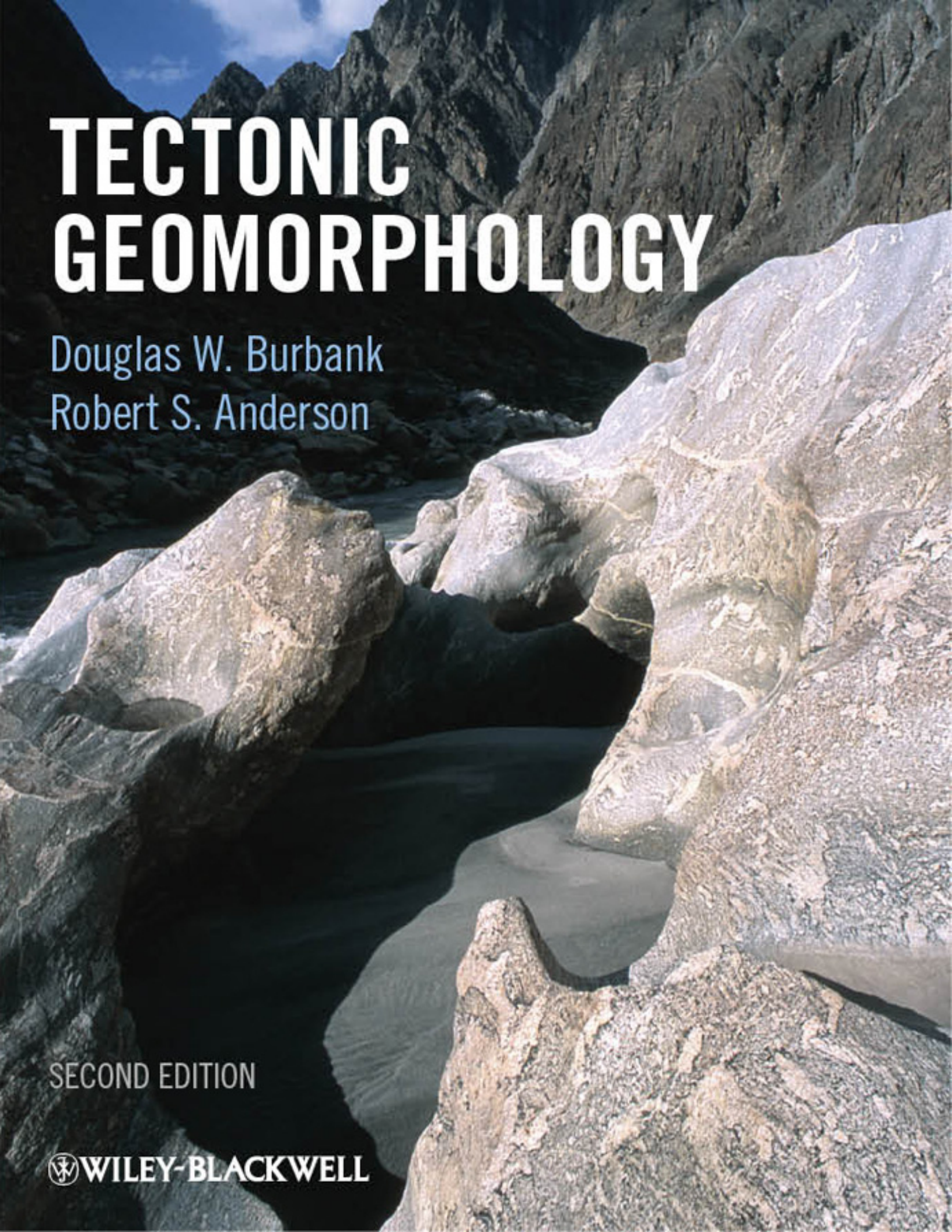




TECTONIC GEOMORPHOLOGY

Douglas W. Burbank
Robert S. Anderson

SECOND EDITION

 WILEY-BLACKWELL

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COMPANION WEBSITE

This book has a companion website:

www.wiley.com/go/burbank/geomorphology

with Figures and Tables from the book for downloading

Tectonic Geomorphology



Second Edition

Douglas W. Burbank
and Robert S. Anderson

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DEDICATED

to

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

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, Eric Fielding, Jérôme Lavé, Niels Hovius, Rudy Slingerland, Hugh Sinclair, Marith Reheis, Peter Molnar, Euan Smith, Ann Blythe, Merri Lisa Formento-Trigilio, and

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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 a 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 Putkonen, Peter Molnar, Mark Quigley, Kip Hodges, Ben Crosby, George Hilley, Jean-Phillipe Avouac, Dork Sahagian, Ramon Arrowsmith, Olaf Zielke, and Ray Weldon.

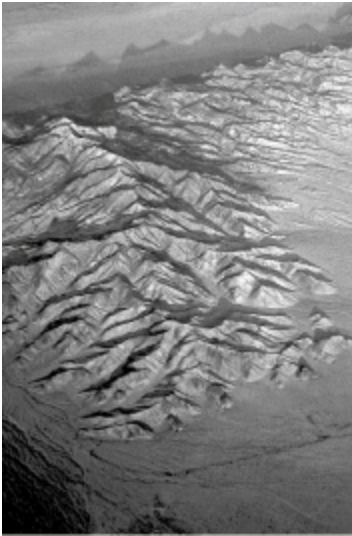
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Doug Burbank
Bob Anderson
April 2011

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 rivers 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