime that characterizes the more continental climate towards the interior of the plateau (Lehmkuhl, 1998) translates to the presence of fewer glaciers as it implies a higher glaciation limit. For the northeastern Tibetan Plateau, ELAs for LGM glaciers have been shown to increase by 100 m per degree of longitude towards the west (Lehmkuhl and Liu, 1994; Lehmkuhl, 1998). An alternative and more speculative explanation for the pattern of glacial erosion can be based on the observation that continental glaciers typically have lower mass balances (e.g., Ahlmann, 1935) and that they are, therefore, more likely to have been cold-based and non-erosive (Dyke, 1993; Kleman, 1994). Thus, it is possible that the distribution of glaciers was uniform, but that the frequency of cold-based glaciers increased towards the west.

5.1. Large scale landscape patterns and evolution

The boundary of the relict upland surface constitutes a topographical knickpoint of fluvial rejuvenation in many parts of the study area. Consistent with past work, we interpret the low relief upland surface, flanked by a steep landscape of fluvial incision, as a result of an ongoing adjustment to plateau uplift (cf. Clark et al., 2004, 2005,

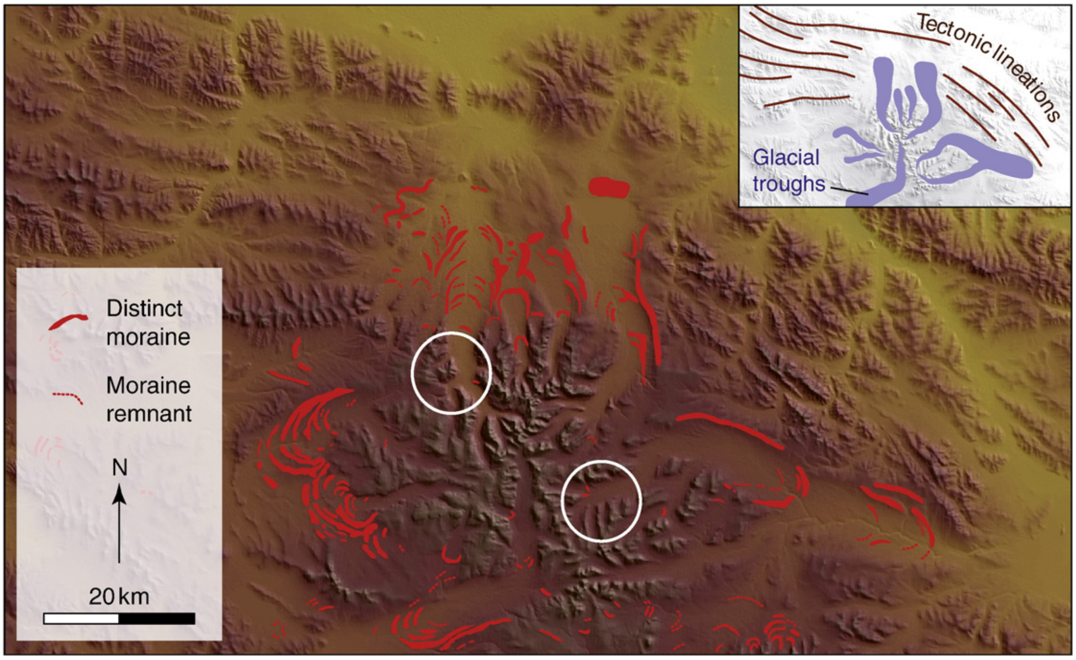

Fig. 11. Detailed pattern of marginal moraines in the Bayan Har Shan (for location, see Fig. 7). White circles identify locations of cross-cutting glacial valleys. Note the large north-trending glacial troughs (insert for location) that have cut down below the level of E-W trending non-glacial valleys. Marginal moraines from Heyman et al. (2008). (This figure is available in colour in the online version of this article.)

2006; Schoebohm et al., 2004, 2006). In this region, mountain blocks that rise above the low relief upland show distinct signs of glaciation, including glacial valleys that are readily apparent from remote sensing and DEMs. Cross-cutting relationships in the glacial valley systems suggest either complex patterns of landscape evolution during individual glaciations or multiple glaciations with different extents and patterns of ice flow (Fig. 11). The distribution of glacial features, such as glacial troughs and moraines, provides a good indication of the extent of former glaciers, but it is still possible that during some stages of glaciation they extended further out onto the flat plateau surface as cold-based, non-erosive ice.

The glacial troughs in the mountainous areas are much wider than the fluvial valleys, and in several instances have valley floors below the level of tributary fluvial valleys (Fig. 11). Areas of non-glacial character between the glacial troughs may indicate that the troughs were formed by valley glaciers constrained to the troughs, while the interfluves remained ice free. Alternatively, it is possible that cold-based and non-erosive ice covered the interfluves, creating a glacial landscape of selective linear erosion (Sugden, 1968, 1974), a hypothesis that can be investigated in more detailed field studies of this area.

From the morphological evidence for the high parts of the plateau surface and over time-spans of glaciations, glacial erosion outpaces fluvial erosion. The situation is different, however, for glacial valleys on the plateau margin. Glacial valleys that lead down to the deep fluvial valleys are characterized by extremely short U-shaped valley sections (Fig. 7). In some locations glacial valleys terminate at the upper limit of the young fluvial landscape, which can be interpreted to imply either that fluvial incision has been more effective than glacial erosion, thus obliterating former glacial landscapes on these slopes, or that ice did not extend further down these fluvial valleys (Fig. 12). The former explanation appears most realistic, because mountains that do not border the relict surface predominantly have large glacial valleys that radiate in all directions (e.g., around the central Bayan Har Shan; Figs. 7 and 11).

While it can be observed that the fluvial rejuvenation of glacial valleys is an ongoing process that reduces the detectable paleo-extent of glaciers along the fluvial margin of the northeastern Tibetan Plateau (Fig. 12), it is equally important to notice that the potential extent of mountain glaciers was severely limited by the steep topography through height-mass balance feedback mechanisms (Oerlemans, 2002). This is because glaciers that extended along the steeper fluvial reaches were likely to be shorter as they more quickly attained lower altitudes, regimes of higher ice melt, and negative mass balance than glaciers on the relict surface. A comparison of the Bayan Har and Anyemaqen Shan provides an ideal case study for this observation. The presently ice free Bayan Har Shan on the relict plateau surface is flanked by glacial troughs of at least 50 km length (Figs. 7 and 11). In contrast, glacial valleys on the Anyemaqen Shan (highest peak 6282 m asl, which is more than 1000 m higher than the Bayan Har Shan) shift into fluvial valleys within 20 km from contemporary glacier margins. Moreover, glacial landforms only occur within 15 km of the contemporary glaciers. The topography of the Anyemaqen Shan, situated on the relict surface margin, is characterised by relatively steep valleys, interpreted as a result of fluvial incision. Because of this difference in landscape hypsometry, Anyemaqen Shan glaciers only grew to an extent limited by the steeper topography while Bayan Har Shan glaciers experienced larger extents because of the relatively flat topography surrounding the mountain block.

5.2. Evaluating the Huang He ice sheet

No glacial erosional morphologies are detectable from remote sensing data and DEMs on the relict plateau surface of the Huang He headwaters, with the exception of glacial valleys in the mountains. The relict plateau surface areas are characterized by plains and low hills that have well-developed fluvial valley systems and basins infilled with alluvial deposits; a landscape largely shaped by fluvial, slope, and eolian processes. Erosional evidence used in the past to support the hypothesis of a Huang He Ice Sheet are four parallel north-south trending lakes ("the finger lakes") north of the Bayan Har Shan, south of Maduo, and east of Eling Hu (Fig. 13), and similar valleys further west (Zhou and Li, 1998). The orientation of the valleys perpendicular to large-scale east-west trending faults (Fig. 5), has been cited as providing support for glacial origin. The large-sale geomorphology of the valleys, with a tributary network and the

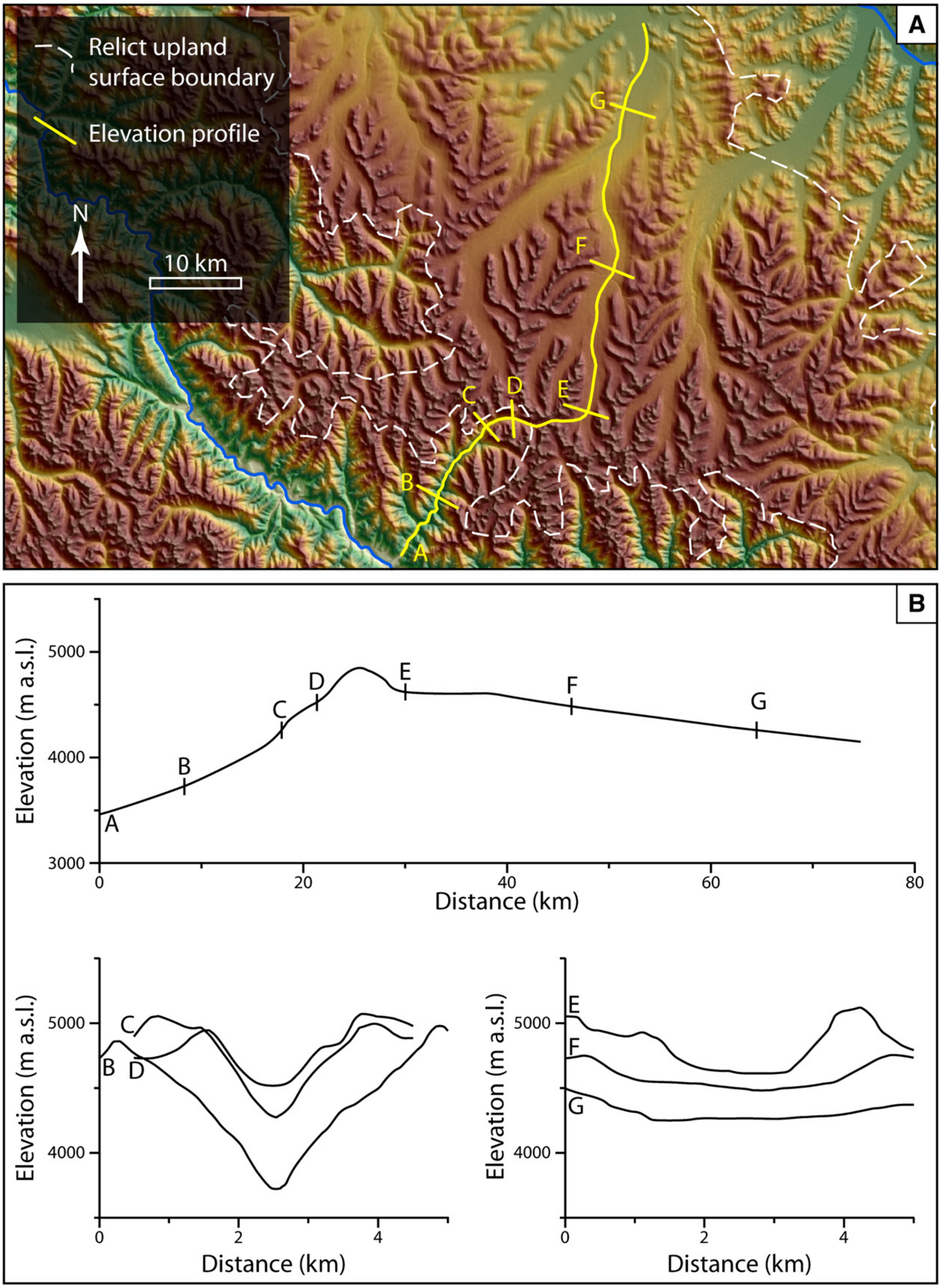

Fig. 12. Interaction between fluvial and glacial processes and forms in valleys on the southern margin of the plateau. (A) DEM map with yellow lines marking the locations of the elevation profiles in B (for location of the depicted area, see Fig. 7). (B) Longitudinal valley profile (upper panel) and transverse valley profiles (lower panels). The northern valley has been carved by glacial erosion and displays a faint U-shaped profile for 45 km (profiles E–G). On the southern side, the glacial imprint has been obliterated by fluvial incision and the glacial valley portion only extends 5 km down-valley (profiles B–D). (This figure is available in colour in the online version of this article.)

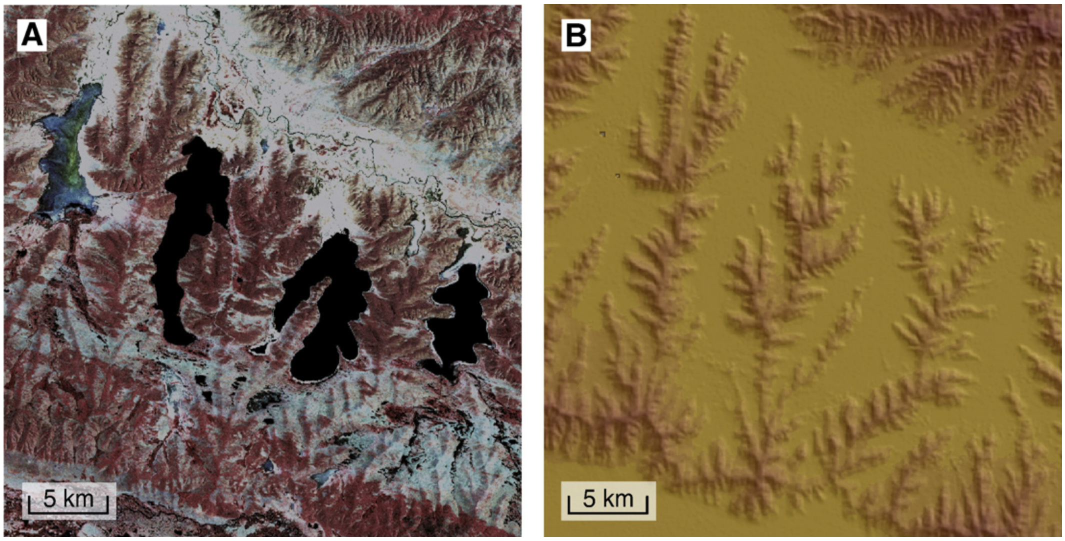

Fig. 13. (A) Satellite and (B) DEM map of the "finger lakes" region south of Maduo and east of Eling Hu (for location, see Fig. 7). Although these lakes have previously been interpreted as glacial lakes, the valleys they occupy show no signs of glaciation (i.e. the typical dendritic patterns visible in the DEM). (This figure is available in colour in the online version of this article.)

presence of spurs, however, suggests to the authors a fluvial origin for the morphologies occupied by these lakes. In addition to the absence of truncated spurs, these valleys are unlike glaciated valleys elsewhere on the plateau in that they lack U-shaped cross-sections, moraines, and glacial hummocky terrain. Another plausible interpretation of the finger lake valleys is that they formed from tectonic processes (cf. Zheng and Rutter, 1998). The valleys are located just south of the east-west trending Kunlun fault and could have formed as a result of extensional tectonics (cf. Fu and Awata, 2007), with later uplift along the east-west trending faults reversing the gradient in lower parts of the valleys, resulting in the formation of lakes in the upper parts of the valleys.

The absence of large-scale glacial geomorphological evidence on the relict plateau surface of the Huang He headwaters is not consistent with the hypothesis of a Huang He Ice Sheet, although one may argue that few glacial traces may have survived subsequent degradational and aggradational processes. The most logical interpretation of the large-scale landscape pattern of the relict surface is that glaciation in this region has been restricted to mountain-based valley glaciers and ice caps. Interestingly, a remarkable correspondence exists between the outline of the palimpsest plateau upland and the outline of the proposed Huang He Ice Sheet (Fig. 14). This coincidence could indicate that what has been described as an ice sheet border is merely the outline of a relict plateau landscape. Alternatively, one could posit a Huang He Ice Sheet, and that it was larger than originally proposed, but that evidence for this has been consumed by fluvial incision at the plateau margin. Based on the evidence available at this time, we regard this latter hypothesis as unlikely (Lehmkuhl et al., 1998; Zheng and Rutter, 1998). Further field investigations, testing for the presence of tills and erratics, and examining deposits and boulders for TCN dating for evidence of extended exposure and burial of bedrock surfaces, will be required to unequivocally evaluate the hypothesis for the Huang He Ice Sheet.

6. Conclusions

As part of a larger investigation into the possible existence of a regional-scale ice sheet in the headwaters of the Huang He, we

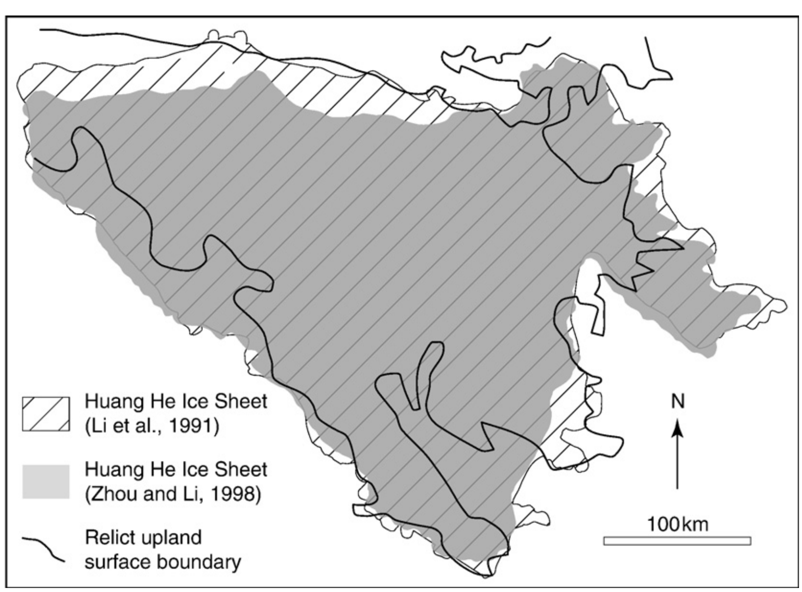

Fig. 14. Comparison of the proposed extents of the Huang He Ice Sheet following Li et al. (1991) and Zhou and Li (1998), with the outline of the relict upland surface as defined by the border between the relict plateau surface and the fluvial landscape (see Fig. 7).

undertook large-scale geomorphological mapping using SRTM and Landsat 7 ETM+ techniques to visualise and analyse the spatial distribution of glacial erosional morphology, to compare overall glacial impact with fluvial impact on the relict plateau surface and on the plateau margin, and to analyse the implications of such observations and comparisons for the glacial history of the region. Salient results of this study are as follows:

- The boundary of the Huang He headwaters relict surface is marked by a pronounced topographical break in slope. The Huang He and Chang Jiang rivers are actively incising this relict surface, thereby diminishing its size and isolating plateau remnants.
- Mapping reveals clear morphological evidence on the plateau for selective linear erosion by topographically controlled mountain glaciers, and a diminishing influence of glaciers on mountain topography from east to west.
- Glaciers have, integrated over time, been more effective than rivers in eroding the mountains on the relict upland surface. The floors of glacial valleys cut into the mountain blocks are generally located at lower altitudes than the floors of adjacent fluvial valleys.
- Rejuvenated fluvial erosion of the northeastern Tibetan margin is currently diminishing the size of the relict upland surface of the Byan Har region and is, thereby, consuming any evidence of former glaciation on that margin.
- A remarkable correspondence exists between the outline of the palimpsest plateau upland and the proposed outline of the Huang He Ice Sheet. This result questions the validity of the Huang He Ice Sheet concept.

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