The Earth’s dynamic surface: an overview

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Catastrophe and continuity in landscape evolution

Debate about the relative roles of catastrophic v. continuous processes of landform evolution is as old as the discipline of Earth Science itself. Over the last 10 years or so, research in the Earth Sciences has focussed strongly on the Earth’s surface and particularly in terms of quantifying rates of processes. This research parallels developments in geomorphology and sedimentology in the quantification of surface processes since the 1950s and 1960s. These surface processes are the manifestation of the large-scale interaction of climate and tectonics operating over a wide range of spatial and temporal scales. Thus, recent research had required integration of the historically distinct subjects of geomorphology, sedimentology, climatology and tectonics. Partly as a cause and partly as a consequence of this integration, there have been many recent developments in quantitative modelling and both laboratory and field-based analytical tools. Together, these have provided new insights into absolute and relative rates of denudation, and the factors that control the many dynamic processes involved.

One of the outstanding issues concerns the balance between tectonics, climate and denudation, and in particular the limiting effects of one on the others and the nature of dynamic feedback mechanisms. The fact that processes can be considered catastrophic or continuous, depending on the timescale of observation or interest, can hinder the predictability of models, depending on how they are formulated. Certain conditions may lead to a steady-state situation in which denudation balances tectonic uplift, leading to a more or less constant topography. Steady-state topography means that detailed study of present day landforms can provide important insights into the nature of surface processes back in time. Such assumptions underpin debates in geomorphology relating to the process-form linkage and the understanding of characteristic forms in the landscape. Alternatively, the recognition of non-steady-state situations and a clearer understanding of why these situations occur provide the key for resolving the climate-tectonics-landscape evolution feedback loop. The transition between the two states will reflect the process response time, and therefore the transitory state may provide a clearer picture of the time lag of topographic response to changes in the rates of climate change and tectonic forcing. However, the response time is not necessarily constant and may have changed considerably at key points in the past, such as the evolution of plants on land in the Palaeozoic and the acceleration of human activity within the landscape in the Holocene.

In terms of denudation (physical erosion and chemical and mechanical weathering), there are clearly catastrophic processes, such as landsliding, which operate discretely and on short timescales and more continuous processes, such as chemical weathering, which can be considerably more protracted. The distinction between discrete catastrophic and continuous modification depends also on the time and spatial scales of interest. These considerations also impact directly on the questions of if and how steady-state topography can be achieved, how the processes controlling this state can be quantified and resolved, what causes departures from a steady-state condition and how topography reflects the coupling between denudation, climate and tectonics.

Some of the key current research areas in the world are tectonically active regions, such as New Zealand (southern Alps), Taiwan and Olympic Mountains (USA). However, the link between tectonics and denudation is complicated in these convergent zones (e.g. Willett et al. 2001), as there is a significant horizontal component to the deformation and, additionally, climatic variations often produce marked asymmetry in denudation, which itself then feedbacks into the isostatic component of vertical motion.

In practice, this research field necessarily involves a broad range of disciplines including field geologists, geomorphologists, structural geologists, geochemists, climatologists and geophysical modellers. These researchers address the observational constraints on
spatial variations and controls on erosion and weathering, the contribution of geochemical and geophysical data in quantifying rates of erosion and surface deformation, and the insights or otherwise of process-oriented numerical models, linking tectonics, climate and denudation.

The aim of the 2004 William Smith conference was to encapsulate the current state of some of the research relevant to this area and promote discussion on the outstanding issues and future research directions (such as technical and analytical developments and the robust integration of modelling and observations). In particular,

- how the geological record preserves the nature and variability of erosion processes over a wide range of time and spatial scales (from years to millions of years);
- how this record can be interrogated through observation and laboratory analysis; and
- how physical models can be integrated with these data to provide a deeper understanding of the interactions between surface processes, climate and tectonics.

This publication contains a selection of the papers presented at the conference. In the first paper, Allen presents an overview of the timescales relevant to understanding the links between tectonic forcing and landscape response, including the sediment routing systems, and provides a conceptual comment on this subject in a recent essay in Nature (Allen 2005), solicited from the meeting. He makes the point that the division of catastrophe v. continuity is somewhat artificial, and suggests it is better to consider the overall system in terms of response times to forcing or perturbations (implicitly acting with variable periodicities), producing steady (buffered) or transient (reactive) conditions. These conditions depend on the relative timescales and coupling of the internal (e.g. tectonics) and external (topography, climate) systems.

These concepts are considered in the context of normal fault systems, such as the western USA, where the tectonic displacement field is reasonably well understood and the depositional systems recording the erosional response are well characterized in terms of fault length, displacement and relief along the fault block. This approach leads to a characteristic timescale for steady-state foothill relief of about $10^6$ years. Analysis of bedrock incision in catchment areas implies response time of $10^2$ years for high concavity regions to more than $10^6$ years for larger low concavity catchments. Here response time is that required to achieve new equilibrium conditions. He also defines a relaxation time, effectively a time constant for the response (e.g. catchment denudation, sediment flux), which is typically an order of magnitude less than the response time determined from bedrock incision models.

Allen extends the analysis beyond the catchment to consider the fluvial response times (flood plains and alluvial) to periodic forcing and the influence on the upstream system. Typical response times are $10^4 – 10^6$ years, being slower for larger gravel fractions in the sediment load and for larger alluvial systems.

This range in, and the complications between, different timescales for equilibrium and relaxation response times, the duration and periodicity of forcing, and the sediment-transport system, clearly have implications for the inference of tectonic signals from the sedimentary record. This aspect is highlighted as a major challenge for the future.

The concept of equilibrium is central to many debates regarding landform evolution, but appears to have become blurred in terms of definition and somewhat muddied in terms of usage. Bracken & Wainwright review the origins and definitions of the terminology and highlight the fact that an appropriate definition depends on context, for example the difference in process regimes and responses between temperate and arid regions. A problem is how to measure or demonstrate geomorphological equilibrium, and previous attempts have included monitoring channel form, grade and correlations between system properties. These appear to suffer from a degree of circular reasoning that makes them generally unsatisfactory, particularly when arguing that form is a proxy for process equilibrium. An unavoidable issue in dryland environments is the fact that much of the activity is concentrated into rare large floods, and they discuss the case for equilibrium and nonequilibrium in the terms of the factors controlling the observed variations in morphology in these environments. They go on to consider the scale dependence (in both space and time) of equilibrium and highlight the common problems associated with choosing these when attempting to define equilibrium conditions. Feedback between different processes is also critical to the attainment of equilibrium, but again the significance depends on the scale, and becomes more difficult over longer timescales and large length scales, as different processes can interact with variable complexity. Finally, they discuss the impact of non-linearity, thresholds and chaotic behaviour on the inference of equilibrium. Overall, equilibrium seems too difficult to demonstrate unequivocally, and many ideas of this state are difficult or impossible to test in practice.

Fleurant et al. employ the CHILD (Channel–Hillslope Integrated Landscape Development) model in a novel context to investigate the formation of karst landscapes. In particular they concentrate on the development of cockpit karst,
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using modelling as a means of evaluating different hypotheses found in the literature. The different elements of a landscape-evolution model driven by dissolution processes are discussed and assembled from an extensive review of the literature. Simulations have been carried out over 10 million years, reflecting the timescale of known cockpit karstification in Jamaica. GIS analysis of measured karst features is used to evaluate the performance of the model. Results suggest that conceptual models that use isotropic dissolution to explain these features are unable to reproduce observed patterns in the landscape. A more complex model version that uses anisotropic dissolution is able to reproduce the observed features closely. This result supports interpretations of cockpit karst as epikarst phenomena, and provides a broader context for the understanding of the longer term soil-landscape evolution in Jamaica.

The theme of continuous versus catastrophic process is addressed directly in the contribution of Bardou & Jaboyedoff. They investigate the evolution of Alpine hillslopes as a response to débris flow activity, which they relate to classic concepts of frequency and magnitude in geomorphology. Data from a wide range of catchments in the Swiss Alps were used, covering a period of at least 25 years. A range of analytical methods suggests a break in behaviour of events, with a threshold event size of about $10^3$ m$^3$. As with other similar studies, the events show power-law scaling patterns. Stochastic modelling of the behaviour of this type of environment suggests that these different patterns can be explained by initial conditions as well as continuous processes such as weathering and catastrophic extreme events. The overall behaviour of such catchments needs to be understood as a complex set of interacting thresholds. Two case studies are then presented that illustrate the way in which these thresholds might evolve. The authors conclude with a brief assessment of how different types of catastrophic or continuous process in the landscape affect the management of risk in these environments at the present time.

Briant et al. address the issue of resolving of even shorter term (days, weeks) events such as flooding from the Quaternary geological record. Such events may dominate the record but the main problem is the lack of extremely high resolution absolute geochronological tools appropriate to this timescale (up to a few tens of thousands of years), coupled with lack of resolution in relative timing from sedimentology and palaeontology. The importance of this question comes from the desire to link longer term fluvial regimes to climate, which also clearly influences flood frequency. Additionally, the deposits produced by rare but large-scale floods may look similar to more frequent high-flow hydrological regimes. The authors examine these issues with a careful case study from central England, concluding that it is possible to link average fluvial activity to climate variations over timescales similar to the marine isotopic substage scale (about 10 ka, Shackleton 1969), but much finer resolution is currently not practical.

Vita-Finzi demonstrates that fluvial history and behaviour can be linked to solar activity. The fluvial history of the Mediterranean basin has long been recognized as having latitudinally diachronous, locally bipartite, episodes of fluvial aggradation during the period AD 500-1900. The theoretical consideration of Vita-Finzi, with support from general climate models, suggests that a decrease in solar radiation would lead to equatorward displacement of the subtropical jet streams and associated mid-latitude depressions. Vita-Finzi identifies a gradual decline in the Sun’s activity from c. 7000 BP followed by a resurgence after AD 500. This episode would account for the observed fluvial aggradation in the Mediterranean basin. Recognition of solar signals in the fluvial record has important implications for not only modelling of fluvial systems but also environmental analysis and flood forecasting.

Frostick et al. report on a series of flume experiments designed to visualize the process of entrainment for gravels and sand–gravel mixtures in order to identify differences that may account for enhanced rates of bedload transport in bimodal sediments common in upland river systems. They use new image analysis techniques of the experimental runs to reveal important differences in entrainment processes. Observations suggest that the presence of sand increases the rates of gravel entrainment and leads to a distinctive patchiness in break-up which will encourage bedform development. In mixtures where sand is removed prior to gravel entrainment the bed becomes destabilized and allows larger areas to be come entrained. These observations show the importance of bed material character in controlling river form and processes. They conclude by emphasizing the need for the inclusion of grain-size measures in the flux/power relationships if such models are to capture some of the complexities of the controls on sediment transport in the natural environment. It is therefore essential that more consideration is given to the range of grain sizes available for transport from reach to drainage basin scales, with less emphasis on the mean grain size in landscape models.

Extending the theme of sediment transport to a field setting, Jones & Frostick address the question of determining the behaviour of ancient rivers, as clearly these are an important aspect of landscape
development models. They deal with this in terms of palaeohydraulic conditions, parameterized in terms of stream power, bed load transport rates and efficiency. To infer these quantitatively, they need to determine palaeo-slope, -depth, -velocity and sediment thickness in Cenozoic/Quaternary gravel bed deposits in the Pyrenees in northern Spain. This determination requires identification and characterization of accretion directions (frontal or lateral) and size of accretionary foresets, measurement of sedimentological depth indicators and clast grain sizes. Such an approach is necessarily empirical and so they also address the uncertainties and bias in their approach systematically for the key parameters. The approach they develop tends to provide lower limits on the efficiency of bedload transport. They conclude that the main factors determining whether a gravel-bed river incises or transports are the sediment supply and the efficiency and rate of transport mechanisms to remove it.

Moving from the fluvial scale to the more regional considerations of landscape development, Calvet & Gunnell reassess the potential for inferring topographic evolution from erosion surfaces, although strongly making the point that a variety of other evidence needs to be considered in such a study. Thus, they also consider stratigraphy, geometrical relationships and palaeontological evidence. It is probably fair to say that erosion surfaces and geomorphological inferences based on them have received a torrid time going back at least 40 years (Chorley 1965, Bishop 1980, Summerfield 1991). These authors argue that some of these criticisms arise out of oversimplifying the formation of erosion surfaces, including the implicit assumption that they represent peneplanation at sea-level. They remap potential erosion surfaces based on the topographic dip from a digital elevation model, and quality-control these measurements with geological maps and field observations. They establish a relative chronology based on the other methods mentioned earlier and suggest that these surfaces reflect a regional control on the landscape as a consequence of well-defined base levels around the Pyrenees in the Miocene. They infer two generations of landforms: the residual summit surface and a lower pediment, and dismiss possible explanations in terms of stream power, bed load transport rates and efficiency. To infer these quantitatively, they need to determine palaeo-slope, -depth, -velocity and sediment thickness in Cenozoic/Quaternary gravel bed deposits in the Pyrenees in northern Spain. This determination requires identification and characterization of accretion directions (frontal or lateral) and size of accretionary foresets, measurement of sedimentological depth indicators and clast grain sizes. Such an approach is necessarily empirical and so they also address the uncertainties and bias in their approach systematically for the key parameters. The approach they develop tends to provide lower limits on the efficiency of bedload transport. They conclude that the main factors determining whether a gravel-bed river incises or advances are the sediment supply and the efficiency and rate of transport mechanisms to remove it.

A related morphometric approach is taken by King in his analysis of landforms in South Africa. An extensive dataset was compiled using data derived from a range of map and remotely sensed sources. These data are used to evaluate the major controls on semi-arid landforms in an area of relatively little tectonic activity. Slope shape seems to be most significantly controlled by rainfall amount and local relief, with rock type exerting a less strong control. At intermediate rainfall amounts, vegetation cover seems be a significant factor in affecting the shape of the landscape. These landscapes seem to be relatively recent (i.e. post-dating Late Pliocene uplift) and the result of pedimentation produced by diffuse overland-flow processes.

Finally, Mitchell presents an overview of recent work on erosion in submarine channels, drawing analogies with the morphologies produced by sub-aerial erosion in river channels. The morphologies can be characterized by longitudinal profiles, displaying variable concavity and gradient-area graphs in which steeper gradients are associated with smaller areas, and tributaries join the main channels with no major change in bathymetry (analogous to Playfair’s law in geomorphology). Although there are many similar features to those observed in river channels, it is difficult to make direct observations of erosion in the submarine environment. One clear difference is that submarine channels are more directly influenced by slope failure and subsequent sediment flow erosion. This tends to occur in discrete local channels at different times. However simple but relevant models for associated channel erosion are quantitatively similar to stream power erosion laws in fluvial bedrock channels. Oceanographic currents can also lead to soft sediment erosion and locally to incision of tens of metres. Additionally, sediment can accumulate between channels preferentially (on interfluves), while it is flushed from within the channels themselves. This process can lead to enhanced channel relief. Currently there are no methods to quantify erosion analogous to those available to subaerial geomorphologists such as cosmogenic exposure dating or thermochronology, and this is a direction for future research. Mitchell discusses simple erosion laws, noting the similarities and differences to the sub-aerial situation. The former include the basic methods of erosion, abrasion, plucking and quarrying by the flow of relatively high density material and the apparent behaviour of knickpoints, while the latter include the sensitivity of flow strength to the nature of the solid load and the controls on shear failure.

Clearly, there remain many outstanding research questions in this field. In terms of conceptual
advances, for example, the relative contributions of climate and tectonics in terms of cause of and effect, the nature of feedbacks, both positive and negative, of controlling factors, their scale dependence in both space and time and the role of thresholds versus continuous processes, are still regarded as open questions. The interrogation of the geological record is always problematic, given its incompleteness and ambiguity. Consequently, although the resolving power of absolute dating tools improves continually, the resolution of short-time scale phenomena in long timescale records remains elusive. Furthermore, understanding the links in, and controls of, a geomorphological system in terms of the processes of in situ chemical and physical breakdown, through transport and sediment routing to depositional basins, requires more integrated studies over a wide range of time and spatial scales.

Currently, many landscape-evolution models are empirically based, often incorporating lumped parameters of little intrinsic physical relevance, and so are difficult to determine independently of the model itself. The next generation of landscape-evolution models needs to move beyond the empirical, providing a sounder basis for understanding past processes in landscape evolution over geological timescales and, perhaps more topically, forecasting landscape development on human timescales.

References