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Article

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The trajectory of geomorphology

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Abstract
Modern geomorphology was founded in the nineteenth century as an exercise of historical interpretation of landscapes. After the mid-twentieth century it dominantly became a quest to understand the processes by which landscapes are modified. This focused attention on the measurement of sediment fluxes on synoptic timescales and on a reductionist, Newtonian programme of construction of low-order theories about those fluxes, largely imported from engineering science. The period also saw the emergence of an applied geomorphology. Toward the end of the twentieth century the subject was dramatically transformed by improved technologies for remote sensing and surveying of Earth's surface, the advent of personal computation and of large-scale computation, and important developments of absolute dating techniques. These technical innovations in turn promoted recognition of geomorphology as a 'system science' and facilitated the reintegration of tectonics into geomorphology, opening the way for a renewed consideration of the history of the landscape. Finally, increasing recognition of the dominance of human agency in contemporary modification of Earth's terrestrial surface has become a significant theme. Important influences on the continuing development of the subject will include the search for physically sound laws for material fluxes; reconciling geomorphological information and process representations across spatial and temporal scales, in both observation and theory; comprehending complexity in geomorphological processes and landform histories; incorporating the geomorphological role of living organisms, particularly micro-organisms; understanding the role of climate in geomorphology, both in the contemporary changing climate and in the long term; and fully admitting the now dominant role of humans as geomorphic agents. Geomorphology is simultaneously developing in diverse directions: on one hand, it is becoming a more rigorous geophysical science – a significant part of a larger earth science discipline; on another, it is becoming more concerned with human social and economic values, with environmental change, conservation ethics, with the human impact on environment, and with issues of social justice and equity.

Keywords
future of geomorphology, history of geomorphology, geomorphology and dating, geomorphology and remote sensing, process geomorphology, significant trends in geomorphology

I Introduction: Historical legacies

Modern geomorphology grew out of the nineteenth-century quest to understand the history of Earth (Chorley *et al.*, 1964; Rudwick, 2008). That quest had two major themes: to comprehend the significance of the rock column and the evidences that it bore of Earth's history, and to understand the development of modern landscapes. Both are essentially historical

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inquiries. Modern geomorphology developed, then, essentially as an exercise of historical interpretation, issuing in the early twentieth century in several competing models for how landscapes might generally evolve by erosional development (Davis, 1899, cf. King and Schumm, 1980; Penck, 1924, cf. Czech and Boswell, 1953; Baulig, 1935, following E. Suess; King, 1953). These were the earliest grand scientific abstractions from the perceived facts of landscape. They developed in parallel with early modern generalizations in the rest of earth science – in particular, with generalizations about tectonics and the construction of relief.

To be sure, there was substantial attention paid in the nineteenth century to the processes that form landscape. In significant measure, current or ostensibly recent processes were studied in the attempt to resolve the prominent debate about whether the modern world is a uniformitarian one, or a world created by successive catastrophic changes (Rudwick, 2008). There were also students of geomorphology who pursued a more systematic, physically based study of the processes at work in the landscape, either for its own sake or in pursuit of practical ends. Arguably the most prominent among them was the American geologist Grove Karl Gilbert (see Yochelson, 1980). There has been considerable discussion about why his approach to geomorphology – a recognizable precursor of approaches taken in the second half of the twentieth century – did not prevail. The most immediately obvious answer lies in the preoccupation of earth science at the time with the great historical questions.

In geomorphology and, indeed, in much of earth science, the nineteenth century ended in about 1950. Up until the time of the second world war, the major questions remained the historical ones and the methods of investigation remained largely the same. The change, when it came, was in substantial measure technology driven. Airborne and seaborne surveying instruments, many initially developed for the purposes of war, gave major impetus to geophysical exploration, making available information about Earth's surface and shallow subsurface never before accessible. On land, the global extension of modern topographic mapping, the increasing availability of aerial photography and rapidly developing access to much of the terrestrial surface all facilitated geomorphological work. An era of unprecedented prosperity in the amphi-Atlantic world after 1950 led to a large extension of technical surveys of landscape and of hydrological and other environmental monitoring programs – largely for resource development purposes – that provided basic data for a systematic approach toward understanding Earth's surface environment. Perhaps even more importantly, it led to a rapid expansion of advanced education and research. Geomorphology participated modestly in and benefited greatly from these developments.

Within the discipline, understanding the processes that formed the surface environment became the major focus of research efforts after 1950. The trend was launched in the English-speaking world by a number of benchmark papers that served as programmatic statements (Strahler, 1952) and early models for practice (Bagnold, 1941; Horton, 1945; Strahler, 1950; Leopold and Maddock, 1953). Much guidance was secured from the engineering literature – from hydraulics, from soil mechanics, and from coastal engineering – while philosophical support derived from a strong positivist influence over the scientific method of the day. The research program of the United States Geological Survey Water Resources Division, under the direction of L.B. Leopold, and work at Columbia University under the direction of Arthur Strahler (see Strahler, 1992, for a retrospective view of the Columbia 'programme') were dominant influences in effecting the reorientation of the discipline. The intention was to interpret landscape in terms of direct observables by the application of Newtonian mechanics, something that engineers had been attempting to do ever since the time of Leonardo. This paradigm seemed to set space and timescales for the subject; they were the everyday human scales, on the order of metres to kilometres and seconds to years, within which well-defined dynamical processes could be observed and reasonably comprehended. They were quite different than the scales of the preceding period.

One singular development that was especially influential in the reorientation of geomorphological timescale was the development of absolute dating methods. Uranium-series methods, under development since early in the century, were closing in on the age of Earth but of more immediate relevance to geomorphology was the development of radiocarbon dating (Libby, 1955; see Walker, 2005, for a recent review). Initially able to furnish an approximate absolute timescale for the most recent 30 ka, and now extendable to about 50 ka, ^{14}C dating powerfully augments the study of recent events and processes, but it scarcely admits a period sufficiently long to appreciate significant development in Earth landscapes. History – apart from continuing study of the Quaternary Period – largely disappeared from the modern subject, at least in the scientifically dominant Anglo-American world.

II Where have we come from?

The geomorphology of the period between 1960 and 1990 (that is, the formative period of this writer's career) was, then, largely dominated by a reductionist, Newtonian paradigm. A basic tenet was Gilbert's (1877) concept of 'dynamic equilibrium', a condition in which landforms are adapted to the dominant exogenous forcing so that form is maintained through time (Strahler, 1950; Hack, 1960; review by Ahnert, 1994). Dynamic equilibrium is a logical consequence of thinking in terms of Newtonian force balances. In the landscape, where synoptic processes and observable events are forced by weather and hydrology, one arrives at timescales that seem short in comparison with any concept of the timescale for landscape evolution that had been arrived at by the early twentieth century. In fact, equilibrating forces leads quickly to the notion of steady state in the landscape, a condition in which landforms maintain their form and gradient relations while material moves through them.

In rivers, for example (this writer inevitably will fall into a river sooner rather than later), these concepts were made explicit in terms of 'regime' – the stable channel dimensions for some governing flow. Correspondingly, 'regime time' is the period during which a channel might be expected to maintain some stable mean form, even though synoptic period scour and fill might occur. 'Regime' in this sense is an engineering term, originated in investigations in the late nineteenth century of the equilibrium dimensions for unlined irrigation canals in then British India and in the Nile delta (see Leliavsky, 1955), signifying the stable channel dimensions for a prescribed design flow. Generalized to alluvial rivers (Leopold and Maddock, 1953), it gives rise to the auxiliary question 'what flow is equivalent to the design flow?' or 'what flow would transfer water and sediment in the same amounts, on average, as are transferred over the range of varying actual flows, while maintaining a stable channel form?'. The question has never been generally resolved (see Pickup and Rieger, 1979; Ferguson and Church, 2009), but it is clear that regime time occupies decennial to centennial timescales – not many millennia – and, in a world not drastically disturbed by human activity, corresponds with periods of approximately stable hydroclimate. This appears to be the timescale that largely absorbed geomorphologists' interest for several decades, even though the occurrence of different patterns of landscape evolution on longer timescales remained perfectly apparent (Schumm and Lichty, 1965). A major problem was the impossibility to retrieve measurements over those longer timescales.

This was a problem because, in the Newtonian paradigm, measurement is the acme of scientific endeavour. Thinking, again, of rivers, the outcome was the explosion of studies of hydraulic geometry using available stream gauging measurements (Leopold and Maddock, 1953; see Ferguson, 1986), intense interest in sediment transport – in particular, that part of the sediment load that substantially influences channel morphology (see, for example, Gomez, 1991) – and in relatively short-term channel adjustments (see, for example, Gregory, 1977). Even after 50 years, however, the problem of alluvial channel form has scarcely been properly constructed, let alone solved (see Eaton *et al*., 2004).

The advent of landscape measurement served to emphasize for the first time the remarkable variability of landforms (see Strahler, 1950). Statistics entered geomorphology as, indeed, it must enter any properly constructed empirical science. Quantitative documentation of variability in landforms and landscape made for a more acute description of the landscape (Strahler, 1954), but it substantially complicated theory building and prediction. Nevertheless, that a significant measure of statistical regularity could be perceived in landscape, and a significant level of insight developed, was demonstrated early on by members of the Strahler school (eg, Schumm, 1956; Melton, 1958a; 1958b; 1960; the impact of Melton's papers is reviewed by Keylock, 2003). R.L. Shreve (1975; 1979) directly tackled the problem of a probabilistic-statistical basis for theory production in geomorphology.

However, the main focus of interest and the principal body of results concerned the measurement and description of contemporary geomorphological processes on synoptic to seasonal scales and the construction of first-order theories to generalize the phenomena. Geomorphology had no strong tradition of physical theorizing, formerly preoccupied as it was with historical reconstruction of particular landscapes. Consequently, there was a significant migration of engineering knowledge into geomorphology and its reorganization in ways appropriate for the description of landscape and the analysis of slope stability, of surface erosion, of fluvial sediment transport and river stability, of coastal sedimentary phenomena and coastal stability, and of the geomorphological effects of wind and ice. This history is to a significant degree summarized in the pages of *Progress in Physical Geography*, in papers on subjects as diverse as weathering (Whalley and McGreevy, 1985), slope processes (Rapp, 1986), soil erosion (Loughran, 1989), river hydraulics (Ferguson, 1986) and morphology (Lewin, 1978), karst (Waltham, 1981), coastal and beach processes (Jolliffe, 1978; Clayton, 1980), wind effects (Pye, 1984; Sarre, 1987) and glaciation (Hart, 1995).

Some more complex geomorphological effects began to be revealed. For example, *PIPG* includes papers on complex features of sediment transport in rivers (Hoey, 1992; Powell, 1998) and on drainage networks (Dunne, 1980; Jones, 1987), leading to the general topic of self-organization in landscapes (Phillips, 1995).

Arguments developed over the appropriate level of reduction to both preserve the essential features of landscape and to create a viable model of landscape-forming processes (eg, Mackin, 1963; Simpson, 1963). Major textbooks of the day (eg, Leopold *et al*., 1964; Selby, 1985) remained in substantial measure descriptive, despite the insidious invasion of equations (but see Carson and Kirkby, 1972), while a purely theoretical text based on a collation of exercises largely conducted outside the main stream over the preceding 50 years (Scheidegger, 1961; 1970) had no great impact on the field. Nevertheless, the period produced a substantially greater appreciation than before for the variability of landscapes – leading, in turn, to the realization that far more extensive sampling programs need to be undertaken in order to comprehend the variability than had classically been conducted. It produced a generation of geomorphologists who had learned to use modern surveying and sampling instruments, who were comfortable at least with standard statistical methods, and who were used to the notion that measurement is the basis upon which modern empirical science is built. Most importantly, it laid the foundations for the analysis of landform- and landscape-forming processes in physical terms. But it did not produce a coherent, unified account of geomorphology. For that, a much longer timeframe is needed than that considered by most investigators in the period.

The period did claim a signal practical achievement. The Newtonian focus and the appropriation of engineering methods of observation and analysis brought geomorphology to the attention of engineers and land managers at a time when there was also increasing concern for the quality of land management and environmental engineering. For the first time, a substantial portion of geomorphology became applied geomorphology (see Coates, 1971 and 1976, for early work; Sherman, 1989, for a philosophical statement; Downs and Gregory, 2004, for an example of more recent and more specialized work). In many contexts, geomorphological investigations came to be defined by practical problems. Ironically, the most valuable contribution of the geomorphologist to the solution of problems of land management is the historical perspective, largely abandoned in this period in basic research. Nonetheless, this movement began to knit geomorphology into a wider community of environmental scientists and managers, it increased the confidence of geomorphologists in the value of the discipline, it imported many technical methods of investigation into the discipline, and it contributed to the increasing sophistication of geomorphological investigations.

Was this period a cul-de-sac? No. It is important for the emergence of geomorphology from being essentially a part of natural history toward being a modern science. Nineteenth-century geomorphology consisted of mapping and observation generalized by inference and speculation; (late) twentieth-century geomorphology came to be characterized by a preoccupation with measurement, with the use of statistics for both descriptive and inferential purposes, and by the application of first-order physical theories to describe and predict the behaviour of earth materials in order to understand dynamical processes at synoptic scales. It has been an essential stage in the growth of the science.

III Bases of the contemporary discipline

Dramatic changes have occurred in geomorphology since about 1980, rapidly gathering momentum after about 1990. The bases for these changes are, again, largely technological. The main influences include: (1) improved technologies for remote sensing and surveying of Earth's surface; (2) the advent of personal computation and of large-scale computation; and (3) important developments of absolute dating techniques. These technical innovations have stimulated two substantive developments of central importance for the discipline: (4) recognition that geomorphology is a 'system science'; and (5) the reintegration of tectonics into geomorphology, opening the way for a renewed consideration of the history of the landscape. Finally, (6) increasing recognition of the dominance of human agency in contemporary modification of Earth's terrestrial surface has become a significant theme.

One additional condition has strongly influenced the development of the discipline over the last 30 years. That is the emergence of a body of younger geomorphological scientists with far more adequate training in physical science and mathematics than had appeared in the subject before, the consequence of training curricula initiated by the 'Newtonian generation'. Some of them have come to geomorphology with background training in other areas of science or engineering. A logical sequel of the later twentieth-century focus on understanding geomorphological processes, this development was largely initiated in several major American universities, but it is now spreading rapidly. These people have enthusiastically appropriated

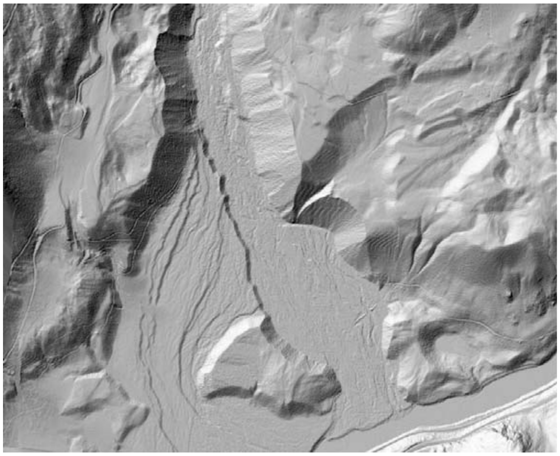

Figure 1. LiDAR image, illustrating the unprecedented clarity with which landforms are displayed. The scene illustrates a modern alluvial fan set within lateglacial outwash terraces with kettles on them. Meltwater channels occur on the hillsides above. Fishtrap Creek, North Thompson Valley, near Kamloops, British Columbia. Image courtesy of Brett Eaton, Department of Geography, The University of British Columbia.

and applied the technical developments – none of them peculiarly geomorphological in intent – listed above.

I Remote sensing and surveying

In terms of global environmental management, this development is commonly associated with satellite remote sensing of Earth. For geomorphology, a whole range of developments in high-resolution remote sensing, performed in the atmosphere and on the surface, are much more important. These include wavelength-specific methods in airborne remote sensing, airborne LiDAR, terrestrial surveying with a range of semi-autonomous instruments that use optical interferometry, advanced sonars for bathymetry and water-column soundings, acoustic detection of water and sediment motion, ground-penetrating radar and the appropriation of seismic techniques and other geophysical sounding methods.

These developments have enhanced two critical dimensions of geomorphological information. First, spatial continuity of information can now be secured at centimetre scale over large areas. Hence, the morphology of Earth's surface – what geomorphology seeks to explain – can now be recorded faithfully at a resolution sufficient to satisfy most information demands for mechanistic explanation. The most striking development in this respect is the recent availability of airborne LiDAR imagery of significant areas (Figure 1), which dramatically improves capabilities for terrain typing and landform measurement. Similarly, terrestrial LiDAR imagery can provide something like a metric digital photograph of landscape features right down to granular scale. Most basically, however, the widespread availability of digitally recorded topography developed from remotely sensed imagery (abetted by developments in computation) has opened up a wide range of analytical possibilities for studying landscape (Lane *et al*., 1993). Other innovations are also important. Wavelength-specific remote sensing can determine soil surface moisture, the water content of snow, and surface temperature, all of which are relevant in particular studies. Spectral methods can be used to determine the texture of surface materials (for example, Carbonneau and Bergeron, 2005: the approach was pioneered in the 1960s in early studies of the lunar surface) and the characteristics of surface vegetation cover.

The second important dimension is depth below Earth's surface. Geomorphologists are frequently concerned with the depth and circulation of water bodies, with depth and character of both subaqueous and terrestrial surficial materials, and with the stratigraphy of sediments. Information of these kinds yields the third spatial dimension necessary to properly understand the development of landforms. Formerly, such information was yielded only by laborious soundings and excavations, hence was very incompletely known. Developments in acoustic sounding during the past three decades, including both the adaptation of older geophysical methods such as electrical resistivity surveys and the introduction of ground-penetrating radar (see Baker and Jol, 2007), have dramatically increased the transparency of Earth's near-surface. In the water column, improvements in frequency-specific sounding and in the interpretation of acoustic signals have yielded dramatic improvements in information about turbulent water flows and transported sediments, and about stratification in water bodies.

An additional technology of critical importance to these developments is the ability to determine position on Earth's surface with unprecedented accuracy by the use of Global Positioning System technology. This technology and technologies associated with optical interferometry also open the way for direct measurement of some of the Earth movements most important to comprehend in geomorphology, varying from soil and rock creep to tectonic and isostatic movements. It is critically important that these technologies have become affordable for individual investigators.

For measurements of geomorphological processes, improvements in sensor capabilities and in digital electronic data recording speed and capacity have similarly revolutionized the collection of information in time. Altogether, the technologies underlying these developments have radically improved the information base upon which geomorphological studies are founded. Until perhaps a decade ago, the major inferential problem in geomorphology was how to penetrate a problem with too few accessible data; for the first time, geomorphologists confront problems of analysis in the face of arguably too many data.

2 Computation

The appearance of the electronic personal computer made computation beyond the level of simple analytical calculations a natural extension of thinking about a problem. Large-scale computation has enabled geomorphologists to construct models of geomorphological systems – models that begin to encompass some of the actual complexity of real landscapes and to allow hypotheses about landscape development to be tested more or less rigorously.

Classical mechanistic science proceeded by seeking closed-form theoretical explanation for observed phenomena – closed in the sense that logically consistent, and preferably mathematically strict, statements based on physical principles led to verifiable predictions about the phenomenon. The mathematical tools preferably took the form of analytic (in the specifically mathematical sense) statements which admit specific solutions. Statistics entered the picture as a means of controlling the variance associated with observations. The method works best in the classically reduced situation of controlled bench experiments wherein simple cause-and-effect relations may be discerned. In the natural world of geomorphology (and other field sciences), the degree of experimental control necessary to test closed-form theories is rarely achieved. In these circumstances, statistical variation of the phenomena becomes an integral part of the substantive appearances, and 'theorizing' more often takes the form of constructing 'model' systems to simulate the phenomena. Such 'models' commonly include bridging empirical statements when theoretically grounded relations are not available. To analyse such systems, large data sets of statistically complex structure must often be investigated and they are usually subjected to computationally extended statistical or simulation procedures (eg, Melton, 1958b, who, in a remarkable pioneering effort, used manually manipulated punched cards to analyse his data). None of this could be routinely accomplished without electronic computers. Nor could the volumes of data delivered by modern remote sensing and monitoring methods be analysed.

An important development for environmental sciences has been the advent of geographic information systems. Basically nothing more than a spatially referenced system for filing data, the addition of functional capacity for manipulating data has created a flexible tool for analysing the many aspects of environmental data with spatial dimensions and patterns of correlation in both space and time.

As a consequence of these possibilities, computing technology has changed the way we construct scientific arguments in every science, including geomorphology. ‘Models’ of complex processes that encompass multiple pathways for the transfer of material and energy can be constructed and tested for range of outcomes and sensitivities to parameter variations. Model studies vary in scale from the hillslope, the fundamental landscape element, through drainage basins, to entire orogens. Martin and Church (2004) summarized the scale relations of these studies, which carry implications for the character of appropriate model constructs. Modelling strategies also create novel problems for prediction and model confirmation (Church, 2003). The most important ramification of this change lies in the emergence of ‘system science’.

3 Dating

The development of techniques that absolutely date aspects of the history of mineral crystals or exposed mineral surfaces has opened the way to decipher an absolute history of landscape development over long periods using native earth materials (neither of which ^{14}C admits). This is arguably the most important single development for contemporary geomorphology because it has reinvigorated interest in long-term landscape evolution. Techniques include radiometric decay series methods (some of them of longer standing, but rarely applied within geomorphology until recent years), methods based on cosmogenic nuclide accumulation, and methods based on radiation exposure, including mineral luminescence and fission tracks. Indirect dating methods include a significant number of geochemical reaction or substitution phenomena. These methods (Walker, 2005), consistent with the primacy of measurement, have brought to geomorphology the possibility for quantitative study of long-term landscape history.

Earth science before the mid-twentieth century had no reliable absolute chronometers.[1] Earth history was recorded in relative terms using the principle of superposition of sediments, fossil sequences and cross-cutting erosional relations inferred from landforms. Laminated sediments that could reliably be ascribed to seasonal or annual effects and the growth rings in woody tissue gave some chronometric information about recent (mainly Holocene) Earth history. After 1950, the well-known radiocarbon method was introduced and methods based on the uranium decay series were steadily improved. Radiocarbon revolutionized Quaternary studies but it is not suited to studies on the temporal scale of significant landscape evolution, except in respect of the most recent major glaciation. Within the last third of a century a suite of methods based on radiometric decay and on radiation exposure has dramatically widened absolute dating possibilities (Table 1) including the possibility to directly date minerals or mineral surfaces. This possibility incidentally also draws geomorphology back toward close association with the geological aspect of its disciplinary roots since it entails the necessity to interpret the geological provenance and context of the material to be dated.

Methods based on cosmogenic isotopes are proving to be particularly versatile: depending on context, they can be used to date times of surface exposure, rates of weathering, and residence times for materials in sedimentary reservoirs. Bierman (1994) and Cerling and Craig (1994) give early reviews, Gosse and Phillips (2001) review theory and applications, and Cockburn and Summerfield (2004) give a more recent review of applications.

4 System science

The notion of geomorphology as a system science, congruent with the advent of large-scale

Table 1. Absolute dating methods in geomorphology. Bold entries have the greatest potential for dating on the scale of landscape evolution. Other methods constrain erosion, sedimentation, landform evolution and event dating.

Method	Age range	Comments	Introduction*
Radioisotopic			
^{137}Cs	10–100 a	bomb produced	1960
^{210}Pb	10–250 a	industrially produced	1960
^{14}C	100 a–50 ka		1950
U/U, U/Th, **U/Pb**	300 a–350 ka	upper limit depends on isotope combination	1950
^{40}K/^{40}Ar	100 ka–3 Ma		1960
^{40}Ar/^{39}Ar	10 ka–1 Ga		1970
Radiation exposure			
^{3}He	1 ka–3 Ma	cosmogenic nuclide	2000
^{10}Be	3 ka–4 Ma	cosmogenic nuclide	1990
^{21}Ne	7 ka–~10 Ma	cosmogenic nuclide	2000
^{26}Al	5 ka–2 Ma	cosmogenic nuclide	1990
^{36}Cl	5 ka–1 Ma	cosmogenic nuclide	1980
TL	100 a–800 ka	thermoluminescence	1980
OSL	0–300 ka	optically stimulated luminescence	1990
Fission-track	100 a–3 Ma		1970
Annual growth			
Dendrochronology	0–~10 ka	upper limit depends on context	1920
Varve chronology	0–~20 ka	upper limit depends on context	1880
Ice stratigraphy	0–~100 ka	upper limit depends on context	1960
Speleothems**	0–~10 ka	upper limit depends on context	1970
Coral**	0–~1 ka	upper limit depends on context	1990

* Decade within which general application began in geomorphological contexts. The initial announcement sometimes precedes the stated date.
** Also dated by isotopic means.

computation, surmounts the practical limitations of reductionist science (though not necessarily philosophical ones) – it opens the way to model complex patterns of interaction among various subsystems that make up the geomorphological landscape. It replaces analytical theories with system models as exemplars or generalizations of landscape in a manner that can conceivably be more faithful to the prototype.

'System sciences' are ones that seek explanation by integrating the effects of many elements and processes. Geomorphology is quintessentially a system science (as is any other environmental science). More specifically, geomorphological systems are characterized by five important features: (1) the juxtaposition of different physical processes at the same place and time (Figure 2), such that the net change in the landscape is the product of a number of synergistic or competing processes; (2) the occurrence of processes on a range of different temporal and spatial scales, so that the net effect at any one place in the landscape is the outcome of a complex interplay of effects at various scales; (3) the occurrence of mass storage points (sediments and sedimentary landforms), so that the further developments in a geomorphological system are always influenced by the prior history; (4) the occurrence of thresholds and limits –

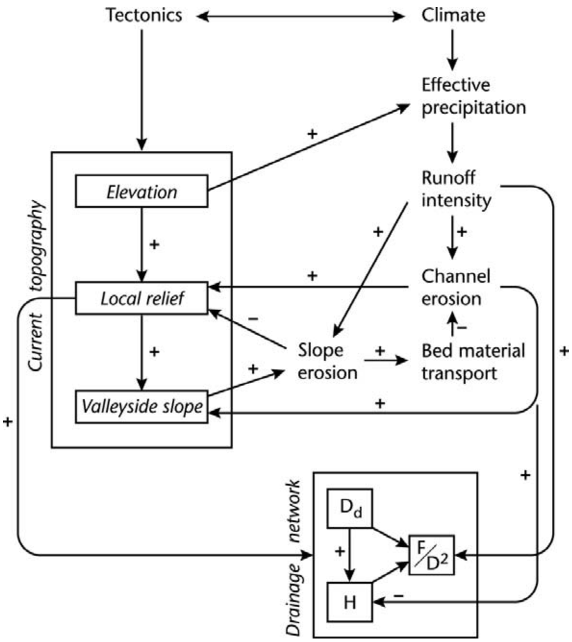

Figure 2. Correlation structure of a montane geomorphic system (largely adapted from results given in Melton, 1958b). The diagram illustrates the multiple pathways of topographic and process dependence in the system. The boxes indicate the principal morphological features. The description of the drainage network includes drainage density, $D_d = L/A_d$; ruggedness number, $H = hD_d$; and relative drainage density, F/D_d^2; wherein L is the total length of stream channels in a drainage basin; A_d is the area of the basin; h is the total relief in a drainage basin (not equivalent to local relief, which may be at sub-basin scale, according to the scale of investigation); $F = N/A_d$ is relative channel frequency; and N is the number of channel links in a drainage basin. The links annotated with +/– signs were measured by Melton and correlated as indicated.

set by material properties, by energetic inputs, or by scale considerations – such that abrupt changes might occur in system behaviour; and (5) the occurrence of variable system forcing over all timescales.

These features have some important consequences for the way we perceive geomorphological systems. The juxtaposition of different processes means that we can rarely isolate a single process in the landscape for experimentally controlled study; furthermore, that understanding the relations among the various processes – whether simply additive or amplifying – often forms the essential basis for successful diagnosis of the system. Variations in temporal and spatial scale often lead to the need for different kinds of theoretical construction over those different scales. For example, a hillslope subject to discrete ('shot' type) failures in the short term might satisfactorily be modelled by a diffusional process in the very long term. But it is important that different theoretical constructs should be appropriately matched; that is, that a shorter-term and more locally specified process should integrate properly to the longer-term solution, at least in concept. The appreciation of mass storage points is critical: it is this feature that confers significant non-linearity on most geomorphological systems (Phillips, 2003). Thresholds and limits introduce abrupt regime change and surprise (Schumm, 1973). Finally, variable forcing eventuates both non-linear response and threshold crossings, and constrains the possibilities for hindcasting or forecasting specific events in specific landscapes. This latter fact strongly constrains the quality of knowledge about the history of a specific landscape – or its future – that it is possible to have (Church, 2003).

The characterization of geomorphology as a system science was early introduced by Chorley (1962) and the concept was developed by Chorley and Kennedy (1971). Schumm (1973) explored some practical consequences without specifically invoking the system framework. However, proper application of the concept really began with the advent of attempts to numerically model geomorphological systems using digital computers.

5 Tectonics and geomorphology

A perversity of geomorphology in the late twentieth century was that, at the very time when the global synthesis of plate tectonics was emerging, the discipline firmly set its course away from the large-scale problems of landscape history with which it had formerly been largely preoccupied. Reawakening to these 'global problems' began in the 1980s, initially driven by geophysicists coming to recognize that erosional histories of the terrestrial landscape, and consequent isostatic adjustments, had to be incorporated into their tectonic mechanics. An early review of the consequent renewal of interest in landscape evolution at the large scale was given by Thomas and Summerfield (1987).

The geophysicists turned to geomorphology to provide information on rates and volumes of sediment transport over large temporal and spatial scales in order that the response of the lithosphere to erosion and sedimentation might be modelled. Empirically, such information was not to be had. The result of this challenge has been the opening of substantial new research directions within geomorphology. To improve the data of long-term trends of erosion and sedimentation, regional studies have been conducted of primary material mobilization by landslides (eg, Hovius *et al*., 1997; 2000). Studies of bedrock erosion utilize the new absolute dating methods (eg, among many studies, Garver *et al*., 1999; Kirchner *et al*., 2001). Particular interest has been focused on the relative efficacy of fluvial versus glacial erosion in the production of alpine relief (see Brocklehurst and Whipple, 2002). Field and experimental exercises are for the first time being conducted specifically to elucidate sediment flux laws in support of model studies to elucidate processes of bedrock erosion and erosional development of landscapes (see Dietrich *et al*., 2003). A major initiative has over the past two decades has been the ongoing attempt to understand fluvial incision of bedrock, a key factor for understanding the production of terrestrial relief.

At the scales of direct tectonic interest, recourse must be had to model exercises to investigate the synthesis of climate, tectonic evolution and erosional development of the landscape. Early work is well represented in the set of papers coordinated by Merritts and Ellis (1994), while Codilean *et al*. (2006) provide a recent critical summary of progress.

Perhaps the most surprising outcome of work to date is the appearance that climate, as well as the erosional development of the landscape, feed back into the ongoing tectonic process (cf. Willett, 1999; Willett *et al*., 2006). Confirmation of this outcome, however, remains difficult (Whipple, 2009). Remarkably, the connections among geophysical phenomena essayed in this work were already crudely apparent in Melton's landscape correlation structure of 50 years ago (Figure 2), even though that structure was mounted upon evidence gained at a much more local scale. Further, models of coupled tectonics and surface processes have gone some way to reconcile the classical, qualitative landscape development models of the turn of the twentieth century with contemporary ideas of landscape evolution (Kooi and Beaumont, 1996). It appears as if the most fundamental ideas in geomorphology may be remarkably consistent across spatial and temporal scales in the landscape, and through the passage of intellectual time.

6 The dominance of human agency

George Perkins Marsh (1864) was the first scholar to explicitly and deeply consider the role of humans in changing Earth's surface environment. Possibly the first quantitative analysis was that of Stafford Happ and his associates (Happ *et al*., 1940), who examined valleybottom sedimentation in the midwestern USA as a consequence of nineteenth-century agricultural clearance, work that was continued in a landmark investigation by Trimble (1983; 1999) and in other modern studies. Hooke (1994; 2000) has examined the issue of humans as geomorphological agents in the long perspective of human history. So far as fragmentary data permit, it appears that the quantitative human impact has increased steadily through human history, in step with the improvement of technology, and

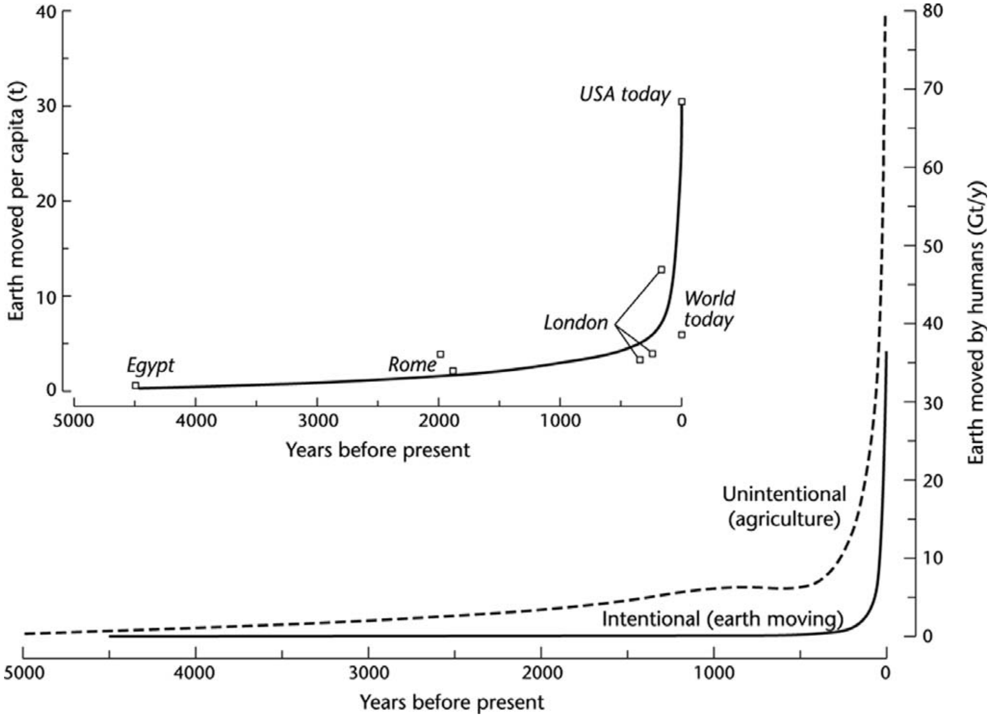

Figure 3. An estimate by Hooke (2000) of earth movements by human agency. The bases of the graph, necessarily highly tenuous, are given by Hooke. It is evident that, throughout human history, agriculture – including land clearance for cropping and pasture – has been a principal causative factor. The introduction of mechanical earth-moving machinery within the past two centuries and the rapid growth of the human population have both contributed to the dramatic recent increase in estimated total. Most of the movement is very local in character (but see Syvitski *et al*., 2005, for one estimate of the human impact on sediment delivery to the world oceans).
Source: Reproduced by permission of the Geological Society of America

most dramatically after the early nineteenth century (Figure 3). Powered machinery has yielded a capacity to modify Earth's surface – in terms of rate and scale of land clearance, of topographic recontouring; of the ability to dam and control watercourses – that is qualitatively different than anything that went before.

For obvious reasons, substantial interest has been paid to soil erosion (Jacks and Whyte, 1939; Montgomery, 2007a; 2007b). On a continuing basis, agricultural activity continues to be the most significant contributor to soil erosion (Figures 3 and 4). Much of what is eroded, however, moves only as far as trunk valley floodplains. In consequence, Holocene histories of valley alleviation are complex (Vita Finzi, 1969; Foulds and Macklin, 2006), but they are in significant measure correlated with the land-clearing and agricultural activities of humans.

Hooke's conclusions are that humans are, today, the principal geomorphological agency on Earth (Hooke, 1994) and that we may within the next century double the impact of all preceding history (Hooke, 2000). Yet, while geomorphologists study specific examples of human agency, there has heretofore been scarcely any attempt to incorporate it into any general view of Earth surface processes or landscape history. Reasons for this might include the generally local and special character of the effects and

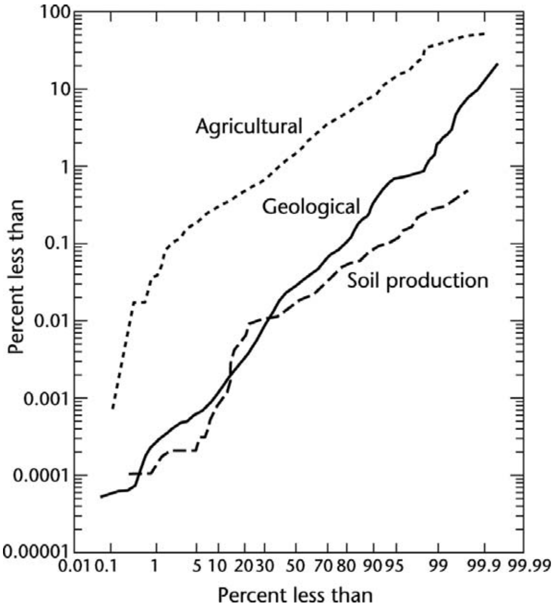

Figure 4. A comparison of agricultural erosion rates with geological erosion rates, based on data compiled by D.R. Montgomery and presented in Montgomery (2007a). Agricultural rates of sediment mobilization exceed geological rates by between 1 and 2 orders of magnitude across the entire range. *Source*: Original material copyright (2007) National Academy of Sciences, USA

their generally incremental rather than novel nature. But there can be no doubt that agriculturally provoked soil movement has had a systematic impact on slope-base colluvial deposits and on river floodplains, in some parts of the world for thousands of years.

IV Contemporary questions and directions

Every geomorphologist will have her/his own perceptions of the major contemporary questions in the discipline, and they will inevitably be coloured by individual experience. The following elaboration of six major conceptual questions – each one really a covering statement for a range of important research questions – is therefore a personal and probably transient view.

1 Geomorphic fluxes and flux laws

Geomorphology is centrally concerned with the evolution of the landscape. As became apparent early in this essay, the subject might be approached from either the perspective of understanding the physicochemical processes by which landforms and landscapes in general evolve, or the perspective of describing the historical development of particular landscapes. Ideally, one would hope to deduce the latter from the former. This is a goal that is unlikely ever to be completely realized, but one may hope for substantial progress.[2] Temporal constraints imposed by the relative scales of human observation and landscape history dictate that progress toward understanding landscape evolution must be essayed by theoretical means, and tested by whatever relevant observations we can muster. Within our contemporary understanding of geomorphology as a system science, that means by system modelling.

Landscape evolution consists of the shifting of earth materials from one place to another on the surface of the planet; hence the principles by which this shifting occurs must be a central focus of interest. That is to say, the kernel of any landscape evolution model must be the mass transport laws that effect this redistribution. Such laws must be applications of the relevant principles of physics and, in complete form, they must incorporate criteria for mobilization, transfer and deposition of earth materials of varying character. They must cover such phenomena as the continuous deformation of surficial material on hillside slopes; episodic failure of surficial and rock material; the transport of sediment by running water, both in channelled and unchannelled flows; transport of material by wave motion and currents along coasts; transport by wind; and transport by glacial ice. A review of progress in developing 'geomorphic transport laws' has been presented by Dietrich *et al.* (2003). After more than a century of modern study, we still do not have an entirely satisfactory view of any specific law, though in fact we have useful approximations for some of them.

Two important aspects of the general problem deserve further notice. The first is that transport laws for particular media and particular geomorphic contexts (for example, sediment carried in suspension in a river, compared with sediment carried in suspension on the wind) have customarily – though by no means exclusively – been studied in isolation from each other. Yet there often are important common features in the underlying physics. It is probable that – for purposes of elucidating the applied physics – considerably less attention ought to be paid to particular contexts, and more attention to generic processes (see Pelletier, 2008, on this topic).

The second is that the particular expression of a geomorphic transport law must be consistent with the scale of representation of the model system within which it is applied, because scale of representation influences the information content of the model. This issue is taken up again in the following paragraphs.

2 Reconciling geomorphic information and process representation across scales

Questions of scale pervade any environmental science. In geomorphology, scale leads to a series of questions that can be divided into two types: (1) questions related to transferring or extrapolating geomorphological information in the landscape; and (2) questions related to the reconciliation of theories/models with different scales of representation.

The first issue, and the underlying reason why it is an issue, is best exemplified by an example. In keeping with the concept that a fundamental theme in geomorphology is the shaping of landscape by the transfer of earth materials from place to place, information abut areal sediment yield on Earth's terrestrial surface represents important geomorphological information. At spatial scales beyond that of an individual hillslope, this information for the subaerial landscape has customarily been collected and presented as the transport of sediment in rivers. Information derived from drainage basins of substantially differing size – all the way up to world compilations – is customarily collated. Yet there are well-known, regionally variable spatial scale effects in sediment yield (eg, Church *et al*., 1999). The effect arises because of spatially systematic variations in source-sink relations for sediment (that is, from reservoir effects). Across all scales of a regional landscape, with varying modes of sediment transfer, the effect can be complex (Figure 5). Geomorphic information needs to be scale-adjusted for valid comparison. Much more needs to be learned about regional scaling relations for geomorphic information in order to place this matter – much better understood today in hydrology – on a firm foundation.

This issue applies to the proper interpretation of 'geomorphological experiments' – more or less controlled manipulations of landscape elements – and, in an extreme form, it leads to questions about the geomorphological relevance of radically reduced model experiments, such as physical models of landscape evolution or of drainage basins conducted with synthetic materials on the scale of metres. S.A. Schumm and his collaborators (Schumm *et al*., 1987) were early proponents of this approach. Recently, landscape model experiments have been run by Hasbargen and Paola (2000), Hancock and Willgoose (2001) and Lague *et al*. (2008), among others. How can such analogue experiments be justified when, plainly, strict scaling of materials and forces cannot apply? Paola justifies the comparison on the basis of self-similarity of the revealed morphology, referring to the effect as 'spontaneous similarity' (in contrast to the 'imposed similarity' of a formally scaled experiment). Recently, Malverti *et al*. (2008) have extended the analogy to apply to some of the actual processes by which the landforms emerge in the world and in the model.

The second issue arises because the range of spatial and temporal scales involved in

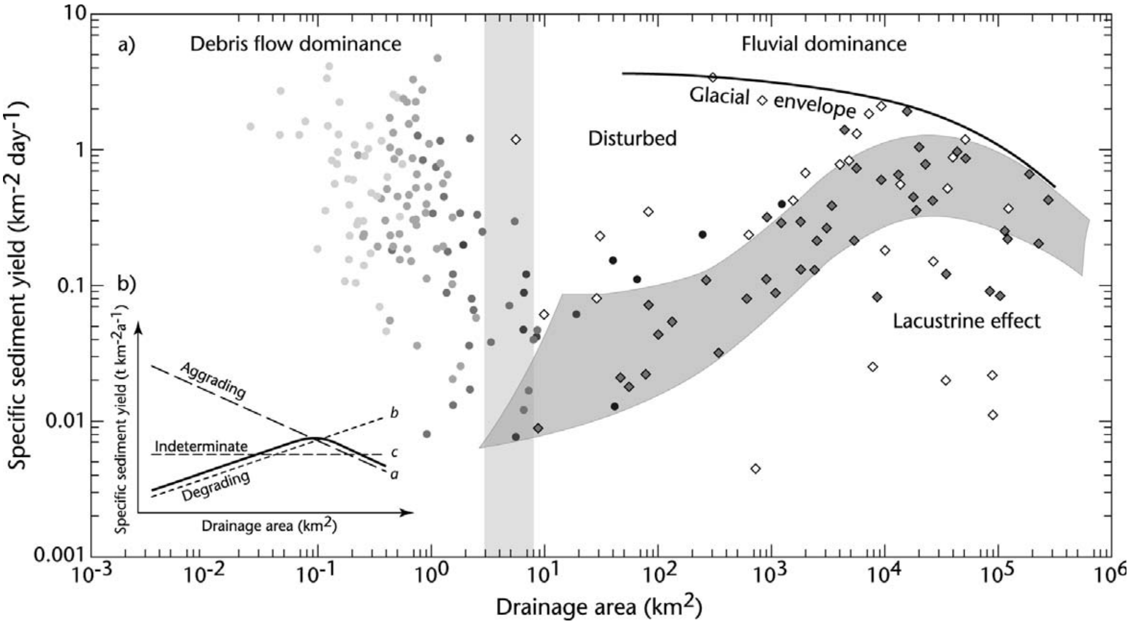

Figure 5. Regional sediment yield in the British Columbia sector of the North American Western Cordillera; data compiled from various studies supervised by the writer. Data of hillslope sediment yield dominated by debris flow (drainage area <3 km^2) derive mainly from one major drainage basin in the Cascade Range of southwest British Columbia; increasing intensity of point shading indicates increasing stream order, from 1 to 4; data of fluvially dominated sediment yield are province-wide. Inset: three characteristic patterns of scale-related variation in sediment yield.

geomorphology impose constraints on the character of theory-based statements that we can make. The representation of a transport law in a landscape evolution model designed to simulate a million years in the development of an orogen must be considerably simplified from the representation we would make for model of fluvial sediment transport in a river over synoptic to perhaps centennial timescales. For both approaches to be consistent with known facts, however, the more specific representation must generalize appropriately to give rise to the more generalized one – in short, theories cast at different levels of representation must be reconcilable.

3 Comprehending complexity

The paradigm of non-linear dynamics has relatively recently become part of the currency of science – it required large-scale computation to be properly comprehended. It turns out that some of the most striking real-world exemplifications of non-linear effects arise in geomorphology. (Such effects are expected in any system science, but geomorphological examples are particularly visible.) A range of examples is given by Murray *et al*. (2009).[3] Those authors listed five characteristics of complexity that have significant implications for geomorphological explanation:

(1) deterministic processes interact locally in a non-linear way to produce complex spatially distributed effects best described as chaotic (that is, presenting no simply predictable outcomes, though they may exhibit some characteristic pattern);

(2) self-organization creates local structure in geomorphological systems as the result of

still more local interactions among elements of the system;

(3) autogenic temporal behaviour occurs, including sudden changes in the system state with no obvious external forcing;
(4) emergent behaviour is seen, such that larger-scale elements of a system exhibit patterns and behaviours that are not simply integrable from more elementary processes (which means that patterns of explanation cannot be entirely reductionist);
(5) self-similarity occurs in morphology and in behaviour over a wide range of scales.

These characteristics, well illustrated now in a range of geomorphological studies, generate challenges for both explanation and prediction (Phillips, 1995; 2003).

4 The intersection with life

There is no doubt that both vegetation and animals play a significant role in geomorphology – the former pervasively. Yet they have been comparatively little considered. Biota are important in a wide variety of roles that range far beyond the familiar ones of providing root reinforcement for soils to resist mass failure on slopes and along stream banks, and ground cover to resist surface erosion. Dietrich and Perron (2006) provide a recent review that provocatively asks whether life has left any unique signature in the landscape.

Microbiota are increasingly implicated in weathering processes, even far below the surface. Soil fauna structure the soil, thereby affecting hydrologic behaviour and erodibility. Animals may achieve significant soil movement on hillslopes and tree-throw contributes to soil disturbance and downslope soil movement.

Vegetation also contributes directly to soil material and mediates the effective climate at the land surface, thereby influencing both the weathering environment and the ability of wind and water to move material. To date, these effects have been investigated in only a summary way, the main interest having normally been focused upon soil erosion under a range of land surface conditions, including studies of erosion under various crop types.

Vegetation also plays a direct morphological role on hillslopes and in rivers when woody material becomes entrained in slope failures, debris flows and water courses. These macroscopic effects are better studied, yet their complexity leaves many questions unanswered.

5 The role of climate in geomorphology

This is by no means a new concern, but it now assumes increased prominence. Again, there are two aspects. In the long term – commensurable with the time for significant geomorphological evolution of landscapes – the mutual interactions of climate, topography and vegetation are a focus of significant inquiry (eg, Molnar and England, 1990; Willett, 1999; Whipple, 2009). It is well accepted that the major features of Earth's relief influence the large-scale steering of the atmospheric circulation and thereby influence regional climate, and it is well known that topography influences climate locally through various topographic effects. It has more recently been realized that climate reciprocally influences the evolution of relief, especially through the influence of precipitation on runoff and erosion, which usually is quite asymmetric around mountains. In the long term, this, in turn, influences isostatic compensation of the crust and the further evolution of relief. There is, in summary, a complex interaction between climate and topography that influences the course of erosion, sedimentation and the entire development of landscape.

In the shorter term, there is concern for the influence of climate change on geomorphological processes. This effect is studied at two principal scales: that of the glacial–interglacial changes of the Pleistocene Epoch, and that of contemporary climate change. While these two themes are closely linked in climatological studies – for the former may bring valuable insights to the latter – this is less true of the geomorphological consequences, for the contemporary climate trend moves us farther from the conditions of a glacial Earth. Conditions of the warm early- to mid-Holocene Epoch may, however, provide significant insight.

The most important way in which contemporary climate change influences geomorphological processes is through the hydrological cycle. The effects of changes in the balance of precipitation and evaporation, and of changes in seasonal snowcover, are easy to comprehend qualitatively. Unfortunately, primary changes to precipitation are more difficult to predict quantitatively than projected thermal changes. Furthermore, they will be more nuanced regionally because of the interaction of precipitation mechanisms with surface topography, and all climate change predictions remain difficult at regional scales. There remains a great deal of work to be done in this area before the geomorphological consequences become entirely clear.

Overall, the questions associated with prospective geomorphological consequences of contemporary climate change have received far less attention than they deserve (see Goudie, 2006; Slaymaker *et al*., 2009).

6 Integrating the human impact

One possible reason for relative ignorance of the geomorphological effects of contemporary climate change is the fact that the effects are overprinted by the pervasive impact of the human presence on Earth. As shown above, humans are, today, the dominant geomorphological agency on the planet, and human impacts extend to almost the entire terrestrial surface (Slaymaker *et al*., 2009). Indeed, geomorphology urgently needs to find a paradigm within which to investigate the intersection of the last two themes with this one, for direct manipulation of land surface cover and modification of the hydrological cycle are the two most important ways in which humans influence the overall course of geomorphological processes. In comparison, direct and deliberate earth-moving operations, while certainly highly significant, are comparatively local in their effect.

To date, consideration of the human impact has, in geomorphological work, largely been cast as an 'applied' study and a sort of footnote to the main narrative of the discipline. In fact, in the contemporary world, it is the major theme. It has perhaps most squarely been faced in studies of soil erosion (eg, Montgomery, 2007b) – by no means exclusively the province of geomorphologists – but it is equally true of fluvial geomorphology in most of the world (cf. Nilsson *et al*., 2005), of aeolian geomorphology, the geomorphology of coasts, and even, increasingly pervasively, of the geomorphology of the world's mountains (see discussions in Slaymaker *et al*., 2009).

V Conclusions: Where are we going?

Prophesy is an exercise best left to oracles. It may nevertheless be useful to record one observer's impression of the orientations that will dominate the discipline in the immediate future, especially in relation to the significant bases and questions for the modern discipline discussed above. There is the appearance, in the contemporary discipline, of a significant dichotomy in orientation.

On the one hand, concerns to firmly ground the discipline in physical principles – to find the fundamental transport laws that govern the redistribution of earth materials on the surface of the planet; to properly reconcile the effects of those laws over large ranges of space and time; and to understand the complex nature of geomorphological processes and effects within the Earth system – seem to dictate a future in which geomorphology becomes increasingly a geophysical science. This process is in fact well under way; geomorphology is increasingly prominent in the affairs of organizations such as the American and European geophysical unions. With this orientation comes a methodological apparatus that requires considerable training in mathematical and physical sciences and an appreciation for the appropriate degree of reductionism to employ in the analysis of particular problems.

An alternative path is largely inspired, I think, by the perception that geomorphology is – or should be – becoming more and more preoccupied with issues such as the broader definition of the Earth system, environmental change in that system, and the dominance of human agency. It defines a subject less narrowly confined by a particular methodological approach. This is a geomorphology that more readily incorporates human social and economic dimensions – as necessary – into its analyses, and that no longer treats humans as a special and somewhat exceptional agency modifying Earth's surface. Some implications of this approach are sketched by Slaymaker (2009). It pays attention to human experience, as well as observations of landscape, as basic facts, it focuses on specific elements of landscape as defining entities for the field, it pays significant attention to the historical dimension of particular landscapes, and it incorporates social values, such as a conservation ethic and a concept of social justice. This is not incompatible with a geophysical approach to understanding geomorphological processes, but it substantially broadens both the purview and the intellectual bases of the subject. Which way to go, or how to reconcile these views of what geomorphology is, is a topic that is perhaps too little pursued. If the history of the discipline be any guide, it is more likely to be resolved by practice than by discussion.

Notes

1. The development of the uranium-lead radioisotopic method began at the turn of the twentieth century with the discovery of radioactivity, but was still under development until after mid-century. Until the invention of precise mass spectrometers, analytical accuracy remained a major problem.
2. This is, in effect, the programme envisaged, within the limits imposed by knowledge of the time, by Charles Lyell for his *Principles of Geology*.
3. See also the set of papers in *Geomorphology* 91 (2007), 173–404, on 'Complexity in geomorphology', the Proceedings of the 38th Binghamton Symposium.

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