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Palaeoglaciation of Bayan Har Shan, northeastern Tibetan Plateau: glacial geology indicates maximum extents limited to ice cap and ice field scales

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ABSTRACT: Key locations within an extensive area of the northeastern Tibetan Plateau, centred on Bayan Har Shan, have been mapped to distinguish glacial from non-glacial deposits. Prior work suggests palaeo-glaciers ranging from valley glaciers and local ice caps in the highest mountains to a regional or even plateau-scale ice sheet. New field data show that glacial deposits are abundant in high mountain areas in association with large-scale glacial landforms. In addition, glacial deposits are present in several locations outside areas with distinct glacial erosional landforms, indicating that the most extensive palaeo-glaciers had little geomorphological impact on the landscape towards their margins. The glacial geological record does indicate extensive maximum glaciation, with local ice caps covering entire elevated mountain areas. However, absence of glacial traces in intervening lower-lying plateau areas suggests that local ice caps did not merge to form a regional ice sheet on the northeastern Tibetan Plateau around Bayan Har Shan. No evidence exists for past ice sheet glaciation.

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KEYWORDS: glacial deposits; Tibetan Plateau; Bayan Har; glacial extent; palaeoglaciology.

Introduction

The large-scale glacial geology of the Tibetan Plateau is still relatively poorly defined. Detailed mapping of glacial landforms and deposits has not been done across extensive areas of the plateau and the data collected to date have mainly been recorded in point form for restricted areas (see Heyman *et al.*, 2008). As a result, there is scant information available with which to reconstruct the extent of former glaciers, and published reconstructions range from restricted mountain glaciation to a plateau-scale ice sheet (e.g. Li *et al.*, 1991; Kuhle, 2004).

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Based on landforms and sediments of inferred glacial origin and reconstructed equilibrium line altitudes (ELA) around the Tibetan Plateau, Kuhle (2004, and references therein) has argued for the existence of a large-scale ice sheet covering practically the entire plateau during the last glaciation. In contrast, a large number of other studies indicate more restricted glacial extent (e.g. Zheng, 1989; Derbyshire *et al.*, 1991; Rutter, 1995; Zheng and Rutter, 1998; Lehmkuhl and Owen, 2005; Owen *et al.*, 2005; Shi *et al.*, 2005). Two circumstances stand out as particularly problematic for the concept of a plateau-scale ice sheet during the last glaciation. First, there is a remarkable absence of glacial evidence (such as glacial lineations, eskers, ribbed moraines, marginal moraines, till and erratic boulders) for extensive areas of the plateau outside mountain areas (e.g. Derbyshire *et al.*, 1991; Zheng and Rutter, 1998; Heyman *et al.*, 2008). Second, terrestrial cosmogenic nuclide (TCN) exposure dating of glacial deposits from high mountain areas has provided a large number of ages significantly older than the late last glaciation (e.g. Schäfer *et al.*, 2002; Owen *et al.*, 2005, 2008), indicating that for at least the last few hundred thousand years there has not been any plateau-scale ice sheet on the Tibetan Plateau.

Based predominantly on the restricted extent of glacial landforms and deposits around elevated mountain areas, it has generally been accepted that Quaternary glacial extent on the Tibetan Plateau was limited to glacier expansion out of the high mountains (cf. Li *et al.*, 1991). However, because of the paucity of glacial geological data from the Tibetan Plateau (cf. Heyman *et al.*, 2008), published glacial reconstructions comprising the entire plateau area are at best schematic estimates, and the former glacial extent is only well established for restricted areas where detailed studies have been conducted.

In addition to the shortage of glacial geological data, attempts to reconstruct the extent of palaeoglaciation have been hindered by misinterpretations of glacial and non-glacial landforms. Reinterpretations have repeatedly given deposits of inferred glacial origin a non-glacial genesis, such as mass movement or fluvial deposition (Fort, 1989, 2000; Holmes and Street-Perrott, 1989; Osmaston, 1989; Derbyshire *et al.*, 1991; Shi *et al.*, 1992; Zheng and Rutter, 1998; Hewitt, 1999; Owen *et al.*, 2002; Liu *et al.*, 2006; Yi *et al.*, 2006), and some large-scale landforms thought to be of glacial origin have been reinterpreted as originating from tectonic processes (Lehmkuhl *et al.*, 1998; Zheng and Rutter, 1998; Stroeven *et al.*, 2009). For high-relief areas of the Tibetan Plateau, several studies have highlighted the similarity between mass movement and glacial diamictons (Owen and Derbyshire, 1988; Holmes and Street-Perrott, 1989; Owen, 1994; Owen *et al.*, 1998; Hewitt, 1999; Fort, 2000; Yi *et al.*, 2006). Glacial deposits may also have been altered or removed by periglacial, paraglacial or fluvial action (Owen and Derbyshire, 1988, 1989; Owen, 1994; Owen *et al.*, 1995; Barnard *et al.*, 2006; Stroeven *et al.*, 2009). As a result of such challenges, several authors have stressed the importance of basing reconstructions on detailed studies that focus on unambiguous glacial evidence (Osmaston, 1989; Derbyshire and Owen, 1990, 1997; Derbyshire *et al.*, 1991; Rutter, 1995; Owen *et al.*, 1998; Zheng and Rutter, 1998; Benn and Owen, 2002; Lehmkuhl and Owen, 2005).

As a part of a larger study aimed at providing data for reconstructions of former glacial extent on the Tibetan Plateau, this paper reports the results of field studies in the Bayan Har Shan (*Shan* = Mountain) on the northeastern Tibetan Plateau (Fig. 1). We present data on the presence and pattern of well-defined glacial and non-glacial deposits, re-examine several proposed indications of former extensive glaciations, and compare the field data with recent remote-sensing based mapping of the glacial geomorphology of the field area (Heyman *et al.*, 2008; Stroeven *et al.*, 2009). The field data reported here enhance our understanding of the Tibetan Plateau glacial geological record and, in combination with recent mapping of glacial landforms, provide a dataset for reconstructing former glacial extent in an extensive (136 500 km^2) area of the northeastern Tibetan Plateau.

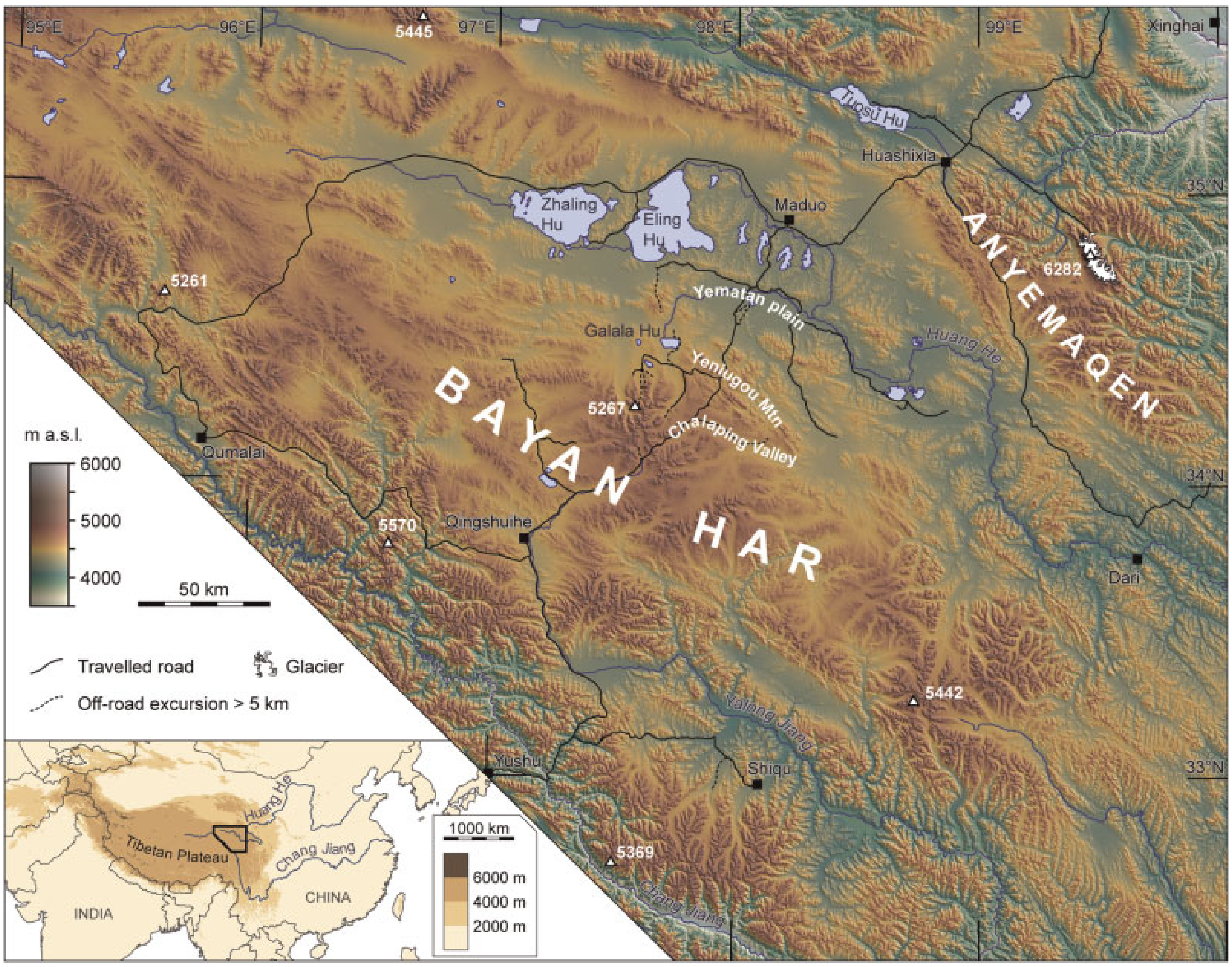

Figure 1 Shaded relief map of the Bayan Har study area located in the northeastern corner of the Tibetan Plateau, showing major roads used to access field sites and routes of off-road excursions longer than 5 km. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

Study area and previous studies

Bayan Har Shan is a mountain belt approximately 500 km long and 150 km wide stretching in a NW–SE orientation on the northeastern Tibetan Plateau. The study area, centred on Bayan Har Shan, encompasses the headwaters of the Huang He (Yellow River) in the north and is delimited in the southwest by the valley gorge of the Chang Jiang (Yangtze River) (Fig. 1). The region includes an extensive low-relief plateau area at ~4300 m a.s.l. with mountain blocks rising 1000–2000 m above the plateau surface, flanked by deep fluvial valleys of the Chang Jiang and Huang He and their tributaries (Stroeven *et al*., 2009; Fig. 2). Extensive areas of the plateau surface are covered by sediments, forming sedimentary plains (e.g. the Yematan plain, Figs 1 and 2(b)). The only contemporary glaciers in the study region are the Anyemaqen Shan ice field and outlet glaciers, located in the northeast. The bedrock of the study area is dominated by sandstones and shales, with granite intrusions in several mountain blocks, and the regional faults generally trend NW–SE (Fig. 3; Liu *et al*., 1988).

Glacial landforms and deposits occur in several areas of the Bayan Har Shan, and have been reported in a number of previous studies. Tafel (1914) noted the presence of U-shaped valleys and erratic granite boulders and concluded that Bayan Har Shan had been extensively glaciated. Hövermann (1987) investigated landforms and sediments of the northeastern Tibetan Plateau and suggested former ice sheet style glaciation with glacier margins reaching below 3000 m a.s.l. Kuhle (1987, 1989) reported the existence of 'ice marginal ramps' in the northern part of the study area. These fan-like landforms were interpreted as formed by glacial and glaciofluvial deposits along the southern margin of a northern ice mass post-dating a Last Glacial Maximum plateau-scale ice sheet. However, Lehmkuhl *et al*. (1998) investigated the 'ice marginal ramps' and concluded, based on the geomorphology and sedimentology of the fan-like features, that these are non-glacial landforms most likely formed from alluvial sediments exposed to tectonic action. In a subsequent paper on glacial features of the northeastern Tibetan Plateau by Kuhle (2003), he no longer referred to 'ice marginal ramps' in this area. Rather, Kuhle (2003, 2004) reported the existence of tills, erratics and roche moutonnées in the area, and used these as evidence for a plateau-scale ice sheet covering practically the entire current study area.

Li *et al*. (1991) mapped the 'extent of palaeoglaciation' of the northeastern Tibetan Plateau as being largely restricted to mountain areas, but in our current study area they additionally showed a 95 000 km^2 regional ice sheet (the Huang He ice sheet). Zhou *et al*. (1994) and Zhou (1995) presented detailed studies of the Bayan Har glacial geology, including observations of glacial landforms such as U-shaped valleys, roche moutonnées and moraine ridges, and deposits of inferred glacial origin. Based mainly on these field observations, a palaeoglaciological reconstruction comprising four glacial stages was presented (Zhou and Li, 1998). For the two youngest stages, tentatively correlated to the early and late last glaciation, alpine-style glaciers restricted to the highest mountain areas were proposed based on the presence of glacial landforms. Two prior and more extensive glacial stages were suggested based on deposits and landforms of inferred glacial origin at lower altitudes and further away from the mountains: the Yematan glaciation and the Huang He ice sheet (Fig. 4; 66 000 km^2 and 86 000 km^2, respectively). These ice masses were envisaged to have formed by the coalescence of glaciers from several mountain blocks, with a main ice mass nourished in the central Bayan Har Shan. The slightly more restricted Yematan glaciation was inferred from erratic boulders and tills, and the timing of this glacial stage was proposed as Marine Isotope Stage (MIS) 6. The reconstructed Huang He ice sheet, reaching further north, was based on the presence of N–S trending valleys, which were interpreted as glacial valleys because they run perpendicular to the dominant regional fault orientation, and erratic boulders and tills. The Huang He ice sheet was tentatively correlated to MIS 12 (Zhou and Li, 1998).

The proposed existence of a former regional ice sheet on the northeastern Tibetan Plateau has been cited frequently in subsequent papers (Derbyshire *et al*., 1991; Shi, 1992; Shi *et al*., 1992; Hövermann *et al*., 1993; Rutter, 1995; Lehmkuhl, 1998; Zhou *et al*., 2004; Lehmkuhl and Owen, 2005; Ehlers and Gibbard, 2007), but the idea has also received criticism (Zheng and Wang, 1996; Lehmkuhl *et al*., 1998; Zheng and Rutter, 1998). Zheng and Wang (1996) argued that glaciation of the area was restricted to isolated glaciated mountain blocks. Zheng and Rutter (1998) pointed out that there are no unambiguous glacial landforms or sediments supporting the existence of an ice sheet in the Huang He area. Similarly, Lehmkuhl *et al*. (1998) noted the absence of glacial deposits in the lower-lying plateau areas north of Bayan Har Shan and favoured a reconstruction with a more restricted glacial extent.

In addition to the ice extent, the glacial chronology of Bayan Har Shan is still to be resolved. The only absolute chronological constraints for glacial deposits in the study area are provided in Owen *et al*. (2003) for Anyemaqen Shan at the northeastern plateau margin. Using TCN exposure age dating of erratic boulders and optically stimulated luminescence dating of glacial and associated sediments, Owen *et al*. (2003) suggested glacial advances of diminishing extent during MIS 3, MIS 2 and the early Holocene. Recent glacial extent (Fig. 1) appears to have been restricted, with dated MIS 2 moraine ridges and deposits located less than 12 km away from the contemporary ice margins of Anyemaqen outlet glaciers.

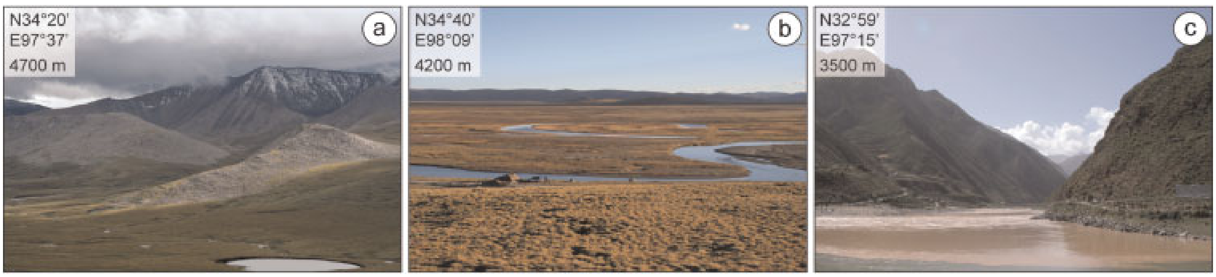

Figure 2 Different landscape types of the Bayan Har Shan study area. (a) The highest and most alpine part of central Bayan Har Shan. (b) The Yematan Sedimentary plain (Fig. 1) seen from the north. (c) Fluvially incised V-shaped valley at Chang Jiang, south of Bayan Har Shan. The coordinates and altitude (m a.s.l.) refer to the location of the viewer. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

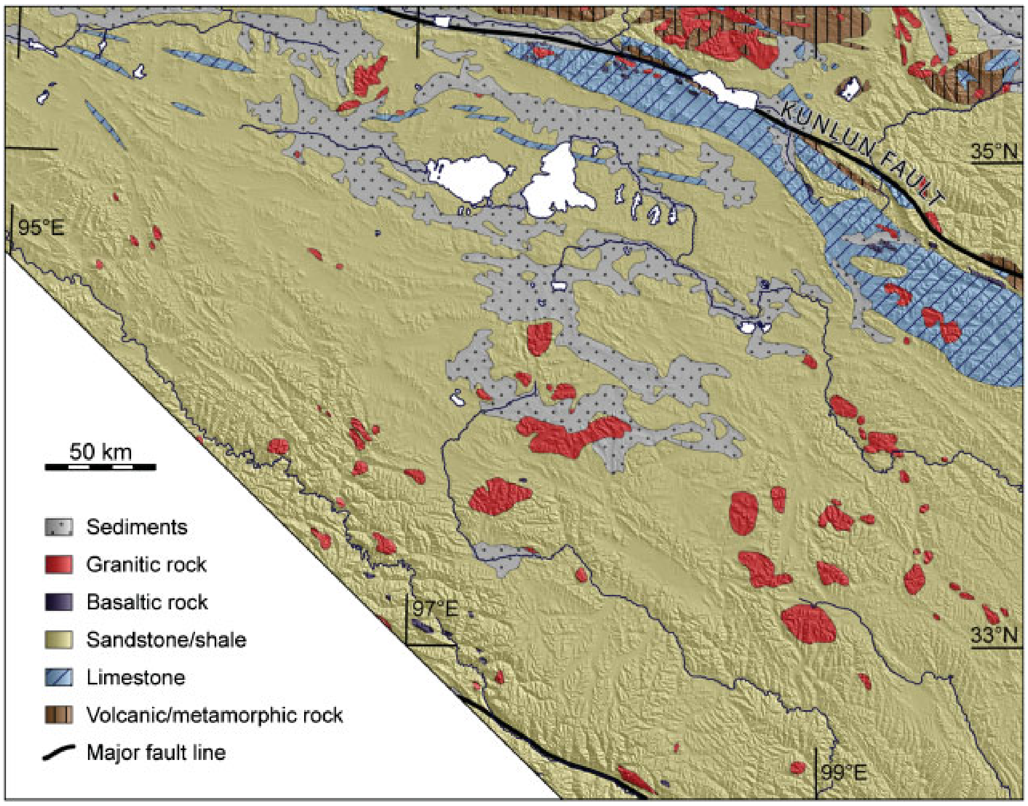

Figure 3 Geology of the study area, based on Liu *et al.* (1988)

Recent geomorphological mapping of the study area using remote sensing techniques further define the glacial imprint on Bayan Har Shan (Heyman *et al.*, 2008; Stroeven *et al.*, 2009). Based on an analysis of large-scale geomorphology, Stroeven *et al.* (2009) developed a map that shows glacially eroded valleys in mountain blocks, extensive relict plateau surfaces and fluvial valleys along the plateau margin. Moreover, they suggested that the N–S trending valleys north of Bayan Har Shan, originally proposed to have formed underneath the Huang He ice sheet (Zhou and Li, 1998), are a product of tectonic action, as they have no clear glacial features and are located in a band just south of the Kunlun Fault. Stroeven *et al.* (2009) found that glacial valleys are confined to elevated mountain blocks and that the outline of the main relict upland surface area closely resembles the outline of the proposed Huang He ice sheet. They therefore argued that the proposed Huang He ice sheet outline (Fig. 4; Zhou and Li, 1998), rather than indicating the maximum glacial extent, may represent the outline of a relict plateau surface remnant. Additional detailed mapping of the glacial geomorphology of the Bayan Har Shan over an area which is more than an order of magnitude larger than previous detailed glacial geomorphological maps of the Tibetan Plateau (Fig. 4; Heyman *et al.*, 2008) revealed a pattern of glacial landforms restricted to high mountain areas, and a notable absence of landform assemblages commonly associated with palaeo-ice sheets, such as glacial lineation swarms, ribbed moraines and eskers. Glacial valleys/troughs, marginal moraines, hummocky terrain and meltwater channels are distributed up to ~60 km away from the highest peaks of central Bayan Har Shan, the area with the richest glacial landform record, indicating alpine style and possibly ice field/ice cap glaciation.

Recent mapping of the glacial geomorphology of Bayan Har Shan (Heyman *et al.*, 2008; Stroeven *et al.*, 2009), compared to the outline of the proposed Yematan glaciation and the Huang He ice sheet (Zhou and Li, 1998; Fig. 4), shows significant inconsistencies between the distribution of glacial landforms and the proposed extensive ice masses. However, while the regional ice sheet hypothesis is based mainly on field observations, the mapping of the glacial geomorphology in this area presented by Heyman *et al.* (2008) and Stroeven *et al.* (2009) relies most heavily on remote sensing. In this paper we present the results of three field seasons of detailed studies of unconsolidated deposits, including field evaluation of sites described in earlier studies as providing evidence of ice sheet-scale glaciation. Combined, the remote sensing and field data form the basis for robust spatial reconstructions of former glaciations.

Methods

The field survey of the study region was focused on areas with distinct unequivocal glacial landforms, areas that have been subject to varied past interpretations, and sites that were key to past interpretations of ice sheet extent. Access to field sites during three field seasons (2005–2007) was controlled in large part by the distribution of roads and tracks accessible by vehicles (Fig. 1).

For sediment exposures, sections were logged in the field and key characteristics indicative of glacial or non-glacial origin (described in detail below) were recorded. Clast fabric measurements of *a*-axis and *b*-axis orientation were carried out on elongate clasts with *a*-axes $\geq$2 cm and *a*/*b*-axis ratios $\geq$2. For each fabric set $\geq$30 individual clasts were measured (cf. Benn, 2004). One set of *ab*-plane strike was measured on 115 clearly disc-shaped gravel clasts. In the laboratory, sediment samples for grain size analysis were wet sieved using sieves of

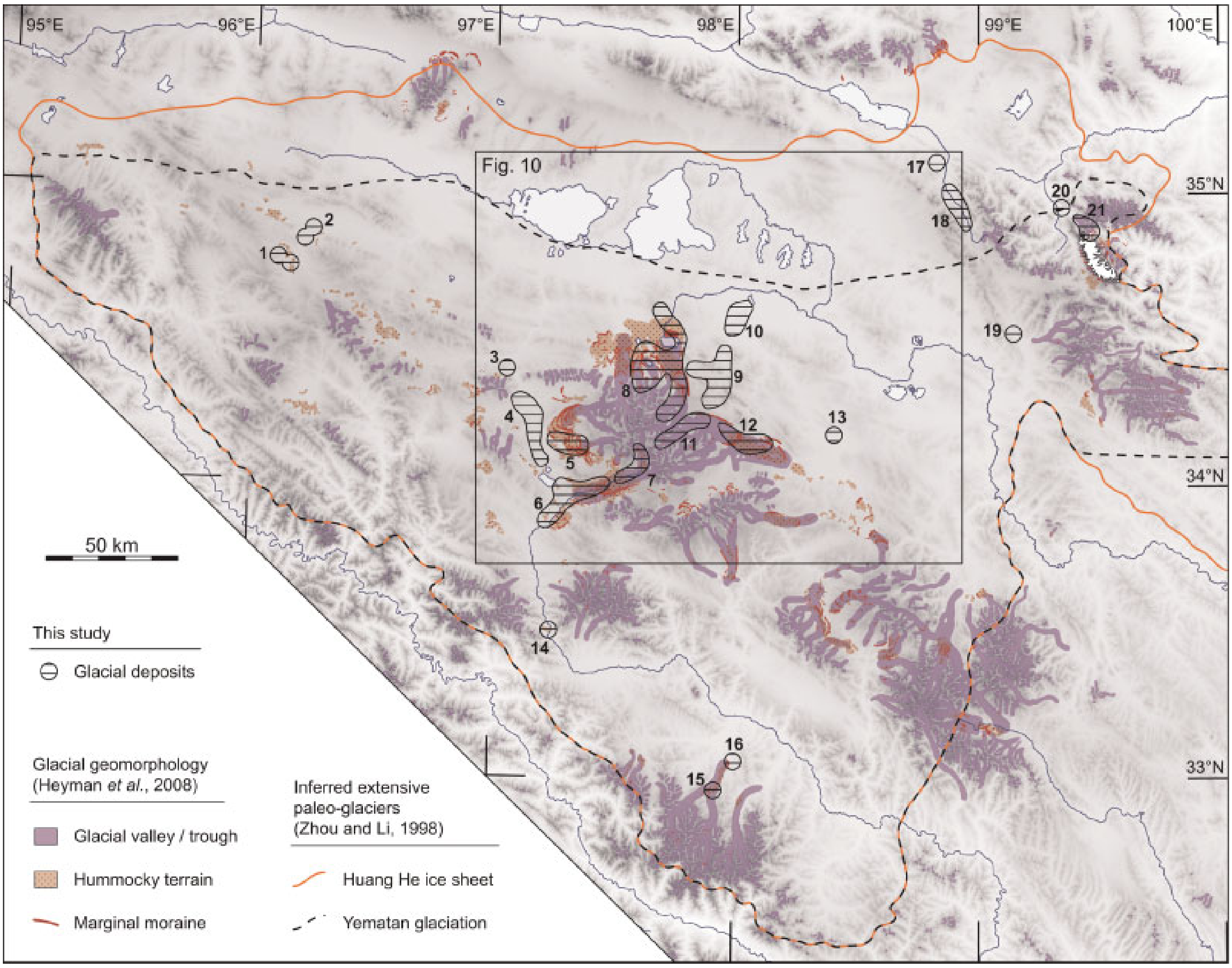

Figure 4 Distribution of glacial deposits, glacial geomorphology (Heyman *et al.* 2008) and the outline of the proposed Yematan and Huang He ice sheet glaciations (Zhou and Li, 1998). The numbers of the glacial deposits refer to Table 1. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

20, 6, 2 and 1 mm. The grain size fraction finer than 1 mm was measured using a Malvern Mastersizer 2000 particle size analyser.

Latitude and longitude coordinates for all sites are given in the WGS 84 reference system, and are derived from handheld GPS measurements. Additional elevation and location data have been derived from GIS analysis of the Shuttle Radar Topography Mission (SRTM) data (Jarvis *et al.*, 2006) and Landsat ETM+ imagery from GLCF (2009). Altitudes for each site are based on handheld GPS measurements, and GPS altitudes for the sites were always within 11 m of the corresponding SRTM altitude.

Glacial deposits: identification

Here we describe our approach for the identification of glacial deposits, relying on the identification of glacial characteristics. We use the term *glacial deposits* for all sediments (including individual boulders) deposited directly by ice or by a process requiring the presence of a glacier, such as tills and glaciofluvial sediments formed in contact with glacier ice or in close proximity to a glacier margin. Given the diverse interpretations of glacial deposits in the study area (Lehmkuhl *et al.*, 1998; Zheng and Rutter, 1998; Zhou and Li, 1998; Kuhle, 2003) we have used the presence of four basic glacial indices to aid in the identification of glacial deposits (Fig. 5; cf. Flint, 1971; Benn and Evans, 1998):

1. *Striae*. Clear striae on clasts (pebbles, cobbles and boulders). Based on the common presence of striated rock surfaces in glacial environments (e.g. Chamberlin, 1888; Iverson, 1991).
2. *Erratic boulders*. Boulders of different lithology from the local bedrock. Based on the common presence of erratic boulders in formerly and contemporary glaciated terrains (e.g. Jamieson, 1862; Knechtel, 1942; Hambrey *et al.*, 2008).
3. *Diamictons*. Unsorted, matrix-supported, massive sediments including grain size fractions from clay to boulders, excluding diamictons below steep slopes which could possibly be mass movement deposits. Based on the common – however, not diagnostic – diamict properties of tills (e.g. Geikie, 1863; Dreimanis, 1989).
4. *Multiple lithologies*. Clasts of multiple lithologies, including erratic clasts. Based on the assumption of glacial transport from multiple source areas (e.g. MacClintock, 1933; Kjær *et al.*, 2003).

Although identification of glacial deposits based on these indices may not be successful in all instances, we encountered no major difficulties. All glacial deposits identified in this study contained striated clasts and erratic boulders were present at

Figure 5 Glacial indices used to identify glacial deposits. (a) Striated stone. (b) Erratic boulder. (c) Diamict sediment section. (d) Clasts of multiple lithologies. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

most locations. However, observations of scattered granite erratics in the field have only infrequently been accompanied by studies of the underlying sediments owing to time constraints. We view the identification scheme used here as a useful tool for the specific settings of the Bayan Har Shan study area, and for the objective of distinguishing between glacial and non-glacial deposits as a key indicator of former glacier presence.

Results: sediment sections

Eight sediment sections were logged, described and sampled for grain size distribution analysis (Figs 6–9). Sections 1 and 2 were chosen from clear end moraine ridges in central Bayan Har Shan, thus representing examples of sediment sections in unambiguous glacial landforms. Sections 3–8 are located outside areas with clear glacial landforms (Heyman *et al.*, 2008) and they represent either units proposed as glacially formed or important recurring sedimentary units of the study area. Based on physical properties, the sediments have been classified into four broad lithofacies associations (A–D). Using the presence of key glacial indices described above, the lithofacies associations were interpreted to be of glacial and non-glacial origins.

Lithofacies association A: gravelly diamicton

Bayan Har Shan (sections 1, 2)

Sections 1 and 2 (Fig. 6(a) and (b)) are both located within subdued end moraine ridges on the eastern side of central Bayan Har Shan, marking the position of glacier margins reaching ~6 km and 40 km, respectively, from inferred glacier heads (Heyman *et al.*, 2008; Fig. 4). In each section, excavated by digging at road pits, there are two sedimentary units. The lower unit is a massive, matrix-supported diamicton that contains striated clasts (lithofacies association A1). Grain sizes range from clay to boulders, with peaks in medium/course gravel and fine sand (Fig. 7: s-1 and s-2). The diamicton is capped by a fine-grained top unit containing occasional clasts (lithofacies association D, see below). Both moraines have numerous metre-sized boulders outcropping at the surface. Within the section 1 moraine, which demarcates a relatively small former valley glacier, only sandstone boulders of local lithology are present. In the section 2 moraine there are also large erratic granite boulders, up to 3 m in diameter, transported at least 30 km due east from the granite outcrops of central Bayan Har Shan.

Huashixia (sections 3, 4)

Sections 3 and 4 are located close together, 2.9 km and 1.5 km west of Huashixia (Fig. 1), respectively, on a relatively flat surface of a ~4 km wide valley. Section 3 (Fig. 6(c)) is a 1.8 m section composed of massive, matrix-supported diamicton (lithofacies association A1) overlain by a 30 cm thick fine-grained top unit (lithofacies association D, see below). The diamicton has a grain size distribution peaking in the medium gravel fraction and the fine sand fraction (Fig. 7: s-3) and contains striated clasts and small (up to ~50 cm) boulders. Clast fabric in the lower part of the diamicton shows poor clustering of the *a*-axis direction ($S_1 = 0.57$; Fig. 6(f)) and a low dip.

Section 4 is a ~3 m high and 20 m wide section at a road pit (Fig. 6(d)). The uppermost part of the section, estimated to ~50 cm, has been removed. Numerous striated clasts and small boulders are abundant throughout. The sediments are com-

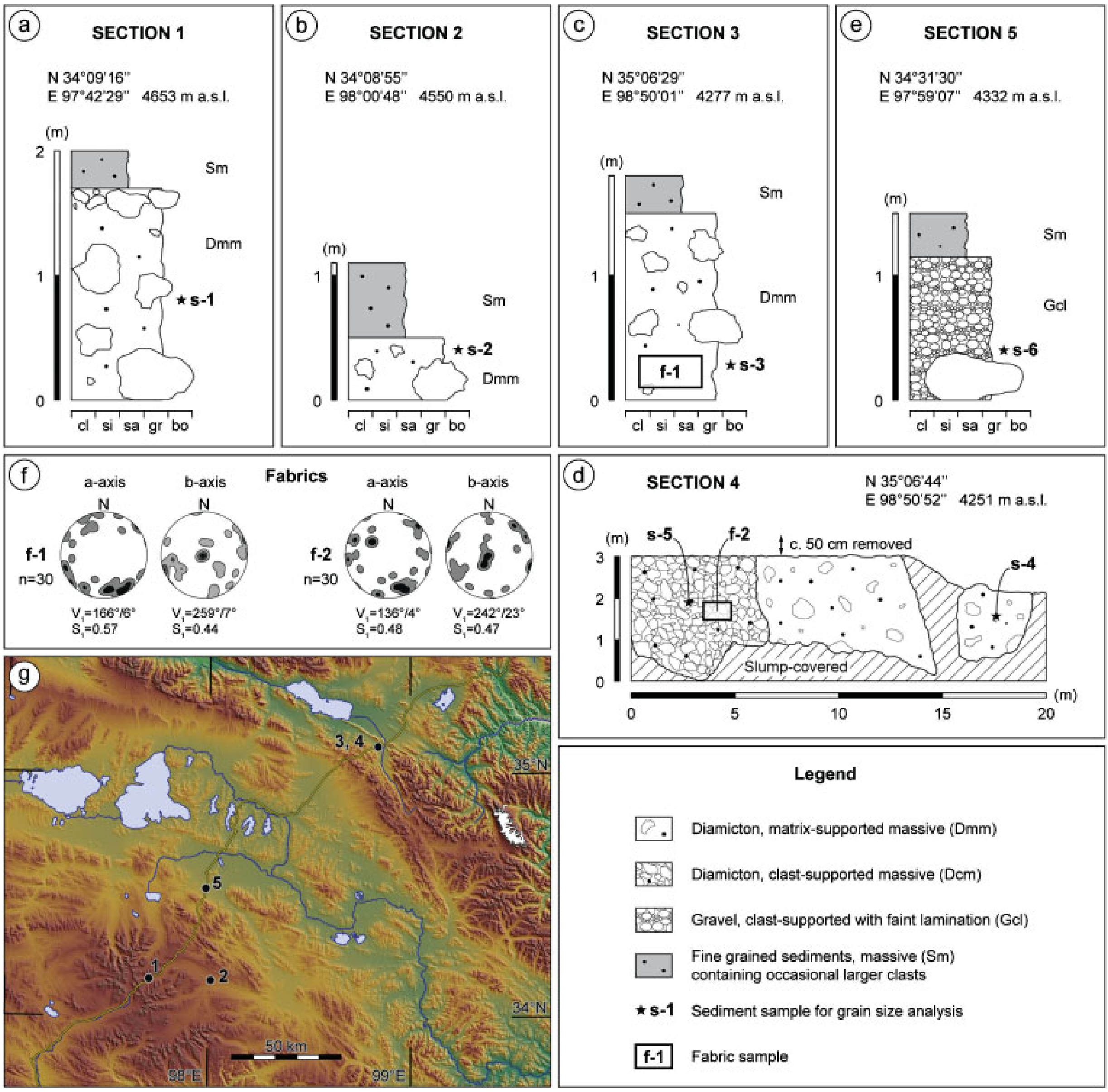

Figure 6 Sediment sections with glacial deposits. (a) Section 1 in an end moraine formed by a ~6 km long valley glacier in central Bayan Har. (b) Section 2 in an end moraine formed by a larger glacier ~30 km east of section 1. (c) Section 3 located 2.9 km west of Huashixia (Fig. 1). (d) Section 4 located 1.5 km west of Huashixia. (e) Section 5 on top of a small hill north of Yeniugou. (f) Clast fabrics measured in sections 3 and 4. Contoured fabrics are displayed using Schmidt equal-area, lower hemisphere projections. (g) Location of the sediment sections

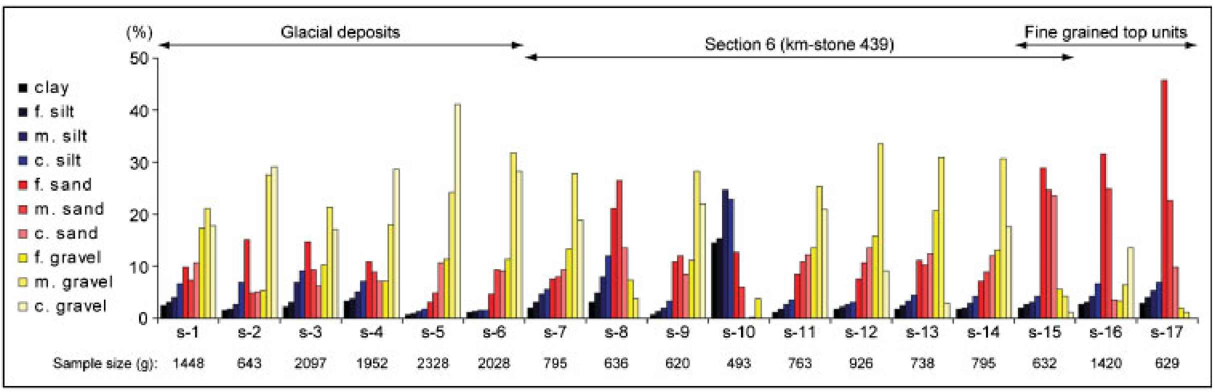

Figure 7 Grain size distributions for sediments from sections 1–8 (Figs 6, 8 and 9). Sample size denotes the dry weight of samples

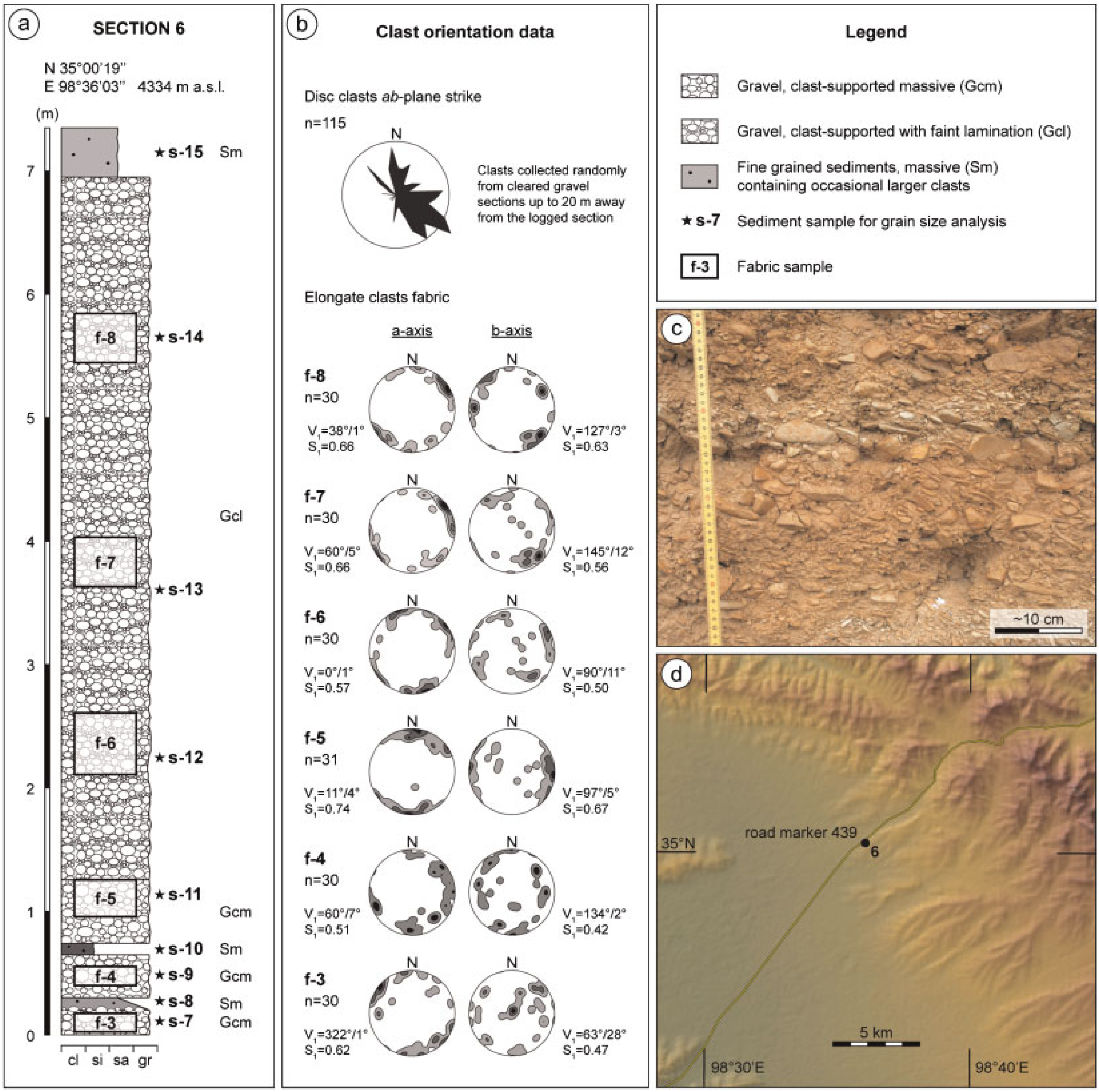

Figure 8 Section 6 located at road marker 439, 27 km southwest of Huashixia (Fig. 1). (a) Section log showing the positions of samples taken for grain size analysis (s-7 to s-15) and fabric measurements (f-3 to f-8). (b) Measured clast orientation data. The rose diagram displays the *ab*-plane strike for 115 disc-shaped clasts collected randomly from cleared gravel sections in an area up to 20 m away from the logged section. The elongate clast fabrics display contoured fabrics for f-3 to f-8 using Schmidt equal-area, lower hemisphere projections. (c) Imbrication and faint lamination are visible at ~2 m. (d) Location of the sample site along the road at km marker 439 in relation to landscape geomorphology. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

posed of massive, matrix-supported diamicton (lithofacies association A1) and massive, clast-supported diamicton (lithofacies association A2). While grain size distributions for both samples peak in the coarse gravel or coarser fraction, only the matrix-supported sample has a secondary peak in the fine sand fraction (Fig. 7: s-4 and s-5). Clast fabric for the clast-supported diamicton (Fig. 6(d), (f)) was similar to the section 3 clast fabric, with poor *a*-axis clustering ($S_1 = 0.48$) and low dip.

Interpretation: glacial deposit

Lithofacies association A contains striated clasts and erratic boulders and is poorly sorted. Clasts of multiple lithologies, including erratic clasts, are present at sections 2, 3 and 4. We thus interpret lithofacies association A to be a glacial deposit, most likely a till. At sections 1 and 2 the position within end moraines strengthens the genetic interpretation. The poor clustering of the clast fabric at section 3 (Fig. 6(f)) indicates deposition without a significant shear stress component. Because a strong fabric is commonly associated with subglacial tills (e.g. Benn and Evans, 1998), a plausible genesis is deposition by supraglacial processes (cf. Kjær and Krüger, 2001). The clast-supported diamicton in section 4 may reflect ice-proximal or subglacial glaciofluvial deposition, in close contact with the diamicton. A glacial interpretation concurs with that of Zhou and Li (1998), who mention till deposits near Huashixia, which we assume correspond to our sections 3 and 4.

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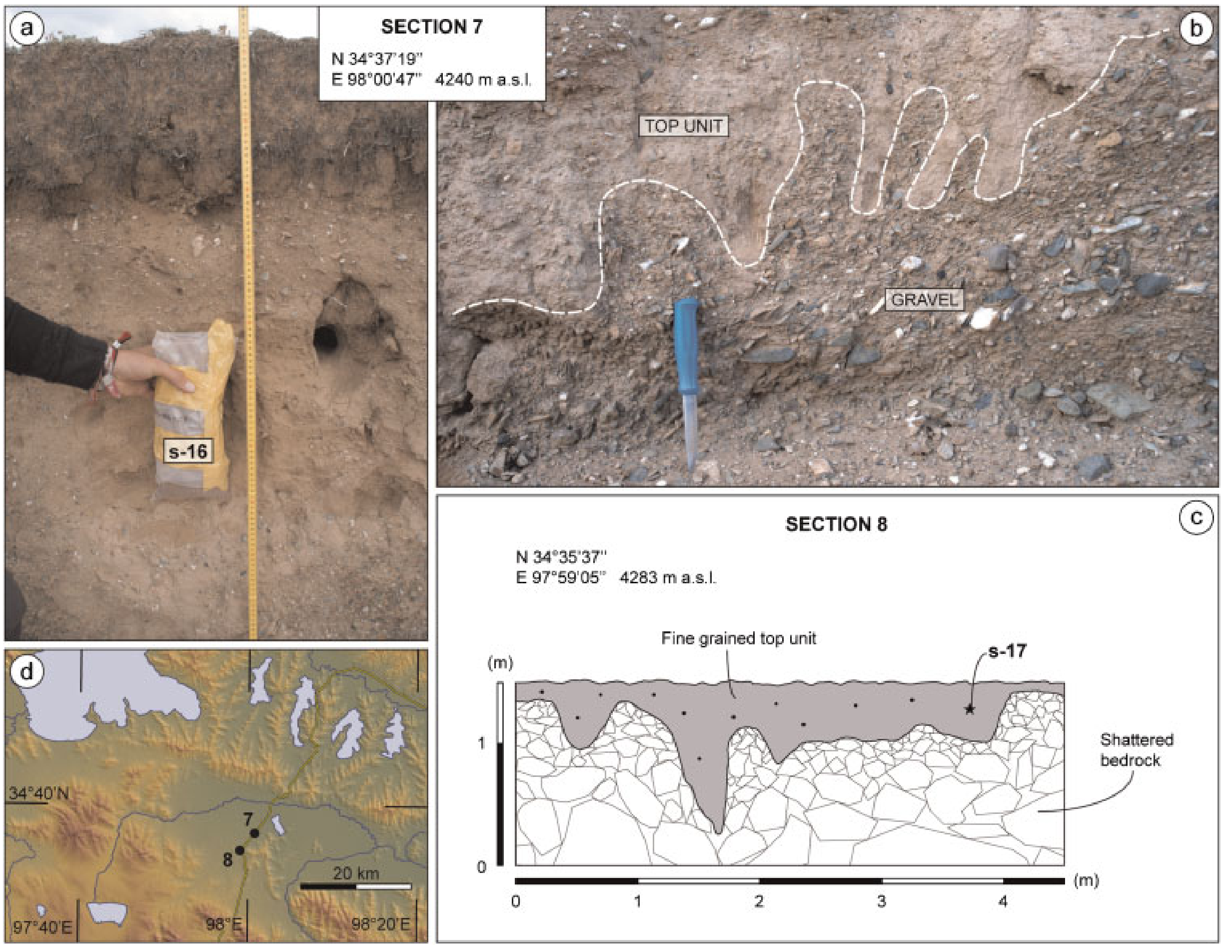

Figure 9 Fine-grained top unit sections at sites on the southern Yematan plain. (a) Section 7 with grain size sample s-16. (b) The lower boundary of the top unit at section 7 with involutions of the underlying gravel. (c) Sketch of section 8 with a sand wedge protruding into frost-shattered bedrock and the location of grain size sample s-17 marked. (d) Location of the sediment sections. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

Lithofacies association B: clast-supported gravel with boulders

Yeniugou (section 5)

Section 5 (1.5 m high) is situated 4.5 km north of the Yeniugou Mountains and 20 km east of Galala Hu (*Hu* = lake), outside the area of mapped glacial landforms (Figs 1 and 4; Heyman *et al.*, 2008). The section is located 35 m above and 1.3 km east of the river, passing the village of Yeniugou on a relatively level area. Lehmkuhl *et al.* (1998) studied a section along the river and reported gravel of inferred fluvial or glaciofluvial origin overlapping a continuous till sheet containing edge-rounded and striated granite clasts.

The bulk of the sediment is composed of clast-supported gravel (Fig. 6(e)) that displays faint stratification and clast imbrication (lithofacies association B). Some of the clasts are striated and large erratic granite boulders are embedded in the gravel. The grain size distribution reveals a poorly sorted sediment peaking in the medium gravel fraction (Fig. 7: s-6). The gravel is covered by 37 cm of a fine-grained top unit with some larger clasts (lithofacies association D, see below).

Interpretation: glaciofluvial gravel

The clast-supported faintly-stratified gravel with imbrication indicates a fluvial origin, while the striated clasts and erratic boulders imply glacial influence. The combination suggests glaciofluvial deposition, in apparent support of findings by Lehmkuhl *et al.* (1998).

Lithofacies association C: clast-supported gravel

Road marker 439 (section 6)

Section 6 is situated at a large road pit close to road marker 439, 27 km southwest of Huashixia and 10 km southwest of the northwestern reaches of the Anyemaqen mountain group (Figs 1 and 8), on the lower part of a slope grading into an extensive plain. The geomorphology of the surroundings is non-glacial, but with one small glacial valley/cirque at an altitude of ~4700 m a.s.l. mapped 14 km east of the site (Heyman *et al.*, 2008). The general surface slope at road marker 439 is towards the southwest but section 6, at 4334 m a.s.l., has a local surface slope towards the west. The road marker 439 sediments were described by Zhou and Li (1998), who interpreted them as till formed by the Huang He ice sheet. We have logged a 7.35 m high section (Fig. 8(a)), and measured six clast fabrics (Fig. 8(b)) and sampled for nine grain size distributions (Fig. 7: s-7 to s-15) from different levels of the section (Fig. 8(a)).

The main part of the section is composed of clast-supported gravel (lithofacies association C), capped by a ~40 cm thick fine-grained unit (lithofacies association D, see below). In the lowermost part of the section, two layers of fine-grained sediments occur; a 10 cm upward-fining sand layer and above that an 8 cm reddish clayey silt layer, separated from each other

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by 35 cm of massive clast-supported gravel. The reddish silt layer contains surfaces of dark organic coating and occasional gravel clasts. Above the silt layer, clast-supported gravel continues upward for 6.2 m. From ~1.3 m depth and upward, the gravel is faintly horizontally stratified and in some parts displays clast imbrication (Fig. 8(c)).

All grain size samples from the gravel peak in the medium gravel fraction. Measured clast fabrics are similar to the fabrics of section 4 and 5 (Fig. 6(f)), and generally display poor clustering (Fig. 8(b)). Only fabric f-5, from the lower part of the gravel above the reddish clayey silt layer, shows a moderately strong clustering, with a preferred N–S orientation of the *a*-axis ($S_1 = 0.74$) and an E–W orientation of the *b*-axis ($S_1 = 0.67$). There is a clear tendency for low *a*-axis dips and more random *b*-axis dips. In addition to standard clast fabric measurements, the *ab*-plane strike was measured for 115 clasts with a distinct disc shape, collected from various parts of the gravel deposit. In general, the orientation of the plane ranges from north to southeast, with strongest prevalence for orientation towards the southeast (Fig. 8(b)).

The gravel clasts are mainly composed of sandstone and shale. Bedrock outcrops of the same lithologies are exposed ~2 km upslope of the section towards the north-northeast, indicating a possible local origin for the gravel clasts. No erratics or striated clasts are present *in situ* in the gravel section, but a handful of faintly striated clasts were found lying loose on the road pit floor.

Interpretation: fluvial gravel

The overall properties of the sediments adjacent to road marker 439 do not meet the glacial criteria described above and they do not support a glacial origin. These sediments are located outside the area of mapped glacial morphology (Heyman *et al.*, 2008; Fig. 4), and the lithology of the gravel clasts indicates a local origin. A fluvial origin for these sediments is suggested by faint horizontal stratification and clast imbrication. The preference for a low dip on the *a*-axis conforms well to a fluvial environment (Schlee, 1957; Rust, 1972), as does the presence of the fine-grained beds, one of which contained clasts with organic coating. Measured disc clasts *ab*-plane strikes clearly indicate planes dipping towards southeast, east and north, which agrees reasonably well with expected palaeo-currents from the northeast and east as judged from topography (Rust, 1972; Kauffman and Ritter, 1981).

Our preferred interpretation is that the gravel has been formed by fluvial deposition onto the extensive plain. This interpretation agrees well with the geomorphology of the area, with gentle slopes grading into the plain (Fig. 8(d)). The only feature of the deposit that could possibly be taken as indicating a glacial origin is the presence of faintly striated clasts on the pit floor. A plausible explanation of the striated clasts could be a short fluvial transportation of originally glacial deposits without obliteration of the striae. However, the striations may also originate from mechanical disturbance associated with the recent road pit construction. The data are therefore inconsistent with the Zhou and Li (1998) interpretation that the deposits adjacent to road marker 439 are glacial in origin.

Lithofacies association D: massive sand

General

At almost all sites we visited in the study area, the top unit is a fine-grained sediment (lithofacies association D; cf. Figs 6 and 8). This top unit is generally 30–100 cm thick and composed of relatively well-sorted and massive sand. In most cases this fine-grained matrix includes occasional and randomly scattered clasts that are typically 1–5 cm in diameter, and occasionally >10 cm. Three different top unit sections have been sampled and analysed for grain size distributions (Figs 7–9). At several locations, the lower boundary of the top unit displays involutions and sand wedges (cf. Fig. 9(b)–(c)).

Road marker 439 (section 6)

The top unit of section 6 is composed of a sandy matrix with occasional larger clasts (Figs 7 and 8). The grain size distribution peaks in the fine sand fraction, but also shows high concentrations in the medium and course sand fractions (Fig. 7: s-15).

Yematan plain (sections 7 and 8)

In the southern part of the Yematan plain northeast of central Bayan Har Shan, two top unit sections were sampled for grain size analysis. Section 7 is located on the Yematan plain and section 8 on top of a bedrock hill rising above the plain (Fig. 9(d)).

At section 7 the top unit is ~1 m thick and contains numerous clasts (Fig. 9(a)). It overlies clast-supported gravel and displays involutions of gravel into the fine-grained sediments (Fig. 9(b)). The grain size distribution displays a peak in the fine sand fraction and a secondary peak in the coarse gravel fraction (Fig. 7: s-16).

The top unit of section 8 overlays frost-shattered meta-morphic sedimentary bedrock (Fig. 9(c)). The lower boundary of the top unit is undulating, and sand wedges filled with top unit sediments protrude into the underlying frost-shattered bedrock. The grain size distribution is the best sorted of all samples, with a clear peak in the fine sand fraction (Fig. 7: s-17). We randomly picked out 50 clasts from the top unit for comparison with the underlying bedrock. All clasts were of the same sedimentary lithology as the bedrock.

Qingshuihe

From one top unit section at Qingshuihe, southwest of central Bayan Har Shan (Fig. 1; 33° 49′ 01″ N, 97° 08′ 09″ E), we randomly picked out 100 clasts from each of two locations located ~20 m apart and overlying bedrock of two separate lithologies (sandstone and slate). All clasts that were collected were of the same lithology as the bedrock directly underlying the sampled top unit.

Interpretation: aeolian sand

The relatively good sorting of this unit, combined with the dominance of the fine sand fraction, its association with sand wedges, its widespread presence and position as the uppermost draping unit indicate an aeolian origin for these sediments. Aeolian deposits are common on the Tibetan Plateau (Lehmkuhl, 1997; Lehmkuhl *et al.*, 2000; Sun *et al.*, 2007). In the study area, sand dunes are abundant in the low-lying

Huang He area northeast of central Bayan Har Shan, and fine-grained top units have been previously interpreted as aeolian deposits (Lehmkuhl, 1997; Lehmkuhl *et al.*, 1998).

The larger clasts within the sand are not consistent with a purely aeolian origin for the deposit. The identical lithology of the clasts and the underlying bedrock indicates a local origin for the top unit clasts. Based on this, and the presence of cryogenic features (sand wedges and involutions), we interpret the clasts as material that has been incorporated into the fine-grained matrix by cryoturbation. Thus we consider the top unit as originally deposited by aeolian processes with subsequent reworking and incorporation of underlying material by cryogenic processes. This interpretation conforms well to the presence of cryogenic structures (Fig. 9(b) and (c); Cheng *et al.*, 2005) and reported sediments of mixed aeolian/cryogenic origin (Lehmkuhl, 1997).

Results: distribution of glacial deposits

In the study area, glacial deposits are abundant in areas where clear glacial landforms have been mapped (Heyman *et al.*, 2008; Stroeven *et al.*, 2009). However, glacial deposits also exist beyond these areas (Fig. 4 and Table 1). Around central Bayan Har Shan, deposits of glacial origin are present up to 25 km outside mapped glacial landforms; ~60 km northeast of (~4230 m a.s.l.), ~70 km east of (~4330 m a.s.l.), and ~40 km west of (~4480 m a.s.l.) the highest peaks of central Bayan Har Shan. In the Anyemaqen Shan area, glacial deposits are scattered up to 15 km northeast of the Weigele Dangxiong outlet glacier (~4070 m a.s.l.). Furthermore, glacial sediments are present at Huashixia ~60 km northwest of the Anyemaqen ice field (~4250 m a.s.l.). In the northwestern sector of the study area, glacial sediments are present ~150 km northwest of central Bayan Har Shan (Fig. 4: sites 1, 2).

One set of glacial features in Bayan Har Shan that has been frequently cited as a marker of extensive glaciation is the presence of erratic granite boulders originating from several granite bedrock outcrops in central Bayan Har Shan (Figs 3 and 10; Rutter, 1995; Lehmkuhl *et al.*, 1998; Zheng and Rutter, 1998; Zhou and Li, 1998; Kuhle, 2003). We have mapped the presence of granite boulders and bedrock source areas in and around central Bayan Har Shan (Fig. 10). Granite erratics are present in the glacial valleys and troughs except for the innermost parts of the glacial valleys emanating towards the south and east. Furthermore, granite erratics exist in areas beyond the extent of mapped glacial landforms (Figs 10 and 11(a)–(c)). East of central Bayan Har Shan, granite erratics are present ~18 km northeast of the mouth of the Chalaping valley (Figs 1 and 10). There are granite erratics throughout the Yeniugou mountains northeast of central Bayan Har Shan, and north of Yeniugou to the southern end of the Yematan plain (Figs 1 and 10; cf. Zhou and Li, 1998). North of central Bayan Har Shan numerous granite erratics are scattered in the landscape of mapped glacial geomorphology and extending 10 km north of Galala Hu (Figs 1 and 10). West of central Bayan Har Shan granite erratics are abundant in and just outside the marginal moraine area and erratics are scattered in an N–S trending river depression ~40 km west of the highest peaks (Fig. 10). Of the locations visited around central Bayan Har Shan, the only place where we have not observed granite erratics extending several kilometres beyond mapped glacial landforms is in the southwest. The outermost granite erratics in the southwest are located at the outermost mapped moraine ridges, ~11 km northeast of Qingshuihe (Figs 1 and 10).

Non-glacial sites and non-glacial granite boulders

In an attempt to map the maximum extent of glacial evidence we have also recorded locations where glacial deposits are lacking (Fig. 10). These are locations where, in addition to a general scanning of the landscape from the roads, an active search for features such as striated clasts, erratic boulders and diamictons was unsuccessful. This search was partly guided by earlier reports of glacial traces (Zhou and Li, 1998; Kuhle, 2003) and was furthermore focused towards locations where, on the basis of preservation and availability arguments, there was an expectation of success, such as on gentle hills rising above sedimentary plains. The non-glacial sites are distributed mainly north and northeast of central Bayan Har Shan, in the Huang He basin, and around Zhaling Hu and Eling Hu, where we concentrated our efforts to find evidence of former glaciation. Three non-glacial sites in the Yeniugou Mountains are located on the tops of hills, at 4867, 4763 and 4560 m a.s.l. Apart from these three locations, glacial indices are present at all examined sites within the areas of glacial deposits, highlighting a distinct difference between the areas of glacial deposits and the non-glacial areas.

Perhaps the most convincing argument for ice sheet glaciation has been the reported presence of presumed Bayan Har Shan granite erratics on the far (northern) shores of Zhaling Hu and Eling Hu (Zhou and Li, 1998). Granite boulders are indeed present at three locations west of Eling Hu (1) and north of Zhaling Hu (2). However, at all these locations there is also granite bedrock either directly underlying or upslope of the granite boulders (Figs 10 and 11(d) and (e)). Hence these granite boulders do not represent erratic lithologies for this area and can therefore not be used as evidence of ice sheet glaciation. *In situ* weathering of the granite bedrock appears to produce edge-rounded granite bodies (cf. Fig. 11(d)), which will eventually turn into granite boulders as they detach from the bedrock. No striated clasts are present in this area.

Discussion

Bayan Har Shan ice cap traces

Glacial deposits are distributed in and around the higher mountain areas (Fig. 4), and there is an absence of glacial landforms and sediments across extensive lower-lying plateau areas (Fig. 10). Glacial deposits exist in all of our sites within the area of glacial landforms. Of particular interest is the fact that glacial deposits are present in mapped hummocky terrain areas west of Bayan Har Shan (Fig. 4, Table 1: sites 1, 2), beyond the area with glacial erosional landforms. In fact, these latter deposits, including striated clasts and erratic boulders, confirm the association of the non-genetic hummocky terrain unit of Heyman *et al.* (2008) with glacial processes. In other locations, glacial deposits are scattered beyond the mapped limit of glacial landforms in Heyman *et al.* (2008), in areas showing non-glacial morphologies at a scale that can be identified from the employed satellite data (Heyman *et al.*, 2008; Stroeven *et al.*, 2009). Thus, the extent of the most extensive glaciation in several areas is only recorded as individual observations of glacial deposits.

Around central Bayan Har Shan, erratic granite boulders are scattered up to ~70 km away from the central parts of the mountain group, an observation similar to those reported in earlier studies (Rutter, 1995; Lehmkuhl *et al.*, 1998; Zheng and

Table 1 Observed glacial deposits of the Bayan Har Shan (see Fig. 4 for locations). Coordinates refer to the position of a glacial deposit within each area

No.	Area	Coordinates	Description
1	W Bayan Har	34° 43′ 46″ N 96° 09′ 00″ E	Occasional erratic boulders, clasts of multiple lithologies, striated clasts
2	W Bayan Har	34° 49′ 37″ N 96° 12′ 36″ E	Clasts of multiple lithologies, striated clasts
3	NW of C Bayan Har	34° 23′ 49″ N 97° 03′ 30″ E	Clasts of multiple lithologies, striated clasts
4	W of C Bayan Har, outer glacial deposits	34° 13′ 31″ N 97° 10′ 47″ E	Scattered erratic granite boulders, striated clasts
5	W of C Bayan Har, inner glacial deposits	34° 08′ 14″ N 97° 17′ 58″ E	Numerous erratic granite boulders, clasts of multiple lithologies, striated clasts
6	SW of C Bayan Har, NE of Qingshuihe	33° 57′ 52″ N 97° 19′ 32″ E	Scattered erratic granite boulders, sediment sections with diamicton, clasts of multiple lithologies, striated clasts
7	S of C Bayan Har, inner area	34° 04′ 30″ N 97° 36′ 35″ E	Sediment sections with diamicton, striated clasts
8	N of C Bayan Har	34° 27′ 00″ N 97° 37′ 09″ E	Numerous erratic granite boulders, sediment sections with diamicton, clasts of multiple lithologies, striated clasts
9	NE of C Bayan Har, Yeniugou Mts	34° 21′ 13″ N 97° 55′ 12″ E	Scattered erratic granite boulders, clasts of multiple lithologies, striated clasts
10	N of Yeniugou Mts until S Yematan plain	34° 35′ 57″ N 97° 59′ 05″ E	Erratic granite boulders (numerous along the southern margin of Yematan plain), clasts of multiple lithologies, striated clasts
11	E of C Bayan Har, inner glacial deposits	34° 09′ 16″ N 97° 42′ 29″ E	Sediment sections with diamicton, striated clasts
12	E of C Bayan Har, outer Chalaping Valley	34° 09′ 25″ N 98° 01′ 13″ E	Scattered erratic granite boulders, sediment sections with diamicton, clasts of multiple lithologies, striated clasts
13	E of C Bayan Har, outside Chalaping Valley	34° 10′ 27″ N 98° 24′ 03″ E	A few erratic granite boulders, clasts of multiple lithologies, striated clasts
14	S of Qingshuihe	33° 29′ 42″ N 97° 14′ 29″ E	Sediment section with diamicton, clasts of multiple lithologies, striated clasts
15	S Bayan Har, inner glacial trough	32° 57′ 40″ N 97° 55′ 16″ E	Scattered erratic quartzite boulders, sediment sections with diamicton, clasts of multiple lithologies, striated clasts
16	S Bayan Har, outer glacial trough	33° 03′ 47″ N 97° 58′ 43″ E	Scattered erratic granite and quartzite boulders, sediment sections with diamicton, clasts of multiple lithologies, striated clasts
17	Huashixia	35° 06′ 44″ N 98° 50′ 52″ E	Sediment sections with diamicton, clasts of multiple lithologies, striated clasts
18	S of Huashixia	34° 58′ 57″ N 98° 53′ 25″ E	Scattered erratic granite boulders, clasts of multiple lithologies, striated clasts
19	SW of Anyemaqen	34° 31′ 06″ N 99° 08′ 48″ E	Scattered erratic granite boulders, clasts of multiple lithologies
20	NW of Anyemaqen	34° 56′ 54″ N 99° 21′ 06″ E	Scattered erratic quartzite and metamorphic bedrock boulders, clasts of multiple lithologies, striated clasts
21	Anyemaqen contemporary glacier	34° 52′ 14″ N 99° 27′ 55″ E	Numerous erratic granite boulders, sediment sections with diamicton, clasts of multiple lithologies, striated clasts

Rutter, 1998). Granite boulders are dispersed along the southern slope of the Yematan plain (Figs 1 and 10). The fact that there is an absence of erratics on the plain further north was interpreted by Zhou and Li (1998) to be the result of burial by subsequent fluvial and lacustrine sediments. We tentatively support this view because the distribution of granite boulders very clearly follows the lower slope break for several kilometres. Along the northern margin of the Yematan plain no glacial traces were found despite intensive searches (Fig. 10), indicating that the ice that deposited the granite boulders on the southern slope of the Yematan plain did not reach the present-day northern Yematan plain margin. Thus the Yematan plain marks an ice-marginal area of the maximum glaciation. This glacial extent, and the glacial extent as indicated by the most distant glacial deposits towards the east, south and west of central Bayan Har Shan, correspond to the margins of one or more extensive ice cap or ice field phases. The glacial geological record of the study area, including glacial erosional morphology, glacial deposits and mapped glacial landforms (Figs 4 and 10; Table 1; Heyman *et al.*, 2008; Stroeven *et al.*, 2009), records the former presence of several separate palaeo-ice caps/ice fields centred over individual mountain areas. Areas outlining the distribution of glacial traces (Fig. 12) can be considered as representing the minimum extent of the maximum glaciation in our study area.

The absence of glacial evidence in intervening lower-lying plateau areas does not definitively prove that glaciers or ice sheets did not cover these areas in the past. Several processes, such as cold-based ice inhibiting glacial erosion and deposition (Kleman, 1994), fluvial removal of landforms and deposits (Stroeven *et al.*, 2009), landform degradation (Putkonen *et al.*, 2008) and postglacial sedimentary burial may result in negligible glacial evidence in a formerly glaciated terrain. However, the complete lack of glacial traces for extensive areas, as revealed by careful field investigations, indicates strongly that former glaciers did not cover these areas (Fig. 12). Until robust glacial indications have been established for these lower-lying plateau areas, they should be assigned to the non-glaciated part of the plateau (cf. Lehmkuhl *et al.*, 1998; Zheng and Rutter, 1998).

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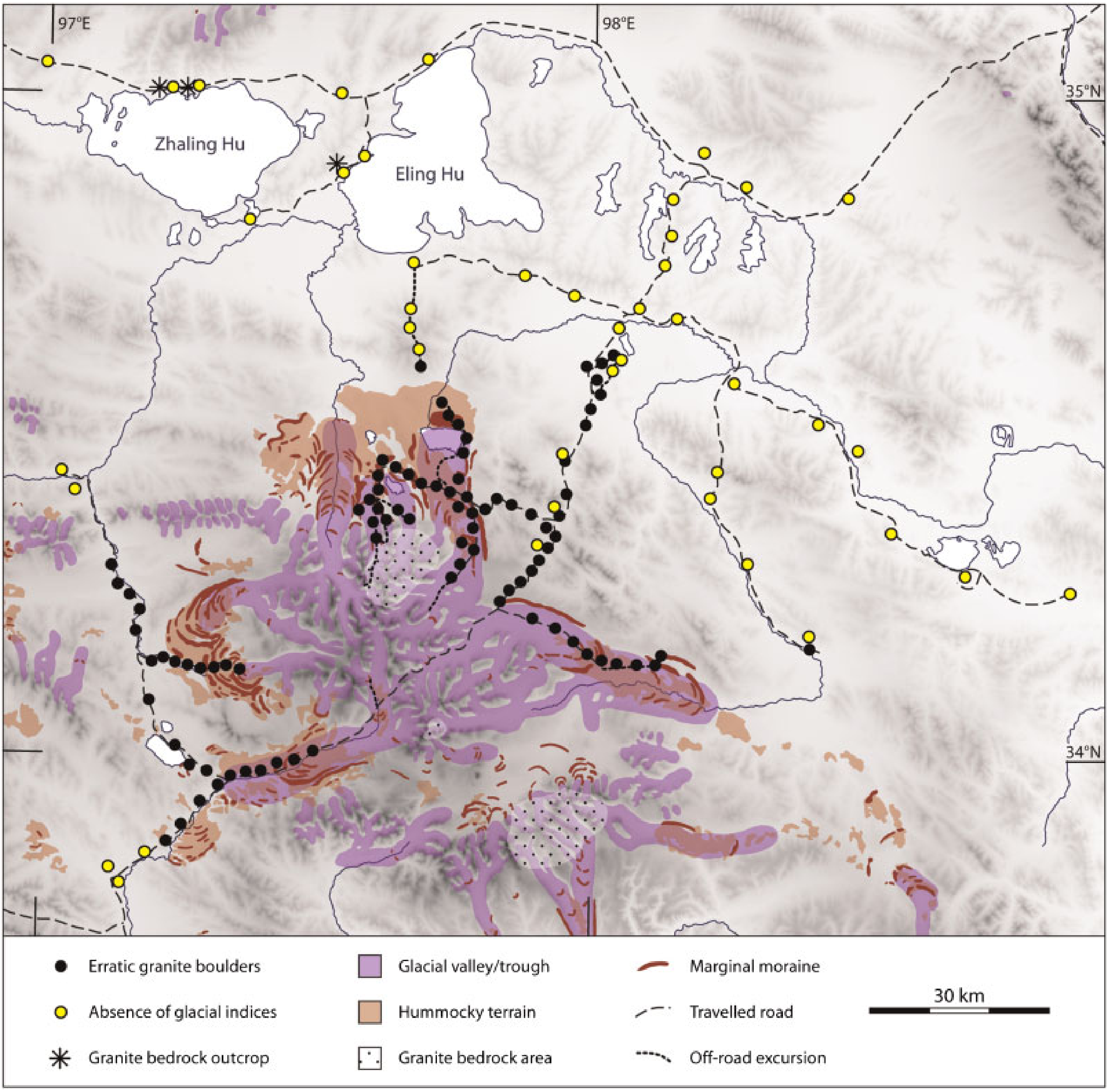

Figure 10 Locations where erratic granite boulders were observed ('Erratic granite boulders') and where they and other glacial morphology were absent ('Absence of glacial indices'), locations of granite bedrock outcrops (source areas for the erratics) in Bayan Har Shan, and granite bedrock outcrops at Zhaling and Eling Hu (see Fig. 11(d) and (e)). These locations are superimposed on a map showing glacial erosional and depositional landforms (see Fig. 4). The granite bedrock areas of central Bayan Har Shan were mapped from Landsat ETM+ imagery, with the margin of the northernmost granite area checked in the field. 'Absence of glacial indices' represents spot locations for areas where an active search for glacial features was conducted but where none were found. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

Regional ice sheet indications

Zhou and Li (1998) presented a record of glacial deposits and landforms for the Bayan Har Shan, and proposed a series of glacial stages associated with these deposits and landforms. In support of their Yematan glaciation ice mass (Fig. 4), they presented glacial deposits that are in general distributed in accordance with our lowermost/outer glacial deposits (Figs 4 and 10). For the Huang He ice sheet glaciation (Fig. 4), however, Zhou and Li (1998) indicated a presence of glacial valleys and erratics in the northern part of the study area. However, the valleys of the four narrow lakes ('the finger lakes') south of Maduo (Fig. 1), interpreted as glacial valleys by Zhou and Li (1998), have been reinterpreted as having a fluvial and tectonic origin by Stroeven *et al.* (2009). This non-glacial association of these lakes is further corroborated by the absence of glacial traces and the reinterpretation of investigated granite boulders along the northern margin (Fig. 10).

In the northeastern part of the study area, Zhou and Li (1998) suggested that deposits close to Huashixia and at road marker 439 were formed by the Huang He ice sheet: 'the sedimentology and geomorphology suggests that the unit can be interpreted as a lodgement till' (Zhou and Li, 1998, p. 139). Based on our investigation of the deposits at road marker 439, we conclude they are of fluvial origin because they are dominated by imbricated and stratified gravel of local origin and have clast orientations indicative of fluvial action.

We further disagree with Zhou and Li (1998) that it would take a Huang He ice sheet to deposit tills in the Huashixia area. Specifically, mountain groups centred southeast of the glacial

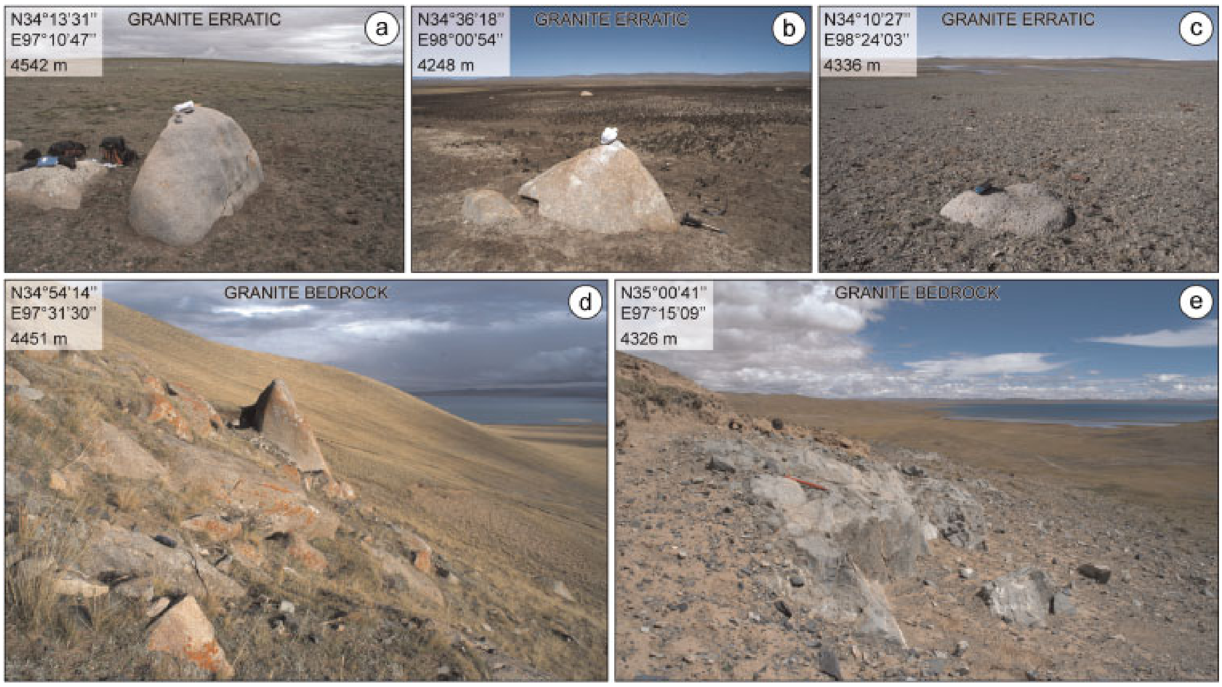

Figure 11 Erratic granite boulders located in landscapes lacking large-scale glacial landforms and granite bedrock outcrops in the Zhaling Hu and Eling Hu area (see Fig. 10). (a) Erratic boulder west of central Bayan Har, 41 km west of the highest peak. (b) Erratic boulder northeast of central Bayan Har at the southern margin of the Yematan plain, 53 km northeast of the highest peak. (c) Erratic boulder east of central Bayan Har, 73 km east of the highest peak. (d) Granite bedrock outcrop west of Eling Hu. (e) Granite bedrock outcrop north of Zhaling Hu. The granite bedrock outcrops indicate that granite boulders at these locations are of local origin as opposed to erratic boulders from central Bayan Har. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

deposits at Huashixia (Figs 4 and 6), including the currently glaciated Anyemaqen, display a number of mapped glacial landforms (Heyman *et al.*, 2008; Fig. 4). Hence, before palaeoglaciers from central Bayan Har Shan and Anyemaqen Shan would coalesce, the Huashixia area would most likely have been overrun by glaciers of the Anyemaqen Shan and adjacent mountains.

The most convincing argument in support of a regional ice sheet has been the reported presence of granite erratics in the Zhaling Hu and Eling Hu area (Zhou and Li, 1998). Zheng and Rutter (1998) speculated that these granite boulders might instead have been transported by alluvial action or drifting ice. However, our observation that there are granite bedrock outcrops at all locations with granite boulders (Figs 10 and 11(d) and (e)) provides a simpler explanation for these boulders as being of local origin, removing the need to invoke either a Huang He ice sheet or alluvial action or drifting ice.

In summary, there are no field data supporting the former existence of a regional ice sheet in the Bayan Har Shan study area.

Proposed plateau-scale ice sheet indications

Kuhle (2003, 2004) has presented a number of sediments and landforms of proposed glacial origin from the northeastern Tibetan Plateau, and has argued that these support the existence of a plateau-scale ice sheet. For several locations in and northeast of the central Bayan Har Shan, Kuhle (2003) reports the presence of ground moraine, erratic boulders and roche moutonnées. The interpretation of sediments as ground moraine is based mainly on grain size data for fractions up to 2 mm and through scanning electron microscopy (SEM) of quartz grains. Considering the diversity of glacial sediments and their formation (Benn and Evans, 1998), and reported similarities between glacial and non-glacial sediments (e.g. Holmes and Street-Perrott, 1989; Owen, 1994), we do not consider the grain size data presented by Kuhle (2003) to be unequivocal evidence for a glacial origin. The SEM analysis is presented by Kuhle (2003, Fig. 17) as a ratio between 'glacially crushed/freshly weathered' and 'dull (aeolian)/lustrous (fluvially polished)' quartz grains. SEM data do not provide unambiguous indications of glacial origin either, because periglacial sediments are difficult to distinguish from glacial sediments (Whalley, 1996). However, the 14 SEM samples of proposed glacial origin (Kuhle, 2003) are still noteworthy. The three highest elevation samples, located in central Bayan Har Shan within the area of mapped glacial landforms and deposits shown in Fig. 4, have the highest ratios of 'glacially crushed/freshly weathered' quartz grains (68–81%). The samples from the lower-lying plateau areas where there is a lack of evidence for glaciation generally show a clear predominance of 'dull (aeolian)/lustrous (fluvially polished)' quartz grains, with five samples with only 5–13% 'glacially crushed/freshly weathered' quartz grains. A plausible explanation for a high percentage of aeolian material in the samples from the lower-lying plateau areas is that the samples were collected from the fine-grained top unit (lithofacies association D which covers or has covered all the sections presented in this study with 30–100 cm), because 12 out of 14 samples were collected 50 cm or less below the surface. In summary, we argue that the grain size and SEM data of Kuhle (2003) do not unequivocally support the interpretation of the sediments in the lower-lying plateau areas as glacially formed 'ground moraine'.

In addition to proposed glacial sediments, Kuhle (2003) has mapped a number of locations in and north of central Bayan Har Shan that he argues include erratic boulders and roche moutonnées. Photos and geographic coordinates are presented from the central part of the Yematan plain (Kuhle, 2004,

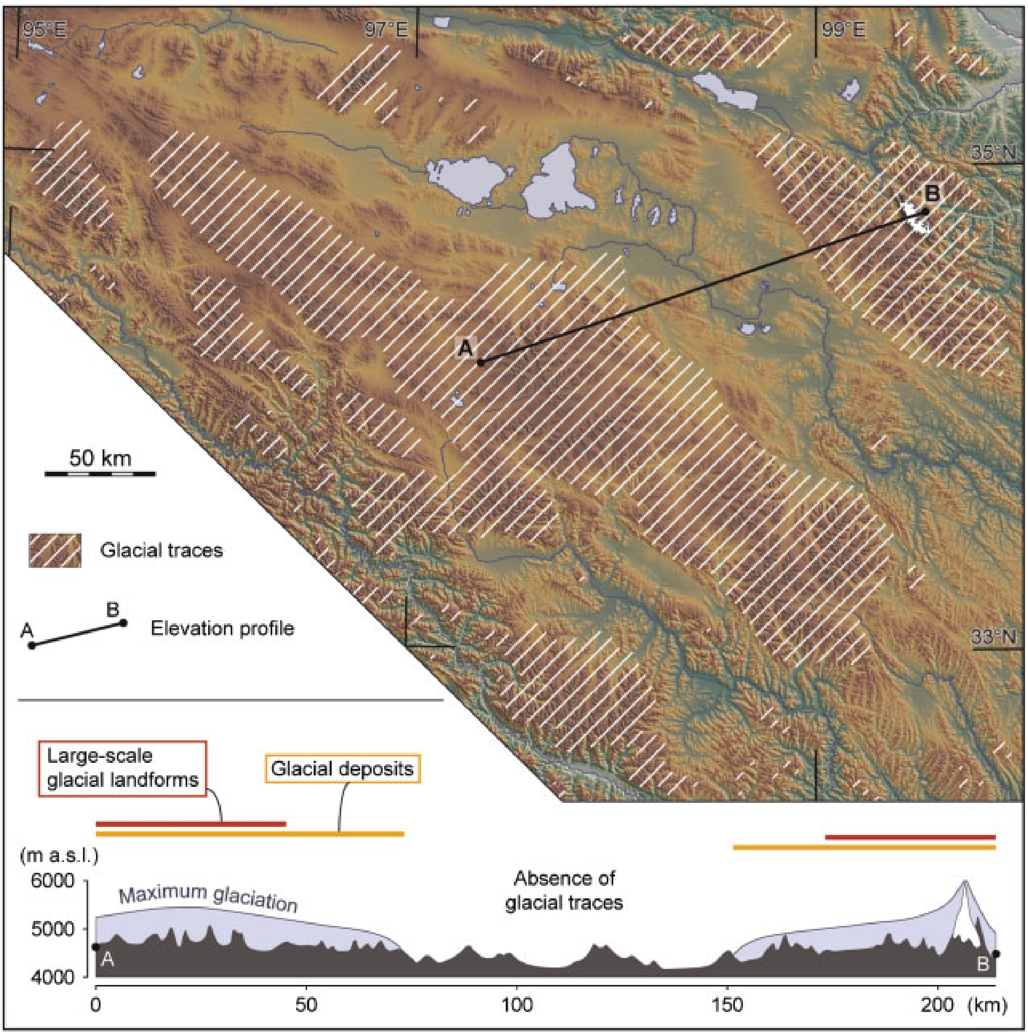

Figure 12 Distribution of glacial traces and a schematic elevation profile. The glacial traces include mapped glacial geomorphology (Heyman *et al.*, 2008; Stroeven *et al.*, 2009) and glacial deposits, and mark a minimum extent for maximum glaciation. The elevation profile highlights the difference between the extent of glacial geomorphology and glacial deposits and displays tentative outlines of the maximum central Bayan Har Shan and Anyemaqen palaeo-glaciers in the form of ice caps or ice fields. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

Fig. 27), the northern margin of Eling Hu (Kuhle, 2003, Fig. 26) and the northern margin of the lake located ~40 km east of Tuosu Hu (Fig. 1; Kuhle, 2003, Fig. 31). These three locations are all situated outside/below the outermost/lowest glacial deposits of the present study (Fig. 4). Field analysis at these locations guided by the published coordinates yielded none of the glacial traces. Because we were unable to replicate the observations presented by Kuhle (2003, 2004), we find that there is no convincing evidence to support the pattern of glacial traces presented for the northeastern Tibetan Plateau by Kuhle (2003, 2004) or the conclusion that there was a large ice sheet covering the study area.

Implications of the distribution of glacial deposits and landforms

Glacial deposits are present in several areas of the study area where glacial landforms are absent (Figs. 4, 10, 12), and this has implications for our understanding of glacial landscape evolution. The presence of unambiguous glacial deposits in landscapes lacking glacial landforms indicates one or more of these alternatives: (i) glacial landforms have been eroded/degraded; (ii) glacial landforms have been buried under younger non-glacial deposits; or (iii) no glacial landforms were formed.

For landforms such as marginal moraines, meltwater channels and hummocky terrain, erosion/degradation of landforms and burial under younger deposits seems plausible. Because marginal moraines, meltwater channels and hummocky terrain are abundant in this area in association with more restricted glacial extents, we presume that the more extensive glaciation(s) produced such landforms as well. From other parts of the Tibetan Plateau, TCN exposure dating has shown that marginal moraines at least several hundred thousand years old are still identifiable (Owen *et al.*, 2005, 2006). The erratic granite boulders scattered up to the margin of the sedimentary Yematan plain indicate that glacial traces beyond these have likely been buried underneath younger postglacial sediments.

The lack of erosional landforms such as U-shaped glacial valleys and troughs in some areas that have glacial deposits is most easily explained as an absence of glacial erosion. Postglacial erosion or degradation of large-scale glacial valleys/troughs is less likely, as the erosion required to erase the glacial signature of a U-shaped valley would not have left the glacial deposits untouched. Burial of glacial valleys/troughs is also discarded as a viable explanation for their absence because mapped glacial valleys/troughs in general terminate higher than the wide sedimentary plains, and are often fringed by bedrock hills down-valley, indicating that the glacial erosion did not reach further. For example, there is an intact bedrock shoulder at least 50 m higher than and immediately north of Galala Hu (Fig. 1) at the terminus of the Galala glacial trough, separating the glacially eroded valley from the Yematan plain in the northeast. Thus we conclude that glacial erosion under the outer/lower parts of glaciers has been negligible.

Two main factors might explain the absence of glacial erosion under the peripheral parts of the most extensive palaeoglaciers, the duration of ice cover and the basal thermal regime of the glacier. While a short duration of ice cover restrains the erosion of wet-bed erosive glaciers (cf. Brook *et al.*, 2006; Kleman *et al.*, 2008), cold-based ice frozen to its bed completely prevents any significant glacial erosion (Kleman, 1994). From the data available, we cannot derive which of these two factors has played the main role for the lack of erosion. The peripheral regions of a glaciation will experience a shorter duration of ice cover than the central regions (cf. Kleman *et al.*, 2008) and a dry continental climate will favour cold-based glaciers due to a low mass turnover (cf. Shi, 2002). A third factor that might explain spatially varying glacial erosion is the topography, with enhanced selective linear erosion resulting from topographical steering of ice flow in high-relief areas (cf. Sugden, 1978; Kessler *et al.*, 2008). However, for Bayan Har Shan the absence of glacial erosional landforms in the Yeniugou Mountains, with a more pronounced relief than some other glacially eroded areas (cf. Figs. 1 and 4), indicate that topography alone cannot explain the absence of glacial erosion under the peripheral parts of a former ice cover.

Summary of glaciation evidence

Bayan Har Shan holds a glacial geological record with glacial traces diminishing away from the highest mountains (Fig. 12). While the highest mountain areas have clear glacial landforms and deposits, formerly ice-covered lower-lying areas only exhibit glacial evidence in the form of glacial sediments, including erratic boulders. These more widespread deposits indicate that glaciers larger than indicated by morphological evidence did develop within the study area. A complete lack of glacial landforms and deposits in the lower-lying plateau area in between central Bayan Har Shan and Anyemaqen Shan indicates that ice caps of these mountain groups did not coalesce. The minimum extent of the largest palaeoglaciological configuration of Bayan Har Shan is indicated by the mapped glacial traces, which cover $\sim$44 000 km^2 of the study area (Fig. 12). The single largest ice mass was a NW–SE trending ice cap or ice field over central Bayan Har which, with an area of at least 26 000 km^2, was more extensive than any contemporary ice mass except for the Greenland and Antarctica ice sheets. However, there are no glacial landforms or deposits commensurate with ice sheet scale glaciation of the extents envisioned by Zhou and Li (1998) and Kuhle (2003, 2004).

The distinct difference between the outer/lower and the inner/higher glacial traces and the number and size of landforms indicate that the Bayan Har Shan glacial traces derive from multiple glaciations. The glacial geological record, therefore, is most likely not the result of the last glaciation alone. The Anyemaqen ice field moraines constrained to MIS 2 (Owen *et al.*, 2003) indicate restricted glaciation during this time, which probably corresponds to central Bayan Har Shan glaciers considerably smaller than its most extensive glaciation. TCN and optically stimulated luminescence dates from the Anyemaqen ice field area yielding MIS 3, MIS 2 and Holocene ages (Owen *et al.*, 2003) are the only published dates from glacial deposits in the study area. Given the paucity of data, more extensive quantitative dating of glacial features is required to constrain the chronology of glacial events for the Bayan Har Shan.

Conclusions

Detailed field observations in the Bayan Har Shan on the northeastern Tibetan Plateau reveal a complex glacial geological record for an extensive study area of 136 500 km^2. Using objective indices for the determination of glacially derived deposits, in conjunction with remote sensing techniques for mapping the glacial geomorphology, we can draw the following conclusions:

- The glacial geological record, including large-scale glacial landforms and glacial deposits, indicates a maximum former glaciation of the Bayan Har Shan study area restricted to separate mountain groups, each covered by ice caps, ice fields or valley glaciers. The most extensive ice mass was a NW–SE trending ice cap of at least 26 000 km^2 centred over Bayan Har Shan, with additional glaciation centres over adjacent mountain groups.
- There is no field evidence supporting either a regional ice sheet or a plateau-wide ice sheet covering the northeastern Tibetan Plateau. Detailed field investigations of extensive low-lying plateau areas highlight an absence of glacial deposits, indicating that former glaciers did not cover these low-lying plateau areas.
- Glacial deposits are abundant in areas of large-scale glacial landforms, but also exist in areas lacking glacial landforms. This implies that the most extensive ice caps/ice fields did not produce significant erosion towards their margins. Evidence for the most extensive Bayan Har Shan glaciation is only present in the form of patches of glacial sediments, including glacial erratics.

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