Landscape development of the Himalayan-Tibetan orogen: a review

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Abstract

The Himalayan-Tibetan orogen provides one of the best natural laboratories to examine the nature and dynamics of landscape development within continental-continental collisions zones. Many new tectonic-climatic-geomorphic theories and models have emerged and/or have been greatly influenced as a consequence of the study of the region and the quest to understand its geomorphic development. These include studies of the interactions among tectonics, climate and surficial processes, notably, the influence of climate on surface uplift by denudational unloading; the limiting of topography by glaciation (the glacial buzz-saw); localized uplift at syntaxes by enhanced fluvial and glacial erosion that, in turn, weaken the lithosphere, enhancing surface uplift and exhumation (the tectonic aneurysm); climate-driven out-of-sequence thrusting and crustal channel flow; glacial damming leading to differential erosion and uplift; paraglaciation; and the influence of extreme events such as earthquakes, landslides, and floods as major formative processes. The development of new technologies, including satellite remote sensing and global positioning systems, and analytical methods such as numerical dating is now allowing these theories and models to be tested and will inevitably lead to new paradigms.

Keywords: Himalaya; Tibet; geomorphology; landscape development; tectonics; glaciation; paraglaciation; earthquakes

The Himalaya and Tibet provide one of the best natural laboratories to examine the nature and dynamics of landscape development within continental-continental collisions zones. Not surprisingly, many new geomorphic theories and models have emerged as the consequence of the study of the region and the quest to understand its geomorphic development. This paper will review the main studies that have been undertaken that have lead to new insights into how mountain belts develop which underlie the new paradigms that landscape development in mountains is a consequence of the interactions among tectonics, climate, and Earth surface processes. The studies will be broadly discussed chronologically to help understand how the different theories and models have evolved.

Early exploration

The earliest studies in the Himalayan-Tibetan orogen were undertaken during the late 19th and early 20th centuries as western explorer-naturalists travelled the region documenting both its cultural and scientific characteristics (e.g. Shaw 1871; Drew 1875). Many of these explorations likely had ulterior motives, being part of the Great Game, the political intrigue between British India and Russia (Keay 1996). Much emphasis was placed on surveying the region, some of which resulted in profound discoveries such as the gravity surveys by Airy (1855) and Pratt (1859) that lead to the realization that the Himalaya and other mountains had deep, low-density roots.

Probably the most notable geomorphic study was undertaken by Drew (1873, 1875) in the Indus valley, who noted numerous glacial, lacustrine, and alluvial fan landforms. In his 1873 paper, Drew was the first to use the term "alluvial fan" and he was influenced by the earlier work of Surell (1841) and Haast (1864) in the Alps and Canterbury Plains of New Zealand (Fig. 1). Drew's work focused on describing the morphology of the landforms, but little attention was given to their sedimentology. Nevertheless, he discussed their likely origins and emphasized the important evidence for past glaciation throughout Kashmir. Later studies focused on examining the glacial geologic record and included the notable works of Dainelli, (1922, 1934, 1935), Norin (1925), Trinkler (1930), Misch (1935), de Terra & Paterson (1939) and Paffen *et al.* (1956) for regions throughout the western end of the Himalayan–Tibetan orogen.

Klute (1930) provides the first comprehensive map of the extent of glaciation for the Last Glacial for the entire Himalayan–Tibetan region. At the same time these studies of landforms and glacial geology were being undertaken, bedrock and structural geology were being examined by numerous geologists, most notably the Swiss geologist Augusto Gansser. Much of Gansser's work was published in his seminal book "Geology of the Himalaya" (Gansser 1964). However, these "hard rock" studies had to await the development of plate tectonic theory in the late 1960s and 1970s before a solid framework was available to appreciate their significance and to provide a foundation for tectonic, geomorphic, and landscape development studies.

Ice Age studies

Early exploration of the Himalaya was concurrent with the development of glacial geology and the realization that the world had experienced extensive glaciation in the recent past. Many observations were made on glacial geology and attempts were made to reconstruct former ice extent throughout the Himalaya. These early studies of glaciation were driven by a desire to correlate Himalayan glacial successions with those recognized in Europe, notably the seminal work of Penck & Brunkner (1909) in the Alps, who argued that four glaciations characterized the Quaternary. As a consequence, numerous researchers assigned their glacial geological evidence to four glaciations throughout areas of Tibet and the Himalaya (e.g. de Terra & Paterson 1939; Porter 1970; Zhang & Shi 1980).

The first truly modern comprehensive studies of glaciation were undertaken by von Wissmann (1959) and Frenzel (1960), who used the observations of the earliest explorers to construct a regional synthesis of the glaciation of Tibet and the Himalaya. They both suggested that during glacial times, ice caps expanded and extensive valley glacial systems developed throughout much of the Himalaya, Pamir, Kunlun, and Qilian Shan. This view was questioned by Kuhle (1985, 1986, 1987, 1988a, 1988b, 1990a, 1990b, 1991, 1993, 1995) who argued for an extensive ice sheet covering most of the Tibetan Plateau during the Last Glacial. This Tibetan ice sheet hypothesis was important throughout the 1980s and 1990s in driving much of the study of the Quaternary glacial geology of Tibet and adjacent regions. Subsequently, however, numerous studies have disproven the existence an extensive ice sheet on Tibet (Derbyshire 1987; Zheng 1989;

Burbank & Kang 1991; Derbyshire *et al.* 1991; Shi 1992; Hovermann *et al*. 1993a, 1993b; Lehmkuhl 1995, 1997, 1998; Rutter 1995; Lehmkuhl *et al*. 1998; Zheng & Rutter 1998; Schäfer *et al*. 2002; Owen *et al.* 2003). In particular, as Owen *et al.* (2008) and Seong *et al.* (2008) point out, the differences in interpretation between Kuhle (1985, 1986, 1987, 1988a, b, 1990a,b, 1991, 1993, 1995) and other researchers is a consequence of their differing interpretation of landforms and sediments, the misuse of equilibrium-line altitudes for determining former ice extent, and poor chronological control. It is now generally accepted that a large ice sheet did not cover the Tibetan Plateau, at least not during the past few glacial cycles. Figure 2 illustrates different reconstructions for the extent of glaciation through the Himalaya and Tibet.

Researchers began to appreciate the complexity of glaciation in the Himalaya and Tibet with the development of marine oxygen isotope stratigraphy for the Quaternary during the 1980s; specifically, that there were many more than four glaciations during the Quaternary Ice Age. However, defining the timing of glaciation in the Himalayan-Tibetan orogen was hindered due to the lack of numerical ages on moraines and associated landforms. This was mainly due to the scarcity of organic matter necessary for radiocarbon dating, the standard dating technique for Quaternary landforms and sediments at that time. Rothlisberger & Geyh (1985), however, were able to obtain enough organic material from moraines in the Himalaya and Karakoram to determine 68 radiocarbon ages to define ~10 glacial advances in the Late Quaternary. Subsequent studies, however, have only provided a few additional radiocarbon ages (e.g., Derbyshire *et al.* 1991; Lehmkuhl 1997).

The development of optically stimulated luminescence (OSL) and terrestrial cosmogenic nuclide (TCN) surface exposure dating since the late 1980s have allowed workers to date glacial and associated landforms that were previously updateable. Furthermore, the techniques have allowed landforms older than >30 ka (the limit of standard radiocarbon dating) to be defined, and in some cases, to be taken back to many hundreds of thousands years. These method have resulted in a plethora of ages on moraines throughout the Himalaya and Tibet (see summary in Owen *et al.* 2008)

Owen *et al.* (2008) highlighted the limitations of OSL and TCN methods by reevaluating published glacial chronologies throughout the Himalaya and Tibet. These limits, for example, include geological factors and uncertainties associated with modeling the appropriate production rates for TCN dating and variation in dose rates for OSL dating. The summary provided by Owen *et al.* (2008) supports the view that expanded ice caps and extensive valley glacier systems existed throughout the Himalaya and Tibet during the late Quaternary, but it is not yet possible to determine whether or not the timing of the extent of maximum glaciation was synchronous throughout the entire region. The data do show considerable variations in the extent of glaciation from one region to the next during a glaciation. Glaciers throughout monsoon-influenced Tibet, the Himalaya, and the Transhimalaya are likely synchronous both with climate change resulting from oscillations in the South Asian monsoon and with Northern Hemisphere cooling cycles. In contrast, glaciers in Pamir in the far western regions of the Himalayan–Tibetan orogen advanced asynchronously to regions that are monsoon-influenced and appear to be mainly in phase with the Northern Hemisphere cooling cycles. Owen *et al.* (2008) also pointed out that broad patterns of local and regional variability based on equilibrium-line altitudes have yet to be fully assessed, but have the potential to help define changes in climatic gradients over time. Clearly, accurate reconstructions of the former extent and timing of glaciation is important for assessing and quantifying the tectonic-climate-landscape models.

Paraglaciation

In the 1970s, studies on Late Quaternary glaciofluvial deposits on Baffen Island and in British Columbia lead to the realization that rates of sedimentation increase significantly during times of deglaciation (Ryder 1971a, 1971b; Church & Ryder 1972). This lead to the concept of paraglaciation, which argues that nonglacial processes are directly conditioned by glaciation and that landscape changes are greatest during times of deglaciation (Ryder 1971a, 1971b; Church & Ryder 1972; and reviewed by Ballantyne 2002, 2004). The term paraglacial was applied to describe the processes that operate and the landforms that are produced during deglaciation as the landscape readjusts to new climatic and environmental conditions. Paraglacial time was considered to be the period when paraglacial processes are dominant, mainly fluvial erosion and resedimentation, and mass movement. Paraglacial processes are particularly important in the transfer and resedimentation of glacial and proglacial sediments within and beyond the high-mountain landscapes, thus helping to contribute to the net denudation of high mountains.

When valley fill successions, river terraces, and alluvial fans began to be studied in the Karakoram during late 1980s and early 1990s, the concept of paraglaciation was applied to help understand their origin (Owen 1989; Derbyshire and Owen 1990; Owen & Derbyshire 1993). Subsequently, many studies have argued for the importance of paraglaciation in the landscape development of the other regions of the Himalayan-Tibetan orogen (Owen *et al.* 1995, 2006; Owen & Sharma 1995; Owen *et al.* 2002; Yang *et al.* 2002; Barnard *et al.* 2004a, 2004b, 2006a, 2006b; Seong *et al.* 2009a, 2009b). Figure 3 illustrates how the relative composition of landforms changes within Himalayan valleys that were deglaciated at different times, showing a change from moraine-dominated to terrace- and fan-dominated with time.

It is now generally accepted that landscapes in the Himalayan-Tibetan orogen have been continuously readjusting to changing climatic and environmental conditions associated with the high frequency of the oscillations of glaciers (on millennial timescales) throughout the late Quaternary.

Glacial lake outburst floods (GLOFs) constitute one of the most dramatic manifestations of paraglaciation. They result from rapid drainage of moraine-dammed or supraglacial lakes and in recent years have attracted much attention due to the potential catastrophic impact they may have on settlements throughout the Himalaya. Their frequency may likely increase as glaciers continue to melt and retreat due to human-induced climate change (Reynolds 2000; Richards & Reynolds 2000; Benn *et al.* 2001). Evidence for past GLOFs is abundant throughout the Himalaya and includes mega-ripples, giant boulder clusters, scour pools, and large terraces (Coxon *et al.* 1996, Barnard *et al.* 2006a; Seong *et al.* 2009a).

Plate tectonics and landscape development

The Himalaya and Tibet received much attention as plate tectonic theory developed in the late 1960s and early 1970s, but logistical and political access to the region was somewhat limited, hindering study of the region. In the late 1970s, a series of new roads were constructed to traverse the Himalaya and Tibet permitting relatively easy access to the region (Owen 1996). Furthermore, China began to strengthen its international research collaboration, allowing more access to Tibet and adjacent regions. It was not until the early 1980s, however, that researchers actually began to describe tectonic landforms and interpret their origin.

Much of the early work on tectonic geomorphology was stimulated by the realization that a significant component of the collision of the Indian and Asian continental lithospheric plates might be accommodated by lateral extrusion of Tibet along major strike-slip faults (Tapponnier & Molnar 1976; Fig. 4). Faulted landforms, notably faulted moraines, were examined to help estimate displacement rates along the major strike-slip faults (Tapponnier & Molnar 1977; Molnar & Tapponnier 1978; Armijo *et al.* 1986).

Other significant tectonic geomorphic work included the study of Seeber & Gornitz (1983) who analyzed the longitudinal profiles of major rivers that drained across the

Himalaya, which emphasized important tectonic controls on knick point development and drainage patterns.

As the structure of the Himalaya and Tibet began to be mapped and examined by integrating thermochronologic and geobarometric methods, areas of differential uplift were identified. Most notable was focused uplift around the Himalayan western and eastern syntaxes, particularly Nanga Parbat (Zeitler. 1985). This lead to the initial examination of the tectonic geomorphology of these zones of focused uplift (e.g. Owen 1988a; Shroder *et al.* 1989). It soon became apparent that relating landforms and deformed sediments to tectonic processes was not simple. Many of the Himalayan landforms are polygenetic in origin (Owen 1989) and therefore any tectonic influences could not easily be elucidated by simple study of landforms. In addition, glacial and mass movement processes in Himalayan-Tibetan environments produce deformation structures that are easily misinterpreted as tectonic, such as the glaciotectonised deposits throughout the Skardu Basin and landslides along the middle Indus valley in Northern Pakistan (Owen 1988a, 1988b; Owen & Derbyshire 1988).

Over the last two decades new mechanical and thermomechanical models to explain the tectonic evolution of Himalayan-Tibetan orogen have been proposed. These have evolved from an orogenic wedge model (notably that of Burchfiel *et al.* 1992), to pervasive ductile flow, indicated by folded isograds within a tectonic wedge (Grujic *et al.* 1996), to channel flow of the middle crust (Jamieson *et al.* 2004), with variants of mid-crustal flow based on numerical modeling (Beaumont *et al.* 2004). Harris (2007) describes the history and essential components of these models and summarizes the current view, which proposes movement of a low-viscosity crustal layer in response to topographic loading. This potential mechanism results in the eastward flow of the Asian lower crust causing the peripheral growth of the Tibetan Plateau and the southward flow of the Indian middle crust and its extrusion along the Himalayan topographic front. Harris (2007) stressed that thermomechanical models for channel flow link extrusion to focused orographic precipitation at the surface. These models are exciting because they recognize the links among tectonics, climate, and surficial processes.

In addition to the tectonic models for the Himalaya, numerous models have been proposed for the evolution of the high elevations in Tibet. Tapponnier *et al.* (2001) summarized two end members: 1) continuous thickening and widespread viscous flow of the crust and mantle beneath the entire plateau; and 2) time-dependent, localized shear between coherent lithosphere blocks. Tapponnier *et al.* (2001) favor the latter and argue for dominant growth of the Tibetan Plateau toward the east and northeast. This in turn has led to the development of new mountain ranges and basins, with the basins becoming progressively filled to form flat, high plains.

Interactions between climate, glacial erosion, uplift and topography

During the late 1980s and 1990s, much attention was focused on the potential role of uplift of the Tibetan-Himalayan orogen in driving Cenozoic global cooling and the growth of large continental ice sheets during the Late Tertiary and Quaternary (Raymo *et al.* 1988; Ruddiman & Kutzbach 1989, 1991; Prell & Kutzbach 1992; Raymo &

Ruddiman 1992). The uplift of the orogen was thought to have altered atmospheric circulation and to have changed the concentrations of gases in the atmosphere as a result of changes in biogeochemical cycles associated with the increased weathering of newly exposed rock surfaces, which, in turn, lead to global cooling. Controversy ensued, however, over defining the timing and magnitude of Tibetan-Himalayan uplift and the complex feedbacks involved in the biogeochemical cycles and climate (Molnar & England 1990; Dupont-Nivet *et al.* 2008; Garzione 2008). In a broad sense, however, it is generally accepted that uplift of the orogen probably played a significant role, in addition to many other factors, in Cenozoic cooling (Ruddiman 1997; Owen 2006). In particular, the uplift of the orogen likely helped initiate the south Asian monsoon at ~8 Ma (Burbank *et al.* 1993), which has had a profound impact on the dynamics of surficial processes in the Central Asia.

The high elevation of the Himalayan-Tibetan orogen makes it the most glaciated region outside of the polar realm. Furthermore, the widespread evidence of more extensive glaciation in the past made it inevitable that glaciers were considered important agents in the denudation that lead to long term lowering of the orogen and limited the orogen’s average elevation (Broecker *et al.* 1990). This view was challenged, however, by Molnar & England (1990) who suggested that glacial erosion generating local relief in the cores of mountain ranges might actually initiate tectonic uplift because of erosional unloading of the crust in the cores of ranges (Fig. 5). Furthermore, Molnar & England (1990) suggested that the onset of the Quaternary Ice Age and enhanced glaciation may have lead to accelerated uplift of Himalayan and Tibetan peaks as a consequence of great glacial and associated erosion. Therefore, in Molnar & England (1990) view there is potential for a significant positive feedback loop in which glacial erosion leads to uplift, which, in turn, results in larger glaciers and more erosion and hence more peak uplift.

Molnar & England's (1990) paper stimulated much debate and similar connections have been suggested elsewhere (e.g. Small and Anderson 1998), but whether localized erosion can actually result in mountain peak uplift remains controversial (Gilchrist and Summerfield 1991).

In contrast, Brozovic *et al.* (1997) argued that topographic data from Nanga Parbat show that glaciers are rapidly eroding topography above the equilibrium-line altitude (ELA) exerting an altitudinal limit on mountain height. This has become known as the glacial buzz-saw model and has subsequently been applied to understanding the topography in other mountains, including the Cascade mountains in Washington, and the Chugach Range in Alaska (Mitchell and Montgomery 2006; Spotila *et al.* 2004; Meigs & Sauber 2000; Montgomery *et al.* 2001). Figure 6 shows the relationship between mountain topography, latitude, and present ELAs.

Other studies, however, such as Whipple *et al.* (1999) argued that there are geomorphic limits to climate-induced increases in topographic relief and that neither fluvial nor glacial erosion is likely to induce significant isostatic peak uplift. Whipple *et al.* (1999) provide a quantitative overview and constraints, including empirical evidence to define the effects of a transition from fluvial to glacial erosion. Whipple *et al.* (1999) showed that in almost all non-glaciated landscapes an increase in erosivity of the fluvial system is anticipated to lead to a reduction both in trunk stream and tributary valley relief. When coupled with the constraint that hillslope relief rapidly attains a maximum in active orogens, this observation implies that ridge to valley bottom relief will actually decrease under these conditions. Whipple *et al*. (1999) suggest that relief increase is possible only if a given climate change induces a decrease in erosivity along headwater channel segments in concert with a simultaneous increase in erosivity downstream. An onset of glaciation increases hillslope relief, valley widening, and the formation of hanging valleys and overdeepenings, and relief reduction over short wavelengths. In contrast, over long wavelengths there is a reduction in relief along trunk and tributary valley profiles. If the upper reaches have thin cold based glaciers, ridges and peaks may be protected from erosion and glacier valley profiles may become more concave, adding potentially to overall glacial relief. However, for warm-based glaciers Whipple *et al.* (1999) argue that relief production associated with each of the various glacial relief production mechanisms scales with ice thickness. They also argue that relief production is limited to several hundred meters and it is unlikely that climate change would induce significant amounts of isostatic relief production.

This ability of glaciers and rivers to accomplish rapid erosion underlies a proposed explanation for localized rapid rock uplift in the syntaxes of the Himalaya, a phenomenon that has been dubbed the “tectonic aneurysm” (Zeitler *et al.* 2001; Koons 2002). The aneurysm model argues that the dynamic interactions of focused erosion, topographic stresses, peak uplift, rapid exhumation, thermal weakening of the lithosphere, and deformation leads to localized feedbacks among erosion, deformation, and uplift (Fig. 7). Significant debate exists, however, over the importance of mountain glaciers versus other processes, such as fluvial erosion and mass movement, in shaping mountain landscapes and driving the tectonic aneurysm (Hallet *et al.* 1996).

The discovery in the 1980s of the South Tibetan Detachment fault near the crest of the Himalaya and the realization that it defined northward normal displacement of Tibet stimulated the development of the extrusive flow model (sometimes referred to as the extrusion model; Burchfiel *et al.* 1992; Fig. 8). The extrusive flow model theorizes southward flow of ductile middle and lower crust that continuously replenishes the Himalayan range front, transporting material from between the Main Frontal thrust and the South Tibetan fault system, especially the rocks bounded by the South Tibetan Detachment fault system above and the Main Central (sole) Thrust below (Hodges *et al.* 2001; Harris 2007). This southward extruding zone is thought to represent the ductile lower crustal channel of Tibet that has ground its way to the surface since the Miocene (Harris 2007). Theoretical models by Beaumont *et al.* (2001) argued that channel flow is maintained by erosion of the Himalayan front. This view was enhanced by geomorphic studies that suggest a feedback between erosion and extrusive flow (Wobus *et al.* 2003; Hodges *et al.* 2004).

Examining the Marsyandi River valley that traverses a region of extremely high exhumation between the South Tibetan Detachment and the Main Central Thrust, and where there is very high precipitation, Burbank *et al.* (2003), argue that there is no direct precipitation-erosion linkage because erosion rates are constant based on apatite fission-track ages that show no systematic trend. Rather they suggest that additional factors that influence river incision rates, such as channel width and sediment concentrations, must compensate for differences in precipitation across the region. Moreover, spatially constant erosion is a response to uniform, upward tectonic transport of Greater Himalayan rock above a crustal ramp.

In contrast, on the basis of geologic mapping of the Marsyandi valley in central Nepal, Hodges *et al.* (2004) showed that a zone of recent faulting is coincident with an abrupt change in river gradient, which is thought to mark the transition from rapid uplift of the Higher Himalaya to a region of slower uplift to the south, and likely reflects active thrusting at the topographic front. They suggest that the zone of active thrusting is coincident with a zone of intense monsoon precipitation, likely indicating a positive feedback between focused erosion and deformation at the front of the Higher Himalayan ranges.

Korup & Montgomery (2008) suggested a new twist on the landscape development of the Himalayan-Tibetan orogen in their study of the geomorphology of Namche Barwa. In theory, rivers in this region should progressively erode towards their heads, resulting in the steady degradation of the plateau’s margins and that over time, knickpoints should migrate upstream and become less apparent as erosion progresses. Recently, however, geologic evidence in the Namche Barwa region has shown that the Tsangpo and its tributary streams that traverse Namche Barwa have likely been stable, remaining at the same positions over at least the last million years, effectively preserving the margin of the Tibetan Plateau (Finnegan *et al.* 2008). Various theories have been invoked to help explain the preservation of the margin of the Himalayan-Tibetan orogen, including theories of differential rock uplift matching erosion and other mechanisms, such as landsliding that armors valley floors and helps protect them from river erosion (Lave & Avouac 2001; Ouimet *et al.* 2007).

Korup & Montgomery (2008) highlight that broad stream valleys with substantial terraces and thick valley fill sediments are present upstream of moraines that mark where glaciers and their moraines dammed the Tsangpo and its tributaries. In contrast, stream channels are more confined and are usually entrenched into bedrock downstream of the moraines. They argued that the glaciers and/or the moraines impounded the streams to produce large lakes that fill with sediment, increasing river sedimentation upstream (Fig. 9). These sediments then essentially protected the upstream valley from erosion as stream power decreased in the newly established broad valleys. The sediments become incised to form terraces, with little overall valley lowering. In contrast, the stream channels are confined as they cut through the moraines, resulting in increased stream power and leading to enhanced erosion and entrenchment into bedrock downstream of the moraine. This, in turn, leads to enhanced bedrock uplift in the gorge sections, essentially preserving the margin of Tibet.

All these models highlight an exciting trend in the Earth sciences linking endogenetic and exogenic processes, and highlighting the complex feedbacks among these processes that are reflected in the landscapes that develop.

Extreme events

The relative roles of high magnitude-low frequency and low magnitude-high frequency events in landscape development have been long debated (Brunsden & Jones 1984). Defining what constitutes a high magnitude-low frequency event is difficult for the Himalayan-Tibetan orogen where geomorphic processes are often an order of magnitude greater in size and effect than most other terrestrial settings, and the definition depends on the temporal and spatial framework that is being considered. However, a catastrophic flood that destroys extensive farmland, highways, and villages, a giant landslide displacing >1 million m^3 of displaced debris, and an earthquake of magnitude 7 or higher clearly constitute high magnitude events. For clarity, this type of event will be referred to as an *extreme event*.

Probably the most evident extreme geomorphic events are landslides triggered by large earthquakes. Yet, there have not been many studies of earthquake-triggered landslides in the Himalayan-Tibetan orogen because of the relatively low occurrence of large earthquakes over the hundred years since records have been kept. However, the 1991 and 1999 Garhwal, the 2001 Kokoxili, the 2005 Kashmir, and the 2008 Wenchuan (Sichuan) earthquakes have provided opportunities to study the effects of earthquake-triggered landslides on landscape development (Owen *et al.* 1996; Barnard *et al.* 2001; Van der Woerd *et al.* 2004).

During the Garhwal earthquakes, landsliding comprised mainly rock and debris avalanches and were concentrated along the lower stretches of the valley slopes. Owen *et al.* (1996) and Barnard *et al.* (2001) calculated the equivalent net lowering (denudation) of the landscape by mapping and measuring the amount of sediment produced and moved during and shortly after the earthquakes and concluded that this was small compared to earthquake-induced landsliding in other mountainous regions. Furthermore, Owen *et al.* (1996) and Barnard *et al.* (2001) were able to show that long-term denudation rates and sediment flux resulting from human and monsoon activity in the region was far more significant than earthquake-induced mass movements and associated processes. These studies, therefore, questioned the relative importance of earthquake-induced landforms and processes in landscape evolution of the Himalaya.

In contrast, landslides triggered by the 2005 Kashmir earthquake were much more numerous occurring throughout a region of >7500 km^2, but were highly concentrated, associated with six geomorphic–geologic–anthropogenic settings (Owen *et al.* 2008; Kamp *et al.* 2008). Owen *et al.* (2008) estimated that several thousand landslides were triggered, mainly rock falls and debris falls, although translational rock and debris slides also occurred. In addition, a debris avalanche (the Hattian Bala sturzstrom) comprising >80 million m^3 occurred at Hattian, which blocked streams created two lakes (Fig. 10). The 2008 Wenchuan earthquake triggered numerous large landslides, including one that buried >700 people (USGS, 2008), and probably many thousands of smaller landslides, yet their full impact has still to be assessed.

Landsliding triggered by the 14 November 2001 magnitude 7.9 Kokoxili earthquake has not been fully assessed, but Van der Woerd *et al.* (2004) were able to map the occurrence of several giant ice avalanches (each involving > 1 million m^3 of ice and snow) initiated by slope failure from ice caps due to strong ground motion. These ice avalanches transported little rock debris, and Van der Woerd *et al.* (2004) concluded that it is unlikely that ice avalanches are very important in contributing to the landscape develop in Tibet. Van der Woerd *et al.* (2004) argued, however, that given the appropriate geologic and climatic conditions, ice avalanching may be an important process in the landscape evolution of high mountainous terrains.

In summary, the importance of earthquake-triggered landslides for landscape development has not been thoroughly assessed and is likely to be an important topic of future research. However, non-earthquake triggered landslides are pervasive throughout much of the Himalaya and are triggered by undercutting of slopes by fluvial and glacial erosion. In monsoon areas, heavy seasonal rainfall enhances landsliding. There are numerous large/giant landslides, which comprise > 1 million m^3 of debris, throughout the orogen. Many of these are ancient. Recent studies are suggesting they their formation is temporally clustered and their movement is associated with times of enhanced monsoon, such as during the early Holocene when higher groundwater levels enhance failures (Bookhagen *et al.* 2005; Dortch *et al.* 2009; Fig. 11).

Landsliding can also initiate extreme flooding events. This occurs when landslides dam drainages and create lakes that may drain catastrophically if the landslide dam fails. The Indus valley provides several infamous examples of such extreme events. The most notable was the Indus flood of 1841, which was the result of the drainage of a > 60 km-long lake in the Indus and Gilgit valleys, which were blocked as the results of the earthquake-triggered collapse of the Lichar Spur on Nanga Parbat in 1840. The flood waters advanced > 400 km out of the Himalaya and devastated a Sikh army that was camped on the Chach Plain near Attock (Mason 1929).

Owen (1996) provides other examples of landslide-dammed lakes that failed catastrophically. The geomorphic consequences of such failures have not been systematically assessed and quantified, but clearly they result in major landscape changes involving large scale erosion and resedimentation.

The Garhwal, Kashmir, and Wenchuan earthquakes have focused much interest on determining the frequency and magnitude of large and great earthquakes along the Himalaya and in Tibet (e.g. Wesnousky *et al.* 1999; Bilham *et al.* 2001, Kumar *et al.* 2001, 2006; Feldl & Bilham 2006; Burchfiel *et al.* 2008; Kondo *et al.* 2008). These studies show that great earthquakes are not uncommon in the Himalaya and are likely very important for landscape development. In addition, they pose a very serious risk to the people living in the orogen.

Future trends

Predicting the advances of future research trends in any discipline is challenging. The major paradigm shifts and new technological developments applied to understanding landscape development of the Himalaya-Tibetan orogen over the last few decades illustrates how difficult it would have been to have predicted where the discipline would have progressed just a few decades ago. Probably one of the greatest challenges for us is to examine the complex variability between regions within the Himalayan-Tibetan orogen, and to quantify the timing, rates, and magnitude of landscape development on different timescales ranging from 10^0 to 10^6 years. The development and application of new technologies, including satellite remote sensing (e.g., studies such as Bookhagen & Burbank 2006) and global positioning systems (e.g., studies such as Chen *et al.* 2004; Jade *et al.* 2004), plus analytical methods such as numerical dating, will allow many of the new theories and models to be tested.

Conclusion

The continuous study of the Himalayan-Tibetan orogen over the last century has resulted in exciting new paradigms on the nature and dynamics of landscape development within continental-continental collisions zones. Of particular note is the realization that complex links, interactions, and feedbacks exist among tectonics, climate, and landscape development. New models based on these complex relationships include the influence of climate on rock uplift by denudational unloading of the crust; the limiting of topography by glaciation (the glacial buzz-saw); localized uplift at syntaxes by enhanced fluvial and glacial erosion that, in turn, weaken the lithosphere and so enhance bedrock uplift (the tectonic aneurysm); climate-driven out-of-sequence thrusting and focused erosion driving extrusion of ductile crustal channels, and glacial damming leading to differential erosion and uplift. Improved mapping and dating of landforms will inevitably allow us to test these models and will likely result in the development of new paradigms.

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Figures

Fig. 1. View of an alluvial fan in at Tigarc in the Nubra valley drawn by Drew (1875). (a) View from the mountains behind Charasa and (b) a profile view looking up the valley.

Fig. 2. Selected reconstructions for the extent of glaciation across Tibet and the bordering mountains for the maximum extent of glaciation during the Last Glacial (after Owen *et al.* 2008). (a) Klute's (1930) reconstruction based on a temperature depression of 4°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 Wissmann (1959) who evaluated the observations of the earliest explorers. (c) Kuhle's (1985) reconstruction based on field observations and extrapolation of large ELA depressions (>1000 m) from the margins of Tibet into the interior regions. (d) Reconstruction of Shi (1992) and Shi *et al.* (1992) based on detailed field mapping of glacial and associated landforms and sediments.

Fig. 3. Percentage of landform types in three valleys in the Lahul Himalaya, which were deglaciated at different times (after Owen *et al.* 1995). The data show an increase in paraglacial fans, screes, and terraces and a decrease of moraines with increasing age of deglaciation.

Fig. 4. Digital elevation model of Tibet and the bordering mountains showing major faults and sutures (adapted from Owen 2004, compiled from Searle 1991; Cunningham *et*

al. 1996; Chung *et al.* 1998; Yin *et al.* 1999; Yin and Harrison 2000; Blisniuk *et al.* 2001; and Hurtado *et al.* 2001). Estimates of Late Quaternary strike-slip, convergent, and extensional rates are shown in mm a^{-1} (after Larson *et al.* 1999 and Tapponnier *et al.* 2001). AKMS – Ayimaqin-Kunlun-Mutztagh Suture; ASRR – Ailao Shan-Red River Shear Zone; AF – Altai Fault; ATF – Altyn Tagh Fault; BNS – Bangong Nujiang Suture; GTFS – Gobi-Tien Shan Fault System; HF – Haiyuan fault; ITS – Indus Tsangpo Suture; JHF – Junggar Hegen Fault; JS- Jinsha Suture; KF - Karakoram Fault; KJFZ – Karakoram Jiali Fault Zone; KLF – Kunlun fault; KS – Kudi Suture; LSF – Longmen Shan Fault; MBT – Main Boundary Thrust; MCT – Main Central Thrust; MKT – Main Karakoram Thrust (Shyok Suture Zone); MMT – Main Mantle Thrust; NB – Namche Barwa; NGF – North Gobi fault; NP – Nanga Parbat; NQS – North Qilian Suture; NTSF – North Tien Shan fault; STSF – South Tien Shan fault; TFF – Talus-Fergana Fault; XF – Xianshuihe Fault.

Fig. 5. Model of relief generation via glacial erosion for the case of mountain erosion after Small and Anderson (1998; modified from Molnar and England 1990). Center panel represents initial condition. When erosion (shaded area) is spatially uniform ($E_S = \hat{E}$), the sum of erosionally-driven rock uplift ($U_{\hat{E}}$) and summit erosion (E_S) results in lower summit elevations (ΔZ_S) (left panel). When erosion is spatially variable (right panel), changes in summit elevation are positive because rock uplift is greater than summit erosion ($\Delta Z_S = E_S + U_{\hat{E}}$ (*x*,*y*)). Rock uplift is the same in each case because average erosion ($\hat{E}$), which drives rock uplift, is equal (shaded areas are the same size). The present geophysical relief ($\check{R}$) is the mean elevation difference between a smooth surface

connecting the highest points in the landscape (dashed line) and the current topography. It represents the average of valley erosion (E_V) minus summit erosion calculated at each point in the landscape, including summit flats.

Fig. 6. Glacial buzz-saw model. (a) The present and minimum snowline elevations during the Last Glacial plotted along a topographic transect along the cordillera of North and South America illustrating the positive relationship between topography and snowline elevation (after Broecker & Denton 1990; Skinner et al. 2004). (b) Frequency distribution of altitude and slope angles for selected physiographic areas within the western syntaxis of the Himalaya (DD – dissected portion of Deosai Plateau, NP – Nanga Parbat, G – Ghujerab mountains (northern Karakoram), SN – area north of Skardu) after Brozović *et al.* (1997). The arrows on the horizontal axis indicate the mean elevation for each region; values are inside the graphs. The dark vertical lines running from top to bottom in the graphs show the range of snowline altitudes for each region. The three subhorizontal gray lines show the 25th (lower line), 50th, and 75th (upper line) percentile of slope distribution as a function of altitude for each region. The light gray shaded areas on the slope distribution curves highlight the regions of moderate slopes that generally coincide with the modal elevations. These graphs illustrate the strong relationship between snowline elevation and topography, suggesting that glaciation places limits on topography.

Fig. 7. Schematic representation illustrating the dynamics of a tectonic aneurysm, shown at a mature stage based on Nanga Parbat (see text for explanation; after Zeitler *et al.* 2001).

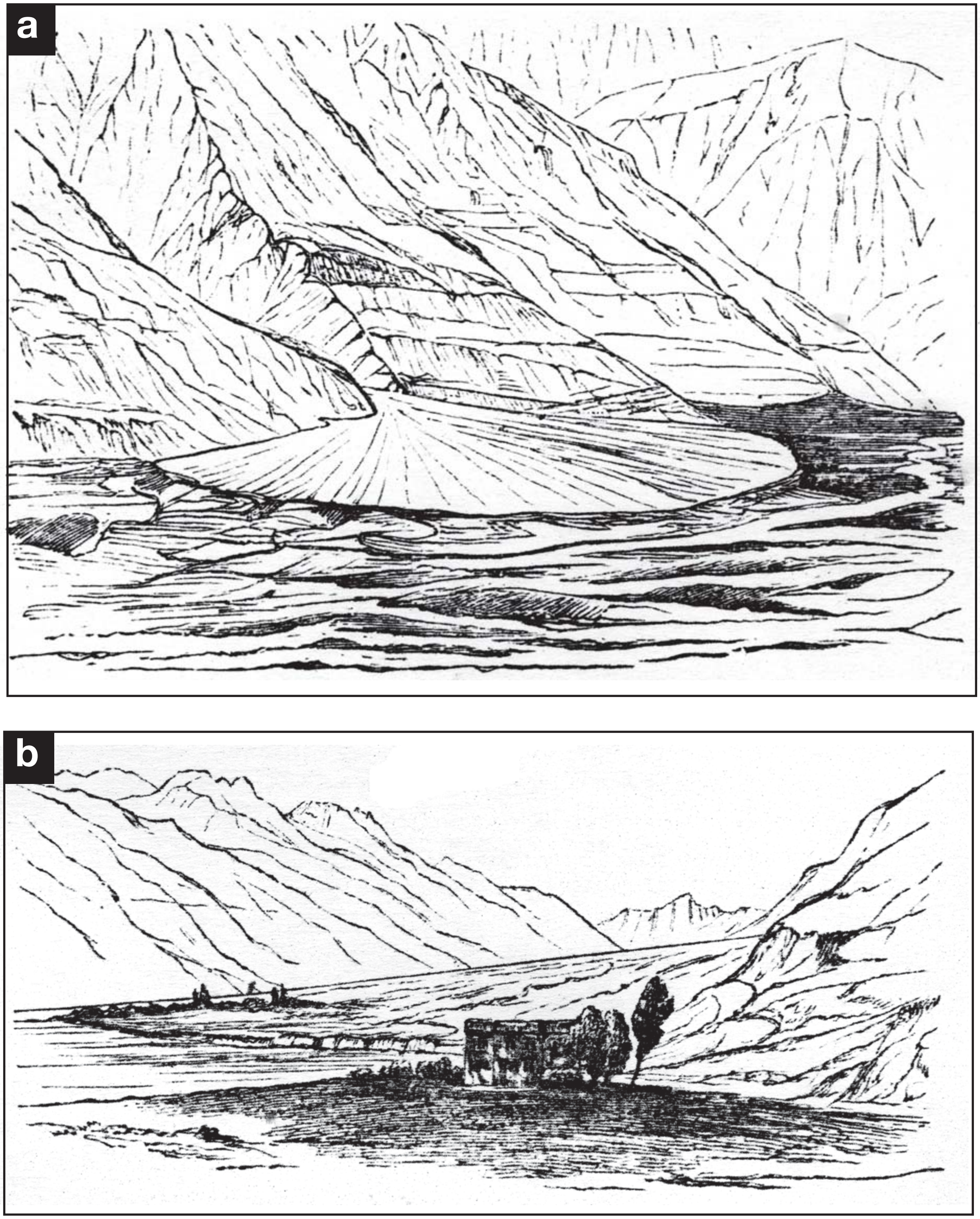
Fig. 8. Schematic section across the Himalaya and southern Tibet illustrating channel flow and extrusion of the channel, and the variation of precipitation, mean hillslope angle, relative stream channel steepness, and annual monsoon precipitation (adapted from Hodges 2006).

Fig. 9. Possible mechanism for the preservation of the edge of southeast Tibet as suggested by Korup and Montgomery (2008) and adapted from Owen (2008) with the following is the sequence of events: 1. Glacier advance dams a river; 2. The deposition of sediments in the resulting upstream lake and stream both protects the valley floor from erosion and reduces the stream's erosive power; 3. Streams draining through the glacier and/or moraine are confined, so stream flow is strong and downstream erosion increases; 4. Stream incision into the bedrock essentially weakens the crust and enhances bedrock uplift to the surface; 5. As streams travel farther from the knick point, smaller gradients reduce their erosive power; 6. The glacier retreats, but the events are repeated numerous times as glaciers advance and retreat in response to climate change. The repetition of this sequence of events maintains equilibrium between erosion and bedrock uplift, essentially preserving the topography of the margin of southeast Tibet.

Fig. 10. The Hattian Bala landslide triggered by the 2005 Kashmir earthquake. The landslide buried four villages resulting in >450 fatalities, blocked two streams, and formed two lakes.

Fig. 11. The relationship between landslides of known age and curves of monsoon intensity and precipitation based on lake cores (after Dortch *et al.* 2009). The thin gray intervals indicate enhanced monsoon phases and subsequent increased precipitation based on lake core data taken from Gasse *et al.* (1996). The histogram uses a 2 ka bin width for landslide occurrence. Dashed horizontal lines on right side show maximum age ranges of rock avalanche clusters crossing the modeled monsoon intensity curve. Thick gray bar is period of enhanced monsoon precipitation between 30 and 40 ka inferred form lake terraces, pollen, lake cores, and ice cores by Shi *et al.* (2001). The three curves in the proxy data section show the simulated monsoon pressure index (DM percentage, solid line) for the Indian Ocean, simulated changes in precipitation (P percentage, thick black dashed line) in southern Asia, and variations in Northern Hemisphere solar radiation (DS percentage, thin gray dashed line) after Prell and Kutzbach (1987).

FIGURE 1 A & B



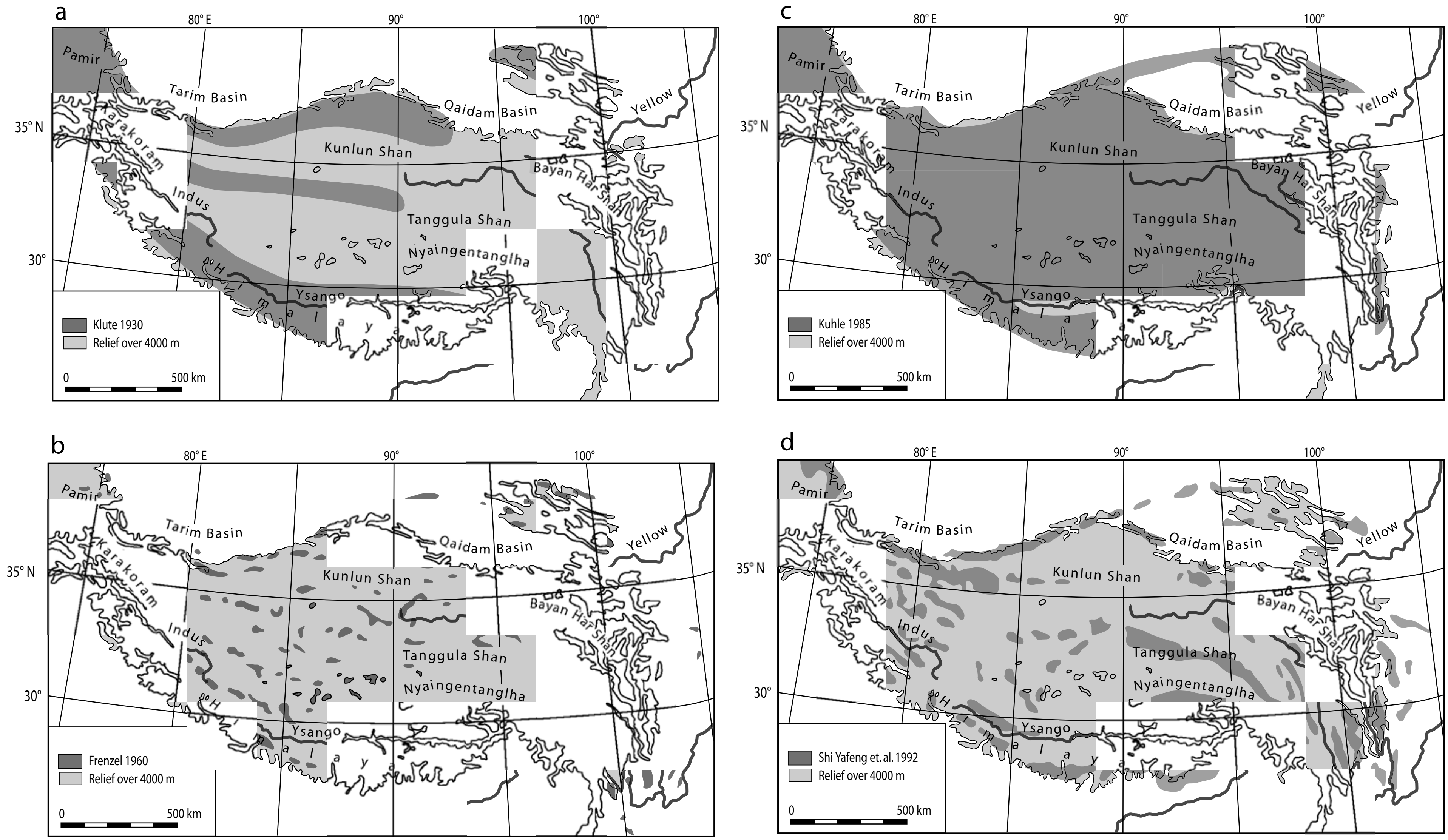
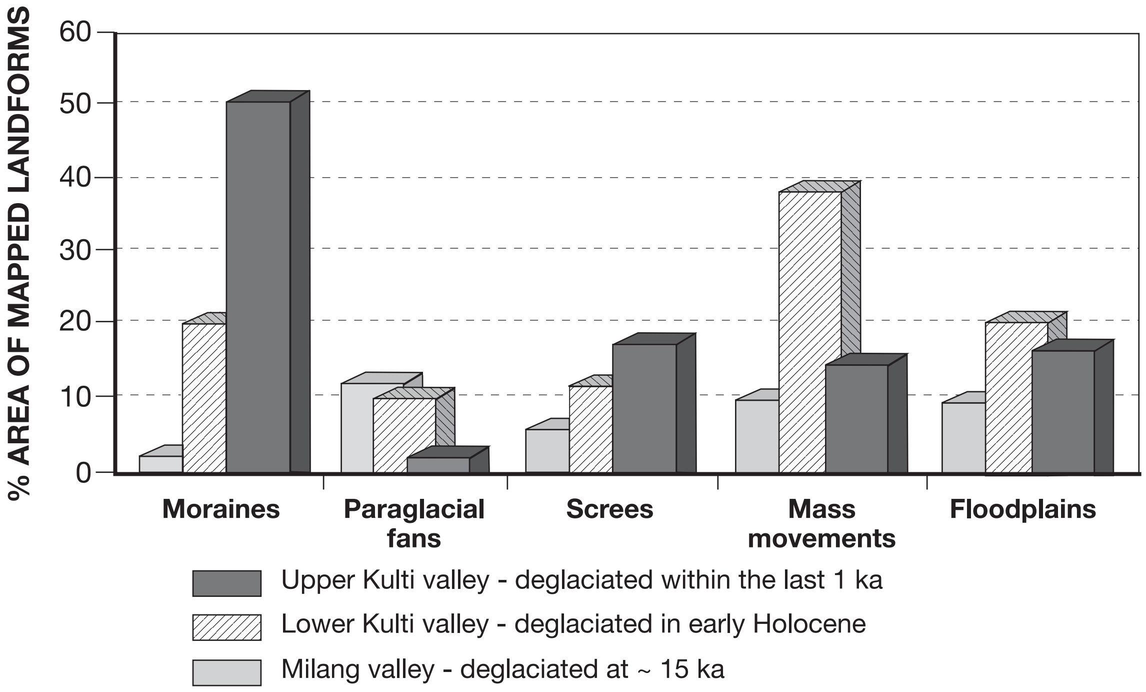

a
80° E
90°
100°
35° N
30°
Pamir
Tarim Basin
Qaidam Basin
Yellow
Karakoram
Kunlun Shan
Bayan Har Shan
Indus
Tanggula Shan
Nyaingentanglha
Himalaya
Ysango
Klute 1930
Relief over 4000 m
0
500 km
b
Frenzel 1960
Relief over 4000 m
c
Kuhle 1985
Relief over 4000 m
d
Shi Yafeng et.al. 1992
Relief over 4000 m

Figure 2

FIGURE 3


% AREA OF MAPPED LANDFORMS
60
50
40
30
20
10
0
Moraines
Paraglacial fans
Screes
Mass movements
Floodplains
Upper Kulti valley - deglaciated within the last 1 ka
Lower Kulti valley - deglaciated in early Holocene
Milang valley - deglaciated at ~ 15 ka

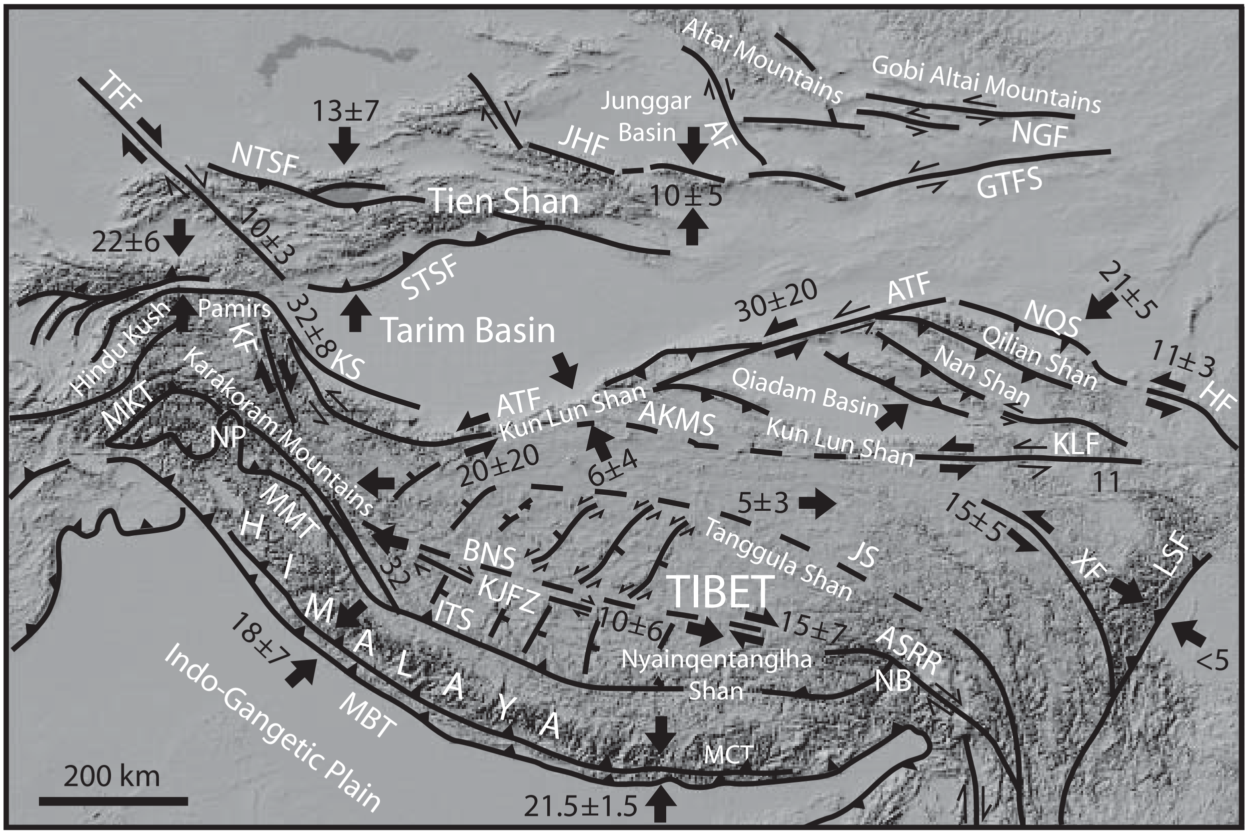
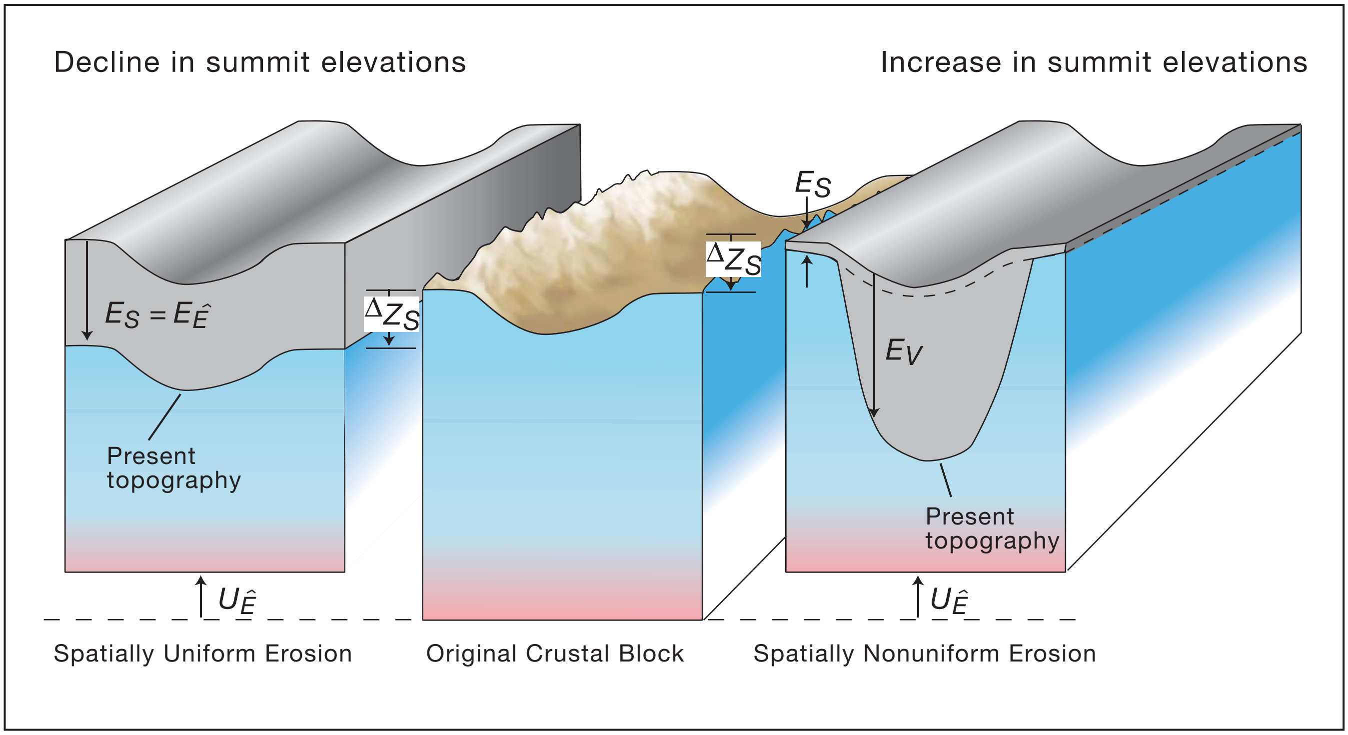

Altai Mountains
Gobi Altai Mountains
TFF
13±7
Junggar
Basin
AF
JHF
NGF
NTSF
GTFS
Tien Shan
10±5
10±3
22±6
STSF
21±5
30±20
ATF
NQS
Pamirs
32±8
KS
Tarim Basin
Qilian Shan
11±3
Hindu Kush
KF
Nan Shan
HF
Karakoram Mountains
ATF
Qiadam Basin
MKT
Kun Lun Shan
AKMS
NP
Kun Lun Shan
KLF
20±20
6±4
11
MMT
5±3
15±5
H
I
BNS
Tanggula Shan
JS
32
XF
LSF
KJFZ
TIBET
M
ITS
10±6
15±7
18±7
A
L
Nyainqentanglha
Shan
ASRR
<5
Indo-Gangetic Plain
MBT
A
Y
A
NB
200 km
MCT
21.5±1.5

Figure 4

FIGURE 5



Decline in summit elevations
Increase in summit elevations
$E_S = E_{\hat{E}}$
ΔZ_S
E_S
ΔZ_S
E_V
Present topography
Present topography
$U_{\hat{E}}$
$U_{\hat{E}}$
Spatially Uniform Erosion
Original Crustal Block
Spatially Nonuniform Erosion

FIGURE 6

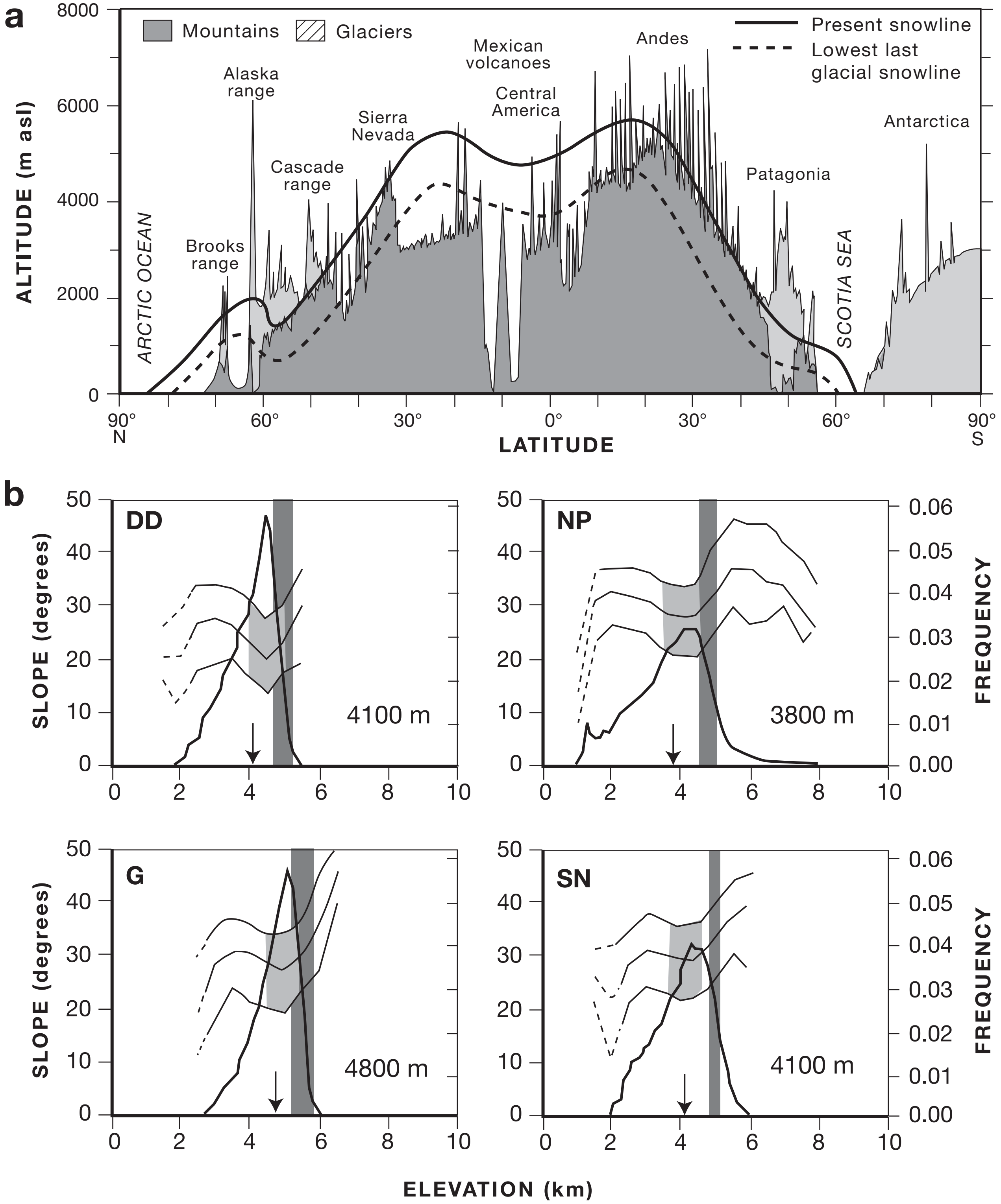

a
Mountains
Glaciers
Present snowline
Lowest last glacial snowline
ALTITUDE (m asl)
LATITUDE
ARCTIC OCEAN
Brooks range
Alaska range
Cascade range
Sierra Nevada
Mexican volcanoes
Central America
Andes
Patagonia
SCOTIA SEA
Antarctica
8000
6000
4000
2000
0
90° N
60°
30°
0°
30°
60°
90° S
b
DD
4100 m
NP
3800 m
G
4800 m
SN
4100 m
SLOPE (degrees)
FREQUENCY
ELEVATION (km)
50
40
30
20
10
0
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
2
4
6
8
10

FIGURE 7

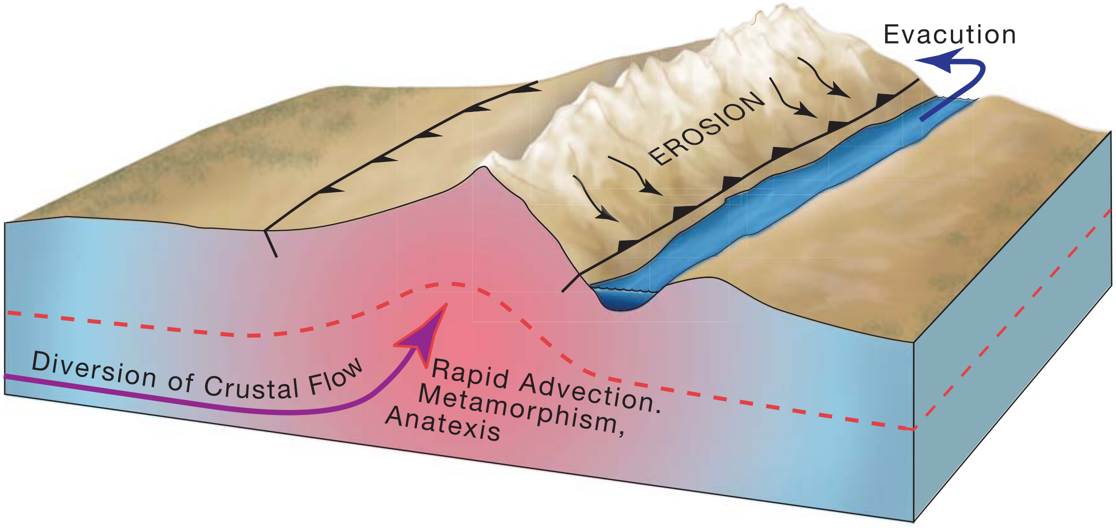

Evacution
EROSION
Diversion of Crustal Flow
Rapid Advection.
Metamorphism,
Anatexis

FIGURE 8

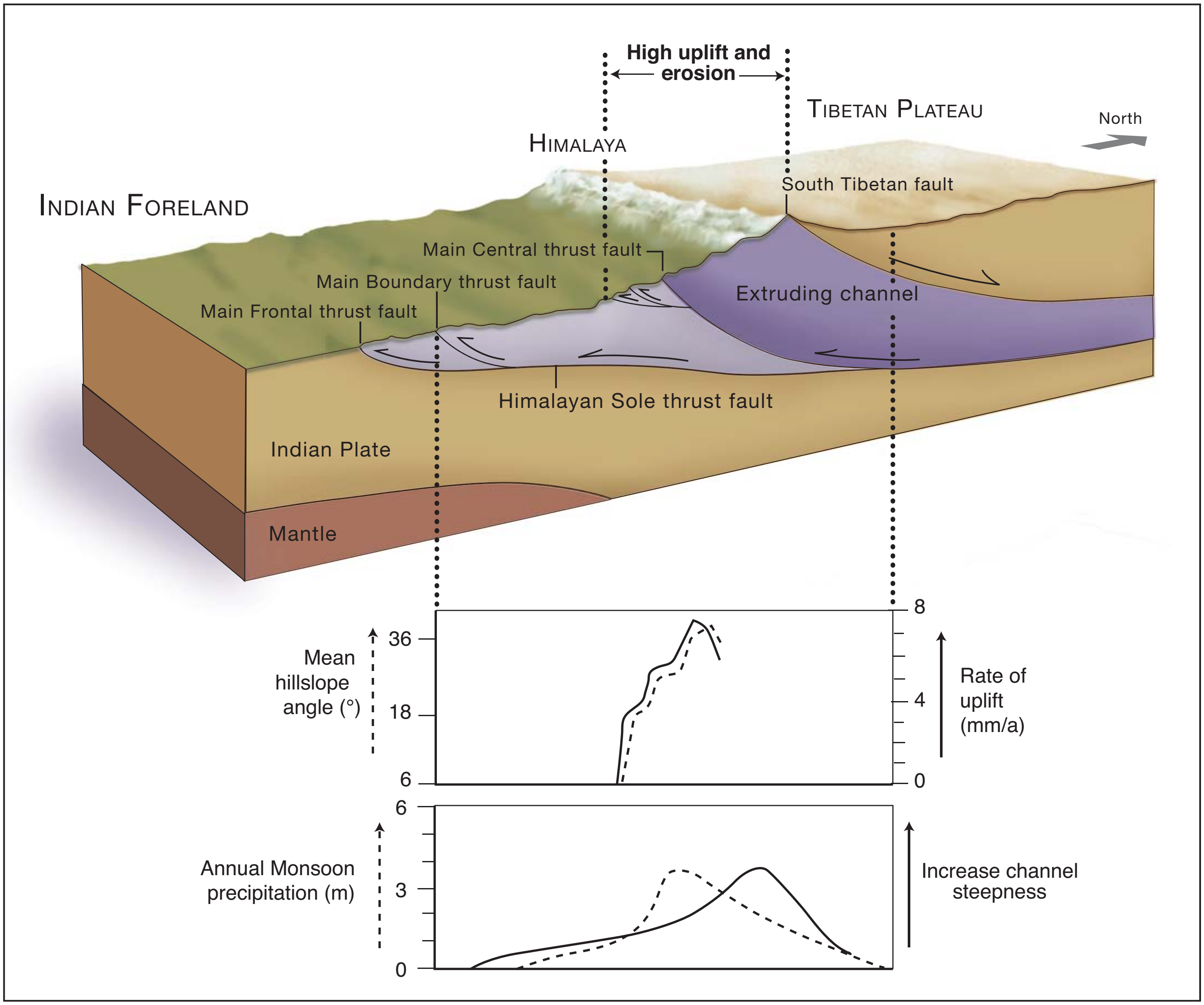
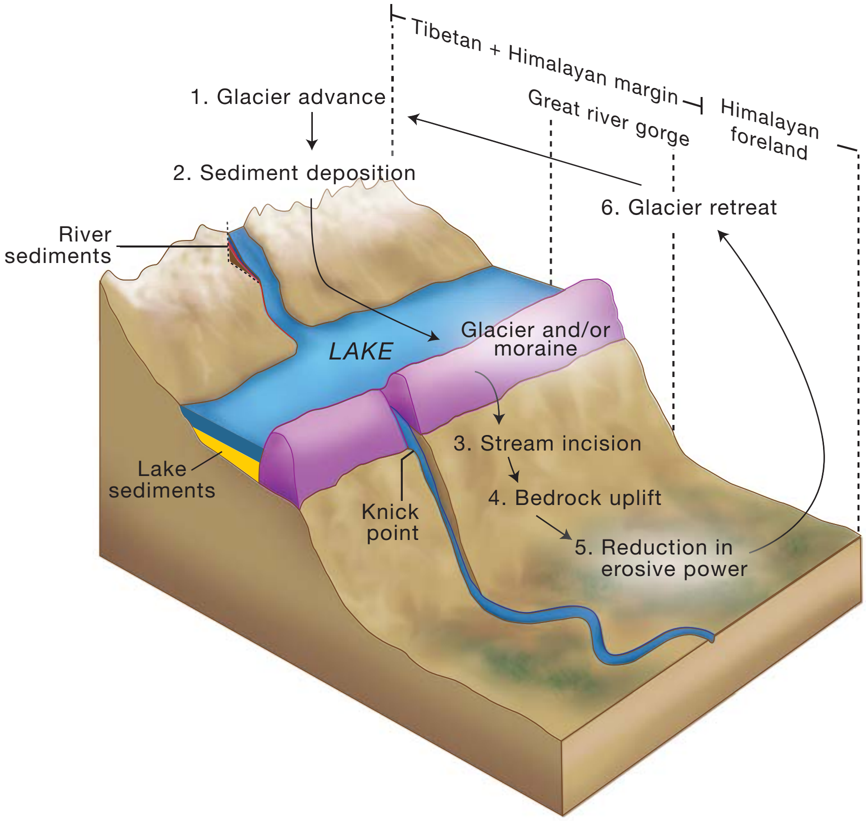
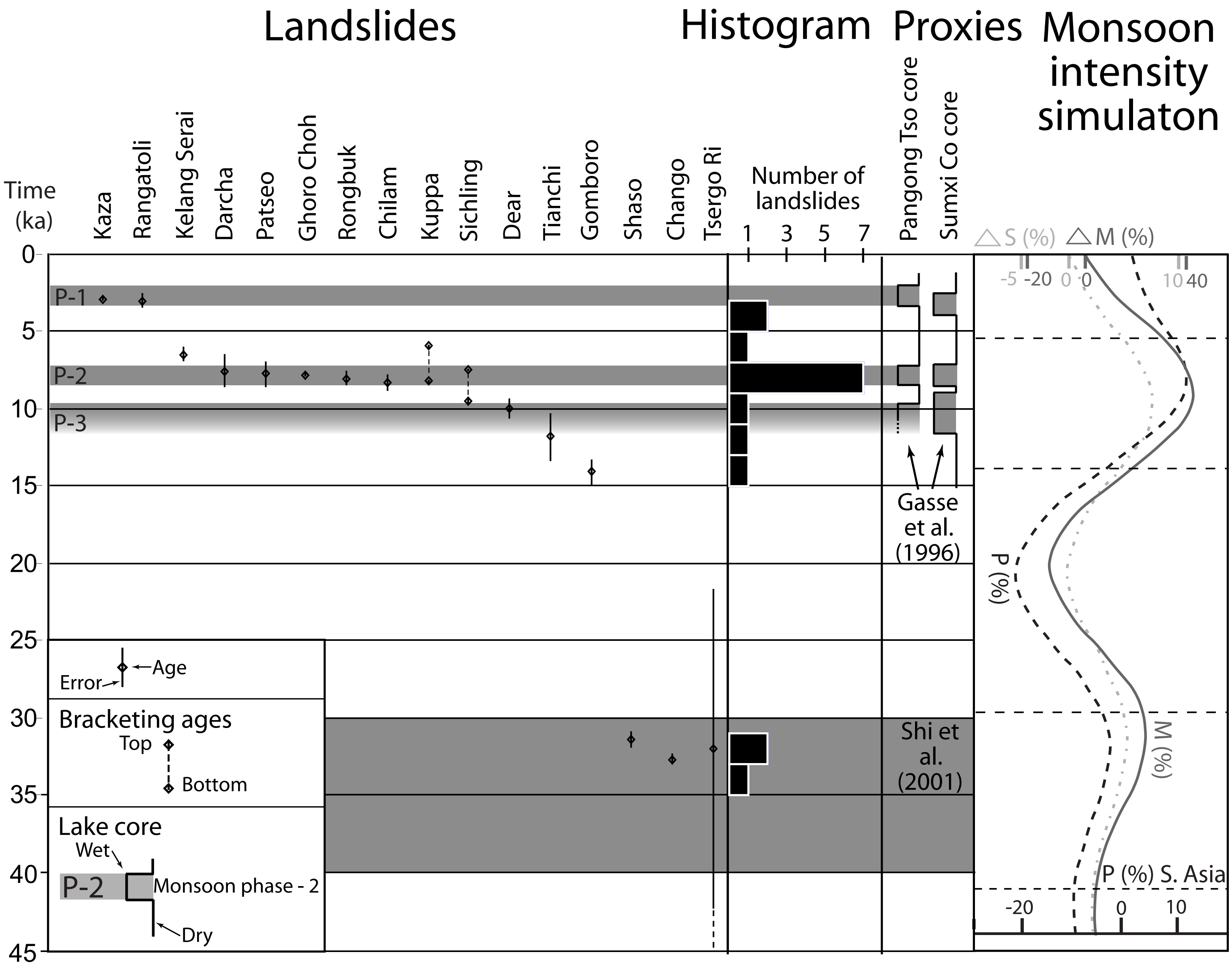

High uplift and erosion
TIBETAN PLATEAU
North
HIMALAYA
INDIAN FORELAND
South Tibetan fault
Main Central thrust fault
Main Boundary thrust fault
Main Frontal thrust fault
Extruding channel
Himalayan Sole thrust fault
Indian Plate
Mantle
Mean hillslope angle (°)
36
18
6
8
4
0
Rate of uplift (mm/a)
Annual Monsoon precipitation (m)
6
3
0
Increase channel steepness

FIGURE 9



Tibetan + Himalayan margin
Himalayan foreland
Great river gorge
1. Glacier advance
2. Sediment deposition
6. Glacier retreat
River sediments
LAKE
Glacier and/or moraine
3. Stream incision
4. Bedrock uplift
5. Reduction in erosive power
Lake sediments
Knick point

Figure 10



Landslides
Histogram
Proxies
Monsoon intensity simulaton
Time (ka)
Kaza
Rangatoli
Kelang Serai
Darcha
Patseo
Ghoro Choh
Rongbuk
Chilam
Kuppa
Sichling
Dear
Tianchi
Gomboro
Shaso
Chango
Tsergo Ri
Number of landslides
1
3
5
7
Pangong Tso core
Sumxi Co core
△S (%)
△M (%)
-5
-20
0
0
10
40
0
5
10
15
20
25
30
35
40
45
P-1
P-2
P-3
Gasse et al. (1996)
Shi et al. (2001)
P (%)
M (%)
P (%) S. Asia
-20
0
10
Age
Error
Bracketing ages
Top
Bottom
Lake core
Wet
P-2
Monsoon phase - 2
Dry

Figure 11