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Landscape evolution: the interactions of tectonics and surface processes

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The last decade has witnessed a resurrection of historical concepts and controversies concerning the evolution of landscapes in active tectonic regimes. New insights into and quantification of spatial patterns of deformation and of surface processes have enlivened this debate and provided an impetus to address some long-standing questions. Under a regime of persistent tectonic forcing, are there predictable stages of topographic form through which a landscape will pass? What are landscape response times to changes in the rate and duration of tectonic forcing? How does the topographic response vary if tectonic forcing is steady over millions of years or is highly pulsed and separated by long intervals of quiescence? To what extent does the topographic form vary as a function of climate and changes in climate? How reliably can we read the record of past tectonic and climatic events in the landscape, and how far back in time can this record be extended? Spurred by improved measurement of deformation at time-scales ranging from co-seismic (Hager *et al.*, 1991) to several millions of years (DeCelles *et al.*, 1998) and by an enhanced understanding of the rates and controls of surface processes, answers to some of these questions are emerging. Although none is likely to be completely answered by individual studies, the papers in this special volume provide a sampling of the range of approaches presently being employed in studies of regional topography and tectonics.

One major advance in studies of active tectonics and topography is that the strain fields associated with individual seismic events are being documented with unprecedented accuracy and breadth. Ground-based surveys have measured the patterns of co-seismic deformation on normal and reverse faults in two dimensions (Stein *et al.*, 1988), and these measurements underpin attempts to understand co-seismic strains in the upper crust using elastic half-space models (King & Ellis, 1990). For the first time, radar interferometric studies are documenting co-seismic displacements over 1000s of km^2 at cm-scale resolution (Massonnet *et al.*, 1993), such that regional patterns of displacement are now being delineated, even at long distances from the active fault. Geodetic measurements, and particularly GPS campaigns, have recently characterized regional interseismic strain fields in many actively deforming areas (e.g. Norabuena *et al.*, 1998). The similarity of geodetically determined strain rates at decadal time-scales to the long-term rates derived from sea-floor spreading rates and plate motions (DeMets *et al.*, 1990) has suggested to many investigators that the decadal geodetic rates provide a reasonable proxy for the long-term rates of plate motions (Donnellan *et al.*, 1993; Abdrakhmatov *et al.*, 1996). If true, geodetic measurements provide an accurate snapshot of the tectonic forcing function at regional scales that drives long-term landscape development. Combined with geological indicators of tectonism, geodesy helps to reveal considerably more than previously possible about the detailed spatial distribution and magnitude of deformation over broad regions and over a wide range of time-scales.

In addition to tectonism, the second major ingredient in shaping actively deforming landscapes is the role played by surface processes. This set of processes not only modifies tectonically generated landforms, but erosion and deposition may actively influence patterns of deformation (Pinter & Brandon, 1997). The debate concerning landscape evolution has been enlivened and advanced by new approaches and the application of new technologies to geomorphic problems. During this debate, several major themes have recurred:

- Numerical models of diverse surface processes can be coupled to create synthetic landscapes whose properties mimic key attributes of real-world landscapes (Willgoose *et al.*, 1991; Howard, 1994; Tucker & Slingerland, 1994; Braun & Sambridge, 1997). When compared with landscapes in which topography, age and geomorphology have been quantified, these models can provide insights concerning the relative importance of specific processes in shaping regional topography. For example, in a surface-process model, it is possible to systematically test how changes in variables such as water discharge, sediment flux, rock strength, glacial erosion rates or stable hillslope angle affect the spatial distribution of topography, erosion and deposition (Tucker & Slingerland, 1996; Densmore *et al.*, 1998).
- In actively deforming mountain belts, interactions and feedback between tectonics, climate and surface processes influence not only the geomorphology but also may control patterns and rates of strain in orogens (Beaumont *et al.*, 1992). Coupled tectonic–geomorphic models often suggest that high strain rates are spatially associated with high erosion rates. For example, the presence of a large, underloaded river in an active mountain belt may permit very rapid erosion, thereby accelerating rock uplift in that area (Koons, 1998). More surprisingly, perhaps, is the prediction that, given identical conditions of tectonic forcing, the direction from which moisture is advected toward an orogen will exert a fundamental control on

the positions of zones of high or low strain (Willett *et al.*, 1997) as the windward flank of a range gathers more precipitation and is subjected to more intense erosion (Hoffman & Grotzinger, 1993).

- A dynamic equilibrium or steady-state topography (Hack, 1960) may develop when rates of tectonic forcing are high and when tectonism is sustained for long intervals (>1 Myr). For example, if rock uplift rates are greater than a few millimetres per year, bedrock will be vertically displaced several kilometres every million years. Because erosion rates tend to increase with increasing altitude (Ahnert, 1984), increases in average regional altitude in growing mountain ranges tend to slow over time. When dynamic equilibrium is attained, the rates of whatever erosional processes control longitudinal valley profiles (river incision or glacial erosion) must match rock uplift rates over the long-term, and hillslopes are likely to be at threshold angles (Schmidt & Montgomery, 1995; Burbank *et al.*, 1996). Under such conditions of dynamic equilibrium, the height of the land surface at any particular point in the landscape may be increasing or decreasing, but the mean height of the region is unchanging, and regional relief should remain nearly constant with time. Dynamic equilibrium does not preclude topographic change at local scales or over short time intervals, but rather refers to characterizations of landscapes at scales relevant to geophysical calculations (≥ 100s of km^2) and at time-scales that typically exceed those of major climatic cycles ($>10^5$ years). Although theoretically attractive, assessing the presence or absence of dynamic equilibrium in real landscapes remains problematic.
- Between the initiation of deformation and the attainment of a dynamic equilibrium, pre-steady-state mountains may evolve through a succession of topographic and structural changes. Although recognition of pre-steady-state conditions is not always straightforward, increases in mean altitude or topographic relief through time or progressive dissection of formerly low-relief geomorphic surfaces are indicative of pre-steady-state mountains (Abbott *et al.*, 1997; Hovius, 1998). The presence of plateau-like regions within mountains is commonly thought to be incompatible with steady state, with the exception of vast areas like the Tibetan Plateau, which may have attained a maximum sustainable height (Molnar *et al.*, 1993). For any collisional range, attainment of an eventual steady state is not inevitable, if the duration and magnitude of tectonic forcing are insufficient. With each major change in the regional strain field, new structures in different orientations may emerge to accommodate the strain, and the competition between erosion and rock uplift will begin anew, with erosion initially lagging rock uplift. In such circumstances of changing tectonic geometries and variation in rates of tectonic forcing, a dynamic equilibrium may never be attained.
- There remains considerable debate concerning the effects of climate and climatic change on regional topography and the evolution of orogens. Much of this debate continues to focus on the role of various climate-driven geomorphic processes in increasing topographic relief. Erosional removal of material causes isostatic compensation and uplift that may be a significant component of total measured rates of rock uplift (Molnar & England, 1990; Small & Anderson, 1995). Given the evidence that glaciation can dramatically increase erosion rates (Hallet *et al.*, 1996), it has been suggested that in mountain ranges located in regions of abundant precipitation, glaciation can create an 'erosional buzzsaw' that removes the majority of rock mass above the glacial equilibrium-line altitude (Brozovic′ *et al.*, 1997). Fluvial incision is probably the dominant agent of relief-generation, and cutting of deep gorges and the resulting isostatic compensation may explain the great height of the Himalayan peaks relative to the low-relief surface of the adjacent Tibetan Plateau (Fielding *et al.*, 1994).
- New data sets, such as digital elevation models, permit characterization and comparison of regional landscapes with a resolution, accuracy and breadth that was heretofore unattainable (Lifton & Chase, 1992; Fielding *et al.*, 1994). Calculations of mean altitude, relief, hypsometry and slope distributions or numerical characterization of drainage networks and river profiles can now be accomplished with a few key strokes. Similarly, new dating tools, such as cosmogenic radionuclide exposure analyses (Nishiizumi *et al.*, 1993; Bierman, 1994), are enabling reliable dating of geomorphic features that were previously uncalibrated. This injection of time facilitates quantitative definitions of tectonic and geomorphic process rates where previously only relative histories and qualitative rate estimates were possible.

The papers within this special volume utilize some of these new data sets, they use field data to document pre-steady-state and possible steady-state landscapes, and they set forth numerical models which quantitatively define landscape evolution as an interplay between geomorphic processes, tectonic deformation and climatic controls.

Numerical models of landscape evolution

The physics of many geomorphic processes are still poorly known. For example, with respect to the process of river incision into bedrock, the role of abrasion vs. plucking, the efficacy of sand in suspension vs. clasts in the bedload as agents of erosion, and the most appropriate quantitative proxy for bedrock erosion (total stream power, bed shear stress, excess shear stress, or specific stream power) are all being debated (Slingerland *et al.*, 1998). Whereas none of these numerical proxies provides a physical description for how erosion actually occurs, several of them yield predictions for varying rates of bedrock incision that are consistent with field observations (Anderson, 1994; Howard *et al.*, 1994; Densmore *et al.*, 1998).

Similar uncertainties with respect to erosion processes pertain to the creation of marine terraces and abrasion platforms: the subject of the paper by **Anderson *et al.*** in this issue. Whereas the actual physical processes by which wave energy is converted into bedrock erosion along sea coasts are poorly known, it is clear that, in conjunction with bedrock resistance and chemical weathering of the rock, the amount of energy delivered by waves to the coast is a key measure of the degree to which an abrasion platform will be widened. Recognizing that part of the far-field energy of waves is dissipated by interaction with the sloping sea floor that lies above wave base, Anderson *et al.* introduce a dissipation function into their energy delivery equation. This dissipative wave-energy equation is combined with climatically driven sea-level variations and nonvarying rock uplift through time in order to model the generation of successive wave-cut platforms. One of the key predictions of the Anderson *et al.* model is that the age and width of preserved abrasion platforms on a rising coast is different with and without energy dissipation. Anderson *et al.* also examine the geomorphic changes that transpire as a pristine abrasion platform–seacliff couplet is raised above sea level and subjected to terrestrial erosion and deposition. Their models predict that, through time, hillslope diffusion, soil production and channel erosion progressively obscure and then obliterate uplifted marine terraces (Anderson, 1994). In essence, the rising coast is viewed as a temporally limited tape recorder which faithfully documents the creation of marine terraces, but which has only a limited memory before remnants of the older terraces are removed from the landscape. Such a model describes a form of steady-state coastal landscape, whereby there is a restricted altitudinal zone within which marine terraces are preserved. They are created at the base of this zone (the shoreline), and by the time they reach the top of the zone, surface processes have removed them as recognizable geomorphic entities in the landscape. The altitudinal width of this zone will be a function of the rapidity of rock uplift, the strength of the rock and the rate of erosion. Anderson *et al.*'s model provides key insights concerning possible ways in which wave energy, rock uplift, varying sea level and terrestrial erosion processes interact to form the fringes of marine terraces that commonly adorn the lower reaches of tectonically active coasts.

Ellis *et al.* present a numerical model for landscape evolution in extensional terranes analogous to the Basin and Range. Building on their previous work with their three-dimensional landscape evolution model termed ZSCAPE (Densmore *et al.*, 1998), they present a finite-difference model designed to quantify erosion, sediment transport and deposition by important terrestrial surface processes, such as bedrock erosion by rivers, production and creep of hillslope regolith and bedrock landsliding. Tectonic forcing is represented by normal faulting increments (earthquakes) which have uniform displacement along the strike of the fault and which are imposed on an initially planar, low-relief surface. Climate is varied by advecting moisture into the range from either one of its opposing flanks, thereby creating precipitation gradients and rain shadows across the ranges. Across the emergent landscape, they track the changes in topographic relief through time. Initially, as rock uplift outpaces erosion, mean relief increases. A key conclusion of their model runs is that relief reaches an approximately constant value after $\sim 1–5 \times 10^5$ years. Because such a condition is one measure of a topographic steady state, their model predicts a geologically rapid evolution toward a dynamic equilibrium in these normal faulted terranes. Interestingly, they also find that the magnitude of relief predicted by their model runs is largely independent of the rate of slip on the normal fault bounding the range. In the experiments presented here, orographic precipitation shifts the drainage divide toward the windward side of the range. This unexpected model prediction results from the inability of the closed windward basin to shed its sediment fill, which therefore increases base-level on the windward side and concomitantly decreases windward stream power.

The three-dimensional landscapes that result from ZSCAPE model runs exhibit many of the attributes commonly seen in Basin-and-Range topography, such as triangular facets, bevelled crests of spurs and concordant spur heights. Interestingly, the topography of interfluves can be seen to be a consequence of the geometry and graded nature of tributary drainages. These fluvial geometries are not imposed as model inputs, but result from the modelled surface processes acting upon the uplifting substrate. The power of such modelling is illustrated by its ability to capture such landscape elements and to suggest which interactions among variables and processes are responsible for the development of these features.

Observations and processes in pre-steady-state landscapes

The remaining three papers in this volume deal with modern landscapes that either clearly display pre-steady-state topography or which may be approaching a steady state. Each of these papers combines analysis of topographic attributes with present-day drainage geometries and geomorphology to gain insights on evolution of the land surface.

In the mountains of central Japan, **Sugai & Ohmori** attempt to define the geomorphic evolution in Japanese mountains of pre-steady-state topography toward a steady state. In the study area in central Japan, a low-relief surface formed at low altitudes and is now being uplifted and attacked by erosion. Sugai & Ohmori distinguish two classes of rivers associated with these uplifted surfaces: one group (α drainages) originates on the upland surface and has a prominent knickpoint that separates the low-gradient reach of the river on the upland surface from the steeper reaches below the surface; the second group (β drainages) originates on the slopes flanking the upland surfaces, such that the upper limits of their catchments generally coincide with the outer edge of the remnants of the low-relief surfaces. As rock uplift increases the altitude of these surfaces, headward erosion by β rivers on their opposing flanks drives the headwater regions of these catchments toward each other. Not only does this process consume the low-relief topography, it also ultimately creates an abrupt, steep-sided drainage divide that becomes the ridgepole of the range. Sugai & Ohmori recognize subregions of the mountainous landscape which appear to represent different stages in the transformation from a pre-steady-state to a steady-state topography. Within these regions, they analyse catchment attributes, such as relief, stream length, drainage spacing, catchment gradient and altitudes of the drainage divide and tributary junctions. Although there are strong correlations among many of the measured attributes, they analyse most of their results as functions of the altitude of the valley head, because this altitude is viewed as a proxy for the amount of rock uplift that has occurred. Given the assumed low relief of the initial surface, this proxy is reasonable until the low-relief surface itself is consumed by erosion, after which, the valley-head altitude sets a lower bound on the actual magnitude of rock uplift. As the altitude of the valley head increases and dissection of former low-relief surface progresses, Sugai & Ohmori document systematic increases in relief, β-stream length and catchment gradient. The steepening gradients indicate that vertical incision and relief development increase more rapidly than does headward erosion in the β catchments. Notably, there are also increases in drainage spacing, as recorded by the distance between β-tributary junctions on opposite flanks of a range. This implies that, with increased rock uplift, there is a subtraction of trunk streams. Such a subtraction (or integration) of trunk streams must occur in order to produce the consistent drainage-spacing to range-width ratios found in many compressional ranges (Hovius, 1996; Talling *et al.*, 1997).

Overall, Sugai & Ohmori's analysis suggests systematic changes in the mountainous landscape of Japan during uplift. Initial dissection of low-relief surfaces produces relatively closely spaced valleys separated by interfluves with trapezoidal cross-sections. Steep β catchments define the flanks of the trapezoid, whereas the low-relief uplands form the top surface. With continuing rock uplift, headward expansion of the β-tributaries eliminates the low-relief surface, increases the drainage spacing and creates a triangular interfluvial geometry. Finally during the approach to steady state and following more rock uplift, slopes steepen to critical angles, drainage spacing and relief increase until critical slopes cover the entire interfluvial area and rates of river incision are matched by rates of lowering of the drainage divides.

The key to testing Sugai & Ohmori's model will come from further studies that inject more time control into the landscape, so that the seemingly logical progression of landforms can be placed in a temporal context. Already some limits on the relevant rates of rock uplift are available, but more data are needed to examine rates of headward erosion, river incision, regional erosion and drainage-divide lowering.

An interesting compliment to the work of Sugai & Ohmori is provided by **Meigs *et al.*** who utilize the tectonic geomorphology of the Santa Monica Mountains in southern California to examine the ongoing competition between rock uplift and erosion. This study provides a clear illustration of the geomorphic contrasts between regions with different lithologies that are subjected to similar rock uplift rates. In fact, Meigs *et al.* suggest that drainage spacing, catchment geometry and relief are all more dependent on rock strength, rather than on the amount or rate of rock uplift. Based upon several different approaches to define rock uplift rates, their data highlight the difficulties and uncertainties that commonly beset calculations of long-term denudation and rock uplift rates. The coastal setting permits them to exploit marine terraces as markers of deformation, and previous geological mapping and drill-hole data allow their development of geological cross-sections of the fold-and-thrust belt. Meigs *et al.* analysed a 30-m DEM of southern California to demonstrate that striking contrasts in drainage density, topographic relief and slope distributions along the range are closely associated with changes in bedrock geology. More resistant substrates tend to produce steeper, more widely spaced drainages with greater topographic relief. Drainage asymmetries across the range tend to mimic the geometry of folding. Modern sediment-discharge data and incision of late Pleistocene marker horizons are used to estimate the present rate of denudation within the Santa Monica range, whereas long-term rates of rock uplift are derived from uplifted marine terraces and structural cross-sections. Given the large uncertainties in the rate calculations, Meigs *et al.* calculate that the rock uplift rates and denudation rates are $\sim 0.5 \pm 0.4$ mm yr^{-1} and that they can be considered to be approximately balanced.

It is debatable whether or not the Santa Monica Mountains have actually attained a topographic steady state. If they have, then the surface processes which are acting on relatively gentle slopes ($<15°$) must result in rates of denudation (0.5 mm yr^{-1}) that appear uncharacteristically high for such slope angles. Alternatively, 20th-century denudation rates may reflect anthropogenically enhanced rates of sediment mobilization and discharge that are atypical of longer-term rates. Similarly, the considerable and unavoidable uncertainties in calculated rates may mask an actual mismatch, whereby uplift systematically outpaces erosion; in such a case, the topography cannot yet be in steady state.

In the Kyrgyz Tien Shan, growing contractional mountain ranges are accommodating as much as 40% of the total convergence between India and Asia. An unusual stratigraphy prevails over much of the Kyrgyz Tien Shan, whereby several kilometres of relatively erodable Cenozoic strata overlie a regionally extensive unconformity that is bevelled across far more resistant Palaeozoic rocks. This stratigraphy sets the stage for an analysis by

Burbank *et al.* of the progressive evolution of a pre-steady-state landscape. As deformation initiates and ranges are raised above local base level, a predictable suite of geomorphic changes ensue. Whereas the Cenozoic strata are readily stripped from above the unconformity surface, the exhumed surface itself can be elevated more than 2 km above local base level without experiencing significant erosion. Until the unconformity surface is dissected by fluvial and hillslope processes, it provides an excellent structural marker that faithfully records the magnitude and geometry of folding and faulting. Burbank *et al.* use digital topography where it corresponds to the exhumed unconformity to demonstrate along-strike variation in fold growth, linkage among multiple structures and the compensation in displacement that occurs near the overlapping termini of *en echelon* folds: as one fold dies in magnitude, the other grows, thus maintaining an approximately uniform shortening across the region. The contrast in erodability between the Cenozoic and Palaeozoic rocks also produces strong geomorphic contrasts among the folds. Folds still mantled by Cenozoic strata are characterized by high drainage densities, low relief across folds, and persistence of antecedent rivers across folds, whereas folds in which the unconformity on the Palaeozoic rocks has been exhumed are characterized by weakly dissected surfaces, high relief across folds and defeat of formerly antecedent rivers. Despite apparently rapid rates of rock uplift (>6 km in less than 2 Myr), the presence of extensive remnants of the exhumed unconformity surface is incompatible with steady-state topography. Although some numerical models would suggest that, when rates of rock uplift are >3 mm yr^{-1} for several million years, a topographic steady state is likely to be attained (Beaumont *et al.*, 1992), the ranges studied by Burbank *et al.* in the Tien Shan provide examples of spectacular, but clearly pre-steady-state topography.

What's next?

The papers in this issue deal primarily with large-scale landscape evolution, and each one reveals key opportunities for further research. Numerical models that rely on erosion equations need to be underpinned by further measurement and quantification of the processes that act in diverse hillslope and channel environments. Whereas it is inevitable that numerical models represent simplifications of actual physical processes, the models need testing against data in order to assess how well their simple calculations approximate actual processes.

All five papers deal with landscape evolution, and all would benefit from greater time control on the development of those landscapes. Without such temporal control, process rates can only be estimated, ages of land surfaces remain speculative and evolutionary models remain uncalibrated. Clearly the development and implementation of new dating techniques and strategies is needed. Judicious choices of study areas will hasten the success of such projects, because the presence of volcanic ashes, datable stratigraphy and geomorphic markers of known age and initial geometry guarantees that rates of geomorphic processes can be calculated.

A third avenue that needs to be pursued in these studies is improved definition of the tectonic processes that drive rock uplift or subsidence. Knowledge of scaling relationships for normal faults has blossomed in recent years (Dawers *et al.*, 1993; Scholz *et al.*, 1993; Cartwright *et al.*, 1995; Dawers & Anders, 1995) and provides some basis for understanding how such faults nucleate, propagate and link together over time. These faults and the displacements associated with them are fundamental building blocks for mountain building in extensional ranges. Unfortunately, similarly detailed data on the scaling and linkage of reverse and thrust faults do not exist at present. Studies that fill this gap or define strain partitioning in transtensional and transpressional settings will underpin further advances in understanding contractional mountain belts and associated tectonic geomorphology.

Finally, water is a key ingredient in many geomorphic processes. Yet, its distribution in mountainous areas as a function of orographic precipitation is poorly known. Given the multitude of weather stations around the world, it is remarkable how few records are available to document precipitation variations within the high mountains that intrigue many tectonic geomorphologists. The availability of digital topography and the advent of increasingly sophisticated means of remotely and directly measuring precipitation provide an opportunity to resolve the problem of precipitation distribution and intensity in the coming years. This will, in turn, improve efforts to understand water's routing through landscapes and its impact on erosion, deposition and transport of sediments in actively deforming mountain belts.

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