Earth surface processes and landscape evolution in the Himalaya: a framework for sustainable development and geohazard mitigation

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Abstract: Successful sustainable development and geohazard mitigation in the Himalaya requires an understanding of the nature and dynamics of Earth surface processes and landscape evolution. In recent years, geoscience studies of Himalayan environments have been increasing due to better accessibility, modern technologies and the understanding that there is a necessity to determine the nature and predict likely environmental changes that are occurring due to natural and human influences. The Himalaya is one of the most dynamically active tectonic and geomorphic regions on our planet, and it is the most glaciated mountain area outside of the polar realms. The high mountains and deep valleys are a consequence of the continued collision of the Indian and Eurasian continental plates, rapid uplift and intense denudation by glacial, fluvial, landsliding, aeolian and weathering processes. These processes change over time, influenced by topographic development, climate change and humans. Defining the rates and magnitudes of these processes and their interactions is fundamental in developing a framework to quantify, model and predict future changes for geohazard mitigation and sustainable development.

The Himalaya and adjacent mountains are among the most tectonically and geomorphically dynamic regions of our planet. They are predominantly the result of the continued collision of the Indian and Eurasian continental plates, intense fluvial and glacial erosion, and ubiquitous mass movement and weathering (Owen & Derbyshire 1993; Bishop *et al.* 2010; Owen 2010*b*, 2014). The people of this region live with the omnipresent threat of natural disasters that are a consequence of the active tectonics and geomorphology, and the climatic settings. Moreover, natural and human-induced climate change will lead to dramatic changes in the types, magnitude and frequency of Earth surface processes in the region, which in turn will have dramatic socio-economic and political consequences in the coming years (Hijioka *et al.* 2014; IPCC 2014). Continued rural and urban development in the region is increasing environment stresses on Himalayan environments, which may lead to future changes in the nature of Earth surface processes and may result in greater geohazards and accelerated environmental degradation.

An understanding of the nature of tectonics, climate, geomorphic processes and landscapes in the Himalaya is necessary to help reduce the likely effects of natural hazards and to help achieve sustainable development in the region. In recent decades, geoscientists have become increasingly involved in the study of Himalayan environments. This is mainly because the region has become more logistically and politically accessible, new technologies are allowing us to better study the region remotely and in the field, and new analytical methods are being developed to analyse the physical, chemical and biological aspects of the Himalaya. This paper emphasizes the need to understand the nature, magnitude and frequency of Earth surfaces processes and landscape evolution in the Himalaya; it highlights the new developments and challenges, and provides the beginnings of a geomorphic framework to help with sustainable development and geohazard mitigation.

Geomorphic setting

The Himalaya as a whole comprise a series of mountain ranges that stretch approximately E–W for *c.* 1500 km from Afghanistan, through Pakistan, NW India, Nepal, NE India, Bhutan and Myanmar. The mountains rise northwards from the Indo-Gangetic Plain to the Tibetan Plateau, and from south to north include the Siwaliks, the Lesser Himalaya, Greater Himalaya and Transhimalaya (Fig. 1). Distinct regions, defined on the basis of their geology, topography, drainage systems and climate, exist within each of these main mountain ranges, including, for example, Chitral, Swat, Hunza, Garhwal, Spiti, Lahul, Zanskar, Ladakh, Lantang and Khumbu.

Arguably, the greatest characteristic of the Himalaya is its diversity of environments, landscapes and landform types (Owen 2014). This is largely because of the different geologic components of the orogen (Fig. 2) that result in differential uplift (Chung *et al.* 1998; Tapponnier *et al.* 2001; Bookhagen & Strecker 2008; Gibson *et al.* 2016), and the resultant topography produces strong orographic affects.

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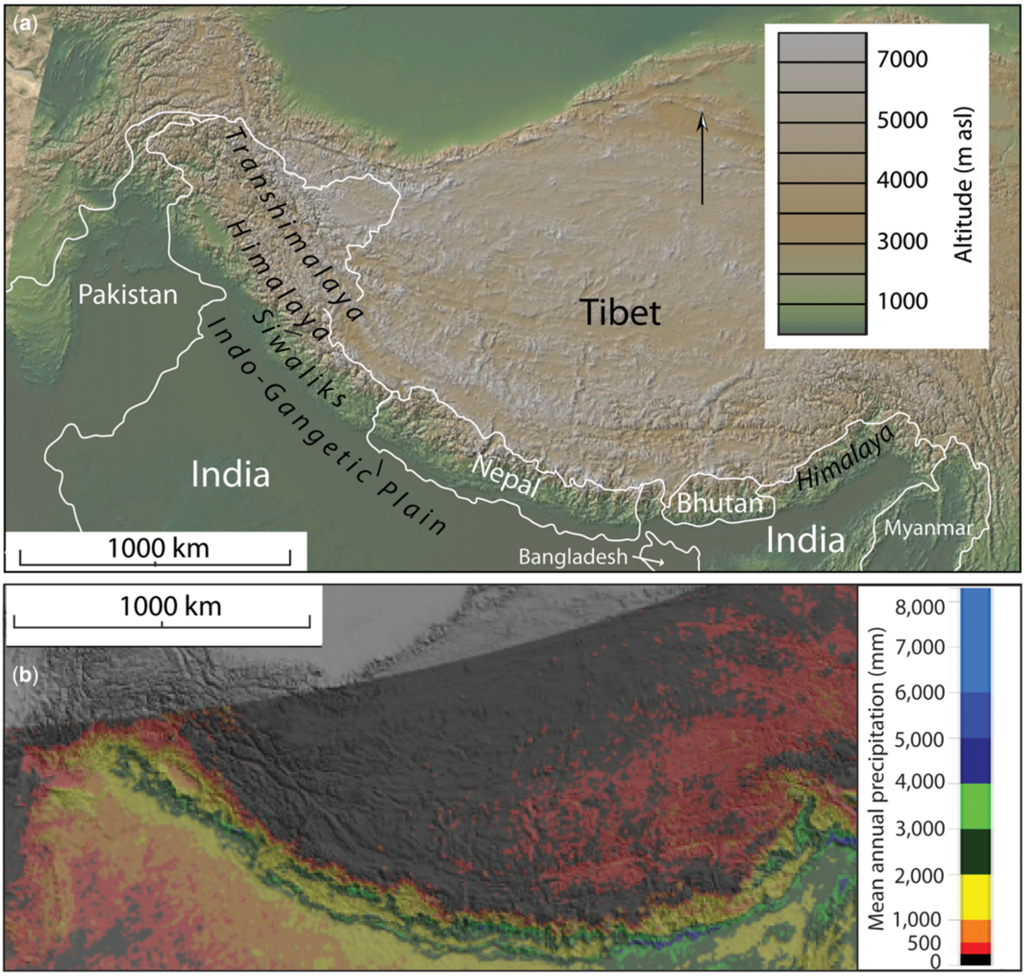

Fig. 1. Geographic and climatic setting of the Himalaya. (**a**) Digital elevation models for the Himalaya and adjacent regions produced using GeoMapApp (http://www.geomapapp.org). (**b**) Annual precipitation averaged for 1998–2009 from TRMM data (http://www.geog.ucsb.edu/~bodo/TRMM/#ascii) draped over the DEM of the Himalaya and adjacent Tibet showing the strong N–S and E–W precipitation gradients (from Owen 2014).

In addition, two dominant climate systems – the south Asian monsoon and mid-latitude westerlies – influence the region which, together with the topography, result in strong N–S and E–W precipitation gradients (Benn & Owen 1998; Fig. 1). Topography is highly variable, with some of the greatest relative relief on Earth in the Transhimalaya, and lesser slopes in the foothills of the Himalaya, to the flatlands of the Indo-Gangetic Plain and plateau regions along the edge of Tibet. Climate and topography have a profound influence on the dominant type and magnitude of Earth surfaces processes and, in particular, on the style and extent of glaciation. Topography has a great influence on surface processes and how Himalayan landscapes evolve (Owen 2014). Some of the world's greatest rivers drain the Himalaya, including the Indus, Ganges and Brahmaputra. Environments along these rivers are diverse, ranging from torrent headwaters to long stretches of wide valleys – most notably along longitudinal drainages – and to deep gorges along the transverse rivers. Collectively this makes Himalayan environments incredibly diverse, ranging from glaciated tracks, mountain deserts, alpine meadows to sub-tropical forests; it is erroneous to make generalizations about the geomorphology and landscape (Owen 2010*b*, 2014).

As a consequence of this geomorphic diversity and dynamism, the region provides one of the best natural laboratories to study the nature of

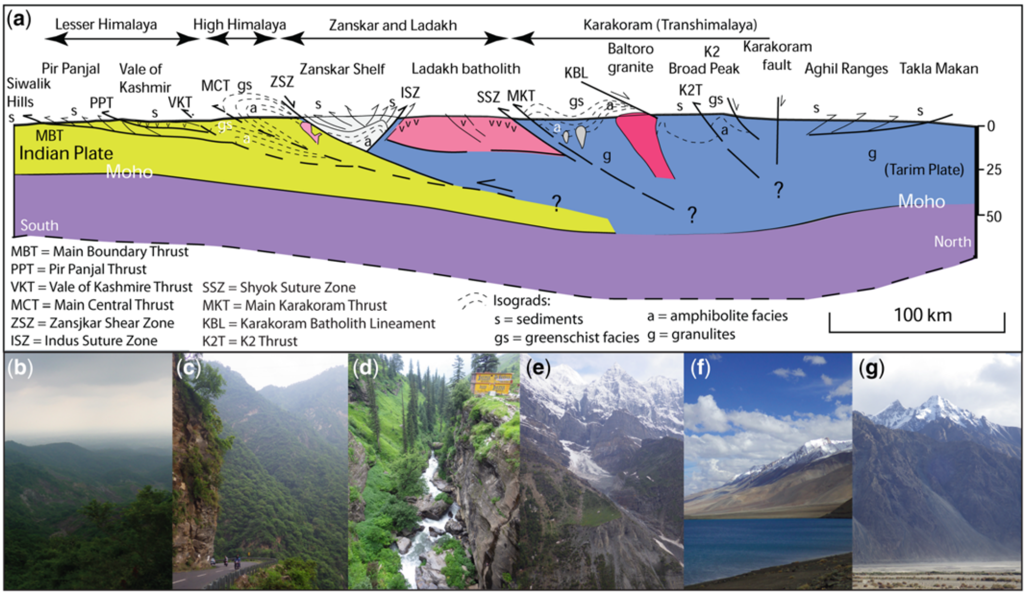

Fig. 2. Schematic illustration showing the complexity of geologic and geomorphic environments across the Himalaya and edge of Tibet (adapted from Owen 2014). (**a**) Schematic cross-section through the western end of the Himalaya through NW India and the Central Karakoram illustrating the major tectonic–geologic features that contribute to the diverse range of landscapes (Owen 2014). (b–g) Examples of typical environments from south to north across northern India. (**b**) View south from the Siwaliks, looking towards the Indo-Gangetic plain near Chandigarh. (**c**) Major transverse drainage of the Ganga in the monsoon-influenced Lesser Himalaya. (**d**) Deeply incised monsoon-influenced tributary valley of the Beas River on the southern slopes of the Pir Panjal near Manali. (**e**) Un-named glacier in the Greater Himalaya of the Bhaga Valley in the rain shadow of the Indian monsoon. (**f**) View of Pangong Tso in the mountain desert of Zanskar. (**g**) View across the Nubra-Shyok desert valley looking at snow-covered Karakoram in the distance.

landscape development within active mountain belts, specifically one created by continental–continental collision. Recent interest in the region has stimulated the development of many new tectonic–climatic–geomorphic theories, models and paradigms. Of particular note is the study of the interactions between tectonics, climate and surface processes, the influence of climate on surface uplift by denudational unloading (Molnar & England 1990) and how topography might be limited by glaciation (glacier buzz-saw model; Brozovic *et al.* 1997). Other notable work examines how zones of localized uplift might be created by enhanced fluvial and glacial erosion that, in turn, weaken the lithosphere, enhancing surface uplift and exhumation, which has become known as the tectonic aneurysm model (Zeitler *et al.* 2001; Finlayson *et al.* 2002; Koons *et al.* 2002, 2012; Finnegan *et al.* 2008), and climate-driven out-of-sequence thrusting and crustal channel flow as a consequence of focused erosion (Beaumont *et al.* 2001; Hodges *et al.* 2001, 2004; Wobus *et al.* 2003; Jamieson *et al.* 2004; Hodges 2006; Harris 2007; Mandal *et al.* 2015). In addition, there has been much interest in how major landscape development occurs during times of climatic instability, known as the paraglaciation concept (Owen *et al.* 1995*b*, 2002; Owen & Sharma 1998; Barnard *et al.* 2004*a*, *b*, 2006*a*, *b*), and the influence of extreme events such as earthquakes, landslides and floods as major formative processes (Brunsden & Jones 1984; Blöthe *et al.* 2015; Kargel *et al.* 2015). There has also been much focus on how climate may modulate geomorphic processes, such as during times of intensified monsoon during the Quaternary which would have resulted in increased terrace formation and landsliding (Bookhagen *et al.* 2005; Dortch *et al.* 2009), and the role of glacial damming leading to differential erosion and uplift (Korup & Montgomery 2008; Owen 2008; Korup *et al.* 2010).

Tectonics

Since collision at *c.* 50 Ma, the Indian lithospheric plate has continued to move northwards at a rate of *c.* 35 mm a^{-1}, indenting 2000 km into the Eurasian plate (Dewey *et al.* 1989; Larson *et al.* 1999; Yin & Harrison 2000; Johnson 2002; Searle & Richard

2007). This has had a profound influence on the distribution of topography, both mountains and valleys. Hodges (2000), Yin & Harrison (2000) and Streule *et al.* (2009) provide useful overviews of the regional geological relations, including details of the timing of movement along the crustal-scale faults that bound the major tectonostratigraphic subdivisions. Crustal shortening and thrust and strike-slip faulting across the region are still active (Tapponnier & Molnar 1977; Hodges *et al.* 2004; Bojar *et al.* 2005; Taylor & Yin 2009; Gavillot *et al.* 2016).

The 8 October 2005 M_w 7.6 Kashmir and 25 April 2015 M_w 7.8 Gorkha earthquakes highlighted the potential disastrous consequences of tectonic processes in the Himalaya and the need to plan for such events. More than 70 000 people died and more than one million people were displaced from their homes during the Kashmir earthquake (Owen *et al.* 2008; Fig. 3). In Nepal, more than 9000 people died with more than 23 000 people injured as a consequence of the Gorkha earthquake (Catlos *et al.* 2015; Kargel *et al.* 2015). Moreover, in 1991 and 1999, earthquakes shook the Garhwal Himalaya killing several hundreds of people and destroying many villages (Owen *et al.* 1996; Barnard *et al.* 2001). Most recently, the 26 October M_w 7.5 earthquake in the Hindu Kush of Afghanistan resulted in widespread destruction of buildings and more than 300 fatalities (USGS 2015). These events illustrate the dramatic effects of tectonic hazards throughout the Himalaya. Palaeoseismic studies are providing important insights into the potential for great earthquakes along the Himalayan front that pose a real and major threat to the vast populations in the Himalaya and adjacent foreland (Wesnousky *et al.* 1999; Kumar *et al.* 2001, 2006; Kondo *et al.* 2008).

Of particular note are the tectonic geomorphic studies on deformed terraces and topography in Nepal and India (Lavé & Avouac 2001; Herman *et al.* 2010; Elliott *et al.* 2016; Kothyari & Luirei 2016; Sinha & Sinha 2016), and along the Karakoram fault that traversed the northwestern end of the Himalaya and Karakoram (Brown *et al.* 2002; Robinson *et al.* 2015). Defining geomorphic rates (10^{0-5} years) of exhumation and uplift is challenging, but recent studies are providing a wealth of data and showing strong contrasts across mountain ranges (Hodges *et al.* 2004; Clift *et al.* 2008; Adams *et al.* 2009; Rahaman *et al.* 2009; Dortch *et al.* 2011*b*; Thiede & Ehlers 2013; van der Beek *et al*. 2015).

Glaciation

The Himalaya and their bordering mountains are the most glaciated regions outside of the polar realms. Glaciers in the Himalaya are diverse, ranging from sub-polar continental types in the semi-arid high mountains to maritime glaciers in the monsoon-

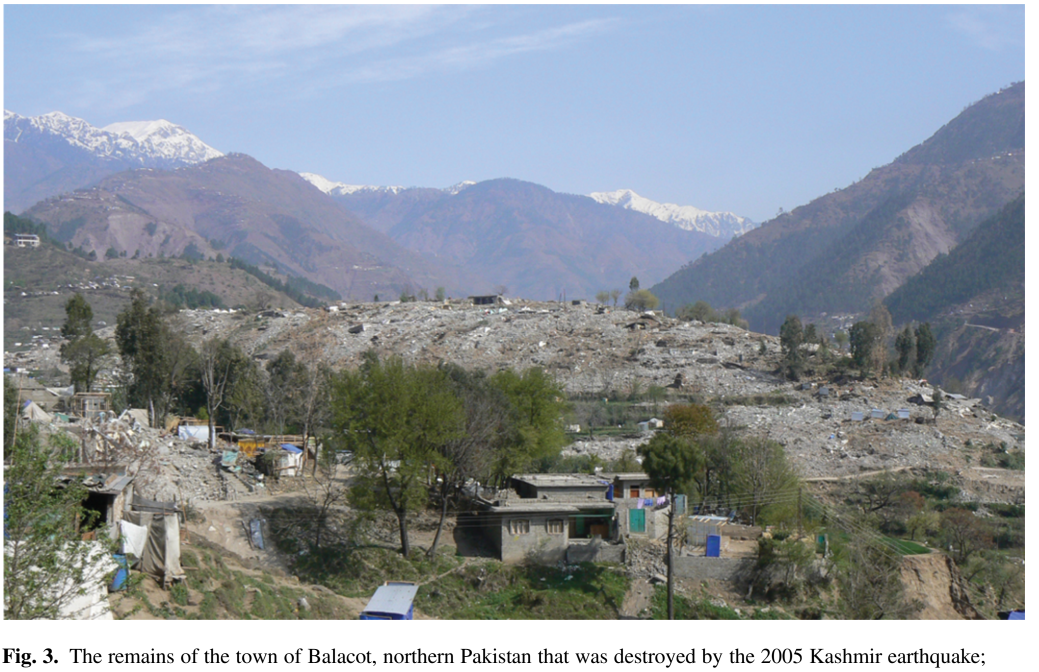

Fig. 3. The remains of the town of Balacot, northern Pakistan that was destroyed by the 2005 Kashmir earthquake; poor building design and location contributed to the catastrophe.

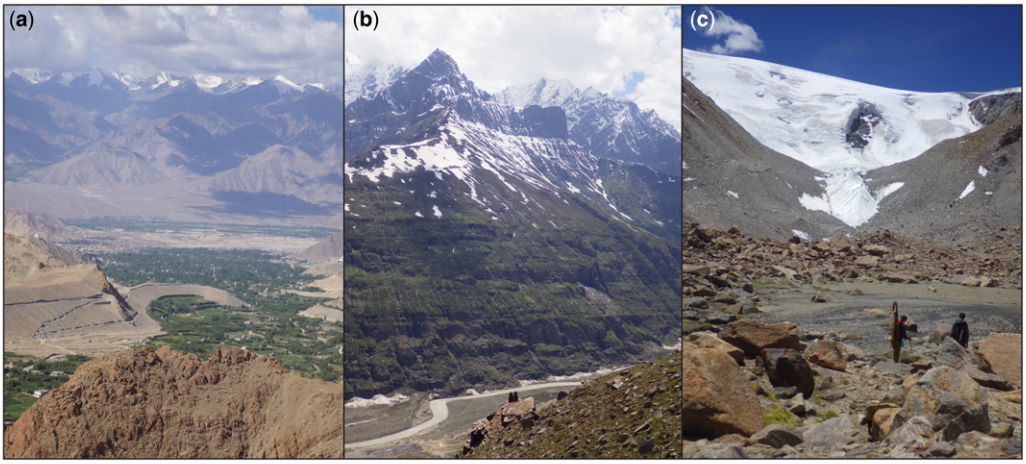

Fig. 4. Examples of glacial geologic evidence in northern India. (**a**) View looking into the Indus valley near Leh showing an impressive latero-frontal moraine (centre of view) that has been dated to older than 300 ka (Owen *et al.* 2006). (**b**) Glacial eroded bedrock slopes along the Chandra valley produced by a large trunk valley glacier that advanced during the latter part of the last glacial (Owen *et al.* 2001). (**c**) Holocene moraines in front of a small continental glacier in Zanskar near Tso Morari. Moraines in this valley were dated by Hedrick *et al.* (2011).

influenced regions (Benn & Owen 2002; Fig. 4). Some of the glaciers, such as Boltoro and Siachen, are among the longest outside of the polar regions, while there are numerous sub-polar-type glaciers that are very small, <1 km^2 in area (Benn & Owen 2002). Glaciers have fluctuated considerably throughout the Quaternary, leaving behind much geomorphic evidence for their former extents and dynamics (Owen & Dortch 2014; Fig. 4). In some regions, such as in the Indus valley in Ladakh, the moraines are of great antiquity and date to >>400 ka (Owen *et al.* 2006; Fig. 4a). In contrast, in other regions such as Langtang there is little evidence for glaciation prior to the last glacial maximum; this is probably because the glacial landforms are not well preserved in these very geomorphic dynamically active areas (Barnard *et al.* 2006*b*).

Owen & Dortch (2014) provide a review of the Quaternary glaciation of the Himalaya and adjacent mountains. They highlight the abundant evidence for significant glacial advances throughout the last few glacial cycles and describe how new dating methods, such as terrestrial cosmogenic nuclide surface exposure dating, are helping to accurately define the timing of glaciation in selected regions. The studies show that glaciers in arid regions of the Himalaya and Tibet during the last glacial cycle reached their maximum extent early in the cycle, and that glacier advances were significantly less extensive during the global last glacial maximum. In contrast, along the more monsoonal-influenced parts of the Himalaya, there is increasing evidence to suggest that glaciation was more extensive later in the last glacial cycle. Owen & Dortch (2014) stressed that the new studies show that throughout most Himalayan and Tibetan regions significant glacier advances occurred during the Late Glacial and early Holocene, with minor advances in some regions during the middle Holocene. These different patterns likely reflect temporal and spatial variability in the two major climate systems – the south Asian monsoon and mid-latitude westerlies – that influence the region, and their consequent resultant regional precipitation gradients.

The chronological control on glaciation is presently not good enough to make very robust correlations across the region and with regions elsewhere in the world (Owen & Dortch 2014). This makes it difficult to assess the relative importance of the different climatic mechanisms that force glaciation across the Himalaya, which in turn make predictions for future change difficult. Nevertheless, Dortch *et al.* (2013) recognized 19 glacial stages during the past *c.* 0.5 Ma, glacial advances across the semi-arid regions at the western end of the Himalaya and Tibet which they named semi-arid western Himalayan–Tibetan stages (SWHTS). Similarly, Murari *et al.* (2014) identified 29 regional glacial stages in the monsoon-influenced regions of the Himalayan and Tibet, which they called monsoon-influenced Himalayan–Tibet stages (MOHITS). Owen & Dortch (2014) argue that some of the MOHITS and SWHTS might be synchronous, but that many are asynchronous due to the different climatic forcing factors associated with different regions across the Himalaya and Tibet.

These glacial geologic studies help highlight how Himalayan landscapes have been greatly influenced by numerous glacial oscillations throughout the Quaternary (Owen 2014). This includes erosion as glaciers advance during glacial times, and landscape readjustment during deglaciation when major resedimentation of moraines form extensive alluvial fans, river terraces and valley fills, a concept known as paraglaciation (Barnard *et al.* 2004*a*, *b*; Bisht *et al.* 2015; Kothyari *et al.* 2016). In addition, there are strong links between glaciers, mass movement and fluvial processes that are important in the long-term evolution of Himalayan valleys (e.g. Burbank *et al.* 1996; Bishop *et al.* 2010; Scherler *et al.* 2011*b*).

Glaciers also influence the aeolian system by enhancing katabatic winds, often resulting in impressive dune systems such as those in the Skardu Basin in Pakistan and at the Nubra–Shyok confluence in northern India (Owen 1988, 2014). Loess is also present in many valleys such as in Swat in northern Pakistan and the Tarangoz valley in northern India (Owen *et al.* 1992; Lee *et al.* 2014).

Hydrological systems

The south Asian summer monsoon, glacier melting and snowmelt are the dominant influence on Himalayan hydrological systems. River discharge varies considerably throughout the year, with the greatest flows occurring during the summer monsoon and as the glaciers and snowfields melt at high altitudes (Bookhagen & Burbank 2010; National Academies 2012). The rivers erode deep gorges and transport vast volumes of sediment to the Indo-Gangetic Plain and adjacent oceans (Fig. 5a) and deposit great thicknesses of sediments at places within the mountains (Fig. 5b). Incision rates vary considerably, both temporally and spatially (Dortch *et al.* 2011*b*). Catastrophic flooding, as a result of lake outbursts or heavy rainfall events, is an important formative process in the Himalaya and evidence for ancient flood events is apparent through many valleys in the Himalaya (Coxon *et al.* 1996; Richardson & Reynolds 2000; Montgomery *et al.* 2004; Dortch *et al.*

Fig. 5. Fluvial and lacustrine landforms in the Himalaya of northern India. (**a**) Deep gorge of the Beas in Kulu, in the Lesser Himalaya. (**b**) Fluvially incised thick (>50 m) fluvial valley fill now occupied by a braided channel system at Sarchu in Zanskar. (**c**) Imbricated boulders deposited to the catastrophic drainage of Pangong Tso, that Dortch *et al.* (2011*a*) dates using ^{10}Be to *c.* 11 ka. (**d**) Kyagar Tsp in Zanskar and ancient lake sediments and shorelines in the middle ground behind the lake.

2011*a*; Syvitski & Brakenridge 2013; Scherler *et al.* 2014; Singh 2014; Fig. 5c).

The thick valley and intermontane fills and impressive river terraces are abundant throughout many Himalayan valleys, and comprise fluvial landslide, glacial and lacustrine deposits which record a long history of hydrological change (Owen 1989; Barnard *et al.* 2004*a*, *b*, 2006*a*, *b*; Ali *et al.* 2013; Fig. 5c). Alluvial fans composed of rivers and debris-flow deposits are common landforms in the semi-arid regions and glaciated valleys of the Himalaya (Derbyshire & Owen 1990; Owen & Sharma 1998).

Lakes are present throughout the Himalaya within tectonic basins, in glacial settings behind ice dams and moraines, and in eroded bedrock depressions from behind blockages caused by debris flows, rock falls and landslides (Owen 1996*b*). Impressive lacustrine deposits are present in many regions providing a testament to the extent of past lakes (Fig. 5d).

Mass movements

Mass movements are ubiquitous throughout the Himalaya; these range in size from metre-scale soil creeps to mega-landslides involving more than a million cubic metres of debris (Owen 2014; Fig. 6). Blöthe *et al.* (2015) highlight that large rock-slope failures occur preferentially below the approximate limit of sporadic alpine permafrost along fluvial and glacial inner gorges cut into a more gentle topography shadowed by steep ridge. Landsliding is most common during the heavy rainfalls of the monsoon season and usually involves shallow slips (less than a few metres) and debris flows in deeply weathered regolith and bedrock. Snow and rock avalanching is also common, occurring mostly in spring and throughout the summer months. Earthquakes are also important in triggering landslides as illustrated during the 20 October 1991 M_w 6.8 and 28 March 1999 M_w 6.8 earthquakes in the Garhwal Himalaya (Owen *et al.* 1995*a*, 1996; Barnard *et al.* 2001) and the 2005 Kashmir earthquake (Owen *et al.* 2008). Most earthquake-triggered landslides are shallow failures of rock avalanche type (Owen *et al.* 1995*a*, 1996, 2008; Barnard *et al.* 2001) although earthquakes may have helped initiate the occasional deep-seated long-run-out landslide (Dortch *et al.* 2009). Kargel *et al.* (2015) mapped 4312 co-seismic and post-seismic landslides as a consequence of the Gorkha earthquake. However, Kargel *et al.* (2015) highlighted that the total number of landslides was far fewer than those generated by comparable earthquakes elsewhere. This was probably because of a lack of surface ruptures, the concentration of

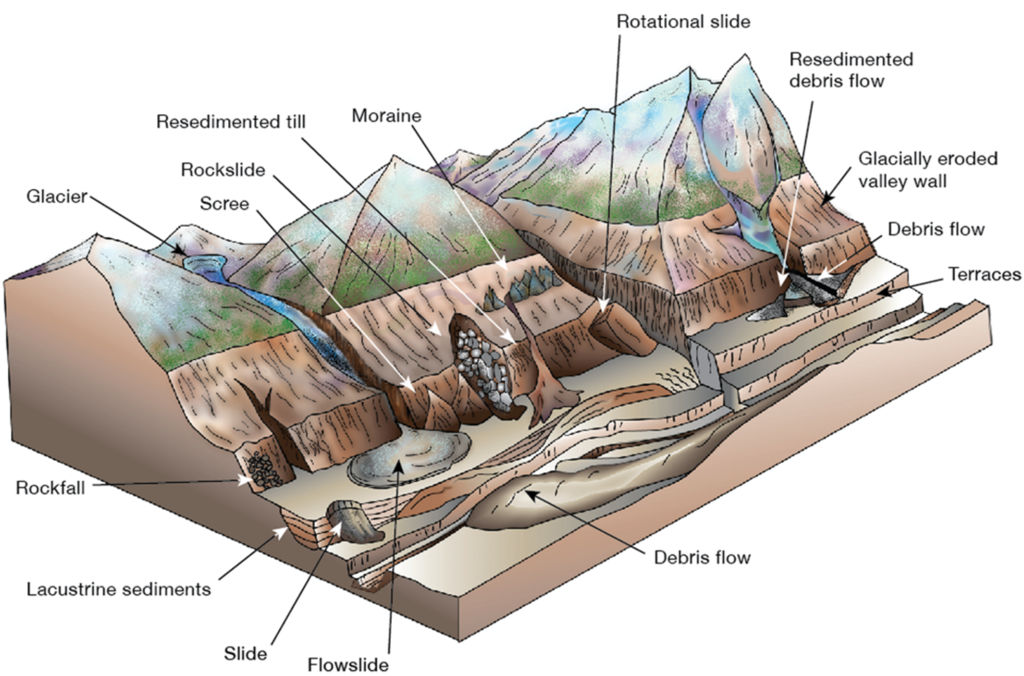

Fig. 6. Schematic diagram illustrating a variety of different geomorphic settings and associated mass movements in a typical Himalaya valley setting (adapted from Owen 1988, 1991).

deformation along the subsurface thrust fault at 10–15 km depth and the regional dominance of competent crystalline rock types.

Korup *et al.* (2010) report conspicuous clustering of hundreds of natural dams along the Indus and the Tsangpo rivers where these cross the Himalayan syntaxes. They highlight that the Indus is riddled with hundreds of dams composed of debris from catastrophic rock avalanches, forming the largest concentration of giant landslide dams known worldwide. They also suggest that glacier and landslide dams act as a negative feedback in response to fluvial dissection of the margin of the Himalayan–Tibetan orogen. As such, these natural dams protect bedrock from river incision and delay headwards knickpoint migration, helping to stabilize the southwestern and southeastern margins of the orogen.

Human activity, such as highway construction where fresh road cuts are devoid of vegetation, has helped to accelerate slope failure in many regions. In Nepal for example, Petley *et al.* (2007) argue that the impact of landsliding and associated fatalities had increased between 1978 and 2005. Petley *et al.* (2007) concluded that a major component of increased landslide impact probably resulted from the rural road-building program, and its attendant changes to physical and natural systems.

Weathering and soil development

Weathering is pervasive throughout the Himalaya (Owen 2014; Fig. 7). Generally chemical processes dominate in the Siwaliks and Lesser Himalaya, while physical, notably cryogenic, processes are more common in the higher altitudes of the Greater Himalaya and Transhimalaya. Weathered bedrock and regolith provide the substrate for the formation of tropical soils in lower altitudes and alpine soils in the high mountains. Longbottom *et al.* (2014) examined variation of soil organic matter across the Himalaya and stressed the importance of soils as storage for carbon in terms of the carbon cycle, especially as we progress into a more CO_2-enriched atmosphere due to human activity (IPCC 2014).

Human influences

Human influences on Himalayan landscapes are many-fold, including alteration/destruction of the vegetation, modification of drainages such as the construction of irrigation canals and dams, and accelerated erosion due to poor land management (Rawat & Rawat 1994; Tiwari 2000). The construction of highways has had a notable affect on increasing landslide occurrence (e.g. Barnard *et al.* 2001; Fig. 8). Much debate has focused on the degree of human influence on the deforestation and environmental degradation in the Himalaya (Ives & Messerli 1989). However, defining the extent and degree of human influence and comparing it to the role of nature processes is challenging, particularly because of the diversity of environments throughout the Indian Himalaya. Knowledge of the natural rates and magnitude of geomorphic

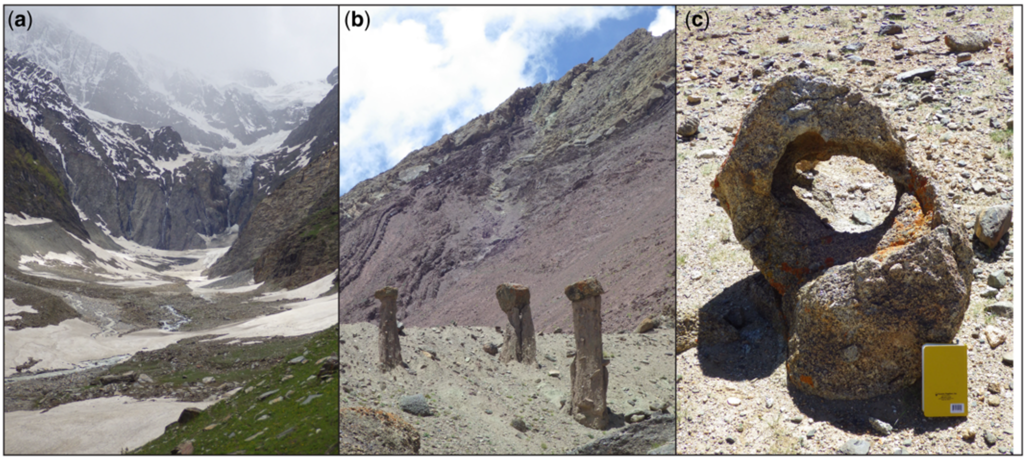

Fig. 7. Weathering in the Himalaya. (**a**) Pervasive cryogenic weathering in the Sheti valley in the Lahul Himalaya, evident from the impressive talus slopes and snow avalanche cones that are partially covered with rock-fall debris generated by freeze–thaw activity of the highly fractured bedrock. (**b**) Earth pillars near Lato in Zanskar formed as till weathers away beneath the protection of large boulders. (**c**) Cavernous weathering within a boulder in Lato, processed mainly by salt crystal weathering in this semi-arid environment.

Fig. 8. Human-induced mass movement along highways in the Himalaya illustrated with examples from northern India. (**a**) Shallow landslide and debris flows during the monsoon season and (**b**) deep snow drifts and rock-fall debris near the Rhotang Pass in Lahul. (**c**) Road maintenance underway through thick talus and bedrock slopes at *c.* 5000 m asl near the Khardungla Pass in Ladakh.

processes and their spatial and temporal variability is essential to fully assess the human impact on Himalayan landscapes.

Landscape evolution

The landscape evolution of areas of the Himalaya can be deduced from study of the landforms and sediments preserved throughout the region, and in particular understanding the nature of tectonics and the various geomorphic systems. Newly developing remote sensing and survey methods are aiding in the construction of surficial and geological maps in the high mountains of central Asia (Heyman *et al.* 2008; Morén *et al.* 2011; Fu *et al.* 2012). In addition, the increasing use of numerical dating is aiding in determining the ages of landforms so that quantitative geomorphic histories can be reconstructed (Owen *et al.* 2002; Barnard *et al.* 2006*a*, *b*; Seong *et al.* 2009; Dortch *et al.* 2011*a*; Blöthe *et al.* 2014; Scherler *et al.* 2014). These studies are now allowing new insights into the nature and dynamics of natural environmental changes in the Himalaya as baselines to allow assessments of the human impact on the environment.

Geohazards

Arguably the most significant long-term geohazards in the Himalaya includes the retreat of glaciers in the coming years, which threatens the water supplies for close to one-sixth of the world's population that live in and around the Himalaya. Population densities in some areas exceed many thousands per square kilometre (Fig. 9). Recent assessments of the impact of climate change in the Himalaya have recently been revised from catastrophic to merely disastrous. In the Himalaya, *c.* 22 800 km^2 (Bolch *et al.* 2012) of glaciers supply 1–10% of the annual and up to 38% of dry season discharge for the Ganges River that provides water for 0.5 billion people on the Indo-Gangetic plains.

Although the UN Intergovernmental Panel on Climate Change (IPCC 2007) erroneously included a misquoted grey literature speculation on the potential complete disappearance of Himalayan glaciers by 2035, an independently revised estimate of substantial melting by 2100 by Yao *et al.* (2012) still points to significant retreat of glaciers throughout most regions. Time-series satellite and ground imagery and field measurements undertaken by Yao *et al.* (2012) show a 9% loss of Himalayan glacier ice

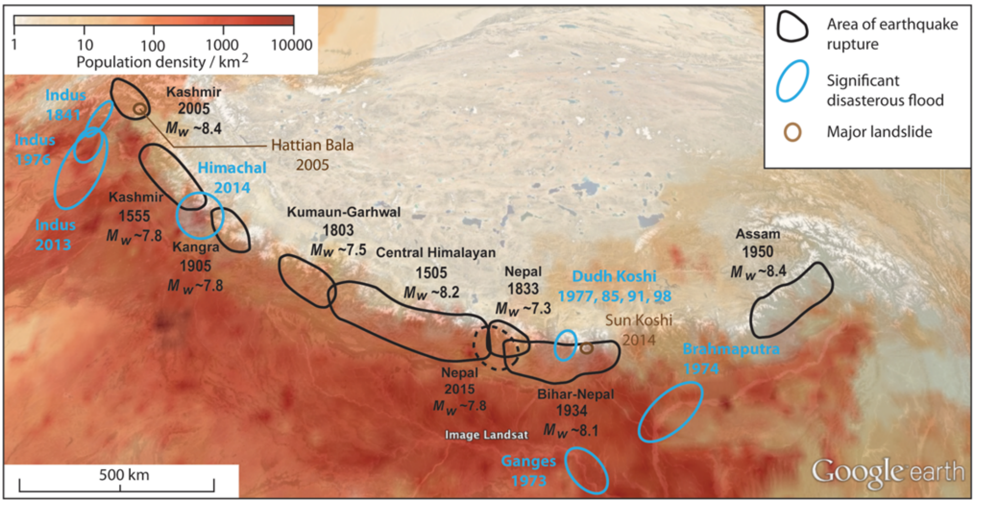

Fig. 9. Significant historical geohazards plotted on an oblique Google Earth view of the Himalaya and adjacent region. The population density of the region is also plotted on the image to illustrate the enormous number of people under threat. Population data is plotted at 0.1° grids from NASA Earth Observations (https://neo.sci.gsfc.nasa.gov/view.php?datasetId=SEDAC_POP). Earthquake rupture extents taken from Kumar *et al.* (2010) and Jayangondaperumal *et al.* (2011). Floods are from O'Connor & Costa (2004) and ICIMOD (2011) and landslides from AGU Landslide Blog (http://blogs.agu.org/landslideblog/2014/08/02/sunkoshi-1/) and Owen *et al.* (2008).

from the 1970s to the early 2000s, and that the rate of glacier retreat has been accelerating over the last decade. Near-term risks associated with melting glaciers are particularly grave for the Indian Himalaya where up to 40% of the dry season water discharge comes from glaciers thinning at 0.6 m a^{-1} (Kääb *et al.* 2012). Scherler *et al.* (2011*a*) highlight the complexities of modelling glacier response to climate change because of varying amounts of supraglacial debris cover, which strongly influence ablation, in different glacial systems throughout the Himalaya.

Agriculture accounts for 86% of water withdrawals from the Ganges (Hosterman *et al.* 2012). Up to 10% of the annual and 38% of the dry season flow of the Ganges is derived from glaciers (Moors & Siderius 2012). Indian Himalayan glaciers receive most of their snowfall from the monsoon. This change in north Indian weather patterns results in wider fluctuations in snowfall and rainfall, ranging from weak monsoons with drought to temporary stalling of the monsoons over small areas of the Himalaya, with catastrophic flooding as seen at Kedarnath during the summer of 2013 that resulted in many thousands of fatalities (Fig. 10; Singh 2014; Das *et al.* 2015; Bhambri *et al.* 2016). Melting glaciers coupled with a more variable monsoon increase the likelihood of drought and flooding on the Gangetic plains, which contain 30% of India's farmland (Owen 2010*a*; Moors *et al.* 2011; Chaturvedi 2012).

Approximately 80% of annual rainfall in India occurs during the monsoon season from June through to September (Kumar *et al.* 2010). Although total rainfall in northern India has remained nearly constant over the last few decades (Kumar *et al.* 2010), the monsoon is generally weaker (Dash *et al.* 2009) and is expected to exhibit greater interannual variability in proportion to atmospheric CO_2 concentrations (Menon *et al.* 2013). Direct cause and effect for the monsoon behaviour of 2013 cannot be proven, but it was truly unprecedented. The monsoon progressed from east to west across nearly all of India between 14 and 15 June 2013, as never before in recorded history, until it was stalled over the Indian Himalaya by strong westerly winds from the Arabian Sea (Ramachandran 2013). Indian monsoon rainclouds were stalled during mid-June by westerly winds over the Kedarnath region, resulting in an almost unprecedented multi-day cloudburst with 16 June being the wettest day in over five decades in northern India (Singh 2014; Das *et al.* 2015).

Catastrophic flooding also occurred in 2010 along the Indus River (Fig. 9). This began in July with unusually intense but not unprecedented rainfall in the upland catchment; over four months, close to 2000 fatalities occurred and *c.* 20 000 000 inhabitants were displaced (Syvitski & Brakenridge 2013). Syvitski & Brakenridge (2013) highlighted that the meteorological events triggered but did not cause this disaster; most damage was caused by dam and barrage-related backwater effects, reduced water and sediment conveyance capacity, and multiple failures of irrigation system levees. They also

Fig. 10. Before and after the June 2013 flood in northern India. (**a**) Views of the holy city of Kedarnath in September 2010, and (**b**) after the June 2013 flood (from http://www.ndtv.com/india-news/kedarnath-temple-compound-damaged-due-to-flood-report-says-50-pilgrims-dead-525885). The Uttarakhand State government estimates that >5700 people died in these floods, largely due to a combination of unprecedented rainfall and 'unscientific' development of roads, bridges, houses, resorts and hotels adjacent to rivers and steep slopes, which themselves contributed to even more flooding and landslides. (**c**) Kedarnath Temple in September 2010 and (**d**) the catastrophic flood and debris flows from June 2013 (right: Times of India, June 25, 2013). The hazard of debris flows and floods from upvalley glaciers was evident long before the disaster.

pointed out that the 2008 flooding of the Kosi River, India was exacerbated by the lack of planned accommodation for the river's high sediment load; its super-elevation above the surrounding terrain set the stage for exceptionally dangerous levee failures and channel avulsions. Other disastrous floods are highlighted in Figure 9.

Continued melting of glaciers will result in associated hazards such as the development of supraglacial and proglacial lakes that may drain catastrophically as glacial lake outburst floods (GLOFs; Reynolds 2000; Richardson & Reynolds 2000; Benn *et al.* 2001; ICIMOD 2011). Infamous examples of GLOFs have occurred in the Dudh Koshi in Nepal, which has included GLOFs in 1977, 1985, 1991 and 1998 that resulted in numerous fatalities and the destruction of bridges, farmland and a hydropower plant (ICIMOD 2011; Fig. 9). Settlements dependent on meltwater-feed irrigation dykes for agriculture have been abandoned in some areas where glaciers have retreated, and this is a potential treat in many regions (Pickering & Owen 1997).

Seismic hazard is also of great concern throughout the Himalaya (Bilham *et al.* 2001). Figure 9 illustrates the extent of surface ruptures during the major historic earthquake throughout the Himalaya, highlighting the immense numbers of people that would be threatened by similar-sized earthquakes in the future. Poor building design is the biggest concern. During the 2005 Kashmir earthquake, more than a million people were displaced due to the building damage (Owen *et al.* 2008). Earthquake-triggered landslides are also a concern. For example, the Hattian Bala landslide was triggered by the Kashmir earthquake burying three villages and killing more than 700 people (Owen *et al.* 2008). Study of the geologic and geomorphic context of such landslides can aid in landslide susceptibility mapping and hazard mitigation (Kamp *et al.* 2008, 2010).

Construction of highways also leads to increased hazards such as landsliding and flooding as the landscape is modified (Owen 1996*a*; Petley *et al.* 2007; Fig. 8). Careful highway design, however, can help mitigate these hazards (Hearn 2011).

There is a need to develop strategies to help mitigate the effects of these geohazards, and plan for effective response and remediation. Understanding threats from geohazards and developing effective response and remediation strategies is still in its infancy, however.

Applying geomorphology

Understanding the nature of environmental and geomorphic change in the Himalaya is challenging. However, we can use the landscape itself to help us predict the future. Study of mountain geomorphology provides important insights into the likelihood of future change. A good example of this is the development of paraglacial studies in the Himalaya, where landforms have evolved during past periods of climatic instability (Owen *et al.* 1995*b*, 2002; Owen & Sharma 1998; Barnard *et al.* 2004*a*, *b*, 2006*a*, *b*; Scherler *et al.* 2015). These studies show us that we would expect an increase in landsliding, flooding and sediment transfer as we progress into a future climate forced by human influences, one that, according to the Hijioka *et al.* (2014), is likely to experience increases in both the mean and extreme precipitation in the Indian summer monsoon.

Another example includes understanding how geopatterns on mountain surfaces arise and what they tell us about processes. Key to our understanding of geohazards and planning for sustainable development is determining how the biogeochemical reactors within mountain surfaces respond to and shape landscapes from local to global scales, and how mountain ecosystems and landscapes co-evolve. We need to know what the transport laws that govern the evolution of mountain surfaces are. We also need to know what controls mountain landscape resilience to change, and how mountain surfaces evolve under human influences.

Clearly, the Himalaya is one of the best natural laboratories to assess the relative roles of Earth's internal and surface processes in the evolution and development of active mountain landscapes. However, there is still much debate on what processes control the height and erosion of mountains, and the role of the interactions and feedbacks between the different sets of processes that influence landscape evolution. Bishop *et al.* (2010) and Owen (2014) illustrate schematically some of these connections, but the parameters of the different systems are not well defined and the magnitudes of the change with time in the linkages still need to be determined. Their framework is however useful when considering geomorphic, tectonic and climate processes and topography and their links in the Himalaya, but the human component needs to be added to the links (Fig. 11). Himalayan environments are so varied and complex that such a

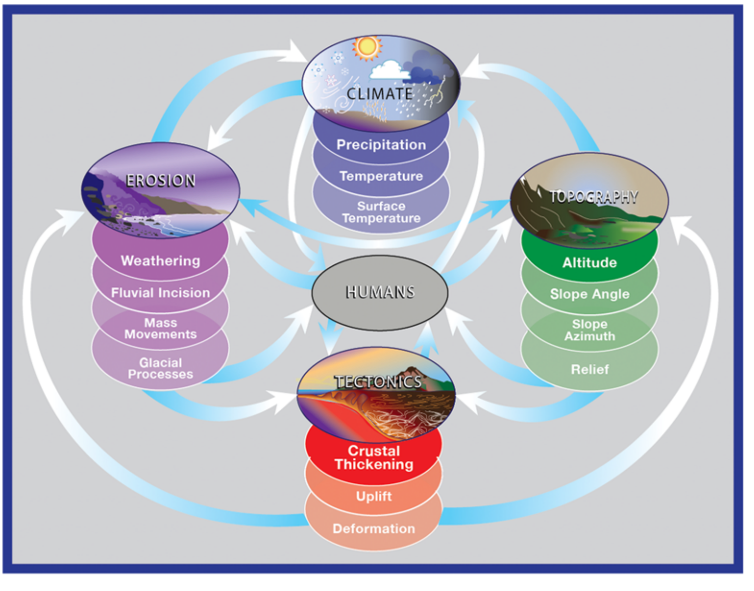

Fig. 11. Interactions and selected feedback pathways for climate, erosion processes, tectonics, topography and humans (adapted from Bishop *et al.* 2010).

framework helps to make study of the geomorphology more manageable. As Owen (2014) highlights, the challenge for future geomorphic research, and especially for hazard mitigation and environmental risk assessment, is to quantify these systems and identify their links, and understand the spatial and temporal variability. Predictions may then be more accurately made about future geomorphic and landscape changes and sustainable development.

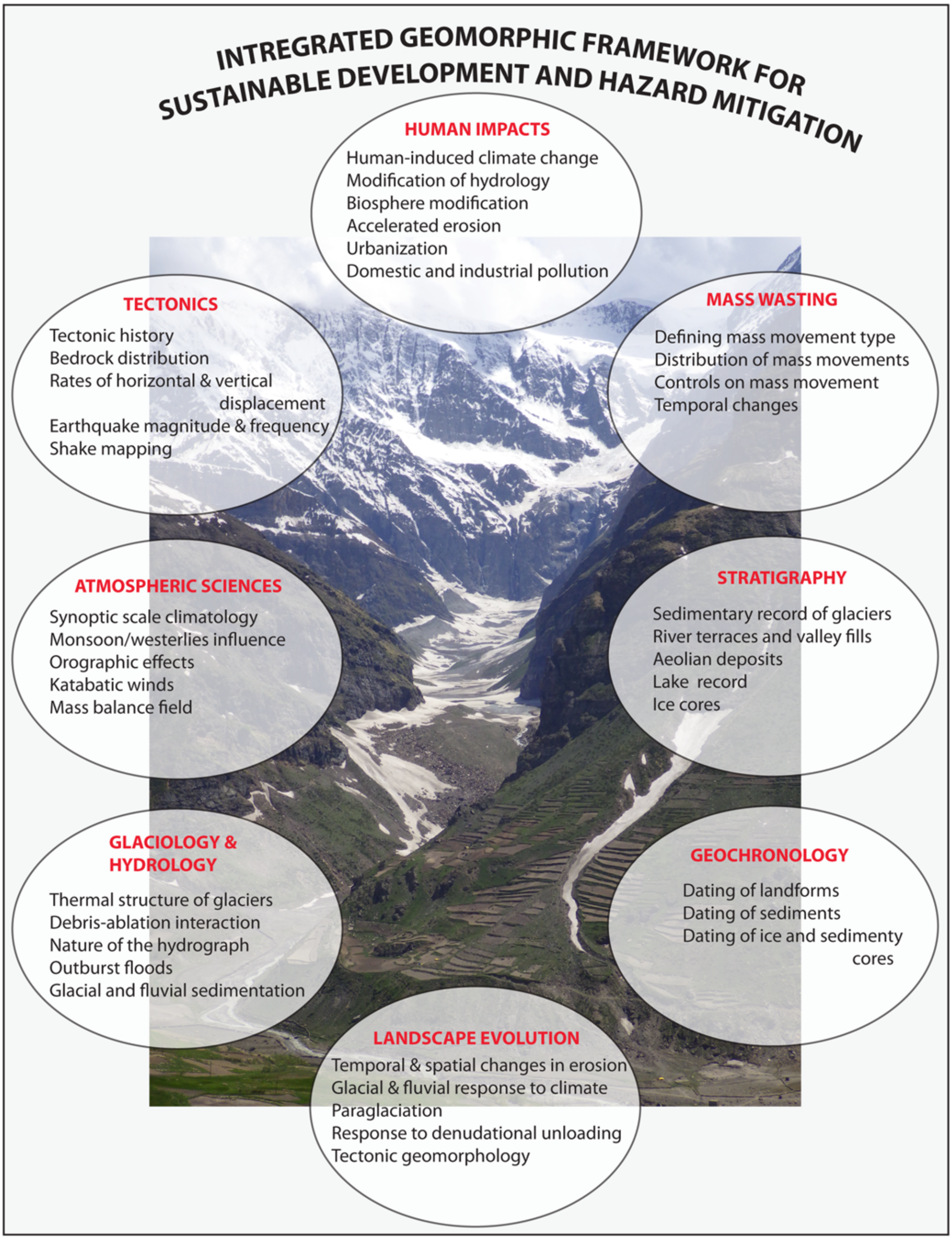

Fig. 12. Integrated research approach to studying Himalayan environments to aid in sustainable development and hazard mitigation.

Applying effective strategies of environmental management requires an integrated approach similar to that suggested by Owen *et al.* (2009) for the study of mountain glaciers. Such an approach should include the research and study of atmospheric science, glaciology, hydrology, glacial hydrology, engineering geology, geochronology, stratigraphy landscape evolution and human impacts (Fig. 12). These components link together to provide a holistic view of mountain environments. The relative components are influenced by human activity as shown in Figure 11. However, linking these components is challenging and involves numerous experts with diverse backgrounds, often unfamiliar with each other's nomenclatures and methodologies.

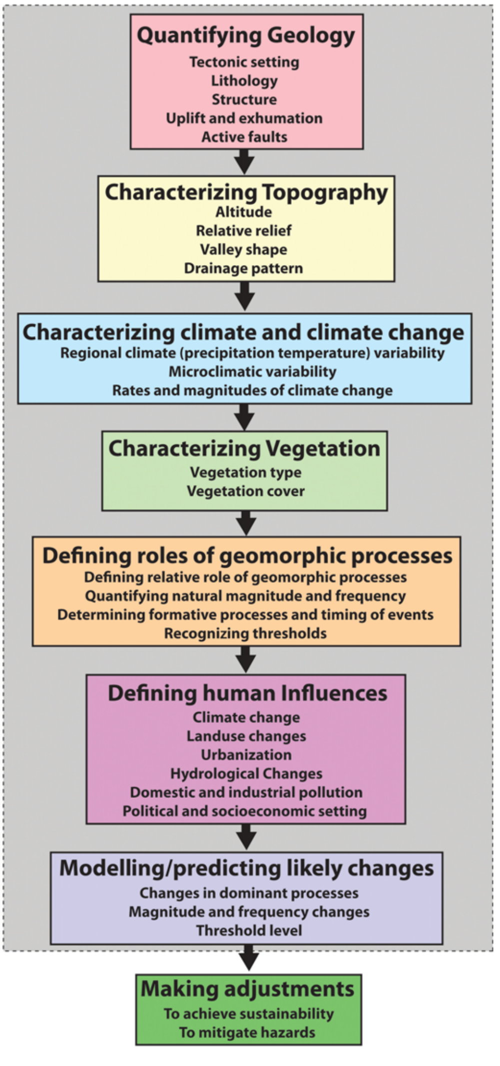

Fig. 13. Process cascade for a geomorphic framework (enclosed within the grey rectangle) to help in achieving sustainable development and for hazard mitigation in Himalayan environments.

A possible structured approach is presented in Figure 13, suggesting that a cascade or hierarchal succession of studies is needed to provide a geomorphic framework for effective sustainable development and hazard mitigation. Quantifying and, in particular, understanding the geology is the keystone of the framework. Understanding climate, topography and vegetation is the next critical step, since these all influence the type, magnitude and frequency of geomorphic processes. Defining the relative role of geomorphic processes follows. In particular, there is a need to define the natural magnitude and frequency of processes, and to identify threshold and formative processes/events. Once the geomorphic setting is characterized then the human influences should be accessed. This should include likely climate changes in the coming years, land-use change, degree of any urbanization and changes to the hydrological system and pollution. Intrinsic to all this is an understanding of the political and socio-economic setting. The next step would include modelling and predicting likely changes in the dominant geomorphic processes, magnitude and frequency of processes, and whether a threshold is being approached or will be exceeded. Moreover, identifying and understanding the occurrence of major disasters throughout the Himalaya can aid in future planning and preparation (Fig. 9). However, there is no systematic and comprehensive database for recording natural and human-induced disasters for the Himalaya. The geomorphic framework and approach suggested here could be used by planners and/or policy makers to make adjustments to try to achieve sustainable development and/or mitigate hazards.

Conclusions

The study of tectonic, geomorphic and climatic–hydrological processes and landscape evolution in the Himalaya is becoming increasingly relevant as the world advances into a time of rapid human-induced climatic and environmental change. The landscapes of the Himalaya are among the most sensitive to these encroaching natural and human-induced changes. The dominant geomorphic processes in Himalayan environments include glacial, fluvial and mass-movement processes, influenced by tectonic, climate and human factors (Fig. 14). Understanding the nature of these processes and future changes is essential for the wellbeing of the vast populations who live within and bordering the region (Fig. 9). The economies of these regions are mostly agriculture based, and are therefore sensitive

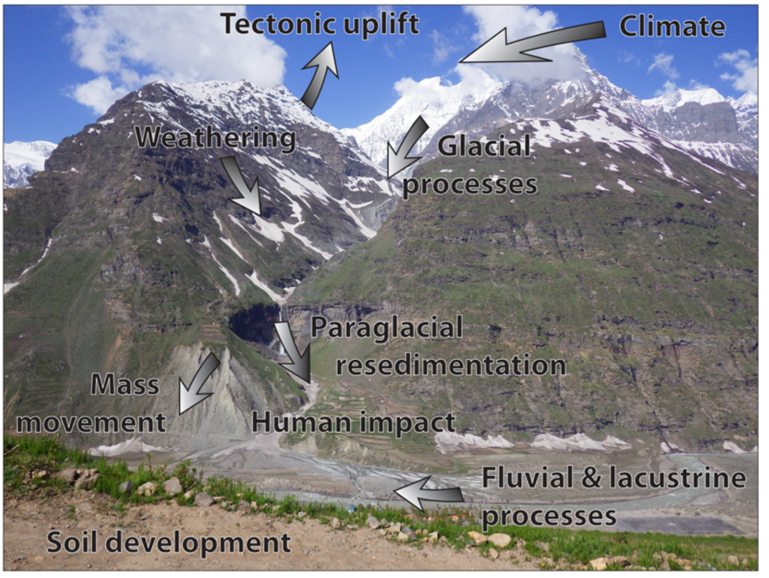

Fig. 14. Summary of main processes/factors contributing to landscape development in a Himalayan valley.

to variations in the glacial and hydrological systems that provide much of the water to these regions.

Defining and predicting landscape change and changes in the frequency and magnitude of surface processes is challenging because of the complexity and diversity of Himalayan–Tibetan environments. Nevertheless, insights from studies of present and past processes and of landscapes provide a framework for addressing future change. Of particular importance is the need to define both spatially and temporally: (1) the nature of glacier oscillations; (2) hydrological changes; (3) the magnitude and frequency of flooding, including rainfall-induced and glacial lake outbursts; (4) rates of erosion and sedimentation; (5) the nature of landsliding; and (6) seismic and associated geomorphic hazards such as earthquake-triggered landslides. Continued research in these and allied areas will aid in geomorphic and tectonic hazard mitigation and sustainable development in the coming years. Moreover, an integrated approach is necessary when studying the geomorphology of Himalayan environments for hazard mitigation and sustainability, as illustrated schematically in Figure 12; to fully develop and implement a geomorphic framework a cascade or hierarchal succession of studies is advisable, as highlighted in Figure 13. Ultimately, the success of applying geomorphic studies relies on scientists effectively communicating their knowledge and understanding to policy makers and planners.

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