



Invited review

Nature and timing of Quaternary glaciation in the Himalayan–Tibetan orogen

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ABSTRACT

Much effort has been made in recent years to define the timing and extent of Quaternary glaciation throughout the Himalayan–Tibetan orogen. These studies are challenging because of the logistical and political inaccessibility of the region, and the inherent problems associated with the application of numerical dating techniques. Nevertheless, the studies are providing abundant evidence for significant glacial advances throughout the last several glacial cycles and are beginning to accurately define the extent and timing of glaciation in selected regions. Studies are showing that Himalayan–Tibetan glaciers in arid regions during the last glacial cycle reached their maximum extent early in the cycle and that global Last Glacial Maximum glacier advances were significantly less extensive. However, along the more monsoonal-influenced Greater Himalaya, there is increasing evidence to suggest that glaciation was more extensive later in the last glacial cycle, but this has yet to be fully assessed. In addition, the new studies are showing that throughout most Himalayan–Tibetan regions, significant glacier advances occurred during the Lateglacial and early Holocene, with minor advances in some regions during the mid-Holocene. The still relatively poor chronological control in the Himalayan–Tibetan orogen, however, makes it difficult to construct correlations across the region, and with regions elsewhere in the world. This in turn makes it hard to assess the relative importance of the different climatic mechanisms that force glaciation across the Himalayan–Tibetan orogen, and to quantify paleoclimate change in this high altitude subtropical region. The Lateglacial and Holocene glacial records, however, are particularly well preserved in several Himalayan–Tibetan regions. Glacial successions such as these have the greatest potential to be examined in detail using newly developing numerical dating, and geomorphic and sedimentologic methods to derive high-resolution terrestrial records of glaciation that will help in paleoclimatic reconstruction for high altitude subtropical regions.

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1. Introduction

The mountains of the Himalayan–Tibetan orogen are the highest on Earth and the orogen is the most glaciated region outside of the polar realms (with ~126,200 km² glacier cover; [Haeberli et al., 1989](#)). Glaciers in Himalayan and Tibetan mountains are the source for numerous rivers that flow across the Indo-Gangetic Plain and central and eastern China, which provide freshwater to billions of people. Furthermore, the Himalayan–Tibetan orogen has a profound influence on regional and global atmospheric circulation and it is therefore important for understanding the dynamics of global environmental change ([Molnar and England 1990](#); [Ruddiman and Kutzbach 1991](#); [Prell](#)

and [Kutzbach, 1992](#); [Owen et al., 2002d](#)). The study of glaciation in the Himalayan–Tibetan orogen is also important for providing a framework to examine glacial controls on the development of topography, conditioning landscapes in mountain systems and focusing erosion in them, and governing tectonic feedbacks to the evolution of mountains ([Brozović et al., 1997](#); [Zietler et al., 2001](#); [Norton et al., 2010](#); [Willett, 2010](#)). Contention exists over the rate at which glaciers are currently receding to the extent that erroneous estimates have suggested that they are receding faster than in any other part of the world and are likely to disappear by at least the AD 2035 ([Intergovernmental Panel on Climate Change, 2007](#); [Bagla, 2009](#)). Impressive glacial landforms and successions of Quaternary glacial sediments are abundant throughout the orogen, recording the nature and style of glacial oscillations.

Yet despite the importance of the region and its potentially useful geologic archive, the nature and dynamics of Himalayan–Tibetan glaciers throughout the Quaternary are not well

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understood. In particular, the timing and extent of past glacier fluctuations are poorly defined. This is partially because the logistical and political inaccessibility of the region has made research there particularly challenging. Nevertheless, the region has had a long history of glacial research, but the older studies were quite restricted in extent because of the logistical and political difficulties. Notably significant historical studies include those of [Drew \(1873\)](#), [Dainelli \(1924–35\)](#), [Norin \(1925\)](#), [Klute \(1930\)](#), [Trinkler \(1930\)](#) and [De Terra and Paterson \(1939\)](#). In recent years, numerous researchers have undertaken detailed studies of the region's Quaternary glacial geology aided by better accessibility, newly developing remote sensing technologies and numerical dating, and a renewed interest in the region and its glaciers. This has resulted in a plethora of publications that are beginning to allow us to develop a dynamic picture for the Quaternary glaciation of the Himalayan–Tibetan orogen.

The aim of this manuscript is to present a review of the Quaternary glacial geology of the Himalayan–Tibetan orogen and to speculate on the role of climate and other forcing factors on glaciation in the region. Our manuscript builds on reviews by [Shi et al. \(1986\)](#), [Derbyshire et al. \(1991\)](#), [Benn and Owen \(1998\)](#), [Lehmkuhl and Owen \(2005\)](#), [Owen et al. \(2008a\)](#), [Owen \(2009, 2013\)](#), and regional syntheses in [Elhers and Gibbard \(2004, 2011\)](#), [Dortch et al. \(2013\)](#), [Murari et al. \(2014\)](#), and notably, [Kamp and Owen \(2011\)](#), [Owen \(2011\)](#) and [Zhou et al. \(2011\)](#).

2. The physical environment

The Himalayan–Tibetan orogen is a consequence of the collision of island arcs with the Eurasian continental plate, and the collision of the Indian and Eurasian continental plates at ~50 Ma and the subsequent continued northward movement of the Indian plate at ~50 mm/a ([Yin and Harrison, 2000](#); [Searle and Richard, 2007](#)). This has resulted in a mountain mass made up of several approximately east–west trending ranges, with a combined average elevation of

~5000 m asl ([Fielding et al., 1994](#)), composed of a complex assemblage of rocks of different ages. The Himalayan–Tibetan orogen now stretches ~2000 km and ~1500 km in an east–west and north–south direction, respectively, the main ranges comprising, from south to north, the Siwaliks, Lesser Himalaya, Greater Himalaya, Transhimalaya, Nyaingentangha Shan, Tanggula Shan, Bayan Har Shan, Kunlun Shan, Altun Shan and Qilian Shan. In addition, the active mountains of the Pamir, Tian Shan and Altai Mountains are also part of the orogen ([Fig. 1](#)). However, we do not discuss the Altai Mountains in this paper as we do not consider them contiguous with the main mountain mass, and so these regions are beyond the scope of this paper.

The mid-latitude westerlies and the south Asian monsoon are the two dominant climatic systems influencing the region ([Benn and Owen, 1998](#); [Fig. 2](#)). As [Lehmkuhl and Owen \(2005\)](#), [Owen and Benn \(2005\)](#), [Owen et al. \(2008a\)](#) and [Owen \(2009\)](#) highlight, numerous studies have attempted to link long-term (thousands of years) variations in these climatic systems, influenced by changes in Northern Hemisphere insolation, and shorter-term variations (years to decades), explained by changes within the climate system, to mountain glacier fluctuations throughout the Quaternary.

The two climatic systems vary spatially with the majority of the southern and eastern regions experiencing a pronounced summer precipitation maximum, reflecting moisture advected northwards from the Indian Ocean by the southwest monsoon. Summer precipitation declines sharply northward across the main Himalayan chain and is very low over western Tibet ([Benn and Owen, 1998](#); [Owen, 2009](#)). The mid-latitude westerlies produce a winter precipitation maximum on the western end of the Himalaya, Transhimalaya and western Tibet as a consequence of moisture being advected from the Mediterranean, Black, and Caspian Seas ([Benn and Owen, 1998](#); [Owen, 2009](#)). These climate systems produce strong north–south and west–east precipitation gradients, as illustrated in [Fig. 3](#), ranging, for example, from one of the wettest places on Earth, the East Khasi Hills (with average annual

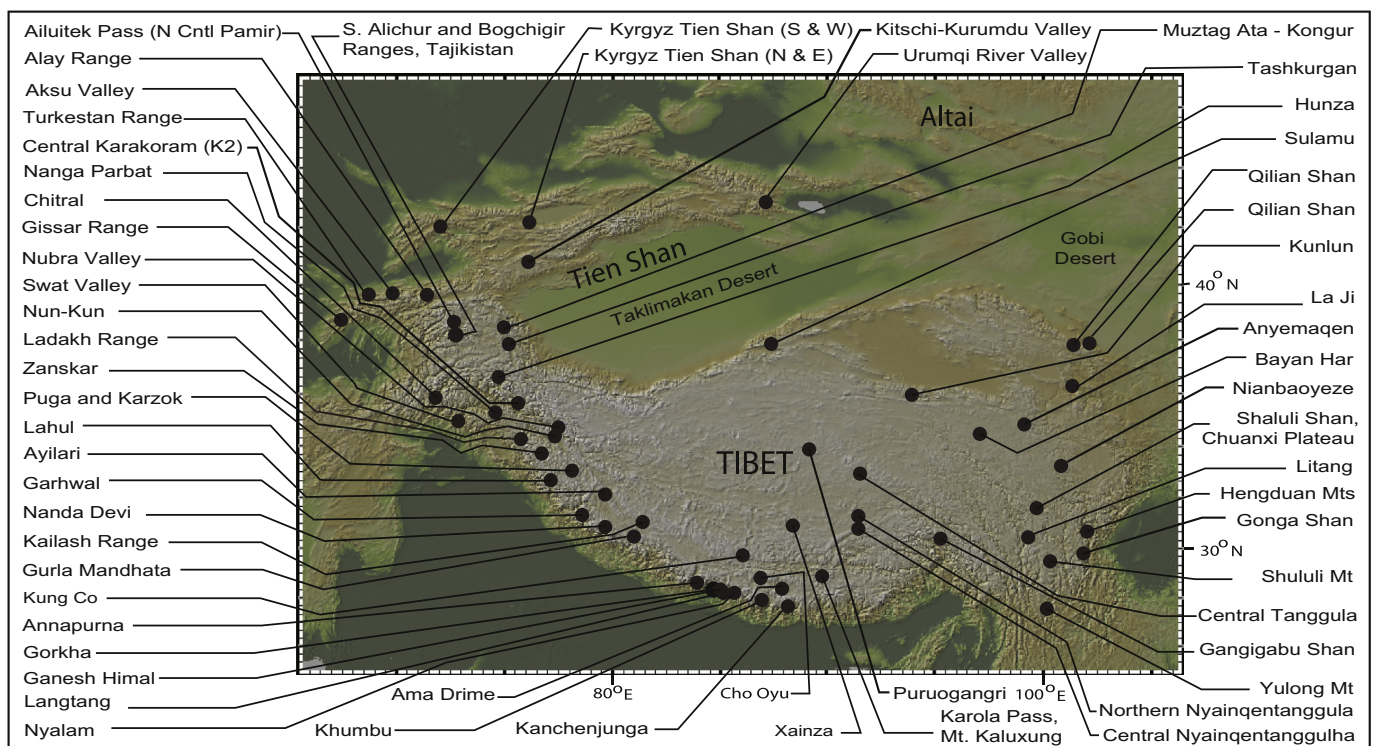


Fig. 1. Digital elevation model produced using GeoMapApp (<http://www.geomapp.org>) showing the area discussed in this paper.

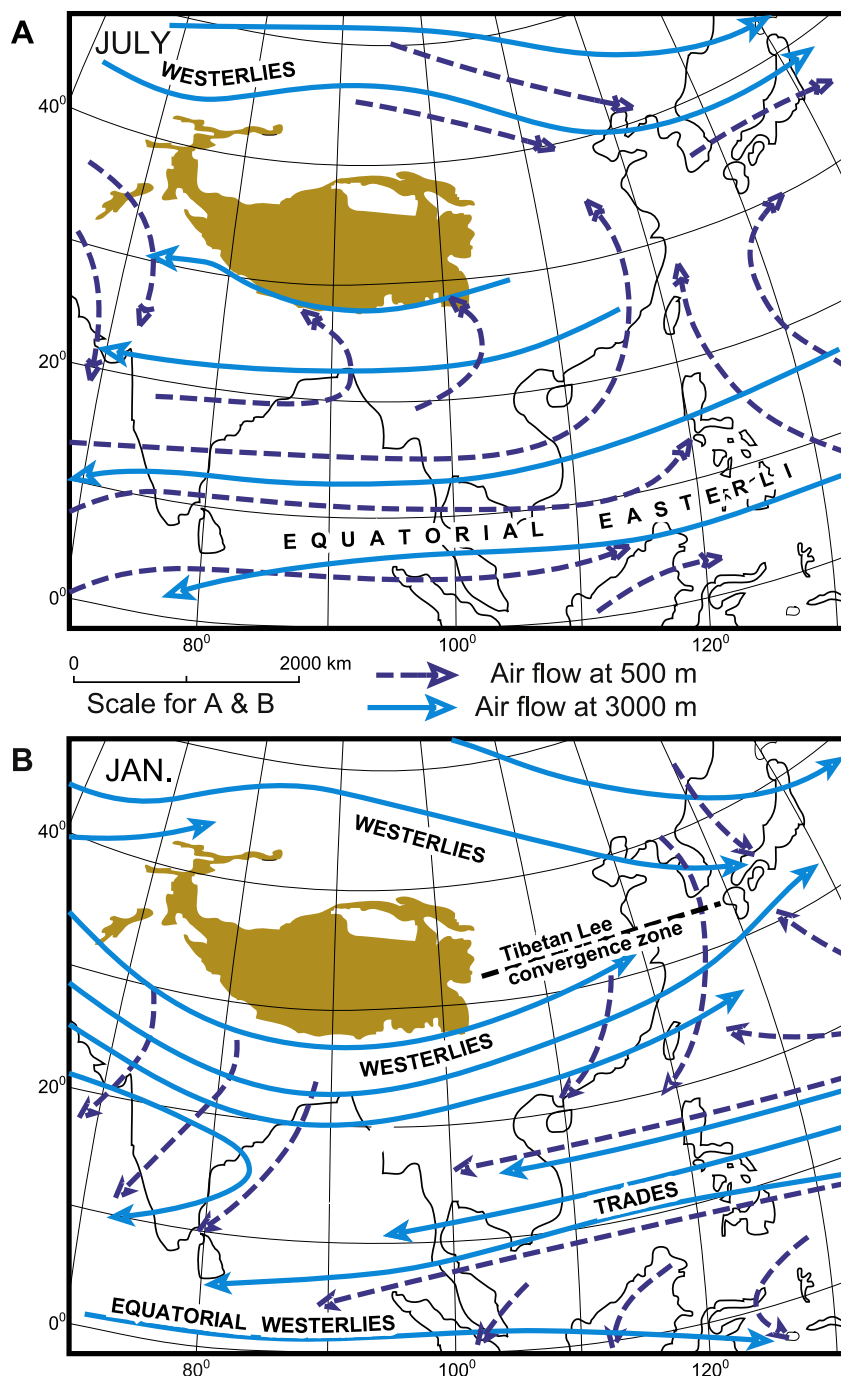


Fig. 2. Simplified views of characteristic summer (A) and winter (B) air circulation over southern and central Asia. The Tibetan Plateau and bordering mountains above 5000 m asl are shown within the areas shaded brown. The blue solid lines in (A) and (B) indicate airflow at about 6000 and 3000 m asl, respectively, and the dark blue dashed lines airflow at about 600 m asl (adapted from Owen and England, 1998; Benn and Owen, 1998; Barry and Chorley, 2003).

precipitation >12 m) to one of the driest, the hyperarid Takla Makan Desert; these gradients strongly influence the rate of a variety of surface processes including mass movements, fluvial incision, alluvial fan deposition, and glaciation (Bookhagen et al., 2005; Bookhagen and Burbank, 2006; Dortch et al., 2011a). There are also strong microclimatic variations within individual mountain ranges and valleys, potentially exerting strong controls over glaciation (Böhner, 2006; Dortch et al., 2011b). Benn and Owen (1998) hypothesized that the relative role of the two dominant climate systems, the south Asian monsoon and mid-latitude westerlies, varied

significantly throughout the Quaternary, resulting in asynchronous glaciation across the orogen. Trying to test this hypothesis has resulted in numerous studies in recent years, which will be discussed in more detail below.

Vegetation varies as a consequence of climate and altitude from thick subtropical forests in the foothills of the Himalaya and SE Tibet to deciduous forests at higher altitude and eventually alpine meadow and mountain tundra at the highest elevations with xerophytic vegetation in the arid interiors of the orogen. The equilibrium-line altitudes (ELAs) for glaciers across the orogen vary

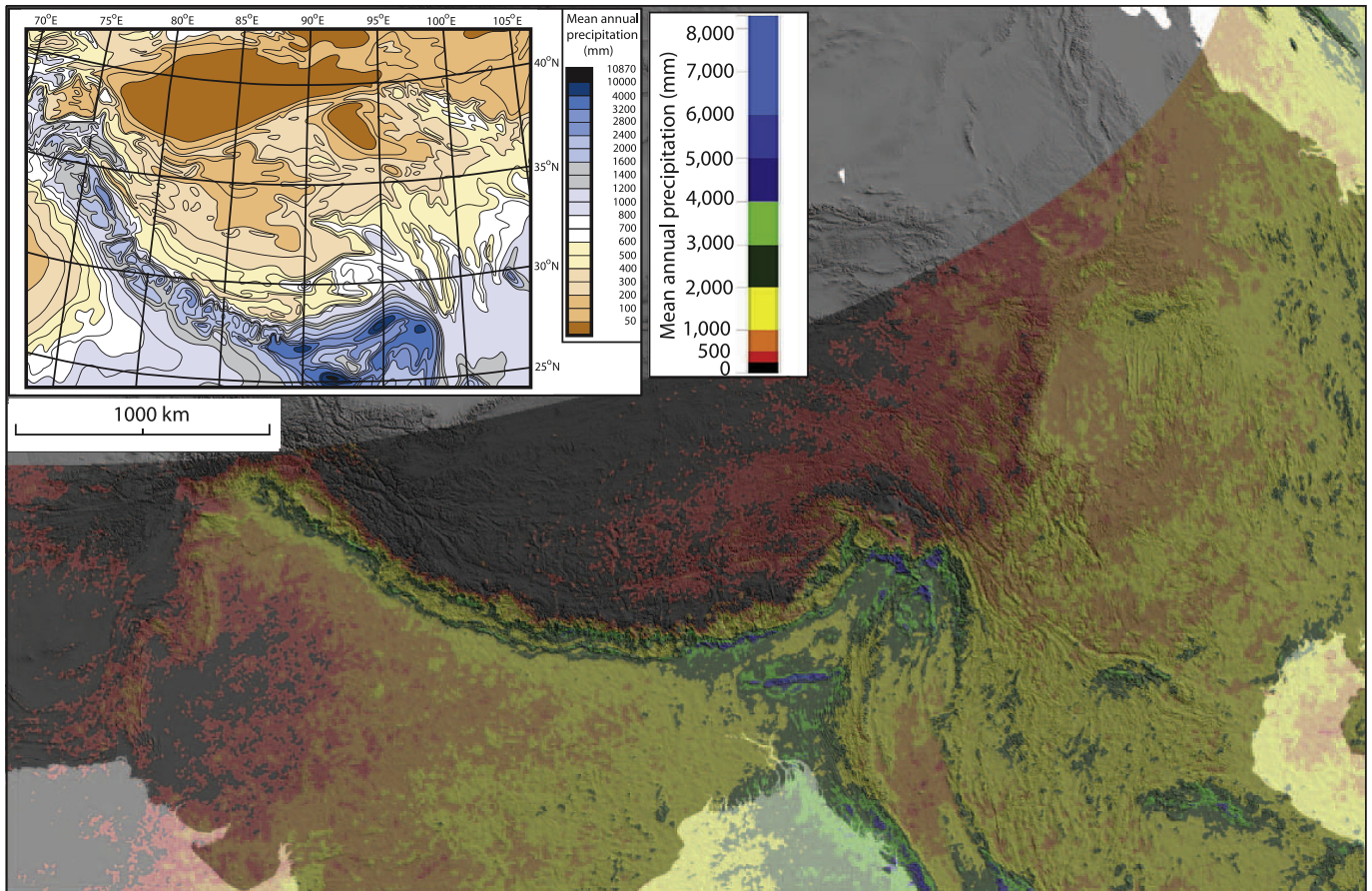


Fig. 3. Precipitation maps with the TRMM data drapped over the DEM with 36% opacity. Units are in mm/a and are averaged over 12 years (1998–2009). From data product 2B31, a combined Precipitation Radar (PR)/TRMM Microwave Imager (TMI) rain-rate product with path-integrated attenuation at 4 km horizontal and 250 m vertical resolutions (Bookhagen and Burbank, 2006, 2010). The inset map (from Owen et al., 2005) shows a larger area to compensate for the regions not covered by TRMM data.

considerably as a consequence of the different roles of the two main climatic systems and the precipitation gradients, for example, ranging from 4300 m asl in southeast Tibet to over 6000 m asl in western Tibet (Owen and Benn, 2005). Benn and Lehmkuhl (2000) and Owen and Benn (2005) describe the controls on mass balance and variation of present and past ELAs through the Himalaya and Tibet. Owen and Benn (2005) highlight that the present regional ELA varies in altitude across ranges; for example, it is 4600–5700 to 6000–6200 m asl south to north across Mount Everest, 5200–5700 m asl south to north across the Garhwal Himalaya, 4500–4700 m asl around Nanga Parbat, and 4600–5300 to 5200–5700 m asl south to north across the Karakoram Mountains.

Climate and topography have a strong influence on the nature of glacial systems throughout the Himalayan–Tibetan orogen. In essence, glacial systems are highly variable. Derbyshire (1982) divided the glaciers into three main types: 1) continental interior types in the central and western parts of the Tibet Plateau; 2) maritime monsoonal types in the Himalaya and in southeastern Tibet; and 3) continental monsoonal types in eastern and north-eastern Tibet (Fig. 4). As Owen and Benn (2005) point out, most glaciers within the region occupy steep, high relief catchments, and have cold, high altitude (>5000 m asl) accumulation areas. Where mass turnover is high, or where debris cover allows glaciers to descend to lower altitudes, ablation zones may be temperate whereas glaciers located in dry high altitude environments are cold throughout. Annual temperature cycles vary with the degree of continentality, altitude and insolation.

The maritime and continental monsoonal glaciers of the Himalaya and southeastern and eastern Tibet are warm-based and have summer accumulation and ablation; they are also highly diverse, including avalanche- and snowfall-fed cirque and valley glaciers, and very steep hanging glaciers (Derbyshire, 1981; Benn and Lehmkuhl, 2000; Benn and Owen, 2002). Benn and Owen (2002) emphasized that snow avalanching from precipitous slopes forms an important component of accumulation on many of these glaciers, and glacier ablation areas can be separated from source areas by steep icefalls or avalanche tracks. These are usually high activity glaciers that may have velocities up to several hundred meters per year (e.g. Seong et al., 2009d). Basin topography, therefore, plays an important role in determining the geometry and mass balance of these monsoonal glaciers.

Alpine continental glaciers in the western part of the orogen (Transhimalaya, Pamir, and Tian Shan) are significantly smaller than their monsoonal counterparts and are generally low flux due to an annual precipitation typically <1000 mm combined with high and cold accumulation areas. In spite of this, they produce landforms (roche moutonnées and large moraines) indicating mixed based if not warm based conditions at times (Koppes et al., 2008; Dortch et al., 2010, 2011b,c; Röhringer et al., 2012). In contrast, the continental ice caps of central and western Tibet have basal ice temperature «0 °C and they have an annual precipitation «1000 mm (at altitudes >5000 m asl). The Guilya icecap, for example, has an ice temperature of –18 °C and has an annual precipitation of 300–400 mm (Shi, 1992). Shi (1992) noted that

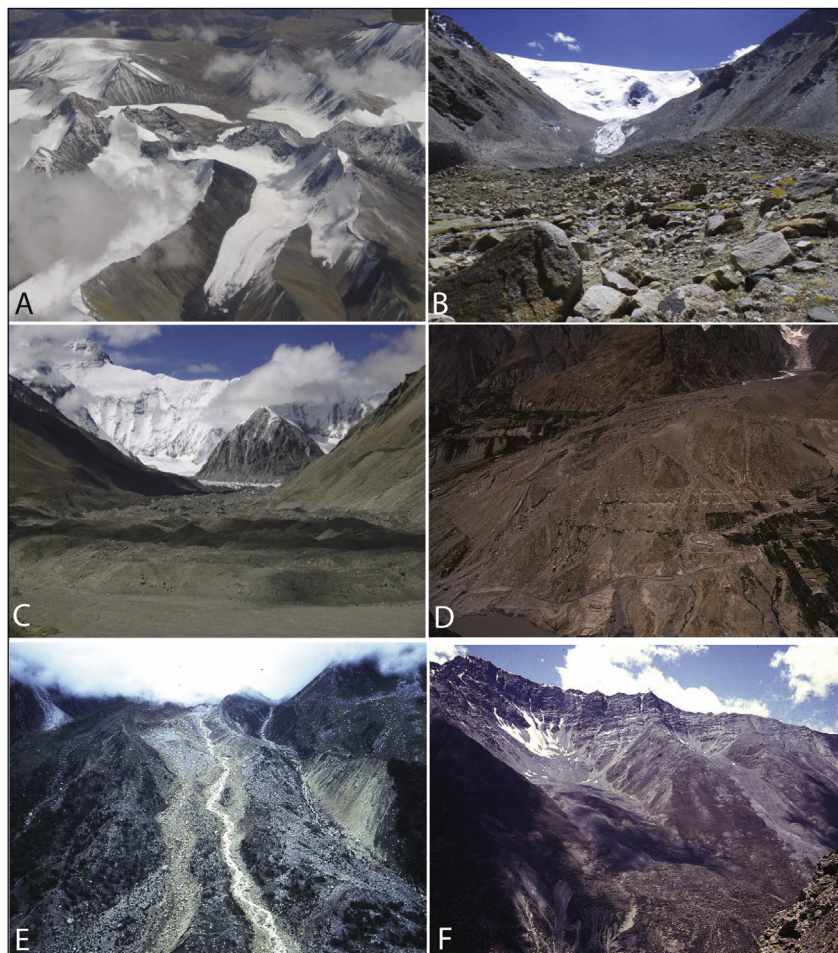


Fig. 4. Glaciers of the Himalayan–Tibetan orogen. A and B) Small valley polar-type continental glaciers in the Zaskar Range of northern India. C) Rongbuk glacier in Tibet and its end moraine on the northern slopes of Mt. Everest. D) Ghulkin glacier in the Karakoram Mountains of Northern Pakistan showing an impressive laterofrontal moraine complex in the fore and middle ground and the accumulation area in the top right of the photograph. E) Maritime-type monsoonal influenced unnamed glacier in the Bhagarathi valley in the Garhwal Himalaya of Northern India. The contemporary laterofrontal moraines and outlet glaciofluvial stream is inset into an older laterofrontal moraine complex. F) Morainic rock glacier in the Milang Valley in Lahul Himalaya of Northern India. The very last remnants of glacial ice can be seen in the top left part of the photograph.

these continental glaciers are similar to sub-polar types, with low surface velocities, usually between 2 and 10 m/a, and may extend outside the permafrost zone. In addition, these glaciers are usually less topographically constrained and generally have limited debris cover compared to those in the Himalaya (Owen and Benn, 2005).

Benn and Owen (2002) provided a review of Himalayan glacial sedimentary systems, describing the complexity of associated landform and lithofacies, and the importance of erosional, depositional and deformational processes. They showed that many Himalayan glaciers have extensive mantles of supraglacial debris on their ablation zones, whereas others have little or no supraglacial debris; a spectrum of glacier types exists between these end members. Benn and Owen (2002) reasoned that the amount of debris cover on glacier surfaces is controlled by a number of factors, the most important of which is the distribution of steep slopes in the glacial catchment from which avalanches can deliver rock debris, either from bedrock or pre-existing glacial and paraglacial sediments. Other factors influencing debris cover include: (1) precipitation, which governs the amount of snowfall relative to rock inputs, and hence the debris concentration on the ice; (2) glacier size (long valley glaciers are most likely to have extensive debris mantles); and (3) bedrock erodibility (resistant, massive rocks such as granite will yield much less debris than highly fractured schists and sedimentary rocks). The abundance of

supraglacial debris helps produce complex latero-frontal moraines that may record one or more glacial oscillations (Fig. 4D and E). Other important studies of the glacial sedimentary system include those of Derbyshire (1981, 1982, 1984), Li et al. (1984) and Owen and Derbyshire (1989).

Supraglacial debris may be so dominant in some glaciated catchments that morainic rock glaciers develop (Owen and England, 1998; Fig. 4F). Protalus rock glaciers may also form in permafrost regions (Owen and England, 1998; Fort, 2003; Iwata et al., 2003). Owen and England (1998) showed that, in the Karakoram and Himalaya of Northern Pakistan and India, morainic and protalus rock glaciers are restricted altitudinally and climatically to sites above ~4000 m asl and in regions where annual precipitation is <1000 mm. Generally in these regions, morainic rock glaciers are large, usually >1 km long, >100 m wide and >15 m thick. Owen and England (1998) suggested that morainic rock glaciers record the advance of ice-cored moraines following retreat of glaciers, likely since the Little Ice Age.

3. Reconstructing past glaciations in the orogen

Many researchers throughout the twentieth century and increasingly over the last few decades have reconstructed the extent of Late Quaternary glaciation throughout the Himalayan–

Tibetan orogen. Important compilations and reconstructions of glaciation throughout the orogen include those of Klute (1930), Frenzel (1960), Li et al. (1991) and Shi (1992), which show expanded ice caps and extensive valley glaciers (Fig. 5). The studies of Klute (1930) and Frenzel (1960) are remarkable given the limited studies that were available to these researchers. The most recent reconstructions by Li et al. (1991) and Shi (1992) represent an impressive compilation of studies and are in general agreement with most recent research showing alpine-style glaciation throughout the region during the last few glacial cycles. Numerous field studies provide regional maps of reconstruction (e.g. Porter, 1970; Derbyshire et al., 1984; Cronin et al., 1989; Holmes and Street-Perrott, 1989; Watanabe et al., 1989; Shiraiwa and Watanabe, 1991; Lehmkuhl and Lui, 1994; Osmaston, 1994; Owen et al., 1995, 1996, 1997, 2000; Taylor and Mitchell, 2000; Lehmkuhl et al., 2004; Heyman et al., 2010, 2011a,b). Most recently, remote sensing has enabled very impressive glacial geologic maps to be reconstructed, notably by Duncan et al. (1998), Heyman et al. (2008), Morén et al. (2011) and Fu et al. (2012).

In contrast to most studies, Kuhle (1985, 1986, 1987, 1988a,b, 1990a,b, 1991, 1993, 1995) argued for an extensive ice sheet covering most of the Tibetan Plateau during the Last Glacial. However, much evidence has been presented against the possibility that an extensive ice sheet could have existed across Tibet during the last 500 ka (Derbyshire, 1987; Burbank and Kang, 1991; Derbyshire et al., 1991; Shi et al., 1992; Hövermann et al., 1993a,b; Lehmkuhl, 1995, 1997, 1998; Rutter, 1995; Lehmkuhl et al., 1998; Zheng and Rutter, 1998; Schäfer et al., 2002; Owen et al., 2003a, 2008a; Seong et al., 2008; Dortch et al., 2013). In particular, Lehmkuhl et al. (1998), Owen et al. (2008a), Seong et al. (2008), and Owen (2010) argue that Kuhle's (1985, 1986, 1987, 1988a,b, 1990a,b, 1991, 1993, 1995) reconstructions likely differ from other researchers because of his misinterpretation of landforms and sediments, the misuse of ELAs for defining former ice extent, and poor chronological control. Specifically, numerical dating that has been undertaken in Tibet shows that moraines for the majority of the most extensive glacial advances formed early in the Last Glacial, the penultimate glacial cycle or much earlier, proving that an ice sheet could not have existed during the Last Glacial, otherwise the moraines would have been destroyed. In an attempt to try to reconcile this evidence with his model for an ice sheet over Tibet, in contrast to all the other research being undertaken with radiocarbon, OSL and TCN dating in the Himalayan–Tibetan orogen and other high mountain regions, Kuhle (2011) dismisses numerical dating, arguing that numerical dating cannot be applied at high altitudes as it is at lower elevations. He argues that all radiometric ages need calibrating to make ages 1/6th or 83% younger than published ages to fit his ice sheet model. However, his conversion factor arguments are spurious, there being no validity to his suggestions. Ironically, this now resolved controversy with Kuhle (1985, 1986, 1987, 1988a,b, 1990a,b, 1991, 1993, 1995) has left the idea for an ice sheet over Tibet firmly out of favor but it may have been possible, although highly unlikely, for an ice sheet to form over Tibet during the early- to mid-Quaternary. Surficial glacial landforms of this period have not been identified, but further insight might come from marine and lake core stratigraphy.

Clearly, accurate reconstructions of former glacial extent rely on the sound interpretation of landforms and sediments as well as geochronology. In particular, researchers such as Derbyshire (1983, 1996), Owen and Derbyshire (1988), Fort (1986), Fort and Derbyshire (1988), Derbyshire and Owen (1990, 1997), Hewitt (1998, 1999), Benn and Owen (2002) and Hewitt et al. (2011), have warned of the dangers of misinterpreting glacial and mass movement landforms in the Himalaya and Tibet. Large landslides

are common throughout the Himalayan–Tibetan orogen and their forms can often resemble moraines (Fig. 6). In addition, a continuum of landforms including moraines, rock glaciers, talus slopes and landslides exists that exacerbates the problems of distinguishing landform types (Owen, 1991; Fort, 2003). Moreover, intense fluvial and glacial erosion often destroys diagnostic morphologies of glacial and mass movement landforms, making their identification difficult (Owen, 1991; Benn and Owen, 2002). Furthermore, the diamictos that comprise mass movement and glacial landforms look very similar and have similar particle size distributions and particle shapes. All this makes it very challenging to identify landforms and sediments correctly unless sediments are examined with due care.

Hewitt (1998, 1999) and Hewitt et al. (2011) provide important examples from the Karakoram of Northern Pakistan where landslides have been misidentified as moraines (Fig. 7). Unfortunately, few papers provide detailed descriptions of the landforms and sediments that are used to reconstruct former glacier extents. This makes it difficult to fully assess the validity of many of the reconstructions. Benn and Owen (2002) provide a useful overview to help researchers recognize the problems associated with identifying landforms and sediments in Himalayan environments and suggest approaches to accurately interpret the glacial geomorphic and sedimentological evidence.

Most detailed reconstructions of former glacial extents within individual study areas apply standard morphostratigraphic methods similar to those outlined in Rose and Menzies (1995). In essence, glacial and associated landforms are mapped, based on their morphostratigraphic positions and the relative weathering of their forms and surfaces in each detailed study area. Often this is made easy because large relief within a landscape helps to separate moraines of different glacial advances at different altitudinal positions. Relative dating methods have included the use of soil development (Guggenberger et al., 1998; Bäumler et al., 1999; Zech et al., 2000), and weathering characteristics and rock varnish development (Owen et al., 1996, 1997; Waragai, 1998, 2005). Commonly, researchers will assign a glacial stage name to a particular suite of glacial and associated landforms that they recognize to have formed during a distinct glacial advance (e.g. Derbyshire et al., 1984; Burbank and Fort, 1985; Seong et al., 2007; 2009b, Owen et al., 2003, 2012). Some studies provide type locations for a particular glacial stage, which may be used by future researchers as a basis for comparing and extending the glacial chronologies (e.g. Seong et al., 2009b; Owen et al., 2012). Other studies simply number moraines of different stages (e.g. Zech et al., 2005; Abramowski et al., 2006; Koopes et al., 2008; Hendrick et al., 2011) or provide no number or name at all (e.g. Kong et al., 2009b). Applying glacial stage names or a numbering scheme allows landforms to be tentatively correlated across a study region and between adjacent regions before a quantitative chronostratigraphy has been established; however, correlation based on the number of stages in a sequence without a chronostratigraphy based on numerical dating should be undertaken with extreme caution. Most recent studies are applying the approach described by Hughes et al. (2005) to develop formal stratigraphies. Fig. 8 shows an example of the morphostratigraphic approach that has been applied to glacial successions within one valley of the Himalayan–Tibetan orogen.

Once a morphostratigraphy has been developed, it can form the framework for numerical dating to help define the timing of each glacial advance/glacial stage. The application of numerical dating will be discussed in detail in the next section. Detailed mapping is also commonly used to reconstruct the size of former glaciers as a basis for determining former ELAs (Benn and Lehmkuhl, 2000; Benn et al., 2005; Owen and Benn, 2005).

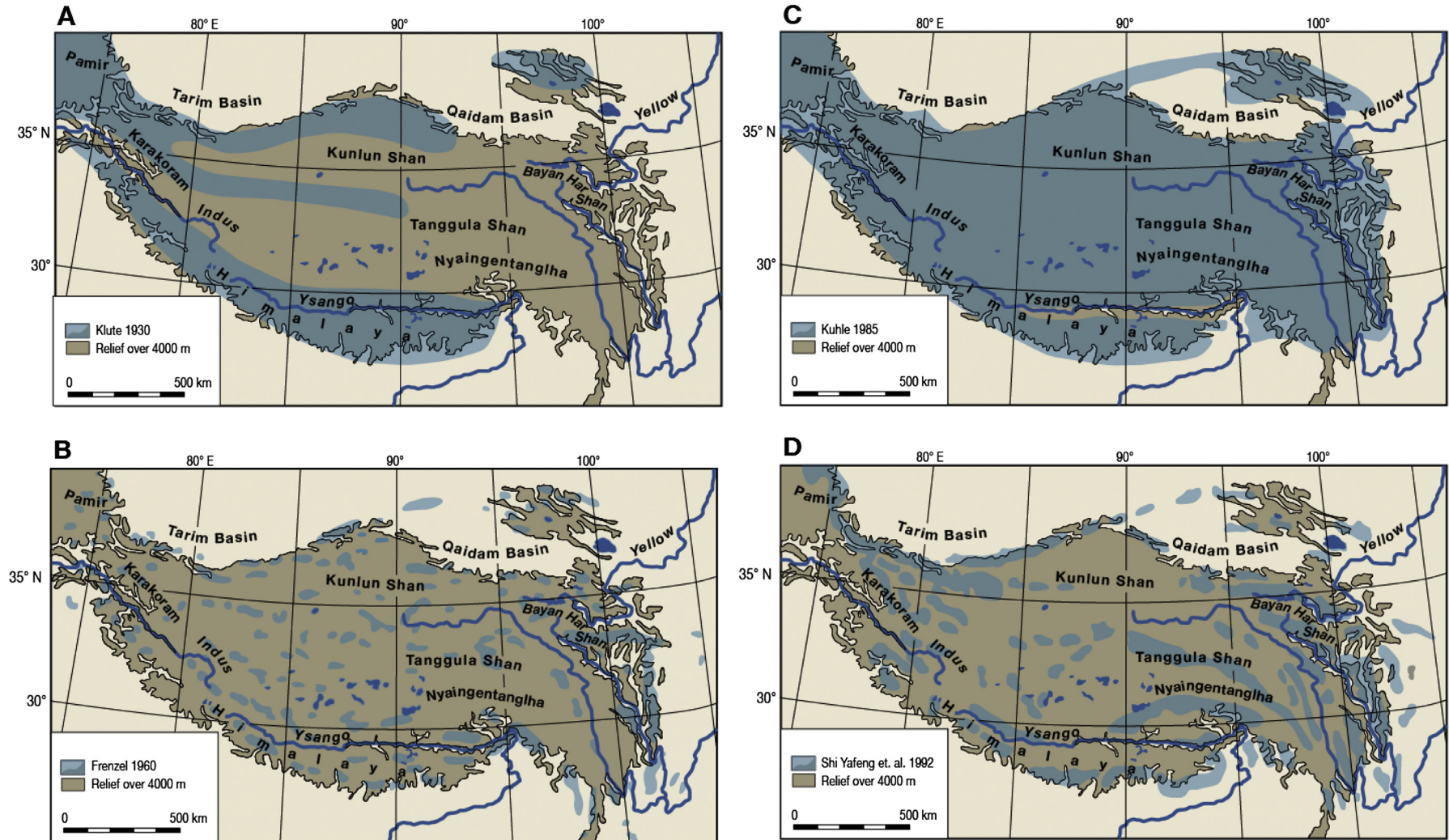


Fig. 5. Selected reconstructions for the maximum extent of glaciation during the Last Glacial across Tibet and the bordering mountains (from Owen et al., 2008a; Owen, 2010). Light brown, relief over 4000 m above sea level; dark blue–gray, areas considered glaciated. A) Klute's (1930) reconstruction based on a temperature depression of $\sim 4^\circ\text{C}$, with a shift of climatic zones to the south and an intensification of atmospheric circulation such that precipitation increased towards the dry areas of central Asia. B) Frenzel's (1960) reconstruction based on the detailed work of Von Wissmann (1959), who evaluated the observations of the earliest explorers. C) Kuhle's (1985) reconstruction based on field observations and extrapolation of large equilibrium-line altitude depressions ($>1000\text{ m}$) from the margins of Tibet into the interior regions. D) Reconstruction of Shi (1992) and Li et al. (1991) based on detailed field mapping of glacial and associated landforms and sediments.

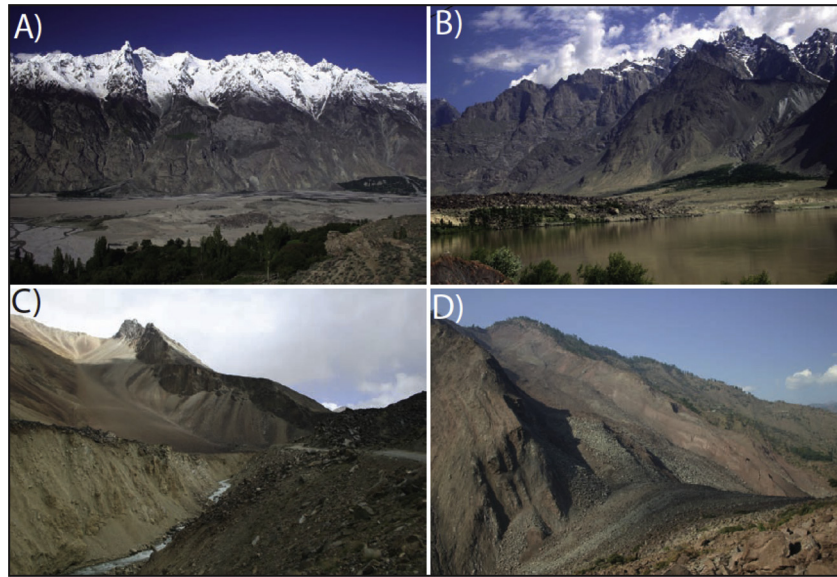


Fig. 6. Examples of large runout landslides in the Himalaya and Karakoram. A) The Goro Cho rock avalanche in the Shigar valley, Karakoram, Northern Pakistan, dated by radiocarbon to ~ 7.1 ka by Hewitt (1999) and by ^{36}Cl to Lateglacial through early Holocene by Shroder et al. (2011). B) Katzarah landslides in the Indus valley of the Karakoram, Northern Pakistan mapped and studied by Hewitt (1999) and dated by Hewitt et al. (2011) to ~ 7.8 ka using ^{10}Be . C) The Kelang Serai landslide in the Lahul Himalaya dated by ^{10}Be to 6.6 ± 0.4 ka by Dortch et al. (2009). D) The Hattian Bala landslide triggered by the 2005 Kashmir earthquake. The landslide buried four villages resulting in ~ 450 fatalities (described in Dunning et al., 2007 and Owen et al., 2008b).

4. Dating methods: challenges and advances

Much effort has been undertaken in recent years to define the timing of glaciation throughout the Himalaya and Tibet but, until the turn of the millennium, few studies presented numerical ages for glacial successions in the Himalayan–Tibetan orogen. Gillespie and Molnar's (1995) review of the timing of mountain glaciation throughout the world, and its asynchronicity with continental glaciers, highlighted the paucity of data for the Himalayan–Tibetan region. Similarly, Benn and Owen's (1998) review and speculation on the relative roles of the summer monsoon and mid-latitude westerlies in driving Himalayan–Tibetan glaciation emphasizes the dearth of numerical ages.

The former lack of numerical ages mainly resulted from a scarcity of organic material needed for radiocarbon dating in most regions. Where organic material was present, $\sim 95\%$ (142 of 149) of ages were limited to the Holocene. This is illustrated by the compilation of radiocarbon dating we present in Table 1 and Fig. 9.

Röthlisberger and Geyh (1985a,b) undertook an extensive study using radiocarbon dating (including 68 radiocarbon ages). They examined eight different regions throughout the Himalaya and Karakoram of Pakistan, India and Nepal to show that glaciers had undergone at least 11 advances since the global Last Glacial Maximum (LGM) (Fig. 9A). However, only relatively modest studies have been undertaken using radiocarbon dating since the work of Röthlisberger and Geyh (1985a,b). Most studies have dated charcoal or wood (e.g. Benedict, 1976; Fushimi, 1977, 1978; Derbyshire et al., 1984; Geyh et al., 1985; Röthlisberger and Geyh, 1985a,b; Zheng and Li, 1986; Wang and Fan, 1987; Zhang, 1988; Zheng and Ma, 1994; Chinese Academy of Sciences, 1996; Narama, 2002; Su et al., 2002; Meyer et al., 2009; Lee et al., 2014), but many have used humic matter (Li and Jiao, 1990; Li and Li, 1992; Iwata and Jiao, 1993; Jiao and Iwata, 1993; Zheng et al., 1995; Owen et al., 1997; Iwata et al., 2002; Jiao et al., 2005; Jiao and Zheng, 2006; Zheng, 2006). Carbonate precipitates have also been dated but these are subject to large uncertainties because of hardwater effects; also the carbonates may have developed significantly later than the

formation of the landform that is being dated yielding very minimum ages (e.g. Mann et al., 1996; Yi et al., 2004).

Yi et al. (2008) reviewed much of the radiocarbon dating Holocene glacial chronologies for Tibet and the surrounding mountains. They compiled 58 ages, but notably omitted the studies of Röthlisberger and Geyh (1985a,b). In addition, Yang et al. (2008) reviewed the radiocarbon dating undertaken to establish the Late Holocene monsoon temperate glacier fluctuations on the Tibetan Plateau. Building on these compilations, we compile the radiocarbon ages for studies throughout the Himalayan–Tibetan orogen and present these in Table 1 and Fig. 9. We plot minimum radiocarbon ages, i.e. ages that are younger than the age of the moraine that is being dated, which are then used to calculate a probability distribution density graph. This allows us to determine whether these age data define the timing of glacial oscillations throughout the Late Quaternary, since the peaks of the probability distributions likely represent revegetation of the glacial foreland, which is assumed to approximate the time of deglaciation. The frequency of peaks is similar to those of the Holocene rapid climate change as suggested by Mayewski et al. (2004). However, this similarity relies on the assumption that glaciations dated by radiocarbon methods are synchronous throughout the orogen. This assumption needs to be tested in future radiocarbon-based studies by targeting Holocene landforms in several climatic regions of the orogen.

Following the significant developments in OSL and TCN surface exposure dating during the 1990s and early 2000s, numerous researchers began to apply these methods throughout the Himalayan–Tibetan orogen. OSL methods were applied before TCN methods, initially using thermoluminescence (TL; e.g. Derbyshire et al., 1984). The first extensive program of OSL dating in the Himalaya was undertaken by Richards (1999) resulting in detailed studies in the Khumbu Himal, Nepal (Richards et al., 2000b), and the Swat and Nanga Parbat regions in Northern Pakistan (Richards et al., 2000a). Other significant studies using OSL include those of Tsukamoto et al. (2002) in the Kanchenjunga Himalaya, Derbyshire et al. (1984) and Spencer and Owen (2004) in the Hunza valley of northern Pakistan, Narama et al. (2007) in the Terskey Alatau Range

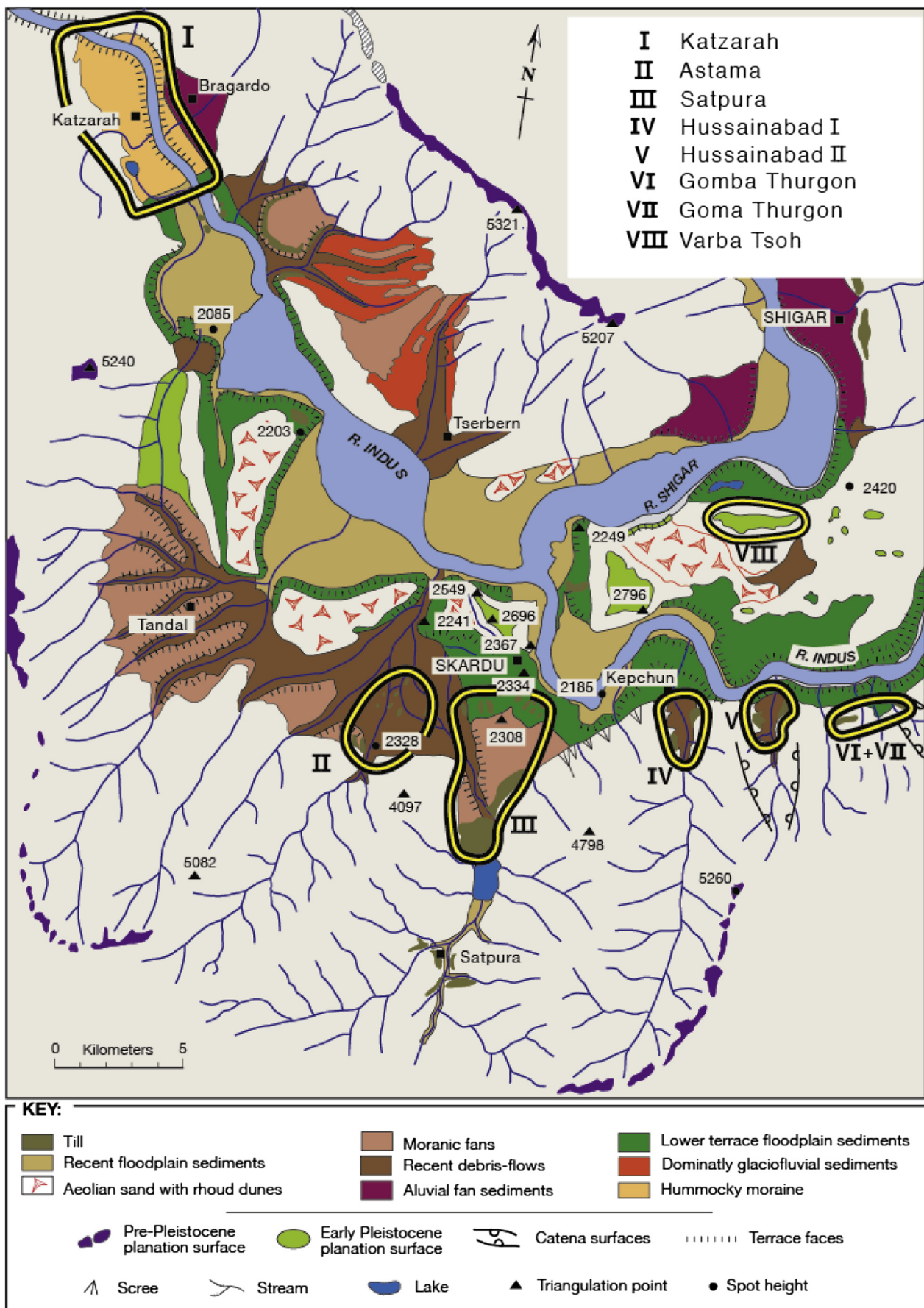


Fig. 7. Geomorphology of the Skardu Basin, Karakoram Mountains, Northern Pakistan (after Owen, 1988). Hewitt (1998, 1999, 2011) argues that some of the mapped moraines are long runout landslides; these are highlighted by the golden ellipses numbered I–VIII (adapted from Kamp and Owen, 2011).

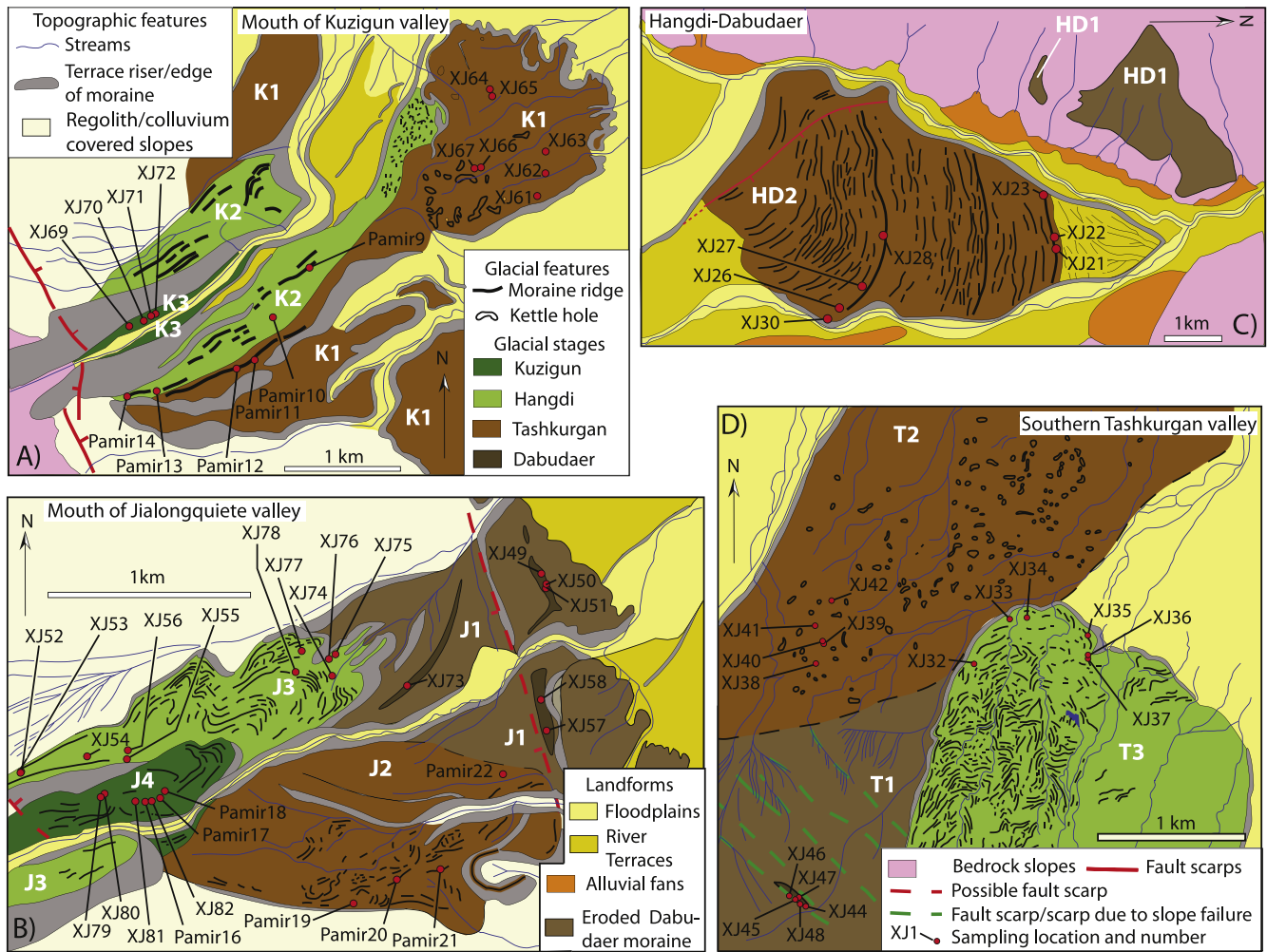


Fig. 8. Examples of geomorphic maps produced by Owen et al. (2012) for developing a morphostratigraphy in the Tashkurgan valley of the Chinese Pamir. A) through D) are individual study areas within the valley. The legends are separated into feature types in different panels, but refer to all panels. The large white text on each moraine is the relative assignment of glacial ages to the landforms. The letters K, J, HD and T refer to the study areas (e.g. K = Kuzigun study area) and the numbers refer to the relative ages (1 being the oldest age glacial landform in the particular study area). Sampling points for ^{10}Be TCN dating are shown to help illustrate a typical strategy for dating. The ^{10}Be ages for these samples are shown in Fig. 12.

(Kyrgyz Republic), and Narama et al. (2009) and Zhao et al. (2012) in the Tien Shan. Richards (2000) discusses the problems associated with the application of OSL methods in the Himalaya, which include those associated with inadequate bleaching of sediment and low luminescence signals (see Fuchs and Owen (2008) for more details about OSL dating of glaciogenic sediments). Table 2 summarizes the OSL dating studies that have been undertaken throughout the Himalayan–Tibetan orogen.

Another potentially important technique, electron spin resonance (ESR) dating has been undertaken in a few areas (e.g. Wu et al., 2001; Zhao et al., 2009, 2012). Researchers using ESR contend that the ESR signal is reset in till by pressure during glacial grinding. However, there is much contention over whether this mechanism can fully reset the ESR signal and, as such, ESR ages should be considered very conservatively.

Arguably, TCN dating has been applied more to the Himalayan–Tibetan glacial successions than any other glaciated mountain region in the world. Currently, for example, there are >1700 ^{10}Be ages on moraine boulders in addition to numerous glacially eroded bedrock surfaces, plus boulder ages and depth profiles on associated landforms. Table 3 lists the ^{10}Be -defined chronologies throughout the Himalayan–Tibetan orogen and Appendix 1

presents all the ^{10}Be ages. Most TCN studies use ^{10}Be for dating, but ^{26}Al has also been applied, usually on the same sample that is being dated with ^{10}Be (e.g. Owen et al., 2001, 2002a, 2003b,c; Schäfer et al., 2002; Tschudi et al., 2003). In addition, ^3He and ^{21}Ne have been applied in several studies (Tschudi et al., 2003; Gayer et al., 2006; Graf et al., 2008; Schäfer et al., 2008; Strasky et al., 2009).

Problems associated with the application of TCN methods to date moraines in the Himalaya, Tibet and elsewhere, have been discussed in depth in numerous studies (e.g. Hallet and Putkonen, 1994; Aoki and Imamura, 1999; Schäfer, 2000; Benn and Owen, 2002; Brown et al., 2002; Owen et al., 2002a, 2003a,c, 2005, 2006a,b, 2008a, 2009, 2010, 2012; Putkonen and Swanson, 2003; Putkonen and O'Neal, 2006; Seong et al., 2007, 2009a; Putkonen et al., 2008; Dortch et al., 2010b; Chevalier et al., 2011; Heyman et al., 2011b). In particular, Owen et al. (2008a), examining 777 published ages, highlighted the uncertainty introduced when calculating TCN ages for Himalayan and Tibetan glacial successions using different scaling models and that this may result in ages that differ by as much as 30% (see Figs. 5 and 6 in Owen et al., 2008a). Here, updated plots including the now >1700 published ages from the orogen show that ages from various researchers differ by up to ~40% from recalculated Lal (1991) – Stone (2000) time

Table 1
Summary of major radiocarbon dating studies for the Himalayan–Tibetan orogen.

Area	Location	Latitude (°N)	Longitude (°E)	Altitude (m asl)	Dated material and geomorphic context	Age in relation to glacial advance	Radiocarbon age (years)		Calibrated age (cal years BP) ^a			Source
								Uncertainty	From	To	%	
Pamir	Ayizhisu River, trib of Wuyitak River, northern slope of Kongur Peak	~38.7 ^b	75.3 ^b	2700 ^b	Wood root in terminal moraines	Younger	110	50	277	8	95.4	Ono et al. (1997)
Tien Shan	Upper Urumqi River valley	43.12	86.82	~4200	Organic carbon coating on boulder	Younger	220	50	431	–4	95.4	Yi et al. (2004)
						Younger	390	120	652	–3	95.3	
					Organic coating on clast	Younger	420	150	676	–3	95.5	
						Younger	1860	100	2035	1545	95.4	
					Till matrix	Younger	6560	150	7700	7165	95.4	
						Contemporaneous	23,080	510	29,201	26,346	95.4	
Karakoram	Minapin Glacier, Hunza Valley	~36.25	~74.52	~2000	Wood in moraines	Contemporaneous	19,010	450	23,811	21,557	95.4	Derbyshire et al. (1984)
						Contemporaneous	19,590	130	23,856	22,691	95.4	
						Younger	325	60	505	158	95.4	
					Soil	Younger	685	45	694	553	95.4	
						Younger	2265	65	2453	2070	95.4	
						Older	90	85	285	...	95.4	
Nun Kun	Gargo Glacier, Gilgit Agency	36.04	74.6	~3100	Soil	Younger	585	80	676	504	95.4	Röthlisberger and Geyh (1985b)
						Older	3620	130	4381	3590	95.5	
						Contemporaneous	19,490	1630	28,473	19,896	95.4	
	Rantac Glacier	34.05	75.94	3100	Humic matter in superposed fossil soil on end moraine	Younger	15,570	770	20,828	17,054	95.4	
						Younger	2230	95	2485	1952	95.4	
						Older	3280	90	3816	3336	95.4	
					Humic matter in fossil soil on lateral moraine	Younger	2395	170	2843	2005	95.4	
						Younger	3630	105	4247	3642	95.4	
					Humic matter in organic horizon in loess on lateral moraine	Younger	4680	60	5583	5307	95.4	
						Younger	4860	60	5731	5469	95.4	
	Tarangoz Glacier	34.05	75.91	3900	Humic matter in fossil soil within lateral moraine	Younger	7405	185	8590	7862	95.4	
						Younger	12,750	190	16,216	14,189	95.4	
						Younger	1620	40	1607	1408	95.4	
Kashmir	Taragoz Glacier	75.91	34.05	3800	Buried soil in loess overlaying moraine	Younger	3150	40	3455	3265	95.4	Lee et al. (2014)
						Younger	4480	40	5298	4975	95.4	
						Older	2230	95	2485	1952	95.4	
					Soil	Older	2230	95	2485	1952	95.4	
						Younger	3280	90	3816	3336	95.4	

Lahul	Risla Glacier	76.01	33.63	3700	Soil	Older	7505	185	8750	7940	95.4	Owen et al. (1997)
					Soil	Younger	12,750	1909	21,950	10,733	95.4	
					Soil	Older	3210	80	3634	3261	95.4	
					Soil	Younger	3660	185	4520	3487	95.4	
					Soil	Older	2190	90	2354	1950	95.4	
	Kolohoi Glacier	75.32	34.27	3870	Soil	Younger	2440	60	2711	2352	95.4	
					Wood	Contemporaneous	2575	80	2844	2364	95.3	
					Soil	Older	2695	160	3210	2360	95.4	
					Soil	Younger	3490	100	4074	3482	95.4	
					Basal peat layer over moraine	Younger	9160	70	10,509	10,212	95.4	
Langtang Himal	Langtang Valley	28.2	85.5	~ 3700	Organic matter in soil on terminal moraines	Younger	550	70	665	500	95.4	Shiraiwa and Watanabe (1991)
Nepal	Gangapurna N. Glacier	84.01	28.64	3680		Younger	2800	110	3244	2741	95.4	Röthlisberger and Geyh (1985b)
						Younger	2850	140	3356	2745	95.4	
						Younger	2980	110	3399	2865	95.4	
						Older	3650	320	4868	3214	95.4	
					Wood (not in situ)	Younger	3860	110	4572	3929	95.4	
					wood in situ	Older	135	50	283	0	95.4	
						Older	1210	55	1274	986	95.4	
						Younger	2330	45	2666	2160	95.5	
						Older	2955	105	3373	2860	95.4	
						Younger	4560	280	5904	4522	95.4	
Khumbu Himal	Khumbu Glacier	27.9	86.8	~ 4600	Charcoal in outwash terraces associated with moraines	Younger	550	85	680	335	95.4	Benedict (1976)
					Charcoal and soil humates in outwash terraces associated with moraines	Younger	530	165	897	–2	95.3	
					Charcoal and shrub fragments in outwash sands associated with moraines	Younger	1155	160	1348	742	95.4	
					Wood in moraine	Younger	410	110	654	–2	95.4	Fushimi (1978)
						Younger	2640	170	3207	2342	95.4	
					Lateral moraine	Younger	480	80	653	317	95.4	Muller (1980)
	Khumbu 1 Glacier					Younger	1150	80	1262	931	95.4	
					Soil	Older	960	70	1050	728	95.4	Röthlisberger and Geyh (1985b)
	Khumbu 1 Glacier				Soil	Older	1310	115	1415	962	95.4	
					Soil	Older	1340	75	1380	1076	95.4	
					Soil	Older	1420	95	1538	1142	95.4	
					Soil	Older	1635	115	1813	1316	95.4	
					Soil	Younger	2215	165	2713	1873	95.4	
					Soil	Younger	2250	190	2749	1834	95.4	
					Soil	Younger	2540	145	2964	2208	95.4	
					Soil	Older	2625	125	2995	2355	95.4	
					Soil	Older	2665	160	3203	2352	95.4	
					Soil	Younger	3115	370	4294	2364	95.4	
					Soil	Younger	3290	550	5271	2314	95.4	
	Khumbu 2a Glacier				Plants	Younger	1150	80	1262	931	95.4	
	Khumbu 2b Glacier				Plants	Younger	480	80	653	317	95.4	
	Kyuwo 3 Glacier	no data			Wood	Contemporaneous	410	100	644	153	95.5	

(continued on next page)

Table 1 (continued)

Area	Location	Latitude (°N)	Longitude (°E)	Altitude (m asl)	Dated material and geomorphic context	Age in relation to glacial advance	Radiocarbon age (years)		Calibrated age (cal years BP) ^a			Source
								Uncertainty	From	To	%	
Bhutan Himalaya	Llotse Nup 1 Glacier	86.895	27.9225	5050	Charcoal	Younger	1200	100	1292	936	95.4	Iwata et al. (2002)
					Soil	Older	1025	110	1226	725	95.4	
					Soil	Older	1190	155	1384	789	95.4	
					Soil	Older	1630	155	1893	1279	95.4	
					Soil	Contemporaneous	3265	700	5576	1986	95.4	
	Nupse 1 Glacier	86.8727778	27.9277778	5170	Soil	Contemporaneous	3385	500	5213	2459	95.4	
					Soil	Younger	565	55	655	515	95.4	
					Soil		4745	730	7245	3700	95.4	
					Soil	Older	5575	500	7555	5323	95.4	
					Organics	Older	610	40	660	541	95.4	
	Llotse Shar 1 Glacier	86.95	27.91	5170								
					Soil	Older	775	110	922	553	95.4	
					Organics	Younger	1135	70	1242	928	95.4	
					Soil organic fragments	Younger	1205	55	1269	984	95.4	
					Soil	Older	1705	95	1860	1403	95.4	
					Soil	Younger	2195	160	2704	1830	95.4	
	Raphstheng Glacier, upper reaches of Lingshi Chu (River) and Goyok Chu	90	28	~4600	Humid soil buried in a terminal moraine	Younger	1710	40	1709	1535	95.4	
Everest	Rongbuk valley				Carbonate precipitate on clast	Younger	2120	40	2302	1992	95.4	Mann et al. (1996)
						Younger	3170	70	3563	3220	95.4	
Namche Barwa		29.63	95.63	2950	Wood in a terminal moraine in front of Zelongnong Glacier	Younger	287	93	514	–4	95.4	Zhang (1988), Chinese Academy of Sciences (1996)
						Younger	394	83	552	159	95.4	
Qilian Shan	Baishui River valley	~38.4	~98.7	~4500	Humic matter in buried soil interlayer in lower part of an overlapped terminal moraines	Younger	1481	134	1705	1094	95.4	Wu (1984a, b)
						Younger	2530	120	2856	2341	95.4	
						Contemporaneous						
	Dunde ice cap	~38.1	94.4	~4800	Humic matter in a lacustrine interlayer in a terminal moraines	Contemporaneous	3110	120	3607	2972	95.4	Li and Jiao (1990)
West Kunlun	Keliya and North glaciers, Chongce ice cap	~35.3	~81.5	~5600	Humic matter in a lacustrine interlayer in terminal moraines	Older	8455	265	10,194	8774	95.4	
							8134	176	9470	8605	95.4	Jiao and Zheng (2006)
East Kunlun	Guoluo Glacier, Bayanhar Mt.	~33	~101	4100	Humic matter 40–60 cm deep in two terminal moraines	Older	8287	160	9549	8776	95.4	Zheng et al. (1995)
						Younger	2540	110	2845	2349	95.4	
Tanggula	Gaerqu River	33	~101	~4100	Humic matter at the bottom of soil covering terminal moraines	Younger	4090	95	4850	4305	95.4	Jiao and Shen (2006) cited in Yi et al. (2008)
						Earlier than	2690	110	3140	2467	95.3	

Eastern Nyainqentanglha	Page Glacier	32	95	4200–4300	Lichen ages on three end moraines	Earlier than Minimum	5410 1809, 1857–1888, 1920	225	6674	5662	95.4	Li et al. (1986)
	Zepu Glacier	30.3	95.15	2960	Detrital wood, trees in moraines, charcoal and humic soil in moraines, Zepu Glacier	Minimum	190	80	430	–4	95.4	Jiao and Iwata (1993); Iwata and Jiao (1993); Jiao et al. (2005)
				3400		Younger	197	80	432	–4	95.4	
				3300		Younger	580	130	767	315	95.4	
				>3000		Younger	720	210	1120	306	95.4	
				>3000		Younger	950	120	1167	670	95.5	
				3200		Younger	1056	115	1256	737	95.4	
				>3000		Younger	1100	160	1305	725	95.4	
				>3000		Younger	1570	300	2302	923	95.4	
				>3000		Younger	3242	101	3716	3220	95.4	
	Arza Glacier	29.77	95.7	~ 3850	Wood in a lateral moraine, Arza Glacier	Younger	2980	150	3470	2785	95.4	Li et al. (1986)
				~ 3835	Tree branches buried in lateral moraine	Younger	1820	100	1987	1530	95.4	Wang and Fan (1987)
				~ 3820	Extreme growth of trees on lateral moraines	Younger	1813–1852, 18,884–1908, 1960					Wang and Fan (1987)
	Ruoguo Glacier	30.3	94.73	3960	Wood in a moraine, Ruoguo Glacier	Younger	1920	110	2143	1573	95.4	Li et al. (1986), Zheng and Li (1986)
				3880		Younger	1740	85	1870	1418	95.4	Li et al. (1986)
				3820		Younger	1540	85	1610	1295	95.4	Li et al. (1986)
				3640	Lichen dates on moraine	Younger	1822 AD					
	Bomi Glacier	29.77	95.7	4000	Age of trees	Contemporaneous	1580–1590, 1860–1890					Bräuning (2006)
	Laigu Glacier	29.33	96.8	~ 4000	Buried tree in lateral moraine	Contemporaneous/ maximum	1150	80	1262	931	95.4	Wang and Fan (1987)
	Luzi Glacier	not provided	not provided	5100	Humic matter in soil 1–2 m below the turf on the terminal moraine	Earlier than/ minimum	3050	100	3461	2961	95.4	Zheng (2006)
Qiangtang Plateau		32.61	89.77	~ 4900	Humic matter in an exposure of a terminal moraine, Gangzari Mt.	Contemporaneous	5760	170	7001	6212	95.4	Li and Li (1992)
Hengduan Mountains	Hailuoguo Glacier, Gongga Shan	29.6	101.95	2850	Wood in lateral and terminal moraines	Younger	150	60	288	–2	95.4	Li et al. (1986); Zheng and Ma (1994)
				2730		Younger	540	70	665	489	95.4	
				~ 3000		Younger	780	90	916	560	95.4	
				2930		Younger	940	50	933	740	95.4	
				~ 2900		Younger	1160	50	1234	960	95.4	
				3000		Younger	1550	80	1610	1300	95.4	
				2750		Younger	1580	60	1607	1345	95.4	
				~ 3000		Older	2170	110	2433	1877	95.4	
				~ 3000		Older	2350	65	2702	2159	95.3	
				2980		Younger	3080	80	3467	3065	95.4	
				~ 3050	Black clay at the bottom of lacustrine sediment	Older	8010	150	9396	8482	95.5	Zheng and Ma (1994)

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Table 1 (continued)

Area	Location	Latitude (°N)	Longitude (°E)	Altitude (m asl)	Dated material and geomorphic context	Age in relation to glacial advance	Radiocarbon age (years)	Calibrated age (cal years BP) ^a				Source
								Uncertainty	From	To	%	
	Diancangshan	25.67	100.09	3985	between two moraines Organic silt over laying moraines	Younger	1310	60	1315	1075	95.4	Yang et al. (2006)
		25.67	100.09	4041		Younger	1600	110	1769	1296	95.4	
		25.72	100.07	4021		Younger	3240	60	3615	3358	95.4	
		25.72	100.07	4012		Younger	3960	60	4778	4184	95.4	
		25.67	100.09	3941		Younger	4830	60	5709	5330	95.4	
	Lhamcoka Glacier	31.82	99.12	4150–4370	Maximum tree ages on moraines	Younger	1760–1780, 1807–1820, 1907–1920					Bräuning (2006)
	Yanzigou Glacier	29.63	101.9	3850–3900	Willow trunk in paleosol between two tills	Contemporaneous	145	100	429	...	95.4	Smiraglia (1997)
						Contemporaneous	235	110	485	–3	95.4	
						Contemporaneous	1305	110	1405	975	95.4	
						Contemporaneous	1610	65	1691	1358	95.4	
						Contemporaneous	1785	65	1865	1558	95.4	
	Nanmenguangou	29.67	101.98	3000	Buried rotten wood in till	Contemporaneous	780	90	916	560	95.4	Zheng and Ma (1994)
	Gongba Glacier	30.5	101.87	3900	Buried rotten wood in till	Contemporaneous	440	50	545	319	95.4	Su et al. (2002)
				3700		Contemporaneous	620	40	662	546	95.4	

^a Radiocarbon ages calibrated using OxCal 4.2 applying IntCal 09.^b Exact location not described in paper, so values are very approximate.^c Exact locations not provided. Ages do not readily match with original publication (in Chinese).

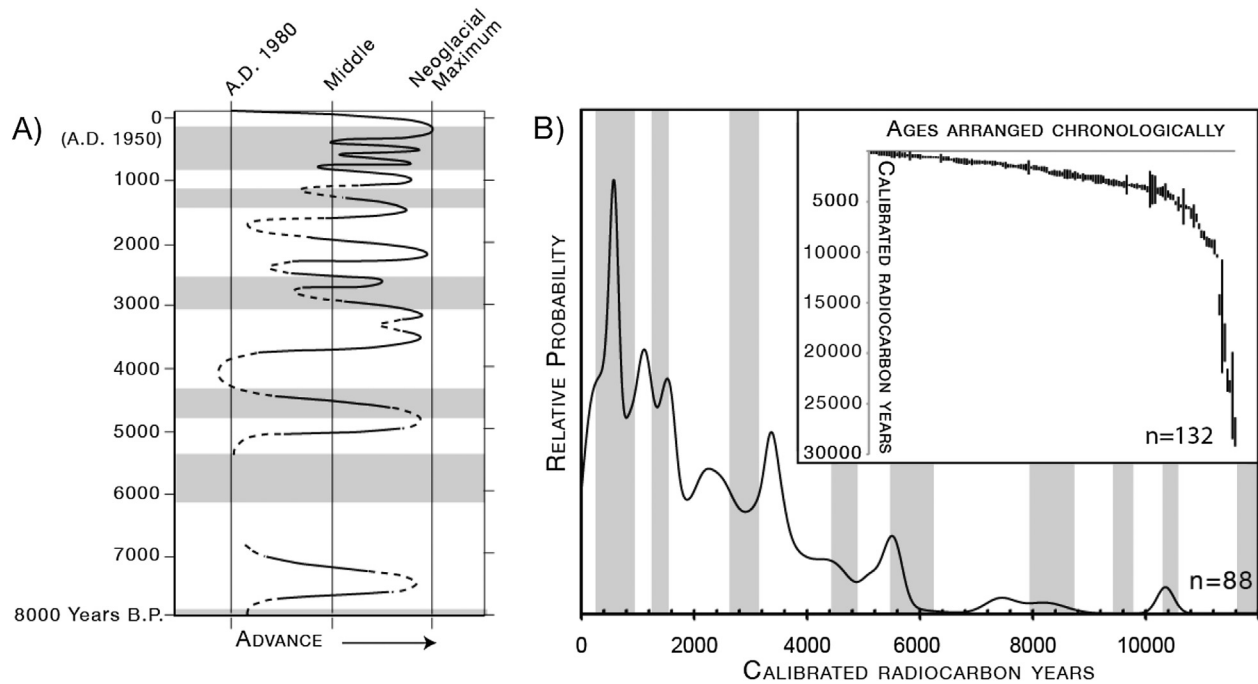


Fig. 9. A) Röthlisberger and Geyh's (1985b) summary of glacier fluctuations in the Himalaya and Karakoram defined by radiocarbon dating. The original curves of Röthlisberger and Geyh (1985b) were plotted on a radiocarbon timescale, but this figure redrafted by Owen (2009) has the broad advances and retreats plotted for calibrated years using Reimer et al.'s timescale (2004). B) Probability distribution frequency plot and scatter graph for radiocarbon ages from the Himalaya–Tibetan orogen. Only minimum radiocarbon ages, that is, ones that are younger than the moraines they are dating are plotted on the probability distribution graph (see Table 1 for data and sources). Light gray bands indicate times of rapid climate changes after Mayewski et al. (2004).

independent ages (CRONUS Calculator Version 2.2; Fig. 10A). We highlight this to illustrate the problems with using published data at face value. Moreover, as Balco et al. (2008) points out, the greatest difference between ages calculated by the different scaling models are those for low latitudes and high altitudes, which encompasses the Himalayan–Tibetan orogen. The resulting differences can be seen in Fig. 10B, where percent difference after using Lifton et al. (2005), Desilets and Zreda (2003, 2006), Dunai (2000), and Lal (1991) – Stone (2000) time dependent scaling schemes have been plotted with respect to Lal (1991) – Stone (2000) time independent ages. These large differences present challenges when

comparing TCN ages with radiocarbon, OSL, and other numerical age methods, as well as climatic records. The accuracy of the reference sea level, high-latitude (SLHL) ^{10}Be production rate has been challenged by the regional rates of Balco et al. (2009), Putnam et al. (2010), Fenton et al. (2011), Kaplan et al. (2011), Briner et al. (2012), and Goehring et al. (2012). The new regional ^{10}Be production rates range between 5 and 15% lower than SLHL and result in older ages. Fig. 10C shows the difference in percent between Balco et al. (2009) and Putnam et al. (2010) regional production rates with respect to Lal (1991) – Stone (2000) SLHL of $4.5 \text{ at } \text{g}^{-1} \text{ yr}^{-1}$ time-independent ages. Although these studies show broad

Table 2

Major optically stimulated luminescence dating projects that has been undertaken for glacial geologic studies in the Himalayan–Tibetan orogen.

Area	Source	Material dated
Ateaoynake River Valley, Tianshan ^a	Zhao et al. (2009)	Till and glaciofluvial outwash
Bogeda Peak area, Tianshan ^a	Zhao et al. (2012)	Tills and associated sediments
Terskey-Alatoo Range, Kyrgyz Republic	Narama et al. (2007)	Glacial and loess deposits
Tien Shan, Yrgyz Republic	Narama et al. (2009)	Glacial and loess deposits
Central Karakoram	Seong et al. (2007)	Glaciofluvial sediment
Hunza valley, Karakoram Mountains	Derbyshire et al. (1984), Spencer and Owen (2004)	Supraglacial and proglacial sediments
Nun Kun	Lee et al. (2014)	Aeolian and colluvial deposits
Zaskar	Taylor and Mitchell (2000)	Glaciofluvial sediments
Chitral	Richards et al. (2000a), Owen et al. (2002b)	Supraglacial and proglacial glaciofluvial sediments
Swat Himalaya	Owen et al. (1992), Richards et al. (2000a)	Colluviated loess overlaying moraines
Nanga Parbat	Richards et al. (2000a)	Proglacial glaciofluvial sediments
Lahul Himalaya	Owen et al. (1997)	Glaciodeltaic sediments
Garhwal Himal	Sharma and Owen (1996)	Englacial and supraglacial glaciofluvial sediments
Central Himalaya	Ali et al. (2013)	Outwash gravels and moraines
Khumbu Himal	Richards et al. (2000b)	Supraglacial and englacial glaciofluvial sediments
Kanchenjunga	Tsukamoto et al. (2002)	Glacial sediments
Rongbuk valley, Everest	Owen et al. (2009)	Supraglacial and proglacial glaciofluvial sediments
Kunlun Mountains	Owen et al. (2006b)	Fluvial and aeolian sediments on terraces
Anyemaquen Mountains	Owen et al. (2003a)	Supraglaciofluvial sediment

^a Also includes ESR dating.

Table 3
Summary of glacial chronologies dated by ^{10}Be methods throughout the Himalayan–Tibetan orogen listing the dating methods applied to define the ages of glacial advances.

Study region	Study	Glacial stage or moraine name
1) Pamir and Tien Shan		
Gissar Range, Western Tajikisyan	Zech et al. (2013)	G1 G2 (not dated) G3 (not dated) G4 G5 (not dated) G6 G7 G8
Aksu Valley, Turkestan Range, Kyrgyzstan Aksu Valley, Turkestan Range, Kyrgyzstan	Abramowski et al. (2006)	AK4 moraine AK3 moraine AK2 moraine AK1 moraine
Koksu Valley, Alay Range Kyrgyzstan Koksu Valley, Alay Range Kyrgyzstan	Abramowski et al. (2006)	AV moraine KK moraine
Ailuitek Pass, north Central Pamir, Tajikistan Ailuitek Pass, north Central Pamir, Tajikistan	Abramowski et al. (2006)	AT moraine TK moraine
S-Alichur Range, Yashikul, Tajikistan S-Alichur Range, Yashikul, Tajikistan	Zech et al. (2005) Zech et al. (2005) Abramowski et al. (2006) Zech et al. (2005) Abramowski et al. (2006) Zech et al. (2005)	M4 moraine M3 moraine BO1 moraine (=M3/YK3 of Zech et al., 2005) M2 moraine BO2 moraine (=M2/YK2 of Zech et al., 2005) M1 moraine
S-Alichur Range, Kol-Uchkol, Tajikistan S-Alichur Range, Kol-Uchkol, Tajikistan	Abramowski et al. (2006)	UK6 moraine UK5 moraine UK4 moraine UK3 moraine UK2 moraine UK1 moraine
S-Alichur Range, Gurumdy, Tajikistan S-Alichur Range, Gurumdy, Tajikistan	Abramowski et al. (2006)	GU4 moraine GU3 moraine GU2 moraine GU1 moraine
Bogchigir Range, Pamir Tajikistan Bogchigir Range, Pamir Tajikistan	Röhringer et al. (2012)	BO8 BO7 BO6 BO5 BO4 BO3 BO1 M1
Mustagata and Kongur Shan, Chinese Pamir Mustagata and Kongur Shan, Chinese Pamir	Seong et al. (2009a)	Olimde glacial stage Subaxh glacial stage Karasu glacial stage
Tashkurgan valley, Chinese Pamir Tashkurgan valley, Chinese Pamir	Owen et al. (2012)	Kuzigun Hangdi Tashkurgan Dabudaer
W Tien Shan, Kyrgyzstan Ala Archa, Wn Tien Shan, Kyrgyzstan Aksai, Wn Tien Shan, Kyrgyzstan	Koppes et al. (2008)	V IV, V IV, V IV, V IV III II I
Central Tien Shan, Kyrgyzstan Kitschi-Kurumdu Valley, Tien Shan, Kyrgyzstan	Zech (2012a)	M1 M2 M3 M4 M5 M6 M7

Table 3 (continued)

Study region	Study	Glacial stage or moraine name
Urumqi River valley, En Tian Shan, China Urumqi River valley, En Tian Shan, China	Kong et al. (2009a)	Lateral moraine, Glacier Observation Station Latero-terminal moraine, lower trough, Shangwanfeng Elevated platform, Gaowangfeng
2) Transhimalaya and Western Tibet Sulamu Tagh, Altyn Tagh Nn Tibet Sulamu Tagh, Altyn Tagh Nn Tibet	Mériaux et al. (2004)	M2 moraine M1 moraine
Central Karakoram (K2), Nn Pakistan Central Karakoram (K2), Nn Pakistan	Seong et al. (2007)	Askole glacial stage Mungo glacial stage Skardu glacial stage
Hunza valley, Karakoram Mts. Nn Pakistan Hunza valley, Karakoram Mts. Nn Pakistan	Owen et al. (2002b)	Batura glacial stage Ghulkin II glacial stage Ghulkin I glacial stage Borit Jheel glacial stage Yunz glacial stage
Ladakh Range, Nn India Ladakh Range, Nn India	Owen et al. (2006a)	Khalling glacial stage Bazgo glacial stage Kar glacial stage Leh glacial stage Indus glacial stage
Ladakh, Nn India Ladakh, Nn India	Dortch et al. (2013)	Pangong cirque Ladakh cirque Ladakh-2 stage Ladakh-4 stage Pangong-2 stage
Nubra and Shyok valley, N Ladakh Nubra valley, N Ladakh Shyok valley, N Ladakh	Dortch et al. (2010a)	Deshkit 1 Deshkit 2 Deshkit 3
Puga valley, Zaskar, Nn India Puga valley, Zaskar, Nn India	Hedrick et al. (2011)	PM-3 PM-2 PM-1 PM-0
Karzok valley, Zaskar, Nn India Karzok valley, Zaskar, Nn India	Hedrick et al. (2011)	KM-4 KM-3 KM-2 KM-1 KM-0
Ayilari Range, Sn Tibet Ayilari Range, Sn Tibet	Chevalier et al. (2005)	M1 moraine M2W (oldest moraine, west) M2E (oldest moraine east)
Ayilari Range, SWn Tibet Ayilari Range, SWn Tibet	Chevalier et al. (2011)	17b: CK M2 inner 17c: CK M2 outer 17a: CK M3
Gurla Mandhata, Sn Tibet Muguru valley, Gurla Mandhata	Owen et al. (2010)	M10 M9 M8 M7 M6 M4 M6 M5 M4b M4a M4c M4b M4b M4a M3 M2 M1c M1b M1a
Manarodi valley, Gurla Mandhata		
Ronggua gorge foreland, Gurla Mandhata		

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Table 3 (continued)

Study region	Study	Glacial stage or moraine name
Gurla Mandhata, Sn Tibet Gurla Mandhata, Sn Tibet	Chevalier et al. (2011)	12a: Pulan M1W 12c: Pulan M1E 12B: Pulan M2
Kailas Range, SWn Tibet Kailas Range, SWn Tibet	Chevalier et al. (2011)	12: EXS 14: WXS 15: A Qu
Rongbuk valley, N. Mt. Everest Rongbuk valley, N. Mt. Everest	Owen et al. (2009)	T7 T6 T5c T5b T4 T4 T3' T3 T2 T1
3) Monsoon-influenced Himalaya Nanga Parbat, Nn Pakistan Nanga Parbat, Nn Pakistan	Phillips et al. (2000)	Mid Holocene advance Maximum Holocene extent MIS-3 advance
Nun Kun, Nn India Nun Kun, Nn India	Lee et al. (2014)	TG3 ST3 ST2 TG1 ST1 NKB1
Lahul Himalaya, Nn India Lahul Himalaya, Nn India	Owen et al. (2001)	Historical Kulti glacial stage Batal glacial stage Chandra glacial stage (not dated)
Gangotri, Garhwal Himalaya, Nn India Gangotri, Garhwal Himalaya, Nn India	Barnard et al. (2004a)	Bhujbas glacial stage Gangotri glacial stage Kedar glacial stage Bhagirathi glacial stage
Central Garhwal, Nn India Bhillangana and Dudhganag valleys, central Garhwal	Murari et al. (2014)	mbd4 mbd3 mbd2 mbd1 mm1
Mayali, central Garhwal Kedarnath, central Garhwal	Murari et al. (2014) Murari et al. (2014)	mk3 mk3 mk1
Western Garhwal Himalaya, Nn. India Tons Valley, Garhwal Himalaya, Nn. India	Scherler et al. (2010)	Tons Valley (location G) Tons Valley (location E) Tons Valley (location F) Tons Valley (location F') Tons Valley (location D) Tons Valley (location C) Tons Valley (location B): Gangar lateral moraine (no stage name) Tons Valley (location B): Gangar Kame deposit Thangi valley: Lateral moraine (no stage name) Thangi valley: Lateral moraine (no stage name) Pin Valley: Lateral moraine (no stage name)
Pin Valley, Wn Garhwal, Nn India Thangi Valley, Wn Garhwal, Nn India Nanda Devi, Garhwal, Nn India Nanda Devi, Garhwal, Nn India	Barnard et al. (2004b)	Moraine m4 Moraine m3 Moraine m2 Moraine m1
Annapurna Range, Nepal Annapurna Range	Pratt-Sitaula (2005) Pratt-Sitaula et al. (2011) Pratt-Sitaula et al. (2011) Pratt-Sitaula (2005) Pratt-Sitaula (2005) Pratt-Sitaula et al. (2011) Pratt-Sitaula et al. (2011)	Yak upper (early-mid Holocene) Danfe Glacier (early-mid Holocene) Syaktan Glacier (early-mid Holocene) Lyapche Glacier (early Holocene) Junam Glacier (Younger Dryas) Kicho Glacier (Younger Dryas) Midim Glacier (Younger Dryas)

Table 3 (continued)

Study region	Study	Glacial stage or moraine name
Annapurna, Nepal Dudh Khola Valley, Annapurna, Nepal	Pratt-Sitaula (2005)	Khudi Glacier (Younger Dryas)
	Pratt-Sitaula (2005)	Yak Glacier lower (Younger Dryas)
	Pratt-Sitaula (2005)	Nar main (Lateglacial)
	Pratt-Sitaula (2005)	Nar Glacier end (LGM)
	Pratt-Sitaula (2005)	Pangri Glacier (LGM)
Marsyandi Valley, Annapurna, Nepal Macha Lhola Valley, Gorkha Himal, Nepal Macha Lhola Valley, Gorkha Himal, Nepal	Zech et al. (2009)	Little Ice Age moraine Neoglacial diamicton
	Abramowski (2004)	MK4: LIA MK7: Neoglacial MK5: Lateglacial MK2: LGM
Milarepa's Glacier, Annapurna Range, Nepal Milarepa's Glacier, Annapurna Range, Nepal	Heimsath and McGlynn (2008)	E moraine crest W moraine crest
Mailun Khola, Ganesh Himal, Nepal Mailun Khola, Ganesh Himal, Nepal	Gayer et al. (2006)	M6 M3 post-M2
Langtang Himal, Nepal Langtang Valley, Langtang Himal, Nepal	Abramowski (2004)	LT6 LT3: Langtang Stage LT2
	Barnard et al. (2006)	Yala I glacial stage Langtang glacial stage
	Schaefer et al. (2008)	Naisa valley moraines: older ridge Naisa valley moraines: younger ridge Fu Qu valley, Puluo moraine sequence: Puluo 2 moraine Fu Qu valley, Puluo moraine sequence: Puluo 1 moraine Nyalam moraine sequence: Moraine #3 Nyalam moraine sequence: Moraine #2 Nyalam moraine sequence: Moraine #1
Ama Drime Range, Sn Tibet Ama Drime Range, Sn Tibet	Chevalier et al. (2011)	8: Dingye N 9b: Dingye S main #1 9c: Dingye S main #2 9d: Dingye S main #3 9a: Dingye S frontal
Khumbu Himal, Nepal Khumbu Himal, Nepal	Finkel et al. (2003)	Lobuche glacial stage and historical Thuklha glacial stage Chhukung glacial stage Periche II glacial stage Periche I glacial stage Thyangboche II glacial stage Thyangboche I glacial stage
4) Monsoon-influenced Tibet Xainza Range, Sn Tibet Xainza Range, Sn Tibet	Chevalier et al. (2011)	3a: M4 #1 3b: M4 #2 3c: M4 #3 4c: M3old 4a: M3 main 4b: M3 inner 5: M2 6: M1 7:M
Kunlun Shan Kunlun Shan (southern slopes)	Owen et al. (2006b)	M2 moraines M1 moraines M2 moraines M2' moraines M1 moraines
La Ji Shan, NE Tibet La Ji Shan, NE Tibet	Owen et al. (2003b)	t3 moraine t2 moraine t1 moraine
Qilian Shan, NE Tibet NW Menyuan, Qilian Shan, NE Tibet	Owen et al. (2003c)	Holocene moraine (Gangshiga valley) LGM moraine (Gangshiga valley) LGM moraine (Laolongwan valley)

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Table 3 (continued)

Study region	Study	Glacial stage or moraine name
Qilian Shan, NE Tibet Xiying He valley, Qilian Shan, NE Tibet	Lasserre et al. (2002)	Unnamed moraine (Laotugou valley) unnamed moraine
Nianbaoyeze Mountains Nianbaoyeze Mountains	Owen et al. (2003a)	Ximencuo glacial stage Jiukehe glacial stage
Anyemaqen Mountains Anyemaqen Mountains	Owen et al. (2003a)	Halong glacial stage Qiemuqu glacial stage Anyemaqen glacial stage
Bayan Har, NE Tibet Bayan Har, NE Tibet	Heyman et al. (2011)	BH-1 BH-2 BH-3 BH-4
Dalijia Shan, NE Tibet Qital Valley, Dalijia Shan, NE Tibet	Wang et al. (2013)	Group D moraines Group C moraines Group B moraines Group A moraines Dalijia Pass moraines
Cental Tanggula Shan Tanggula Pass, Central Tanggula Shan	Colgan et al. (2006) Owen et al. (2005), Colgan et al. (2006) Schäfer et al. (2002), Owen et al. (2005) Owen et al. (2005), Colgan et al. (2006)	Longxiazai glacial stage (youngest) Basicuo glacial stage Zhajiazangbo glacial stage Tanggula glacial stage
Nyainqentanglha Shan, Central Tibet SE Samdainkangsang, Nyainqentanglha Shan	Owen et al. (2005)	Un-named (youngest) moraine Un-named (intermediate age) moraine Un-named (oldest) moraine
Nyainqentanggula, South Central Tibet Nyainqentanggula, South Central Tibet	Chevalier et al. (2011)	2b: ybj inner 2a: ybj outer W 2c: ybj outer E 2d: ybj outer N 1a: Gulu W 1b: Gulu E
KungCo, Sn Tibet KungCo, Sn Tibet	Chevalier et al. (2011)	11: KungCo
Cho Oyu Range, S Central Tibet	Chevalier et al. (2011)	10: Cho Oyo
Shaluli Shan, Chuanxi Plateau, En Tibet Shaluli Shan, Chuanxi Plateau, En Tibet	Graf et al. (2008) includes Ne-21 too	Cuo Ji Gang Wa and Cuo Naleng paleoglaciers: lateral moraine Cuo Ji Gang Wa and Cuo Naleng paleoglaciers: outer end moraine Cuo Ji Gang Wa and Cuo Naleng paleoglaciers: middle end moraine Cuo Ji Gang Wa and Cuo Naleng paleoglaciers: inner end moraine Chuanxi and northern outlet glacier: resting on HAI-2 Chuanxi and northern outlet glacier: on smaller moraine ridge Chuanxi and northern outlet glacier: embedded in basal till
Shaluli Shan, Haizishan Plateau, En Tibet Shaluli Shan, Haizishan Plateau, En Tibet	Fu et al. (2013)	innermost moraine sequence intermediate moraine sequence outermost moraine sequence
Shaluli Shan, Xinlong Plateau, En Tibet Shaluli Shan, Xinlong Plateau, En Tibet	Fu et al. (2013)	outermost moraine sequence
Shaluli Shan, Nata, En Tibet Shaluli Shan, Nata, En Tibet	Fu et al. (2013)	outermost moraine sequence
Shaluli Shan, Heranseba, En Tibet Shaluli Shan, Heranseba, En Tibet	Fu et al. (2013)	outermost moraine sequence
Litang County, En Tibet Litang County, En Tibet	Schäfer et al. (2002)	Un-named moraine (youngest) Un-named moraine (oldest)
Hengduan Mountains, SE Tibet Kangding, Daxue Shan, Hengduan Mts., SE Tibet	Tschudi et al. (2003), Strasky et al. (2009)	Zhheduo valley moraine ridge
Mt. Kaluxung, Sn Tibet Karola Pass, Mt. Kaluxung, Sn Tibet	Owen et al. (2005)	Un-named (youngest) moraine Un-named (intermediate age) moraine Un-named (oldest) moraine
Gangrigabu Shan, SE Tibet Bodui Zangbo River, Gangrigabu SE Tibet	Zhou et al. (2007, 2010)	East moraines: Baiyu Glaciation West younger moraine: Baiyu Glaciation West older moraine: Baiyu Glaciation Area C: Guxiang Glaciation
Gonga Shan, SE Tibet	Monsoon Tibet	

Table 3 (continued)

Study region	Study	Glacial stage or moraine name
Hailuoguo Valley, Gongga Shan, SE Tibet	Owen et al. (2005)	Little Ice Age moraines Neoglacial moraines "Recessional moraine" Local LGM moraines
Shaluli Mountain, SE Tibet		
Haizi Shan, Shaluli Mountain, SE Tibet	Wang et al. (2006)	Kuzhaori end moraine
Yulong Mountains, SE Tibet		
Renhe valley, Yulong Mountains, SE Tibet	Kong et al. (2009b)	No stage name given
Xinlian valley, Yulong Mountains, SE Tibet	Kong et al. (2009b)	No stage name given
Baishui valley, Yulong Mountains, SE Tibet	Kong et al. (2009b)	No stage name given
Ganheba, Ganheba Mountains, SE Tibet	Kong et al. (2009b)	No stage name given

agreement, they only cover a limited temporal (<15 ka) and elevation (<1500 m asl) scale and a regional calibration site comparing radiocarbon and TCN methods has not been defined in the Himalayan–Tibetan orogen. Moreover, differences in isostatic rebound, air-pressure, and differing paleomagnetic field effects could create significant offsets when extrapolating to dissimilar regions (e.g. Balco et al., 2009). Thus, extrapolation of production rates from calibration sites to high elevation (>4000 m) and old landforms (50–700 ka) should only be undertaken with extreme caution. Moreover, the TCN data used in calibration papers do not have perfect gaussian distributions; thus, when using the subsequent production rates, researchers should use the same statistical methods to examine clustering of ages. Unfortunately, there is no scaling scheme or production rate that has been rigorously proven to be the most accurate, leaving researchers free to choose the scheme that they deem best, or best fits their interpretations. Ironically, if carefully chosen, using the combination of new production rates and scaling scheme, ~78% ($n = 1331$) of all ages yield results within 10% of time-independent Lal (1991) – Stone (2000) ages when between 11 and 700 ka; whereas only ~10% ($n = 169$) of all ages are within 15% between 5 and 11 ka (Fig. 10D). These correction factors do not appear to be quite as significant when taken in the context of normal individual age errors of 5–10%.

Irrespective of these various correction schemes, the geologic error associated with TCN dating and the statistical treatment of ages to identify outliers has a far more significant effect on dating moraines and other landforms. As Hallet and Putkonen (1994), Owen et al. (2008a,b) and numerous other researchers point out, geological factors present the largest uncertainty in applying TCN surface exposure dating methods. These include early stabilization and denudation of the landform, as well as weathering, exhumation, prior exposure and shielding of the surface that is being dated by snow and/or sediment. Generally these processes reduce the concentration of TCNs, resulting in an underestimate of the true age of the landform, with the exception of prior exposure that results in an overestimation of the landform's age. The net result of these processes can be a large spread in apparent exposure ages of individual boulders on a single landform, such as a moraine, or in different positions on an extensive rock surface such as glacially eroded bedrock. For example, Dortch et al. (2013) show that 40% of all ages in the western semi-arid part of the orogen are outliers with age underestimation occurring four times more often than inheritance. They show that inherited outliers are 60% older than the landform age on average, with numerous samples having up to 300% inheritance, while underestimation diverges from moraine age by an average of ~55% younger with numerous samples diverging by up to 90%. Due to possible post-processes, researchers typically interpret TCN ages as representing the timing of deglaciation. Researchers usually collect multiple samples on a surface in an attempt to assess these effects. The combined results of Dortch

et al. (2013; $n = 95$) and Murari et al. (2014; $n = 208$) that included the examination of 303 local glacial stages shows that when ≤ 4 samples are collected, the probability of obtaining three ages that fit a normal distribution is ~27%, but dramatically shifts to at 5 samples to is ~77%, and increases with ≥ 6 samples to ~98% (Fig. 11). The basic rationale is that the presence of multiple boulders or surface samples having similar apparent ages is taken as evidence that the boulders were not derived from a range of older surfaces and/or were not weathered, exhumed or covered. Additionally, sequences of landforms are often dated to assess the relative behavior of clustered TCN ages. Hence the ages are then considered to be representative of the true age of the surface. However, it is not common to have strong clustering of ages, particularly for Pleistocene moraines, and the spread of ages is generally greater with antiquity.

Fig. 12 provides an example of a large, reasonably well-clustered data set for a study area within the Himalayan–Tibetan orogen. Each rectangle encloses individual ^{10}Be ages for a particular glacial stage. Clearly, the clustering of ^{10}Be ages is tightest for the younger glacial stages. The greatest challenge is interpreting the broad spread of ages. Many researchers, including Hallet and Putkonen (1994), Zreda et al. (1994), Putkonen and Swanson (2003), Briner et al. (2005), Zech et al. (2008), Applegate et al. (2010) and Heyman et al. (2011), favor assigning the glacial age based on the age of the oldest boulder (if not an “obvious” outlier) determined for a surface. The oldest boulder method implies that the boulder has been least weathered, shielded or exhumed. However, the oldest age might be a consequence of inherited TCNs. Moreover, the method of determining if a boulder is an “obvious” outlier varies from a simple judgment call to using a non-stringent statistical test (e.g. beyond 2σ of the mean of the population). In contrast, the youngest boulder might be considered most representative since it is least likely to have inherited TCNs from former exposure. Putkonen and Swanson (2003) and Heyman et al. (2011) argue that only a small percent of dated moraine boulders have had prior exposure, which lends favor to the oldest boulder method. To reiterate the point, Dortch et al. (2013) caution that 8% of all glacial boulders dated in the semi-arid western portion of the orogen show inheritance typically ranging from 5 to 300% with rarer examples with up to 1200% of the landform age (for ages <1–350 ka) and that outliers are not always obvious. Similar analysis by Murari et al. (2014) supports this view. They show that 10% of all glacial boulders dated in the monsoon influenced regions of Himalaya and Tibet show inheritance typically ranging from 6 to 300% with rare examples exceeding 1000%. To add complication, both studies show that young outliers occur 3–4 times more often than inherited outliers and argue that statistical analysis is required to identify the most correct ages.

Numerous researchers suggest statistical analysis of ages, such as applying the mean square of weighted deviates method

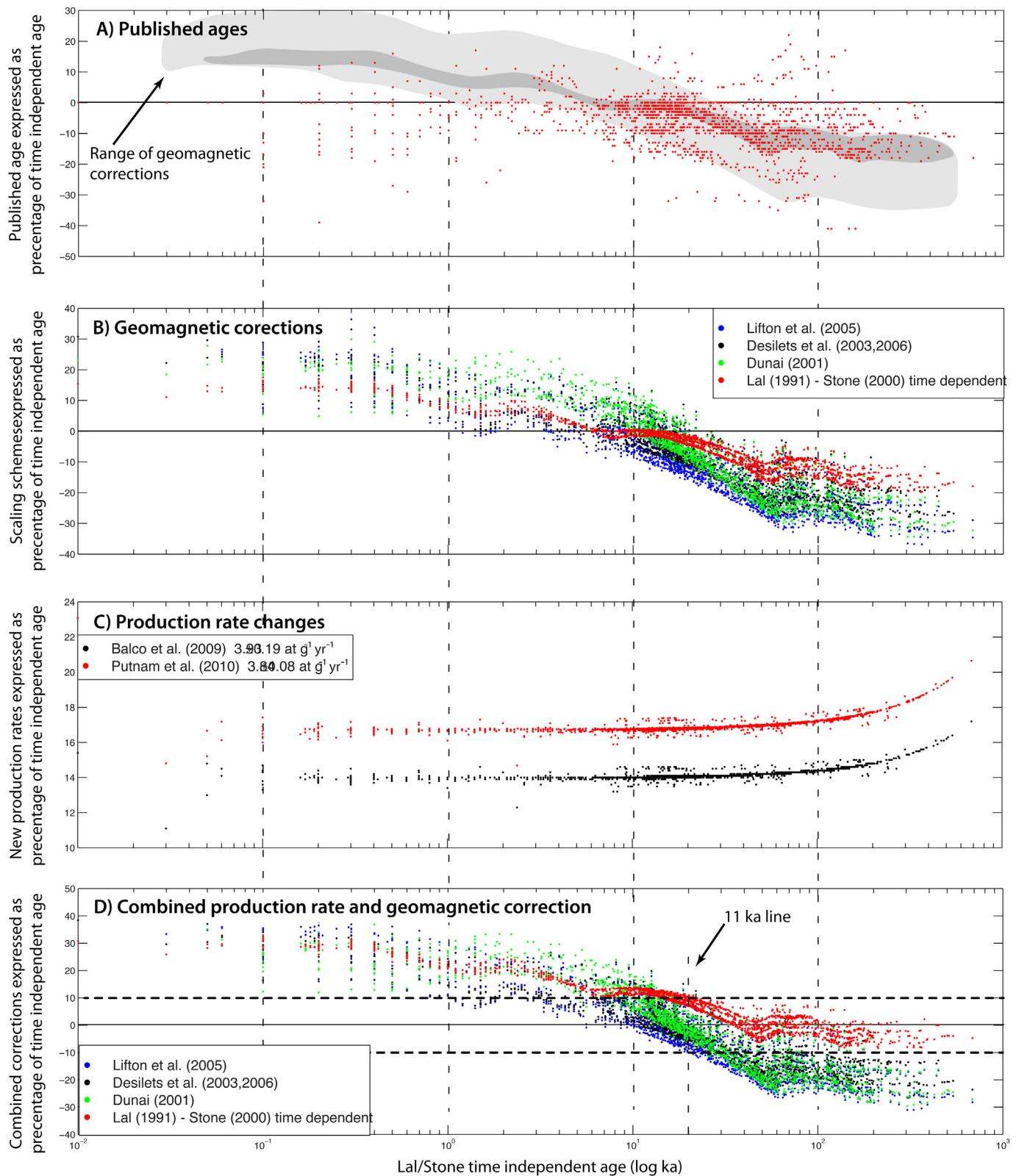


Fig. 10. Log-normal plots of >1700 TCN ages from the Tibetan–Himalayan orogen expressed as percentage difference from the Lal (1991) – Stone (2000) time-independent scaling scheme. A) Published ages, light gray shading shows ages with differences that would fit within geomagnetic corrections schemes. Dark gray area delineates ages that fit in the Lal (1991) – Stone (2000) time dependent scheme specifically, which covers the majority of geomagnetic corrected ages. B) scaling schemes including geomagnetic correction, C) time-independent ages using new regional production rates, and D) Balco et al. (2009) regional production rate combined with scaling schemes including geomagnetic corrections. Thick horizontal dashed lines enclose 10% deviation from time-independent ages. All primary data are presented in Appendix 1.

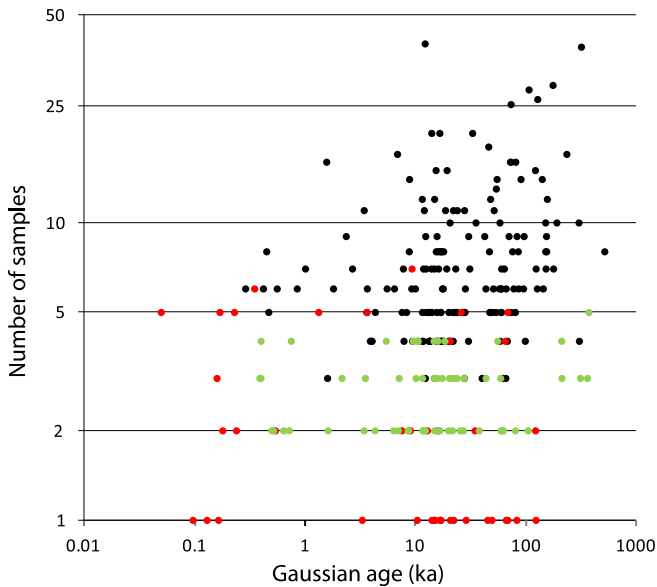


Fig. 11. Log-normal plot of 267 probability frequency distributions that represent regional glacial stages (combined local glacial stages) for the semi-arid western end and the monsoon-influenced areas of the Himalayan–Tibetan orogen of Dortch et al. (2013) and Murari et al. (2014), respectively. Y-axis position is determined by the total number of samples from a landform(s). Black dots indicate component probability frequency distributions that enclose 3 or more ages. Green dots represent component probability frequency distributions that enclose two ages and are considered tentative. Red dots represent either the oldest probability frequency distributions from a dataset that was too scattered to fit a normal distribution or landforms with a single age. The 31 probability frequency distributions from landforms that do not follow morphostratigraphic order are excluded from this plot.

(MSWD); iterative reduced chi-squared, is more appropriate because it is a much stricter test and easily identifies outliers (e.g. Gosse et al., 1995; Finkel et al., 2003; Mériaux et al., 2004; Chevalier et al., 2005; Owen et al., 2005; Dortch et al., 2010a,b, 2011a,b,c; Hedrick et al., 2011). However, Ivy-Ochs et al. (2007) argue that using MSWD and the resulting weighted mean unjustly skews ages because younger ages typically have smaller uncertainties. Dortch et al. (2014) separated gaussians from cumulative probability frequency distributions to obtain best fits on TCN data for semi-arid

regions at the western end of the Himalayan–Tibetan orogen, which they then used to delimit local glacial stages. Student's *t*-test was used to correlate TCN age clusters across the region, the results of which will be discussed in more detail below. Clearly, the issue of understanding age data needs to be resolved and care must be taken when considering the ages of glacial events in the Himalayan–Tibetan orogen. Fortunately, most researchers present all their primary data so that future researchers can manipulate published data and make their own interpretations. However, we suggest that studies focused on the timing of glaciation and the links to climatic records should use the Lal (1991) – Stone (2000) time-independent scaling scheme for comparability until geomagnetic correction and SLHL productions rate uncertainties are better constrained and that significant attention needs to be given to developing a standard for the statistical treatment of ages.

A strategy taken by some researchers to try to overcome problems with dating is to apply both OSL and TCN methods within a study area. This has the advantage of providing depositional ages (OSL dating) and deglaciation ages (minimum ages with TCN dating). Benn and Owen (2002) set out possible sampling strategies that might be applied using both OSL and TCN methods, as illustrated in Fig. 13. Unfortunately, one of the main limitations of using this strategy is the availability of good exposures of sediment for OSL dating. This strategy has been successfully applied in several regions, most notably in the Khumbu Himal and Rongbuk valley on the south and north sides of Mount Everest, respectively. Fig. 14 shows an example of a laterofrontal moraine complex that was dated using both OSL and TCN methods at the Lhotse Nup glacier terminus at Chhukung in the Khumbu Himal (Richards et al., 2000b; Finkel et al., 2003). ^{10}Be surface exposure ages on this moraine are between 2.6 and 3.5 ka whereas an OSL age on the upper sediment unit is 1.1 ± 0.2 ka, supporting the view that the moraine represents a Late Holocene glacial advance. In this case, the older TCN ages might reflect a thousand or years of prior exposure. Unlike TCN methods, OSL dating also allowed an earlier advance to be defined to the early Holocene (~ 10 ka) by dating the lower sediment unit at this site. Fig. 15 shows the chronologies for the Rongbuk valley, which are well defined by both ^{10}Be TCN and OSL dating methods.

5. Evidence of extremely old glaciations

There is abundant geomorphic and sedimentological evidence for glaciation predating the penultimate glacial cycle in the Himalayan–Tibet orogen. In some cases moraines are well preserved, especially in the semi-arid regions of Tibet and the Transhimalaya, but in most regions old moraines are denuded. Amongst the oldest moraines are those of the Indus glacial stage in Ladakh. Owen et al. (2006a) showed these to have been formed when extensive valley glaciers advanced to an elevation below 3250 m asl; they are dated to >430 ka (Fig. 16A). Other extremely old moraines are present on the west side of Gurla Mandata in southernmost central Tibet (Fig. 16B). Based on ^{10}Be dating of boulders, Owen et al. (2010) argued that these moraines are considerably older than 300 ka and thus likely formed during MIS 10 or during an earlier glacial cycle when ice caps expanded during the Naimona'nyi glaciation. In addition, in the Rongbuk valley on the northern side of Mt Everest, Owen (2009) dated erratics to >330 ka, which they argued formed by extensive valley glaciers advancing northwards from Mount Everest. In the Central Karakoram, Seong et al. (2007) recognized an extensive valley glacier system, which they dated to MIS 6 or older. Other moraines of great antiquity (penultimate or earlier glacial cycle) have been dated using TCN methods by Owen et al. (2006b), Chevalier et al. (2005, 2011), Schaefer et al. (2008) and Hedrick et al. (2011) in the Kunlun Shan, Ayilari Range, Nyalam, Xainza graben in

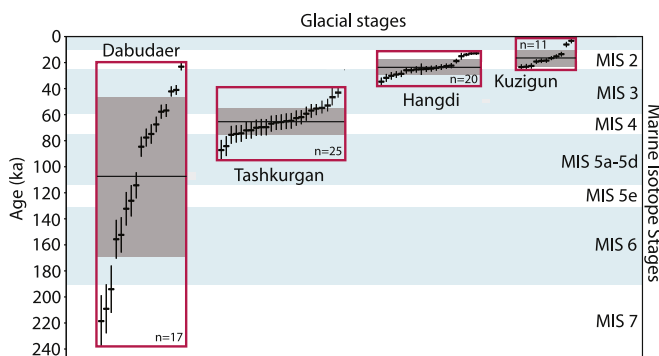


Fig. 12. An example of the spread of ^{10}Be ages for glacial boulders dated to define glacial stages from Owen et al. (2012) for the Tashkurgan valley in the Pamir. The glacial stages are plotted by relative age (oldest to the left). The horizontal black lines and the dark gray bands show the mean and 1σ for each glacial stage, respectively. The light blue bands highlight interstadials and interglacials based on the Marine Oxygen Isotope Stages (MIS) of Martinson et al. (1987). Note how the spread of ages for each glacial stage becomes progressively larger with increasing age, likely reflecting geologic effects such as weathering, exhumation and toppling of boulders resulting in anomalously young ages.

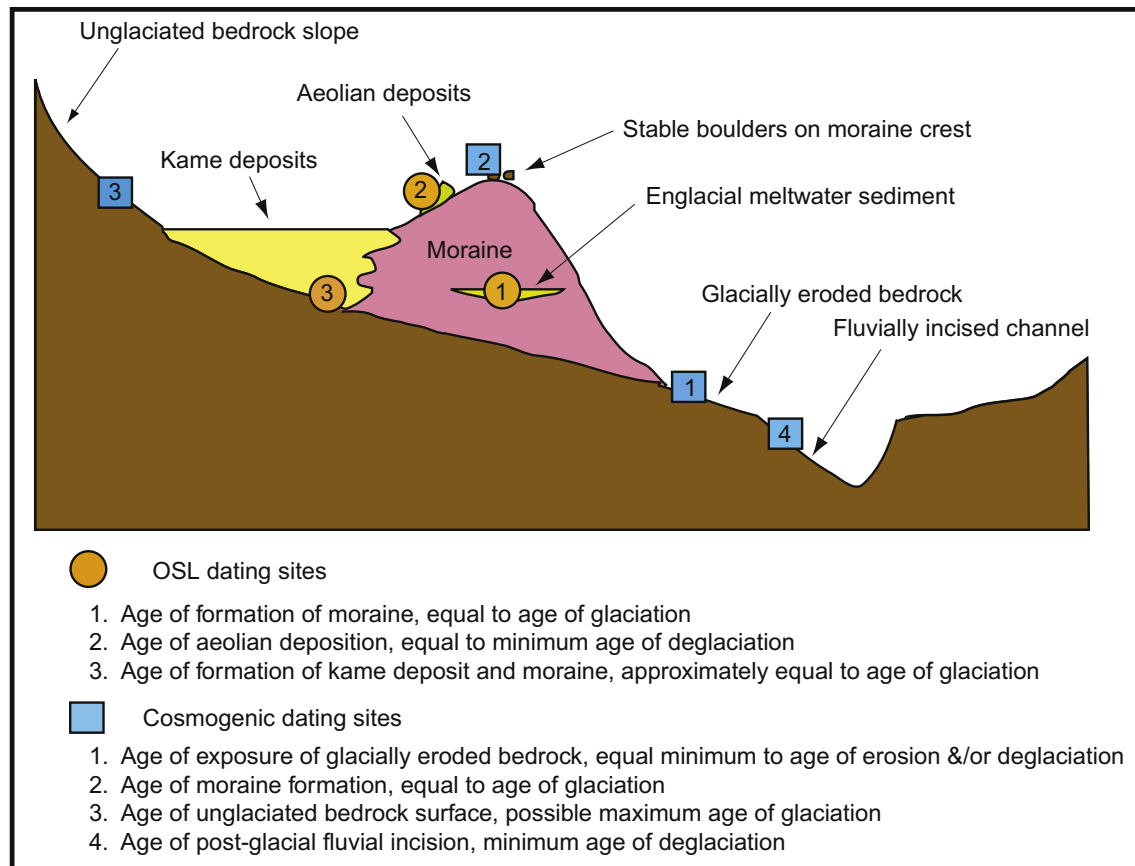


Fig. 13. Sampling strategies for OSL and TCN dating of moraines and associated deposits and landforms proposed by Benn and Owen (2002) showing the significance of each dating site.

south central Tibet, and the Zaskar, respectively. On Muztag Ata, in the Chinese Pamir, Seong et al. (2009a) showed that ice caps expanded during the Karasu glacial stage, which they dated to the penultimate glacial cycle or earlier using ^{10}Be dating. Just south of Muztag Ata in the Tashkurgan valley, Owen et al. (2012) dated moraines of the Dabudaer glacial stage using ^{10}Be to the penultimate glacial cycle and/or earlier (Fig. 16C).

Using ESR and TL methods, Wu et al. (2001) dated tills of the Wangkun Glaciation on the Kunlun Pass to between 0.7 and 0.5 Ma. In addition, using ESR methods, Zhou et al. (2001) dated till of the Gaowangfeng Glacial Stage in the headwaters of the Urumqi River in the Eastern Tien Shan to ~400–470 ka, while Zhao et al. (2009) dated till of the Qingshantou Glacial Stage in the Ateayinake River Valley of the central Tien Shan to ~440 ka. Till of the Zhonglianggan glaciation in the Qilian Mountains was also dated using ESR methods by Zhou et al. (2001, 2006) yielding an age of ~463 ka.

The large uncertainty associated with dating these old moraines and sediments precludes regional correlation. Moreover, it is difficult to correlate convincingly the old moraines within a region. Owen et al. (2012) for example, stated that moraines assigned to their Dabudaer glacial stage in the Tashkurgan valley might represent several glaciations, since the strong degree of weathering of Dabudaer glacial stage landforms does not allow subtle morphostratigraphic distinctions to be made.

Old moraines (penultimate glacial cycle or older) and sediments in high-precipitation monsoon-influenced Himalayan regions are not as common as for the semi-arid regions, however. This might simply be because the preservation potential for old moraines is

low due to intense denudation, mainly by fluvial and mass movement processes, which characterize these wetter environments. It is also possible that Lateglacial and Holocene glacial advances may have been more extensive than early glaciations and hence may have destroyed any landform or sedimentary evidence of earlier glaciations in the monsoon-influenced Himalayan regions. Due to the great relief in these settings, some evidence of older glaciations is expected because of the large altitudinal separation of landforms. On the other hand, the high relief yields more gravitational potential, which would drive quicker reworking of landforms through various surface processes.

Owen et al. (2005, 2006a, 2008a, 2010, 2012) and Seong et al. (2009a) noted, that in regions where there is evidence for very old glaciation there is a progressive change in style of glaciation with a significant reduction in glacial extent over successive glacial cycles. Owen et al. (2005, 2006a, 2008a, 2012) and Seong et al. (2009a) hypothesized that this could reflect a change in regional climatic forcing that might be the result of the progressive surface uplift of adjacent mountain ranges that restricted moist input and hence precipitation in their regions. They cautioned that drawing links between mountain uplift and changes in regional climate is very tentative because it is not possible to define the timing and magnitude of surface uplift for most mountain ranges. However, since this pattern of glaciation occurs in disparate regions across the Transhimalaya and Tibet, Owen et al. (2005, 2006a, 2008a, 2010, 2012) and Seong et al. (2009a) argued that it might reflect regional climate change rather than localized tectonics. In contrast, Dortch et al. (2013) argue that most major glacial events are driven by monsoonal precipitation and that change in regional climate is

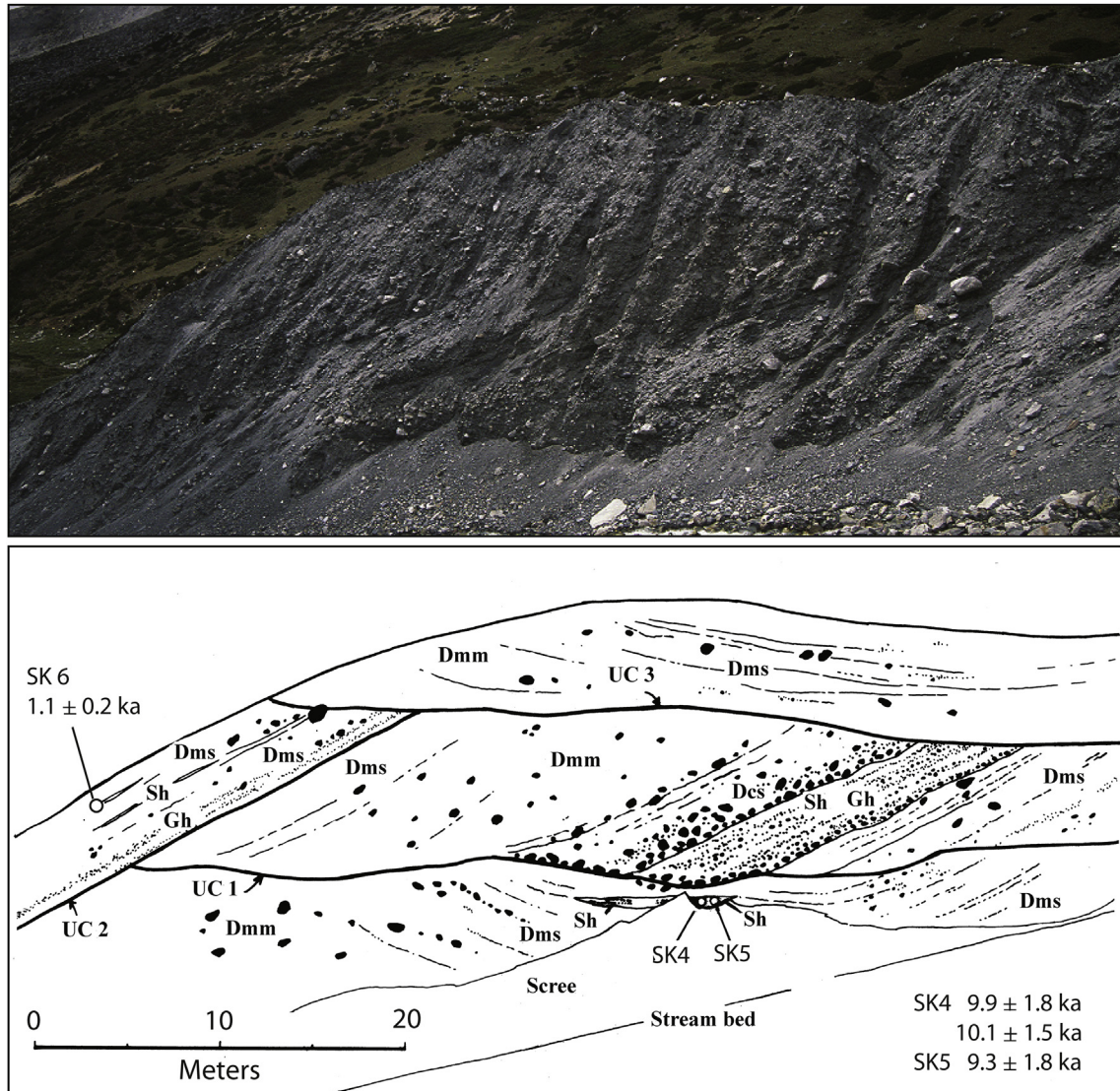


Fig. 14. View of section through a composite latero-frontal moraine at Lhotse-Nup in the Khumbu Himal, Nepal. Measured drawing after Richards et al. (2000b). UC1, UC2, and UC3 represent three unconformities. OSL dating undertaken by Richards et al. (2000b) is shown to illustrate the long and complex history of this landform. The lithofacies codes of Eyles et al. (1983) are used to describe the sedimentology (Dmm—massive matrix-supported diamict; Dms—stratified, matrix-supported diamict; Dcs—stratified, clast-supported diamict; Sh—low-angle, cross-stratified, very fine to very coarse sands; Gh—horizontally bedded gravels).

not likely responsible for decreased glacial extent during the late Quaternary. An alternative mechanism is the adjustment of topographic hypsometry to glacial erosion and the lowering of accumulation area driving the reduction of glacial extent during late Quaternary cycles (e.g. Kaplan et al., 2009; Pendersen and Egholm, 2013). The reason for this apparent changing pattern of glaciation through time, however, has yet to be resolved.

6. The Last Glacial

There is abundant evidence in the Himalayan–Tibetan orogen for multiple glacial advances throughout the last glacial cycle. In some regions up to five distinct glacial advances have been recognized, for example, in the Khumbu Himal (Finkel et al., 2003), Muztag Ata-Kongus Shan (Seong et al., 2009a), and Xainza Range (Chevalier et al., 2011). Care must be taken, however, when interpreting and trying to correlate glacial successions because the preservation of the glacial geologic record may well be biased by likely preservation potential (Gibbons et al., 1984).

Given the large number of ^{10}Be ages that have been generated in recent years, Owen et al. (2008a) and Chevalier et al. (2011) examined the timing of glaciation by generating probability distribution frequency plots for the ^{10}Be ages for selected time slices and regions. Fig. 17 builds on the analysis of Owen et al. (2008a) by increasing their data set from 777 to >1700 ^{10}Be ages. The new plots in Fig. 17 use only moraine boulder ages. As in Owen et al. (2008a,b), we recognize that pooling all the ages runs the risk of including ages that may be too old or too young to represent the true age of a glacial advance because of the geological problems highlighted above. Given the great number of ages, however, clear patterns emerge. As in the study by Owen et al. (2008a), the probability plots shown in Fig. 17 demonstrate a decrease in sample frequency with increasing age. This is essentially a function of preservation, with younger landforms being better preserved, more common and less difficult to date. Multiple peaks are apparent for most of the probability plots during MIS 3 and the Lateglacial, and several peaks occur within the Holocene. The new plots support the view of Owen et al. (2008a) that there is not a dominant peak for

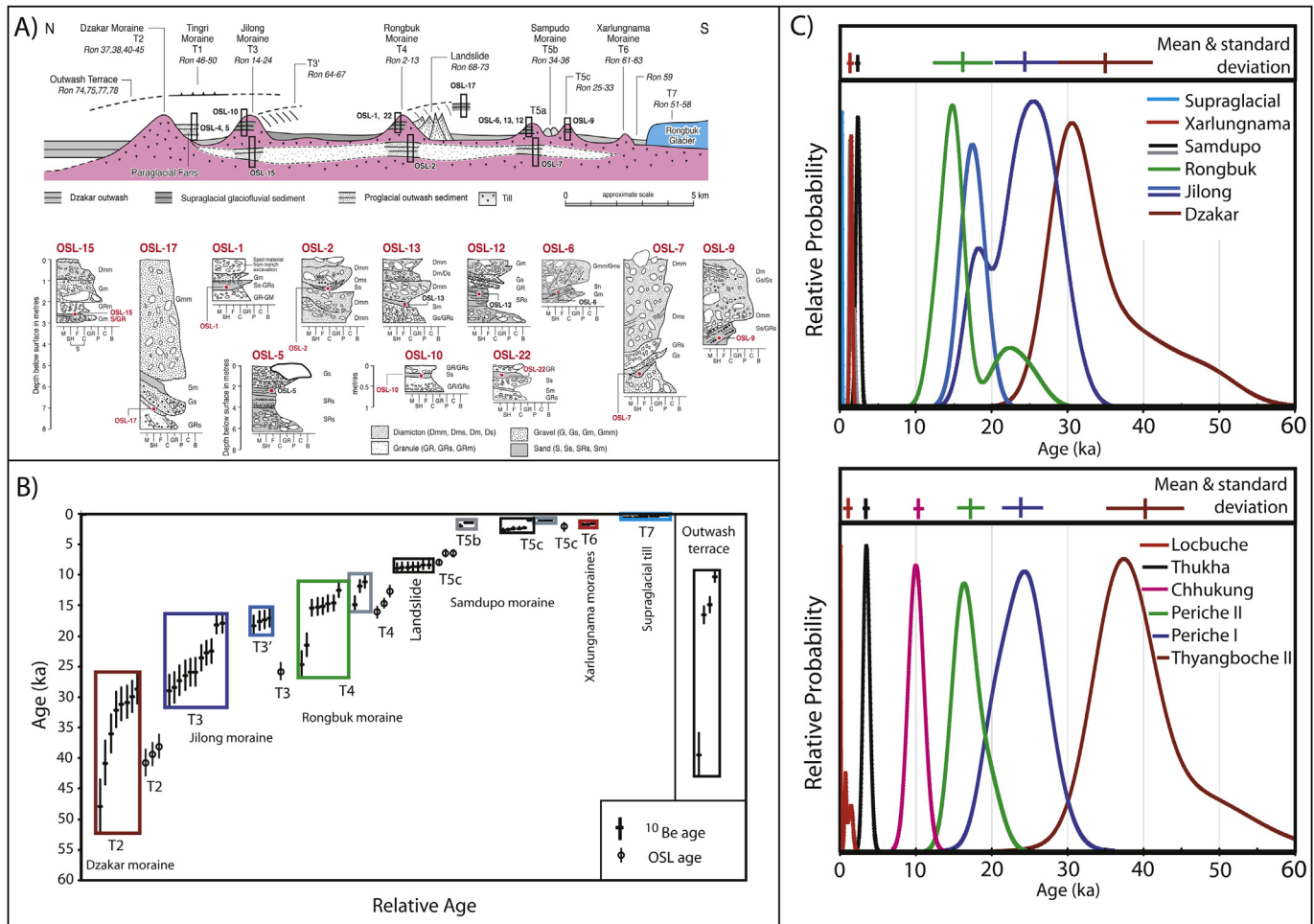


Fig. 15. Glacial chronology for Mount Everest after Finkel et al. (2003) and Owen et al. (2009). A) Schematic diagram showing the stratigraphic context and locations, and graphic sedimentary logs for samples for OSL (in red samples OSL-1 to OSL-22) and ^{10}Be (in black Ron 1–78) for the Rongbuk valley on the northern side of Mount Everest (after Owen et al., 2009). The ages for these samples are shown in part B. B) ^{10}Be and OSL ages for moraines for the Rongbuk valley. Ages for each dated moraine are enclosed by a different color rectangle. The proximal outwash terrace is also dated (after Owen et al., 2009). C) Probability distribution plots for ^{10}Be ages for glacial stages on either side of Mount Everest (upper plots = Rongbuk valley and lower plots = Khumbu Himal on the south side of Mt. Everest) are compared (after Owen et al., 2009).

the global LGM centered on 21 ka but, instead, a dominant peak occurs in the Lateglacial and is centered around 12–14 ka. In addition, the multiple peaks during the Holocene suggest that Himalayan–Tibetan glaciers may be sensitive to climate oscillations, reflecting times of Holocene rapid climate change emphasized by Mayewski et al. (2004).

The probability distribution frequency plots presented in Fig. 17, however, may be spurious since they combine data from climatically different regions where glaciers may be responding differently to different climate forcing. To test for regional patterns, as in Owen et al. (2008a), the ^{10}Be data have been sorted into four climatic-topographic regions (Fig. 18): 1) Pamir and Tien Shan dominated by the mid-latitude westerlies; 2) semi-arid Transhimalaya and western Tibet dominated by the mid-latitude westerlies; 3) monsoon-influenced Himalaya including northern Pakistan, India and Nepal; 4) monsoon-influenced Tibet, including southern central, central, SE and NE Tibet. Three time slices are considered: 1) all ^{10}Be boulder ages back to 200 ka; 2) all ^{10}Be boulder ages younger than 74 (MIS 5a); and 3) all ^{10}Be boulder ages younger than 15 ka (to include Lateglacial and Holocene ages). The study areas are listed in Table 3 and Appendix 1.

The caveats in Fig. 17 apply to the plots in Fig. 18 when interpreting the data. Clearly the probability plots still reflect bias in

occurrence and sampling of younger moraines and the distributions are broadly similar. It is notable that there is no peak centered on ~30–50 ka (MIS 3) for the Pamir and Tien Shan data, but rather there is a peak at 60–75 ka (MIS 4); however, there is no peak at this time for the other three regions (Fig. 18A). However, due to significantly fewer samples collected from landforms >30 ka in age, erosional processes could easily diminish any >30 ka peak into the background so that the sampled regions of Pamir and Tien Shan may only reflect a particular peak due to very dry conditions promoting preservation. The Pamir and Tien Shan data have apparent bimodal peaks between the Lateglacial through to the global LGM, whereas no other data set has a peak at the global LGM (Fig. 18B). As pointed out by Owen et al. (2008a), this suggests that glaciation in the Pamir and Tien Shan has responded differently compared to the other three regions. In contrast, Dortch et al. (2013) shows a strong regional glacial signal at 20 ± 2 ka in the Pamir and Western Transhimalaya by analyzing individual datasets, highlighting the weakness of combining datasets without first eliminating outliers. It is likely that glaciation in the Pamir and Tien Shan is forced by northern hemisphere climate change and is broadly synchronous with oscillations in the northern hemisphere ice sheets. In contrast, as suggested by numerous researchers, in other areas of the Himalayan–Tibetan orogen, glaciers respond to changes in the south

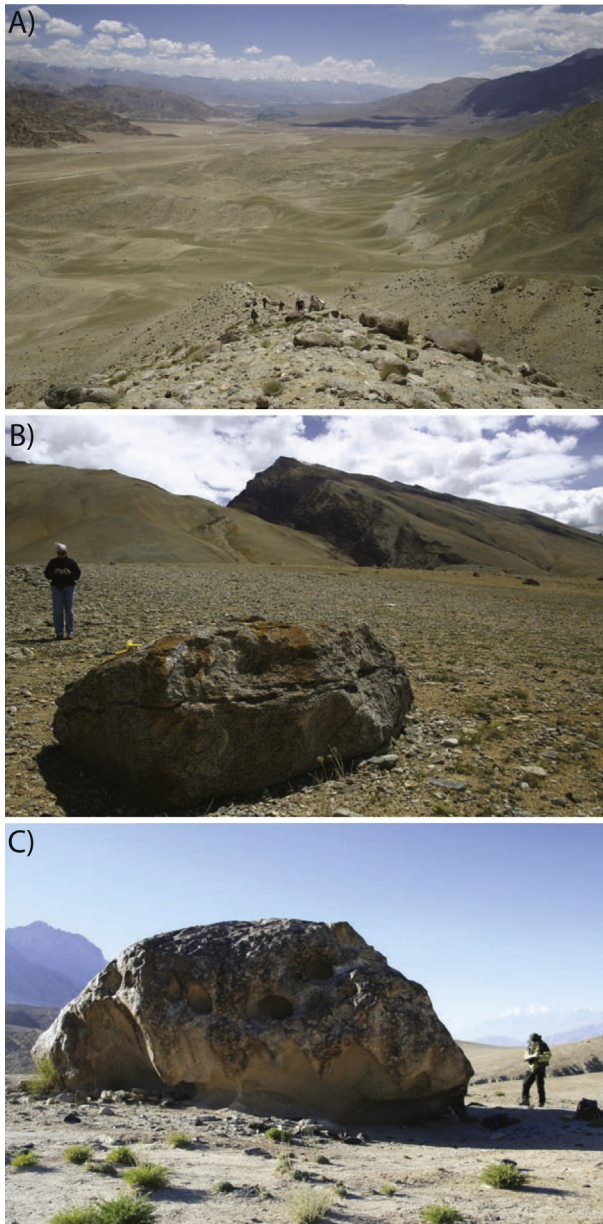


Fig. 16. Examples of evidence for very old glaciation in the Himalayan–Tibetan orogen. A) View looking east along the Indus Valley from a Leh glacial stage moraine (penultimate or older glacial cycle) towards Indus glacial stage moraines in the middle distance that date to more 430 ka (Owen et al., 2006a). B) Naimona'nyi glacial stage moraine dating to MIS 10 or older in the foreland of the Ronggua Gorge on the west side of Gurla Mandata. This particular boulder was dated using ^{10}Be TCN to $\sim 482 \pm 48$ ka (Owen et al., 2010). C) Dabudaer glacial stage moraine near the mouth of the Jialongquite valley in the Tashkurgan valley, which dates to penultimate or an earlier glacial cycle. This particular boulder was dated to 291 ± 20 ka using ^{10}Be TCNs (Owen et al., 2012).

Asian monsoon. In particular, the peak centered around MIS 3 supports the view that glaciers advanced during a time of increased insolation, which helped drive the monsoon influence farther into the orogen resulting in increased precipitation and cloudiness, further resulting in positive glacier mass balances (e.g. Finkel et al., 2003; Owen et al., 2003a, 2005, 2006b, 2009; Rupper et al., 2009). Moreover, the ages and glacial geologic evidence shows that, in many regions of the Himalayan–Tibetan orogen, glaciers advanced to their largest extents earlier in the last glacial cycle than the

northern hemisphere ice sheets, thus supporting the views of Gillespie and Molnar (1995) and Thackray et al. (2008).

The probability distribution frequency plots also show a significant Lateglacial advance (Fig. 18C). The peaks are broad and it is not possible to assign the advance to a particular stadial such as the Younger Dryas.

Fig. 19 examines regional variability in more detail. The picture that emerges is complex, it being evident that many of the glacial advances span long durations, in some cases many tens of thousands of years. This largely reflects the uncertainty in the chronological control. As a consequence, it is clear that a lot of age data are dispersed within probability distribution frequency plots but, nevertheless, the plots are useful for examining possible broad trends. The bars representing glacial advances shown in Fig. 19 are color coded to help recognize correlations. Particularly notable is the lack of glacial advances prior to the Lateglacial in many of the monsoon-influenced regions of the Himalaya and Tibet. Possible reasons for this were discussed above. Notable glacial advances occurred during the Lateglacial, early Holocene, mid-Holocene, Neoglacial and during the last millennia in nearly all areas. The data suggest broad patterns with glaciers responding at Milankovitch and sub-Milankovitch frequencies; it is likely that, for most regions both the monsoon and mid-latitude westerlies force glaciation, albeit to different extents. This makes it difficult to correlate glacial stages across the orogen.

When considered in more detail, the patterns are even more complex. Fig. 20, for example, highlights the main study areas at the western end of the Himalayan–Tibetan orogen. The timing of the local last glacial maximum is indicated on the left of the figure, with approximate maximum extents of glaciation. ELA data are not presented because of the complexity of determining them for each region (see Benn and Lehmkuhl, 2000; Benn et al., 2005; Owen and Benn, 2005 for more discussion). The pattern that emerges is very complex with the local last glacial maximum occurring at very different times across the western end of the orogen. Fig. 20 also compares these data with the climate modeling presented in Bishop et al. (2010) that covers the same aerial extent. The variation in snowfall across the region and between time slices is striking. Although the modeling focuses on the global LGM and the Holocene, it illustrates the complex and differing patterns across the region at different times. It is therefore not surprising that the style and timing of glaciation across the orogen is complex.

Despite this complexity, Dortch et al. (2013) examined the glacial successions and ^{10}Be ages across the semi-arid regions at the western end of the Himalayan–Tibetan orogen to develop a regional framework for glaciation across these dryland regions. Using Gaussian separation, Dortch et al. (2013) recognized nineteen regional glacial stages that they named the semi-arid western Himalayan–Tibetan stages (SWHTS). These are illustrated in Fig. 21. The data suggest that regional glacial stages older than 21 ka are broadly correlated with a greater monsoonal influence. SWHTS that are 21 ka or younger have smaller uncertainties and broadly correlate with global ice volume as defined by marine oxygen isotope stages and northern hemisphere climatic events (Oldest Dryas, Older Dryas, Younger Dryas, Roman Humid Period, and Little Ice Age). The pattern of glaciation that emerges shows no significant spatial clustering within the study area even though several correlative advances throughout the region were identified. The lack of spatial grouping and correlation between glacial chronologies and climatic records led Dortch et al. (2013) to speculate that the arid regions respond to small fluctuations in precipitation brought via the mid-latitude westerlies, sediments being subsequently wiped out by larger, less frequent monsoon driven advances. This view is in agreement with Seong et al. (2009a) regarding westerly control of post-LGM advances outlined below.

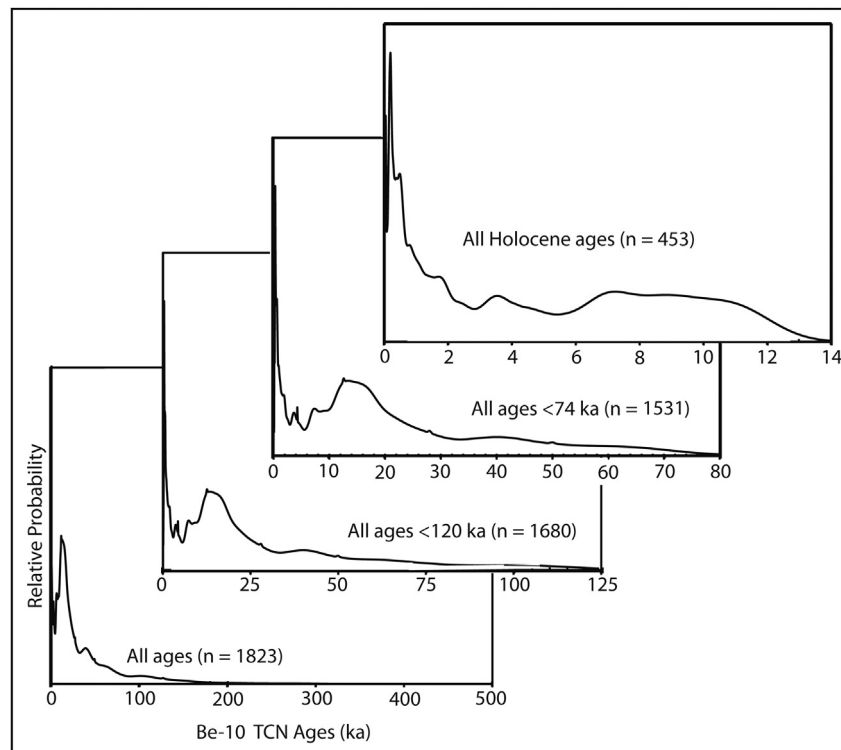


Fig. 17. Probability distribution plots for ^{10}Be TCN moraine boulder ages for the Himalayan–Tibetan orogen presented for different time slices. All ages were recalculated using the Lal (1991)–Stone (2000) time dependent model (see Appendix 1 for the data).

Using the methods of Dortch et al. (2013), Murari et al. (2014), together with new ^{10}Be -ages to define the timing of glaciation in SW Garhwal, examined the glacial chronologies throughout the monsoon-influenced regions of the Himalaya. They recognized 29 regional glacial stages, which they called monsoon-influenced Himalayan–Tibet stages (MOHITS). Murari et al. (2014) suggest that there are strong correlations with both periods of strong monsoons and northern hemisphere events throughout the entire chronologic range. They identify 16 stages linked to the monsoon and 11 stages linked to the mid-latitude westerlies (two unassigned) with a complex pattern of glaciation influenced by two climatic systems since the mid/late Quaternary. The larger number of regional glacial stages compared to the semi-arid regions suggests more frequent moraine deposition during the last glacial cycle and the Holocene. However, this may be an artifact of the larger number of dated glacial sediments and landforms in the monsoon influenced regions.

Comparison between the semi-arid and monsoon influenced regions are shown in Fig. 21 and visually compared with the SWHTS, and statically compared using the student *t*-test in Table 4. We recognize that much care must be taken when making such correlations within between regions as large as the Himalayan–Tibetan orogen because some detailed complexity may be lost with grouping of data statistically. However, the correlations provide a framework for future studies. Moreover, it is very striking the large dataset is now developing to define the timing of glacier oscillations throughout the region over the last half million years, and the high frequency of those oscillations.

7. Holocene glaciation

Zhou et al. (1991), Yi et al. (2008) and Owen (2011) provide useful summaries of the nature of Holocene glacier fluctuations in

the Himalaya and Tibet. In particular, Owen (2011) drew attention to the paucity of comprehensive studies of Holocene glaciation in the region, but emphasized the potential to derive a high-resolution (sub-millennial scale) record of glaciation for paleoclimatic change using the Holocene glacial record. This is because the Holocene glacial record is better preserved than older moraine successions and numerical dating can be more readily and successfully applied to younger moraines. The Yi et al. (2008) review included a compilation of 53 radiocarbon ages for Holocene glacial advances in Tibet, which they argued that glaciers advanced at 9.4–8.8 ka, 3.5–1.4 ka, and 1.0–0.13 ka, suggesting that glaciation in Tibet is synchronous with cooling periods identified in the $\delta^{18}\text{O}$ record of ice core. Zhou et al. (1991) showed that Holocene continental glaciers in northwest China advanced at ~9.3 ka, 6.4 ka, 4.5 ka, and 0.5 ka (~8300, 5700, 4000 and 400 ^{14}C years BP), while maritime-influenced glaciers in southeastern Tibet advanced at 3.1 ka, 1.9 ka, 0.9 ka, and 0.3 ka (~3000, 2000, 1000, and 200 ^{14}C years BP), arguing for a 2500-year climate cycle at ~9.3 ka, 6.4 ka, 3.2 ka and 0.3 ka (8300, 5700, 3000 and 200 ^{14}C years BP), and a ~1000-year climate cycle at 3.2 ka, 1.9 ka, 0.9 ka, and 0.3 ka (~3000, 2000, 1000, and 200 ^{14}C years BP).

Röthlisberger and Geyh (1985a,b) and Seong et al. (2009a) are arguably the two most significant quantitative studies of Holocene moraines in the Himalayan–Tibetan orogen that present primary data. Both studies also included an examination of global LGM and Lateglacial moraines. Röthlisberger and Geyh (1985a,b), presented 68 radiocarbon ages from around 16 different glaciers in Pakistan, India and Nepal to show that glaciers advanced at ~8.3 ka, 5.4–5.1 ka, 4.2–3.3 ka, and 2.7–2.2 ka (7400, 4900–4600, 3700–3100, 2700–2100 ^{14}C years BP) with relatively small extensions at 2.6–2.4 ka (2500–2300 ^{14}C years BP), 1.7–1.4 ka, 1.3–0.9 ka, 0.8–0.55 ka and 0.5–0.1 ka (1700–1500, 1200–950, 800, 550 and 400–100 ^{14}C years BP; Fig. 9).

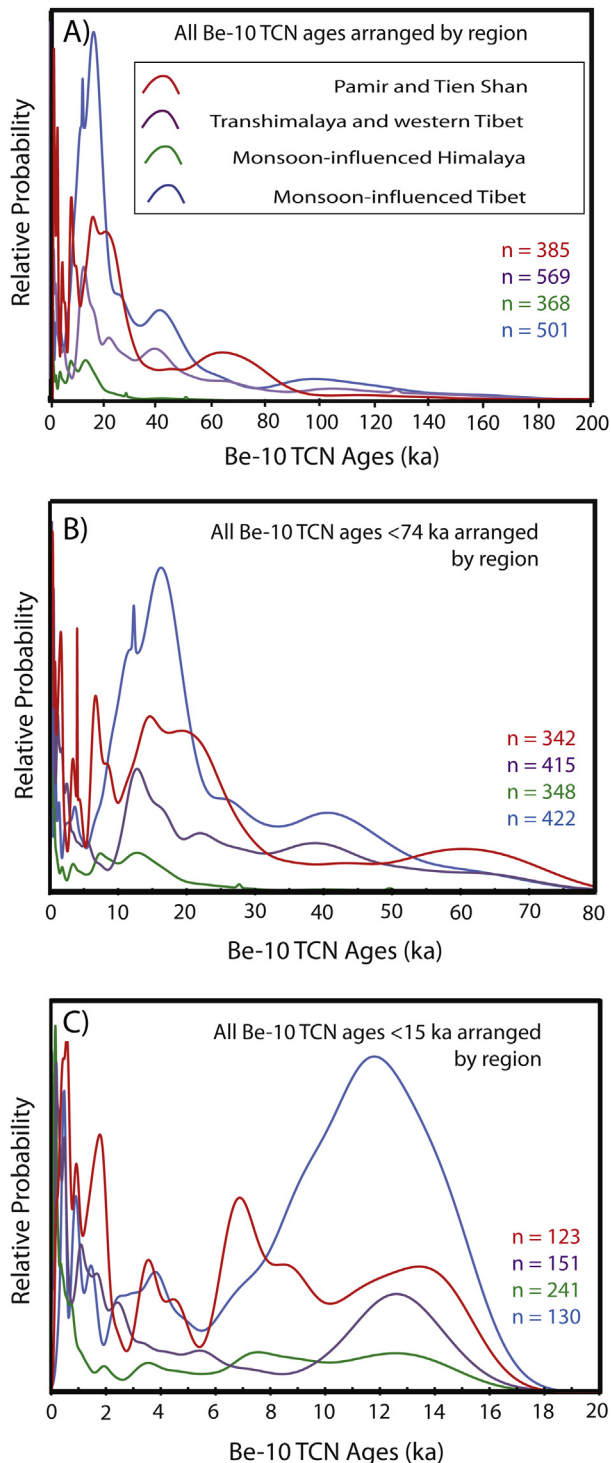


Fig. 18. Probability distribution frequency plots for ^{10}Be TCN moraine boulder ages for different time slices for four regional subdivisions of the Himalayan–Tibetan orogen building on the methods of Owen et al. (2008a). Compared to Owen et al. (2008a), the data set has increased from 777 to >1700 ages (see Appendix 1 for data). All ages were recalculated using the Lal (1991)–Stone (2000) time dependent model.

The study of Seong et al. (2009a) utilized ^{10}Be TCN dating of moraines around Mustah Ata and Kongur Shan in the Chinese Pamir to show that glaciers advanced at ~ 11.2 ka, 10.2 ka, 8.4 ka, 6.7 ka, 4.2 ka, 3.3 ka, 1.4 ka, and at a few hundred years before the present (Fig. 22). They argued that, since the global LGM, glaciers in

western Tibet likely responded to Northern Hemisphere climate oscillations, with minor influences from the south Asian monsoon, responding on millennial timescales to Holocene rapid climate changes that were highlighted by Bond et al. (1997, 2001) and Mayewski et al. (2004) (Fig. 22).

The probability distribution plots in Fig. 18C, and introduced in the previous section, show significant early Holocene peaks. The early Holocene advance likely reflects similar monsoonal forcing to the MIS 3 advance, since this was a time of increased insolation and enhanced monsoonal influence. Climate modeling supports the view that increased precipitation and snowfall throughout much of the Himalayan–Tibetan region took place during the early Holocene (Bush, 2004; Li and Harrison, 2008; Rupper et al., 2009; Bishop et al., 2010). Rupper et al. (2009) argued that an increase in cloudiness reduces incoming shortwave radiation that results in greater cooling at the surface of the glacier and accounts for more of the ELA lowering than an increase in monsoon precipitation. Multiple peaks are evident for the mid- and late Holocene, representing millennial-scale glacier oscillations. These glacial advances may reflect periods of rapid climate change influenced by teleconnections to Northern Hemisphere climate systems as suggested by Seong et al. (2009a) and Owen (2009).

As Owen (2009) underscored, these studies support the view that Himalayan and Tibetan glaciers oscillated at a comparable frequency to that recognized in ice cores from the Greenland Ice Sheet and in deep-sea sediment cores from the North Atlantic, where a quasi-periodicity of ~ 1470 years is apparent throughout the Lateglacial and Holocene (Bond et al., 1997, 2001). Seong et al. (2009a) and Owen (2009) pointed out that the duration of quasi-periodicity of glacial oscillations throughout the Holocene is similar to climatic oscillations recognized in the North Atlantic by Mayewski et al. (2004), and suggested that regional climate change in Tibet may well be forced by teleconnections via mid-latitude westerlies and Atlantic climate change. Moreover, Owen (2009) suggested that it is likely that as many as eight significant glacial advances would be expected to have occurred throughout the Holocene in Himalayan–Tibetan regions. He also stressed that rapid climate change and accompanied glacial oscillations is also supported by the ice core data from Tibetan ice sheets, which show short (millennial–centennial) abrupt oscillations in climate throughout the Late Quaternary (Thompson et al., 1989, 1997; Yao et al., 1996, 1997; Thompson, 2000). In addition, Dortch et al. (2013) recognized late-Pleistocene and early Holocene glacial advances that correlate with Heinrich events. They documented three regional glacial advances during the later part of the Holocene in the semi-arid western end of the Himalayan–Tibetan orogen at 3.7 ± 0.6 ka (SWHT 1C), 1.6 ± 0.3 ka (SWHTS 1B) and 0.4 ± 0.1 ka (SWHTS 1A) that they argue broadly correlate with Northern Hemisphere climatic events (Fig. 21).

Unlike many other mountain regions throughout the world, the most extensive glacial advance during the Holocene in the Himalayan–Tibetan orogen occurred during the early Holocene (cf. Clapperton, 1993; Porter, 2000; Grove, 2004). This advance is represented by impressive suites of sharp-crested moraines which have been dated by numerous researchers using radiocarbon, OSL and TCN methods to between ~ 11.5 and 8.0 ka (Shiraiwa, 1993; Sharma and Owen, 1996; Phillips et al., 2000; Richards et al., 2000a; Owen et al., 2001, 2002b, 2003a,c, 2005, 2006a,b; Finkel et al., 2003; Zech et al., 2003a,b, 2005; Barnard et al., 2004a,b, 2006; Spencer and Owen, 2004; Abramowski et al., 2006; Jiao and Shen, 2006; Seong et al., 2007, 2009a; Meyer et al., 2009; Chevalier et al., 2011). The extent of glacial advances and ELA depressions during the early Holocene varies considerably between regions; for example, glaciers only advanced a few kilometers in the Muztag Ata-Konga Shan and Hunza regions with an ELA depression of

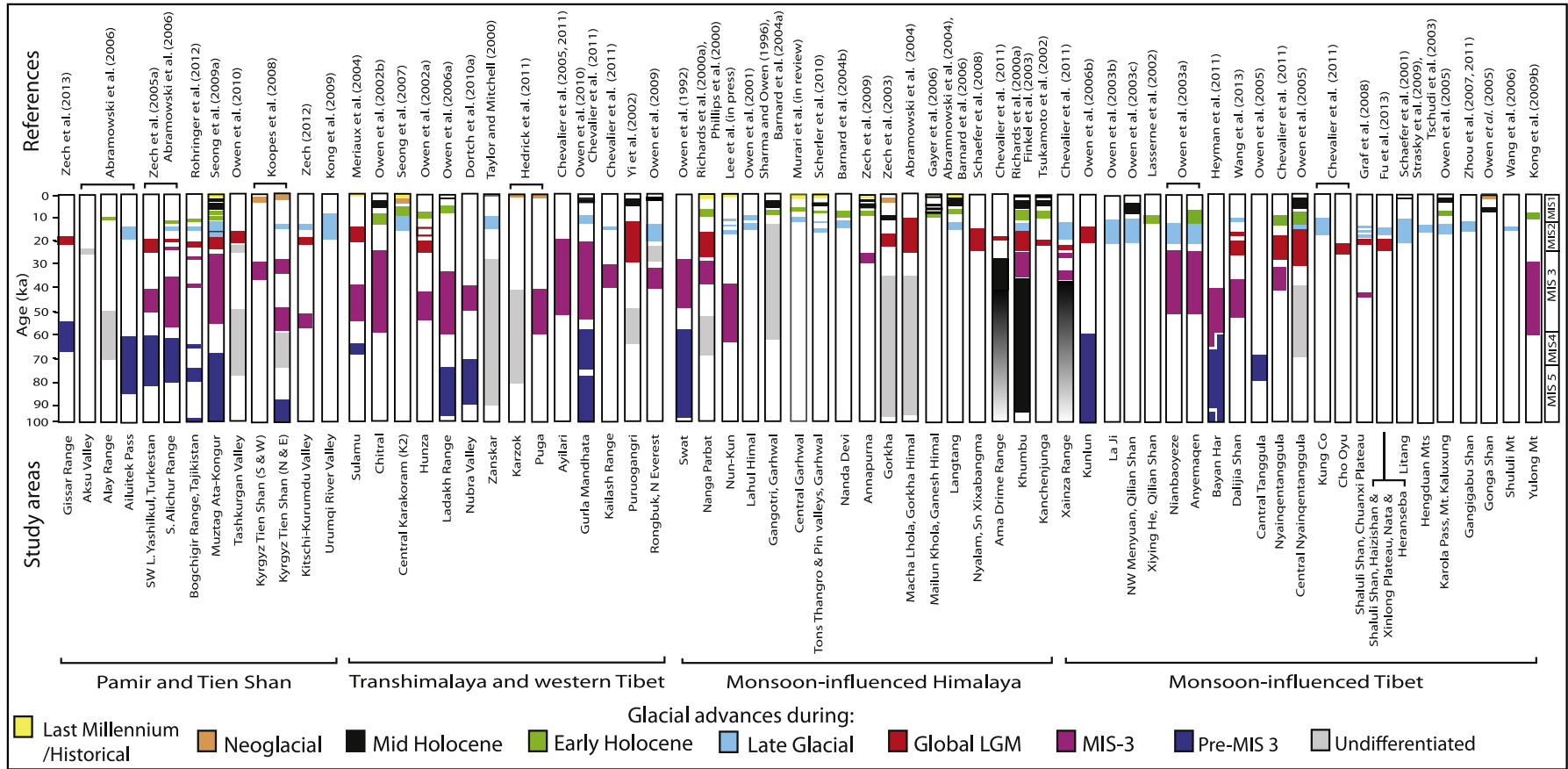


Fig. 19. Simplified glacial chronologies for each region in the Himalayan–Tibetan orogen back to 100 ka (adapted from Owen et al., 2012). The color bars represent times of glacial advances and their duration includes the likely uncertainty in the ages. The color scheme is used to suggest tentative regional correlations. Marine Oxygen Isotope Stages are shown to the far right.

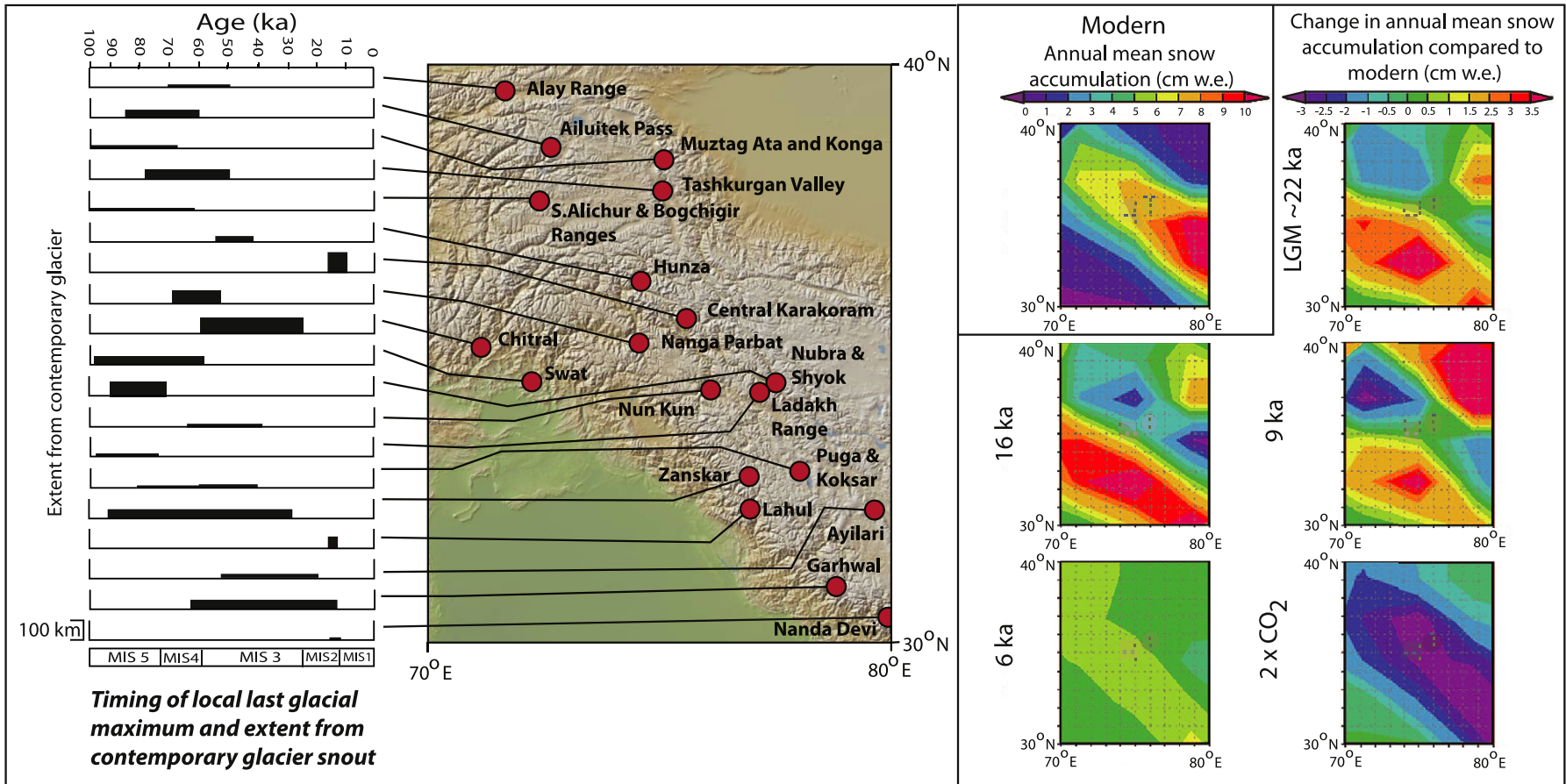


Fig. 20. Glacial geologic study areas at the western end of the Himalayan–Tibetan orogen showing the ages of local last glacial maxima and approximate extent of valley glaciation. Data from Owen et al. (1992, 2001, 2010, 2002b, 2002a, 2006a), Sharma and Owen (1996), Phillips et al. (2000), Richards et al. (2000a), Taylor and Mitchell (2000), Barnard et al. (2004a, b), Zech et al. (2005), Chevalier et al. (2005, 2011), Abramowski et al. (2006), Seong et al. (2009a), Dortch et al. (2010a, 2011b,c), Hedrick et al. (2011), Röhringer et al. (2012) and Lee et al. (2014). The area shown in the right panel is same area that was modeled by Bishop et al. (2010) using a seventy-year simulation with a fully coupled atmosphere-ocean general circulation model for the global LGM, 16 ka, 9 ka, 6 ka and a doubling of CO₂.

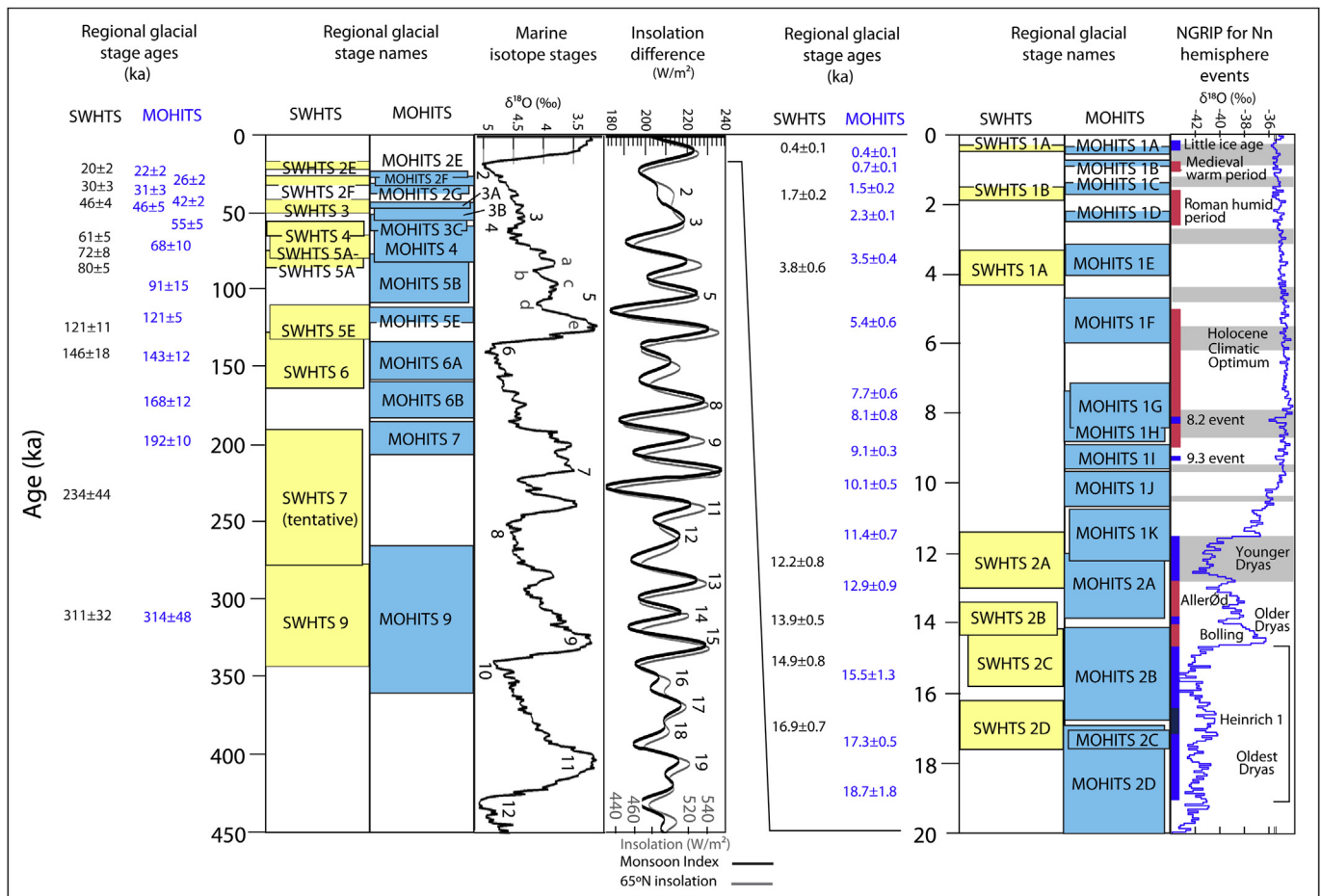


Fig. 21. Age plot of regional glacial stages (semi-arid western Himalaya–Tibetan Stage: SWHTS) for the semi-arid regions at the western end of the Himalayan–Tibetan orogen defined by Dortch et al. (2013) and for the monsoon-influenced Himalayan–Tibetan orogen (monsoon Himalayan–Tibetan stages: MOHITS) defined by Murari et al. (2014). Ages for regional glacial stages are distinct at the 95% confidence interval despite some overlap. SWHTS calculations were based on 352 out of 695 ^{10}Be ages that were analyzed; 98 failed the cluster analysis, 192 and 50 were excluded for being too young and too old, respectively. MOHITS calculations were based on 520 out of 1119 ^{10}Be ages that were analyzed; 185 failed the cluster analysis, 316 and 98 were excluded for being too young and too old, respectively. Stacked marine $\delta^{18}\text{O}$ curves of Lisiecki and Raymo (2005), simulated monsoon index and 65°N insolation of Leuschner and Sirocko (2003) and the NGRIP (2004) $\delta^{18}\text{O}$ curve are provided for comparison. The duration of specific climatic events are marked by red and dark blue bars in the far right column. Light gray horizontal bands in the far right column indicate times of rapid climate change after Mayewski et al. (2004).

<200 m (Benn et al., 2005; Seong et al., 2009c) as compared to the Central Karakoram where glaciers advanced several tens of kilometers with an ELA depression of >500 m (Seong et al., 2009b). The disparity of ELA depression may be due to relief control of precipitation as outlined by Bookhagen and Burbank (2006), with the high-relief Karakoram receiving more precipitation due to orographic effects.

Fig. 19 highlights this early Holocene regional signal, but the resolution of the dating in most of the studies, which generally utilize TCN methods, is too coarse to determine whether this apparent correlation is synchronous on a millennial scale. Moreover, most of the dating does not allow us to distinguish whether the early Holocene advance was synchronous with the early Holocene insolation maximum, and hence is a monsoon signal, or the 8.5 ka cold event, or both. Reducing the dating uncertainty on early Holocene moraines is clearly an area that needs attention in order to advance understanding of the nature of early Holocene glaciation and climate change.

Owen (2011) pointed out that mid-Holocene (~8.0–3.0 ka, Hypsithermal) moraines have been dated in several regions of the Himalaya and Tibet. These moraines are generally well preserved and often comprise latero-frontal moraine complexes. As Owen

(2011) points out, the Hypsithermal has yet to be adequately defined by glacial geologic proxies for the Himalaya and Tibet and the use of the term in this region should therefore be used very conservatively. Moreover, it may be diachronous in monsoonal Asia (An et al., 2000). Significant glacial advances (a few kilometers beyond present ice margins) have been recognized, however, for selected glaciers in Tibet (Zhou et al., 1991), in the Khumbu Himal (Finkel et al., 2003), the Diancang Mountain in the Hengduan Range (Yang et al., 2006), Qilian Shan (Wu, 1984a), and in Muztag Ata and Konga Shan (Seong et al., 2009a). Climatic simulations support the view that increased monsoon precipitation and cloudiness, and summer cooling over the Himalaya and Tibet would have helped force glaciation during the mid-Holocene, albeit not as great as during the early Holocene (Bush, 2002, 2004; Li and Harrison, 2008; Rupper et al., 2009).

Many studies have attributed sharp-crested, well-preserved moraines within a kilometer of the present glacier margin to the Neoglaciation, which is younger than ~3–2.7 ka (e.g. Benedict, 1976; Fushimi, 1978; Derbyshire et al., 1984; Wu, 1984a; Zheng, 1997; Richards et al., 2000a; Finkel et al., 2003; Owen et al., 2005; Jiao and Shen, 2006; Meyer et al., 2009; Seong et al., 2009a). Yet many of these studies do not have adequate

Table 4

Regional glaciers stages of Dortch et al. (2013) and Murari et al. (2014) for the semi-arid western end and the monsoonal-influenced areas of the Himalayan–Tibetan orogen, respectively. Student's *T*-Test is utilized to compare the populations of TCN ages between glacial stages in the two regions. The resulting *P*-values are presented in the middle column where bold numbers indicate failure to reject the null hypothesis and the possibility of the two stages being correlative is good. Italicized *P*-values indicate the regional stage is distinct from all other regional stages at $\geq 95\%$ confidence interval; in these cases, the highest *P*-value is presented.

Semi-arid western end of the Himalayan–Tibetan orogen		<i>P</i> -value	Monsoon-influenced Himalayan–Tibetan orogen	
Regional glacial stage name	Age		Regional glacial stage name	Age
SWHTS9	311 ± 32	0.00	MOHITS10	483 ± 38
SWHTS7	234 ± 44	0.92	MOHITS9	314 ± 48
		0.18	MOHITS7	192 ± 10
		0.04	MOHITS6B	168 ± 12
SWHTS6	146 ± 18	0.64	MOHITS6A	143 ± 12
SWHTS5E	121 ± 11	0.97	MOHITS5E	121 ± 5
		0.02	MOHITS5B	91 ± 15
SWHTS5A	80 ± 5	0.02		
SWHTS5A-	72 ± 8	0.00		
SWHTS4	61 ± 5	0.12	MOHITS4	68 ± 10
		0.00	MOHITS3C	55 ± 5
SWHTS3	46 ± 4	0.75	MOHITS3B	46 ± 5
		0.00	MOHITS3A	42 ± 2
SWHTS2F	30 ± 3	0.25	MOHITS2G	31 ± 3
		0.01	MOHITS2F	26 ± 2
		0.00	MOHITS2E	22 ± 3
SWHTS2E	20 ± 2	0.03		
		0.03	MOHITS2D	18.7 ± 1.8
SWHTS2D	16.9 ± 0.7	0.21	MOHITS2C	17.3 ± 0.3
SWHTS2C	14.9 ± 0.8	0.23	MOHITS2B	15.5 ± 1.3
SWHTS2B	13.9 ± 0.5	0.00		
SWHTS2A	12.2 ± 0.8	0.01	MOHITS2A	12.9 ± 0.9
		0.00	MOHITS1K	11.4 ± 0.7
		0.00	MOHITS1J	10.1 ± 0.5
		0.00	MOHITS1I	9.1 ± 0.3
1E	8.7 ± 0.2	0.16	MOHITS1H	8.1 ± 0.8
1D	6.9 ± 0.1	0.00	MOHITS1G	7.7 ± 0.6
Askole 1	5.5 ± 0.3	0.42	MOHITS1F	5.4 ± 0.6
1C	3.8 ± 0.6	0.37	MOHITS1E	3.5 ± 0.4
PM-2	2.8 ± 1.2	0.54	MOHITS1D	2.3 ± 0.1
1B	1.7 ± 0.2	0.15	MOHITS1C	1.5 ± 0.2
Askole 3	1.1 ± 0.1	0.03	MOHITS1B	0.7 ± 0.1
1A	0.4 ± 0.1	0.25	MOHITS1A	0.4 ± 0.1

numerical dating to show moraines are, indeed, Neoglacial and the extensive early Holocene advance can be easily misinterpreted as Neoglacial. Moreover, as Owen (2011) points out, the onset of the Neoglacial in the Himalayan–Tibetan orogen may be asynchronous.

Pu (1991), for example, defines four Neoglacial advances (Neoglaciation I–IV) in western China, including Tibet, which date to ~9.2–7.8 ka, 6.7–5.6 ka, 3.6–2.4 ka, and 0.5–0.03 ka (~7000–8200, 4900–5800, 2400–3320 and 450–30 ^{14}C years BP). Clearly, by the definition of Neoglacial (see Porter and Denton, 1967;

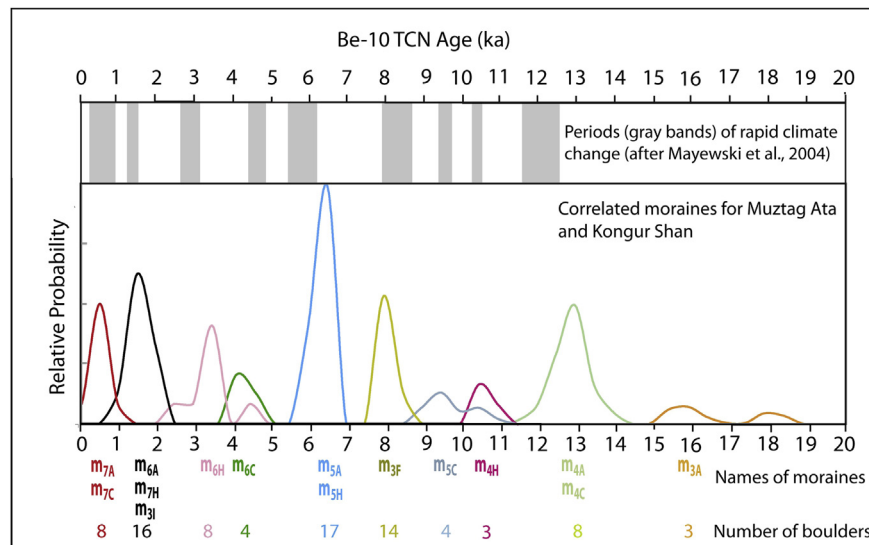


Fig. 22. Probability distribution plots for ^{10}Be TCN surface-exposure ages for glacial advances in Muztag Ata and Kongur Shan in the Chinese Pamir for the last 20 ka (after Seong et al., 2009a). Moraines of similar advances are grouped with each different color representing a distinct glacial advance. Light gray bands indicate times of rapid climate change after Mayewski et al. (2004). The number of boulders dated per each advance is shown at the bottom of the figure.

Denton and Karlén, 1973; Porter, 2000), the first two of these advances did not occur in the Neoglacial. Therefore, as Owen (2011) emphasizes, confused nomenclature as well as the challenges of dating moraines adds to the complexity of understanding Holocene glaciation in the Himalayan–Tibetan orogen. Yang et al. (2008) showed three main periods of glacial advance at around 1.8–1.4 ka, 1.2–1.15 ka, and 0.6–0.08 ka in the Hengduan Mountains, the central and eastern parts of the Himalaya and the eastern Nyainqentanglha Range of SE Tibet. This complex array of ages suggests that glaciers likely would have been responding to climate change throughout the Himalayan–Tibetan orogen in a very complicated fashion.

Glacial advances during the Little Ice Age (LIA) in the Himalayan–Tibetan orogen are not well defined. There are few definitive studies providing ages on moraines that can be attributed to the LIA. The most notable ones include studies in the Khumbu Himal that have been dated by both radiocarbon and TCN methods (Benedict, 1976; Fushimi, 1978; Finkel et al., 2003). Yi et al. (2008) collates all the published radiocarbon ages for LIA moraines from Nyainqentanglha, Karakoram, Langtang, the western slopes of Namjagbarwa Peak in the eastern Himalaya and Gongga in SE Tibet to show that the LIA in Tibet had three substages between 1.0 and 0.13 ka. Dortch et al. (2013) showed that a significant regional glacial stage is recognized across the semi-arid western end of the Himalayan–Tibetan orogen at 0.4 ± 0.1 ka (Fig. 21).

8. Historical and predicted future changes

In most areas of the Himalayan–Tibetan orogen, glaciers began to retreat after the LIA at the beginning of the 20th Century and have continued to retreat since (Mayewski and Jeschke, 1979; Mayewski et al., 1980; Ono, 1984, 1985, 1986; Fujita et al., 1997; Ono et al., 1997; Shi and Lui, 2000; Su and Shi, 2002; Ren et al., 2004; Bolch et al., 2008). Cogley (2011) provides a comprehensive glacier inventory for the Himalaya and Karakoram containing 20,812 glaciers covering an area of 43,178 km². Undertaking a glacier-by-glacier analysis, Cogley (2011) suggests that up to about one-fifth of the glaciers present in 1985 may have disappeared. Furthermore, Cogley (2011) argues that, if mass loss were to remain constant at the average rate for 1975–2008, from 3000 to 13,000 more glaciers might disappear by 2035. Moreover, he suggests that if mass loss were to continue to accelerate as inferred for 1985–2008, only a few thousand to a few hundred glaciers might remain in 2035. Cogley (2011) acknowledges that these projections are uncertain and neglect some possibly important mitigating controls, but they demonstrate the need for more complete analyses to help define the reduction and assess its potential effects.

Su and Shi (2002) argue that, since the height of the LIA during 17th century, the mean temperature of temperate monsoonal glaciers in China has increased by 0.8 °C and their area has decreased by ~3900 km², an amount equivalent to 30% of the area of modern glaciers. Moreover, Su and Shi (2002) argue that if temperature rises by 2.1 °C as may be likely by the year 2100, then temperate monsoonal glaciers in China are likely to decrease by 75%, an ~9900 km² loss of area. Furthermore, if precipitation decreases as well, then the retreat of the glaciers will be even faster. However, Su and Shi (2002) argue that the area reduction percentage of the glaciers is unlikely to exceed 80%. Some regions have experienced accelerated glacier retreat in recent decades often resulting in the formation of impressive supraglacial lakes (Benn et al., 2001).

The rate of retreat over the past 30 years in some regions, however, has been less than during the earlier part of the 20th century (Copland et al., 2011). In some regions, certain glaciers have begun to stabilize and/or advance during the past few years. Some glaciers have even been remarkably stable, such as Baltoro Glacier

in northern Pakistan that has varied by no more than ± 200 m since the 1850s (Mayer et al., 2006). In some regions, such as the Karakoram, individual glaciers have advanced and retreated during the last century, sometimes surging (Hewitt, 1969, 2005; Barrand and Murray, 2006; Copland et al., 2011).

Predicting whether increasing mean annual temperatures due to human activity will cause glaciers to melt, retreat and eventually disappear is challenging. Other factors including, for example, increased deposition of black carbon on glaciers, will enhance melting. However, the large altitudinal range, and the complex topographic setting, and microclimatic variations make it difficult to quantify future temperature change and its net effect on glacier melting. In monsoon-influenced regions, predicted increased snowfall and increased cloudiness may lead to positive glacier mass balances. Consequently, some glaciers may thicken and advance. These glaciers may eventually retreat as the increase of mean annual temperature out-competes the increased glacier growth due to enhanced snowfall and cloudiness; this change may be rapid if summer snows become summer rain.

9. Future progress

Understanding of the nature, timing, and extent of Late Quaternary glaciation in the Himalayan–Tibetan orogen has advanced rapidly and significantly in the past decade or so, specifically aided by improvements in remote sensing and dating methods, but the vastness and the political and logistical inaccessibility of much of the region still present significant challenges. Numerical dating studies suggest that, on millennial timescales, glaciation is broadly synchronous throughout the orogen, but the exact timing and extent of glaciation varies considerably within and between different mountain ranges within Highland Asia. The complex patterns of glaciation that are emerging imply that glaciation throughout the Himalayan–Tibetan orogen reflects temporal and spatial variability of forcing by the different climatic systems that dominate the region. As Owen (2009, 2013) indicated the style and timing of glaciation appears to be strongly controlled by climatic gradients, but topography may also have an important control. Correlation between regions is hindered because of large uncertainties related to the dating methods, mainly TCN and OSL methods. Reducing these uncertainties and developing stronger correlations can be achieved by improving the dating methods, and by using two or more dating techniques (for example Owen et al., 2001, 2009). A productive area of research might include numerical modeling of landform degradation to help explain the distribution of TCN ages on landforms since a post-depositional modification of landforms results can result in significant underestimates of TCN ages. In spite of these challenges, geologic error outweighs uncertainties in current dating methodologies. In addition, the lack of a standard way in which to interpret TCN results can lead to erroneous correlations or the missing of valid correlations. Thorough numerical analysis of dating results using methods such as those described by Dortch et al. (2013) is beginning to allow regional glacial stages to be recognized, forming a stronger foundation for the study of Quaternary glaciation in the Himalayan–Tibetan realm.

Owen et al. (2005, 2009, 2010, 2012) and Owen (2013) pointed out that the extent of glaciation has become increasingly restricted throughout the Late Quaternary in the more arid regions of Highland Asia, which has helped preserve very old (pre-last glacial cycle) glacial landforms. In regions very strongly influenced by the monsoon, the preservation potential of pre-Late Glacial moraines is poor. Owen et al. (2005) suggest that this may be because Late-glacial and Holocene glacial advances were the most extensive, destroying the geomorphic or sedimentary evidence of earlier

glaciations, together with the intense fluvial and mass movement denudation that is characteristic of the wetter regions.

Mid-Holocene Neoglaciation, LIA, and historical glacial records testify to a progressive retreat of glaciers during the twentieth century and warn of a continued retreat during the coming century, but the pattern is complex and the glaciers may be asynchronous during these climatostratigraphic times. These are issues that need to be considered in more detail. Fortunately, because of the better preservation of the Holocene glacial record and because numerical dating can more readily be applied to Holocene landforms and sediment, we should target interesting times of climatic instability: the early Holocene, Neoglaciation, and specifically, the LIA. The use of other geologic proxies such as lake, aeolian and ice core records should be further utilized. Climatic and glacial modeling also has great potential to provide valuable information regarding the patterns and possible complexity of change.

In sum, the Himalayan–Tibetan orogen provides an exciting natural laboratory for the examination of the links between climatic and glacial systems which, in turn has important implications for the geomorphology and hydrology of the high mountains and their forelands in Asia. The numerous studies that have been undertaken in this region have established a broad framework, which can be also be used to develop and identify intriguing, more specific questions about climatic–glacial–erosional linkages.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quascirev.2013.11.016>.

References

- Abramowski, U., 2004. The Use of ^{10}Be Surface Exposure Dating of Erratic Boulders in the Reconstruction of the Late Pleistocene Glaciation History of Mountainous Regions, with Examples from Nepal and Central Asia (Unpublished PhD.). Universität Bayreuth, Germany, p. 167.
- Abramowski, U., Bergau, A., Seebach, D., Zech, R., Glaser, B., Sosin, P., Kubik, P.W., Zech, W., 2006. Pleistocene glaciations of Central Asia: results from ^{10}Be surface exposure ages of erratic boulders from the Pamir (Tajikistan) and the Alay–Turkistan range (Kyrgyzstan). *Quat. Sci. Rev.* 25, 1080–1096.
- Ali, S.N., Biswas, R.H., Shukla, A.D., Juyal, N., 2013. Chronology and climatic implications of Late Quaternary glaciations in the Goriganga valley, central Himalaya, India. *Quat. Sci. Rev.* 73, 59–76.
- An, Z., Porter, S.C., Kutzbach, J.E., Wu, X., Wang, S., Liu, X., Li, X., Zhou, W., 2000. Asynchronous Holocene optimum of the East Asian monsoon. *Quat. Sci. Rev.* 19, 743–762.
- Aoki, T., Imamura, M., 1999. Reconstructing the glacial chronology based on the ^{10}Be exposure age in the Khumbu Glacier, Eastern Nepal Himalaya. In: Proceedings of the Korea–Japan/Japan–Korea Geomorphological Conference, pp. 134–135.
- Applegate, P.J., Urban, N.M., Laabs, B.J.C., Keller, K., Alley, R.B., 2010. Modeling the statistical distributions of cosmogenic exposure dates from moraines. *Geosci. Model Develop.* 3, 293–307.
- Bagla, P., 2009. No sign yet of Himalayan meltdown, Indian report finds. *Science* 326, 924–925.
- Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quat. Geochronol.* 8, 174–195.
- Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., Schaefer, J.M., 2009. Regional beryllium–10 production rate calibration for northeastern North America. *Quat. Geochronol.* 4, 93–107.
- Barnard, P.L., Owen, L.A., Finkel, R.C., 2004a. Style and timing of glacial and paraglacial sedimentation in a monsoonal influenced high Himalayan environment, the upper Bhagirathi Valley, Garhwal Himalaya. *Sediment. Geol.* 165, 199–221.
- Barnard, P.L., Owen, L.A., Sharma, M.C., Finkel, R.C., 2004b. Late Quaternary (Holocene) landscape evolution of a monsoon-influenced high Himalayan valley, Gori Ganga, Nanda Devi, NE Garhwal. *Geomorphology* 61, 91–110.
- Barnard, P.L., Owen, L.A., Finkel, R.C., Asahi, K., 2006. Landscape response to deglaciation in a high relief, monsoon-influenced alpine environment, Langtang Himal, Nepal. *Quat. Sci. Rev.* 25, 2162–2176.
- Barrand, N.E., Murray, T., 2006. Multivariate controls on the incidence of glacier surging in the Karakoram Himalaya. *Arct. Antarct. Alp. Res.* 38, 489–498.
- Barry, R.G., Chorley, R.J., 2003. Atmosphere, Weather, and Climate, eight ed. Routledge, London.
- Bäumler, R., Zech, W., Ni, A.A., Savoskul, O., 1999. Soil geographical and pedo-geochemical studies on Pleistocene and Holocene glaciation in the North-western Tien Shan (Uzbekistan). *Z. Gletsch. Glazialgeol.* 35, 147–173.
- Benedict, J.B., 1976. Khumbu glacier series, Nepal. In: Buckley, J. (Ed.), *Isotopes' Radiocarbon Measurements XI Radiocarbon*, vol. 18, pp. 177–178.
- Benn, D.I., Lehmkuhl, F., 2000. Mass balance and equilibrium-line altitudes of glaciers in high mountain environments. *Quat. Int.* 65/66, 15–29.
- Benn, D.I., Owen, L.A., 1998. The role of the Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation: review and speculative discussion. *J. Geol. Soc.* 155, 353–363.
- Benn, D.I., Owen, L.A., 2002. Himalayan glacial sedimentary environments: a framework for reconstructing and dating former glacial extents in high mountain regions. *Quat. Int.* 97/98, 3–26.
- Benn, D.I., Wiseman, S., Hands, K.A., 2001. Growth and drainage of supraglacial lakes on debris-mantled Ngozumpa Glacier, Khumbu Himal, Nepal. *J. Glaciol.* 47, 626–638.
- Benn, D.I., Owen, L.A., Osmaston, H.A., Seltzer, G.O., Porter, C.S., Mark, B., 2005. Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers. *Quat. Int.* 138/139, 8–21.
- Bishop, M.P., Bush, A., Copland, L., Kamp, U., Owen, L.A., Seong, Y.B., Shroder, J.F., 2010. Climate change and mountain topographic evolution in the central Karakoram, Pakistan. *Ann. Geogr.* 100, 1–22.
- Böhner, J., 2006. General climatic controls and topoclimatic variations in Central and High Asia. *Boreas* 35, 279–295.
- Bolch, T., Buchroithner, M.F., Pieczonka, T., Kunert, A., 2008. Planimetric and volumetric glacier changes in the Khumbu Himalaya since 1962 using Corona, Landsat TM and ASTER data. *J. Glaciol.* 54, 592–600.
- Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* 278, 1257–1266.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* 294, 2130–2136.
- Bookhagen, B., Burbank, D.W., 2006. Topography, relief, and TRMM-derived rainfall variations along the Himalaya. *Geophys. Res. Lett.* 33, L08405. <http://dx.doi.org/10.1029/2006GL026037>.
- Bookhagen, B., Thiede, R.C., Strecker, M.R., 2005. Late Quaternary intensified monsoon phases control landscape evolution in the northwest Himalaya. *Geology* 33, 149–152.
- Bookhagen, B., Burbank, D.W., 2010. Towards a complete Himalayan hydrological budget: the spatiotemporal distribution of snow melt and rainfall and their impact on river discharge. *J. Geophys. Res. Earth Surf.* <http://dx.doi.org/10.1029/2009Jf001426>.
- Bräuning, A., 2006. Tree-ring evidence of “Little Ice Age” glacier advances in southern Tibet. *Holocene* 16, 369–380.
- Briner, J.P., Kaufman, D.S., Manley, W.F., Finkel, R.C., Caffee, M.W., 2005. Cosmogenic exposure dating of late Pleistocene moraine stabilization in Alaska. *Geol. Soc. Am. Bull.* 117, 1108–1120.
- Briner, J.P., Young, N.E., Goehring, B.M., Schaefer, J.M., 2012. Constraining Holocene ^{10}Be production rates in Greenland. *J. Quat. Sci.* 27, 2–6.
- Brown, E.T., Bendick, R., Bourles, D.L., Gaur, V., Molnar, P., Raisbeck, G.M., Yiou, F., 2002. Slip rates of the Karakoram fault, Ladakh, India, determined determined using cosmic ray exposure dating of debris flows and moraines. *J. Geophys. Res.* 107 (B9), 2192, 7–1–7–8.
- Brozović, N., Burbank, D.W., Meigs, A.J., 1997. Climatic limits on landscape development in the northwestern Himalaya. *Science* 276, 571–574.
- Burbank, D.W., Fort, M.B., 1985. Bedrock control on glacial limits: examples from the Ladakh and Zaskar Ranges, north-western Himalaya, India. *J. Glaciol.* 31, 143–149.
- Burbank, D.W., Kang, J.C., 1991. Relative dating of Quaternary moraines, Rongbuk Valley, Mount Everest, Tibet: implications for an ice sheet on the Tibetan Plateau. *Quat. Res.* 36, 1–18.
- Bush, A.B.G., 2002. A comparison of simulated monsoon circulations and snow accumulation in Asia during the mid-Holocene and at the Last Glacial Maximum. *Global Planet. Change* 32, 331–347.
- Bush, A.B.G., 2004. Modeling of late Quaternary climate over Asia; a synthesis. *Boreas* 33, 155–163.
- Chevalier, M.-L., Ryerson, F.J., Tapponnier, P., Finkel, R.C., Van Der Woerd, J., Haibing, L., Qing, L., 2005. Slip-rate measurements on the Karakoram Fault may imply secular variations in fault motion. *Science* 307, 411–414.
- Chevalier, M.-L., Hilley, G., Tapponnier, P., Van Der Woerd, J., Liu-Zeng, J., Finkel, R.C., Ryerson, F.J., Li Haibing, L., Liu, X., 2011. Constraints on the late Quaternary

- glaciations in Tibet from cosmogenic exposure ages of moraine surfaces. *Quat. Sci. Rev.* 30, 528–554.
- Chinese Academy of Sciences, 1996. *Physical Geography and Natural Resources in the Mount Nanjiabawa Region*. Science Press, Beijing, pp. 1–210 (in Chinese).
- Clapperton, C., 1993. *Quaternary Geology and Geomorphology of South America*. Elsevier, Amsterdam.
- Cogley, J.G., 2011. Present and future states of Himalaya and Karakoram glaciers. *Ann. Glaciol.* 52, 69–73.
- Colgan, P.M., Munroe, J.S., Zhou, S., 2006. Cosmogenic radionuclide evidence for the limited extent of last glacial maximum glaciers in the Tanggula Shan of the central Tibetan Plateau. *Quat. Res.* 65, 336–339.
- Copland, L., Sylvestre, T., Bishop, M.P., Shroder, J.F., Seong, Y.B., Owen, L.A., Bush, A., Kamp, U., 2011. Expanded and recently increased glacier surging the Karakoram. *Arct. Alp. Antarct. Res.* 43, 503–516.
- Cronin, V.S., Johnson, W.P., Johnson, N.M., Johnson, G.D., 1989. Chronostratigraphy of the upper Cenozoic Buntang sequence and possible mechanisms controlling base level in Skardu intermontane basin, Karakoram Himalaya, Pakistan. *Geol. Soc. Am. Spec. Pap.* 232, 295–309.
- Dainelli, G., 1924–35. *Relazioni Scientifiche della Spedizione Italiana De Filippi nell'Himalaia, Caracorum e Turchestan Chinese (1913–1914)*. Series II, vol. 10. Zanichelli, Bologna.
- De Terra, H., Paterson, T.T., 1939. *Studies on the Ice Age in India and associated human cultures*, vol. 493. Carnegie Institute of Washington Publications, p. 354.
- Denton, G.H., Karlén, 1973. Holocene climatic variations – their pattern and possible cause. *Quat. Res.* 3, 155–205.
- Derbyshire, E., 1981. Glacier regime and glacial sediment facies: a hypothetical framework for the Qinghai-Xizang Plateau. In: *Proceedings of Symposium on Qinghai-Xizang (Tibet) Plateau*, Beijing, China. Geological and Ecological Studies of Qinghai-Xizang Plateau, vol. 2. Science Press, Beijing, pp. 1649–1656.
- Derbyshire, E., 1982. Glacier regime and glacial sediment facies: a hypothetical framework for the Qinghai-Xizang Plateau. In: *Proceedings of Symposium on Qinghai-Xizang (Tibet) Plateau*, Beijing, China. Geological and Ecological Studies of Qinghai-Xizang Plateau, vol. 2. Science Press, Beijing, pp. 1649–1656.
- Derbyshire, E., 1983. The Lushan Dilemma: Pleistocene glaciation south of the Changjiang (Yangtze River). *Z. Geomorphol.* 27, 445–471.
- Derbyshire, E., 1984. Sedimentological analysis of glacial and proglacial debris: a framework for the study of Karakoram glaciers. In: Miller, K.J. (Ed.), *The International Karakoram Project*, vol. 1. Cambridge University Press, Cambridge, pp. 347–364.
- Derbyshire, E., 1987. A history of the glacial stratigraphy in China. *Quat. Sci. Rev.* 6, 301–314.
- Derbyshire, E., 1996. Quaternary glacial sediments, glaciation style, climate and uplift in the Karakoram and northwest Himalaya: review and speculations. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 120, 147–157.
- Derbyshire, E., Owen, L.A., 1990. Quaternary alluvial fans in the Karakoram Mountains. In: Rachocki, A.H., Church, M. (Eds.), *Alluvial Fans: a Field Approach*. John Wiley & Sons Ltd., pp. 27–53.
- Derbyshire, E., Owen, L.A., 1997. Quaternary glacial history of the Karakoram Mountains and Northwest Himalayas: a review. *Quat. Int.* 38/39, 85–102.
- Derbyshire, E., Li, J., Perrott, F.A., Xu, S., Waters, R.S., 1984. Quaternary glacial history of the Hunza valley Karakoram Mountains, Pakistan. In: Miller, K. (Ed.), *International Karakoram Project*. Cambridge University Press, Cambridge, pp. 456–495.
- Derbyshire, E., Shi, Y., Li, J., Zheng, B., Li, S., Wang, J., 1991. Quaternary glaciation of Tibet: the geological evidence. *Quat. Sci. Rev.* 10, 485–510.
- Desilets, D., Zreda, M., 2003. Spatial and temporal distribution of secondary cosmic-ray nucleon intensities and applications to in situ cosmogenic dating. *Earth Planet. Sci. Lett.* 206, 21–42.
- Desilets, D., Zreda, M., 2006. Elevation dependence of cosmogenic ^{36}Cl production in Hawaiian lava flows. *Earth Planet. Sci. Lett.* 246, 277–287.
- Dortch, J.M., Owen, L.A., Haneberg, W.C., Caffee, M.W., Dietsch, C., Kamp, U., 2009. Nature and timing of mega-landslides in northern India. *Quat. Sci. Rev.* 28, 1037–1056.
- Dortch, J.M., Owen, L.A., Caffee, M.W., 2010a. Quaternary glaciation in the Nubra and Shyok valley confluence, northernmost Ladakh, India. *Quat. Res.* 74, 132–144.
- Dortch, J.M., Owen, L.A., Caffee, M.W., Brease, P., 2010b. Late Quaternary glaciation and equilibrium line altitude variations of the McKinley River region, central Alaska Range. *Boreas* 39, 233–246.
- Dortch, J.M., Owen, L.A., Dietsch, C., Caffee, M.W., Bovard, K., 2011a. Episodic fluvial incision of rivers and rock uplift in the Himalaya and Transhimalaya. *J. Geol. Soc. London* 168, 783–804.
- Dortch, J.M., Owen, L.A., Schoenbohm, L.M., Caffee, M.W., 2011b. Asymmetrical erosion and morphological development of the central Ladakh Range, northern India. *Geomorphology* 135, 167–180.
- Dortch, J.M., Owen, L.A., Caffee, M.W., Kamp, U., 2011c. Catastrophic partial drainage of Pangong Tso, northern India and Tibet. *Geomorphology* 125, 109–121.
- Dortch, J.M., Owen, L.A., Caffee, M.W., 2013. Timing and climatic drivers for glaciation across semi-arid western Himalayan–Tibetan orogen. *Quat. Sci. Rev.* 78, 188–208.
- Drew, F., 1873. Alluvial and lacustrine deposits and glacial records of the upper Indus basin; part 1, alluvial deposits. *Geol. Soc. London Quart. J.* 29, 449–471.
- Dunai, T.J., 2000. Scaling factors for production rates of in situ produced cosmogenic nuclides: a critical reevaluation. *Earth Planet. Sci. Lett.* 176, 157–169.
- Duncan, C.C., Klein, A.J., Masek, J.G., Isacks, B.L., 1998. Late Pleistocene and modern glaciations in Central Nepal from digital elevation data and satellite imagery. *Quat. Res.* 49, 241–254.
- Dunning, S.A., Mitchell, W.A., Rosser, N.J., Petley, D.N., 2007. The Hattian Bala rock avalanche and associated landslides triggered by the Kashmir earthquake of 8 October 2005. *Eng. Geol.* 93, 130–144.
- Ehlers, J., Gibbard, P. (Eds.), 2004. *Quaternary Glaciations – Extent and Chronologies. Part III: South America, Asia, Africa, Australia, Antarctica*. Developments in Quaternary Science, vol. 2, p. 380.
- Elhers, J., Gibbard, P., Hughes, P.D. (Eds.), 2011. *Quaternary Glaciations – Extent and Chronology: a Closer Look*. Developments in Quaternary Science, second ed., vol. 15. Elsevier, Amsterdam, pp. 929–942.
- Eyles, N., Eyles, C.H., Miall, A.D., 1983. Lithofacies types and vertical profile models, an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. *Sedimentology* 30, 393–410.
- Fenton, C.R., Hermanns, R.L., Blikra, L.H., Kubik, P.W., Bryant, C., Niedermann, S., Meixner, Anette, Goethals, M.M., 2011. Regional ^{10}Be production rate calibration for the past 12 ka deduced from the radiocarbon-dated Gröttlandsura and Russenes rock avalanches at 69° N, Norway. *Quat. Geochronol.* 6, 437–452.
- Fielding, E., Isacks, B., Barazangi, M., Duncan, C., 1994. How flat is Tibet? *Geology* 22, 163–167.
- Finkel, R.C., Owen, L.A., Barnard, P.L., Caffee, M.W., 2003. Beryllium-10 dating of Mount Everest moraines indicates a strong monsoonal influence and glacial synchronicity throughout the Himalaya. *Geology* 31, 561–564.
- Fort, M., 1986. Glacial extension and catastrophic dynamics along the Annapurna front, Nepal Himalaya. In: Kuhle, M. (Ed.), *Internationales über Tibet und Hochasien vom 8.-11. Oktober 1985 im Geographischen Institut der Universität Göttingen*. Verlag Erich Goltze GmbH & Co. KG, Göttingen, pp. 105–125.
- Fort, M., 2003. Are high altitude, lava stream-like, debris mixtures all rock glaciers? A perspective from the Western Himalaya. *Z. Geomorphol.* 130, 11–29.
- Fort, M., Derbyshire, E., 1988. Some characteristics of tills in the Annapurna Range, Nepal. In: Chen, E. (Ed.), *Proceedings of the Second Conference on the Palaeoenvironment of East Asia from the Mid-tertiary, Geology, Sea Level Changes, Palaeoclimatology and Palaeobotany*, vol. 1. University of Hong Kong, Hong Kong, pp. 195–214.
- Frenzel, B., 1960. Die Vegetations- und Landschaftszonen Nordeuropas während der letzten Eiszeit und während der Postglazialen Warmezeit. In: *Akademie der Wissenschaften und der Literatur in Mainz, Abhandlungen der Mathematisch-Naturwissenschaftlichen Klasse*, vol. 13, pp. 937–1099.
- Fu, P., Heyman, J., Hattestrand, C., Stroeve, A.J., Harbor, J.M., 2012. Glacial geomorphology of the Shaluli Shan area, southeastern Tibetan Plateau. *J. Maps* 8, 48–55.
- Fu, P., Stroeve, A.P., Harbor, J.M., Hattestrand, C., Heyman, J., Caffee, M.W., Zhou, L., 2013. Paleoglaciology of Shaluli Shan, southeastern Tibetan Plateau. *Quat. Sci. Rev.* 64, 121–135.
- Fuchs, M., Owen, L.A., 2008. Luminescence dating of glacial and associated sediments: review, recommendations and future directions. *Boreas* 37, 636–659.
- Fujita, K., Nakawo, M., Fujii, Y., Paudyal, P., 1997. Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994. *J. Glaciol.* 43, 583–588.
- Fushimi, H., 1977. Glaciations in the Khumbu Himal (1). *Seppyo* 39, 60–67.
- Fushimi, H., 1978. Glaciations in the Khumbu Himal (2). *Seppyo* 40, 71–77.
- Gayer, E., Lavé, J., Pik, R., France-Lanord, C., 2006. Monsoonal forcing of Holocene glacier fluctuations in Ganesh Himal (central Nepal) constrained by cosmogenic ^{36}Ar exposure ages of garnets. *Earth Planet. Sci. Lett.* 252, 275–288.
- Geyh, M., Rothlisberger, F., Gellant, A.F., 1985. Reliability tests of C14 dates from paleosol in glacier environments. *Z. Gletsch. Glazialgeol.* 21, 275–281.
- Gibbons, A.B., Megeath, J.D., Pierce, K.L., 1984. Probability of moraine survival in a succession of glacial advances. *Geology* 12, 327–330.
- Gillespie, A., Molnar, P., 1995. Asynchronous maximum advances of mountain and continental glaciers. *Rev. Geophys.* 33, 311–364.
- Goehring, B.M., Lohne, Ø.S., Mangerud, J., Svendsen, J.I., Gyllencreutz, R., Schaefer, J., Finkel, R., 2012. Late glacial and Holocene ^{10}Be production rates for western Norway. *J. Quat. Sci.* 27, 89–96.
- Gosse, J., Klein, J., Evenson, E.B., Lawn, B., Middleton, R., 1995. Beryllium-10 dating of the duration and retreat of the last Pinedale glacial sequence. *Science* 228, 1329–1333.
- Graf, A.A., Strasky, S., Zhao, Z.Z., Akçar, N., Ivy-Ochs, S., Kubik, P.W., Christl, M., Kasper, H.U., Wieler, R., Schluchter, C., 2008. Glacier extension on the eastern Tibetan Plateau in response to MIS 2 cooling, with a contribution to ^{10}Be and ^{21}Ne methodology. In: Strasky, S. (Ed.), *Glacial Response to Global Climate Changes: Cosmogenic Nuclide Chronologies from High and Low Latitudes*. ETH Zurich (PhD thesis).
- Grove, J.M., 2004. *The Little Ice Age: Ancient and Modern*, second ed., vol. 1. Routledge, London, p. 432.
- Guggenberger, G., Bäumler, R., Zech, W., 1998. Weathering of soils developed in eolian material overlying glacial deposits in Eastern Nepal. *Soil Sci.* 163, 325–337.
- Haeblerli, W., Bosch, H., Scherler, K., Ostrem, G., Wallen, C.C., 1989. *World Glacier Inventory: Status 1988*. Compiled by the World Glacier Monitoring Service, IAHS-UNEP-UNESCO, Wallingford, UK.
- Hallet, B., Pitkonen, J., 1994. Surface dating of dynamic landforms: young boulders on aging moraines. *Science* 265, 937–940.
- Hedrick, K.A., Seong, Y.B., Owen, L.A., Caffee, M.C., Dietsch, C., 2011. Towards defining the transition in style and timing of Quaternary glaciation between the monsoon-influenced Greater Himalaya and the semi-arid Transhimalaya of Northern India. *Quat. Int.* 236, 21–33.
- Heimsath, A.M., McGlynn, R., 2008. Quantifying periglacial erosion in the Nepal high Himalaya. *Geomorphology* 97, 5–23.

- Hewitt, K., 1969. Glacier surges in the Karakoram Himalaya (Central Asia). *Can. J. Earth Sci.* 6, 1009–1018.
- Hewitt, K., 1998. Catastrophic landslides and their effects on the Upper Indus streams, Karakoram Himalaya, northern Pakistan. *Geomorphology* 26, 47–80.
- Hewitt, K., 1999. Quaternary moraines vs catastrophic avalanches in the Karakoram Himalaya, northern Pakistan. *Quat. Res.* 51, 220–237.
- Hewitt, K., 2005. The Karakoram anomaly? Glacier expansion and the 'Elevation effect'. *Karakoram Himalaya. Mt. Res. Dev.* 25, 332–340.
- Hewitt, K., Gosse, J., Clague, J.J., 2011. Rock avalanches and the pace of late Quaternary development of river valleys in the Karakoram Himalaya. *Geol. Soc. Am. Bull.* 123, 1836–1850.
- Heyman, J., Hattestrand, C., Stroeve, A.P., 2008. Glacial geomorphology of the Bayan Har sector of the NE Tibetan plateau. *J. Maps* 2008, 42–62.
- Heyman, J., Stroeve, A.P., Caffee, M.W., Hattestrand, C., Harbor, J., Li, Y.K., Alexanderson, H., Zhou, L.P., Hubbard, A., 2010. Palaeoglaciology of Bayan Har Shan, NE Tibetan Plateau: the case of a missing LGM expansion. In: Heyman, J. (Ed.), *Palaeoglaciology of the Northeastern Tibetan Plateau*. Stockholm University (PhD thesis).
- Heyman, J., Stroeve, A.P., Caffee, M.W., Hattestrand, C., Harbor, J.M., Li, Y.K., Alexanderson, H., Zhou, L.P., Hubbard, A., 2011a. Palaeoglaciology of Bayan Har Shan, NE Tibetan Plateau: exposure ages reveal a missing LGM expansion. *Quat. Sci. Rev.* 30, 1988–2001.
- Heyman, J., Stroeve, A., Harbor, J., Caffee, M.W., 2011b. Too young or too old: evaluating 884 cosmogenic exposure dating based on an analysis of compiled boulder exposure 885 ages. *Earth Planet. Sci. Lett.* 302, 71–80.
- Holmes, J.A., Street-Perrott, F.A., 1989. The Quaternary glacial history of Kashmir, North-West Himalaya: a revision of de Terra and Paterson's Sequence. *Z. Geomorphol.* 76, 195–212.
- Höfermann, J., Lehmkuhl, F., Pörtge, K.-H., 1993a. Pleistocene glaciations in Eastern and Central Tibet—preliminary results of the Chinese-German joint expeditions. *Z. Geomorphol.* 92, 85–96.
- Höfermann, J., Lehmkuhl, F., Süßenberger, H., 1993b. Neue Befunde zur Paläoklimatologie Nordafrikas und Zentralasiens. *Abh. Braunsch. Wiss. Ges.* 43, 127–150.
- Hughes, P.D., Gibbard, P.L., Woodward, J.C., 2005. Quaternary glacial records in mountain regions: a formal stratigraphical approach. *Episodes* 28, 85–92.
- Intergovernmental Panel on Climate Change, 2007. *Climate change 2007: impacts, adaptations and vulnerability*. In: Parry, M., Canziani, O., Palutikof, J., Van der Linden, P., Hanson, C. (Eds.), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, p. 976.
- Ivy-Ochs, S., Kerschner, H., Schlüchter, C., 2007. Cosmogenic nuclides and the dating of lateglacial and Early Holocene glacier variations: the Alpine perspective. *Quat. Int.* 164–165, 53–63.
- Iwata, S.J., Jiao, K.Q., 1993. Fluctuations of the Zepu Glacier in late Holocene Epoch, the eastern Nyainqentanglha Mountains. In: Yao, T.D., Ageda, Y. (Eds.), *Glaciation Climate and Environment in Qinghai–Tibet Plateau*. Science Press, Beijing, pp. 130–138.
- Iwata, S.J., Naramaa, C.K., Karma, 2002. Three Holocene and late Pleistocene glacial stages inferred from moraines in the Lingshi and Thanza village areas, Bhutan. *Quat. Int.* 97/98, 69–78.
- Iwata, S., Naito, N., Naramaa, C., 2003. Rock glaciers and the lower limit of permafrost in the Bhutan Himalayas. *Z. Geomorphol.* 130, 129–143.
- Jiao, K.Q., Iwata, S.J., 1993. The glacier variation in Kunlun pass area and southeast Tibet area since last glaciation. In: Yao, T.D., Ageda, Y. (Eds.), *Glaciation Climate and Environment in Qinghai–Tibet Plateau*. Science Press, Beijing, pp. 120–129.
- Jiao, K.Q., Shen, Y.P., 2006. Quaternary glaciations in Tanggula Mountains. In: Shi, Y.F., Su, Z., Cui, Z.J. (Eds.), *The Quaternary Glaciations and Environmental Variations in China*. Science and Technology Press of Hebei Province, Shijiazhuang, pp. 326–356.
- Jiao, K.Q., Zheng, B.X., 2006. Quaternary glaciations in Kunlun Mountains. In: Shi, Y.F., Su, Z., Cui, Z.J. (Eds.), *The Quaternary Glaciations and Environmental Variations in China*. Science and Technology Press of Hebei Province, Shijiazhuang, pp. 326–356.
- Jiao, K., Iwata, S., Yao, T., Jing, Z., Li, Z., 2005. Variation of Zepu Glacier and environmental change in the eastern Nyainqentanglha Range since 3.2 ka BP. *J. Glaciol. Geocryol.* 27, 74–79.
- Kamp, U., Owen, L.A., 2011. Late Quaternary glaciation of northern Pakistan. In: Ehlers, J., Gibbard, P., Hughes, P.D. (Eds.), *Quaternary Glaciations – Extent and Chronology: a Closer Look, Developments in Quaternary Science*, vol. 15. Elsevier, Amsterdam, pp. 909–927.
- Kaplan, M.R., Hein, A.S., Hubbard, A., Lax, S.M., 2009. Can glacial erosion limit the extent of glaciation? *Geomorphology* 103, 172–179.
- Kaplan, M.R., Strelin, J.A., Schaefer, J.M., Denton, G.H., Finkel, R.C., Schwartz, R., Putnam, A.E., Vandergoes, M.J., Goehring, B.M., Travis, S.G., 2011. In-situ cosmogenic ^{10}Be production rate at Lago Argentino, Patagonia: implications for late-glacial climate chronology. *Earth Planet. Sci. Lett.* 309, 21–32.
- Klute, F., 1930. Verschiebung der Klimagebiete der letzten Eiszeit. *Petermanns Mitt. Ergänz.* 209, 166–182.
- Kong, P., Fink, D., Na, C.G., Huang, F.X., 2009a. Late Quaternary glaciation of the Tianshan, central Asia, using cosmogenic ^{10}Be surface exposure dating. *Quat. Res.* 72, 229–233.
- Kong, P., Na, C.G., Fink, D., Zhao, X.T., Xiao, W., 2009b. Moraine dam related to late Quaternary glaciation in the Yulong Mountains, southwest China, and impacts on the Jinsha River. *Quat. Sci. Rev.* 28, 3224–3235.
- Koppes, M., Gillespie, A.R., Burke, R.M., Thompson, S.C., Stone, J., 2008. Late Quaternary glaciation in the Kyrgyz Tien Shan. *Quat. Sci. Rev.* 27, 846–866.
- Kuhle, M., May 1985. Ein Subtropisches Inlandeis Als Eiszeitauslöser, Südtibet Un Mt. Everest Expedition 1984. *Nachrichten aus der Universität Göttingen, Georgia Augusta*, pp. 1–17.
- Kuhle, M., 1986. The upper limit of glaciation in the Himalayas. *Geojournal* 13, 331–346.
- Kuhle, M., 1987. The problem of a Pleistocene inland glaciation of the northeastern Qinghai-Xizang Plateau. In: Höfermann, J., Wang, W. (Eds.), *Reports of the Qinghai-Xizang (Tibet) Plateau*, pp. 250–315. Beijing.
- Kuhle, M., 1988a. Geomorphological findings on the built-up of Pleistocene glaciation in Southern Tibet and on the problem of inland ice. *Geojournal* 17, 457–512.
- Kuhle, M., 1988b. Topography as a fundamental element of glacial systems. *Geojournal* 17, 545–568.
- Kuhle, M., 1990a. The cold deserts of high Asia (Tibet and contiguous mountains). *Geojournal* 20, 319–323.
- Kuhle, M., 1990b. Ice marginal ramps and alluvial fans in semiarid mountains: convergence and difference. In: Rachocki, A.H., Church, M. (Eds.), *Alluvial Fans: a Field Approach*. John Wiley and Sons, Chichester, pp. 55–68.
- Kuhle, M., 1991. Observations supporting the Pleistocene inland glaciation of High Asia. *Geojournal* 25, 131–231.
- Kuhle, M., 1993. A short report of the Tibet excursion 14-A, part of the XIII INQUA Congress 1991 in Beijing. *Geojournal* 29, 426–427.
- Kuhle, M., 1995. Glacial isostatic uplift of Tibet as a consequence of a former ice sheet. *Geojournal* 37, 431–449.
- Kuhle, M., 2011. The High Glacial (Last Ice Age and Last Glacial Maximum) ice cover of high and Central Asia, with critical review of some recent OSL and TCN dates. In: Ehlers, J., Gibbard, P., Hughes, P.D. (Eds.), *Quaternary Glaciations – Extent and Chronology: a Closer Look, Developments in Quaternary Science*, second ed., vol. 15. Elsevier, Amsterdam, pp. 943–965.
- Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth Planet. Sci. Lett.* 104, 429–439.
- Lasserre, C., Gaudemer, Y., Tapponnier, P., Mériaux, A.-S., Van der Woerd, J., Yuan, D., Ryerson, F.J., Finkel, R.C., Caffee, M.W., 2002. Fast late Pleistocene slip rate on the Leng Long Ling segment of the Haiyuan fault, Qinghai, China. *J. Geophys. Res.* 107 (B11), 2276.
- Lee, S.Y., Seong, Y.B., Owen, L.A., Murari, M.K., Lim, H.S., Yoon, H.I., Yoo, K.-C., 2014. Late Quaternary glaciation in the Nun-Kun massif, northwestern India. *Boreas* 43, 67–89.
- Lehmkuhl, F., 1995. Geomorphologische Untersuchungen zum Klima des Holozäns und jungpleistozäns Osttibets. *Gött. Geogr. Abh.* 102, 1–184.
- Lehmkuhl, F., 1997. Late Pleistocene, Late-glacial and Holocene glacier advances on the Tibetan Plateau. *Quat. Int.* 38/39, 77–83.
- Lehmkuhl, F., 1998. Extent and spatial distribution of Pleistocene glaciations in Eastern Tibet. *Quat. Int.* 45/46, 123–134.
- Lehmkuhl, F., Lui, S., 1994. An outline of physical geography including Pleistocene glacial landforms of Eastern Tibet (Provinces Sichuan and Qinghai). *Geojournal* 34, 7–30.
- Lehmkuhl, F., Owen, L.A., 2005. Late Quaternary glaciation of Tibet and the bordering mountains: a review. *Boreas* 34, 87–100.
- Lehmkuhl, F., Owen, L.A., Derbyshire, E., 1998. Late Quaternary glacial history of northeastern Tibet. *Quat. Proc.* 6, 121–142.
- Lehmkuhl, F., Klinge, M., Stauch, G., 2004. The extent of Late Pleistocene Glaciations in the Altai and Khangai Mountains. In: Ehlers, J., Gibbard, P.L. (Eds.), *Quaternary Glaciations – Extent and Chronologies, Part III: South America, Asia, Africa, Australia, Antarctica*. Elsevier, Oxford, pp. 243–254.
- Leuschner, D.C., Sirocko, F., 2003. Orbital insolation forcing of the Indian monsoon – a motor for global climate change. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 197, 83–95.
- Li, Y., Harrison, S.P., 2008. Simulations of the impact of orbital forcing and ocean on the Asian summer monsoon during the Holocene. *Global Planet. Change* 60, 505–522.
- Li, S.J., Jiao, K.Q., 1990. Glacier variation on the south slope of west Kunlun Mountains since 30000 ^{14}C yr BP. (Chinese with English summary). *J. Glaciol. Geocryol.* 12, 311–318.
- Li, S.J., Li, S.D., 1992. Quaternary glacial and environmental changes in the region of Hoh Xil, Qinghai Province. *J. Glaciol. Geocryol.* 14, 316–324 (Chinese with English summary).
- Li, J.J., Derbyshire, E., Street-Perrott, F.A., Xu, S.Y., Waters, R.S., 1984. Glacial and paraglacial sediments of the Hunza valley, north-west Pakistan: a preliminary analysis. In: Miller, K. (Ed.), *The International Karakoram Project*. Cambridge University Press, Cambridge, pp. 496–535.
- Li, J.J., Zheng, B.X., Yang, X.J., 1986. Glacier in Tibet. Science Press, Beijing, pp. 1–275.
- Shi Y. (Scientific Advisor). In: Li, B., Li, J., Cui, Z. (Eds.), *Quaternary Glacial Distribution Map of Qinghai-Xizang (Tibet) Plateau 1:3,000,000*. Quaternary Glacier, and Environment Research Center, Lanzhou University.
- Lifton, N.A., Bieber, J.W., Clem, J.M., Duldig, M.L., Evenson, P., Humble, J.E., Pyle, R., 2005. Addressing solar modulation and long-term uncertainties in scaling secondary cosmic rays for in situ cosmogenic nuclide applications. *Earth Planet. Sci. Lett.* 239, 140–161.
- Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography* 20, PA1003. <http://dx.doi.org/10.1029/2004PA001071>.

- Mann, D.H., Sletten, R.S., Reanier, R.E., 1996. Quaternary glaciation of the Rongbuk Valley, Tibet. *J. Quat. Sci.* 11, 267–280.
- Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of ice ages: development of a high resolution 0 to 300,000-year chronology. *Quat. Res.* 27, 1–29.
- Mayer, C., Lambrecht, A., Belò, M., Smiraglia, C., Diolaiuti, G., 2006. Glaciological characteristics of the ablation zone of Baltoro glacier, Karakoram, Pakistan. *Ann. Glaciol.* 43, 123–131.
- Mayewski, P.A., Jeschke, P.A., 1979. Himalayan and Trans-Himalayan glacier fluctuations since AD 1812. *Arct. Alp. Res.* 11, 267–287.
- Mayewski, P.A., Pregel, G.P., Jeschke, P.A., Ahmad, N., 1980. Himalayan and Trans-Himalayan glacier fluctuations and the South Asian Monsoon record. *Arct. Alp. Res.* 12, 171–182.
- Mayewski, P.A., Rohling, E.E., Stager, C.J., Karlén, W., Maasch, A., Meeker, L.D., Meyerson, E.A., Gasse, F., Van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. *Quat. Res.* 62, 243–255.
- Mériaux, A.-S., Ryerson, F.J., Tapponnier, P., Van der Woerd, J., Finkel, R.C., Xu, X., Xu, Z., Caffee, M.W., 2004. Rapid slip along the central Altyn Tagh Fault: morphochronologic evidence from Cherchen He and Sulamu Tagh. *J. Geophys. Res.* 109, B06401.
- Meyer, M.C., Hofmann, Ch.-Ch., Gemmell, A.M.D., Haslinger, E., Häusler, H., Wangda, D., 2009. Holocene glacier fluctuations and migration of Neolithic yak pastoralists into the high valleys of northwest Bhutan. *Quat. Sci. Rev.* 28, 1217–1237.
- Molnar, P., England, P., 1990. Late Cenozoic uplift of mountain ranges and global climatic change: chicken or egg? *Nature* 46, 29–34.
- Morén, B., Heyman, J., Stroeve, A.P., 2011. Glacial geomorphology of the central Tibetan Plateau. *J. Maps*, 115–125.
- Muller, F., 1980. Present and late Pleistocene equilibrium line altitudes in the Mt. Everest region—an application of the glacier inventory. *World Glacier Invent.* 126, 75–94.
- Murari, M.K., Owen, L.A., Dortch, J.M., Caffee, M.W., Dietsch, C., Fuchs, M., Haneberg, W.C., Sharma, M.C., Townsend-Small, A., 2014. Timing and climatic drivers for glaciation across monsoon-influenced regions of the Himalayan–Tibetan orogen. *Quat. Sci. Rev.* 88, 159–182. <http://dx.doi.org/10.1016/j.quascirev.2014.01.013>.
- Narama, C., 2002. Late Holocene variation of the Raigorodskogo Glacier and climate change in the Pamir–Alai, central Asia. *Catena* 48, 21–37.
- Narama, C., Kondo, R., Tsukamoto, S., Kajiura, T., Ormukov, C., Abdrakhmatov, K., 2007. OSL dating of glacial deposits during the Last Glacial in the Terskey–Alatau Range, Kyrgyz Republic. *Quat. Geochronol.* 2, 249–254.
- Narama, C., Kondo, R., Tsukamoto, S., Kajiura, T., Duishonakunov, M., Abdrakhmatov, K., 2009. Timing of glacier expansion during the Last Glacial in the inner Tien Shan, Yrgyz Republic by OSL dating. *Quat. Int.* 199, 147–156.
- NGRIP Members, 2004. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* 431, 147–151.
- Norin, E., 1925. Preliminary notes on the Late Quaternary glaciation of the North Western Himalaya. *Geograf. Ann.* 7, 165–194.
- Norton, K.P., Abbühl, L.M., Schlunegger, F., 2010. Glacial conditioning as an erosional driving force in the Central Alps. *Geology* 38, 655–658.
- Ono, Y., 1984. Annual moraine ridges and recent fluctuation of Yala (Dakpatsen) Glacier, Langtang Himal. In: Higuchi, K. (Ed.), *Glacier Studies in Langtang Valley*, vol. 2. Data Center for Glacier Research, Japan Society for Snow and Ice, pp. 73–83.
- Ono, Y., 1985. Recent fluctuations of the Yala (Dakpatsen) Glacier, Langtang Himal, reconstructed from Annual moraine ridges. *Z. Gletsch. Glazialgeol.* 21, 251–258.
- Ono, Y., 1986. Glacial fluctuations in the Langtang valley Nepal Himalaya. In: Kuhle, M. (Ed.), *Internationales über Tibet und Hochasien vom 8.–11. Oktober 1985 im Geographischen Institut der Universität Göttingen*. Verlag Erich Goltze GmbH & Co. KG, Göttingen, pp. 31–38.
- Ono, Y., Liu, D., Zhao, Y., 1997. Paleoenvironments of Tibetan Plateau from glacial fluctuations in the northern foot of the West Kunlun Mountains. *J. Geogr.* 106, 184–198 (in Japanese).
- Osmaston, H., 1994. The geology, geomorphology and Quaternary history of Zangskar. In: Crook, J., Osmaston, H. (Eds.), *Himalayan Buddhist Villages*. University of Bristol Press, UK, pp. 1–36.
- Owen, L.A., 1988. Wet-sediment deformation of Quaternary and Recent sediments in the Skardu Basin, Karakoram Mountains, Pakistan. In: Croots, D. (Ed.), *Glaciotectionics*. A. A. Balkema, Rotterdam, pp. 123–147.
- Owen, L.A., 1991. Mass movement deposits in the Karakoram Mountains: their sedimentary characteristics, recognition and role in Karakoram landform evolution. *Z. Geomorphol.* 35 (4), 401–424.
- Owen, L.A., 2009. Latest Pleistocene and Holocene glacier fluctuations in the Himalaya and Tibet. *Quat. Sci. Rev.* 28, 2150–2164.
- Owen, L.A., 2010. Landscape development of the Himalayan–Tibetan orogen: a review. In: *Special Publication of the Geological Society of London*, vol. 338, pp. 389–407.
- Owen, L.A., 2011. Quaternary glaciation of Northern India. In: Elhers, J., Gibbard, P., Hughes, P.D. (Eds.), *Quaternary Glaciations – Extent and Chronology: a Closer Look*, Developments in Quaternary Science, second ed., vol. 15. Elsevier, Amsterdam, pp. 929–942.
- Owen, L.A., 2013. Late Quaternary glaciations in Highland Asia. In: Scott, E.A. (Ed.), *Encyclopedia of Quaternary Science*, vol. 2. Elsevier, Amsterdam, pp. 236–244.
- Owen, L.A., Benn, D.I., 2005. Equilibrium-line altitudes of the Last Glacial Maximum for the Himalaya and Tibet: an assessment and evaluation of results. *Quat. Int.* 138/139, 55–78.
- Owen, L.A., Derbyshire, E., 1988. Glacially deformed diamictites in the Karakoram Mountains, Northern Pakistan. In: Croots, D. (Ed.), *Glaciotectionics*. A. A. Balkema, Rotterdam, pp. 149–176.
- Owen, L.A., Derbyshire, E., 1989. The Karakoram glacial depositional system. *Z. Geomorphol.* 76, 33–74.
- Owen, L.A., England, J., 1998. Observations on rock glaciers in the Himalayas and Karakoram Mountains of northern Pakistan and India. *Geomorphology* 26, 199–213.
- Owen, L.A., White, B., Rendell, H., Derbyshire, E., 1992. Loessic silts in the western Himalayas: their sedimentology, genesis and age. *Catena* 19, 493–509.
- Owen, L.A., Benn, D.I., Derbyshire, E., Evans, D.J.A., Mitchell, W.A., Thompson, D., Richardson, S., Lloyd, M., Holden, C., 1995. The geomorphology and landscape evolution of the Lahul Himalaya, Northern India. *Z. Geomorphol.* 39, 145–174.
- Owen, L.A., Derbyshire, E., Richardson, S., Benn, D.I., Evans, D.J.A., Mitchell, W.A., 1996. The Quaternary glacial history of the Lahul Himalaya, Northern India. *J. Quat. Sci.* 11, 25–42.
- Owen, L.A., Mitchell, W., Bailey, R.M., Coxon, P., Rhodes, E., 1997. Style and timing of Glaciation in the Lahul Himalaya, northern India: a framework for reconstructing late Quaternary palaeoclimatic change in the western Himalayas. *J. Quat. Sci.* 12, 83–109.
- Owen, L.A., Scott, C.H., Derbyshire, E., 2000. The Quaternary glacial history of Nanga Parbat. *Quat. Int.* 65/66, 63–79.
- Owen, L.A., Gualtieri, L., Finkel, R.C., Caffee, M.W., Benn, D.I., Sharma, M.C., 2001. Cosmogenic radionuclide dating of glacial landforms in the Lahul Himalaya, Northern India: defining the timing of Late Quaternary glaciation. *J. Quat. Sci.* 16, 555–563.
- Owen, L.A., Finkel, R.C., Caffee, M.W., Gualtieri, L., 2002a. Timing of multiple glaciations during the Late Quaternary in the Hunza Valley, Karakoram Mountains, Northern Pakistan: defined by cosmogenic radionuclide dating of moraines. *Geol. Soc. Am. Bull.* 114, 593–604.
- Owen, L.A., Kamp, U., Spencer, J.Q., Haserodt, K., 2002b. Timing and style of Late Quaternary glaciation in the eastern Hindu Kush, Chitral, northern Pakistan: a review and revision of the glacial chronology based on new optically stimulated luminescence dating. *Quat. Int.* 97–98, 41–56.
- Owen, L.A., Finkel, R.C., Caffee, M.W., 2002d. A note on the extent of glaciation throughout the Himalaya during the global Last Glacial Maximum. *Quat. Sci. Rev.* 21, 147–157.
- Owen, L.A., Finkel, R.C., Ma, H., Spencer, J.Q., Derbyshire, E., Barnard, P.L., Caffee, M.W., 2003a. Timing and style of Late Quaternary glaciations in NE Tibet. *Geol. Soc. Am. Bull.* 11, 1356–1364.
- Owen, L.A., Ma, Haizhou, Derbyshire, E., Spencer, J.Q., Barnard, P.L., Nian, Zeng Yong, Finkel, R.C., Caffee, M.W., 2003b. The timing and style of Late Quaternary glaciation in the La Ji Mountains, NE Tibet: evidence for restricted glaciation during the latter part of the Last Glacial. *Z. Geomorphol.* 130, 263–276.
- Owen, L.A., Spencer, J.Q., Ma, H., Barnard, P.L., Derbyshire, E., Finkel, R.C., Caffee, M.W., Nian, Zeng Yong, 2003c. Timing of Late Quaternary glaciation along the southwestern slopes of the Qilian Shan. *Boreas* 32, 281–291.
- Owen, L.A., Finkel, R.C., Barnard, P.L., Ma, H., Asahi, K., Caffee, M.W., Derbyshire, E., 2005. Climatic and topographic controls on the style and timing of Late Quaternary glaciation throughout Tibet and the Himalaya defined by ¹⁰Be cosmogenic radionuclide surface exposure dating. *Quat. Sci. Rev.* 24, 1391–1411.
- Owen, L.A., Caffee, M., Bovard, K., Finkel, R.C., Sharma, M., 2006a. Terrestrial cosmogenic surface exposure dating of the oldest glacial successions in the Himalayan orogen. *Geol. Soc. Am. Bull.* 118, 383–392.
- Owen, L.A., Finkel, R.C., Ma, Haizhou, Barnard, P.L., 2006b. Late Quaternary landscape evolution in the Kunlun Mountains and Qaidam Basin, Northern Tibet: a framework for examining the links between glaciation, lake level changes and alluvial fan formation. *Quat. Int.* 154–155, 73–86.
- Owen, L.A., Caffee, M.W., Finkel, R.C., Seong, B.Y., 2008a. Quaternary glaciations of the Himalayan–Tibetan orogen. *J. Quat. Sci.* 23, 513–532.
- Owen, L.A., Kamp, U., Khattak, G.A., Harp, E.L., Keefer, D.K., Bauer, M.A., 2008b. Landslides triggered by the October 8, 2005, Kashmir Earthquake. *Geomorphology* 94, 1–9.
- Owen, L.A., Robinson, R., Benn, D.I., Finkel, R.C., Davis, N.K., Yi, C., Putkonen, J., Li, D., Murray, A.S., 2009. Quaternary glaciation of Mount Everest. *Quat. Sci. Rev.* 28, 1412–1433.
- Owen, L.A., Yi, C., Finkel, R.C., Davis, N., 2010. Quaternary glaciation of Gurla Mandata (Naimon'anyi). *Quat. Sci. Rev.* 29, 1817–1830.
- Owen, L.A., Chen, J., Hedrick, K.A., Caffee, M.W., Robinson, A., Schoenbohm, L.M., Zhao, Y., Li, W., Imrecke, D., Liu, J., 2012. Quaternary glaciation of the Tashkurgan Valley, Southeast Pamir. *Quat. Sci. Rev.* 47, 56–72.
- Pendersen, V.K., Egholm, D.L., 2013. Glaciations in response to climate variations preconditioned by evolving topography. *Nature* 493, 206–210.
- Phillips, W.M., Sloan, V.F., Shroder Jr., J.F., Sharma, P., Clarke, M.L., Rendell, H.M., 2000. Asynchronous glaciation at Nanga Parbat, northwestern Himalaya Mountains, Pakistan. *Geology* 28, 431–434.
- Porter, S.C., 1970. Quaternary glacial record in the Swat Kohistan, West Pakistan. *Geol. Soc. Am. Bull.* 81, 1421–1446.
- Porter, S.C., 2000. Onset of neoglaciation in the Southern Hemisphere. *J. Quat. Sci.* 15, 395–408.
- Porter, S.C., Denton, G.H., 1967. Chronology of neoglaciation in the North American cordillera. *Am. J. Sci.* 265, 177–210.
- Pratt-Sitaula, B., 2005. *Glaciers, Climate, and Topography in the Nepalese Himalaya* (PhD thesis). University of California, Santa Barbara.

- Pratt-Sitaula, B., Burbank, D.W., Heimsath, A.M., Humphrey, N.F., Oskin, M., Putkonen, J., 2011. Topographic control of asynchronous glacial advances: a case study from Annapurna, Nepal. *Geophys. Res. Lett.* 38, L245092. <http://dx.doi.org/10.1029/2011GL049940>.
- Prell, W.L., Kutzbach, J.F., 1992. Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution. *Nature* 360, 647–652.
- Pu, Q., 1991. Quaternary glaciers in China. In: Zhang, Z., Shao, S., Tong, G., Cao, J. (Eds.), *The Quaternary of China*. China Ocean Press, Beijing, pp. 240–273.
- Putkonen, J., O'Neal, M.A., 2006. Degradation of unconsolidated Quaternary landforms in the western North America. *Geomorphology* 75, 408–419.
- Putkonen, J., Swanson, T., 2003. Accuracy of cosmogenic ages for moraines. *Quat. Res.* 59, 255–261.
- Putkonen, J., Connolly, J., Orloff, T., 2008. Landscape evolution degrades the geologic signature of past glaciations. *Geomorphology* 97, 208–217.
- Putnam, A., Schaefer, J.M., Barrell, D.J.A., vandergees, M., denton, G.H., Kaplan, M.R., Finkel, R.C., Schwartz, R., Goehring, B.M., Kelley, S.E., 2010. In situ cosmogenic ^{10}Be production-rate calibration from the Southern Alps, New Zealand. *Quat. Geochronol.* 5, 392–409.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughes, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. INTCAL04 terrestrial radiocarbon age calibration, 0–26 Cal Kyr BP. *Radiocarbon* 46, 1029–1058.
- Ren, J., Qin, D., Kang, S., Hou, S., Pu, J., Jing, Z., 2004. Glacier variations and climate warming and drying in the central Himalayas. *Chinese Sci. Bull.* 49, 65–69.
- Richards, B.W.M., 1999. Paleoclimate of South Asia over the Last 80 ka: Luminescence Ages of Sediment from Former Glaciations in Nepal and Pakistan (Unpublished PhD thesis). Royal Holloway, University of London, UK.
- Richards, B.W.M., 2000. Luminescence dating of Quaternary sediments in the Himalaya and High Asia: a practical guide to its use and limitations for constraining the timing of glaciation. *Quat. Int.* 65/66, 49–61.
- Richards, B.W.M., Owen, L.A., Rhodes, E.J., 2000a. Timing of Late Quaternary glaciations in the Himalayas of northern Pakistan. *J. Quat. Sci.* 15, 283–297.
- Richards, B.W.M., Benn, D., Owen, L.A., Rhodes, E.J., Spencer, J.Q., 2000b. Timing of Late Quaternary glaciations south of Mount Everest in the Khumbu Himal, Nepal. *Geol. Soc. Am. Bull.* 112, 1621–1632.
- Röhringer, I., Zech, R., Abramowski, U., Sosin, P., Aldahan, A., Kubik, P.W., Zoller, L., Zech, W., 2012. The late Pleistocene glaciation in the Bogchigir Valleys (Pamir, Tajikistan) based on ^{10}Be surface exposure dating. *Quat. Res.* 78, 590–597.
- Rose, J., Menzies, J., 1995. *Glacial stratigraphy*. In: Menzies, J. (Ed.), *Past Glacial Environments: Sediments, Forms and Techniques*. Butterworth Heinemann, Oxford, pp. 253–284.
- Röthlisberger, F., Geyh, M.A., 1985a. Gletscherschwankungen der letzten 10.000 Jahre – Ein Vergleich zwischen Nord- und Südhemisphäre (Alpen, Himalaya, Alaska, Südamerika, Neuseeland). Verlag Sauerländer, Aarau.
- Röthlisberger, F., Geyh, M., 1985b. Glacier variations in Himalayas and Karakoram. *Z. Gletsch. Glazialgeol.* 21, 237–249.
- Ruddiman, W.F., Kutzbach, J.E., 1991. Plateau uplift and climate change. *Sci. Am.* 264, 42–51.
- Rupper, S., Roe, G., Gillespie, A., 2008. Spatial patterns of Holocene glacier advance and retreat in central Asia. *Quat. Res.* 72, 337–346.
- Rutter, N.W., 1995. Problematic ice sheets. *Quat. Int.* 28, 19–37.
- Schaefer, J.M., Oberholzer, P., Zhao, Z.Z., Ivy-Ochs, S., Wieler, R., Baur, H., Kubik, P.W., Schluchter, C., 2008. Cosmogenic beryllium-10 and neon-21 dating of late Pleistocene glaciations in Nyalam, monsoonal Himalayas. *Quat. Sci. Rev.* 27, 295–311.
- Schäfer, J.M., 2000. Reconstruction of Landscape Evolution and Continental Paleoglaciations Using In-situ Cosmogenic Nuclides: Examples from Antarctica and the Tibetan Plateau. Diss. ETH Zürich, Der Andere Verlag, Osnabrück.
- Schäfer, J.M., Tschudi, S., Zhao, Z., Wu, X., Ivy-Ochs, S., Wieler, R., Baur, H., Kubik, P.W., Schluchter, C., 2002. The limited influence of glaciations in Tibet on global climate over the past 170,000 yr. *Earth Planet. Sci. Lett.* 194, 287–297.
- Schäfer, J.M., Oberholzer, P., Zhao, Z.Z., Ivy-Ochs, S., Wieler, R., Baur, H., Kubik, P.W., Schluchter, C., 2008. Cosmogenic beryllium-10 and neon-21 dating of late Pleistocene glaciations in Nyalam, monsoonal Himalayas. *Quat. Sci. Rev.* 27, 295–311.
- Scherler, D., Bookhagen, B., Strecker, M.R., von Blanckenburg, F., Rood, D., 2010. Timing and extent of late Quaternary glaciation in the western Himalaya constrained by ^{10}Be moraine dating in Garhwal, India. *Quat. Sci. Rev.* 29, 815–831.
- Searle, M.P., Richard, J.P., 2007. Relationships between right-lateral shear along the Karakoram fault and metamorphism, magmatism, exhumation and uplift: evidence from the K2–Gasherbrum, Pangong Ranges, north Pakistan and Ladakh. *J. Geol. Soc. London* 164, 439–450.
- Seong, Y.B., Owen, L.A., Bishop, M.P., Bush, A., Clendon, P., Copland, P., Finkel, R.C., Kamp, U., Shroder, J.F., 2007. Quaternary glacial history of the Central Karakoram. *Quat. Sci. Rev.* 26, 3384–3405.
- Seong, Y.B., Owen, L.A., Bishop, M.P., Bush, A., Clendon, P., Copland, P., Finkel, R., Kamp, U., Shroder, J.F., 2008. Reply to comments by Matthias Kuhle on “Quaternary glacial history of the central Karakoram”. *Quat. Sci. Rev.* 27, 1656–1658.
- Seong, Y.B., Owen, L.A., Yi, C., Finkel, R.C., 2009a. Quaternary glaciation of Muztag Ata and Kongur Shan: evidence for glacier response to rapid climate changes throughout the Late Glacial and Holocene in westernmost Tibet. *Geol. Soc. Am. Bull.* 121, 348–365.
- Seong, Y.B., Bishop, M.P., Bush, A., Clendon, P., Copland, P., Finkel, R., Kamp, U., Owen, L.A., Shroder, J.F., 2009b. Landforms and landscape evolution in the Skardu, Shigar and Braldu Valleys, Central Karakoram. *Geomorphology* 103, 251–267.
- Seong, Y.B., Owen, L.A., Yi, C., Finkel, R.C., Schoenbohm, L., 2009c. Geomorphology of anomalously high glaciated mountains at the northwestern end of Tibet: Muztag Ata and Kongur Shan. *Geomorphology* 103, 227–250.
- Seong, Y.B., Owen, L.A., Caffee, M.W., Kamp, U., Bishop, M.P., Bush, A., Copland, L., Shroder, J.F., 2009d. Rates of basin-wide rockwall retreat in the K2 region of the Central Karakoram defined by terrestrial cosmogenic nuclide ^{10}Be . *Geomorphology* 107, 254–262.
- Sharma, M.C., Owen, L.A., 1996. Quaternary glacial history of NW Garhwal Himalayas. *Quat. Sci. Rev.* 15, 335–365.
- Shi, Y., 1992. Glaciers and glacial geomorphology in China. *Zeitschrift für Geomorphologie* 86, 19–35.
- Shi, Y., Lui, S., 2000. Estimation on the response of glaciers in China to global warming in the 21st century. *Chinese Sci. Bull.* 45, 668–672.
- Shi, Y., Ren, B., Wang, J., Derbyshire, E., 1986. Quaternary glaciation in China. *Quat. Sci. Rev.* 5, 503–510.
- Shi, Y., Zheng, B., Li, S., 1992. Last glaciation and maximum glaciation in the Qinghai-Xizang (Tibet) Plateau: a controversy to M.Kuhle's ice sheet hypothesis. *Z. Geomorphol.* 84, 19–35.
- Shiraiwa, T., 1993. Glacier Fluctuations and Cryogenic Environments in the Langtang Valley, Nepal Himalaya. Contributions from the Institute of Low Temperature Science. The Institute of Low Temperature Sciences, Hokkaido University, Sapporo, Japan, 98 pp.
- Shiraiwa, T., Watanabe, T., 1991. Late Quaternary glacial fluctuations in the Langtang Valley, Nepal Himalaya, reconstructed by relative dating methods. *Arct. Alp. Res.* 23, 404–416.
- Shroder, J., Owen, L.A., Seong, Y.B., Bishop, M.P., Bush, B., Caffee, M.W., Finkel, R.C., Kamp, U., 2011. The role of mass movement on landscape evolution in the Central Karakoram: discussion and speculation. *Quat. Int.* 236, 34–47.
- Smiraglia, C., 1997. Holocene variations of the Yanzigou Glacier (Gongga Shan Massif, Da Xueshan, China). *Geografica Fisica e Dinamica Quaternaria* 20, 339–351.
- Spencer, J.Q., Owen, L.A., 2004. Optically stimulated luminescence dating of Late Quaternary glaciogenic sediments in the upper Hunza valley: validating the timing of glaciation and assessing dating methods. *Quat. Sci. Rev.* 23, 175–191.
- Stone, J.O., 2000. Air pressure and cosmogenic isotope production. *J. Geophys. Res.* 105, 23753–23759.
- Strasky, S., Graf, A.A., Zhao, Z.Z., Kubik, P.W., Baur, H., Schluchter, C., Wieler, R., 2009. Late glacial ice advances in southeast Tibet. *J. Asian Earth Sci.* 34, 458–465.
- Su, Z., Shi, Y., 2002. Response of monsoonal temperate glaciers to global warming since the Little Ice Age. *Quat. Int.* 97–98, 123–132.
- Su, Z., Shi, Y., Zheng, B., 2002. Quaternary glacial remains on the Gongga Mountain and the division of glacial period. *Adv. Earth Sci.* 17, 647–2002.
- Taylor, P.J., Mitchell, W.A., 2000. Late Quaternary glacial history of the Zaskar Range, North-west Indian Himalaya. *Quat. Int.* 65/66, 81–100.
- Thackray, G.D., Owen, L.A., Yi, C.L., 2008. Timing and nature of late Quaternary mountain glaciation. *J. Quat. Sci.* 23, 503–508.
- Thompson, L.G., 2000. Ice core evidence for climate change in the Tropics: implications for our future. *Quat. Sci. Rev.* 19, 19–35.
- Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Bolzan, J.F., Dai, J., Yao, T., Gundestrup, N., Wu, X., Klein, L., Xie, Z., 1989. Holocene–Late Pleistocene climatic ice core records from Qinghai-Tibetan Plateau. *Science* 246, 474–477.
- Thompson, L.G., Yao, T., Davis, M.E., Henderson, K.A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.A., Cole-Dai, J., Bolzan, J.F., 1997. Tropical climate instability: the Last Glacial Cycle from a Qinghai–Tibetan ice core. *Science* 276, 1821–1825.
- Trinkler, E., 1930. The Ice-Age on the Tibetan Plateau and in the adjacent region. *Geogr. J.* 75, 225–232.
- Tschudi, S., Schäfer, J.M., Zhao, Z.Z., Wu, X.H., Ivy-Ochs, S., Kubik, P.W., Schluchter, C., 2003. Glacial advances in Tibet during the Younger Dryas? Evidence from cosmogenic ^{10}Be , ^{26}Al , and ^{21}Ne . *J. Asian Earth Sci.* 22, 301–306.
- Tsukamoto, S., Asahi, K., Watanabe, T., Kondo, R., Rink, W.J., 2002. Timing of past glaciation in Kanchenjunga Himal, Nepal by optically stimulated luminescence dating of tills. *Quat. Int.* 97/98, 57–68.
- Von Wissmann, H., 1959. Die heutige Vergletscherung und Schneegrenze in Hochasien mit Hinweisen auf die Vergletscherung der letzten Eiszeit. In: *Akademie der Wissenschaften und der Literatur in Mainz, Abhandlungen der Mathematisch-Naturwissenschaftlichen Klasse*, vol. 14, pp. 121–123.
- Wang, F., Fan, C.Y., 1987. Climatic changes in the Qinghai-Xizang (Tibetan) region of China during the Holocene. *Quat. Res.* 28, 50–60.
- Wang, J., Raisbeck, G., Xu, X.B., Yiou, F., Bai, S.B., 2006. In situ cosmogenic ^{10}Be dating of the Quaternary glaciations in the southern Shaluli Mountain on the southeastern Tibetan Plateau. *Sci. China Ser. D Earth Sci.* 49, 1291–1298.
- Wang, J., Kassab, C., Harbor, J.M., Caffee, M.W., Cui, H., Zhang, G., 2013. Cosmogenic nuclide constraints on late Quaternary glacial chronology on the Dalijia Shan, northeastern Tibetan Plateau. *Quat. Res.* 79, 439–451.
- Waragai, T., 1998. Effects of rock surface temperature on exfoliation, rock varnish, and lichens on a boulder in the Hunza Valley, Karakoram Mountains, Pakistan. *Arct. Alp. Res.* 30, 184–192.
- Waragai, T., 2005. Holocene calcrete crust deposits on the moraine of Batura Glacier, northern Pakistan. *Island Arc* 14, 368–377.
- Watanabe, T., Shiraiwa, T., Ono, Y., 1989. Distribution of periglacial landforms in the Langtang Valley, Nepal Himalaya. *Bull. Glacier Res.* 7, 209–220.

- Willett, S.D., 2010. Erosion on a line. *Tectonophysics* 484, 168–180.
- Wu, G.H., 1984a. The preliminary observation of Neoglaciation in the Qilian Mountains. *J. Glaciol. Geocryol.* 6, 53–60 (in Chinese with English summary).
- Wu, G.H., 1984b. The Quaternary glaciation questions in Qilian mountains. In: *Memoirs of Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Science* (No. 5): Glacier Changes and Utilizations in Qilian Mountains. Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Science. Science Press, Beijing, pp. 116–123.
- Wu, Y., Cui, Z., Liu, G., Ge, D., Yin, J., Xu, Q., Pang, Q., 2001. Quaternary geomorphological evolution of the Kunlun Pass area and uplift of the Qinghai-Xizang (Tibet) Plateau. *Geomorphology* 36, 203–216.
- Yang, J.Q., Zhang, W., Cui, Z.J., Yi, C.L., Liu, K.X., Ju, Y.J., 2006. Late Pleistocene glaciation of Diancang Mountains and Gongwang Mountains, southeastern margin of the Tibetan Plateau. *Quat. Int.* 154–155, 52–62.
- Yang, B., Brauning, A., Dong, Z., Zhang, Z., Keqing, J., 2008. Late Holocene monsoonal temperate glacier fluctuations on the Tibetan Plateau. *Global Planet. Change* 60, 126–140.
- Yao, T., Thompson, L.G., Mosley-Thompson, E., Yang, Z., Zhang, X., Lin, P., 1996. Climatological significance of $\delta^{18}\text{O}$ in north Tibetan ice cores. *J. Geophys. Res.* 101 (D23), 29,531–29,537.
- Yao, T., Shi, Y., Thompson, L.G., 1997. High resolution record of paleoclimate since the Little Ice Age from the Tibetan ice cores. *Quat. Int.* 37, 19–23.
- Yi, C., Liu, K.X., Cui, Z.J., Jiao, K.Q., Yao, T.D., He, Y.Q., 2004. AMS radiocarbon dating of late Quaternary glacial landforms, the source area of the Urumqi River, Tien Shan: a pilot study of ^{14}C dating on inorganic carbon. *Quat. Int.* 121, 99–107.
- Yi, C., Chen, H., Yang, J., Liu, B., Fu, P., Liu, K., Li, S., 2008. Review of Holocene glacial chronologies based on radiocarbon dating in Tibet and its surrounding mountains. *J. Quat. Sci.* 23, 533–558.
- Yin, A., Harrison, T.M., 2000. Geologic evolution of the Himalayan–Tibetan orogen. *Ann. Rev. Earth Planet. Sci.* 28, 211–280.
- Zech, W., 2012a. A Late Pleistocene glacial chronology from the Kitschi-Kurumdu Valley, Tien Shan (Kyrgyzstan), based on ^{10}Be surface exposure dating. *Quat. Res.* 77, 281–288.
- Zech, W., Glaser, B., Ni, A., Petrov, M., Lemzin, I., 2000. Soil as indicators of the Pleistocene and Holocene landscape history: Alay Range (Khyrgyzstan). *Quat. Int.* 65/66, 161–170.
- Zech, W., Glaser, B., Abramowski, U., Dittmar, C., Kubik, P.W., 2003a. Reconstruction of the Late Quaternary Glaciation of the Macha Khola valley (Gorkha Himal, Nepal) using relative and absolute (^{14}C , ^{10}Be , dendrochronology) dating techniques. *Quat. Sci. Rev.* 22, 2253–2265.
- Zech, W., Glaser, B., Sosin, P., Kubik, P.W., Zech, W., 2003b. Evidence for long-lasting landform surface instability on hummocky moraines in the Pamir Mountains (Tajikistan) from ^{10}Be surface exposure dating. *Earth Planet. Sci. Lett.* 237, 453–461.
- Zech, R., Abramowski, U., Glaser, B., Sosin, P., Kubik, P.W., Zech, W., 2005. Late Quaternary glacier and climate history of the Pamir Mountains derived from cosmogenic ^{10}Be exposure ages. *Quat. Res.* 64, 212–220.
- Zech, R., May, J.H., Kull, C., Ilgner, J., Kubik, P.W., Veit, H., 2008. Timing of the late Quaternary glaciation in the Andes from 15 to 40S. *J. Quat. Sci.* 23, 635–647.
- Zech, R., Zech, M., Kubik, P.W., Kharki, K., Zech, W., 2009. Deglaciation and landscape history around Annapurna, Nepal, based on ^{10}Be surface exposure dating. *Quat. Sci. Rev.* 28, 1106–1118.
- Zech, R., Röhringer, I., Sosin, P., Kabgov, H., Merchel, S., Akhmadaliev, S., Zech, W., 2013. Late Pleistocene glaciations in the Gissar Range, Tajikistan, based on ^{10}Be surface exposure dating. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 369, 253–261.
- Zeitler, P.K., Meltzer, A.S., Koons, P.O., Craw, D., Hallet, B., Chamberlain, C.P., Kidd, W.S.F., Park, S.K., Seeber, L., Bishop, M., Shroder, J.F., 2001. Erosion, Himalayan geodynamics and the geomorphology of metamorphism. *GSA Today* 11, 4–8.
- Zhang, Z.S., 1988. Fluctuation of glaciers on the northwest slope of Mt. Nanjagbarwa since the last glaciation. *J. Glaciol. Geocryol.* 10, 180–188 (Chinese with English summary).
- Zhao, J., Liu, S., He, Y., Song, Y., 2009. Quaternary glacial chronology of the Ateoyinake River Valley, Tianshan Mountains, China. *Geomorphology* 103, 276–284.
- Zhao, J., Lai, Z., Liu, S., Song, Y., Li, Z., Yin, X., 2012. OSL and ESR dating of glacial deposits and its implications for glacial landform evolution in the Bogeda Peak area, Tianshan range, China. *Quat. Geochronol.* 10, 237–243.
- Zheng, B., 1997. Glacier variation in the monsoon maritime glacial region since the last glaciation on the Qinghai-Xizang (Tibetan) plateau. In: *The Changing Face of East Asia During the Tertiary and Quaternary*. Center of Asian Studies, The University of Hong Kong, pp. 103–112.
- Zheng, B.X., 2006. Quaternary glaciations in Nyainqentanglha Mountains. In: Shi, Y.F., Su, Z., Cui, Z.J. (Eds.), *The Quaternary Glaciations and Environmental Variations in China*. Science and Technology Press of Hebei Province, Shijiazhuang, pp. 374–400.
- Zheng, B.X., Li, J.J., 1986. Regional divisions of existing glaciers in Xizang region. In: Li, J.J., Zheng, B.X., Yang, X.J. (Eds.), *Glaciers of Xizang (Tibet)*. Science Press, Beijing, pp. 130–148.
- Zheng, B.X., Ma, Q.H., 1994. The glacier variation, climatic change and the river valley development in the Holocene on the Gongga Mountains. *Acta Geogr. Sin.* 49, 500–508 (Chinese with English summary).
- Zheng, B., Rutter, N., 1998. On the problem of Quaternary glaciations, and the extent and patterns of Pleistocene ice cover in the Qinghai-Xizang (Tibet) plateau. *Quat. Int.* 45/46, 109–122.
- Zheng, B.X., Li, S.J., Wang, S.M., 1995. The Quaternary glacier evolution history in the surrounding high mountains, Zoige Basin. In: *Expert Committee on Qingzang Program* (Ed.), *The Formation Evolution, Environmental Variance, and Ecosystem Research in Qinghai–Tibet Plateau*. Science Press, Beijing, pp. 218–226.
- Zhou, S.Z., Chen, F.H., Pan, B.T., Cao, J.J., Li, J., Derbyshire, E., 1991. Environmental change during the Holocene in western China on a millennial timescale. *Holocene* 1, 151–156.
- Zhou, S.Z., Yi, C.L., Shi, Y.F., Ye, Y.G., 2001. Study on the ice age MIS 12 in Western China. *J. Geomech.* 7 (4), 321–327 (in Chinese with English Abstract).
- Zhou, S.Z., Wang, X.L., Wang, J., Xu, L.B., 2006. A preliminary study on timing of the oldest Pleistocene glaciation in Qinghai–Tibetan Plateau. *Quat. Int.* 154/155, 44–51.
- Zhou, S.Z., Xu, L.B., Colgan, P.M., Mickelson, D.M., Wang, X.L., Wang, J., Zhong, W., 2007. Cosmogenic ^{10}Be dating of Guxiang and Baiyu glaciations. *Chinese Sci. Bull.* 52, 1387–1393.
- Zhou, S.Z., Wang, J., Xu, L.B., Wang, X.L., Colgan, P.M., Mickelson, D.M., 2010. Glacial advances in southeastern Tibet during late Quaternary and their implications for climatic changes. *Quat. Int.* 218, 58–66.
- Zhou, S., Li, J., Zhao, J., Wang, J., Zheng, J., 2011. Quaternary glaciations: extent and chronology in China. In: Elhers, J., Gibbard, P., Hughes, P.D. (Eds.), *Quaternary Glaciations – Extent and Chronology: a Closer Look, Developments in Quaternary Science*, second ed., vol. 15. Elsevier, Amsterdam, pp. 981–1002.
- Zreda, M.G., Phillips, F.M., Elmore, D., 1994. Cosmogenic ^{36}Cl accumulation in unstable landforms: 2. Simulations and observations on eroding moraines. *Water Resour. Res.* 30, 3127–3136.