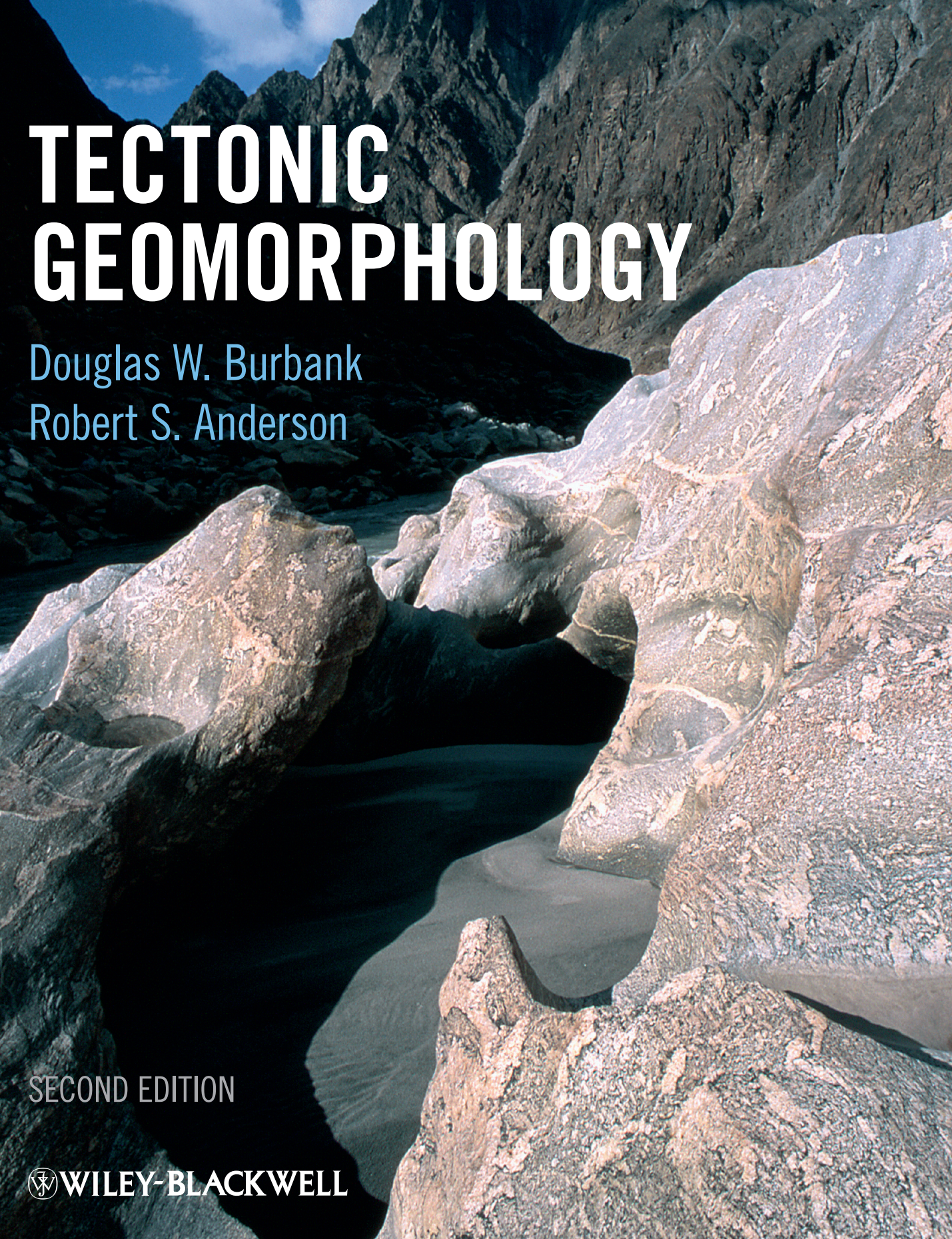




TECTONIC GEOMORPHOLOGY

Douglas W. Burbank

Robert S. Anderson

SECOND EDITION

 WILEY-BLACKWELL

TECTONIC GEOMORPHOLOGY

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Tectonic Geomorphology



Second Edition

**Douglas W. Burbank
and Robert S. Anderson**

 **WILEY-BLACKWELL**

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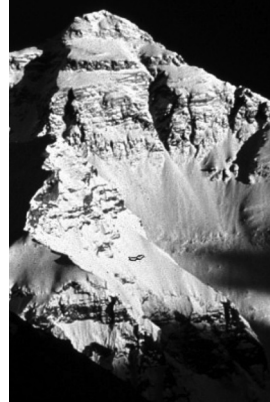
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DEDICATED

to

Rachel and Suzanne, Helen and Jack, Flodie and Andy.

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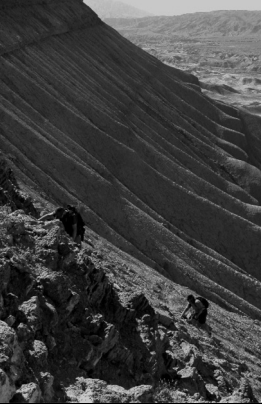
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Preface to First Edition

No one can gaze at satellite images of the earth's surface without being struck by the crumpled zones of rocks that delineate regions of ongoing and past tectonic deformation. Landscapes in tectonically active areas result from a complex integration of the effects of vertical and horizontal motions of crustal rocks and erosion or deposition by surface processes. In a sense, many landscapes can be thought of as resulting from a competition among those processes acting to elevate the earth's surface and those that tend to lower it. The study of this competition and the interpretation of the geodynamic and geomorphic implications of such landscapes is the focus of tectonic geomorphology.

Tectonic geomorphology is a wonderfully integrative field that presents stimulating challenges to anyone trying to extract information from deforming landscapes. Consider, for example, a typical subject for a tectonic geomorphic study: a growing fold in the hangingwall of a thrust fault. The fault cuts the surface along much of its length, but diminishes in displacement towards its tip, where no surface break is present. How is the shape of the fold related to the mechanical properties of the faulted material? How much slip occurs in an individual earthquake on that thrust fault and what is the detailed pattern of deformation? How far does the tip of the thrust propagate laterally and how much does the hangingwall grow with each rupture? Is a similar pattern of deformation repeated in successive earthquakes? What is the interval between earthquakes? Can the preserved structural form of

the fold be explained as the sum of deformation during earthquakes alone, or is there significant interseismic deformation? How is the surface of the fold modified by erosion and deposition as it grows in length and height, and are there systematic changes along the fold that define a predictable evolutionary pattern of the landscape above such faults? Are the patterns and rates of erosion influenced more by tectonic or climatic forcing? What are the relative and absolute rates of rock uplift and erosion within the hangingwall and how is any imbalance reflected by the resulting landscape? In order to answer these questions, one has to draw on an understanding of paleoseismology, geodesy, structural geology, geomorphology, geochronology, paleoclimatology, stratigraphy, and rock mechanics, because each underpins some aspects of the interplay of tectonics and erosion. Key parts of the answer to each question are embedded in the landscape and are the subject of tectonic geomorphology.

Although efforts to interpret the processes that generate dynamic landscapes are not new, several key advances in the past few decades have provided a more robust foundation for rigorous analysis, and have opened up entirely new avenues of research.

- The development of new chronologic techniques permits us to inject time control into many facets of a landscape that were formerly unconstrained. The plethora of new dating approaches underpins most of the success in defining rates of processes.

- Process-oriented geomorphic studies have served to improve our understanding of the physical basis of surface processes. Insights into the key physical phenomena that control erosion and sediment transport have led to the development of both conceptual and quantitative models that can be applied in landscape analysis.
- Understanding of the record of past climate change has deepened immeasurably, such that the magnitude and rate of past climatic variability is now better calibrated than ever before. The impact of climate change on surface processes and landform development can now be better addressed in this detailed framework.
- New geodetic tools are providing an incomparable overview of rates of deformation of the earth's surface. Not only can changes in distances between specific points be documented with unprecedented accuracy, but the spatial pattern of deformation following an earthquake can now be documented across vast areas.
- Paleoseismology, the study of the record of past earthquakes, has matured into a diverse discipline and has provided a basis for documenting the behavior of faults, their impact on adjacent landscapes, and the societal hazards that they pose.
- Instead of conducting regional tectonic analyses, many structural geologists have focussed increasingly on the physical characterization of faulting and folding, on scaling relationships, and on the interactions among faults. Such studies show how fundamental building blocks like faults evolve through time and influence patterns of deformation.
- The widespread availability of digital topography and the development of new ways to obtain accurate topographic data through forest canopies, clouds, and oceans has facilitated a time-efficient quantification of topographic attributes that was previously unattainable.
- The accessibility to high-speed computing has underpinned the development of numerical models that exploit the results of many

of the fields enumerated above. More importantly than providing a means to numerically re-create some observation, these models facilitate exploration of the potential interactions, sensitivities, and response times among changing processes.

The list could be much longer, but the point is clear: this is a time of unusual opportunity in tectonic geomorphology. The confluence of new approaches, tools, and data bases is leading to rapid changes in our understanding of how the surface of the earth evolves in regions of active tectonism. These topics are the focus of the present book.

This book is organized somewhat differently than most other books on this topic. The initial chapters are devoted to fundamental building blocks and individual disciplines in tectonic geomorphic studies: geochronology, structural characteristics of faults and folds, the nature of geomorphic "markers" that can be used to keep track of deformation, geodesy, paleoseismology, and strategies for calculating rock uplift and erosion rates. Rather than following these chapters with discussions of tectonic geomorphology in specific geomorphic settings, such as fluvial or coastal environments, we have chosen to view the landscape within different time frames, ranging from $<10^4$ yr to more than 1 million years. The choice of each time window is not arbitrary, but instead reflects our understanding of how the tectonic and geomorphic information that can be extracted from a landscape varies as a function of time. In our view, these time scales reflect the relative dominance of surface or tectonic processes in shaping a landscape, the degree to which a landscape preserves the record of individual or small groups of events, and the time scale of interactions between climate, erosion, and tectonics. Contrasting types of tectonic geomorphic information are embedded in landscapes at these different time scales. The appropriate questions to ask and the proper techniques for extracting answers also differ as a function of time.

The reasoning behind this subdivision of our text may become more clear if you again

consider the fold growing above a thrust fault. Individual earthquake ruptures occur at Holocene time scales. Essentially instantaneous, co-seismic deformation changes geomorphic gradients and forces adjustments within the geomorphic system. Just after the earthquake, the entire displacement field will be almost perfectly recorded by the deformed ground surface and consequently provides an excellent opportunity to delineate relationships among rock properties, displacement gradients, and seismic characteristics. Over the ensuing centuries, fault scarps will degrade, and geomorphic processes will modify the hillslopes and the channels of the landscape toward a new equilibrium with the altered geometry of the surface – until the next earthquake induces another cycle of adjustment. Throughout this interval, the average geomorphic surface is likely to mimic the aggregate strain accumulated over several seismic cycles.

At times scales of 100,000 years or more, major swings in the climate will have occurred, dozens of earthquakes will have progressively deformed the fold, and geomorphic processes will have incised uplifted surfaces of the fold. The geomorphic surface is less likely to mimic the strain field, and climatic changes are likely to have created a distinctive imprint on the fold's surface. The steepest portions of a river crossing the fold may now occur over the fold crest, rather than on the forelimb of the fold. At these time scales, the geomorphic system associated with the fold will evolve as the structural relief increases and the fold propagates laterally.

At intervals of a million years, it is likely that the blind thrust beneath the fold has linked up with other faults, or has died, or is now embedded in a series of growing structures. The topography and the regional pattern of accumulated strain may be largely decoupled, such that the highest topography may not match the structural crest of the fold. But the gradients of rivers, the presence of water gaps, and the spatial array of geomorphic elements, such as catchment geometries or slope distributions, will reflect the long-term evolution of the fold-and-thrust belt.

The final chapter of this book is devoted to numerical modeling of landscapes. These

models have now evolved to be able to handle the complexity of the deformation fields, and the temporal and spatial complexity of the geomorphic processes that modify a landscape. They can be used to test old conceptual models of landscape evolution, to generate new strategies for field documentation of the relevant processes and their rates, and as educational tools to allow visualization of landscape evolution. We do not attempt to provide a complete guide or a cookbook for such modeling. Rather, this chapter represents an introduction to different types and scales of numerical models, and provides what could be termed “building blocks” for landscapes: the displacement fields associated with individual faults, and with orogen-scale deformation fields at depth, and the “rules” commonly used for movement of regolith on hillslopes, the transport of sediment in channels, and bedrock incision of streams. We illustrate the linkage of tectonic and geomorphic process models with examples ranging from simple models of evolving fault scarps to more complex models of entire tectonically active landscapes.

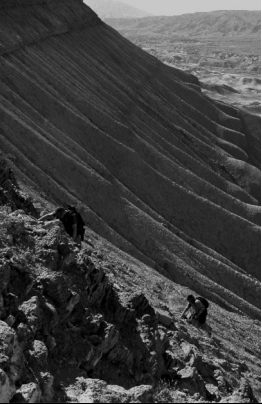
The field of tectonic geomorphology has been advancing and expanding so rapidly that it has been difficult to keep this text abreast of the latest developments. Despite its obvious shortfalls, it is our hope that this text will serve as a useful springboard for those geologists wanting an introduction to tectonic geomorphology and as a helpful reference for those of us who are pursuing research in aspects of this broad, highly integrative, and rapidly evolving field. It is our hope that upper level undergraduates and students early in their graduate careers will find this to be a useful and accessible introduction to tectonic geomorphology.

Many people played a role in the production of this book. John Grotzinger invited one of us (DWB) to come to MIT as a Crosby Lecturer and to develop a course on tectonic geomorphology. The idea of this book sprang from those lectures and the realization that there appeared to be a need for such a text. Doug Hammond and Bob Douglas at USC and Dick Walcott at Victoria University provided logistical support

during various stages of writing, while Bill Bull, Steve Wells, Ed Keller, and Paul Hoffman provided early suggestions regarding content and format. We greatly appreciate the wisdom and guidance of our own teachers and research advisors, who set us on a path that has allowed us to range widely through the disciplines of the earth sciences. These include Steve Porter, Tom Dunne, Noye Johnson, Bernard Hallet, Jim Smith, Peter Haff, and Gary Johnson. Our research collaborators, colleagues, and many former students provoked us with their ideas and engaged us in discussions that helped shape this book. In particular, we would like to thank Nic Brozovic, Andrew Meigs, Julio Friedmann, Jaume Vergés, Richard Beck, Fritz Schlunegger, Ian Brewer, Mike Ellis, Jeff Marshall, Alex Densmore, Greg Hancock, Eric Small, Dan Orange, Kelin Whipple, Liz Safran,

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Doug Burbank
Bob Anderson



Preface to Second Edition

This past decade has seen an explosion in research across the entire spectrum of tectonic geomorphology. Such a blossoming of creative approaches and novel results has begun to generate a new perspective on the interactions of tectonics with surface processes: a perspective that has spurred us to produce a second edition of our 2001 book.

Several key elements have underpinned significant advances over the past decade. The abundance of readily available, high-resolution digital topography for much of the globe, such as that made publicly available at increasingly higher resolution by NASA, has enabled a new quantification and comparison of landscapes. New imagery around the globe that is accessible through portals like Google Earth™ has ushered in a new era of armchair exploration and analysis of distant and remote landscapes by geomorphologists, whereas meter-scale topography, such as that derived from radar altimetry, such as Lidar, has provided unprecedented spatial resolution and a striking view of the “bare Earth” in which trees and shrubs have been removed. Soon, we expect that terrestrial laser scanning will represent a common tool exploited by geodesists and geomorphologists for cm-scale (and smaller) measurements, whereas Google Earth may enable meter-scale measurements of rivers, glaciers, and landslides.

This improved quantification of landscapes has proceeded hand-in-hand with an enhanced view of how the Earth deforms. Not only has InSAR analysis matured, but the number of continuous GPS sites has increased by an order

of magnitude since 2000. Currently, some tectonically active terrains, such as Taiwan or the western US, host dozens of geodetic arrays that provide mm-scale precision at sub-annual time scales. Similarly, dense seismological arrays are yielding better reconstructions than ever before of earthquake ruptures, fault geometries, and seismogenic structures in the crust.

New syntheses of space-based observations of the earth, oceans, and atmospheres are providing both a more holistic Earth view, as well as an enhanced ability to draw quantitative comparisons. Satellite measurements of rainfall on an annual, seasonal, and even daily basis are now available at high spatial resolution for mid-to-low latitudes. The topography of the sea floor and height of the ocean surface is better defined than ever before. Such data provide a valuable starting point for exploring climate-tectonic linkages, topographic gradients, and subsurface loads. No longer do we need to merely speculate about either the magnitude of orographic precipitation gradients or the relationship of submarine and subaerial topography: these can be quantitatively examined.

Our ability to date landscape features and geomorphic or tectonic events continues to improve. New, low-temperature thermochronometers continue to be developed. Cheaper, faster, and smaller sample processing with many chronologic methods enables far more ages to be measured. As a consequence, the timing and rates of diverse events and processes are better known than ever before. Long- and short-term erosion rates, recurrence intervals, and

innumerable deformed geomorphic features are now much better calibrated.

Our process-based understanding of phenomena ranging from rupture dynamics and fault creep to landslide triggering and fluvial erosion is rapidly improving. Geomorphologists seem to have become increasingly clever at finding those atypical field sites where enough variables can be held constant that the controls on some process can be reasonably explored. In addition, experimental facilities and approaches have permitted assessment of conceptual models, calibration of controlling parameters, and examination of the interplay and trade-offs within simple systems. As a consequence, an improved physics-based understanding of both tectonic and geomorphic processes has emerged.

The use of numerical models to explore the tectonic and geomorphic world has grown rapidly in the past decade. Increasingly powerful computers now enable modeling of landscapes and deformation at spatial and temporal scales that are appropriately scaled for geomorphic and tectonic processes. Models with foci ranging from lithospheric dynamics to atmospheric interactions with topography can now be used to predict dynamic topography, rainfall distributions, river profiles, glacial flow, and spatial variations in erosion. Moreover, our expanded quantification of rates of processes, as well as their geomorphic and tectonic signatures, enables better testing and improvement of model predictions.

Finally, a new generation of tectonic geomorphologists has emerged in the past decade. Armed with broad array of analytical skills, the ability to quantify processes better than anytime in the past, and a suite of numerical tools, modeling skills, and global data sets, these new scientists have sustained and accelerated the rejuvenation of the field that is the subject of this book.

We have retained the organization of our original book in which we begin with some basics on useful geomorphic features for tracking deformation, on approaches for dating such features, and on crustal structures that result from faulting and folding. We then examine

both geodetic approaches to quantifying ongoing deformation, as well as paleoseismic techniques for reconstructing the history of past earthquakes. After an exploration of approaches to define variations in erosion or uplift (in its various forms), we turn to a time-based framework to examine interactions between landscapes and tectonics with three chapters that focus on timescales encompassing the Holocene, late to mid Pleistocene, and late Cenozoic. These temporal divisions are chosen because contrasting balances between tectonics and erosion prevail within each era. At Holocene time scales, tectonic deformation can act as a first-order control on landscapes, which are commonly in disequilibrium. At increasingly longer time scales, erosion and rock uplift may approach an equilibrium, whereas at still-longer time scales, tectonics and associated landscapes may wax and wane.

Our final chapter is devoted to numerical modeling of landscapes, orographic precipitation, and the thermal structure of a dynamic crust. As in the previous edition, we initially introduce different types and scales of numerical models, and then focus on “building blocks” for deforming and eroding landscapes. We include a new emphasis on interactions of topography with climate, the thermochronologic signal of differential erosion, dynamic topography, and long-term landscape evolution.

Throughout this edition, we incorporate research results from the past decade. Over 500 new references and more than 150 new figures have been added: most of these have been newly published since 2000. We bring to the fore a selection of the new techniques and results that appear to open inspiring vistas on interactions between geomorphology and tectonics.

We have not, however, attempted a thorough coverage of this burgeoning field. For example, despite the amazing new views of the seafloor that are continuing to emerge, we have largely ignored submarine topography and the unique perspective it offers of tectonic-geomorphic interactions. Similarly, we largely ignore volcanic terranes, and we cover only a modest selection

of the remarkable array of chronologic and geochemical techniques that are now being applied to tectonic geomorphic problems. Nonetheless, we hope that this edition will provide an accessible and effective foundation for upper-level undergraduates and graduate students with interests in tectonic geomorphology and that it will serve as a helpful reference for more skilled professionals.

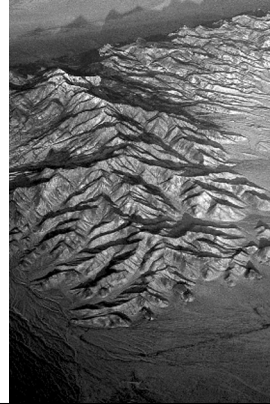
Many people played a role in the second edition of this book. Macquarie University and the University of Canterbury hosted one of us (DWB) on a sabbatical during which much of the writing and drafting occurred. Our research collaborators, colleagues, and many former students provoked us with their ideas and engaged us in discussions that helped shape this book. In particular, we would like to thank Bodo Bookhagen, Eric Kirby, Mike Oskin, Jérôme Lavé, Nathan Niemi, Colin Amos, Brian Clarke, Alison Duvall, Beth Pratt-Sitaula, Ian Brewer, Mike Ellis, Jeff Marshall, Alex Densmore, Greg Hancock, Eric Small, Dan Orange, Liz Safran, Niels Hovius, Kelin Whipple, Manfred Strecker, Neil Humphrey, Ann Blythe, Todd Ehlers, Jaakko

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Doug Burbank
Bob Anderson
April 2011

1 Introduction to tectonic geomorphology



Introduction

The unrelenting competition between tectonic processes that tend to build topography and surface processes that tend to tear them down represents the core of tectonic geomorphology. Anyone interested in the Earth's surface has wondered why it has the shape it does and what forces are responsible for that shape. For more than a century, this natural curiosity has inspired numerous conceptual models of landscape evolution under varied tectonic and climatic regimes. In the past, our ability to assign reliable ages to geomorphic and tectonic features was commonly very limited. In the absence of a chronological framework, testing competing concepts of landscape evolution was nearly impossible. As a consequence, these unquantified models were often viewed skeptically and treated as speculative notions.

During the past few decades, innovative applications of new techniques for determining the ages of landscape features, for assessing the mechanisms and rates of geomorphic processes, and for defining rates of crustal movement, have helped revitalize the field of tectonic geomorphology. It is now possible to measure at the scale of millimeters how rapidly a given site is moving with respect to another and how those rates of relative convergence or divergence are partitioned among various faults and folds. Similarly, we can now quantify how rapidly

ivers and glaciers are incising into bedrock and the rates at which landslides are stripping mountain slopes. Clearly, the merger of such data sets can underpin a new understanding of the balance between the rates at which crustal material is added at a given site and the rates at which this material is eroded away. Defining this balance and interpreting the landscape that results from this competition represents a major component of modern tectonic geomorphology.

One of the remarkable attributes of tectonic geomorphology is the breadth of fields it often encompasses. Few other geological fields easily blend as disparate topics as seismology, Quaternary climate change, geochronology, structure, geodesy, and geomorphology. In fact, such breadth makes this field particularly exciting, as new data and ideas emerge from fields as diverse as paleobotany and fault mechanics. This diversity also presents a formidable challenge, because successful studies commonly require blending of appropriate data from specialized fields that were traditionally considered to be unrelated. Certainly, specialists in well-established disciplines like structural geology or stratigraphy often make important contributions to tectonic geomorphology. Fundamental leaps in our understanding, however, more commonly emerge from an integration across several disciplines.

This book is intended primarily for readers who are familiar with basic geomorphological and structural concepts and terms. Although we

define many terms and review basic concepts and models throughout the book, we assume that our audience understands many commonly used geomorphological and structural terms, such as *base level* or *conjugate faults*. For those readers without such a background, occasional reference to a basic geomorphological or structural text will probably be helpful.

It is beyond the scope of this book to cover the contributions of each of the subdisciplines of tectonic geomorphology. Instead, we focus on some of the key tools, approaches, and concepts that have served to advance tectonic geomorphological studies during the past few decades. Several building blocks underpin many such studies, including a knowledge of how the Earth deforms both during earthquakes and between them, what sorts of features can be used to track deformation in the past, and what types of techniques are useful for dating features of interest.

Initially, we introduce geomorphic markers: landscape features, such as marine or fluvial terraces, that can be used to track deformation. Prior to deformation, the surfaces of these markers represent planar or linear features with a known geometry that can be predictably tracked across the landscape. Faulting or folding can subsequently deform such markers. Documentation of any departure from their unperturbed shape can serve to define the magnitude of deformation. Consequently, the recognition and measurement of such displaced or deformed markers is critical to many tectonic-geomorphic studies. These deformed markers are the raw data that cry out for interpretation.

In order to delineate rates of deformation, both the timing and amount of deformation must be defined. Fortunately, dozens of techniques have been used successfully to define the age of displaced features. In a chapter on dating, we present examples of some of the more commonly used techniques, and we try to convey a sense of the situations in which use of each technique would be appropriate. For each technique, we provide its conceptual underpinnings, discuss some of its limitations, and describe what data are actually collected in the field.

The oft-used term “tectonic processes” is a grab-bag expression that encompasses all types of deformation, including the motion of tectonic plates, slip on individual faults, ductile deformation, and isostatic processes. We concern ourselves here primarily with those processes that are most relevant to relatively localized deformation of the Earth’s surface. In this book, we have generally chosen to ignore deformation and surface processes related to volcanism. Many of the concepts that are developed here are descriptive of landscape responses to volcanic processes, but the way in which material is added to the system (sometimes from above or only from below), as well as the time and spatial scales, are commonly different between volcanic and non-volcanic settings.

Because the accumulated movements of individual faults and folds have built many landscapes, we describe some current concepts from seismology and structural geology concerning coseismic rupture, the scaling of fault slip, fault-related folding, and geometries of deformation in different tectonic settings (compressional, extensional, and strike-slip environments). This deformation generates the fundamental topographic morphology on which erosive forces act. Much has been learned about ongoing deformation of the Earth’s surface through geodetic studies: detailed surveys that delineate regional to local crustal displacements, often at time scales of a few years. During the past two decades, the increasingly widespread application of new techniques, such as the Global Positioning System (GPS) and radar interferometry, has yielded spectacular new images of current crustal motions. In a chapter on geodesy, we describe these techniques and some of the insights gained from them. In many ways, it is in the context of this greatly improved understanding of modern deformation that we now can make the largest strides in interpreting past deformation and landscape evolution.

Knowledge of current rates of crustal deformation leads to a host of provocative (and socially relevant) questions: Have these rates been steady over time? Do individual faults rupture at regular intervals and produce earthquakes of similar magnitude through time? Do groups of

faults accelerate synchronously at the expense of other faults? How large are the earthquake ruptures that accommodate the stress that is built by the incessant deformation of the crust? In a chapter on paleoseismology, we discuss some of the techniques for delineating the past behavior of faults, defining recurrence intervals and paleoslip rates, and assessing whether earthquakes occur with temporal regularity or randomness or in clusters.

Naturally, discovering ways to measure the amount and rate of erosional losses from an area and to define changes in the height of the surface of that same area through time lies at the heart of many tectonic-geomorphic studies. Armed with new tools for dating and with digital topographic databases, we can now address these topics more accurately than in the past. In a chapter on erosion and uplift, we describe several strategies for quantification of rates of erosion, surface uplift, and rock uplift, and we illustrate how these can be synthesized to examine the balance between building and tearing down of topography.

In the latter half of this book, we step away from a focus on the key building blocks and instead introduce concepts and examples of landscape evolution and tectonic interpretations at different time scales. Moreover, rather than examine specific geomorphic environments or topics, such as the ways in which rivers and fluvial features can provide insights on tectonic processes, we focus on more integrated studies. The key issues can be encompassed by two questions: "What information from the Earth's surface improves our understanding of the nature of the interactions between tectonics and geomorphological processes?" and "How do we interpret preserved geomorphic features in order to reveal rates and patterns of tectonic deformation in the past?" The more recent record is often best suited to answer the first question, whereas great value comes from studies that are able to answer the second question for intervals in the distant past.

There is a natural, time-dependent progression in the nature of tectonic-geomorphic landscapes and the insights that can be gained from them. Perhaps surprisingly, part of this progression is dictated by past climate changes (Fig. 1.1).

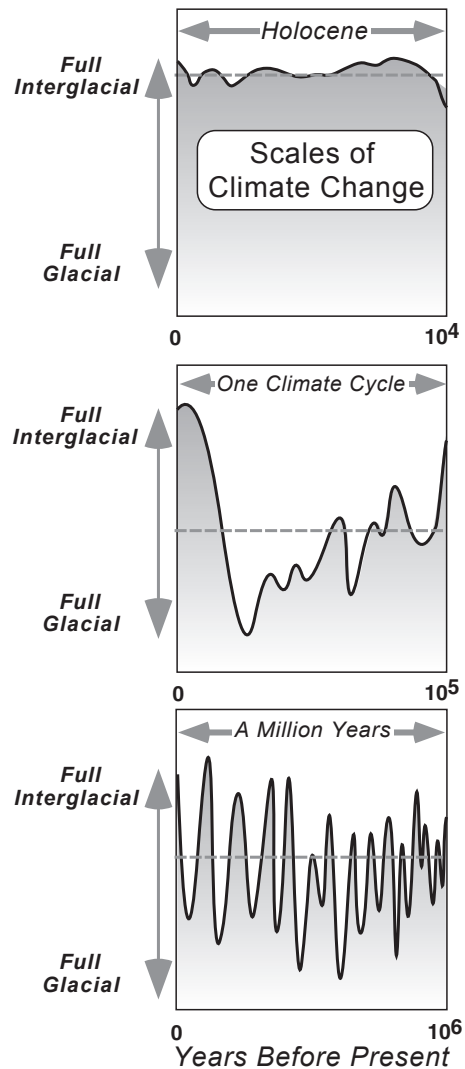


Fig. 1.1 Schematic illustration of climate change scaled at orders of magnitude (Holocene, one glacial cycle, Middle-Late Pleistocene).

The relative stability of the Holocene climate is atypical of a full glacial-interglacial, 100-kyr cycle. Similarly, the sawtooth pattern of change during past glacial-interglacial cycles does not show oscillations of similar magnitude, as is typical of the past million years.

At Holocene time scales, we are confined to a post-glacial era in which climatic conditions have varied relatively little. At time scales of 100 000 years or more, complete or multiple glacial-interglacial cycles have occurred.

Large-scale changes in sea level, the size of glaciers, and the discharge of rivers at these time scales leave strong imprints on the landscape. These climate cycles are often the “drivers” that generate the geomorphic markers, in the form of moraines or marine and fluvial terraces, that are so important in the field of tectonic geomorphology. At time scales of a million years or more, numerous climatic cycles can create a more “time-averaged” landscape.

These different time scales also often create a natural segregation of the focus of tectonic-geomorphic studies. At Holocene time scales, cause and effect can be examined rather directly. For example, if faulting causes the land surface to tilt in a given direction, the timing and rate of diversion of rivers in response to that tilt can be measured. Present rates of crustal deformation can be compared against the sediment load of rivers. Commonly, geomorphic markers, such as river terraces, are almost untouched by erosion and can function as pristine recorders of Holocene deformation. The strength of Holocene studies is that the record is often most complete, the dating is most precise, rates of many competing processes can be directly measured, and their interactions can be examined. At least three potential disadvantages can limit Holocene studies. First, the rates of tectonic processes may be sufficiently slow or the occurrence of deformational events, such as earthquakes, may be sufficiently rare that the tectonic signal is obscure. Second, rates of geomorphic processes during Holocene (interglacial) times may not be very representative of long-term rates. Third, the time it takes for geomorphic systems to respond to a change imposed by tectonic forcing can be longer than the Holocene. Thus, the geomorphic system may be in a state of transition with respect to tectonic perturbations imposed upon it.

As described in subsequent chapters, the limited precision of most dating techniques means that, as one delves beyond the Holocene and farther into the past, it becomes progressively more challenging to associate specific events in time. Thus, it can be difficult to define direct responses to individual forcing events. On the other hand, major climate changes often have created robust geomorphic markers, such as

river terraces, that persist as recognizable features and provide a lengthy time framework within which to document patterns of deformation. At short time scales, tectonic forcing is commonly unsteady, because it results from discrete events, such as earthquakes, that are widely separated in time. At time scales of more than 10^4 yr, this unsteadiness is commonly smoothed out, and average rates of deformation can be defined. Because many geomorphic markers persist in the landscape at time scales of single glacial-interglacial cycles, this is an ideal interval within which to document past rates of tectonic forcing. At still longer time scales, erosion has typically removed most markers that are more than about 10^5 yr old. Yet, it is at this time scale that large-scale landscape responses to sustained tectonic forcing can be clearly seen. Typically, landscapes must be treated at a coarse spatial scale in order to examine the products of tectonic-geomorphic interactions, such as the topographic characteristics of a collisional mountain belt or the broad swath of deformation that occurs as a continent passes over a hot spot.

We conclude with a chapter on numerical modeling of tectonically active landscapes. In contrast to efforts aimed at directly measuring tectonic-geomorphic processes, the interactions between deformation and surface processes can also be studied theoretically. If we could write numerical rules that represent phenomena such as the displacement of the crust due to faulting or the erosion and redistribution of mass due to surface processes, we could proceed to investigate interactions among these processes. Consider, for example, displacement on a normal fault that bounds the front of a mountain range. The topographic offset will change the local gradient of any river crossing the fault, and a numerical rule for river incision could predict how that reach of the river would respond and how that response would be propagated upstream.

Rather complex models for landscape evolution in different tectonic environments have recently been formulated. It is not our intent to describe or compare these in detail. Instead, we describe several of the basic building blocks that could go into a numerical model, and we illustrate some of the predictions of these models.

In our view, the usefulness of numerical models is not in creating a reproduction of some actual landscape. Instead, models provide a means to explore potential interactions within a landscape, so that we have a firmer basis for understanding how variables as diverse as crustal rigidity, susceptibility of bedrock to landslides, and the distribution of precipitation may interact with each other, perhaps in unexpected ways. Such models are meant to develop our insight into the complex interactions among the processes, and they can serve to point toward measurements one might make in the field that would most efficiently constrain the process rates.

Energetics

Energy drives the interactions between tectonics and surface processes. In order to build topography, work must be done against gravity. The energy needed to accomplish this work comes ultimately from the conversion of a small fraction of the energy involved in the horizontal motions of the lithospheric plates that constitute the more rigid exterior of the planet. The energy driving plate tectonics comes from primordial heat associated with building of the planet, from the decay of radioisotopes, and from phase changes in the interior of the Earth.

It is perhaps surprising to cast the energy expenditure represented by plate motion in everyday terms. Consider, for example, a simple calculation of the kinetic energy of that part of the Indian Plate lying south of where it is colliding with mainland Asia and building the Himalaya. We may specify its approximate dimensions as 3000 km wide by 7000 km long by 50 km thick. If we assume a mean density of 3000 kg/m³, this yields a mass of approximately 3×10^{21} kg. Taking a mean plate velocity of 5 cm/yr yields a kinetic energy ($\frac{1}{2}mv^2$) for the plate of about 4×10^3 J (joules), equivalent to about 1/200 of a “Snickers” bar (10^6 J)! On the other hand, the rate of energy expenditure required to move the Indian Plate (force $\times$ distance/second) is equivalent to approximately 10^{13} J/s or 10^7 “Snickers” bars per second! Over the past 50 million years, some tiny fraction ($\sim 1/100$ of 1%) of that energy

has been expended (or converted, really, to potential energy) in elevating the crust of the Himalaya and Tibet far above the geoid and thereby creating the world’s largest topographic anomaly, averaging about 5 km above sea level.

The energy for driving surface processes derives from a combination of gravitational potential energy and solar energy. All rocks that have been elevated above the geoid have a potential energy equivalent to the product of their mass, gravitational acceleration, and their height above the geoid ($PE = mgh$). At the top of the atmosphere, the Earth receives solar energy equivalent to about 1300 W/m². The solar energy received at the Earth’s surface is several orders of magnitude greater than the energy that leaks out from the Earth’s internal heat engine (~ 40 mW/m²). Solar energy evaporates water and heats the air that carries the moisture with it as the air rises, expands, and cools. The water attains its maximum potential energy at the top of its atmospheric trajectory. When the vapor condenses and falls as precipitation, it converts some of its potential energy to kinetic energy that it delivers to the surface of the Earth with the force of its impact. The potential energy that is represented by the mass of water at some elevation above the geoid is then available to be expended doing geomorphic work or to be lost through heat dissipation or frictional processes. Solar energy is also an important factor in chemical weathering processes, especially in any temperature-dependent reactions, as well as in mechanical weathering processes, such as freeze–thaw cycles.

Active tectonics and models of landscape development

Sharp contrasts in the appearances of landscapes in a given climatic or tectonic regime inspired geologists in the past to devise schemes to explain those contrasts. One of the most prominent such geologists was William Morris Davis, who in the late 1800s and early 1900s developed the well-known geomorphic models (Davis, 1899) showing a progression from “youth” to “maturity” to “old age” (Fig. 1.2). Living in the wake of the revolutionary ideas of

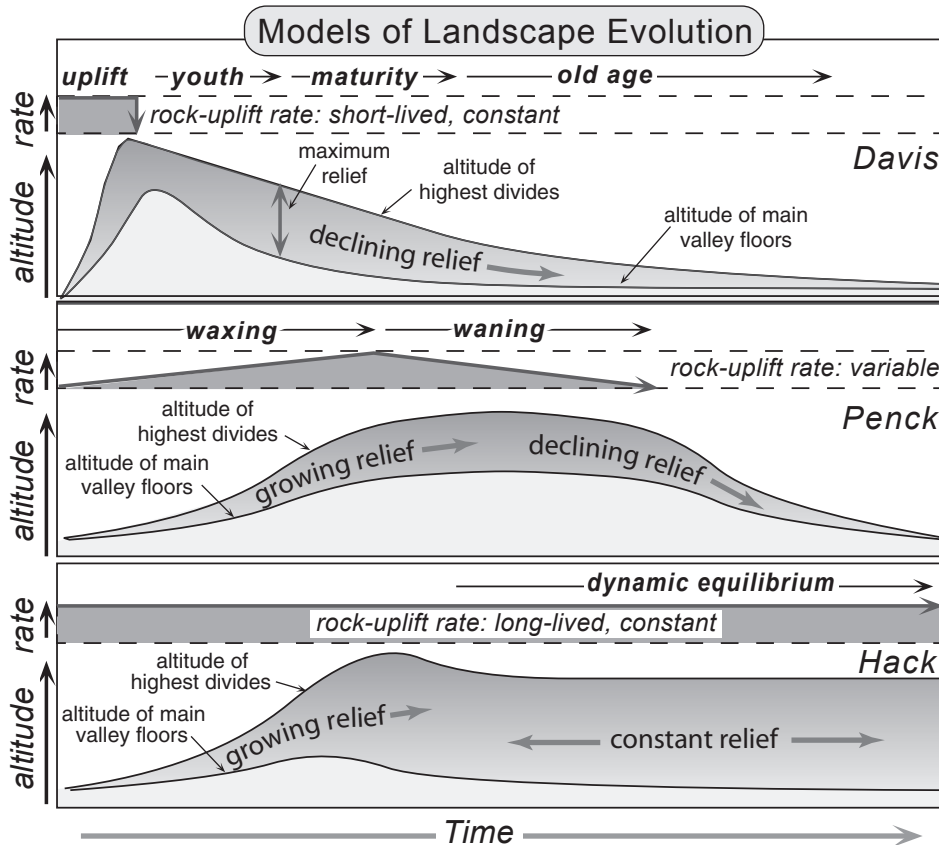


Fig. 1.2 Classical models of tectonic forcing and landscape responses.

Based on the landscape response theories of (top) Davis (1899), (middle) Penck (1953), and (bottom) Hack (1975), each panel is characterized by differences in the duration and rate of tectonic forcing (rock uplift) and by the topographic response engendered by these different styles of rock uplift. Modified after Summerfield (1991).

Charles Darwin, it was perhaps natural to conceive of landscapes as evolving from one stage to the next. In Davis's models, tectonic forcing is an impulsive phenomenon that occurs at the beginning of the "geomorphic cycle." All of the building of topography occurs at the start of the cycle (Fig. 1.2). Subsequently, geomorphic processes attack and degrade the topography, with the end-result predicted to be a peneplain. This view of landscape evolution prevailed through much of the 1900s and is still widely cited by introductory geology textbooks.

A new theory of landscape development that opposed Davis's models was promoted by Walther Penck in the 1950s (Penck, 1953). Rather than having all of the tectonic deformation at

the beginning of a cycle, Penck suggested a more wave-like pattern of tectonic forcing through time. In this scheme, the magnitude of deformation gradually increases toward a climax and then slowly wanes away. Instead of calling upon an impulsive building of topography followed by long intervals of erosion, Penck's model invoked steadily increasing rates of deformation that would accelerate rock uplift and gradually build the topography toward a maximum state of topographic relief. Geomorphic processes were conceived as attacking the uplifting region throughout the period of mountain building, so that the resulting landscape could be interpreted as a product of this competition between deformation and erosion. As the

rate of mountain building waned, erosion was proposed to overtake deformation rates, thereby causing a gradual reduction in the residual topography (see Fig. 1.2).

A third approach to landscape development was proposed by Hack (1975), who suggested that, when rates of deformation and rates of erosion are sustained for long intervals, landscapes will come into a sort of balance or dynamic equilibrium. Given the finite strength of rocks, Hack realized that topography could not increase without limit, even if rates of tectonic forcing persisted for very long periods. At some point, as topography grew and grew, the relief on hillslopes would create forces exceeding the rock strength, and they would collapse. With continued uplift of the bedrock, additional slope failures would limit the height that the topography could attain. Eventually, the topography would enter into a rough steady state or a dynamic equilibrium. Consequently, in this model, rates of mountain building and rates of erosion would come into a long-term balance (see Fig. 1.2). Unlike the models of Davis or Penck, there is no need for rates of deformation to become negligible, or even to wane at all. Similarly, after attaining a maximum sustained topography, there is no need for the landscape to “evolve.” Instead, it simply fluctuates around an equilibrium topography until such time as the rates of tectonic forcing change.

One might wonder whether any of these theories are applicable to real landscapes. One way to consider this problem is to compare the time scales of deformation and of geomorphic responses. For example, an earthquake is a very impulsive event that “instantaneously” creates topographic change, say in the form of a fault scarp. If the time between earthquakes is long relative to the time it takes geomorphic processes to cause significant topographic evolution, the scarp will be degraded before the next earthquake. This topographic change could be thought of as a small-scale version of a Davisian scheme for landscape evolution. On the other hand, if the recurrence interval between earthquakes is short, then the scarp will be continuously refreshed and will not degrade in a predictable fashion toward a

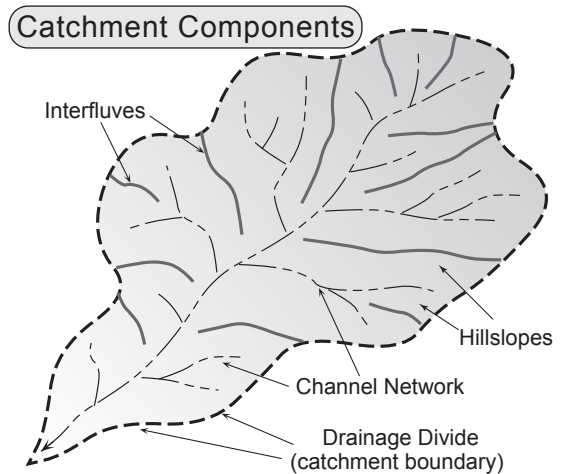


Fig. 1.3 Geomorphic elements of a drainage basin. Diverse geomorphic components of a catchment have a hierarchy of inertia to change, with the channel network as most responsive, and the drainage divide as least responsive.

low-relief surface. In fact, some balance might be expected to develop between the renewal of the scarp by faulting and erosion of it during interseismic periods. Thus, even though the total displacement grows through time, the scarp itself might attain a “steady-state” shape.

It is also useful to consider the response times or inertia of different elements in a geomorphic system. Consider, for example, a drainage basin in a mountain belt (Fig. 1.3). The basin consists of river channels, hillslopes, the crests of interfluvies, and the drainage divide that defines the shape of the catchment. Some of these elements will respond more rapidly to changes imposed on them than will others. Suppose that, near its outlet from the mountains, this basin is bounded by a normal fault. How will the various basin elements respond to displacement on that fault? The channel that crosses the fault will “see” the displacement first. The local base level will have fallen abruptly, causing the river gradient to steepen locally and erosion of the channel to intensify. At this point, all other positions in the catchment will have been undisturbed by the faulting event, so the faulting elicits no initial geomorphic response. Subsequently, a wave of erosion of the channel bed can be expected to

propagate up the fluvial system. As this channel erosion passes the base of an adjacent hillslope, it causes the hillslope gradient to increase and will initiate a change in the rate of hillslope processes. These hillslope processes could eventually affect the interfluvies and finally the shape of the entire catchment. Large geomorphic elements, such as the catchment shape, are unlikely to be affected by individual seismic events. Thus, a clear hierarchy of response times exists (rivers respond sooner than hillslopes, etc.), and an analogous hierarchy of topographic inertia is evident (catchment shape is resistant to change, whereas river gradients are susceptible to small perturbations).

Consideration of the scaling of elements in a given geomorphic system, of response times or inertia of those elements with respect to imposed changes, and of the rates, magnitude, and duration of different styles of tectonic forcing suggests a way in which the apparently incompatible landscape evolution concepts of Davis, Penck, and Hack can be reconciled. In fact, recent numerical models of tectonically perturbed landscapes have explicitly addressed this problem. Using a surface-process model that links channel incision, sediment transport, and hillslope erosion, Kooi and Beaumont (1996) developed a model that predicts a lag between the onset of deformation and the response of the geomorphic system to that deformation (Fig. 1.4). The overall response of the geomorphic system and the magnitude of the lag depend strongly on the nature of the tectonic forcing. If the forcing is impulsive (*à la* Davis), then the topography is rapidly created and simply degrades through time. If the deformation increases to a maximum through time and then wanes (*à la* Penck), topography gradually builds in the face of progressively increasing rates of erosion. The maximum topographic expression occurs slightly after the rate of deformation begins to wane, because the rock uplift still outpaces the rate of erosion. Finally, in the latter half of the cycle, the topography wanes, despite gradually diminishing rates of erosion. If the tectonic forcing is continuously sustained, then the Kooi and Beaumont model predicts that, after an initial interval of building of topography, rates of rock uplift and erosion will

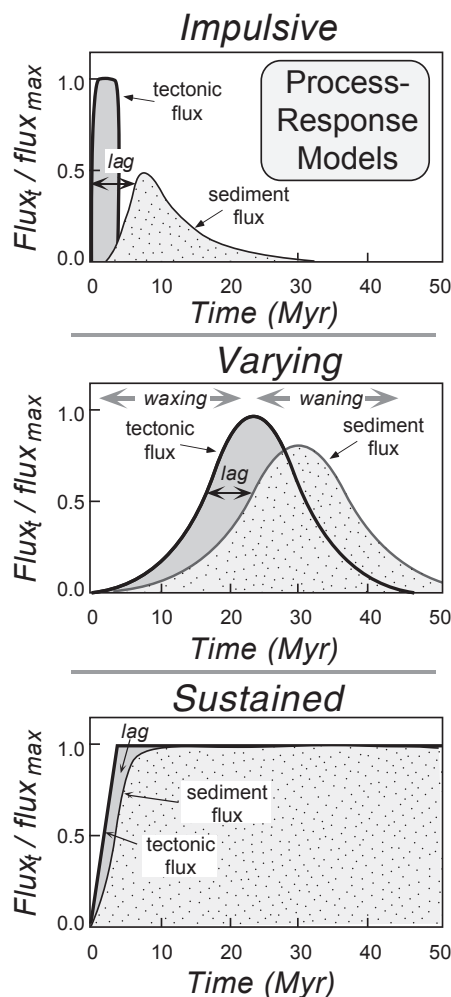


Fig. 1.4 Tectonic versus sediment flux process-response models.

Duration and magnitude of rock uplift (the vertical tectonic flux) are compared with the erosional sediment flux from uplifted mountains. The three scenarios (impulsive, varying, sustained) are analogous to the models of Davis, Penck, and Hack (Fig. 1.2). Note that the time lag between tectonic forcing and sediment response is variable. Modified after Kooi and Beaumont (1996).

become balanced (*à la* Hack), and the topography will attain a persistent dynamic equilibrium (Fig. 1.4). A change in the rate of tectonic forcing would push the system toward a new equilibrium, whereas cessation of deformation would return the system to an almost Davisian state in which the topography is systematically degraded.

These predictions are the output of a numerical model that represents a great simplification of both tectonic and geomorphic processes. In fact, the physics of many of these processes are still poorly understood. Nonetheless, it is satisfying to think that the thoughtful, yet apparently contradictory, landscape development models put forth during the past 100 years are indeed reconcilable and that simple numerical models can help enhance our understanding of tectonically active landscapes.

The new world

Over the past two decades, technological advances have dramatically improved our view of the Earth. As the diversity and availability of digital topography has expanded, our ability to visualize the shape of the Earth's surface has become much easier and more accurate. For 11 days in February 2000, NASA's Space Shuttle used an active radar system to map the topography of the world between 60°N and 60°S (Farr *et al.*, 2007). The digital elevation model (DEM) derived from this mission now provides almost complete elevation coverage with a spatial resolution of 90m. Still more recently, a higher-resolution, 30-m DEM that covers the world between 83°N and 83°S has been developed from satellite stereoisimages and is freely available (<http://www.gdem.aster.ersdac.or.jp/>). The success of Google Earth in merging such topographic data with remote sensing images has provided tectonic geomorphologists with an unprecedented opportunity to explore the Earth's surface. As high-resolution (≤ 1 m) imagery is increasingly incorporated into Google Earth, individual fault scarps, uplifted marine terraces, and channels on actively growing folds in previously inaccessible areas can now be visually explored from a computer almost anywhere in the world!

In the temperate mid-latitudes, however, where forests blanket much of the landscape, even high-resolution imagery does not commonly permit a clear view of the actual land surface. But, this restriction is also changing. A new technology, lidar (light detection and ranging), which is also

known as laser scanning (Carter *et al.*, 2007), uses concentrated pulses of light emitted from an airborne instrument to penetrate through openings in a forest canopy. By measuring the return time and direction of the light, the vector to the ground can be calculated from the "last returns" (those that were not reflected by above-ground vegetation). Via an integration of all of the last returns and with precise knowledge of the position of the aircraft, a *bare-Earth* topographic image of the Earth's surface can be created. The resolution of the image depends on how high the aircraft is flying and the nature of the light beam, but commonly DEMs are created with 1-m spatial resolution and topographic uncertainties of a few centimeters. The stunning success of lidar in revealing previously unknown fault scarps beneath the canopy of dense northwestern US forests (Fig. 1.5) made converts of skeptics and launched widespread efforts to acquire lidar data over diverse tectonic and geomorphic targets. Tripod-mounted laser scanners are also gaining increasing popularity. Based on the same physical principles, these instruments permit topographic reconstructions with millimeter- to centimeter-scale uncertainties to be created of individual hillslopes, fault scarps, or river beds; and, with a series of topographic scenes over time, the details of landscape changes can be recorded and quantified. The vastly improved accuracy of these new topographic views, ranging from global topography to individual hillslopes, has underpinned a new view of the Earth and the processes that mold its surface.

Some modern controversies

At present, many lively controversies animate studies in tectonic geomorphology. Some of these provide an interesting backdrop for reading subsequent chapters of this book. For example, the history of Cenozoic cooling of the rocks within many mountain ranges has been interpreted to suggest that the ranges experienced accelerated rates of uplift during late Cenozoic times. With increased recognition that this apparent increase was approximately coeval with the onset of the "Ice Ages," it was commonly

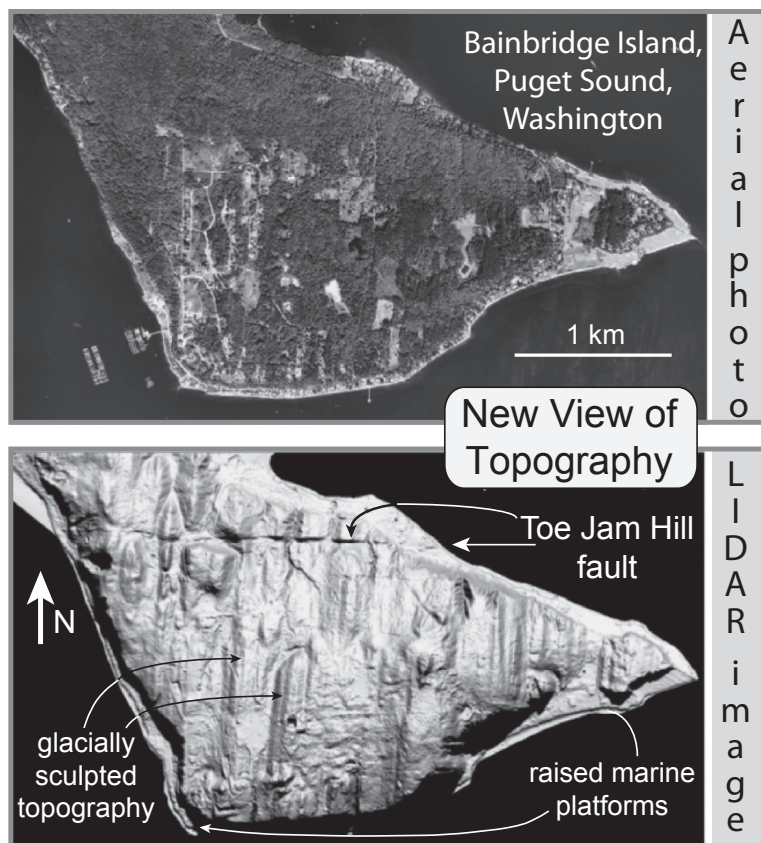


Fig. 1.5 Comparison of aerial photograph with “bare-Earth” lidar image of an active fault.

Dense forest obscures geological structure and geomorphology in an aerial photograph of the southern tip of Bainbridge Island in Washington’s Puget Sound (top). Removal of the forest canopy using lidar data (bottom) yields a shaded-relief, bare-Earth model whose topography reflects the climatic and tectonic history of the site. Glacial grooves and ridges reveal the former ice flow direction to the south, whereas the abrupt linear escarpment in the north shows the surface expression of the Toe Jam Hill Fault, a fault that was not previously known to break the surface. This fault is a north-dipping backthrust of the Seattle Fault, and the lidar imagery provided the foundation for a trenching campaign that revealed the earthquake history of this hazard-producing fault zone (Nelson *et al.*, 2003). Images courtesy of Samuel Johnson and the USGS.

believed that mountain uplift led to cooling and helped to precipitate the Ice Ages. In 1990, Molnar and England challenged this entrenched idea and suggested nearly the opposite: as climate changed to more glacial conditions in late Cenozoic times, enhanced rates of erosion within mountain belts caused increased rates of valley incision, which in turn incited isostatic uplift of the residual peaks (Molnar and England, 1990). Although isostatic uplift can produce ranges with higher summits, it does not implicate tectonic uplift as the cause of climate change.

So, how do we tell whether the climate caused uplift of the summits or whether surface uplift of the ranges caused changes in climate? Potential resolutions to this quandary require many ingredients, including the nature and magnitude of changes in mean elevation of mountains, in rates of erosion, in climate, and in elevations of summits and valley bottoms. Moreover, we would

like to know when and how rapidly changes took place. If you think carefully about any one of these ingredients, you quickly realize the reason why tectonic geomorphological studies are often interdisciplinary in nature. Consider, for example, the concept of mean elevation of a range. Using digital topographic data, the current mean elevation is straightforward to calculate. But how do you determine mean elevations in the past? As described in subsequent chapters, approaches to estimating former altitudes range from paleobotanical to isotopic studies. Or, consider the effects of changes in climate. During Ice Age times, was there more precipitation or less? Did the expansion of glaciers lead to enhanced rates of erosion? There is intense interest in, and considerable argument about, whether glaciers are effective agents of erosion in comparison to rivers. The controversy has spawned a flood of recent research into the physical and

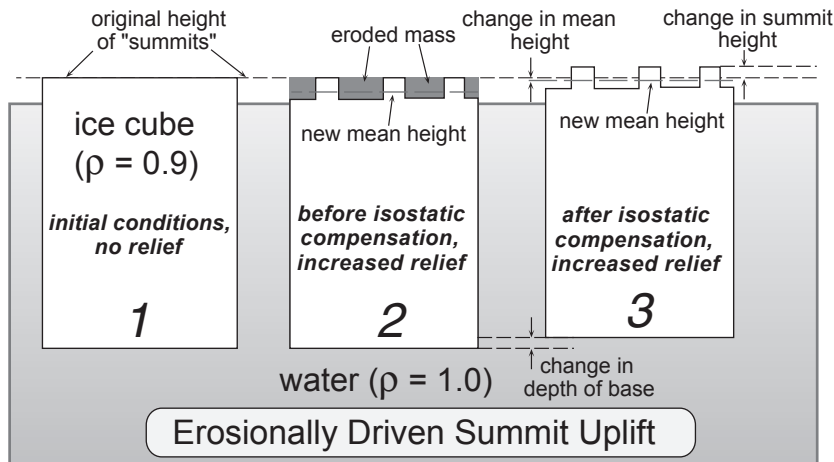


Fig. 1.6 Isostatic uplift of mountain summits due to enhanced erosion.

The density contrasts of ice and water are analogous to crust and mantle contrasts, respectively. Erosion of the top of the ice cube decreases its mass and its mean height. More rapid erosion of valley bottoms than of summits leads to increased relief and uplift of summits, at the same time that the mean elevation decreases. Note that stage 2 will never occur unless some force restrains the ice cube from rebounding due to melting at the surface.

chemical processes involved in erosion of bedrock by both fluvial and glacial processes.

Can enhanced erosion drive uplift of mountain summits? Yes, but only if there is an increase in topographic relief associated with the erosion. In essence, there has to be less erosion of the summits than there is of the valley bottoms. Think about an ice cube floating in a drink (Fig. 1.6). Its upper surface is at a mean elevation equivalent to $\sim 1/10$ th of its total thickness, equivalent to $(1 - \rho_{\text{ice}}/\rho_{\text{water}})$, where ρ = density. If you were to cut canyons into the upper surface of the cube, the mean elevation of the cube's surface would decrease and the base of the cube would bob upward in the water in order to maintain the isostatic balance (maintaining $1/10$ th of the total mass above the water surface). If you could cut the canyons without "eroding" other parts of the upper surface of the cube, these remnants would actually rise higher than their original height in response to the lowering of the mean elevation.

Although melting of an ice cube demonstrates that peak uplift can occur due to enhanced erosion, has this commonly occurred in the past, is it related to a more "erosive" climate, and what are the magnitudes of the uplift of peaks involved? The common view has been that increased rates

of erosion tend to increase topographic relief and, therefore, would promote the uplift of summits. On the other hand, theoretical studies of river profiles suggest that increased erosive power causes river gradients to decrease (Whipple, 2004). If this is true, then, in order to generate an increase in topographic relief in the landscape, hillslopes would have to be concurrently lengthened and steepened. Tectonic-geomorphic studies that document the temporal evolution of both the valley bottoms and the adjacent hillslopes are needed to resolve these issues.

Another modern controversy in tectonic geomorphology revolves around earthquake prediction. Over the past two decades, a substantial research effort has focused on answering such questions as: "Which fault is most likely to rupture in the next large earthquake?", "When is that event likely to occur?", and "How large an earthquake can we expect to occur?" Many scientists would maintain that the best way to make such predictions is to understand the past history of faulting. Such topics fall into the realm of paleoseismology with its focus on the reconstruction of past earthquakes in terms of their distribution in space and time, coseismic displacements, and interactions among faults.

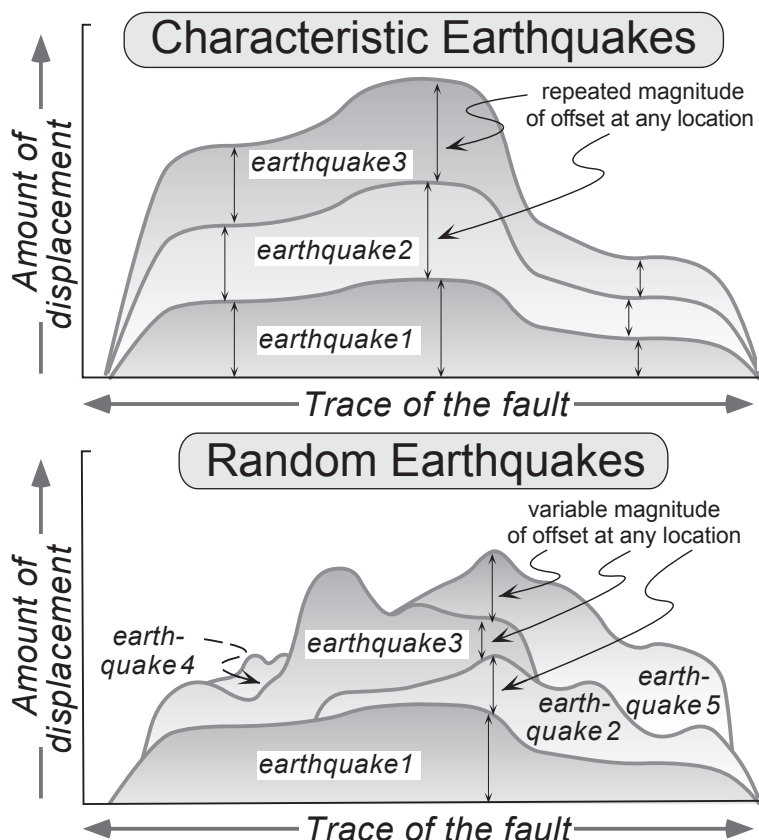


Fig. 1.7 Scenario of characteristic earthquake displacement versus unpredictable, random displacement.

Characteristic earthquakes repeatedly rupture the same part of a fault and show similar along-strike variations in coseismic displacements from one event to the next. Random earthquakes vary in both the location of the rupture and patterns of displacement.

If paleoseismological studies were to indicate that successive ruptures of a particular fault occurred at regularly spaced intervals in time, it would then be possible to define a “recurrence interval.” If we also know when the last rupture occurred, we could predict when the next earthquake was likely to happen. But, do faults display regularity in their rupture histories? The known paleoseismological record commonly extends back through only a few earthquakes, making it difficult to define a statistically significant recurrence interval.

One popular model among paleoseismologists suggests that many faults can be said to experience “characteristic earthquakes,” implying that each successive rupture mimics the displacement of the previous event. If true, this implies that, along any particular section of a fault, the amount of displacement that results

from a single earthquake will be duplicated in subsequent ruptures (Fig. 1.7). Imagine the predictive power that would result if faults were shown to generate both characteristic earthquakes and to have predictable recurrence intervals! City planners and paleoseismologists would all be delighted. For most faults, however, this seductively attractive concept has yet to be demonstrated. Consequently, much current debate revolves around whether or not certain faults display characteristic earthquakes and predictable recurrence intervals. Or, could some faults display a very irregular behavior in both the time between ruptures and displacement variations in successive events? Far from being resolved, this debate lies at the core of paleoseismology, and has spawned much recent work both in the field and in numerical models of the faulting process.

Many paleoseismological studies rely on trenches that are dug across faults to reveal the slip in past earthquakes. Measurements of displaced strata serve to define the magnitude of displacement in an earthquake, whereas dating of those strata can determine when the rupture occurred. But do such measurements capture the full slip history? Might they overestimate the slip? Several recent discoveries complicate the interpretation of trenches. As faults approach the Earth's surface, slip commonly decreases, so trench exposures at the surface may tend to underestimate the total coseismic slip. This underestimate is especially likely for "blind" thrust faults that do not rupture the surface. Even where faults do break the surface, is it possible that significant strain occurs as diffuse deformation between faults? Although difficult to quantify, such broadly distributed strain may represent a significant fraction of the total deformation. In such conditions, displacement in trenches would be underestimates of the integrated deformation across an area. The advent of extensive geodetic networks (mostly relying on GPS) has provided new insights on slip during and between earthquakes. Recent recognition of "slow earthquakes" that occur over hours to days (Heki *et al.*, 1997) indicates that slip during an earthquake may be equaled by slow slip of nearly equal magnitude. If such slip were propagated to the surface, it would be impossible to recognize as a slow slip event in an exposure within a paleoseismic trench.

The rates of convergence between tectonic plates, as well as measured rates of local deformation, indicate that, in many active mountain ranges, rocks are moving upward with respect to sea level at rates of several millimeters per year. Recall that a rate of 1 mm/yr is equivalent to 1 km in a million years. Thus, in the absence of erosion, vertical rock uplift rates of several mm/yr would build very high mountains in only a few million years. Clearly, mountains do not grow indefinitely: only 14 peaks poke more than 8 km above sea level. But what controls their ultimate height? Is there a limit to the energy available to lift the mass of rock and increase its potential energy? Does rock strength set the height limits, or do

changing rates of erosion determine the topography of ranges? Such questions lie at the core of another current controversy in tectonic geomorphology: Can the concept of "dynamic equilibrium" be applied in active orogens at the mountain range scale? Dynamic equilibrium implies that, on average over time, the landscape maintains a steady-state form, whereby the height of the summits, the steepness of the valley walls, and the topographic relief fluctuate around long-term mean values. If the mean height of the mountains stays the same through time, this persistence implies that rates of rock uplift (vertical movement of rocks with respect to sea level or the geoid) are balanced by rates of erosion. How is this accomplished? Are surface processes capable of eroding at several mm/yr? Which processes are responsible (river erosion, landsliding, glacial erosion, conversion of rock to soil) and do these processes operate in different ways in different mountain belts? Or, is the traditional idea correct that rapid rates of rock uplift are commonly compensated, not by geomorphic agents at all, but by events of tectonic denudation (extensional faulting) that efficiently lower the regional height of the landscape?

In order to answer such questions, we have to be able to document rates of modern and past erosion, to quantify rates of rock uplift and changes in the mean elevation and topographic relief of mountain ranges (Fig. 1.8), and to document the role of extension within orogens. Also, because climate undergoes large glacial–interglacial fluctuations at 100 000-year intervals, rates of erosion that are responsive to climate (most erosional processes are) will also vary strongly through time. Consequently, when thinking about the problem of dynamic equilibrium and steady-state topography, it is most useful to consider time spans that exceed a full glacial–interglacial cycle, so that average rates can be determined.

Such constraints present some great challenges to researchers in tectonic geomorphology. It is inadequate to document only modern rates (which are difficult enough to measure accurately!). Rates from intervals throughout a climate cycle or rates that integrate an entire

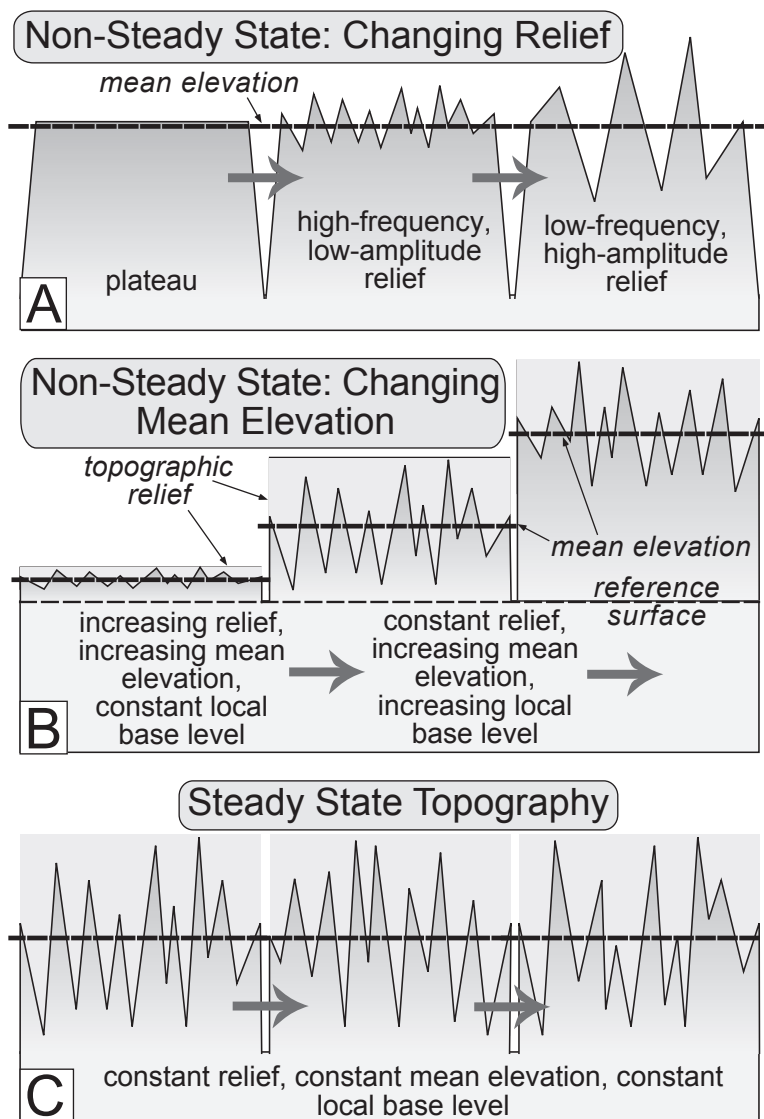


Fig. 1.8 Steady-state versus non-steady-state topographic characteristics.

Non-steady-state topography can have (A) constant mean elevation, but changing topographic relief, or (B) constant relief, but changing mean elevation. In steady-state conditions, (C) relief, mean elevation, and base level remain constant, although the elevation of an individual point can vary through time.

cycle are needed. This integration requires clever ways to measure quantities of material removed from or added to a landscape. Moreover, researchers must somehow inject a reliable “clock” into the rock record, because rate calculations can be no more precise than the time interval across which they are measured. Such measurements are difficult to make. An alternative approach would be to determine the operational “rules” by which various surface processes erode the landscape, and to incorporate them into a

theoretical model of landscape evolution. For example, how does the rate of bedrock erosion at the base of a glacier relate to the speed at which the glacier is sliding, its thickness, the steepness of its bed, freezing and thawing at the ice–rock interface, and the resistance of the bedrock beneath it? Only if we can both define these rate relationships and determine how glaciers have extended and retreated in the past, will we be able to model the mean rates of erosion within this portion of the landscape.