

Editorial

Quantifying rates and timescales of geomorphic processes

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Introduction

In the past decade, the application of a variety of new tools has spurred significant advances in quantifying the rates and timing of geomorphic processes. These advancements resulted from improvements in methods for collecting and interpreting data, increased access to analytical facilities, and creative applications of techniques to new problems. New analytical techniques are emerging as mainstream procedures for evaluating the temporal and spatial variations of Earth surface processes. In this and the next issue of *Earth Surface Processes and Landforms* we highlight new applications of geochemical, field and modelling methods applied to problems in landform evolution. These applications address processes related to erosion and sedimentation on small, intermediate and large temporal and spatial scales. We present an overview of techniques and applications discussed in these two special issues, as well as some of the limitations and future challenges inherent to these techniques.

Overview of Contributions

This is an exciting time for furthering our understanding of how the Earth's surface changes under the influence of climatic, tectonic and anthropogenic forcings. Analytical developments across many disciplines over the past few decades enable quantification of the rates and timescales of geomorphic processes in ways never possible before. Methods such as *in situ*-produced cosmogenic nuclides, apatite (U-Th)/He thermochronometry, U-series dating, luminescence dating, short-lived fallout isotopes, and chemical mass balances are tools used to evaluate relationships between climate, tectonics and surface processes. Technological advancements in these fields provide enhanced understanding of geomorphic processes such as rates of fluvial bedrock incision and floodplain sedimentation, glacial erosion rates and magnitudes, post-orogenic topographic evolution, and more.

The diversity of studies captured by papers in these two special issues reflects the interests of researchers across disciplines. These papers represent a cross-section of the research presented at a special session of the same title convened at the December 2003 Annual Meeting of the American Geophysical Union in San Francisco. We organized this special session, with help from Liam Reinhardt, and subsequently solicited papers from the presenting authors, as well as others. A selection of these papers is presented in these two special issues.

The studies presented utilize a wide range of methods and applications. Here we provide a quick overview of the papers that fill these two special issues, reflecting many of the techniques currently applied to studying the Earth's surface. Methods applied range from short-lived, fallout-derived radionuclides, such as ⁷Be, ²¹⁰Pb and ¹³⁷Cs, to infer decadal-scale rates of sediment movement to apatite (U-Th)/He and fission track dating to infer million-year scale rates of landscape evolution. Millennial-scale signals are captured using concentrations of *in situ*-produced cosmogenic nuclides, primarily ¹⁰Be, ²⁶Al and ³⁶Cl, while measurements of photon emissions liberated from quartz provide optically stimulated luminescence (OSL) dates spanning centuries to millennia. Despite the heightened understanding of the Earth's surface enabled by such quantitative methodologies, each one has limitations and requires further development.

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Table I. Quantifying rates and timescales of geomorphic processes: content of two special issues (vol. 30, nos. 8 and 9)

This issue	
<i>Cosmogenic Nuclides</i>	
Wilkinson <i>et al.</i>	Soil production in heath and forest: Blue Mountains, Australia: influence of lithology and palaeodimate
Bierman <i>et al.</i>	Using cosmogenic nuclides to contrast rates of erosion and sediment yield in a semi-arid, arroyo-dominated landscape, Rio Puerco Basin, New Mexico
Schaller <i>et al.</i>	Fluvial bedrock incision in the active mountain belt of Taiwan from <i>in situ</i> -produced cosmogenic nuclides
Garvin <i>et al.</i>	Episodic incision of the Colorado River in Glen Canyon, Utah
Stock <i>et al.</i>	Rates of erosion and topographic evolution of the Sierra Nevada, California, inferred from cosmogenic ^{26}Al and ^{10}Be concentrations
Safran <i>et al.</i>	Erosion rates driven by channel network incision in the Bolivian Andes
Ferrier <i>et al.</i>	Erosion rates over millennial and decadal timescales at Caspar Creek and Redwood Creek, Northern California Coast Ranges
Li <i>et al.</i>	Ice sheet erosion patterns in valley systems in northern Sweden investigated using cosmogenic nuclides
Balco and Stone	Measuring middle Pleistocene erosion rates with cosmic-ray-produced nuclides in buried alluvial sediment, Fisher Valley, southeastern Utah
Next issue	
<i>Interdisciplinary and Modelling</i>	
Friedman <i>et al.</i>	Dating floodplain sediments using tree-ring response to burial
Duan and Julien	Numerical simulation of the inception of channel meandering
Arsenault and Meigs	Contribution of deep-seated bedrock landslides to erosion of a glaciated basin in southern Alaska
Parker and Perg	Probabilistic formulation of conservation of cosmogenic nuclides: effect of surface elevation fluctuations on approach to steady state
Staiger <i>et al.</i>	Quaternary relief generation by polythermal glacier ice
<i>Fallout and OSL</i>	
Rowland <i>et al.</i>	Tie channel sedimentation rates, oxbow formation age and channel migration rate from optically stimulated luminescence (OSL) analysis of floodplain deposits
Fornes <i>et al.</i>	Caesium-137-derived erosion rates in an agricultural setting: the effects of model assumptions and management practices
Matisoff <i>et al.</i>	The $^{7}\text{Be}/^{210}\text{Pb}_{\text{ex}}$ ratio as an indicator of suspended sediment age or fraction new sediment in suspension
<i>Thermochronology</i>	
Braun and Robert	Constraints on the rate of post-orogenic erosional decay from low-temperature thermochronological data: application to the Dabie Shan, China

Table I shows the organization of papers in the two special issues. We organized the papers by the primary method used, rather than the geomorphic process studied, in order to accentuate the diversity of processes and problems that the different methods address. Brief discussion of the issues and highlights of results from the different approaches used are presented below.

Cosmogenic isotopes

The first issue includes nine papers detailing applications of *in situ*-produced cosmogenic nuclides. These studies utilize ^{26}Al , ^{10}Be and ^{36}Cl , which are the nuclides most commonly applied to Earth surface processes and chronologies. These isotopes are produced primarily by spallation and muon reactions on O, Si, Ca, K and Cl caused by cosmic ray bombardment within quartz, calcite and feldspar. Although the cosmogenic nuclide methodology is reasonably well established and applied widely to diverse geomorphic problems, there are several uncertainties that complicate certain applications. One of the issues surrounding applications of *in situ*-produced cosmogenic nuclides include uncertainty in long-term production rates, especially how they may vary with altitude and latitude and with modulations in solar and galactic forcing. Related to this is the effect that muogenic nuclide production has on rapidly eroding samples. Other aspects of cosmogenic nuclide applications that demand further exploration relate to the geomorphic context samples are collected from. Specifically, inferences of drainage basin average erosion rates or timing of sediment burial from $^{26}\text{Al}/^{10}\text{Be}$ burial ages are sensitive to both the exposure history of the sediments, and stochastic processes generating, transporting, and depositing the sediment. Analytical precision of nuclide measurements and uncertainty in the nuclide decay constants are of critical concern for the $^{26}\text{Al}/^{10}\text{Be}$ burial method. Uncertainties in these techniques are driving several current research efforts and focusing the applicability of the detrital methodology. Many of the papers in these issues address these problems directly.

Leading the first issue, Wilkinson *et al.* determine soil production rates across a field site with variable lithology and vegetation in the Blue Mountains of Australia. Their results contrast dramatically with soil production rates that decrease exponentially with increasing soil depths, determined by other studies, and support the hypothesis that maximum rates occur beneath a finite soil cover. Furthermore, their study quantifies rates across very different parent material lithology and highlights complexities inherent in coupling surface morphometry with nuclide-determined soil production rates. Their use of OSL to date burial times for quartz sand in their soils leads to insight into how the Pleistocene–Holocene transition affected soil production rates for the region. Continuing the upland focus, Bierman *et al.* quantify erosion rates across the Rio Puerco basin of northern New Mexico and build a comprehensive study of soil production and transport rates as functions of both precipitation and erodibility of the bedrock. Their scaling of rates as functions of vegetation, precipitation and rock erodibility enables a new level of understanding of the controls on erosion. They also determine wide variability of physical erosion rates that account for almost 99 per cent of the mass lost, when compared to chemical denudation rates for the region. Finally, their comparison of nuclide-determined rates with contemporary rates shows that long-term rates are roughly half the current sediment yields, suggesting a connection with land-use patterns for the region.

Four studies focus on quantifying rates and processes of fluvial incision, the primary erosional process dictating the pace at which most landscapes evolve. Schaller *et al.* calculate average short-term incision rates of *c.* 26 mm a⁻¹ using an elevation profile of ³⁶Cl concentrations in the bedrock walls of the Taroko Gorge, Taiwan. They infer that the long-term gorge development is influenced by short-term variations in incision rates due to changes in climate or regional tectonics. Stock *et al.* determine incision rates from ²⁶Al/¹⁰Be burial ages of sediments preserved in a series of caves perched above modern river channels in the Sierra Nevada, California. They find that incision rates accelerated at *c.* 3 Ma to 0.3 mm a⁻¹ and slowed thereafter, consistent with recent tectonism, and also find that incision rates outpace rates of bedrock interfluvial erosion by as much as an order of magnitude, thereby increasing topographic relief. Garvin *et al.* report episodic incision of the Colorado River in Utah using an interdisciplinary dating effort of two levels of Quaternary deposits adjacent to Glen Canyon. They determine that incision rates increased from *c.* 0.4 to *c.* 0.7 mm a⁻¹ roughly 250 000 years ago, suggest a state of disequilibrium with the erosion of the Grand Canyon and highlight the need for further examination of incision through the Colorado Plateau. Safran *et al.* use ¹⁰Be concentrations measured in alluvium from the Upper Beni River in the northern Bolivian thrust belt to determine erosion rates that vary from 0.4 to 1.35 mm a⁻¹ across the region. They show that these millennial-scale catchment-average erosion rates are within the range of long-term erosion rates from apatite fission track thermochronology, but are an order of magnitude lower than rates from the Ganges headwaters in the Himalaya and an order of magnitude greater than rates reported from the European Alps. Furthermore, by coupling their erosion rate measurements with measures of basin steepness, they suggest that climate and lithology are not the primary controls on the patterns of erosion in the Bolivian Andes.

Other cosmogenic nuclide studies in the first issue include the work of Ferrier *et al.* that compares millennial-scale denudation rates from ¹⁰Be concentrations and decadal-scale sediment yields to quantify temporal variations in sediment delivery in northern California streams. Their measurements of ¹⁰Be across one catchment suggest a nearly uniform erosion rate of 0.09 mm a⁻¹, while samples from another catchment show rates that vary from 0.14 to 0.44 mm a⁻¹. Differences between these rates and the short-term rates determined from sediment flux measurements are greatest at the smallest tributaries, but vary by less than a factor of three for the catchments as a whole. Li *et al.* examine glacial erosion in Sweden using measurement of bedrock ¹⁰Be concentrations, along with inferred nuclide inheritance, to infer spatial patterns in erosion magnitudes across glaciated valleys. They determine that glacial valley formation is a result of multiple glacial cycles rather than a single cycle, and quantify the pattern and scale of erosion with nuclide samples from transects across four glaciated valleys. Finally, Balco and Stone infer ancient erosion rates by combining ²⁶Al and ¹⁰Be measurements of buried detrital sediments deposited in the Fisher Valley, southeastern Utah, with a depositional model. Using stratigraphic observations, as well as an independent age model, to constrain their nuclide measurement, they present an important method to untangle potential changes in erosion rates over time. Their findings suggest the role of episodic subsidence, rather than climate changes, in driving changes in erosion rates; they highlight a topic that deserves critical attention as most landscape evolution questions are generally motivated by understanding how changes in climate or tectonics affect the erosion rate. The previous papers span a wide range of applications for cosmogenic nuclides and offer important insights into the issues and complications surrounding this methodology.

Interdisciplinary and modelling studies

Five studies in the second special issue present either interdisciplinary approaches that integrate different techniques and/or modelling-intensive studies that advance our knowledge of the physical processes underlying various geomorphic

systems. These studies address a wide range of fluvial, hillslope and glacial processes. Two studies address fluvial processes. First, Friedman *et al.* measured both floodplain sediment thickness and tree-ring structure to quantify the sedimentation history of the Rio Puerco in New Mexico. Their approach reliably dates most sediment beds thicker than about 30 cm, constraining the temporal variability of floodplain sedimentation. Second, a numerical modelling study presented by Duan and Julien addresses the inception of fluvial channel meandering. They develop a depth-averaged two-dimensional hydrodynamic model to simulate bed- and suspended-load transport and channel meandering processes. This study evaluates the important parameters influencing the inception of channel meandering and replicates downstream translation and lateral extension of modern fluvial systems.

Basin-average landslide erosion rates are addressed by Arsenault and Meigs through examination of four bedrock landslide deposits in the Chugach-St. Elias Range of Alaska. Their approach integrates high-resolution field surveys with a time series of remote sensing images. Their results advance our understanding of landslide processes and rates in a high-latitude setting. Parker and Perg present a stochastic approach to modelling the effect of episodic erosion on cosmogenic nuclide concentrations. They use a probability density function to model the variation of sample elevation as a function of erosion rates and processes. Their model estimates the time to steady state for nuclide concentrations sampled from an evolving landscape in terms of two different scenarios. In their model, an initial steady state is perturbed by, first, an increase in erosion rate and, second, a constant erosion rate, but with the initial absence of cosmogenic nuclides. An analytical solution to their model and a simple plot enabling estimation of the time required to reach steady state promises to be of great interest to cosmogenic nuclide studies.

Finally, Staiger *et al.* evaluate glacial erosion magnitudes and rates in northeastern Canada by integrating bedrock cosmogenic nuclide concentrations with a thermodynamic ice sheet model that simulates erosion as a function of basal shear stress. They estimate valley glacial erosion magnitudes of >2 m during a single glacial–interglacial cycle and low long-term erosion rates of <1.4 m Ma⁻¹ on summit plateaus.

Fallout and optically stimulated luminescence

Fallout-derived, short-lived isotopes and OSL offer great potential for sediment transport and chronology studies, but have not been as widely or successfully applied as cosmogenic nuclides. Atmospheric fallout (primarily wet deposition) of particle-reactive atmospheric nuclides such as ⁷Be, ²¹⁰Pb and ¹³⁷Cs enable the tracking of ‘tagged’ sediments over both short (days to weeks) and medium (several decades) timescales. Beryllium-7 seems to label topsoil horizons very specifically, because subsequent decay prevents it from penetrating to the middle and lower mineral soil. Lead-210 and ¹³⁷Cs have similar half-lives but different source terms and are useful for decadal studies. Although measurements of nuclide concentrations are relatively easy, poor constraints on the source histories and the potential for transport by solution or macropore flow have prevented wider application of this methodology. OSL also acts as a particle tracer and is well applied and tested in Australia and Europe, but less so in the United States. This technique is particularly useful for quantifying rates of geomorphic processes in terrestrial settings where other techniques are limited in their application. Development of more OSL laboratories in the future will hopefully broaden applications of this technique.

Rowland *et al.* report OSL analyses in floodplain deposits from the Mississippi River, Yukon River, Alaska, and the Fly River, Papua New Guinea. These dates allow them to determine vertical accretion rates, tie channel advancement rates, and oxbow lake ages. Their study also determines lateral migration rates of the Fly River and compares modern and natural rates of deposition, directly correlating tie channel advancement with changes in the sediment load of the main stem river.

Two papers use short-lived isotopes to examine erosional processes in fluvial and agricultural settings. Matisoff *et al.* present an application of short-lived isotopes, specifically the ratio of ⁷Be to ²¹⁰Pb, to determine the age of suspended sediment. They develop a model that determines the fraction of suspended sediment recently eroded from the landscape and apply it to field measurements from Ohio, Alabama and Oregon. They show how decreases in the ⁷Be/²¹⁰Pb_{xs} ratio in sediments can either be interpreted as a result of increased age of the sediment, or as dilution of newly eroded sediment by sediment derived by bank or bed erosion. Fornes *et al.* use a different, fallout-derived short-lived isotope, ¹³⁷Cs, to determine erosion rates across an agricultural landscape in Iowa. They use a multi-box numerical model that incorporates time-dependent isotope deposition and apply it to a site previously examined to quantify erosion rates over three time periods. By using different models to interpret the isotope inventories, they also show that variations in atmospheric deposition and/or cultivation practices can significantly affect interpretation of the data. Both studies highlight the advantages of using fallout-derived isotopes, and how to account for the sources of uncertainty in the methodology.

Thermochronology

Recent advances in low-temperature (*c.* 40–600 °C) thermochronometry have facilitated the applications of this technique to quantify long-term (million-year timescales) rates of landscape evolution. The most commonly used thermochronometers are $^{40}\text{Ar}/^{39}\text{Ar}$ in micas, amphiboles and K-feldspar, fission-tracks in apatite and zircon, and (U-Th)/He in apatite and zircon. These techniques have typical closure temperatures ranging from as high as 400–600 °C for $^{40}\text{Ar}/^{39}\text{Ar}$ in micas and amphiboles to as low as 60–70 °C for apatite (U-Th)/He. In the last decade modelling approaches have moved beyond one-dimensional applications to consider the influence of two- and three-dimensional heat transfer on thermochronometer age interpretation. Recognition that thermal gradients in the upper 1–5 km of the crust are spatially variable within orogens due to topography, faulting and other processes has sparked interest in using thermochronometer data to quantify the rates of tectonics and erosional processes. As a result, thermochronometer data are now increasingly used to constrain thermal-kinematic and geodynamic models of tectonic, topographic and erosional processes. The second special issue concludes with a paper by Braun and Robert that integrates previously published apatite fission track and apatite (U-Th)/He data with a numerical model that solves the advection–diffusion equation and accounts for the effects of changing relief and flexural isostatic rebound. They demonstrate that relief of the Dabie Shan range of China has decreased by a factor of 2.5 to 4.5 during the last 60–80 Ma. This study demonstrates how application of a numerical model that simulates the geological processes influencing rock cooling histories enhances the interpretation of thermochronometer data.

Future Prospects

These special issues represent the application of diverse geochemical and numerical modelling techniques to quantify geomorphic processes on timescales from decades to millions of years. Each study demonstrates expertise in specific laboratory, field, mathematical, and numerical modelling approaches. One of the biggest challenges facing Earth scientists today is the successful integration of geochemical and numerical modelling techniques. The geomorphology community is challenged to not only quantify how individual geomorphic processes operate on the timescale of the methods used, but also to develop an ensemble of different techniques that can be integrated to quantify geomorphic processes across a spectrum of timescales. Evaluating rates and magnitudes of geomorphic processes on different timescales is an important step towards quantifying the Earth's surface as a system of interconnected processes, including geomorphology, climate and tectonics. We still need to identify more completely the important parameters, couplings and feedbacks that modulate landscape evolution on both short and long (geological) timescales.

Although significant progress in integrating different techniques has been made over the last decade, well-calibrated deterministic and stochastic models of landform evolution are not yet mainstream tools. One key to addressing how the Earth's surface evolves as a system of interconnected processes lies in increasing communication between investigators using different techniques, a continued openness of laboratory facilities to outside investigators, and, most importantly, the preparation and training of students to be proficient in multiple techniques for an integrated analysis of geomorphic problems. Our hope in organizing these special issues is that curious readers gain an appreciation for how multiple state-of-the-art tools can be applied to quantifying geomorphic processes. Furthermore, we hope readers gain new insights on how different techniques can be integrated to work on problems of interest to them. We are especially hopeful that such a compilation of papers provokes studies that further address both the uncertainties in analytical techniques as well as the mysteries of the Earth's surface.

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