Cambridge University Press
978-0-521-51978-6 - Geomorphology: The Mechanics and Chemistry of Landscapes
Robert S. Anderson and Suzanne P. Anderson
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Geomorphology

This textbook provides a modern, quantitative, and process-oriented approach to equip students with the tools to understand geomorphology. Insight into the interpretation of landscapes is developed from basic principles and simple models, and by stepping through the equations that capture the essence of the mechanics and chemistry of landscapes. Boxed worked examples and real-world applications bring the subject to life for students, allowing them to apply the theory to their own experience. The book covers cutting-edge topics, including the revolutionary cosmogenic nuclide dating methods and modeling, highlights links to other Earth sciences through up-to-date summaries of current research, and illustrates the importance of geomorphology in understanding environmental changes. Setting up problems as a conservation of mass, ice, soil, or heat, this book arms students with tools to fully explore processes, understand landscapes, and participate in this rapidly evolving field.

BOB ANDERSON has taught geomorphology since 1988, first at University of California, Santa Cruz, and now at University of Colorado, Boulder. Bob has now studied most parts of landscapes, from their glaciated tips to their coastal toes, with significant attention to sediment transport mechanics, the interaction of the geophysical and geomorphic processes that shape mountain ranges, and the evolution of bedrock canyons and glaciated landscapes. He has participated in the development of a new tool kit that employs cosmogenic radionuclides to establish timing in the landscape. He develops numerical models of landscapes that honor both field observations and the first principles of conservation; these models in turn have served to hone his field efforts. In the course of this academic adventure he has been founding editor of the *Journal of Geophysical Research – Earth Surface*, co-authored the textbook *Tectonic Geomorphology* (2000, Wiley-Blackwell) with Doug Burbank, and has been honored by election as a Fellow of the American Geophysical Union.

SUZANNE ANDERSON has been on the faculty at University of Colorado, Boulder, since 2004, where she teaches courses on geomorphology, Earth's Critical Zone, landscapes and water, and glaciers and permafrost. Her awards include an Outstanding Graduate Student Instructor award at University of California, Berkeley, a NASA Graduate Student Fellowship in Global Change Research, and an NSF Earth Sciences Post-doctoral Fellowship. Suzanne's research has taken her to Svalbard, Alaska, Oregon, and Nepal, and has focused on interactions between chemical weathering, hydrology, and physical erosion mechanisms. She currently directs the Boulder Creek Critical Zone Observatory, an NSF environmental observatory based at the University of Colorado that involves researchers from four institutions and agencies. Suzanne was editor of *Arctic, Antarctic, and Alpine Research* from 2004–2006, and served as an associate editor of the *Journal of Geophysical Research – Earth Surface* from 2002–2006.

Praise for this textbook

"This book is terrific! Anderson and Anderson have hit it just right on all the main points: their book is engaging and informal; thorough but not pedantic; and shot through with the sheer pleasure of understanding how things work. It's packed with physical insight, useful information, and interesting problems; and it is simply a pleasure to read. This is a model of what a textbook should be, and it's also the first place I'd send a student or colleague to get them excited about landscapes and how we study them."
CHRIS PAOLA – *Professor of Geology and Geophysics, St. Anthony Falls Laboratory, Minneapolis*

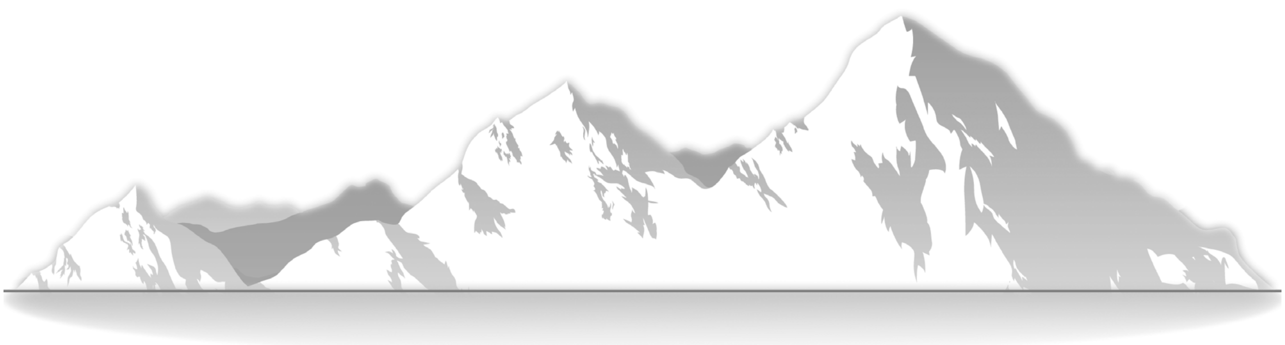
"This much needed, skilfully crafted text will be welcomed by the geomorphology community. . . . I applaud Bob's and Suzanne's approach of focusing on "how geomorphic things work" independently of where and when . . . From this perspective the text is aptly titled, and it will have a long, healthy lifespan . . . The text offers a systematic coverage of essential ingredients . . . the presentation of various topics spans a range of sophistication . . . so that the text can be used for an introductory course, or as part of a more advanced course. The writing is clear, sometimes playful, and possesses personality. The overall reaction of my students using a draft version has been very positive."
DAVID JON FURBISH – *Professor and Chair, Department of Earth and Environmental Sciences, Vanderbilt University*

"Geomorphology has entered a new era. Building on decades of research on the mechanisms of Earth surface processes and driven by stunning new tools that provide both the age and elevation of the landscape, geomorphologists now endeavor to truly predict the form of the Earth. The Anderson's new book is the first to pull this information together in a consistent framework. Its synthesis will be used to date the arrival of geomorphology as a mature, coherent, predictive science. The book is both authoritative and accessible, encouraging students (and instructors) to think creatively and precisely about how the landscape evolves. Unlike previous geomorphology texts, it provides a consistent approach for defining and solving models for the full range of features found on the surface of the Earth."
PETER R. WILCOCK – *Professor and Associate Chair, Department of Geography and Environmental Engineering, Johns Hopkins University*

"A wonderful, wide ranging review of the modern science of geomorphology."
NIELS HOVIUS – *Lecturer, Department of Earth Sciences, University of Cambridge*

Geomorphology

THE MECHANICS AND CHEMISTRY OF LANDSCAPES



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The Blue Hills badlands in central Utah comprise a landscape of diffusive hillslopes developed in the shales of the Cretaceous interior seaway, bounded by incising channels. Downcutting of the sinuous channel here is accomplished by a series of headward-migrating knickpoints, and reflects baselevel control by the Fremont River. In the middle distance is a silhouette of South Caineville Plateau, capped with 60 m of massive sandstone. The snow-capped laccolithic Henry Mountains in the distance were the subject of Grove Karl Gilbert's 1877 "Report on the Geology of the Henry Mountains", which laid the foundation for modern geomorphology.

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PREFACE

Geomorphology is the study of the shape of the Earth. In this book we take this quite literally, and address the shape of the Earth at many scales. We ask why it is spherical, or not quite spherical, why it has a distribution of elevations that is bimodal, one mode characterizing a quite well-organized set of ocean basins, another the terrestrial landscape. At smaller scales, we address why hilltops are convex, why glacial troughs are U-shaped, why rivers are concave up. At yet smaller scales, sand is rippled, beaches are cusped, hillslopes are striped, and mud is cracked. These are some of nature's most remarkable and visible examples of self-organizing systems. Each cries out for both explanation and appreciation.

Goals

We wrote this textbook to provide modern teachers and students of geomorphology with a formal treatment of geomorphic processes that acknowledges the blossoming of this field within the last two decades. It brings together between two covers the background that serves to attach our field with those of geophysics, atmospheric sciences, geochemistry, and geochronology. It honors the heightened importance of geomorphology in understanding the environment and its changes, with an attendant need to pose these problems more formally.

The book is intended to be used in an introductory geomorphology course in which the attention is more on the processes that shape landscapes than on the cataloging of landforms. Most likely such a course will fit into a third and fourth year undergraduate or an introductory graduate curriculum. The students must be comfortable with or be accepting of the challenge of a mathematical treatment of the topic. We have tried to be friendly by providing steps in the derivations, by providing a comprehensive math backdrop in the appendix, and by setting a conversational tone, as if we were in the room teaching.

The long gestation of the book (we began this book a decade ago) is in part due to the breadth of the territory we have tried to cover. But it also reflects the high productivity of the community of scientists for whom this book is intended. The last decade has seen the emergence of new journals in which to publish, new methods to employ in the field, and, of course, continued growth of computational capacity available to the field. These new papers serve as a distraction at the very least, and as new material to try to synthesize or incorporate in some fashion. The field is therefore a moving target, as it should be in any burgeoning field of science. We have tried to capture it in motion, and to give a sense that it is ever-broadening through incorporating the latest material.

Our goal is to allow the reader of this book to view landscapes in a more systematic way. We focus on the formal treatment of geomorphic processes that allows the student to see the connective tissue between sub-disciplines in geomorphology. We show how one can set up problems by employing the concept of continuity, or of conservation of some quantity, in, for example, hillslopes, glaciers, alluvial rivers, and dating methods. The word picture for all of these problems is: the rate of change of storage of some quantity = the rate of inputs minus the rate of loss of that quantity. Setting up the problem in this way then demands that we understand quantitatively how material (or energy) moves in the environment, and what the sources or sinks of that material might be. This then motivates both theoretical work on fluxes, and field experiments designed to constrain such theory. The student is encouraged to gain an appreciation of this approach by sheer repetition, from application to application, from chapter to chapter. If by the end of the book, or of the course based upon it, the student is heard to groan "not again . . .," we will have succeeded.

The practice of modern geomorphology often includes the generation of numerical models of landscapes or of key landforms. This exercise absolutely requires the formal problem set-up we advocate. The computer demands that we think in concrete, careful, and logical terms. In this textbook we honor that demand and demonstrate through repeated use of this approach how to set up quantitative problems in geomorphology. In this sense this textbook therefore connects more directly to similar approaches in our sister sciences of physics and chemistry.

So that the student need not scurry off to find another math or physics textbook, we have both provided detailed derivations within the textbook, and have supported the steps with reference to an extensive math appendix meant to serve as a refresher for all math from algebra through differential equations and probability density functions.

Novelties

We cover explicitly several topics that are not broken out in most geomorphology textbooks. These include several of the first chapters in the book:

- The whole Earth shape (Chapter 2). We ask why the Earth is a sphere, or really not quite a sphere, and what governs the largest features on the Earth. This introduces isostasy.
- Large-scale forms attributable to large-scale geophysical processes (in the mantle) (Chapter 3).
- Tectonic geomorphology (Chapter 4). Here we discuss the geophysical processes responsible for the growth of individual mountain ranges. As most of these involve faults, this requires addressing slip rates and how we know them, which verges on paleoseismology.
- Establishing timing in the landscape (Chapter 6). Here we dwell on the developments in the use of cosmogenic radionuclides, and break out a section on thermochronometry as it has become so useful in constraining long-term exhumation patterns.

The end of the book is ornamented with two novel chapters:

- The geomorphology of big floods (Chapter 17). We could not help but assemble in one place all those stories we hear about in different corners of the literature about the biggest of the geomorphic events – the big floods: Bonneville, Spokane, Lake Agassiz, and so on. These are the stories we all tell around the campfire, discussing when we would like to have lived, what events we would like to have witnessed. The evidence for these is writ large on some landscapes, for there has not been the power in any subsequent event to erase them from the landscape.
- Whole landscapes (Chapter 18). In this chapter we assemble information from all quarters on the evolution of the Santa Cruz landscape as an illustration of how all of the parts of the book are useful in compiling a more comprehensive understanding of one landscape.

Geomorphology is indeed the most visible of the Earth science disciplines. It is the study of the scenery that inspires photography. We launch each chapter with a photograph meant to capture the beauty of the topic, accompanied by a quote or a poem similarly inspired.

Arrangement of the book

We have organized the book to proceed from large scale to small scale. Treatment of the large scale requires an acknowledgement of the various roles of geophysics in generating and in accommodating topography. We augment these precursor chapters with one on dating (Chapter 6) and one on the roles of the atmosphere in geomorphology (Chapter 5). Armed with these tools, we then tackle the more classical topics within geomorphology – those that tear down and attack the geophysically generated topography. We treat first the processes and forms that characterize cold environments. We admit these are topics of particularly strong interest for both of us. But these lie a little outside the organization that naturally arises in the remainder of the book. After treatment of cold environments (in Chapters 8 and 9), we have organized the remainder of the topics according to what one needs to know first: we need to produce regolith before we can transport it. We need to know how material moves on hillslopes before it gets to the rivers. We need to know how water moves on hillslopes and in rivers before we can address how water transports sediment. Finally, we need to know all of these pieces before we can fully understand a particular landscape. We employ the Santa Cruz landscape in coastal California as our chief example. Tectonics matters, sea level variation matters, orographic precipitation matters, and so on.

How to use the book

One may teach a course based on the material in this book in many ways. The more common approaches to teaching geomorphology would skip the large-scale material in the first few chapters and begin with the small scale, e.g., sediment transport, hillslopes, or wind. After all, it is often these topics that have attracted the student into a class on geomorphology. As the book is designed such that all chapters can stand alone, one may order the course however one wishes. If the students have been exposed to the large-scale backdrop material in other classes, then begin with glaciers, or sediment transport. We recommend, however, that the course designer sweep through the text to locate where we have introduced certain topics. The table of contents is a good place to start. For example, fluid mechanics is introduced in earnest in the chapter on rivers (Chapter 12), the development of the full Navier–Stokes equation being tucked in an appendix to that chapter. Heat transfer is covered in the chapter on the effects of large-scale geophysics (Chapter 3), as this is where we first encounter conduction and diffusion in studying the bathymetry of ocean basins. Settling speeds are introduced in the hillslopes chapter (Chapter 10), as it is here that we need them first to calculate the kinetic energies of raindrops. The student will need this backdrop on settling speeds again in studying sediment transport mechanics; we spare the space by not reproducing the development in that chapter (Chapter 14).

Student and teacher support

We have included material in boxes scattered throughout the book. These boxes serve several purposes: to allow us the occasional historical aside, to illustrate a topic with an example, or to develop an analogy with another field altogether. For example, corduroy roads are analogous to eolian ripples; the common day grilling of a cheese sandwich develops insight into thermal problems.

We have posed several student problems at the end of each chapter in order to challenge the student to use the material and the approaches presented. Some of these exercises simply promote paying close attention to one or another illustration in the text. Others involve more complicated calculations. We also pose a couple of thought questions, which are more qualitative, open-ended questions meant to inspire review of the chapter or connection with other chapters.

We also point the reader to a smaller text in which the guiding principles of this larger book are illustrated. In this *Little Book of Geomorphology*, available on the web since January 2008 at http://instaar.colorado.edu/~andersrs/The_little_book_010708_web.pdf, many of the geomorphic examples we discuss in this larger book are sketched and briefly discussed. The little book is subtitled "exercises in continuity." Its brevity places the analyses more cheek by jowl to allow more immediate appreciation of this theme. The little book will continue to be available on the website.

Finally, we have included a very thorough and up-to-date reference list, so that the book is tightly attached to the modern literature. Each chapter ends with a list of suggested reading. These are usually key books in the field covered in that chapter, to which

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the reader should turn for a more extensive discussion of the literature.

All the figures in the book will be available on a long-lived website so that professors may use them to illustrate lectures based on the material. This site will also have other photographs to support the material.

What we do not cover

In writing any textbook one must choose what to cover and what to omit. We have not covered karst landscapes. We have not surrounded the growing literature on submarine landscapes. And we have stuck to our own planet Earth. While the examples that we cover are overwhelmingly terrestrial, the general principles and the approach to posing geomorphic problems more formally can be applied to the surface of any object in the solar system (or beyond) if the appropriate environmental conditions are considered. In this new century, in which we have already marveled at how several landers have crawled around the surface of Mars, have launched a mission to Mercury, and have watched as a spacecraft slipped through the rings of Saturn to begin a several-year exploration of the Saturnian system, it is relevant to ask how well our understanding of surface processes here on Earth translates into an ability to understand the features of other bodies in our solar system. These extra-terrestrial landscapes serve as ultimate tests of our knowledge, as they represent natural experiments in which the controlling variables have been significantly tweaked from those on Earth: gravity, wind speed, atmospheric composition, solar radiation, tectonic rates, the mechanical and chemical properties of the materials comprising the surface, and so on. It is indeed an exciting time to be a student of not only our planet but of planets in general.

ACKNOWLEDGEMENTS

We were initially inspired to write a textbook during a conversation with Tom Dunne many years ago. He challenged us to articulate the fundamental principles of geomorphology. We have tried to take up that challenge, pulling most strongly on the theme of conservation. We thank Roger Hooke for carefully reading a draft of the book. Dave Furbish has been a strong supporter of our effort, including sponsoring an altogether too brief writing visit for Suzanne. Pete Adams, Greg Hancock, Eric Kirby, Kirsten Menking, Noah Snyder, and perhaps a few others have used the book in draft form in classes, and their feedback and encouragement has been very helpful.

We also acknowledge deeply those who have inspired us through their teaching, both formal and informal: among them, Bernard Hallet, Tom Dunne, Bill Dietrich, Peter Haff, Ron Shreve, and Bob Sharp have set the highest of standards. As professors, we also learn through the eyes, ears, legs, minds, and hearts of our students. To those students and post-docs at UC Santa Cruz and at Colorado, we offer our heartfelt thanks for the challenges you accepted, and the adventures in which you shared.

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**We dedicate this work to our parents,
John and Florence Anderson and
Ken and Lois Prestrud, who first introduced
us to mountain landscapes and spawned
our love of science.**

**We also dedicate this work to our children,
Hannah and Grace Anderson, who have never
known a time when mom and dad were not
working on the book, who will help carry their
generation forward, and who we hope will
strive to understand their surroundings and
sustain their environment.**

**Suzanne dedicates her contributions to the
memory of her brother, Kris.**