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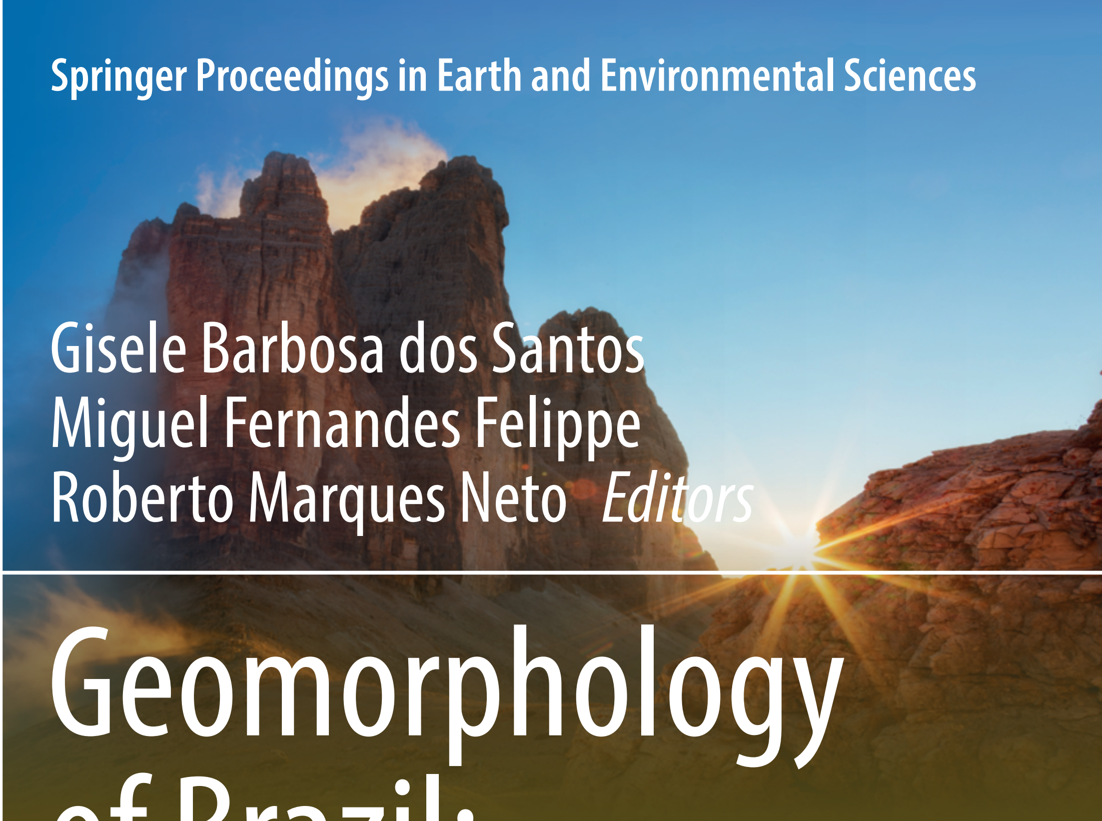

Gisele Barbosa dos Santos
Miguel Fernandes Felippe
Roberto Marques Neto *Editors*

Geomorphology of Brazil: Complexity, Interscale and Landscape

XIII SINAGEO (National Symposium of Geomorphology)

Springer

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Gisele Barbosa dos Santos ·
Miguel Fernandes Felippe · Roberto Marques Neto
Editors

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Editors
Gisele Barbosa dos Santos
Department of Geosciences
Universidade Federal de Juiz de Fora
Juiz de Fora, Brazil

Miguel Fernandes Felippe
Department of Geosciences
Universidade Federal de Juiz de Fora
Juiz de Fora, Brazil

Roberto Marques Neto
Department of Geosciences
Universidade Federal de Juiz de Fora
Juiz de Fora, Brazil

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Introduction: Geomorphology at the Start of the Twenty-First Century

Andrew S. Goudie

1 Introduction

Geomorphology is the study of the Earth's surface and the processes which shape it (Goudie and Viles 2010a, b). It is largely carried out by geologists and geographers. However, it is also an interdisciplinary discipline that has linkages to hydrology, archaeology, environmental history, engineering, ecology, and climatology. The discipline's recent history has been reviewed by Burt et al. (2008), Goudie (2016a), Gardner (2020), and Burt et al. (2022), while the role of various national schools has been recounted by Walker and Grabau (1993). Geomorphology has also become increasingly international in scope, as evidenced by the establishment of the International Association of Geomorphologists in 1989, and by the participation of geomorphologists in the meetings of the EGU.

The purpose of this chapter is to highlight some of the major features of Geomorphology at the start of the twenty-first century.

2 Development of Techniques

In recent decades there has been an explosion of techniques that have become available to geomorphologists (Goudie 1990). These have (i) allowed improved field measurements (e.g., through the use of GPS and data loggers), (ii) improved surveying of landform distribution and morphometry (through remote sensing, LIDAR, GIS, unmanned aerial vehicles, etc.) (Eckardt 2022), (iii) geophysical

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A. S. Goudie (✉)
School of Geography, University of Oxford, South Parks Road, Oxford OX1 3QY, UK
e-mail: andrew.goudie@stx.ox.ac.uk

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techniques to permit two- or three-dimensional views of the materials and structures which make up the landscape (e.g., Ground Penetrating Radar and resistivity surveys), (iv) superior analyses of geochemical properties of materials, by, for example, the use of XRD and XRF, (v) assessment of the hardness of rocks (Viles et al. 2011), (vi) absolute dating of landforms and deposits by means of isotopes, optically stimulated luminescence, Caesium-137, cosmogenic nuclides, and thermochronology, including fission track dating (Anderson 2022), (vii) experimentation in the laboratory and under real field conditions, using programmable environmental cabinets, wind tunnels, rainfall simulators, dust and sand traps, electronic sensors, etc. (Church 2022), (viii) detailed environmental reconstruction (especially by miscellaneous types of core analysis), (ix) statistical analyses of large sets of data by means of computers, (x) and computer-based modelling (Church 2010; Martin 2022). Without all these technical developments, geomorphology would be a very different discipline from the one it has become.

3 Development of Landscapes Over Time

A major concern of geomorphologists for much of the past two centuries was the study of the long-term development of landscapes in response to climate changes and tectonic history. This involved the study of cycles of erosion, the establishment of denudation chronologies, and the analysis of landscape development in response to changes in climate (e.g., Büdel 1982) and base levels. Although in the second half of the twentieth century this historical/evolutionary approach became less dominant in the discipline, it has recently been re-energized because of the availability of a suite of new dating techniques (e.g., optical dating, cosmogenic radionuclides) and techniques for environmental reconstruction (e.g., by coring) (Anderson et al. 2013; Anderson 2022). There has been a renewed burst of interest in the role of Late Cenozoic environmental changes at a wide range of temporal scales. Quaternary geomorphology is a vibrant field, not least in lower latitudes, where the impact of pluvial and arid phases has been fundamental for understanding landscapes, including those of Brazil (de Paula Barros and Junior 2020; Mescolotti et al. 2021).

Longer-term studies of landform evolution have also blossomed because of an interest in plate tectonics, continental drift, sea-floor spreading, epeirogeny, and orogeny (Summerfield 2000). This enables one to explain such phenomena as drainage-basin evolution at a continental scale (e.g. Goudie 2005), the evolution of great escarpments on passive margins, and the distribution of volcanoes around the world.

Geomorphologists have also been much concerned with shorter-term environmental history and it is here that their work overlaps with that of environmental historians (see Hudson et al. 2008) and geoarchaeologists. Geoarchaeology is a fertile field of research with its own journals. Working with prehistorians and archaeologists, geomorphologists have investigated the effects of climatic, tectonic, and sea-level changes on human societies (e.g., Flemming 1999) and have assessed the relationship of archaeological sites to geomorphological settings, including dunes (Allchin et al. 1978), arroyos, colluvium, calcareous tufas, caves, lakes and lunette dunes, coastal erosion and construction, deltas, old river systems, badlands and alluvial deposits (Vita-Finzi 1967).

4 Rocks and Relief

Understanding the impact of rock types of landscapes is a fundamental component of Geomorphology. Thus the study of the links between rocks and relief has a long history during which studies have been performed on the links between particular rock types and landscape patterns. These have included studies of landforms on limestones and dolomites (Ford and Williams 2007), sandstones and conglomerates (Young et al. 2009), and granites (Migoń 2007). However, notwithstanding Yatsu's (1966) exhortation, quantification of the links between rock properties and landforms remains an under-researched part of Geomorphology. There was indeed a great school of rock control work that arose in Japan (Ouchi 1996), notably by Suzuki and colleagues (see Suzuki et al. 2000 for a history of this work). As Goudie (2016b) argued, rock properties occur at a range variety of scales, from large lineaments and fractures (which are measured in the field) through to individual rock micro-pores (which are calculated in the laboratory). At the mega-scale, there are discontinuities—faults, joints, and bedding planes. At the mesoscale, rock strength can be determined both in the laboratory and in the field by measuring such properties as abrasiveness and abradability, compressive, shear and tensile strengths, penetrometer resistance, surface hardness, and Young's Modulus of Elasticity. At a smaller scale, rocks can be tested in the laboratory to establish their resistance to weathering (particularly frost and salt action) and to assess the role of such factors as their porosities and water absorption capacities A new technique for the small-scale analysis of materials that was first developed in the 1930s but evolved from the 1960s onwards, was Scanning Electron Microscopy (SEM) (Whalley 1978).

Techniques such as the assessment of rock mass strength (RMS) (Selby 1980) and the study of the relationships between rock pore characteristics and resistance to weathering (e.g., Yu and Oguchi 2009) are indicative of the progress that is now being achieved. Rock hardness determination has developed as a research field (Viles et al. 2011), involving the use of the Schmidt Hammer (SH) (Goudie 2006), the Equotip, the Grindosonic, and dilatometric and sonometric techniques. Efforts have been made to relate this to such diverse phenomena as slope forms and instability, the morphology of shore platforms, glacial trough geometry, river channel dimensions, valley forms, the formation of cavernous weathering features, and inselberg development (Duszyński et al. 2022).

5 Processes

There are two main types of Earth surface processes: exogenic and endogenic (Goudie 2016a). The former refers to those processes (weathering, erosion, sediment transport, etc.) that are ultimately fuelled by the Sun's energy and which operate via the climate system. Particularly since the 1960s geomorphology has concerned itself with these exogenic processes, often at a reductionist level and using quantitative techniques, such as computational fluid dynamics (Lane et al. 1999). As a result of the quantitative revolution, great efforts have been made to measure such processes as grain entrainment and solute movements in small catchments. Classic and influential examples of this genre are those by Leopold et al. (1964) on rivers, by Carson and Kirkby (1972) on slopes, by Drewry (1986) on glaciers, by Washburn (1979) on the cryosphere, by Yatsu (1988) on weathering, by Masselink and Hughes (2003) on coasts, and by Gillette (1977) on aeolian processes. Discussions on recent developments in three of the biggest components of geomorphology—rivers, coasts, and slopes—are provided by Ferguson et al. (2022), Spencer and French (2022), and Kirkby (2022), respectively.

On the other hand, the latter refers to volcanic and tectonic processes powered by energy derived from the inside of the Earth. These exogenic processes operate over long time scales and over great regional extents. Since the 1960s, they have received increased attention as a consequence of the emergence of the plate tectonics paradigm (Burbank and Anderson 2011), and have contributed to a greater understanding of the global pattern of phenomena such as volcanoes, rift valleys, mountain ranges, and guyots (Summerfield 1991, 2022). They have also helped us to understand rates of denudation and fluvial incision in areas of active orogeny (Whipple and Meade 2006; Whittaker et al. 2007). Moreover, current work has shown that climate, as well as the erosional development of the landscape, feeds back into the ongoing tectonic processes (Whipple 2009). As Dadson (2010, p. 390) remarked 'the results from coupled geomorphic and geodynamic models suggest that climate-driven erosion is of first-order significance in the evolution of mountain belts across a range of time scales'. The study of rates of chemical weathering and physical denudation under different climatic and tectonic conditions has been boosted by a concern with how these processes relate to global carbon cycle (Goudie and Viles 2012). Exogenic process geomorphology and the new models of long-term landscape evolution, associated with new ideas on plate tectonics and novel geochronometric techniques, need to be combined more effectively than they have been in the past (Summerfield 2005; Bishop 2007).

More traditional evaluations of the links between climate conditions and the nature and rate of geomorphological processes persist as an active area of research, with syntheses of geomorphological phenomena in different climatic zones being produced, including those of humid tropical environments (Thomas 1994), glaciated areas (Benn and Evans 2010), deserts (Goudie 2013), and periglacial and permafrost regions (French 2017).

6 Living Landscapes

Organic agencies are crucial for understanding landform development. Thus since the 1980s, there has been a burgeoning concern with establishing links between plants, animals, and geomorphology, and the terms biogeomorphology (Viles 1988), zoogeomorphology (Butler 1995), ecogeomorphology, and geoecology have been used. Coombes (2016b) and Viles (2020) undertook citation analyses, which showed that publications in biogeomorphology increased exponentially during the 1990s.

Biogeomorphology is ‘an approach to geomorphology which explicitly considers the role of organisms’ (Viles 1988, p. 1), or as Coombes (2016a) defined it, ‘Biogeomorphology is the scientific study of interactions and feedbacks between living and non-living parts of the landscape’. Viles recognized that there are two linked foci in biogeomorphology: ‘The influence of landforms/geomorphology on the distributions and development of plants, animals, and microorganisms’, and ‘The influence of plants, animals and microorganisms on earth surface processes and the development of landforms.’ The whole spectrum of biological life-forms is involved in biogeomorphological interactions, from bacteria and fungi affecting weathering and mineral precipitation to elephants excavating wallows, to cows causing ground compaction, to the effects of a large forest on the behavior of river catchments (Viles 2004).

Undoubtedly during the evolution of life, the impact of organisms on geomorphological processes has also evolved, and, for example, the Palaeozoic development of plant life about 440 million years ago would have dramatically changed the channel activity of rivers (Ielpi and Lapôtre 2020). Likewise, Algeo and Scheckler (1998) argued that the evolution of trees and seed plants and the appearance of multi-storied forests in the Devonian led to an intensification of soil formation and increased fluvial solute fluxes.

Recent work has tried to provide quantitative measures of relief complexity and to link this to biodiversity. Landforms have been seen as important components of habitat, particularly in river floodplains (e.g., Graf 2001; Bennett and Simon 2004). Moreover, geomorphological processes enhance an area’s biodiversity by introducing dynamism and creating new habitats (Viles et al. 2008). Plants and animals are not merely passive occupiers of the Earth’s surface. They play an active and key role in many geomorphological processes and can create unique landforms (beaver dams, coral and serpulid reefs, termitaria, phytogenic dunes, animal dens, ant mounds, etc.). Above all, biological influences can either accelerate or retard the rate of operation of exogenic processes. Organisms such as ants, notwithstanding their small size, achieve a remarkable amount of geomorphological work (Viles et al. 2021). Processes, including tree fall and root penetration, have major effects on slope forms, shallow landslides, and creep, while vegetation cover influences rainfall interception, infiltration rates, runoff, and sub-surface flow, temperature characteristics, and wind action. Riparian vegetation impacts upon river channel forms, flood plains, and bank erosion. Vegetation cover is also a crucial factor in controlling wind velocities and turbulence at the ground surface and in reducing wind erosion, dust storm generation, and sand dune movements. The combined effects of erosion reduction and accretion enhancement can be termed ‘bioprotection’ (Carter and Viles 2005), but conversely, organisms can accelerate erosion, a process which is called ‘bioerosion’.

7 Submarine Geomorphology

Using an array of new techniques, geomorphologists have started to discover a great deal about the ocean floors (Micallef et al. 2022) and extra-terrestrial landscapes (Conway 2022).

For a long time, the former remained largely unexplored directly by humans, apart from some submarine-based expeditions, but their major features have now been mapped through ship and satellite-based remote sensing. Together, these have been used to create global topographic maps or digital elevation models (DEMs) of the ocean floor. Sidescan sonar and 3D seismic survey are among the techniques that allow the creation of ‘images’ of surface and sub-surface materials. Many large-scale features have been found which reflect the impact of glacial action (Ottesen and Dowdeswell 2009), tectonics, mass movements, and other processes. One particularly productive area of recent research has been the identification and interpretation of subsea mass movements, for landslides, creep phenomena, flows, slumps, slides, and falls are all common on the seafloor (Micallef et al 2007; 2009; 2018).

These mass movements can be hazardous to humans (Innocenti et al. 2021) and so this is a major research frontier for applied geomorphologists (Moore et al. 2018). Landslides in fjords, in the Gulf of Mexico (Fan et al. 2020), and on the flanks of oceanic islands, such as the Canaries, can generate tsunamis (Coppo et al. 2009), though this is not always the case (Løvholt et al. 2017). In addition, turbidity currents can pose challenges for engineering structures such as oil platforms (Clare et al. 2020). Submarine geomorphology also has implications for finding and developing hydrocarbons in places like the Congo and Angola Fans in the Atlantic off western Africa (Anka et al. 2010), the delta of the Nile (Li et al 2021), and the South China Sea (Wang et al. 2021a, b).

8 Extra-Terrestrial Geomorphology

Today, planetary geomorphology, thanks to the pioneering work of people like Greely and colleagues (Greeley and Iversen 1985), is a flourishing area of study (Baker 2008; Diniega et al. 2021; Conway 2022). Much work has been undertaken on Mars. Among the many Martian phenomena for which analogs have been sought on Earth, are wind scouring, yardangs and ventifacts, mass movements, flood deposits and alluvial fans, dunes, sand ripples, saltation phenomena, wind streaks, haloclasty and split rocks, chemical coatings on rocks groundwater-sapping features, relief inversion, coastal sabkhas, and dust events (Bhardwaj et al. 2021). This has stimulated research on a number of landforms and processes and has also led to research in a number of

Earth's drylands, including the Namib (Bourke and Goudie 2009), the Western Desert of Egypt (El-Baz and Maxwell 1982), Australia (Mann et al. 2004), the sandstone terrains of Utah (Chan et al. 2011) and the Qaidam Basin of the Tibetan Plateau (Xiao et al. 2017).

Titan is the largest of Saturn's moons and following the Cassini mission, which was launched in 1997 and remained active until 2017, we now know much more about its characteristics. The images sent back have revealed a landscape that is quite similar to that on Earth—except that the surface is composed of water ice, not rock, and is sculpted by liquid methane, not water. It has some interesting landform features (Lopes et al. 2020), including thousands of linear dunes (Radebaugh et al. 2010), and the largest cover of dune fields in our solar system (Bourke et al. 2010). There are also some stubby drainage networks that may have been generated by methane spring-sapping (Soderblom et al. 2007), tropical endorheic lakes (Tokano 2020), volcanic craters (Keane 2019), and alluvial fans (Birch et al. 2016).

9 Geomorphology and Earth System Science

In the 1980s, Earth System Science (ESS) evolved (see Steffen et al. 2006). It concentrates on modeling, treats the Earth as an integrated system, and seeks a more profound understanding of the physical, chemical, biological and human interactions that determine the past, current, and future states of the Earth's lithosphere, hydrosphere (including the cryosphere), biosphere, and atmosphere. It emerged in response to (i) the realization that biogeochemical systems operate globally and (ii) an increasing appreciation that Earth is a single system. Dadson (2022) provides a good survey of the role of ESS in geomorphology. Geomorphologists have created Earth System Models (Paola et al. 2006; Fan et al. 2019). A prime illustration of the way in which geomorphology contributes to Earth System Science is through understanding the links between silicate weathering in different geomorphological settings (e.g., island areas, mountains, glaciated terrains), the global carbon cycle, and long-term climate changes (Dupré et al. 2003). Examples of the effects of geomorphological change on the Earth System relate to biogeochemical cycling (Viles et al. 2008; Quinton et al. 2010), and silica and carbon budgets (Zhang et al. 2017). Soil erosion by wind may play a significant role in these (Webb et al. 2012; Chappell et al. 2013), but so may water erosion from agricultural fields, and the burning and subsidence of peat.

10 Global Change

In the 1970s, widespread employment of the term 'Global Change' emerged, as seen in the development of the *International Geosphere-Biosphere Programme: A Study of Global Change* (1986). The significance of this for geomorphology is demonstrated in the works of Steffen et al. (2006) and Slaymaker et al. (2009). Global warming, allied with the growth of more local human impacts on the environment, will have major effects on future landscapes. Indeed, they are already doing so.

Climate change is only one of the drivers of landscape change, and it is imperative that we weigh up the relative and/or combined impacts of global climate change and local human impacts. At the regional scale, land cover changes (such as tropical deforestation) may cause climate changes of comparable dimensions to those predicted to arise from global warming (e.g., Deo et al. 2009). Changes in runoff and sediment loads caused by land cover changes or dam construction may surpass those caused by future changes in rainfall quantities (e.g., Xu et al. 2007). Loss of coastal wetlands due to direct human action may be greater than those caused by sea-level rise (Nicholls et al. 1999), and the changing incidence of landslides may owe more to changes in human activity than to climate changes (Crozier 2010).

11 Global Warming

Global warming is one component of global change. Interest in this has developed since the early 1980s and has progressively created considerable interest in its consequences for a range of geomorphological phenomena (Goudie 1990, 2020) (Table 1). Of great importance has been the search for areas that will be particularly sensitive for four reasons: (i) their threshold reliance with respect to particular temperature, precipitation, and vegetation cover conditions, (ii) the compounding effects of climate change on other human actions, (iii) the presence of susceptible, fragile features and (iv) the fact that they are present in zones where climate change will be specially marked (e.g., higher latitudes and the margins of deserts).

Some phenomena that may as a consequence of these characteristics react very substantially to future heating are valley glaciers (especially on tropical mountains), permafrost features, floodplains, relict dune fields, low-lying coasts, areas exposed to tropical storms and hurricanes, and snow-fed rivers (IPCC 2021). Some locations will be subject to very rapid change because of the combined effects of climate change and other anthropogenic pressures, as is the case with many of the world's great deltas (Tessler et al. 2018) and with American rivers (Wan et al. 2017). As recent events in many parts of the world have shown, fire frequencies and severities could change, which would in turn have potentially huge impacts on slope processes (including mudflows) and surface runoff.

Moreover, most of the climatic models from 25 years ago have seemingly been correct in the scenarios they presented. The magnitude of geomorphological changes is becoming more evident by the day. Ongoing monitoring since the mid-1990s has shown that many geomorphological environments are changing rapidly. Equally, active layer thicknesses above permafrost have been increasing in many Arctic regions. Moreover, the World Glacier Monitoring Service has suggested that globally the average annual mass loss of glaciers between 1996 and 2005 was twice that of

Table 1 Some geomorphological consequences of global warming (modified from Goudie and Viles 2016, Table 11.1)

Hydrological
Increased evapotranspiration loss leading to river flow diminution, less soil cohesion, etc.
Overall increase in global precipitation leading to increased flood activity
Increased percentage of precipitation as rainfall at expense of winter snowfall leading to changes in river regimes
Increased precipitation as snowfall in very high latitudes leading to changes in river regimes
Possible increased risk of cyclones (greater latitudinal spread, frequency, and intensity)
Changes in the state of lakes, wetlands, and peatbogs
Less use of water by vegetation because of increased CO_2 effect on stomatal closure
Vegetational Controls
Major changes in latitudinal extent of biomes—reduction in boreal forest, increase in grassland and drylands, etc.
Major changes in altitudinal distribution of vegetation types (i.e., 500 m for 3 °C)
Growth enhancement by CO_2 fertilization
Changes due to increases in fire frequencies
Cryospheric
Permafrost decay, thermokarst, increased thickness of active layer, instability of slopes, degradation of river banks and shorelines
Changes in glacier and ice sheet rates of ablation and accumulation: glacier retreat
Changes in glacier lakes and outburst floods
Removal of glacial buttresses from slopes, leading to slope instability
Sea ice melting increasing wave attack conditions in Arctic regions
Coastal
Inundation of low-lying areas by sea-level rise (including wetlands, deltas, swamps, marshes, reefs, lagoons, etc.)
Increased storm surge activity associated with tropical storms, hurricanes, etc.
Accelerated coast recession (particularly on sandy beaches)
Changes in rates of reef growth and coral bleaching
Spread of mangrove swamps into higher latitudes
Aeolian
Increased dust storm activity in areas of moisture deficit, but reduced activity in areas of global stilling
Dune reactivation in areas of moisture deficit
Soil Erosion
Changes in response to changes in land use, fires, natural vegetation cover, rainfall erosivity, etc.
Changes resulting from soil erodibility modification (e.g., sodium and organic contents)

(continued)

Table 1 (continued)

Subsidence
Desiccation of clays under conditions of increased summer drought Thermokarst as a result of permafrost melting
Weathering
Reduction in number of frosts Salt weathering changes in response to groundwater levels and temperature and humidity cycles

the previous decade (1986–1995) and over four times that from 1976–1985. Retreat rates are unprecedented (Zemp et al. 2015).

Some selected studies from 2020/2021 are listed in Table 2. The list is not comprehensive but gives a taste of the huge increase in studies that have taken place in the

Table 2 Select studies of the geomorphological effects of global warming undertaken in 2020/2021

Phenomenon	Source
Coastal erosion	Masselink et al. (2020)
Coastal plain submergence	Antinioli et al. (2020)
Coral bleaching	Goreau and Hayes (2021)
Coral reefs—turbid situations	Morgan et al. (2020)
Coral reefs—accreting situations	Masselink et al. (2021)
Cryosphere melting	Ding et al. (2020)
Fire-induced erosion	Moran-Ordonez et al. (2020)
Glacial lake formation	Shugar et al. (2020)
Glacier outburst floods	Zheng et al. (2021)
Glacier retreat	Sommer et al. (2020)
Ice cap retreat	Wood et al. (2020)
Mangrove swamps	Bozi et al. (2021)
Peat bog degradation	Lin et al. (2021)
River floods	Di Sante et al. 2021
Salt marshes	Cahoon et al. (2021)
Sedimentary conditions	East and Sankey (2020)
Siberian discharges	Wang et al. (2021a, b)
Slope instability	Savi et al. (2021)
Small island submergence	Lin et al. (2020)
Soil erosion and desertification	Ma et al. (2021)
Storm surges	Chen et al. (2020)
Thermokarst	Turetsky et al. (2020)
Wave attack	Morim et al. (2021)

twenty-first century. They demonstrate both the range and the importance of global warming for geomorphological processes and forms.

The complexity of future changes in the environment creates severe problems for prediction and modeling (Blum and Törnqvist 2000). As Bogaart et al. (2003) pointed out, landscape response to climate change is (i) highly non-linear, and (ii) characterized by numerous feedbacks between different variables and by lead-lag phenomena. An example they cite is a precipitation increase in an initially semi-arid area. This would initiate hillslope erosion and increased sediment transport capacity. However, over time, soil and vegetation conditions would adjust to the new moisture conditions, resulting in an improved soil structure and greater vegetation cover. As a result, after a time lag, slope erosion and sediment yields might diminish.

Interest has also arisen in the role that global warming might play in accentuating or triggering geohazards (McGuire 2010). For example, accelerated thawing of submarine permafrost and the release of gas hydrates therefrom might promote submarine slope failure within turn might lead to tsunamis (Day and Maslin 2010). Equally, changes in the extent of ice sheets would modify the amount of loading on Earth's crust and so might have an influence on seismic and volcanic activity.

12 The Human Impact and the Anthropocene

Particularly over the last few centuries of the Anthropocene, and over the 'Great Acceleration' since the 1950s (Steffen et al. 2010), humans have become major agents of landscape change (Goudie and Viles 2016; Goudie 2018; Hudson et al. 2015), not least in Brazil (Junior et al. 2018) The Anthropocene concept has arisen (Ellis 2018). This was introduced by Crutzen (2002) as a name for a new epoch in Earth's history—an epoch when human activities have 'become so profound and pervasive that they rival, or exceed the great forces of Nature in influencing the functioning of the Earth System' (Steffen 2010, p. 443).

Anthropogeomorphology studies both the nature of deliberate land-forming processes (Szabo et al. 2010; da Luz and Rodrigues 2015), such as the creation of sea defenses, artificial islands, embankments, levees, spoil heaps, agricultural terraces, mines, quarries, canals and reservoirs, and the less deliberate changes in the operation of processes. Deforestation, grazing, plowing, city growth, atmospheric pollution, construction, and hydrological manipulation, have a wide range of impacts. They may accelerate a number of hazards, including mass movements, ground subsidence, soil erosion, rock weathering, and even seismic activity caused by fracking (Table 3).

Direct human interventions can have linked unforeseen and unwanted indirect impacts on landscapes. For instance, there are many examples of attempts to reduce coastal erosion which exacerbated it rather than solved it. Protecting one piece of coast, which comprises a component of a natural sediment circulation system, without realizing its larger setting, can lead to unanticipated knock-on effects elsewhere. For example, groyne construction to stop beach erosion, by reducing sediment transport downdrift can deplete beaches and lead to accelerated cliff retreat.

Table 3 Some major anthropogeomorphic processes (based on Goudie 2018, Table 6.2)

Direct processes
Constructional
Tipping, molding, plowing, terracing, reclamation
Excavational
Digging, cutting, mining, blasting of cohesive or non-cohesive materials Trampling, churning
Hydrological
Flooding, damming, canal construction, dredging, channel modification, draining, coastal protection
Indirect processes
Acceleration of erosion and sedimentation
Agricultural activity and clearance of vegetation Engineering, especially road construction and urbanization Modifications of hydrological regime by dams, etc.
Subsidence: collapse, settling
Mining (e.g., of coal and salt) Hydraulic (e.g., groundwater and hydrocarbon pumping) Thermokarst (melting of permafrost) Draining and desiccation of organic soils
Slope failure: landslides, flows, accelerated creep
Loading by spoil, buildings etc. Undercutting by road construction, etc. Shaking Lubrication by irrigation water, broken sewers, etc.
Seismic activity
Loading by reservoirs Lubrication along fault planes Fracking
Weathering
Acidification of precipitation by sulfate emissions Accelerated salinization following changes in groundwater levels Lateritization following vegetation removal

Anthropogenic modifications of erosion and sedimentation rates have been a major concern. Various studies (e.g., Hooke 1994; Douglas and Lawson 2001; Walling 2006) suggest that the amount of material moved by humans is somewhat greater than that moved by the world's rivers to the oceans. As technology evolves, this ability grows still further (Haff 2010). Furthermore, land-use changes, and in particular developments in farming, have led to a leap in erosion rates (Wilkinson and McElroy 2007). Conversely, Syvitski et al. (2005) calculated that sediment retention behind dams has led to a reduction in the annual net flux of sediment reaching the world's coasts by around 1.4 billion tonnes, with a total of more than 100 billion tonnes being trapped within the last 50 years. Syvitski and Milliman (2007) estimated that reservoirs behind dams now trap around 26% of the global sediment delivery to the oceans. Data on increasing sediment accumulation rates in eastern USA are presented in Rodriguez et al. (2020). Cooper et al. (2018, p. 222) argued that 'the annual direct anthropogenic contribution to the global production of sediment in 2015 was conservatively some 316 Gt (150 km^3), a figure more than 24 times greater than the sediment supplied annually by the world's major rivers to the oceans.'

It is now appreciated that human impacts on geomorphology go back a long way into prehistory (Braje 2015). Smith and Zeder (2013) argued that the Anthropocene commenced around 10,000 years ago at the Holocene/Pleistocene boundary, with the first domestication of plants and animals and the development of agriculture and pastoralism. In antiquity, huge changes in land cover in Europe took place (Kaplan et al. 2009), and there is increasing evidence to suggest that Bronze and Iron Age valley fill resulted from accelerated slope erosion produced by the activities of early farmers. Macklin et al. (2014) employed the term 'Anthropocene Alluvium' to describe human-generated floodplain sediments. Indeed, in recent years, studies in Britain have shown the importance of changes in sedimentation rate caused by humans at different times in the Holocene (e.g., Foster et al. 2009). In some parts of the world, more landscape change may have been achieved in prehistoric times than has been achieved by humans since. For example, in the circum-Mediterranean lands and the Levant, huge tracts of land are characterized by terraces, check dams, rainwater harvesting structures, and the like, while in Central America there are raised fields, drainage channels, reservoirs, and other structures produced in what Beach et al. (2015) described as the 'Mayacene'.

13 Geomorphological Hazards

As Latrubesse (2009) and Alcántara-Ayala and Goudie (2010) have shown, geomorphologists have become more and more concerned with geomorphological hazards. Although high magnitude, low frequency, catastrophic events, such as hurricanes or earthquakes with their concomitant geomorphic hazards, gain attention because of the casualties and financial losses they lead to, there are many more pervasive and less spectacular changes that are also highly significant for the welfare and livelihoods of human populations. These may have slower speeds of onset, longer durations, wider spatial extents, and a higher frequency. Examples include weathering phenomena (Goudie and Viles 1997), which can threaten a wide range of engineering structures (Goudie and Viles 2010a, b), and soil erosion (Boardman and Poesen 2006), which causes soil loss and the incision of adlands.

Geomorphological hazards are very diverse. Mass movements are one major category (Crozier 2010). There is also a range of fluvial hazards, such as flooding and changes in channels. In areas with volcanic activity, disasters are caused by eruptions, lava flows, ash falls, and lahars (Thouret 2010). In coastal regions inundation caused by storm surges, rapid coastal erosion and siltation, dune encroachment, and sea-level rise are all significant (Walker and McCraw 2010). In glacial areas surging glaciers, outwash floods, pro-glacial lake formation, and impedance of drainage are severe hazards. Permafrost regions are hazardous because of ground heaving, thermokarst development, slumping of slopes and banks, icings, etc. There is also a wide range of ground subsidence hazards caused, *inter alia*, by solution of limestone, dolomites, and evaporites (Gutierrez 2010), degradation of organic soils and peats, sediment hydrocompaction, and mining of groundwater, brines, and hydrocarbons. In drylands, wind erosion (Shao 2008), flash floods, deflation of susceptible surfaces, dust storm generation (Goudie and Middleton 2006), and dune migration, pose hazards. Large modern cities are not immune from these sorts of hazards (Garcia-Soriano et al. 2020), and urbanization may increase their incidence.

14 Applied Geomorphology

For many years, geomorphologists, collaborating with engineers and engineering geologists (Fookes et al. 2005), have used their skills to mitigate problems facing humanity, including hazards of the type mentioned above (Cooke and Doornkamp 1990; Hooke 2020). Indeed, applied geomorphology is a developing field (Keller et al. 2020; Griffiths and Lee 2022).

Notable examples of recent work in this area include mapping geomorphological phenomena for terrain evaluation (Smith et al. 2011); assessing the effects of river restoration following dam removal (e.g., Foley et al. 2017; Wohl 2020); developing means of forest management to control erosion (Phillips et al. 2018); managing of coasts to reduce erosion (Lazarus et al. 2016); establishing the flood histories of rivers in the Holocene by surveying and dating slack-water deposits laid down by earlier floods (Harden et al. 2010); and management of the effects of water and sediment control structures on river flows (Nichols et al. 2018). Geomorphologists are no longer simply spectators of geomorphological change but have become active in promoting it. Slope stabilization and river channelization, for example, clearly manifest the role of engineering geomorphology in modifying the landscape. Recognition of negative and persistent human impacts has encouraged research and applications in river restoration, including large-scale dam removal (Wohl 2014).

15 Geoconservation and Education

Geomorphologists have taken an increasing interest in how they can make an impact in terms of landscape conservation. There are major contributions that geomorphologists can make to landscape conservation and the preservation of Geodiversity (Gray 2013; Singh et al. 2021). The ‘Convention Concerning the Protection of the World Cultural and Natural Heritage’ was adopted by UNESCO in November 1972, and came into force in December 1975. This created a burgeoning interest in landscape conservation and interpretation. UNESCO has now established an annual International Geodiversity Day. It has also commissioned reports on the need to designate areas of karst and caves (Williams 2008), volcanic landforms (Wood 2009), and deserts (Goudie and Seely 2011). There are already a large number of essentially geomorphological World Heritage Sites in the natural category, as well as some cultural sites that may also have geomorphological value (https://whc.unesco.org/en/list/) (accessed 22nd September 2021). Related to this is the establishment of Geoparks and Geomorphosites (Joyce 2010; Santos et al. 2019). At present, there are 169 UNESCO Global Geoparks in 44 countries (https://en.unesco.org/global-geoparks) (accessed 22nd September 2021). Individual countries, such as the USA, have national parks and State Parks that may exist primarily because of their beautiful landforms. Geotourism is a developing field that shows the need for geomorphological education and explanation (e.g., Wang et al. 2019). The series edited by Piotr Migoń, *World Geomorphological Landscapes* (published by Springer), is an immensely valuable source of information on geomorphological diversity and contains 25 volumes (https://www.springer.com/series/10852) (accessed 22nd September 2021).

16 Conclusions

In the early twenty-first century, Geomorphology has become a discipline that is both wide-ranging and speedily evolving. This is because of the development of a wide spectrum of techniques, by the arising of the plate tectonics paradigm, by the ability to explore both extra-terrestrial and submarine landscapes, by the continued success of Quaternary studies, by an appreciation of the growing role of human and biological activities, by its engagement with research on the newly developed and controversial concept of the Anthropocene, by the application of the discipline to solving and managing various issues of concern to humans, including hazards, and geoconservation and stewardship of landscapes. However, geomorphology is also engaged, though perhaps not yet sufficiently, with issues raised by both Earth System Science, and by global environmental change associated with land cover changes and with global warming.

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