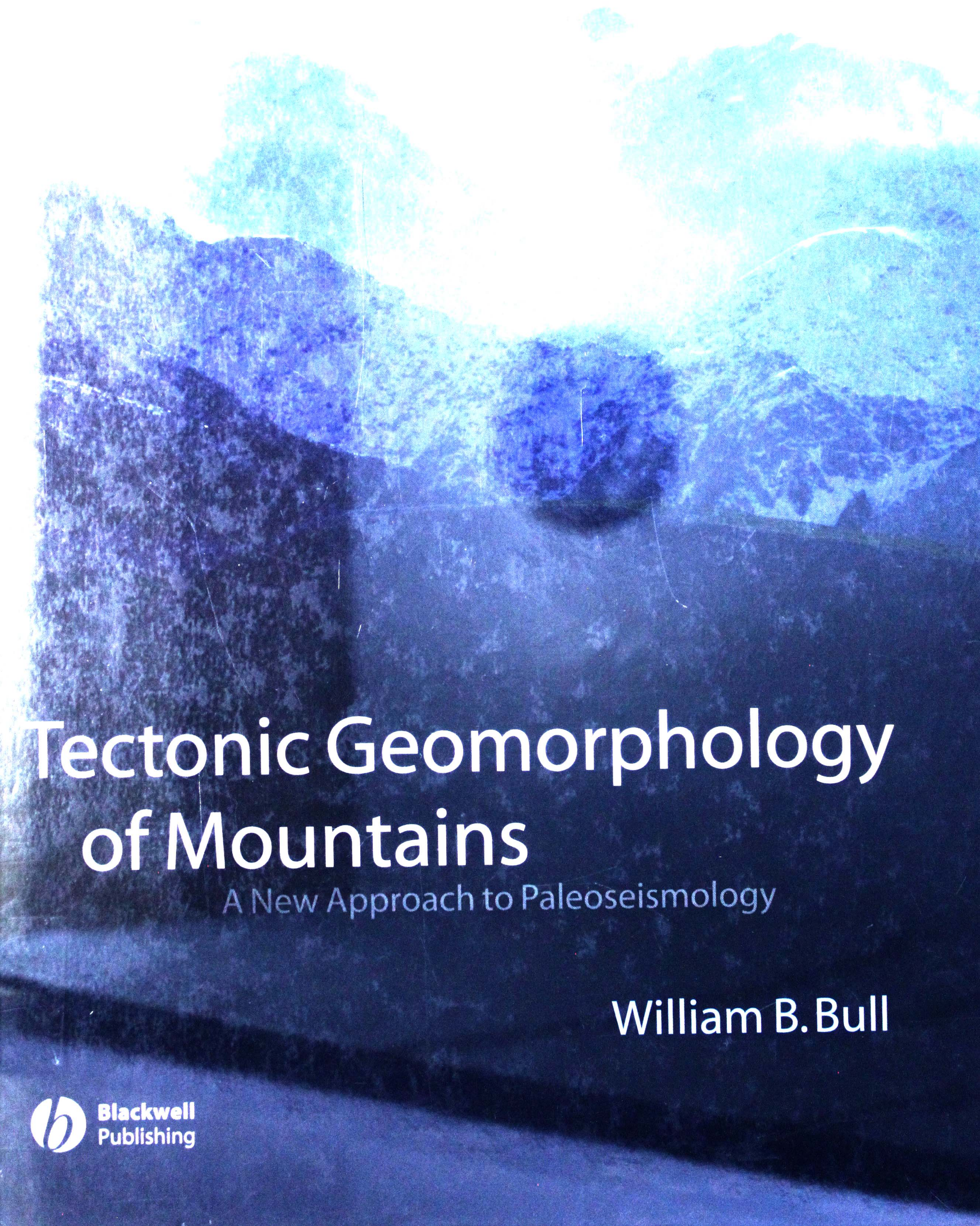


Tectonic Geomorphology of Mountains

A New Approach to Paleoseismology

William B. Bull

Blackwell Publishing

Tectonic Geomorphology of Mountains:

A New Approach to Paleoseismology

William B. Bull

Blackwell Publishing

BLACKWELL PUBLISHING
350 Main Street, Malden, MA 02148-5020, USA
9600 Garsington Road, Oxford OX4 2DQ, UK
550 Swanston Street, Carlton, Victoria 3053, Australia

First published 2007 by Blackwell Publishing Ltd

1 2007

Library of Congress Cataloging-in-Publication Data

Bull, William B., 1930–
Tectonic geomorphology of mountains : a new approach to paleoseismology / William B. Bull.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-1-4051-5479-6 (hardback : alk. paper)
ISBN-10: 1-4051-5479-9 (hardback : alk. paper) 1. Morphotectonics. 2. Paleoseismology. I. Title.

QE511.44.B85 2007
551.43'2–dc22

2006100890

A catalogue record for this title is available from the British Library.

Set in 10.74/11pt AGaramond
by SPi Publisher Services, Pondicherry, India
Printed and bound in Singapore
by C.O.S Printers Pte Ltd

The publisher's policy is to use permanent paper from mills that operate a sustainable forestry policy, and which has been manufactured from pulp processed using acid-free and elementary chlorine-free practices. Furthermore, the publisher ensures that the text paper and cover board used have met acceptable environmental accreditation standards.

For further information on
Blackwell Publishing, visit our website:
www.blackwellpublishing.com

Preface

Uplift by mountain-building forces changes fluvial landscapes. Pulsatory tectonic activity on a range-bounding fault increases relief, changes rates of geomorphic processes, and modifies the shapes of hills and streams. Landscape responses to uplift occupy a critical time frame for studies of past earthquakes between the brevity of instrumental seismic data and long-term geologic crustal shifts. The appealing challenge for us is to determine how and when nearby and distant parts of the landscape change in consecutive reaches upstream from a tectonically active range front. Each climatic and lithologic setting has a characteristic style and rate of erosion, which adds spice to the scientific challenge. Landscape analyses include the geomorphic consequences of seismic shaking and surface rupture and their associated hazards to humankind. Tectonic geomorphology is essential for complete paleoseismology investigations. Locations, sizes, times, and patterns of seismic shaking by prehistorical earthquakes can be described and surface rupture and seismic-shaking hazards evaluated.

This book explores tectonic geomorphology of mountain fronts on many temporal and spatial scales to encourage expansion of paleoseismology inquiries from the present emphasis on stratigraphic investigations in trench exposures. Evaluating earthquake hazards is in part a study of mountain-front segments. Cumulative displacements over late Quaternary time spans create landscape assemblages with distinctive signatures that are functions of uplift rate, rock mass strength, and the geomorphic processes of erosion and deposition. Such interactions define classes of relative uplift. Tectonic activity class maps define tectonically inactive regions as well as fronts of slow to rapidly rising mountains. Fault scarps focus our attention on recent surface ruptures and propagation of active faults. Dating and describing the characteristics of single prehistoric surface-ruptures is important. But now we can link sequences of events and depict sequences of prehistorical earthquakes along complex plate boundary fault zones. Examples here include the Alpine fault in New Zealand and the northern Basin and Range Province in the United States.

This book applies a variety of geomorphic concepts to tectonics and paleoseismology. Don't expect landscape summaries for all major mountain ranges. Repetitive descriptions would dilute explanation and application of basic principles. Do expect essential concepts that should help you better understand the landscape evolution of your favorite mountains. Mountain front tectonic geomorphology studies can determine:

1) Which faults are active [Holocene ruptures],
2) Fault slip rates for short time spans [offset landforms] and long time spans [landscape evolution],
3) Time of most recent surface rupture and degree of irregularity of earthquake recurrence interval, and
4) Intensity and extent of seismic shaking.

The amount of related literature cited borders on being unwieldy because of topic diversity of and the rapidly increasing interest of earth scientists in these subjects. I had to pick and choose so as to not overwhelm the content with citations of relevant literature. My citations are merely a gateway to related literature.

Dating times of prehistoric earthquakes and estimating rates of tectonic and geomorphic processes continue to be of paramount importance. Study methods are changing, and precision and accuracy are improving. Diffusion-equation modeling of fault scarps and stratigraphic radiocarbon dates on pre- or post earthquake material collected from trenches have long been bastions for approximate age estimates. Sykes and Nishenko made a plea in 1984 for better ways of dating frequent earthquakes along plate boundary fault zones whose earthquake recurrence intervals may be shorter than the intervals defined by groups of overlapping radiocarbon age estimates. The rapid development of terrestrial cosmogenic nuclides broadens dating perspectives by estimating ages beyond the reach of radiocarbon analyses and by making surface-exposure dating a cornerstone for studies of geomorphic processes. Tree-ring analyses and lichenometry have potential for dating prehistorical earthquakes with a precision of ± 5 years.

Both methods are used here in a study of Alpine fault, New Zealand, earthquake history.

The subjects of the six chapters are wideranging. Acknowledging the scrunch and stretch horizontal components of bedrock uplift is assessed from a geomorphic standpoint in Chapter 1. Diverse, essential conceptual models and methods for fluvial tectonic geomorphology are presented in Chapter 2. Contrasting tectonic landforms and landscape evolution associated with thrust and normal faults are the focus of Chapter 3. Uplift, stream-channel downcutting, and piedmont aggradation are interrelated base-level processes that are used to define relative classes of mountain-front tectonic activity in Chapter 4. The fault scarps of Chapter 5 are incipient mountain fronts with surface-rupture recurrence intervals ranging from 200 years to 200,000 years. Chapter 6 considers how mountains crumble from seismic shaking. It uses coseismic rockfalls and tree-ring analyses for precise, accurate dating of earthquakes of the past 1,000 years and for mapping the intensity of seismic shaking of these prehistorical events.

Readers should know basic geologic principles as these essays are written for earth scientists and students of geomorphic processes, landscape evolution, and earthquake studies. This book is appropriate for upper division and graduate-level courses in active tectonics, geologic hazards, tectonic geomorphology, physical geography and geomorphology, engineering geology, and paleoseismology.

This project began in 1975 when Luna Leopold encouraged me to embark on selected in-depth geomorphic syntheses using book manuscripts as a career development tool. Global climate change and tectonic deformation are major factors influencing the behavior of fluvial geomorphic systems. Book goals determined my study emphases in a series of projects. "Geomorphic Responses to Climatic Change" (Bull, 1991) revealed pervasive impacts on geomorphic processes of arid and humid regions. This second book examines tectonic geomorphology of mountain ranges in a paleoseismology context.

Of course the varied content of this book is indeed a team effort by the earth-science community. Students in the Geosciences Department at the University of Arizona played essential roles in every chapter. Peter Knuepfer, Larry Mayer, Les McFadden, Dorothy Merritts, and Janet Slate were among the many who tested the conceptual models of Chapter 2 with field-based studies. The first true positive test of the fault segmentation model (Schwartz and Coppersmith, 1984) in Chapter 3 is the work of Kirk Vincent. Les McFadden and Chris Menges broke new ground with me for the Chapter 4 elucidation of tectonic activity classes of mountain fronts of the Mojave Desert and Transverse Ranges of southern California. Susanna Calvo, Oliver Chadwick, Karen Demsey, Julia Fonseca, Susan Hecker, Phil Pearthree, and Kirk Vincent helped define the essential aspects for studies of normal-fault scarps of the Basin and Range Province in a vast region stretching from Idaho into Mexico. Andrew Wells kindly provided fascinating details about the sensitivity of New Zealand coastal and fluvial landscapes to seismic shaking. The integration of geomorphic and structural features shown in the Figure 1.12 map is the work of Jarg Pettinga. Kurt Frankel and Mike Oskin shared results and concepts of work in progress and Figures 5.35–5.40.

The book project expanded in scope during a decade when a new lichenometry method was developed to date and describe how seismic shaking influences rockfalls and other landslides. Lichenometry projects included expeditions into the Southern Alps and Sierra Nevada with Fanchen Kong, Tom Moutoux, and Bill Phillips. Their careful fieldwork and willingness to express divergent opinions were essential ingredients for this paleoseismology breakthrough. I appreciate the assistance of John King in sampling and crossdating the annual growth rings of trees in Yosemite, and of Jim Brune's help in measuring lichen sizes near the Honey Lake fault zone. Jonathan Palmer introduced me to Oroko Swamp in New Zealand, which turned out to be a key dendroseismology site.

Images are essential for landscape analysis and portrayal. Tom Farr of the Jet Propulsion Laboratory of the California Institute of Technology always seemed to have time to help find the essential NASA and JPL images used here. The banner photo for Chapter 2 and Figure 4.14 are the artistry of Peter Kresan. I thank

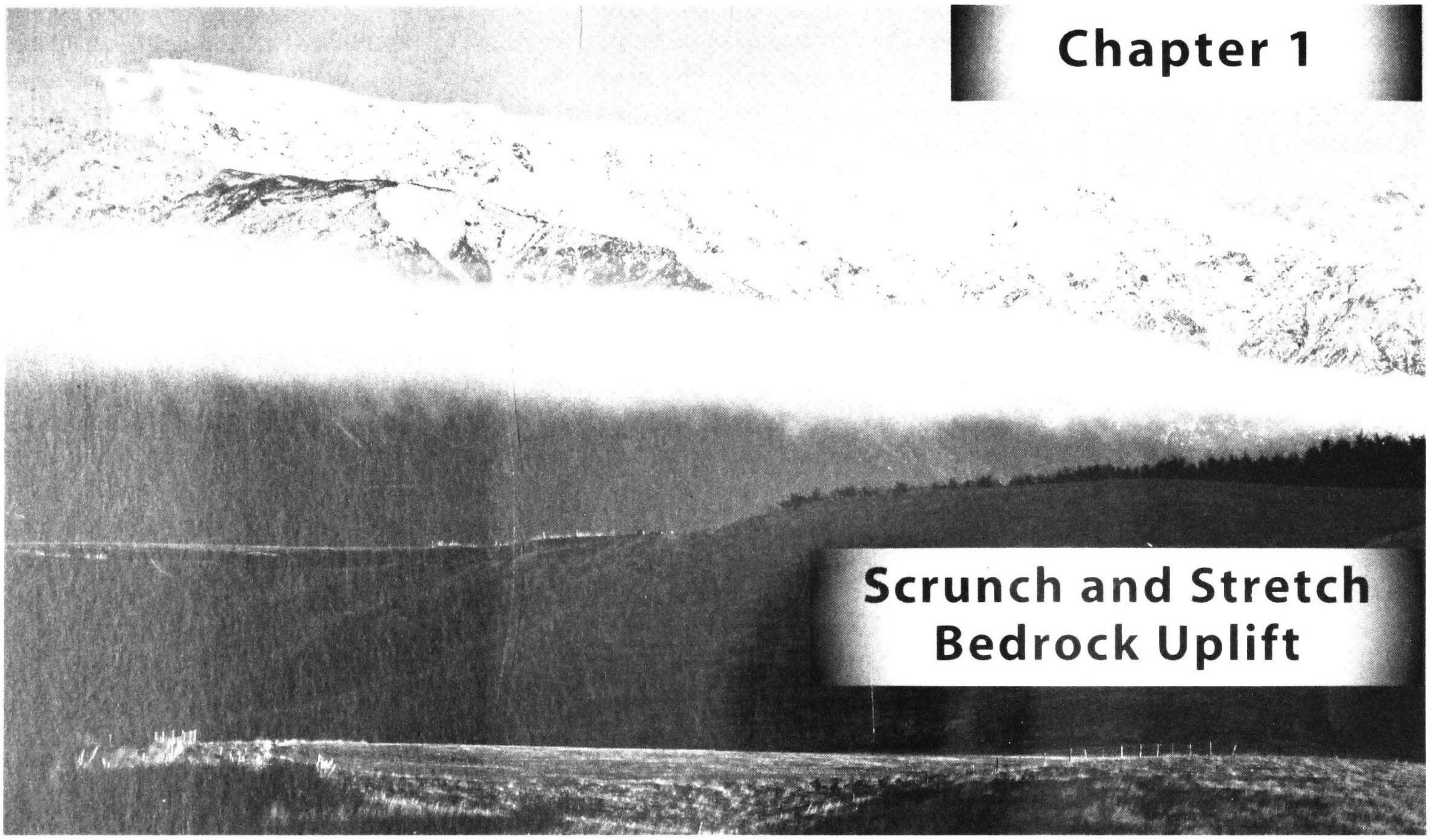
Frank Pazagglia for Figure 2.4, Malcolm Clark for the Chapter 4 banner photo, Tom Rockwell for the Figure 5.28 image, Greg Berghoff for Figure 5.34, Scott Miller for Figure 6.2 and Eric Frost for Figure 6.9A.

Formal reviews of the entire book manuscript by Lewis Owen and Philip Owens provided numerous suggestions that greatly improved book organization and content. I am especially indebted to Wendy Langford for her meticulous proofreading and to Rosie Hayden for editorial suggestions. Their thoroughness improved format and uniformity of expression. It was a pleasure to work with the efficient production staff at Blackwell Publishing including Ian Francis, Rosie Hayden, and Delia Sandford.

Essential financial and logistical support for this work was supplied by the U.S. National Science Foundation, National Earthquake Hazards Reduction Program of the U.S. Geological Survey, National Geographic Society, University of Canterbury in New Zealand, Hebrew University of Jerusalem, Royal Swedish Academy of Sciences, and Cambridge University in the United Kingdom.

Contents

Chapter 1



Scrunch and Stretch Bedrock Uplift

Earthquakes! Active Tectonics! Evolution of Mountainous Landscapes! Landscapes have a fascinating story to tell us. Tectonic geomorphology intrigues laypersons needing practical information as well as scientists curious about Earth's history.

How fast are the mountains rising? When will the next large earthquake occur? Will the seismic shaking disrupt the infrastructures that we depend on? How do the landscapes surrounding us record mountain-building forces within the Earth's crust, and how does long-term erosion influence crustal processes? Humans are intrigued by tectonic geomorphology on scales that include origins of continents, grandeur of their favorite mountain range, and the active fault near their homes.

Let us expand on the purpose and scope summarized in the Preface by elaborating on the structure of this book. I introduce, describe and use geomorphic concepts to solve problems in tectonics and paleoseismology. The intended geographical focus is global application of examples from southwestern North America and New Zealand. A fluvial emphasis excludes glaciers, sand seas, and active volcanoes. I present data and analyses from diverse tectonic, climatic, and lithologic settings so you can resolve similar problems in other geographical settings.

This book emphasizes responses of fluvial systems to uplift, or more specifically the adjustments of geomorphic processes to base-level fall. Uplift terminology usage continues to change since the hallmark paper by Molnar and England (1990). Geomorphologists may use uplift terms in a different context than structural geologists. So Chapter 1 is a brief review of terminology and types of base-level change induced by tectonic deformation in extensional and contractional settings. Such crustal stretching and scrunching is nicely recorded by landforms ranging in size from mountain ranges to fault scarps.

A variety of useful geomorphic concepts are assembled in Chapter 2 instead of being scattered. Get familiar with these principles. This broad base of essential concepts lets you evaluate and explore new and diverse approaches in tectonic geomorphology. These include a sensitive erosional–depositional threshold, time lags of response to ***perturbations*** (changes in variables of a system), types of equilibrium (graded) conditions in stream

Photograph of 59,000 and 96,000 marine terraces (Ota et al., 1996) and 330,000 year old mountains (Bull, 1984, 1985) rising out of the sea at Kaikoura, New Zealand systems, local and ultimate base levels, and the process of tectonically induced downcutting to the base level of erosion. These guidelines are a foundation for understanding interrelations between tectonics and topography in the next three chapters.

Chapter 3 compares the landscape evolution and useful tectonic landforms for mountain ranges being raised by slip on active thrust and normal faults. These fluvial systems are affected differently by the two styles of tectonic base-level fall. Strike-slip faulting tends to tear drainage basins apart: a much different subject that is not emphasized here. Some tectonic landforms, like triangular facets, are rather similar in different tectonic settings. But piedmont landforms are much different in thrust- and normal-fault landscapes. Comparable contrasts should be expected elsewhere, such as the countries bordering the Mediterranean Sea, and Mongolia.

The next three chapters discuss tectonic geomorphology for three distinct time spans (Fig. 1.1) of about 2,000,000, 12,000, and 1,000 years. The tectonic-geomorphology theme continues to be applications for paleoseismology. The landscape tectonic activity classes of Chapter 4 are based on universal geomorphic responses to different rates of base-level fall during the Quaternary time span. The resulting diagnostic landscape assemblages are defined and mapped for diverse tectonic and structural settings in California. This model could have been created, and applied, just as easily for suites of mountain fronts in Japan, China, Mongolia, and Russia.

Fault scarps are the focus of Chapter 5, with an emphasis on the Holocene time span. Choosing to discuss recent surface ruptures in southwestern North America was done in part to hold variations of several controlling factors to a limited range. These include climate and alluvium mass strength. Such studies of incipient mountain fronts can be made just as easily in the Tibetan Plateau, the Middle East, and Africa.

New approaches are overdue to decipher the sequences of frequent earthquakes that characterize plate-boundary fault zones. Chapter 6 develops a new geomorphic way to precisely date earthquakes in New Zealand and to describe their seismic shaking. It then tests the model in California. This geomor-

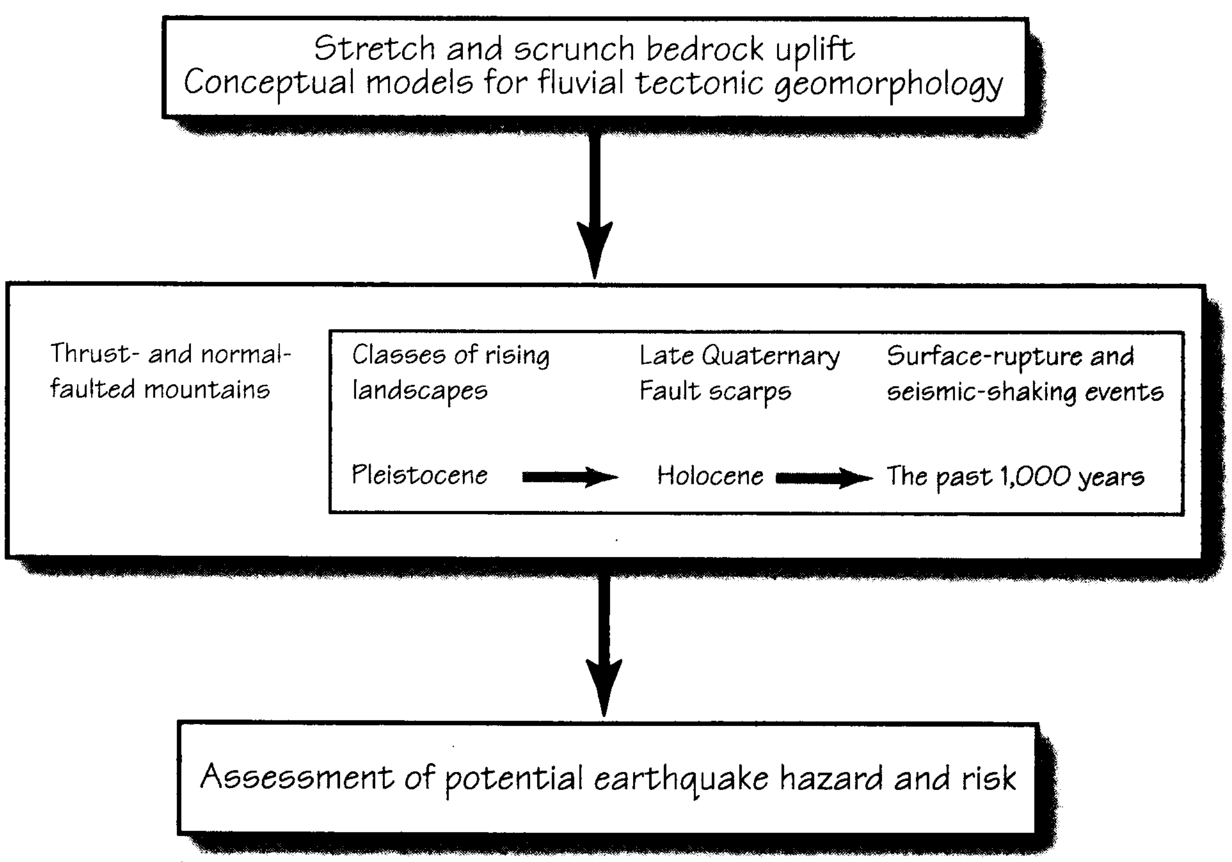


Figure 1.1 Major topics of this book and their application to paleoseismology.

phic approach to paleoseismology provides essential information about the frequency and magnitude of recurrent tectonic perturbations such as surface ruptures and seismic shaking. Other plate-boundary settings, such as the Andes of South America, Anatolian fault zone of Turkey, and the Himalayas may be even better suited for this way to study earthquakes than my main study areas.

This book uses two primary, diverse study regions to develop concepts in tectonic geomorphology for fluvial systems in a global sense. Principal sites in New Zealand are shown in Figure 1.2 and southwestern North America sites in Figure 1.3 together with the links to their chapter section numbers.

1.1 Introduction

Continental landscapes of planet earth are formed in large part by interactions of tectonic and fluvial processes, which are modulated by the pervasive influence of late Quaternary climate changes. ***Tectonics*** is the study of crustal deformation: the evolution of

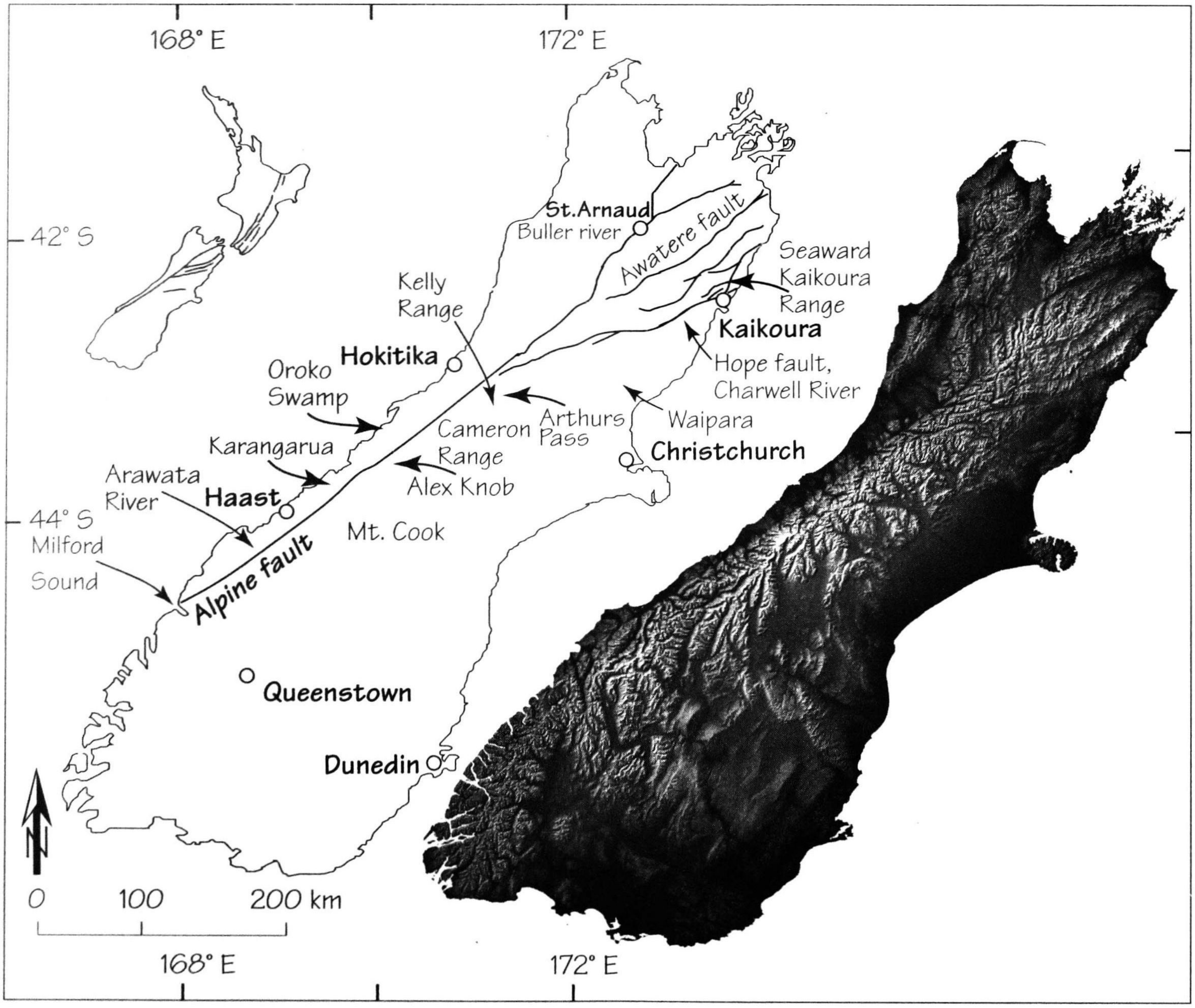


Figure 1.2 Locations of Southern Alps study sites in the South Island of New Zealand discussed in Sections 1.2, 2.4, 2.5, 2.6, and 6.2.1. This is a grayscale version of Shuttle Radar Topography Mission image PIA06662 furnished courtesy of NASA and JPL.


Washington
Montana
Oregon
Idaho
Wyoming
California
Utah
GP
NPR
Denver
Nevada
GP
Colorado
Los Angeles
Arizona
New Mexico
ST
SM
LS
PIT
Texas
Mexico

geologic structures ranging from broad transition zones between crustal plates to small faults and folds. ***Geomorphology*** is the study of landscapes and the processes that shape them. The influences of vertical and horizontal earth deformation on fluvial, coastal, and glacial processes and the resulting landscapes comprise the domain of ***tectonic geomorphology***. The main emphasis here is on fluvial system responses to tectonic deformation.

The challenge for all of us is to more fully recognize and use tectonic signals in the landscapes around us. The consequences of earth deformation by specific geologic structures profoundly affect geomorphic processes and landscape evolution. Conversely, evolution of landscape assemblages can be used to decipher the kinematics of faults and folds.

Changes in style, rate, and locations of faulting and folding change the landscape too. An example is the Hope fault of New Zealand where Eusden et al. (2000) describe a 13 km long and 1.3 km wide transpressional duplex structure (adjacent areas of rise and fall) that has migrated northeast along a range-bounding oblique-slip fault that is as active as the San Andreas fault of California, USA. This leading portion of the duplex structure is rising on thrust faults. In the trailing southwest portion, formerly active duplex structures are now collapsing, undergoing a reversal of slip style to become normal faults. Rising geomorphic base levels become falling base levels with dramatic consequences for hills and streams of upstream watersheds. Another example is drainage nets that change as tips of faults propagate (Jackson et al., 1996). Structural geologists need to recognize how tectonic deformation affects erosion, deposition, and landforms.

Tectonic geomorphology aids tectonic inquiries on many temporal and spatial scales. Some of us seek to understand how horizontal, as well as vertical, earth deformation affects the shapes of hills and streams in a quest to better understand long-term partitioning of strain along plate boundary-fault systems (Lettis and Hanson, 1991). Others study landslides in order to determine earthquake recurrence intervals and to make maps depicting patterns of seismic shaking caused by prehistorical earthquakes (Chapter 6).

Tectonic geomorphology, seismology, and paleoseismology are cornerstone disciplines for studies of ***active tectonics*** (neotectonics). ***Seismology*** – historical instrumental studies of earthquakes – contributes much to our understanding of crustal structure and tectonics by 1) defining earthquake hypocenters (location and depth of initial rupture along a fault plane), 2) describing earthquake focal mechanisms (strike-slip, normal, and reverse styles of displacement), 3) evaluating the frequency, magnitude, and spatial distributions of present-day earthquakes, and 4) modeling how yesterday's earthquake changes the distribution of crustal stresses that will cause future earthquakes. ***Paleoseismology*** – the study of prehistorical earthquakes – utilizes many earth science disciplines including dendrochronology, geochronology, geodesy, geomorphology, seismology, soils genesis, stratigraphy, and structural geology. Tectonic geomorphology is indispensable for complete paleoseis-

Figure 1.3 Locations of study sites in the western United States and northern Mexico and their book section numbers [5.5]. B, Pleistocene Lake Bonneville [5.2.3]; BL, Big Lost River [5.3]; BP, Borah Peak and the Lost River Range [3.3.4]; CD, Curry Draw [2.2.3]; CP, Colorado Plateau; DR, Diablo Range [4.2.3.2]; DV, Death Valley, Panamint Range, and Saline Valley; FR, Front Range [1.3]; GC, Grand Canyon [2.5.2]; GP, Great Plains [1.3]; HL, Hebgen Lake [5.6.2]; KR, Kings River [6.2.2.2]; L, Pleistocene Lake Lahontan [5.2.3]; LS, Laguna Salada [2.1]; MC, McCoy Mountains [3.2.2]; MD, Mojave Desert [4.2.3.2]; ML, Mount Lassen and the southern end of the subduction related Cascade volcanoes [4.1]; MR, Mogollon Rim [4.2.2]; NPR, North Platte River [1.3]; OM, Olympic Mountains [1.2.2, 5.5]; PIT, Pitaycachi fault [2.2.5, 5.4.2]; PR, Panamint Range, Death Valley, and Saline Valley [4.1, 4.2.2, 4.2.3]; PS, Puget Sound [5.5]; RG, Rio Grande River and extensional rift valley [1.3]; RM, Rocky Mountains [1.3]; S, Socorro [6.6.1]; SGM, San Gabriel Mountains [3.2, 3.3.1, 4.2.3.2]; SJV, San Joaquin Valley [4.1, 4.2.3.2]; SM, Sheep Mountain [4.2.2]; SN, Sierra Nevada microplate [4.1, 6.2.2]; ST, Salton Trough [4.2.3.2]; TR, Tobin Range, Pleasant Valley, Dixie Valley, and the Stillwater Range [3.2.1, 4.2.3.2, 5.1, 5.6.2]; WC, Wallace Creek [2.5.2]; WL, Walker Lake [5.2.3]; WR, Wasatch Range [3.3.3]; YO, Yosemite National Park [6.2.2.1, 6.2.2.3]. Digital topography courtesy of Richard J. Pike, US Geological Survey.

mology investigations. For example, stream-channel downcutting and diffusion-equation modeling of scarp erosion to complement stratigraphic information gleaned from trenches across the fault scarp.

Quaternary temporal terms (Table 1.1) have been assigned conventional ages*. The 12-ka age assignment for the beginning of the Holocene is arbitrary and is preceded by the transition between full-glacial and interglacial climatic conditions. Unless specifically noted, radiocarbon ages are conventional (using the old 5,568 year half-life allows comparison with dates in the older literature) and have been corrected for isotope fractionation. The term "calendric radiocarbon age" means that the correct 5,730 year half-life is used and that variations in atmospheric ^{14}C have been accounted for, using the techniques of Stuiver et al. (1998). Calibration of radiocarbon ages (Bard et al., 1990) shows that the peak of full-glacial conditions may be as old as 22 ka instead of the conventional radiocarbon age estimate of 18 ka. The 125 and 790-ka ages are radiometric and paleomagnetic ages that have been fine-tuned using the astronomical clock (Johnson, 1982; Edwards et al., 1987a, b). The 1,650-ka age is near the top of the Olduvai reversed polarity event (Berggren et al., 1995).

Landscape evolution studies accommodate many time spans. Topics such as the consequences of rapid mountain-range erosion on crustal processes involve time spans of more than 1 My. Examinations of how Quaternary climate changes modulate fluvial system behavior generally emphasize the most recent 50 ky. Understanding the behavior of fault zones concentrates on events of the past 10 ky.

Age	***Ka***
Holocene	
Late	0-4
Middle	4-8
Early	8-12
Pleistocene	
Latest	12-22
Late	12-125
Middle	125-790
Early	790-1650

Table 1.1 Assigned ages of Quaternary temporal terms, in thousands of years before present (ka).

*1 ky = 1000 years; 1 ka = 1 ky before present.
1 My = 1 million years; 1 Ma = 1 My before present.

The first concepts discussion about examines several processes that raise and lower the land surfaces of Chapter 1 study sites. Streams respond to uplift by eroding mountain ranges into drainage basins. So Chapter 2 then examines how far streams can cut down into bedrock – their base level limit. We also explore the behavior of fluvial systems to lithologic and climatic controls in different tectonic settings in the context of response times, the threshold of critical power, and tectonically induced downcutting. These concepts will give you a foundation for perceiving tectonic nuances of mountain fronts and hillslopes.

1.2 Pure Uplift, Stretch and Scrunch

Bedrock Uplift

1.2.1 Isostatic and Tectonic Uplift

My approach to tectonic geomorphology examines some of the myriad ways that uplift may influence fluvial landscapes. Many new methods and models alter our perceptions of tectonics and topography as we seek to better understand everything from landscapes and prehistorical earthquakes to crustal dynamics. So we begin this chapter by examining the intriguing and occasionally puzzling meanings of the term "uplift". My emphasis is on how subsurface processes affect altitudes of all points in a landscape. Read England and Molnar's 1990 article and you will come away with a fascinating perspective about several components that influence uplift of points on the surface of a large mountain range. The key to using their breakthrough is to recognize the factors influencing uplift of bedrock, not only at the land surface but also at many positions in the Earth's crust. I introduce additional parameters that also influence rock uplift. Both tectonic and geomorphic processes influence bedrock uplift (Fig. 1.4).

S.I. Hayakawa's semantics philosophy (1949) certainly rings true here; "The word is not the object, the map is not the territory". Not only will each of us have different (and changing) impressions of uplift terminology, but also my attempts to neatly organize key variables are hindered by substantial overlap between categories. Fault displacements do more than raise and lower bedrock (***pure uplift***), because

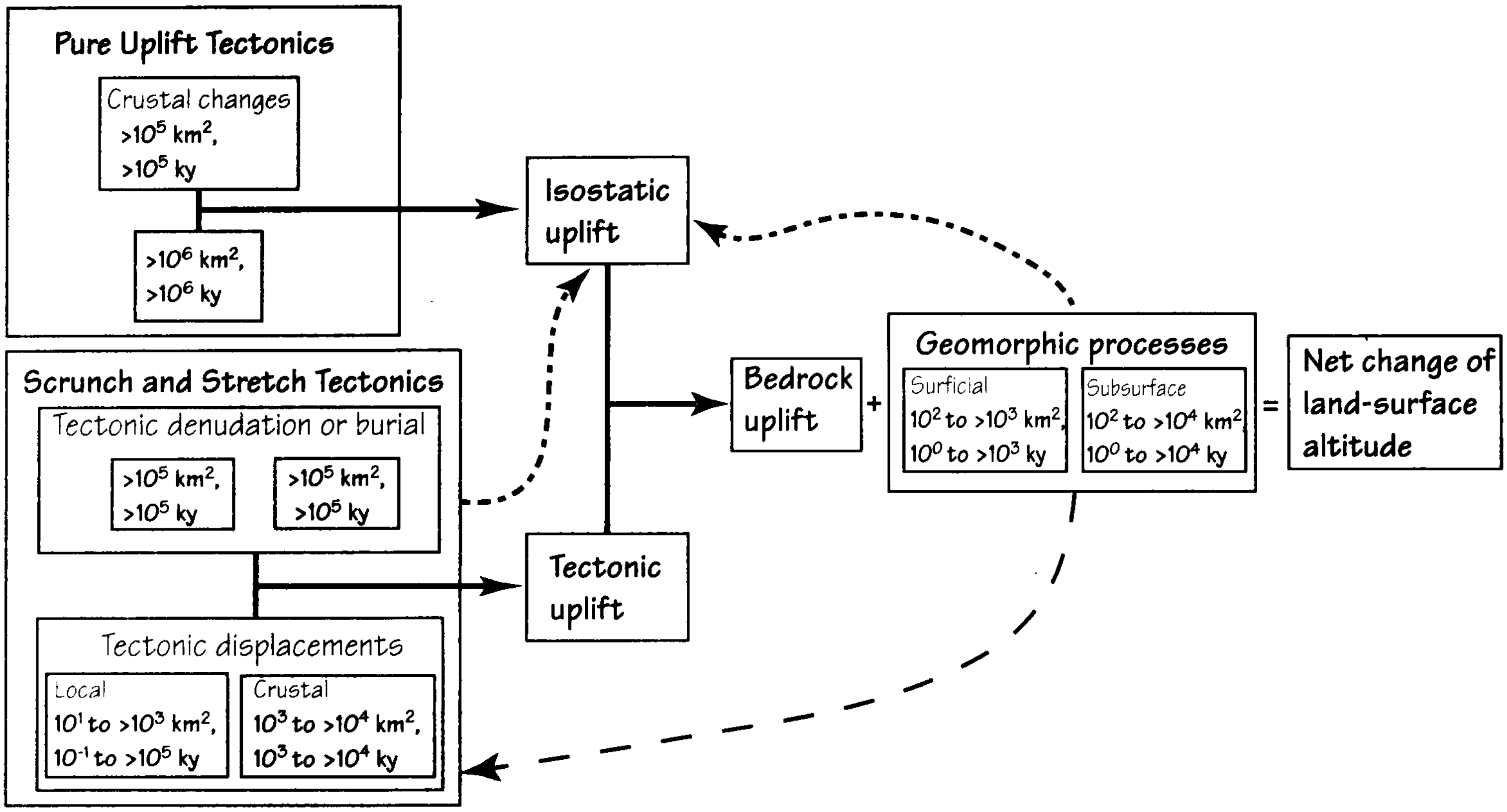


Figure 1.4 Links between tectonic, isostatic, and nontectonic variables affecting landscape altitudes and bedrock uplift. Feedback mechanisms to isostatic and tectonic uplift are shown with dashed lines.

earth deformation usually entails tectonic shortening (***scrunch***) and extension (***stretch***) processes. So, rocks move both vertically and horizontally (Willett, Slingerland, and Hovius, 2001). Do not expect crisp black-and-white definitions, because a model of fuzzy overlap is closer to the truth in the world of scrunch-and-stretch tectonics.

Erosion of mountains is like rain falling on a marine iceberg; the height of both results from buoyant support. Rainfall can never melt enough ice to lower the surface of an iceberg to the water line. This is because ice melted above the waterline is largely replaced by "uplift" of submerged ice. Sea level is a handy reference datum for uplift of ice or mountain ranges. Uplifted materials may be above or below that worldwide waterline. ***Altitude*** is the specific term for height above present sea level, whereas the engineering term "***elevation***" can have several geologic connotations, including uplift. Isostatic uplift occurs because ice is only 90 % as dense as seawater. If 100 tons is melted from the exposed surface of an iceberg, it is compensated by 90 tons of ice raised by isostatic uplift. This is pure uplift because it is not complicated by shearing or tensional failure of ice.

Similarly, isostatic uplift of mountain ranges continues despite eons of surficial erosion because continental crust "floats" on the denser rocks of the Earth's mantle. Continental crust with a density of about 2,700 kg/m^3 is in effect floating on mantle with a density of about 3,300 kg/m^3– a density contrast of roughly 82% (90% contrast for oceanic crust with a density of 3,000 kg/m^3). The iceberg analogy is appropriate because materials deep in the earth behave as viscous fluids over geologic time spans (Jackson, 2002). Fluvial and glacial denudation of 1,000 m only seems to significantly lower a mountain range because it is largely compensated by 820 m of concurrent isostatic rebound.

Neither ice nor rock landscapes remain the same, unless erosional lowering is the same for all points in a landscape. Relief and altitudes of peaks increase if melt of ice, or erosion of rocks, is mainly along valley floors. Removal of mass above our sea-level datum causes pure isostatic uplift of all parts of the landscape. The average altitude of both the iceberg and the mountain range decreases with time because buoyancy-driven isostasy can never fully compensate for the mass lost by erosion.

A substantial proportion of mountain-range uplift is the result of these crustal isostatic adjustments (Molnar and England, 1990; Gilchrist et al, 1994; Montgomery, 1994; Montgomery and Greenberg, 2000). Isostatic uplift is both regional and continuous (Gilchrist and Summerfield, 1991), and generally does not cause pulses of renewed mountain building. This is done by scrunch and stretch tectonics.

A major difference between icebergs and mountain ranges is that mountains do not float in a Newtonian fluid such as water, which has no shear strength. Continental rock masses float on hot lithospheric materials whose rigidity provides some support. Rocks at shallower depths are stronger (cooler) and respond to changes in load by flexing in an elastic manner. Small, local changes in rock mass will not cause the lithosphere to flex because it has enough strength to support minor changes in load. But beveling of a 10,000 km^2 mountain range will indeed influence crustal dynamics. Prolonged erosion has resulted in substantial cumulative isostatic rebound of the Appalachian Mountains of the eastern United States for more than 100 My.

Tectonic geomorphologists would prefer to discern how different uplift rates influence landforms and geomorphic processes, but reality is not that simple. Mountain-building forces may continue long after tectonic quiescence seems to have begun, as revealed by strath terraces (a tectonic landform discussed in Sections 2.4.1 and 2.6) in pretty dormant places like Australia (Bierman and Turner, 1995). Space and time frameworks of references vary greatly for the Figure 1.4 surface-uplift variables. Generally, they are large and long for pure uplift, tectonic denudation, or burial, and small and short for tectonic displacements and geomorphic processes.

The predicament is that uplift has two components – tectonic and isostatic. Tectonic mountain-building forces may cease but the resulting isostatic adjustments will continue as long as streams transfer mass from mountains to sea. The best we can do at present is to observe landscape responses to the algebraic sum of tectonic and isostatic uplift.

$$\text{Bedrock uplift} = \text{Tectonic uplift} + \text{Isostatic uplift} \quad (1.1)$$

This seems simple, until we attempt to quantify the Figure 1.4 variables that influence tectonic uplift and isostatic uplift.

The term ***bedrock*** is used here in a tectonic instead of a lithologic context. Bedrock is any earth material that is being raised, with no regard as to the degree of lithification or age. We should note the "fuzziness" of this definition.

Three exceptions are acknowledged; these occur when the nontectonic surficial process of deposition raises a landscape. The most obvious and dramatic is volcanic eruption, which raises landscape altitudes by depositing lava and tephra. Of course volcanic eruptions may also be associated with tectonic shortening and extension.

Tectonic geomorphologists are interested in how climate change affects the behavior of streams in humid and arid regions. Mountain valleys and piedmonts undergo aggradation events as a result of major climate changes (Bull, 1991) that change the discharge of water and sediment. We do not class such stream alluvium as bedrock because its deposition is the result of a nontectonic process that raises valley-floor altitudes. Alluvium laid down before the particular time span that we are interested in would be treated like other earth materials, as bedrock. Studies of Pleistocene uplift would treat Miocene fluvial sand and gravel as bedrock. Thirdly, nontectonic deposition includes eolian processes such as the creation of sand dunes. Least obvious, but far more widespread, is deposition of loessial dust. In New Zealand windblown dust is derived largely from riverbeds after floods and the loessial blanket that covers much of the stable parts of the landscape may contain layers of volcanic ash, such as the 26.5 ka Kawakawa tephra (Roering et al., 2002, 2004). Hillslopes where this ash has been buried by 0.5 to 5 m of loess are landscapes where deposition has slowly raised the altitudes of points on the land surface during the 26 ky time span at average rates of <0.02 to >0.1 m/ky. Deposition – by volcanic ejecta, inability of a stream to convey all bedload supplied from hillslopes, and dust fall – is just one of several nontectonic geomorphic processes that change altitudes of points in a landscape (Fig. 1.4).

I prefer to emphasize bedload transport rates in this book because bedload governs stream-channel responses to bedrock uplift. Rivers transport mainly suspended load to the oceans and deposit silty sand and clay on floodplains. Dissolved load is bedrock conveyed in solution. Both require little stream power, but the unit stream power required to mobilize and transport bedload reduces the energy available for tectonically induced downcutting of stream channels. Saltating cobbles and boulders are tools for abrasion of bedrock. With suspended load being