Geomorphology and Earth system science

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Abstract: This chapter surveys the history of geomorphology and Earth system science from 1965 to 2000. With roots in Enlightenment thought from Hutton, Somerville, Humboldt and Darwin, we see a preoccupation with a holistic form of Earth system science develop through the reductionist, mechanistic ideas of the nineteenth and twentieth century to be reawoken in the 1960s and 1970s environmental movements and the space age, culminating in the major research programmes set by NASA and others subsequently. At the same time the chapter charts the evolution in geomorphology to consider plate tectonics and the origins of mountain ranges, geochemistry and its links between surfaces systems and the atmosphere, to later ideas emphasizing the interplay between landforms and life. This chapter surveys changing interconnected ideas within this field and draws parallels and contrasts between the holistic depictions of Earth system science in the early part of the subject's history and the fundamental challenges facing us today as we grapple to find science-led solutions to global environmental change.

> No natural phenomenon can be adequately studied in itself alone – but, to be understood, it must be considered as it stands connected with all Nature
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> (Francis Bacon – the opening quotation from Mary Somerville, 1843, *On the Connexion of the Physical Sciences*).

Situated at the boundary between lithosphere, atmosphere, biosphere and hydrosphere, the Earth's surface maintains the critical zone which permits life. Yet, changing ideas about the interactions between the surface and these components of the Earth system have given rise to significantly different ways in which geomorphologists have seen a place for their discipline in studies of the Earth system. History offers a range of positions: from the early modern concept of a holistic, often prescient, yet resolutely qualitative Earth science advanced by James Hutton, Mary Somerville and Alexander von Humboldt, through to the development of mechanistic governing principles from the sciences of geochemistry and geophysics which emerged from the reductionism of the nineteenth and twentieth centuries. In the late twentieth century, these principles were to become aggregated into a *systems* view of the Earth, with prevailing thought directed towards its interacting components, to be understood as operating in unison.

The purpose of this chapter is to survey the development of these concerns in the period 1965–2000, and to account for some ways in which geomorphologists – and those in other disciplines of the Earth sciences who engage with surface processes – have seen the nature and context of their enquiry change. Fundamental advances including plate tectonics, changing ideas about palaeoclimate and the role of the biosphere coincided with the emergence of pressing environmental issues such as biodiversity loss, acid rain, accelerated soil erosion and climate change. Yet, the trend towards an interdisciplinary Earth system view of geomorphology during the period in question cannot be separated from the shift towards more quantitative process studies. In one sense, the two go hand in hand: one cannot construct a science of the Earth system without rigorously defined components. At the same time, Earth system science offers a welcome opportunity to bring a broader landscape- and planetary-scale view back to a discipline which has moved to significantly finer scales in its quest for process realism. Nor should we see the trajectory of late twentieth-century geomorphology as approaching an inevitable pinnacle of greater understanding from which to look down upon views from the past, although undoubtedly there has been much new knowledge produced through the careful and far-sighted application of novel field, laboratory and theoretical techniques. Even in the twentieth century, the seeds were sown for a forthcoming critique of the globalizing, totalizing dominion of Earth system science. And although the present vantage point offers only a relatively brief retrospect, by the time of writing several commentators had sought to bring a grandly-elevated 'science of everywhere' back down to Earth.

Origins and ideas

Connected science

Earth system science was described by a NASA committee in 1988 in a report entitled *Earth System Science: A Closer View*, as seeking:

> [A] scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all timescales
>
> (Bretherton 1988, p. 11).

Like much interdisciplinary science, crucial in its genesis has been the ability to draw on advances in its respective component disciplines, including the life sciences, and to 'develop the capability to predict those changes that will occur in the next decade to century, both naturally and in response to human activity' (Bretherton 1988, p. 11) (Fig. 1).

How much further back into the history of environmental thought we need go is debatable. However, it is worth considering for a moment that the deepest roots of this enterprise can be pieced together from late eighteenth-century thought (Kennedy 1992). James Hutton articulated his interconnected *Theory of the Earth* that the planet should be viewed as a 'superorganism, and that its proper study should be by physiology' (Hutton 1788). Alexander von Humboldt's later travels with Aimé Bonpland in Central and South America (1799–1804) were recorded in their joint *Essai sur la Géographie des Plantes; Accompagné d'un Tableau Physique des Régions Équinoxiales* (von Humboldt and Bonpland 1805), which, together with Mary Somerville's *On the Connexion of the Physical Sciences* (Somerville 1834), served to inspire Humboldt's vision for an integrative science of the Earth articulated in *Kosmos* (von Humboldt 1845).

With Hutton having earlier suggested that the take-up of carbon dioxide by plants might lock atmospheric carbon into the ground, it was French chemist Jacques-Joseph Ébelmen who first identified the drawdown of atmospheric carbon

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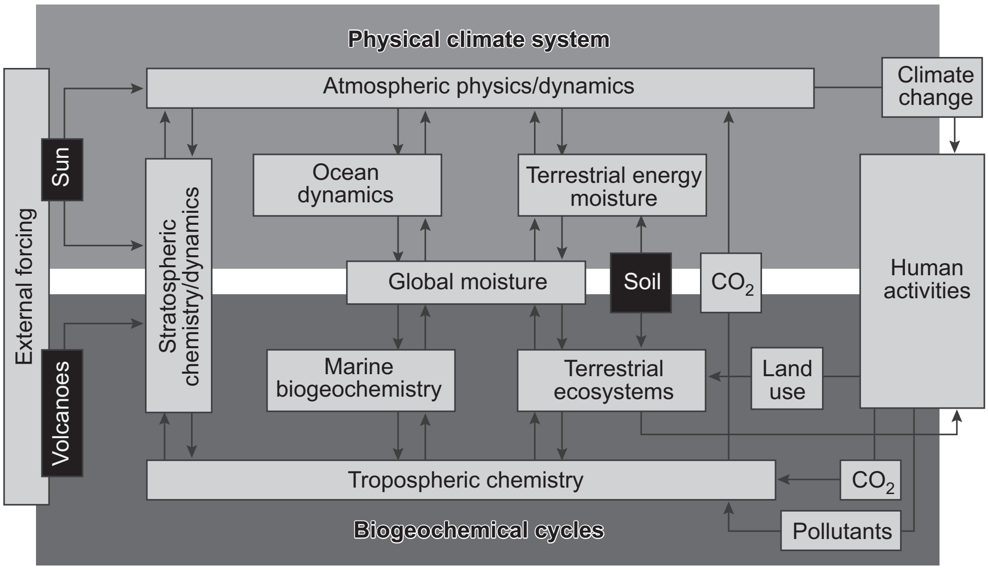

Fig. 1. The Earth system and its interactions as envisaged by NASA in 1988. Redrafted by Steffen *et al.* (2020) from Bretherton (1988).

dioxide via weathering of silicate and carbonate rocks (Ebelmen 1845). He proposed the subsequent volcanic return of carbon to the atmosphere, completing what he termed the 'carbon rotation'. It is for this early identification of the global carbon and sulfur cycles that Ébelmen was dubbed the father of Earth system science (Berner 2012). Preceded by Nicolas de Saussure (son of the well-known glaciologist Horace-Benedict) and Joseph Fourier, a suite of laboratory demonstrations by the American botanist Eunice Foote in 1856 and Irishman John Tyndall in 1859 confirmed that atmospheric water vapour and carbon dioxide act to warm the climate (Foote 1856; Tyndall 1861).

Thus, even at the outset of modern geology, the study of the lithosphere was linked with that of the atmosphere and oceans. The invention of the term 'biosphere' came later, attributed to Russian mineralogist V.I. Vernadsky, who in 1926 described a cohesive biosphere connecting living things to each other, and to geology (Vernadsky 1997). These ideas remained relatively obscure until the 1970s, when promoted by a special issue dedicated to 'The Biosphere' in *Scientific American* (Hutchinson 1970). Vernadsky's ideas were to gain yet further exposure when extended by James Lovelock, in his *Gaia* hypothesis (Lovelock 1979). Lovelock, proposing that Earth's biosphere maintains the geochemical and climatic conditions for life, hypothesized a capacity for planetary self-regulation or homeostasis. The theory posited that Earth was maintained away from thermodynamic equilibrium by the presence of life. Whilst some elements of his theory – such as the importance of biota in biogeochemical cycles – were consistent with mainstream views, other aspects remained controversial. Most notable of these was Lovelock's original teleological view which imputed a purpose to the coevolution of the biosphere on the planet. What is important about the trajectory of these ideas is not so much *Gaia* itself: the idea is now widely critiqued as either self-evident or so broad as to be untestable (cf. Kirchner 1989). Rather – as Hutton had foreshadowed almost 200 years earlier – we can see over this period the development of a science of biogeochemical cycles based on interacting components which are best understood only when the system is treated as a whole.

Systems approach

It was not only in biogeochemistry that a systems approach gained mid-century traction. An influential 1962 paper by R.J. Chorley envisioned a systems approach to geomorphology which broke with the prevailing Davisian cycle, preferring to see a suite of natural and human systems linked in a hierarchy of scales. Originating with ideas put forward by biologist von Bertalanffy in his 1932 *Theoretische Biologie* (translated into English in 1950), a system is defined as a set of elements each with variable attributes, together with a set of relationships which must be defined between the attributes. If the system is closed, then no exchange with the environment is possible. By contrast, for an open system this assumption is relaxed and a set of relationships between attributes and the external environment must be defined too (Bertalanffy 1950).

The agenda-setting volume by Chorley and Kennedy (1971) introduced the liberalized aims and methods of a systems approach to a broader geographical audience. Undoubtedly, the prowess of a systems approach lay in the ability which it conferred on the analyst to piece together the interactions within an environmental system. If the success of such an approach is measured by the number of systems diagrams which subsequently populated the field's undergraduate textbooks, then its originators cannot have been disappointed. Nonetheless, as Kennedy (1979) later came to suspect, the principal philosophical trouble arose from the call to remove historical, place-based, contingent aspects of the real world, leaving a system which could conform to the sterile requirements of the theory. A similar critique is offered by Scheidegger (1992), who objects that the systems approach requires an integrated view across many stochastic components. When we wish to understand the contingent historical trajectories of specific landscapes, the assumption that it is possible to generalize from an ensemble of many members ceases to be valid. The lesson offers insights for post-millennial practitioners of Earth system science, to which we will return.

A central theme of the 1970s, then, was the emergence of Earth's surface as a critical zone at the interface of the atmosphere, lithosphere, hydrosphere and biosphere with human systems (Chorley and Kennedy 1971). At the landscape scale, a systems approach saw steady-state landscapes arising from the continual input of material by tectonic processes balanced against fluvial or glacial erosion. By the end of the period, qualitative ideas of landscape development had been replaced with the 'open system' view of tectonically active landscapes reaching a 'steady state' far from thermodynamic equilibrium. This language remains current today (Willett and Brandon 2002). In retrospect, the greatest value of a systems approach in geomorphology was to contain the field's move towards reductionist studies of fundamental physical and chemical processes

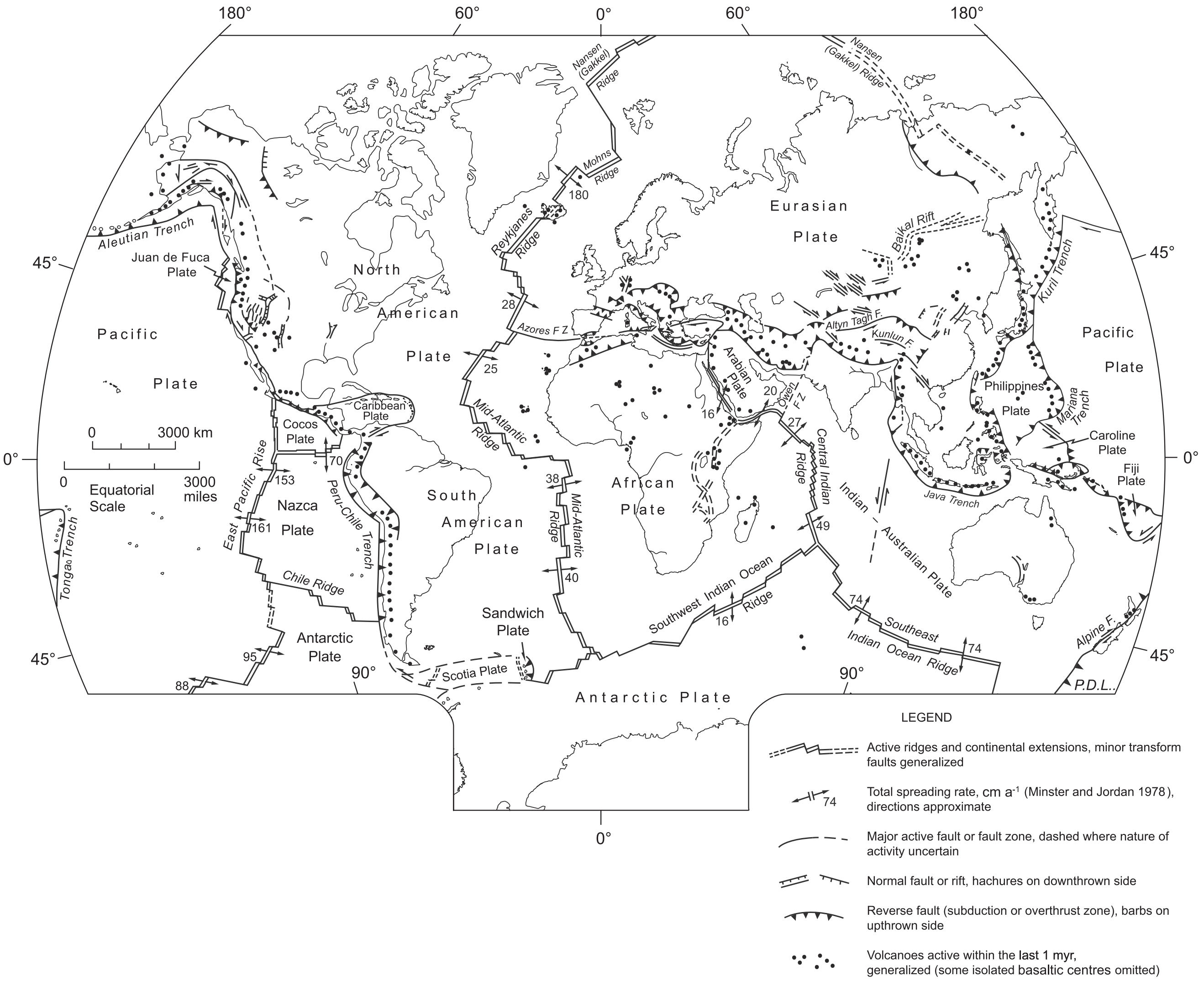

Fig. 2. Global tectonic and volcanic activity of the last 1 myr (source: Lowman 1981). *F Z*, Fault Zone; P.D.L., P. D. Lowman (original illustrator).

whilst retaining its landscape-scale context, a feature of Earth system science which is discussed next.

Global impacts

Just as important as this shift to integrated systems thinking were the major advances in our collective understanding of fundamental geophysics (e.g. via plate tectonics, sediment delivery from continents to ocean basins and advances in fluid dynamics of surface processes: Fig. 2), geochemistry (through the use of stable isotopes in deep-sea and ice cores to establish palaeoenvironmental history) and changing views of Earth surface systems in biogeochemical cycles (Fig. 3).

The period saw new observation techniques applied across wider domains, funded in many cases by new agencies linked

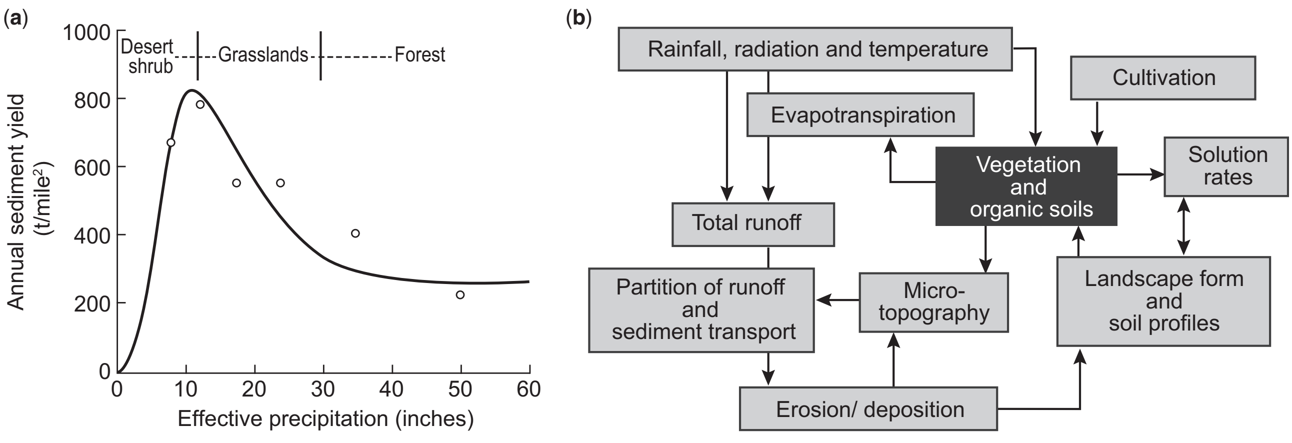

Fig. 3. Interactions between vegetation and Earth surface processes. (**a**) The climatic variation of sediment yield (Langbein and Schumm 1958). (**b**) Relations between climate, vegetation and landform. Redrafted after Kirkby (1995).

to technical research requirements of the post-war political landscape: enhanced computing facilities, national laboratories and coordinated intergovernmental research programmes. The greatest single innovation in these times has been the arrival of satellite Earth observation, which has made it possible for national and international space agencies to mount their 'missions to planet Earth'. Yet, if the first images of the Moon landings struck a sense of technological pride, they were matched by a longer-enduring angst looking back at planetary fragility. Flanked alongside the global environmental movements emerging around the time of Rachel Carson's *Silent Spring* (Carson 1962), it is hardly surprising that in order to motivate such an agenda the Earth observation movement had to engage with an interdisciplinary range of scientists studying the planetary environment in its entirety.

The integration of climate change into Earth system science, notably accelerated through interdisciplinary syntheses (cf. the Intergovernmental Panel on Climate Change (IPCC)), stimulated a central connection with public policy, economics and governance. Indeed, as a result of awareness-raising around climate change, Earth system science has become essential knowledge for the policymaker, valued not least for the coherent framework it provides to understand complex, interacting environmental policy levers. Earth system science is not the only lens through which the human impact on the environment can be studied; but we find in its breadth an imperative to understand specific connections with other disciplines of the Earth sciences. The remainder of this chapter will describe and discuss some of the key results which have brought geomorphology into Earth system science.

Progress and development

Linking tectonics and topography

What was realized during the late twentieth century is the significant impact that changing topography had on the oceans, atmosphere and biosphere. Yet, prior to the acceptance of plate tectonics, the precise mechanisms that control the shape of mountain ranges were unclear. The recognition of plate tectonics – the idea that the lithosphere can be divided into rigid plates moving on a sphere (Fig. 2) – resolved a number of topographical mysteries. Magnetic and seismic detectors developed in the 1950s enabled mapping of submarine morphology of ocean basins (Oreskes 2001), which had become the object of frenzied study as the need arose for bathymetry to support Cold War military operations, and seismometer networks to pinpoint nuclear tests (Doel 2003). Marine geophysical studies revealed newly detailed morphology of mid-ocean ridges and seamounts in a lineage that connects deep-sea soundings from the first explorations of HMS *Challenger* (1872–76), through to the World War II submarine charts plotted by Harry Hess and colleagues. These detailed surveys advanced our understanding of hazards posed by large, historical submarine landslides such as the complex identified on the Norwegian continental margin at Storegga (Jansen *et al.* 1987). Global datasets, including the ETOPO5 bathymetry compilation (Smith and Sandwell 1997), enabled subsequent work linking the morphology of submarine depositional systems to the subaerial erosional systems from which they are fed (Milliman and Syvitski 1992).

In spite of these advances, it was a plate tectonic explanation for the morphology and development of the continents that geomorphologists found wanting. It took much longer for this explanation to come for lithospheric deformation on continents than in the oceans, because the complexity of continental tectonics defies simple expression through Eulerian rotations on a sphere. By contrast, with the clear patterns seen at ocean margins, the accommodation of strain across continental margins is spread across an area typically far larger than the elastic thickness of the lithosphere. At fine scales (less than *c.* 30 km), deformation can be structurally more complicated than relative plate motions alone would predict (England and Jackson 1989). The earliest studies of the India–Eurasia collision, using images from NASA's 1972 Earth Resource Technology Satellite ERTS-1 (later renamed Landsat-1, the first of many), sought to address among other things the first-order question of how crustal shortening during continent–continent collision is expressed geomorphologically at the surface. Seeing topographical and other geophysical evidence (including that from teleseismic focal mechanisms), Molnar and Tapponnier (1975) inferred that a significant fraction of the total shortening must be taken up not by the thrusting of India beneath Tibet but instead through lateral east–west motion on the major strike-slip faults in China and Mongolia (Fig. 2).

Firmly situated in geophysics, these studies used geomorphology as a simple tool to diagnose tectonic processes and history. Ground-breaking though these conclusions were, their straightforward use of topographical information raises no claim to connect tectonics with other disciplines, as advocated by the agenda for Earth system science. Yet, the field of tectonic geomorphology was to accumulate many such discoveries in the subsequent decade, against the current of smaller time and space scales in fluvial and aeolian process studies. After a Binghamton Symposium on the topic of tectonic geomorphology, which resulted in a volume of the same name edited by Morisawa and Hack (1985), pace accelerated towards the ultimate goal of understanding the fundamental relationships between tectonics and landforms. Within that volume, a paper by Adams (1985) concerning the Southern Alps of New Zealand suggested a balance between the tectonic processes responsible for mountain growth and erosional processes responsible for orogenic decay.

The hypothesized idea that mountain ranges might arrive at a steady state – or equilibrium – was to stimulate opinion-making in the decades to come (see Willett and Brandon 2002 for a later review). Quite what the steady state might entail remained elusive: not a static landscape, but a simple mass balance? Or, perhaps, a dynamic equilibrium between driving climatic and tectonic conditions that could be inferred from morphology alone? Whilst the idea had resonated widely amongst earlier geologists and geographers, later discussions on its utility or otherwise judged that talk of geomorphic equilibrium had generated more heat than light (Kennedy 1992; Thorn and Welford 1994). However, by the late 1990s, careful definitions were in place and new tools available – based on isotopic dating techniques and thermochronometry (Willett 1999). So, work to quantify the steady-state response of tectonically active regions focused on reconciling the balance between tectonic and climatic drivers of change in active mountain belts such as New Zealand (Koons 1989), the Himalayas (Beaumont *et al.* 1992) and Taiwan (Dadson *et al.* 2003). Gradually, these studies pieced together the importance of subaerial denudation in controlling the shape of mountain relief, finding erosion rates consistently equivalent to rates of tectonic uplift across multiple timescales from decades to millions of years.

Even more significance can be attached to the active part played by tectonics and topography in driving our planet's *climatic* history. Among the earliest connections to be quantified were the changes in circumpolar ocean currents after the Eocene break-up of Australia and Antarctica *c.* 55 myr BP. Thus began the cooling of the Tertiary climate from the Oligocene to the Miocene, which, driven by global reductions in carbon dioxide, allowed the formation of a permanent

Antarctic ice cap (Kennet 1977). The subsequent opening of Drake's Passage, *c.* 23.5 myr BP (Barker and Burrell 1977), broke the link between South America and Antarctica, provoking the onset of the Antarctic Circumpolar Current growing the ice-sheet further. It was early in the era of global climate modelling that pioneering climate modellers Hahn and Manabe (1975) performed a pivotal numerical experiment which revealed the importance not only of mechanical but also thermodynamic effects of Tibetan plateau uplift in driving the pace and extent of the South Asian monsoon. Further numerical experiments by Ruddiman and Kutzbach (1989) established that a suite of other regional climatic changes in the late Cenozoic could be explained by plateau uplift in Tibet and the American west, from winter cooling in the northern hemisphere to summer desiccation in Europe, the Mediterranean and North America.

So it was that from the late-1980s onwards the links between tectonics and topography came to be studied in a different way. Released from the view that tectonics acted first only then for contemporary subaerial processes to play a subordinate role, some now classic studies had demonstrated the opposite. Isostatic compensation for climate-driven erosional unloading could control the regional pattern of uplift and therefore *create* relief. At first, this link between fluvial incision and growth of mountain relief suggested a controversial feedback: the isostatic response to fluvial incision would elevate mountain summits. As higher peaks accumulated snow and ice, enhanced glacial erosion would incise relief yet further. An intriguing possibility emerged: that rapid weathering and erosion of newly uplifted silicate minerals would drawdown carbon dioxide from the atmosphere, further reducing global temperature (Molnar and England 1990). In this way, it was hypothesized that the global transition to a colder climate – one with more glacial erosion – in the late Tertiary and Quaternary would serve to create mountain relief.

The trouble with the isostatic feedback thesis was that it required hillslopes to steepen reliably, and inexorably, in response to fluvial incision. This response may have been viable in relatively subdued terrain but, as Schmidt and Montgomery (1995) demonstrated in the western USA, natural slopes in rapidly uplifting terrain seldom steepen beyond their natural angle of repose. In a series of studies in the northwestern Himalayas, Burbank *et al.* (1996) confirmed the idea, finding widespread evidence that average slopes are set not by erosion rate but via the threshold behaviour of hillslopes. Of course, earlier statistical studies had demonstrated that higher erosion rates were correlated with reduced relief (Melton 1957), but by the 1990s landscape morphometry had adopted different techniques. If, as Whipple *et al.* (1999) were to contend, hillslopes had reached their critical angle in many mountain belts prior to late Cenozoic cooling, then topographical relief could arise only through bedrock incision in mountain streams.

Biogeochemical cycles

Just as the physical influence of tectonics had been revealed, so the chemical influence of Earth surface processes was to emerge through the link with weathering. Beginning with the prescient conjecture of Chamberlin (1899) that whilst limestone and dolomite could precipitate in the sea as a result of carbonate weathering on land, so the weathering of silicate minerals may have caused permanent drawdown of atmospheric carbon dioxide, leading to ice ages in the geological past. Earlier speculation had afforced silicate weathering to this causal chain, including that of Ebelman (1847) who had half a century earlier put the case for silicate weathering as the counterpart carbon sink to balance volcanic outgassing.

Much later, Walker *et al.* (1981) proposed silicate weathering as a stabilizing mechanism to counteract the gradual increase in solar luminosity experienced since Earth's origin, supposing weathering to maintain a stable surface temperature. The explicit link to geomorphology lay dormant until provoked by palaeo-oceanographers who observed late Miocene continental weathering products delivered from the Himalayan and Andean mountain ranges abundant in ocean sediments (Raymo *et al.* 1988). This positive feedback, initiated by the uplift of the Tibetan plateau, was hypothesized to have enhanced silicate weathering and drawndown atmospheric carbon dioxide, triggering global cooling over the past 40 myr (Raymo and Ruddiman 1992). The weathering–erosion hypothesis met its most rigorous test against a careful compilation of river chemistry data, from which Gaillardet *et al.* (1999) disentangled not only the global importance of silicate weathering but also the necessity for rapid physical erosion to sustain its pace.

Their central role in depicting the interactions between components of the Earth system explains, if any special explanation is needed, the extraordinary prominence of biogeochemical cycles in Earth system science, and therefore their rise to dominate environmental discourse in the late twentieth century. However, there were now even more important factors which allowed those geomorphologists willing to step into the arena of interdisciplinary Earth system science the chance to see for themselves a central place. No longer relegated to the orographic background, nor viewed simply as the passive recipient of tectonics and climate change, landscapes could now be seen as critical zones where the atmosphere, lithosphere and biosphere met, shaping the Earth's tectonic evolution and regulating its climate.

Life and its landscapes

Of course, this was not the first time that planetary-scale thinking had been directed towards links with the biosphere. This connection had motivated Somerville's celebrated thesis upon which Humboldt and Darwin had each drawn to diagnose the fine adjustment between life and its landscapes. Yet, with the links between chemistry and surface processes having been quantified, the way was clear to admit that vital feature of Earth system science which in its proponents' minds distinguishes it from prior thinking: the role of biology itself (Viles 1988).

One suite of observations which first quantified the influence of precipitation on vegetation, and therefore on sediment yield, were those of Langbein and Schumm (1958). Their analysis revealed clearly that above an annual precipitation threshold of *c.* 250–360 mm a^{-1}, the presence of vegetation strongly reduced sediment yield (Fig. 3). As might be expected, the interplay between vegetation and Earth surface processes varies with timescale: at short timescales, vegetation dictates the response of the surface to individual storms. By contrast, at intermediate timescales, global environmental change elicits a complex interacting response; and at geological timescales, vegetation is coeval with topography (Kirkby 1995).

The impact of biota extends to animals too, with Darwin's iconic 1881 studies of earthworms (*Lumbricus* spp.: Darwin 1881) finding their modern counterpart in the beaver (*Castor fiber*) and the pocket gopher (*Thomomys bottae*) of the American west (Thorn 1978; Gurnell 1998). Less charming in character, but no less crucial in effect, the mucopolysaccharide exudates (i.e. slime) of terrestrial and aquatic microbes were discovered to increase cohesion by an order of magnitude, stabilizing otherwise mobile fluvial and marine sediments (Dade *et al.* 1990).

The dramatic geomorphic response to large-scale destruction of vegetation over relatively short timescales (*c.* 10 years) after human disturbance was shown by Strahler (1956), who observed that air pollution from a copper smelter in Ducktown, Tennessee killed vegetation and increased gully erosion. Over much longer timescales, the greatest mass extinction in Earth's history occurred at the end of the Permian, *c.* 300 myr BP. An event so severe that terrestrial vegetation took 30 myr to recover can be expected to have brought great change in the global terrestrial environment (Schumm 1968). Indeed, this conjecture was proved true with evidence that large rivers of South Africa experienced a significant, long-lived shift from meandering to braided planform due to reduced cohesion after the extinction of deep-rooted plants (Ward *et al.* 2000).

The role of the Earth surface in modulating the carbon cycle thus became the object of significant work, particularly using isotopic measurements of carbon and other elements which could be used as tracers. The newly quantified sedimentary record of carbon exported from erosional environments to the deep sea was found to be closely linked to episodes of focused erosion and onward sediment transport in river systems. Identifying critical nutrient fluxes delivered through rivers to ocean basins, the work of Meybeck (1982) serves as the first global compilation of its kind. The significance of the coastal ocean as a primary site of net carbon oxidation is interesting in its own right (Smith and Hollibaugh 1993), but also because the input to the coastal ocean has been heavily influenced by human activities on land since mechanized agriculture accelerated soil erosion (Hooke 1994).

The identification of buried organic carbon of Himalayan origin, delivered via the Ganges and Brahmaputra rivers to the Bengal Fan, revealed afresh the close connection between the carbon cycle and the geomorphic export of sediment to floodplains, estuaries, shelf seas and the oceans. Moreover, studies showing the net burial rate of organic carbon to be double or treble its rate of consumption due to silicate weathering have overturned the view that only silicate weathering needs be considered in the search for feedbacks associated with mountain uplift (France-Lanord and Derry 1997). In spite of these advances, geomorphic links between terrestrial biological productivity and carbon burial perplexed the biogeochemical community, with a missing terrestrial carbon sink sought well into the twenty-first century. A mismatch emerged in the 1990s between the amount of carbon emitted through combustion of fossil fuels and that which was measured in the atmosphere and ocean. The hunt for this 'missing' carbon sink on land left no stone unturned, as the pioneering assemblage of data on terrestrial carbon stores revealed significant geomorphic sequestration of carbon via clastic sedimentation of soil-derived carbon and organic sedimentation of carbon transported into lakes, reservoirs and wetlands (Stallard 1998).

Worldwide, a significant proportion of this carbon is evacuated to continental shelves and ocean basins. However, in polar latitudes, storage in organic soils creates carbon-rich permafrost subject to instabilities that can create tipping points (Mackay 1970). Identification of significant sites of clathrate formation initially prompted concern that this methane might be released from submarine and terrestrial stores by offshore and onshore slope instability (cf. Storegga slides), but later consensus found their importance for global climate was only slight (Kvenvolden 1988). Nonetheless, carbon emissions from soils themselves in response to warming create a positive feedback which was identified in field data by Adams *et al.* (1990) and used to inform modelling of feedbacks by Jenkinson *et al.* (1991).

Aside from fluvial and colluvial transport, aeolian processes also contribute to biogeochemical cycling. Wind-blown mineral aerosols from the Sahara ultimately enrich the tropical North Atlantic and Caribbean Sea; and in winter, they supply nutrients to the Amazon Basin, which can influence the biological productivity of vegetation (Prospero *et al.* 1981). Subsequent efforts to quantify these effects globally have found anthropogenic disturbance in source regions responsible for half the global aerosol dust load, decreasing net radiative forcing by 1 W m^{-2} (Tegen *et al.* 1996), an effect often exceeding that due to sulfate aerosols and comparable to that of clouds (Sokolik and Toon 1996).

Challenges and outlook

Technology

Rapid innovation during the period of this survey (1965–2000) has enabled the field to overcome serious technical challenges and to see its outlook evolve in striking new ways. Alongside the expansion of planetary studies has been the development of global-scale monitoring technologies. Whilst remote Earth observation has opened many new questions, it requires accurate ground-truthing and cannot replace fieldwork. Large quantities of data at ever-increasing spatial and temporal resolutions have accelerated progress, not by themselves but allied with growing computer power and new algorithms. Examples from surface studies include synthetic aperture radar (SAR) instruments, which have be used to produce detailed topographical datasets. Multispectral imagers like Landsat, Terra (carrying the ASTER and MODIS imaging radiometers), SPOT and later IKONOS take credit for enabling comprehensive land-surface classification programmes. Yet, the pioneering GTOPO30 and ETOPO5 datasets provided only a prelude to the twenty-first century explosion in Earth observation for geomorphology. The first Shuttle Radar Topography Mission (SRTM) of the new millennium, STS-99, saw *Endeavour* carry a spaceborne imaging radar (SIR-C) to produce surface topographical data, initially available at 90 m resolution for the majority of non-polar regions (Farr *et al.* 2007).

The field has also been one of more sophisticated computer modelling with democratization of access to computing power and datasets. Early accounts from researchers in the 1960s and 1970s who had developed computer models include diffusion-based models for slope processes (Kirkby 1971; Ahnert 1976), models for river meandering (Parker 1976), and numerous models of soil erosion, slope stability and landscape response to climate and tectonics (Willgoose *et al.* 1991). These models have taken the field in different directions: for example, when used to underpin predictions of landslide susceptibility, river bank erosion or nutrients and pollution in rivers. But they have also been used to explore deeper hypotheses on the evolution of steady-state topography (Willett 1999), the response of topography to climate and land-cover change, and the interactions between tectonics and climate at global scales (Tucker and Slingerland 1994, 1997).

Institutions

The epoch of this survey distinguishes itself as one in which teams of people and their host institutions have contributed as much to the direction of research agendas as the stereotypical lone genius of earlier times. Interdisciplinarity is not sufficient for Earth system science, but it is necessary. Likewise, to retain depth whilst increasing breadth it has become necessary for scientists to specialize. One persistent trend is the requirement for significant investment in research infrastructure to tackle major global environmental issues such as acid rain, biodiversity loss, stratospheric ozone depletion, major perturbation to the nitrogen cycle and, of course, global climate change.

Recognizing that there was much to be gained from co-locating the interactions between geologists, meteorologists, ecologists, hydrologists and others, many university departments reinvented themselves to encompass Earth and environmental sciences (Pitman 2005). Of course, physical geographers had attempted to co-locate such interdisciplinary environmental interests for many years prior to the advent of Earth system science, although the evident irony of vesting interdisciplinary responsibility within one specific department is not lost on Richards and Clifford (2008). Just as interdisciplinarity entered university departments, so it featured in the research programmes of well-funded national laboratories, research institutes, and programmes of international coordination such as the IPCC, the World Meteorological Organization (WMO) and the International Geosphere–Biosphere Programme (IGBP). It is hard to convey the importance of interconnected interdisciplinary science in NASA's mission. Its research programmes have included climate science, hydrology and ecology, not just of Earth but also of other planets.

Although a casual observer of the literature would struggle to diagnose it from the scientific papers alone, these developments in discovery science spun out into interdisciplinary applied geomorphology, tackling problems related to nuclear waste disposal location, hydropower, earthquake resilience, slope stability and civil engineering. Towards the end of the period the grand concerns of hard engineering made way for geomorphologists to tackle ecological concerns, with the fields of river restoration and conservation geomorphology seeing a resurgence as the environmental impact of twentieth-century engineering took hold. The growing awareness of global environmental issues pivoted large-scale research themes towards climate and land-use change, overseas environmental development, and environmental science as a stimulus for economic growth.

Insights

From tectonics to topography, silicate weathering and the interactions with vegetation that drive organic carbon burial, this survey has charted the influence of geomorphology on Earth system science and vice versa between 1965 and 2000. Much of the emerging focus on global environmental change has drawn on themes from earlier work, albeit qualitative in nature, underpinned by advances in geophysics, geochemistry and ecology. In drawing to a close, some enduring geomorphological challenges are noted for the insights they offer the developing field of Earth system science. Two conceptual novelties emerging across the fields are the identification of non-linear interactions amongst system components, especially the presence of thresholds or tipping points, and scale. If anything, the advances of Earth system science have broadened the application of concepts in geomorphology connected with tipping points and thresholds (Brunsden and Thornes 1979), shown here in relation to warming due to permafrost thaw and the degradation of organic soils (Adams *et al.* 1990). The same quest for non-linear responses revealed other geomorphically induced tipping points in the Earth system. For example, the onset of the Younger Dryas *c.* 1–10 kyr BP, was hypothesized to have been triggered by the effect on North Atlantic Deep Water formation of meltwater from glacial Lake Agassiz, which had been diverted from its usual route down the Mississippi instead via the St Lawrence River (Broecker *et al.* 1989).

The other major theme was scale. Although for the discipline as a whole it might well be said that the period since 1965 was characterized by a reductionist turn, the extent to which geomorphologists turned away from studying landscape history through the lens of generalists like Hutton, Somerville, Darwin and Davis towards a mechanistic understanding of interactions between Earth surface elements is debatable. Certainly, as time went on, Earth system science provided a means to find a legitimate object of scientific discovery at a scale broader than, say, the study of turbulent environmental flows without lapsing into the qualitative reasoning of nineteenth-century generalists. This rigour is commendable, but it sweeps across many equally interesting aspects of a field which often seeks answers across least 12 orders of magnitude, from one day considering flows in porous media (*c.* 10^{-6} m), to the next day considering the distribution of water resources at the planetary scale (*c.* 10^{6} m). It is quite fitting that not only should our sense of the rightful method of scientific enquiry change from one scale to the next (Schumm and Lichty 1965), but so too should the nature of our theoretical postulates and the observations that support them (Church and Mark 1980).

An enduring truism in the move towards a global environmental science is that we must *think* globally, but often must *act* locally. Whilst the laws of physics operate similarly in all locations, the specifically configured geographical circumstances in which they apply do not (Church 1998). Moreover, the socially contingent factors that skew scientists' theory choice are even less universal. Reacting against the 'view from nowhere', once seen as totemic in the definition of what it meant to be a scientist, the idea emerged that theories were of their time and were pieced together by investigators to fit facts that they sought to explain. In fact, the publication in 1962 of Thomas Kuhn's *Structure of Scientific Revolutions* marked a seminal moment in the transition of ideas in this field. The assertion that in an open system it may be impossible to localize the theoretical adjustment required to accommodate a recalcitrant observation is particularly apposite for an interdisciplinary, interconnected Earth system science (Oreskes *et al.* 1994). Some of the roots emerge of a late twentieth-century turn towards ethnographic studies of what scientists *do* rather than historical studies of what they have *written*. These historical and ethnographic works provide a sharp but scholarly inoculation against the temptations of a totalizing, global form of Earth system science (Shapin 1998).

Conclusions

As this account approaches the turn of the millennium it must draw together the enduring strands of geomorphology's engagement with Earth system science. If the turn towards Earth system science is to be seen in any coherent light, it must also be remembered that the developments outlined so far have occurred alongside and interwoven with the traditional development of the discipline. At the end of his chapter on the revolution in fluvial geomorphology in *The History of the Study of Landforms, Volume 4*, R.J. Chorley (2008) expressed a sense of excitement at the renewal arising from the adoption of a systems approach. The dynamical turn – not just in fluvial but across all branches of geomorphology – has served the discipline well. Can the same be said of Earth system science? Should it be said that Earth systems science has broadened geomorphology's outlook, with its focus on biogeochemical cycles and global environmental issues? Or has Earth system science assaulted the discipline in ways that omit or obscure hard-won insights at finer scales? How, if at all, has Earth system science itself been altered by the inclusion of geomorphology as a participant within its domain?

It would be quite wrong to conclude that Earth system science had, in some sense, taken geomorphology's agenda hostage. It is even more mistaken to suppose that geomorphology had been reduced to the servant of a larger machine in the sense feared by Richards and Clifford (2008). Where some commentators have seen the benefits of a subdiscipline federated into a broader scientific endeavour (Pitman 2005), others see the loss of disciplinary independence as undermining geomorphology's status, reducing their science to an ancillary component in a bigger machine. It is, of course, true that in our perception of the Earth system, geomorphology is only one of many components. But this broadens its applicability, for many interesting problems provoke the geomorphologist's interest from the perspective of Earth system science (Dadson 2010). Theoretical developments in Earth system science focus on the planet's surface as a site of interactions and feedbacks. It is hoped that they will sustain an era of interdisciplinary geomorphological studies in which the connections between physics, chemistry and biology are evident, and are made relevant to the local and global issues which society must tackle in the twenty-first century in new and fulfilling ways yet to be fully explored.

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