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Hillslope Form and Process:

History 1960- 2000+

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Abstract

The study of hillslopes has been dominated by the expansion of studies into process rates and mechanisms. Perhaps the greatest volume of work has been on the 'wash' processes of soil erosion, but there has also been significant work on the diffusive mass movements of linear and non-linear 'creep' that shape the convexity of hilltops, on more rapid mass movements and on solution processes. There has also been fresh work on distinctive processes in coastal, arid and cold-climate environments.

Accompanying and integrated with process understanding, and made possible by ubiquitous computational power, modelling has developed from soluble mathematical simplifications to complex simulations that incorporate much of our understanding of process and climate.

Particular topics that have seen significant advance include a more complete understanding of drainage density and texture, and a broadening of interest to encompass the 'critical zone' that constructively unifies the land surface with the lower atmosphere, the biosphere and the regolith. There has also been a change of focus towards steeplands, dominated by mass movements, supply limited removal and tectonic activity.

Most recently, and now incorporated into the concept of the 'Anthropocene', human impact is now receiving increasing attention as we acknowledge its accelerating role in changing landscapes and their relationships.

Key-words

Processes, models, steeplands, drainage density, critical zone.

Our understanding of hillslopes has long alternated between the two poles of form and process, changing direction with the development of new techniques and new approaches, many of them following developments in cognate sciences. In the 1960s there was a decisive shift away from studies of form, dominated by denudation chronology and the identification of erosion surfaces, towards detailed process studies that tried to measure rates of sediment transport. This change in direction was partly a changing of the guard as new generations took over the science but was particularly stimulated by developments, initially in the USA, and many of them rooted in fluvial engineering.

There are two fundamental, and interconnected, research problems for hillslope science, related to processes of formation and history of the landform. For process, we ask how hillslopes are formed, in two and three dimensions, and how the formational processes respond to climatic and evolutionary conditions. From the form of hillslopes, we try to elucidate the processes responsible and the history of the landform, asking how far and how uniquely these components can be deduced from what is essentially an erosional landform that destroys rather than preserves evidence. In both cases, it is desirable, and increasingly possible, to enrich the discussion with additional information about, for example, the regolith, the vegetation cover and anthropogenic modification.

Perhaps the most significant changes in our understanding of hillslopes during the second half of the 20th century has been driven by the application of new technical advances. The greatest single advance has come through the availability of high-quality digital mapping, both from satellite and ground-based data. Remote sensing has provided digital topographic maps at increasing resolution and with global extent. Improvements in photogrammetric methods (**Chandler,1999**), combined with increasing computer power and laser-based surveying, have allowed accurate ground-based survey, and repeat surveys that begin to allow sufficiently aqccurate direct measurement of net changes to the land surface. The second major advance has been in the development and availability of direct radiometric dating methods that can give the age of surfaces and sedimentary deposits. The third major advance has been in available computational power that not only supports the analysis of the ever-increasing mass of topographic data but has also allowed the development of landscape evolution models that are a vital tool in linking hillslope form and hillslope process. These technical advances have been accompanied by the revolution in earth sciences that has been brought about by understanding of plate tectonics, and by the exponential growth of publication in this, as in all, fields. The history of developments in these fields is set out in Sections A and B in this book. Here the focus is on the impact of these changes on our understanding of the relationships between hillslope forms and processes.

Until the 1960s, the predominant area of hillslope research lay in the identification of erosion surfaces that represented former lowland or shoreline areas that had since been relatively uplifted, through tectonics and/or changing sea level. Although some areas provided stratigraphic correlation, there was a marked lack of direct dating, and a proliferation of potential surfaces, inciting Chorley to remark, in jest, that the number of surfaces was proportional to the square of the number of researchers. There was also heated discussion about the amount of residual relief allowable within a single surface and about whether surfaces had been warped during uplift. These discussions are now largely moribund, except in the more limited contexts of river and shoreline terraces, partly due to the limitations of dating and the poor quality of detailed topographic data, and partly because the dominant paradigms had moved on. It is worth noting that the underlying assumption was of Davisian peneplanation, and research was concentrated in areas of modest tectonic activity.

In the 1950s, much of the discussion about hillslope evolution was focussed on the applicability of models proposed by **W.M. Davis (1899**) and **Walter Penck (1924**). In its simplest form, Davis' cycle of erosion, developed in the gently rolling landscapes of New England, assumed initial uplift of an undulating surface, followed by steady incision and lowering towards a low-relief peneplain. In contrast, Penck, working in South America, proposed a continual interaction between erosion and tectonic activity, allowing, among other things, the persistence of parallel retreat on steep slopes. As more emphasis was placed on process rates and mechanisms, this dialogue became less meaningful, gradually replaced by more mechanistic understanding of hillslope development.

In Volume 4 in this series, **Burt (2008) and Werrity (2008)** surveyed the state of hillslope geomorphology from the respective viewpoints of 'Runoff and Erosion', and 'Geometry and Evolution'. Burt concluded that "the revolution in (hillslope) geomorphology had been completed and normal science had been resumed". Since the mid-twentieth century, a strong emphasis on more and more detailed process studies has continued, representing the normal science component of progress in the science, but there have also been substantial changes in direction and some changes in the consensus about the central issues in the subject.

A seminal text that helped to kick-start developments in work on hillslopes was **Leopold, Wolman and Miller's (1964)** *Fluvial Processes in Geomorphology*, explicitly providing a template for **Carson and Kirkby's (1972)** *Hillslope Form and Process,* which helped to cement the gradual switch in research emphasis from landscape form to landscape process.

A number of fundamental concepts in geomorphology have been significant for hillslope research. The balance between the magnitude and frequency of geomorphic events has been most widely applied in fluvial contexts (**Wolman and Miller, 1960**), but the analogy with the actions of a constantly busy dwarf, a man and a huge giant who spends most of his time sleeping is equally relevant for hillslope processes and remains a powerful influence. The concept of thresholds has also been important (**Schumm, 1979**), even if there is often confusion between clear thresholds (**Carson, 1971**) and changes in dominant process. A number of authors have also drawn attention to the potential for the non-linear systems we deal with to exhibit chaotic behaviour (**Phillips, 1992**) and potential catastrophic bifurcations (**Thornes, 1983).** The concept of equilibrium, or of a steady state (**Hack, 1960**) has also been widely applied as a useful, if never completely valid, working hypothesis.

Excursions into other disciplines have led to more controversial attempts to reframe the subject in terms of general systems theory (**Chorley, 1962; Chorley and Kennedy, 1971**) or entropy minimisation (**Leopold and Langbein, 1962)**, and to ask whether hillslope form carries an unambiguous signature of life (**Dietrich, 2006**).

Process rates and mechanisms

The study of hillslope form, and its relation to process, can perhaps be most directly traced back to G.K**. Gilbert's** observations in the Henry Mountains (**1877**) and on the convexity of divides (**1909)**, and followed by Kirk **Bryan (1922**) on hillslopes in Arizona. This work recognised the existence of a functional relationship between gradient and flow power that shaped hillslope form. Some authors consider that there is a unique relationship between process and form, so that the forms can be analysed to reveal the formative processes, but most (**Cox, 1979**; **Brazier et al., 2000; Tucker et al., 2001**) consider that there is some degree of equifinality. An additional dimension of influence lies in the history of a landform, focussing discussion on the time taken for a landform to become characteristic of the formative processes (which may themselves change over time), and on the extent to which landforms reflect their history rather than current processes. These issues are closely allied to issues of response times and spatial scale (**Hack, 1960; Schumm and Lichty, 1965**). In general, more sediment throughput is needed to change large features than small details, and so that they require longer to develop conformity with current processes (**Brunsden and Thornes, 1979**).

One important strand in hillslope understanding came from the study of stream network patterns, stimulated by the work of **RE Horton (1931**) and continued by AN Strahler at Columbia University. In the 1950's **Strahler (1950, 1952**) combined notions of stream ordering with the distribution of elevations within a catchments, through the hypsometric integral, scaled to the elevation range, but it became clear that most 'mature' catchments showed rather limited variations in the integral, so that it was not a very sensitive indicator of evolutionary development.

Strahler's influence was felt most directly through his students, notable Stan Schumm, Richard Chorley, Mark Melton and Marie Morisawa. **Schumm,** in his study of the artificial Perth Amboy Badlands (**1956b**) and in comparable work on natural semi-arid slopes in Colorado (**1956a),** showed that rates of erosion could be directly measured, leading to conclusions about processes and rates of hillslope sediment transport and their seasonal variation. This work presaged a mass of work on process measurements, much of it instigated through students of Chorley in Britain, and, as has always been the case, in tandem with cognate research in civil engineering and geology (**Hutchinson , 1967; Skempton,1964**; **Hovius et al. ,2000)**.

Another important influence has been through agricultural research on soil erosion (e.g. **Meginnis 1935**; **Musgrave, 1947**), culminating in the formulation of the Universal Soil Loss Equation (**Wischmeier and Smith, 1958**). Although the methodology of soil erosion plots and laboratory experiments was focussed on the loss of soil on a field scale, nevertheless the wash processes involved form a major influence of long-term landform development, and have stimulated research on the evolution of hillslope form. The mass of work on soil erosion was consolidated, and very widely applied within the field of geomorphology (**Schumm 1956, 1967; de Ploey , 1990; Savat, 1977; Bryan and Poesen, 1989;Yair, 1990; Govers, 1992; Abrahams et al., 1995; Morgan, 1980)** and many others).

Empirical formulations for sediment transport in terms of discharge, and gradient could readily be used to predict erosion and sedimentation down hillslopes. It was also recognised that grain size, particularly of larger rock fragments, and vegetation cover (**Sanchez and Puigdefabregas, 1994)** protect the surface and significantly reduce sediment transport (**Poesen et al., 1990)**, and that bare patches were important in initiating more concentrated erosion (**Prosser et al., 1995).** Methods of measurement generally consisted of sediment traps below erosion plots, and from the exposure of pegs inserted into the soil, (**Campbell, 1970**) and were applied on field sites or in laboratory experiments. Sprinklers and flumes mimicked natural rainfall patterns and flow from upslope (**Dunne at al., 2010**. There was also a renewed interest in measuring rainsplash, surrounding target cells with splash cups to detect detachment and the trajectory of displaced material.

All of this work has raised the level of understanding of the wash processes that are together responsible for soil erosion, separating the physical detachment and dispersion of soil aggregates from the downslope net movement of material. Combinations of these components, and the concomitant re-deposition of material, have created a complex lexicon of possible sub-processes. (**Kinnell, 1990**; **Hairsine and Rose, 1992**). Total loss of soil over the last century can also now be monitored using the Caesium-137 and Lead-210 radiometric methods (**Quine et al., 1997**).

The direct measurement of surface lowering was refined in the Micro Erosion Meter (MEM), in which a micrometer screw was mounted between three fixed reference points and lowered to the surface investigated, for measuring changes in bedrock surfaces (**High and Hanna 1970**). These measurements were pioneered to monitor the solution of limestone surfaces, and work on hillslope processes was strongly stimulated, although less directly relevant to advances in karst geomorphology (**Sweeting, 1950; Viles and Trudgill, 1984**).

Other relatively slow processes were also being measured. One pioneering work measured movement of desert sand (**Bagnold, 1936**). Soil Creep, identified **by Sharpe (1938**) as 'imperceptible, except by measurements over long periods of time' was investigated through detecting the movement of buried markers in the soil (**Young, 1960**), the tilting of vertical pegs inserted into the soil (**Kirkby, 1967**) and the deformation of flexible tubes (**Finlayson, 1981**). These and other comparable measurements set the scene to generate 'process-response' models through which rates of sediment movement could be interpreted in terms of evolving hillslope form.

Work on steep slopes in the western United States provided evidence that, as gradients approached the limit of stability for loose material, the rate of diffusive sediment transport increased, leading to the formulation of a non-linear model that implied very high rates as gradient approached an upper threshold (**Roering et al., 2001**). The associated hillslope profile would then retain a convex summit, but the convexity would decrease downslope, with the gradient tending asymptotically toward a uniform slope at a threshold angle. The way in which these diffusive processes grade into more rapid mass movements remains an area of discussion, particularly for describing failures on slopes above the ultimate angle of repose (**Hutchinson, 1967; Carson, 1971**), whether modelled as a continuous process (**Kirkby, 1984)**, or, more realistically, treated as episodic (**Terzaghi, 1950**).

As the outcome of these marriages between form and process, it became widely accepted that hilltop convexities were produced by diffusive processes such as creep and rainsplash, quantifying **Gilbert's (1909**) argument; and that advective wash/ soil erosion processes driven by running water produced concave slope profiles. The transition in dominance between these process groups was associated with the area of inflexion from convex to concave profiles, although the precise position also responded to conditions at the base of the slope, whether aggrading, fixed or degrading, in both the vertical and lateral directions.

The ‘normal science’ represented by these and many other studies continues apace, leading to improving descriptions of sediment transport processes for modelling and forecasting purposes. Most relationships retain a large empirical content even as workers try to improve their physical basis. There have, however, been some attempts to fundamentally re-think the physical basis of hillslope process models (**Phillips and Davies, 1991**; **Iverson, 1997, 2005**), taking account of improved understanding of controls on soil depth (**Heimsath et al., 1997**), and increasing interest in the distribution of individual particle movements and non-local effects (**Culling, 1988).**

One consistent component in these advances has been the increasing attention paid to water as both a driver of sediment transport and as the medium for exporting solutes. Solute removal in runoff, though, in humid regions, often the major component in long-term denudation **(Miller, 1960; Walling, 1980**) has generally been less researched, except in limestone terrains, though with some thought provoking analyses (**Berry and Ruxton, 1959; Yatsu, 1988**) until cosmogenic dating provided a tool to observe the distribution of weathering products, and subsurface monitoring was sufficiently intensive (**Anderson et al 1997)**

As reported in previous volumes of this historical survey (**Burt, 2008**), from the 1960s there was a sharp break with the past and hillslope geomorphology became dominated by process studies. ‘If it moves, measure it!’ became the catchphrase, and considerable ingenuity was applied to new ways of measuring and monitoring changes in landscape form over time and sediment transport across hillslopes. These changes inherently involved a change in the spatial areas of interest, from catchments and larger areas down to small sections of a single hillslope. This shift in focus inevitably further hastened the loss of interest in erosion surfaces and similar broad-scale features. The strongest advances have been with respect to transport by running water (wash) processes. Gullies, and particularly their initiation, have proved a more intractable problem (**Poesen et al., 2003**), combining hillslope and fluvial processes and calling on understanding of the controls on drainage density. Other processes and process domains have been less intensively researched, but there has been substantial progress on debris flows, landslides (**Skempton**, **1964**), cold climate processes (**Rapp, 1960**; **Washburn, 1989**) and coastal settings (**Sunamura, 2015**).

Alluvial fans represent a distinct form that is intermediate between hillslopes and channels. Fans differ from other hillslopes in being primarily depositional. The intra-fan erosion and (normally net) deposition are driven by channel processes and the source material derived from a mixture of slope and channel sediment transport. Some major fans, such as the Okavango in southern Africa, are essentially the deltas of ephemeral rivers that terminate inland (**Stanistreet and McCarthy, 1993**). Many others form where sediment eroded from uplifted mountain blocks overwhelms the transporting capacity of local rivers, most commonly in arid and semi-arid regions. For areas such as Death Valley (CA), where fans dominate the local relief, fundamental process relationships and the dynamics of alternating of cut and fill within a fan, have been established through fieldwork (**Denny, 1967**) and experiment (**Hooke, 1967**). Later studies have examined the behaviour of discontinuous streams (**Bull, 1997**) and the balance between fluvial and debris flow inputs (**Blair, 1999**). While the largest fans are in tectonically active semi-arid areas. it is recognized that they occur at all scales and in a wide range of environments (**Harvey, 2011**). Cosmogenic dating now provides valuable estimates of both fan accumulation and source area erosion rates (**Granger et al., 1996**).

There has also been rapid change in the methodologies and data sources that are available to delineate and quantify the shape of the landscape. Until the 1970s, landform data were either taken from topographic maps or from surveyed slope profiles. Improvements in the convenience of, and access to, more accurate terrestrial and methods now not only detect changes between successive re-surveys with millimetre accuracy, but also accurately describe the three-dimensional topography, re-connecting hillslopes with their associated channel networks, and so linking back to the pioneering work of Strahler. In addition, satellite data have, since the first LANDSAT data in 1972, added global coverage of features and topography at steadily improving resolution. Current (2020) technology provides global data at 5 m resolution, and this continues to improve. Better local resolution (0.5-2 m) for many areas can be provided by airborne LIDAR systems. The utility of these data is related to the underlying assumptions of researchers. In particular, researchers assign different levels of importance to micro-topography, while most recognise that all connected channel networks are of significance to hillslope form and process, setting an upper limit on acceptable resolution which can now generally be met **(Zhang et al., 2008**).

The availability of digital topographic data, together with improved understanding of how hillslope sediment processes influence form, have allowed some inference of process from observed form. Both forward and inverse landform evolution models rely on assumptions that can only be partially verified. In the case of forward modelling, assumptions relate to initial and boundary conditions. For inverse modelling, assumptions commonly need to be made about equilibrium, or quasi-equilibrium with simple basal conditions. The simplest, and most widely used assumption is that the landscape is in equilibrium with a uniform rate of denudation and tectonic uplift, driven from the base of the slope. If, for example, it is further assumed that sediment transport rate is given by a function of distance (or area drained per unit contour width) multiplied by gradient to a known power (often 1.0), then a surveyed hillslope profile estimates the distance function for the formative processes. Difficulties with this approach lie in the security of the framing assumptions – Has denudation rate been constant; and for long enough to achieve equilibrium? – and the knowledge that diffusive processes systematically destroy arbitrary initial perturbations, such as stepped field boundaries or archaeological mounds. Nevertheless, these inverse methods, combined with the availability of ever improving digital elevation data, are increasingly providing an important tool for hillslope understanding.

[Figure 1 near here]

Although radiocarbon dating of organic material has been available since the 1950s, the opportunities for dating have, since then, been very greatly enhanced, allowing a wider range of materials and a wider range of ages to be determined. Luminescence dating methods have provided dates for the burial of inorganic sediments since the 1980s (**Wintle and Huntley, 1982**), and advances in Atomic Mass Spectrometer design allowed cosmogenic dating of quartz in rock samples (**Klein et al., 1982; Nishiizumi et al., 1986**). As these methods have become more widely available, it has been possible to directly date many Holocene terrace deposits and to obtain direct measurements of upland surfaces where there are undisturbed boulders. The integrated products of erosion from upland surfaces, gathered together as fluvial gravels, can also be subjected to cosmogenic dating, identifying the sources of the eroded material. These dating methods have started to enable direct dating of undisturbed surfaces, and so re-energise what had seemed to be moribund discussions about the age of upland areas and surfaces. Cosmogenic dating has also allowed probing of the soil and opened significant ongoing discussions about the evolution of the soil and the rates of sediment transport (**McKean et al., 1993**)

Drainage Texture: How long is a hillslope?

Although the direct impact of network analysis has lessened over the last 50 years, **Horton's (1945)** analysis of channel networks paper remains influential. The statistics generated from stream ordering and bifurcation ratios launched many studies of morphometry, and were initially thought to encapsulate some deeper truths about catchment development. Subsequent work shown that many of the constant rations between stream orders to be the properties of almost all such tree-like networks **(Shreve, 1966**). Various attempts (**Smart,1968**; **Surkan, 1969**) have been made to revive this approach, both through enlarging databases or through looking at more details of branching structures and junction angles than are contained within the rather sparse stream ordering analysis. Perhaps the most valuable results suggest that branching angles reflect the modes of network enlargement and that the network structure is related to the hydrological response (**Rinaldo et al., 1993**) of a catchment. Other applications of network structures have been found through the concept of connectivity considering not only flows of water but also linkages though sediment transport and ecology. Others (**Evans, 2012**.) have continued to pursue morphometry as a descriptor of landscapes, greatly assisted by the availability of high-resolution digital maps.

One of the most important issues that has been explored, and to some extent resolved, is the scale of the landscape, expressed in the concept of drainage density, the total length of channels per unit catchment area, which is the reciprocal of mean valley width. Even though the geometry of a single hillslope profile can perhaps be modelled satisfactorily in terms of the processes acting, this understanding is constrained by the boundary conditions of the model – that is by assuming a known hillslope length. To derive and explain the controls on hillslope length requires an understanding of the relationships between the hillslope and channel processes. The consensus that has emerged is that the channel head is defined by the balance between diffusive processes, such as creep and rainsplash in competition with advective processes driven by running water. Diffusive processes and small mass movements tend to fill in potential channel heads, reducing the length of the channel network and reducing drainage density. Advective processes tend to extend channel heads and increase drainage density. The theoretical basis of this balance was set out succinctly by **Smith and Bretherton (1972)** and has been exemplified and verified in field studies in the 1980s (**Montgomery and Dietrich, 1989**). As these relationships have been explored in greater depth, it has become clear that the nature of the diffusive and advective processes is important in determining the style of the stream heads and the dynamics of their position in the landscape. Both the diffusive and advective processes vary in magnitude and frequency, so that stream head positions change over time, reflecting the most recent cut and fill events.

On gentle slopes, diffusive processes consist mainly of creep and rainsplash, whereas on steeper slopes, discrete mass movements tend to be more important, creating a more episodic history of events that fill stream head hollows, potentially dominated by periods of soil saturation. Headward cutting of stream channels tends to be associated with intense storm events, which need not be synchronised with filling of hollows. The combined result of these processes may be to create a headwater area of advancing and retreating stream heads, which may be tightly constrained or more diffuse. The exact geometry of this region reflects the frequency distributions of the competing processes as they interact within the evolving three-dimensional form.

One operational difficulty in understanding the factors that control drainage density has always been to map the position of stream heads. In any network, half of the links (between junctions and/or stream heads) consist of unbranched finger-tip streams, so that inconsistencies in defining stream head positions may have a significant effect on catchment behaviour. Although early attempts to define stream heads relied largely on field appraisal, most research is now based on extracting features from DEMs, so that there is a danger of circularity in defining what is a channel, if we are to seek better understanding of how drainage density is determined. In many cases, 'channels' are necessarily defined by the occurrence of plan and/or profile curvature but they might also be defined by, for example, the occurrence of flow (**Carlston, 1963**; **Gregory and Walling, 1968**).

In a significant early study, **Melton (1957)** surveyed many small semi-arid catchments, and showed a significant relationships between drainage density and climate, vegetation and infiltration capacity. with highest densities in the most arid areas. In terms of the balance between diffusive and advective processes, this inter-dependence was consistent with the greater dominance of advective wash processes in more arid areas, a trend also implicit in **Langbein and Schumm's (1958**) influential paper on the relationship between climate and sediment yield. However other work (**Patton and Schumm 1975; Tarboton et al., 1992**) began to suggest that there was also a strong inverse relationship between drainage density and gradient, and this was reinforced by the work of Dietrich and co-authors (**Montgomery and Dietrich, 1989; Iijavasquez and Bras, 1995**). These field-based observations indicated that the threshold stream head catchment area, and so drainage density, was almost inversely proportional to gradient (Figure 2). Other workers (**Vandaele et al., 1996**) have also found an inverse relationship between stream or gully threshold area and gradient, but relationships are generally weaker ($A \sim S^{-n}$ for $n<1$).

[Figure 2 near here]

Although the controls on drainage density are perhaps the most important consideration for hillslope morphology, the other controls on profile evolution are also important; initial conditions, boundary conditions and the rates of sediment transport processes acting throughout. Initial conditions are required to provide the starting point for any evolutionary model, and generally depend on an understanding of the regional history determined by direct or stratigraphic dating. Alternatively, local assumptions can be made about the behaviour of channels – for example that the entire slope is in a steady state, in equilibrium with a constant rate of downcutting and uplift (**Hack, 1960; Ahnert, 1994**) or that the position of the slope-base stream is unchanging over time (**Kirkby, 1971**). Although these types of assumption subsume issues of both initial and boundary conditions, the consideration of boundary conditions deserves greater attention that it has generally received. In some limited cases (**Savigear, 1952**), it has also been proposed that space may be substituted for time, so that a spatial set of profiles represents an evolutionary sequence over time, but this approach has not generally been successfully applied to entire hillslopes.

The evolution of a slope profiles is generally considered in isolation, but may also be fruitfully considered as a valley cross-section in which erosional development may not only lower but also translate the hillslopes, so that divides and streams migrate laterally as they erode. One driver of asymmetry is the contrast in process rates due to the opposing aspects and consequent differences in vegetation cover and erosion rates (**Perron et al., 2009**). These relationships can be viewed either as a ridge between two streams, or as a channel between opposing hillslopes. In a two-dimensional cross-section, a ridge between two fixed streams at different heights will show steady migration of the divide towards the higher stream, but the rate of migration is too slow to allow extensive stream capture. In a three-dimensional landscape, however, low elevation stream heads are able to cut back into the side of a neighbouring valley at higher elevation, allowing widespread divide migration and capture of upland areas by adjacent steeper catchments. Viewed from the channel, it has been hypothesised that the channel will migrate laterally until the sediment delivery from opposing hillslopes is equal. This condition seems appropriate where sediment removal in the channel is ‘transport limited’, but may not apply where it is ‘supply limited’, allowing migration towards the steeper slope. The various possibilities are now being discussed, but not yet fully resolved.

Landscape Evolution and models

Changes in emphasis towards process mechanisms and finer scales not only shifted the primary focus of research from entire landscapes to the individual hillslope, but occurred at the same time as a major re-definition of major paradigms in geography and more widely. The 'quantitative revolution' **(Burton, 1963),** initially driven by more rigorous and data-hungry statistical analysis in Human Geography, accompanied the wider availability of computer power, beginning in the 1960s and eventually reaching individual desktops in the 1980s. For hillslopes, these technical advances allowed the development of models for hillslope development, essentially partial differential equations that could only be 'solved' numerically. They also expanded the possibilities for theoretical development (**Scheidegger, 1961**) and furthered other quantitative methods (**King, 1966)**

Process-response models were essentially built upon the continuity equation, that states that change in elevation over time is a necessary concomitant of spatial differences in sediment transport. If more sediment leaves a section of hillslope that it receives, that difference must be accommodated by a net erosion within the section. This statement of continuity provides a fundamental link between space and time. Spatial differences in sediment transport rates drive change in form over time. At its simplest, for a sediment transport process, the rate of which is driven by a linear dependence on gradient, this leads to a differential equation familiar to students of diffusion. Analytical solutions of this equation were well documented for thermal conduction and first applied for soil creep (**Culling, 1963**), the rate of which had been widely assumed, though with surprisingly little concrete justification, to be linearly dependent on gradient, and so cementing the analogy.

With the widespread availability of computing power, there was a sharp increase in computational models, led by the work of **Ahnert (1964, 1976**), in which processes were separately identified and their rates represented as functions of distance from the divide (or unit drainage area) and gradient. **Kirkby (1971**) was another exponent of this approach, attempting to provide a more physically-based approach through the use of highly empirical sediment transport 'laws'. For the sediment carried downslope by running water (i.e. wash processes) these relationships relied heavily on the earlier agricultural engineering work on soil erosion.

Over time, the number of processes and sub-processes, and the resolution and three-dimensionality of the topography, has increased greatly, allowing the models to represent more complex inter-relationships between form and process. One important step was the introduction of solutional and weathering processes, allowing the explicit inclusion of a regolith layer within models (**Kirkby, 1985**). Most of the process-response models operated in a continuum of time and space, so that inclusion of mass movements, inherently episodic, could only be stochastic or make continuum approximations (**Kirkby, 1984**).

One important direction of modelling since the 1990s has been in the development of more complex and innovative modular platforms (**Martin and Church, 2004**). The MIT group, headed by Rafael Bras have made two significant contributions in the SIBERIA (**Willgoose et al.,1991 a, b**) and CHILD (**Tucker et al., 2001**) models, and these platforms are still being actively elaborated to include other features. Other widely used model include CAESAR

(**Coulthard et al., 2000**) and CASCADE **Tomkin and Braun, 1999**). A very high level of visual realism is now shown in some more recent models (**Egholm et al., 2009**), bringing together the strands of modelling over the previous 50 years, and, significantly, incorporating the response of process rates to climatic drivers and elevation. This offers the opportunity to drive models with independently derived climate reconstructions and scenarios for the future. Some of these recent models also have the capability to include individual storms, demonstrating that the apparently random occurrence of large storms can lead to significant unpredictability in the outcomes, and some models have been proposed in which storm incidence is the key driver of the model (**Chase, 1992**)

In models of landscape evolution, it is now technically possible to include soil formation, individual storm events, climate change and vegetation cover within a single model, but the resulting complexity, and the uncertainty surrounding poorly researched interactions, makes complete integration difficult, if not impossible to achieve, and clearer insights and intuitive understanding are often provided by simpler, if more limited LEMs. For example, models such as CREAMS, EPIC, SWAT **(Krysanova and Arnold, 2008**) and WEPP (**Laflen et al., 1994)** are focussed on erosion in cultivated areas during individual storms, but are not primarily concerned with longer term landscape change.

The availability of models has, naturally, raised issues of calibration, validation and equifinality. Until the 1980s, laborious computing and surveying combined to make comparisons crude, far from the directness of fitting hydrographs generated from storm rainfall events. Should scientists make many model runs, constrained by the known uncertainty of process rate models, asking the target landform to lie within the envelope of model outcomes? Or should the model be compared with a bundle of surveyed profiles? Few modellers adequately embraced either of these approaches, generally relying on the incorporation of guesstimated process rates to justify comparisons.

Steeplands and Tectonics

For many years, much of the research on hillslope form and process has concentrated on landscape of low or modest relief, implicitly tied to Davisian assumptions of gradual denudation towards, although rarely reaching, a low-relief peneplain, and in which tectonics plays only a subsidiary part. Within this framework, a mantling regolith is rarely absent, so that sediment transport processes can generally be assumed to be transport limited, with little influence of control through the weathering and release of fresh material. However, since the 1980s, the influence of plate tectonics has been felt by geomorphologists and other earth scientists, and there has been a marked upsurge in work on steepland settings. This focus has been linked to increased concentration on supply-limited removal, both from mountain slopes and within rivers.

Although outside the direct scope of this chapter, it may be noted that fluvial sediment movement is essentially transport limited for fine grained material and at high flows, and increasingly supply limited for the coarsest material and at low flows. This has led to the formulation of stream power models (**Whipple and Tucker, 1999)** that express channel denudation rates as a direct function of gradient and discharge or catchment area, rather than mediated by the continuity equation together with a sediment transport capacity. This allows the whole evolution of the landscape, both the hillslopes and channels, to be expressed directly in terms of denudation rates, significantly changing many relatively well-established conclusions of earlier work. Interwoven with these development, the emergence of plate tectonics as the dominant geological paradigm in the 1960s has gradually been incorporated into geomorphological thinking, much of it driven by earth scientists rather than geographers. Taking these trends together, there has also been a necessary broadening in the spatial scale of interest, since one of the key responses to erosion is through isostatic adjustment, which occurs at the scale of mountain ranges rather than over a single hillslope (**Davy and Crave, 2000; Kooi and Beaumont, 1994**). Furthermore, many mountain ranges have glaciated areas, so that the relationships between water-driven and glacially driven erosion also become important (**Egholm et al., 2009**).

In this view of steepland evolution, mountains are built from the subduction or collision of tectonic plates. As mountains rise and gradients steepen, mass movements dominate erosion, at a rate that increases with, and may become proportional to relief (**Ahnert, 1970**). Earthquakes and major storms (hurricanes, typhoons) trigger mass movements as steep slopes weather and reach a critical state. Material is transported in steep rivers, whose stream power, and the availability of coarse material as tools, allows them to progressively incise their beds, cutting gorges with steepening sidewalls. Flexural isostatic response to the localised fluvial incision increases summit relief in a broad area surrounding the deepening river gorge, further increasing local relief. Weathering is enhanced by the increased precipitation on the windward flank of mountain ranges, so that erosion and isostatic uplift are greater there, and the range grows preferentially into the wind (**Kooi and Beaumont, 1994; Tucker and Slingerland, 1994**). If a mountain massif is high enough to support glaciers, then the increased rate of erosion beneath and around the ice, the 'glacial buzzsaw' (**Egholm at al, 2009**), further interacts with other erosional and flexural processes. There may also be limits to relief set by inherent rock strength (**Schmidt and Montgomery, 1995).**

This steepland model of hillslope evolution differs radically from earlier paradigms in geomorphology, both in its characteristic scale and in the range of dominant processes and forms. Mass movement, tectonics and fluvial incision describe a landscape that is formed as a dynamic balance between uplift and erosion, closer to the spirit of **Penck's (1924**) view of landscape evolution, and in which sediment removal is dominated by its availability rather than by the transporting capacity of each sediment process.

There is perhaps scope to merge these two views of the landscape into a single unity, in which tectonics and mass movements are fully accommodated in models of lowland landscapes (**Egholm et al., 2002**), and the transition between supply and transport limited removal is more fully incorporated into steepland geomorphology (**Gunnell and Fleitout, 1998**). An important conceptual dichotomy in sediment transport is the issue of 'supply limited' or 'transport limited' removal (**Carson and Kirkby, 1972**, p104). This has led to some bifurcation in the directions of hillslope modelling that are still not fully resolved, and there have been only limited attempts to bridge this divide (**Foster and Meyer, 1972**; **Kirkby, 1992; Howard, 1994**).

A second expanding strand of research that has greatest relevance in steepland landscapes is the interaction between landslides, weathering rates and the deep circulation of water within bedrock and partially weathered material (**Hack and Goodlett, 1960; Kirkby, 1973**).

The Critical Zone

Hillslope geomorphology has, historically, been concerned more with the surface expression of the land than with the underlying soil and rock. This is, in part, because soil properties can only be sampled at a small number of locations. Windows into this world have been opened up as landscape evolution models have increasingly included soil/regolith components (**Willgoose, 2018**) while techniques including ground penetrating radar (**Conyers and Goodman, 1997**) and cosmogenic dating have begun to provide tools to probe the forms and processes in the subsurface.

Since the 1990s, there has been much more investment in directly instrumenting subsurface processes linked to water flow chemistry **(Anderson et al., 2002**), and this is now leading to fresh insights about weathering and the initiation of mass movements. It has also led to the identification of the 'critical zone' as the "heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources". This definition (**NRC, 2001**) led to the establishment of 'Critical Zone Observatories', initially in USA and now globally (**ESDAC, 2020**), and this approach has, to some extent, changed the focus of instrumented catchment studies, putting more emphasis on the vertical exchanges between the surface, the soil and the biota (figure 3). So far, however, these approaches have, perhaps, generated more questions than answers, but they become increasingly important as we focus on the impacts of global heating.

[Figure 3 near here]

These developments show the potential to bring together several strands of research discussed above. They emphasize the important role of subsurface water, both within the soil and bedrock, in controlling weathering processes, soil formation and the stability of potential mass movements. The concept of the critical zone has cast new light on many of the interacting processes in and on hillslopes, and has great potential for refreshing existing concepts (**Abernethy at al, 1998**)

A, partly parallel development has been the adoption and instrumentation of artificially created areas within which the early stages of hillslope and catchment evolution may be observed. The 'Chicken Run' catchment (**Gerwin et al., 2009**) has been established on the tailings of opencast coal mining and has begun to show the evolution of soils and drainage. A completely artificial hillslope and enclosure (LEO) has been constructed in Arizona to control conditions even more completely (**Pangle et al., 2015**). Comparison of such artificial hillslopes with evolutionary models (**Willgoose and Riley, 1998**) has proved challenging.

Evolution models, particularly for summit convexities, have begun to probe beneath the simplicity of **Gilbert's (1909**) argument, and ask how depth-controlled rates of soil formation interact with strength-controlled rates of diffusive transport to subtly modify the forms and rates of development (**Heimsath et al., 1999**). There has also been renewed interest in the fate of soil organic matter, examining the dynamics of translocation, decomposition and burial in downslope transport.

The Anthropocene

With an increasing understanding of mankind's role in transforming the planet has come the realisation that human influence has long played an important part in the evolution of hillslope and other environments through land use change. This has culminated in the proposal, still under discussion, that the Anthropocene should be defined as the distinct geological epoch during which human activity has produced distinctive nuclear and other markers, and during which there is an ongoing mass extinction event. Geomorphologists have generally chosen to work in semi-natural environments, but there is an increasing focus on human-accelerated soil erosion, reflected in recent reviews (**Montgomery, 2007; Thornes, 2007; Verheijen et al., 2009**) as a significant modifier of natural slopes through re-distribution or removal of mineral and organic soil by running water, often in association with extensive gullying where bare soil is exposed for cultivation.

Dating methods have significantly advanced understanding of Holocene and historic events, particularly through the application of luminescence, Caesium 135 and Lead 210 and lichenometry methods (**Innes, 1983;.Lindstrom et al., 1992**)

In the 1990s there was also a recognition of the process of tillage erosion, in which repeated ploughing systematically moves material downslope (**Govers et al., 1994**; **Quine et al., 1997**; **Poesen et al., 1997**) at a rate that increases with gradient. In cultivated areas, this process generates a diffusive flux that can be several orders of magnitude greater than the natural diffusive processes of creep and rainsplash **(Lobb et al., 1995)**. Although little material leaves the base of a hillslope, tillage erosion significantly denudes the landscape, lowering the centre of mass of the land as material moves downslope (**van Oost et al., 2005)** Tillage Erosion is also responsible for re-distributing soil organic matter along a hillslope, a topic of current interest in the context of global warming and carbon sequestration.(**Gregorich et al., 1998; Lal, 2005**).

Conclusions

Since 1950, hillslope geomorphology has been completely re-vitalized, a change that has been initially driven by the emphasis on process rates and mechanisms that was just beginning to take off in the 1950s and 1960s. Continuing work on processes still represents the greatest bulk of the ever-growing volume of published material, and still offers new insights and some surprises. However, there have been more fundamental insights that transcend this normal science, particularly in the greater understanding of landscape scale and drainage density, and in the behaviour of steepland terrains, and some of these insights have been sharpened by comparison with other planetary surfaces. The concept of the critical zone now offers new windows on hillslope behaviour, and may be accelerating the immersion of geomorphology within a broader environmental context. The threats and opportunities opened up by the reality of global heating are now also beginning to shift our focus from longer term geological timescales to the immediacy of shorter term potential impacts, so that the future of hillslope geomorphology may look very different from its recent past.

During the second half of the twentieth century, a few personalities stand out, both for their own contribution and through their students. In America, the genealogy of Luna Leopold, Tom Dunne and Bill Dietrich (Geotree, 2020) stands out for their contributions to hillslope geomorphology in this period. The pioneering work of other researchers has also been inspiring, for example Anders Rapp, Jan De Ploey and his successors. In Britain the most widely felt influences have perhaps been through Dick Chorley, John Thornes and Denys Brunsden. Similarly, and in many cases through the agency of significant participants, a number of organisations have played a seminal role in spreading and exchanging ideas. Some of these super-spreader roles have been played by the Binghampton Geomorphology Symposium (1970), the Benelux Colloquium on Geomorphological Processes (1976), the IGU Commission on Measurements and Theory Application in Geomorphology (COMTAG) and its successors, as well as The British Society for Geomorphology (BGRG/ BSG) and the Hydrology Division of the American Geophysical Union.

[figure 4 near here]

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Figure captions

1: The characteristic form of hillslope profiles with different denudational processes (from Kirkby, 1971, Figure 15.10)

2: Drainage area versus local slope for channel heads in Oregon and California. Local slope was determined in the field, and drainage area from topographic base maps. Channel heads define a threshold between channelled and unchanneled regions of the landscape. (from Montgomery and Dietrich, 1989, figure 4)

3: Equilibrium chemical depletion ratio (=ratio of chemical to total denudation, shown by diagonal lines) in terms of rates of mechanical and chemical denudation. Points and broken curve indicate average 4,000 km^2 basins at ca 15ºC mean annual temperature, from Langbein and Schumm (1958), Langbein and Dawdy (1964) and Strakhov (1967). Adapted from Carson and Kirkby, 1973; figure 9.18). Numbers beside the curve indicate mean annual rainfall (mm).

4: Some leading scientists who have been engaged in researching hillslope form and process, 1960-2000.