Tectonics, Climate, and Landscape Evolution

Edited by

Sean D. Willett
Department of Earth and Space Sciences
University of Washington
Seattle, Washington 98070
USA

Niels Hovius
Department of Earth Sciences
University of Cambridge
Cambridge CB2 3EQ
UK

Mark T. Brandon
Department of Geology and Geophysics
Yale University
New Haven, Connecticut, 06520
USA

Donald M. Fisher
Department of Geosciences
The Pennsylvania State University
University Park, Pennsylvania 16802
USA

THE GEOLOGICAL SOCIETY OF AMERICA

Special Paper 398
Penrose Conference Series
3300 Penrose Place, P.O. Box 9140 • Boulder, Colorado 80301-9140, USA

2006
### Contents

**Introduction**  ........................................................................................................................................... vii  
S.D. Willett, N. Hovius, M.T. Brandon, and D.M. Fisher

**Weather, Climate, and Topography**

1. *Progress on the theory of orographic precipitation* ................................................................. 1  
   R.B. Smith

2. *From weather to climate—Seasonal and interannual variability of storms and implications for erosion processes in the Himalaya* ...................................................................................... 17  
   A.P. Barros, S. Chiao, T.J. Lang, D. Burbank, and J. Putkonen

3. *Spatial patterns of precipitation and topography in the Himalaya* ........................................... 39  

**Inferring Tectonics and Climate Change from Topography**

4. *Tectonics from topography: Procedures, promise, and pitfalls* ................................................. 55  
   C. Wobus, K.X. Whipple, E. Kirby, N. Snyder, J. Johnson, K. Spyropolou, B. Crosby, and D. Sheehan

5. *Surface uplift and climate change: The geomorphic evolution of the Western Escarpment of the Andes of northern Chile between the Miocene and present* ......................................................... 75  
   F. Kober, F. Schlunegger, G. Zeilinger, and H. Schneider

6. *The application of drainage system analysis in constraining spatial patterns of uplift in the Coastal Cordillera of northern Chile* ................................................................. 87  
   A.E. Mather and A.J. Hartley

7. *Influence of incision rate, rock strength, and bedload supply on bedrock river gradients and valley-flat widths: Field-based evidence and calibrations from western Alpine rivers (southeast France)* ......................................................................................................................... 101  
   G.Y. Brocard and P.A. van der Beek

**Transport Processes and Fluxes**

   N.M. Gasparini, R.L. Bras, and K.X. Whipple
9. *Changes of bedload characteristics along the Marsyandi River (central Nepal): Implications for understanding hillslope sediment supply, sediment load evolution along fluvial networks, and denudation in active orogenic belts* .......................................................... 143  
M. Attal and J. Lavé

10. *Escarpet erosion and landscape evolution in southeastern Australia* ................................................................. 173  
A.M. Heimsath, J. Chappel, R.C. Finkel, K. Fifield, and A. Alimanovic

11. *A parametric study of soil transport mechanisms* ................................................................................................. 191  
F. Herman and J. Braun

**Coupled Models of Tectonics, Climate, and Erosion**

12. *Influence of erosion on the kinematics of bivergent orogens: Results from scaled sandbox simulations* ................................................................................................. 201  
S. Hoth, J. Adam, N. Kukowski, and O. Oncken

13. *Response of a steady-state critical wedge orogen to changes in climate and tectonic forcing* ................................................................. 227  
G.H. Roe, D.B. Stolar, and S.D. Willett

14. *Climatic and tectonic forcing of a critical orogen* ................................................................................................. 241  
D.B. Stolar, S.D. Willett, and G.H. Roe

15. *First-order topography over blind thrusts* ................................................................................................. 251  
M.A. Ellis and A.L. Densmore

16. *Influence of erosion and deposition on deformation in fold belts* ................................................................................................. 267  
G. Simpson

17. *Long-term evolution of tectonic lakes: Climatic controls on the development of internally drained basins* ................................................................................................. 283  
D. Garcia-Castellanos

18. *Knickpoints and hillslope failures: Interactions in a steady-state experimental landscape* ................................................................................................. 295  
A. Bigi, L.E. Hasbargen, A. Montanari, and C. Paola

**Geochemical Proxies of Topography and Erosion**

19. *Stable isotopic evidence for a pre–late Miocene elevation gradient in the Great Plains–Rocky Mountain region, USA* ................................................................................................. 309  
D.J. Sjostrom, M.T. Hren, T.W. Horton, J.R. Waldbauer, and C.P. Chamberlain

20. *Downstream development of a detrital cooling-age signal: Insights from *40*Ar/39*Ar muscovite thermochronology in the Nepalese Himalaya* ................................................................................................. 321  
I.D. Brewer, D.W. Burbank, and K.V. Hodges

21. *The geochemistry of rivers in tectonically active areas of Taiwan and New Zealand* ................................................................................................. 339  
A.E. Carey, S.-J. Kao, D.M. Hicks, C.A. Nezat, and W.B. Lyons
Field Studies of Tectonics, Climate, and Landscapes

22. Active tectonics in the Subandean belt inferred from the morphology of the Rio Pilcomayo (Bolivia) ................................................................. 353
   J.-L. Mugnier, D. Becel, and D. Granjeon

23. Tectonically driven exhumation of a young orogen: An example from the southern Apennines, Italy .............................................................. 371
   M. Schiattarella, P. Di Leo, P. Beneduce, S.I. Giano, and C. Martino

24. Slow, patchy landscape evolution in northern Sweden despite repeated ice-sheet glaciation ........................................................... 387
   A.P. Stroeven, J. Harbor, D. Fabel, J. Kleman, C. Hättestrand, D. Elmore, D. Fink, and O. Fredin

25. Facing reality: Late Cenozoic evolution of smooth peaks, glacially ornamented valleys, and deep river gorges of Colorado’s Front Range .................................................... 397

26. Mountain fronts, base-level fall, and landscape evolution: Insights from the southern Rocky Mountains .................................................. 419
   K.L. Frankel and F.J. Pazzaglia

Index .................................................................................................................................................. 435
Introduction

Sean D. Willett
Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98070, USA

Niels Hovius
Department of Earth Sciences, Cambridge University, Cambridge CB2 3EQ, UK

Mark T. Brandon
Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06520-810, USA

Donald M. Fisher
Department of Geosciences, The Pennsylvania State University, University Park, Pennsylvania 16802, USA

TAIWAN PENROSE CONFERENCE

The Liwu River runs a short course; its channel head at the water divide in Taiwan’s Central Range is a mere 35 km from its outflow into the Pacific Ocean. But in those short 35 km, the Liwu has carved one of the world’s geographic wonders: the spectacular Taroko Gorge with marble and granite walls soaring nearly 1000 m above the river channel. The Liwu River itself is less impressive. Many visitors have marveled that the little trickle at the base of the gorge has carved such a massive canyon. As tourists marvel at the white marble around the river, however, they may notice the lack of vegetation within the channel, and finally, looking up, realize that the gorge bottom has been scouried by flood waters that reach tens of meters above the channel floor. Indeed, few visitors have seen the Liwu at flood stage, when run-off from typhoon rains causes a rise in the height of the river in the gorge to several hundreds of meters. The rush of turbulent water is able to carry large boulders and abrade and deepen the bedrock channel. The typhoon rains also strip alluvium from the surrounding hillslopes and trigger massive landslides, increasing the load of sediment carried through the gorge.

The Liwu is not a pretty place during floods, and man’s perilous coexistence with nature there is symbolized perfectly by the beautiful shrine at the base of the gorge (cover); the shrine is dedicated to the hundreds of construction workers who lost their lives, most in flood-related landslides, while carving the highway through the gorge in the 1950s. As a final ironic act of nature, the shrine itself was twice destroyed by landslides in the 1980s, and rebuilt each time.

Taroko Gorge was a fitting venue for a Penrose Conference in 2003 that addressed the coupled processes of tectonics, climate, and landscape evolution. The young mountains, extreme weather, and dramatic landforms provided an appropriate backdrop to wide-ranging discussions of geomorphic processes, climate and meteorology, sediment generation and transport, the effects of erosion on tectonics, and new analytical and modeling tools used to address these processes and problems. The Penrose Conference also provided an opportunity to assess progress in the field over the past decade since a Chapman Conference on the same topic held at Snowbird, Utah, in 1992 (Merritts and Ellis, 1994). The earlier conference helped motivate a decade of research into the roles of tectonics, surface processes, and climate in creating the topography of Earth. The 2003 conference provided an opportunity to discuss progress made through that decade, and to look ahead to future challenges. Papers in this volume reflect and advance these developments.

COUPLED DYNAMIC SYSTEM

All papers in this volume deal in some form with the physical interactions between tectonics, surface erosion processes, and climate (Fig. 1). The connections in this dynamic system are manifold and many feedback pathways have yet to be explored. However, many of the fundamental relationships between the tectonic growth of topography, erosional destruction of topography, and climatic influence on erosion rates have been identified. Tectonic processes elevate regions of Earth’s surface primarily through the isostatic response to crustal thickening (Fig. 1: path A). Tectonics also increases relief at multiple length scales through isostatic uplift, faulting, and folding (Fig. 1: path B). Increased elevation relative to regional base level increases river channel gradients and thus increases rates of erosion by fluvial incision and transport. In addition, topography at almost any length scale tends to increase orographically localized precipitation. This in turn gives rise to increased river discharge and incision. Insofar as river channels set the local base level for hillslope processes, enhanced...
channel incision leads to increased hillslope failure and sediment supply to channels. Tectonics can directly influence erosion rates at short timescales, as is evident from earthquake triggering of landslides and seismic weakening of rockmass (Fig. 1: path D). Another link between tectonics and erosion is the increase in cumulative erosion and sediment yield that occurs as a tectonic region expands, for example, by accretion of new crustal material. As the domain affected by deformation grows, a larger area becomes subjected to high erosion rates and total sediment yield increases (Fig. 1: path C).

Climate links surface uplift and erosion rates through several mechanisms, including orographic forcing of precipitation (Fig. 1: path E). A second link is provided by the onset or increased efficiency of alpine glaciation, which develops as mountains reach altitudes sufficient to produce and maintain perennial ice (Fig. 1: path F). Alpine glaciation is a strongly nonlinear feedback as its onset only occurs when topography grows above the threshold for growing alpine ice (e.g., equilibrium limit altitude).

The feedback of erosion on tectonics is provided by the redistribution of near-surface mass. Tectonic processes are strongly influenced by gravity and surface redistribution of mass will influence gravitational stresses and thus tectonic deformation (Fig. 1: path H). The tectonic response can be complex, but the general response, at least of a convergent mountain belt, will be a reduction in the rate of growth of mean elevation and surface area (Fig. 1: path G). If erosional fluxes outpace the rate at which tectonics can thicken the crust, mean elevation and orogenic area will be progressively reduced, leading to a progressive decrease in sediment yield and erosional flux.

Mechanisms also exist for erosion to affect climate on a global scale, through influences on the carbon cycle. Weathering of Mg and Ca silicate rocks provides the essential buffer that balances the introduction of CO$_2$ into the atmosphere and the sequestration of that CO$_2$ in carbonate rocks (Fig. 1: path I). Erosional refreshing of exposed rock surfaces ensures that chemical weathering can occur at or close to its kinetic limits. Erosion also promotes drawdown of CO$_2$ by harvesting of life biomass and burial of this material in sedimentary basins, thereby reducing the amount of actively cycling carbon. Together, these two erosion-driven mechanisms are responsible for countering the outgassing of primary CO$_2$ and stabilizing Earth’s climate in a narrow range of conditions suitable for the evolution of life.

**RECENT SCIENTIFIC ADVANCES AND THIS VOLUME**

The papers collected in this volume reach across fields that have experienced rapid advances in the past decade. Here, we briefly outline some key developments to provide a context for these contributions.

**Emergence of Digital Elevation Models**

Digital elevation models (DEMs) have become widely available for a large part of the planet and are now established as a common resource for topographic analysis. In addition, computing power and software capabilities have increased dramatically, permitting innovative exploitation of DEMs. Applications range from routine use of digital relief maps as a base for presentation of other data, to mathematically sophisticated analyses to infer physical processes from landscape attributes (Wobus et al., this volume, Chapter 4). Nearly a quarter of the papers in this volume use digital topographic data in some form.

**Physics of Geomorphic Processes**

As quantitative models of landscape evolution were developed in the 1990s (Willgoose et al., 1991; Chase, 1992; Beaumont et al., 1992; Tucker and Slingerland, 1994), it became clear that progress was limited by the theoretical understanding of the principal surface processes. The representation of tectonic processes and the numerical algorithms used in geodynamic models and landscape evolution models (Braun and Sambridge, 1997; Tucker et al., 2001; Tomkin and Braun, 2002) have grown increasingly sophisticated, but the representation of geomorphic processes has lagged behind. In response, surface processes thought to be important at the landscape scale have been given increasing attention. Much emphasis has been placed on fluvial bedrock incision (Howard et al., 1994; Whipple and Tucker, 1999; Sklar and Dietrich, 2001; Hartshorn et al., 2002). This process is thought to be crucial to landscape evolution because it sets the local base level for hillslope processes, for example, providing the rate control for shallow and deep-
seated landslides, thereby governing the timescale of evolution for both channel and hillslope processes. Bedrock landsliding has itself garnered considerable attention in recent years, as it has become clear that this is the principal hillslope process in tectonically active mountain landscapes (Burbank et al., 1996; Hovius et al., 1997). Although simple quantitative paradigms for key erosion processes are now firmly in place, many questions remain about the mechanics, patterns, and rates of these processes, and about the mechanisms and scales of their interactions. In this volume, papers by Gasparini et al. (Chapter 8) and Herman and Braun (Chapter 11) are contributions that quantify and parameterize geomorphic processes, and provide important progress toward building more complete surface processes models.

Critical Orogenic Wedges

The influence of erosion on tectonics is plausible in theory, if somewhat problematic to demonstrate in practice. Critical, convergent orogens are a tectonic setting where the response to erosion is predictable, immediate, and large. These orogens are defined by mountain belts that attain a critical topographic slope forming an orogenic wedge with a fixed taper angle (Davis et al., 1983). Under critical conditions, an orogenic wedge is everywhere at or near plastic failure, which implies that deformation is very sensitive to small changes in stress as occur, for example, by mass redistribution by erosion or sediment deposition. The consequence of erosion is thus a reorganization of deformation, internal kinematics, and patterns of uplift to restore the critical taper of a wedge (Willett, 1999). This is a clear example of coupling with feedback, in which erosion affects crustal deformation and rock uplift, which, in turn, affects erosion rates. Under simple conditions, the response of a critical frictional wedge to erosion can be treated analytically (Hilley and Strecker, 2004; Whipple and Meade, 2004). In this volume, the problem of an eroding critical wedge is addressed through the use of analog models (Hoth et al., Chapter 12), analytical solutions (Roe et al., Chapter 13), and numerical models (Stolar et al., Chapter 14).

From Weather to Climate

The influence of climate on erosion processes, landscape evolution, and orogen dynamics is suggested by the close match in some areas of localized precipitation and localized erosion (e.g., Reiners et al., 2003). As advanced landscape evolution models demonstrate important sensitivity to the spatial and temporal distribution of precipitation (Lague et al., 2005), researchers have turned to more complex climate models or even mesoscale meteorological models to drive erosion. In recent decades, vast resources have been invested in the modeling of weather and climate, and leading models deliver detailed constraints on many atmospheric attributes and their changes. However, precipitation in these models varies over a range of timescales and it is not clear how this variability impacts erosion rates over long timescales. It is therefore difficult to define and quantify climate in a way that is meaningful to the evolution of topography. In many ways, this problem parallels the challenge of relating modern topography or modern erosion rates to long-term geologic processes. In this volume, Smith (Chapter 1) reviews a new model that provides a simplified prediction of how stable atmospheric flow interacts with topography to produce precipitation. Barros et al. (Chapter 2) and Anders et al. (Chapter 3) use remotely sensed and direct measurement of precipitation in the Himalaya to resolve patterns of precipitation and their relationship to topography. Interestingly, they observe that precipitation patterns are correlated with topography on scales of tens of kilometers, suggesting that topography and climate may coevolve through time even at limited spatial scales. The linear theory of Smith (Chapter 1) for orographic precipitation predicts this short-wavelength correlation between topography and precipitation.

Thermochronometry and Cosmogenic Dating

Advances in low-temperature thermochronometry and exposure dating with cosmogenic isotopes have greatly increased our ability to resolve the timing and rates of erosional processes (von Blanckenburg, 2005; Reiners and Brandon, 2006). New techniques in (U-Th)/He dating of apatite and zircon have increased the temperature range and precision of mineral cooling histories (Farley, 2002). When added to fission-track dating of zircon andapatite and 40Ar/39Ar dating of micas andfeldspars, rock cooling histories can now be resolved from 350 °C to 70 °C. Exhumation can now be constrained from mid-crustal depth to within a few kilometers from Earth’s surface, thus completing a near-continuum of measurements of long-term surface erosion rates, particularly combined with surface erosion rates provided by cosmogenic nuclides. In addition, statistical methods have been developed for evaluating grain age distributions in modern or ancient sediments, providing catchment-wide estimates of (paleo-)erosion rates (Brandon, 1996; Granger et al., 1996). Brewer et al. (Chapter 20) provide an example of this approach, using 40Ar/39Ar dating of muscovite from modern sediments to resolve the spatial variability of erosion rates in a drainage basin in the Himalaya.

Paleoaltimetry

The ability to estimate paleo-elevation land surfaces back through geologic time has advanced considerably in recent years with the development of stable isotope paleoaltimetry, based on the fractionation of oxygen and hydrogen during Rayleigh distillation in the atmosphere (Poage and Chamberlain, 2001; Rowley et al., 2001; Rowley and Currie, 2006). These new techniques hold great promise to resolve issues of timing of surface uplift and the formation of high topography. In this volume, Sjostrom et al. (Chapter 19) measure isotopic compositions of smectites across the western U.S. and use these results to argue that the Rocky Mountains have been elevated since at least 50 Ma.
REFERENCES CITED


