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Penrose Conference Proceedings: Tectonics, Climate and Landscape Evolution
Introduction

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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 kilometers from its outflow into the Pacific Ocean. But in those short 35 kilometers, the Liwu has carved one of the world's geographic wonders, the spectacular

Taroko Gorge with marble and granite walls soaring nearly 1000 meters 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. However, as tourists marvel at the white marble around the river, they may notice the lack of vegetation within the channel, and finally, looking up, realize that the gorge bottom has been scoured by flood waters that reach tens of meters above the channel floor. Indeed, few visitors have seen the Liwu at flood stage, when runoff 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 co-existence 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 last 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 the 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 the 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. In so far 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 non-linear 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 draw down 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.

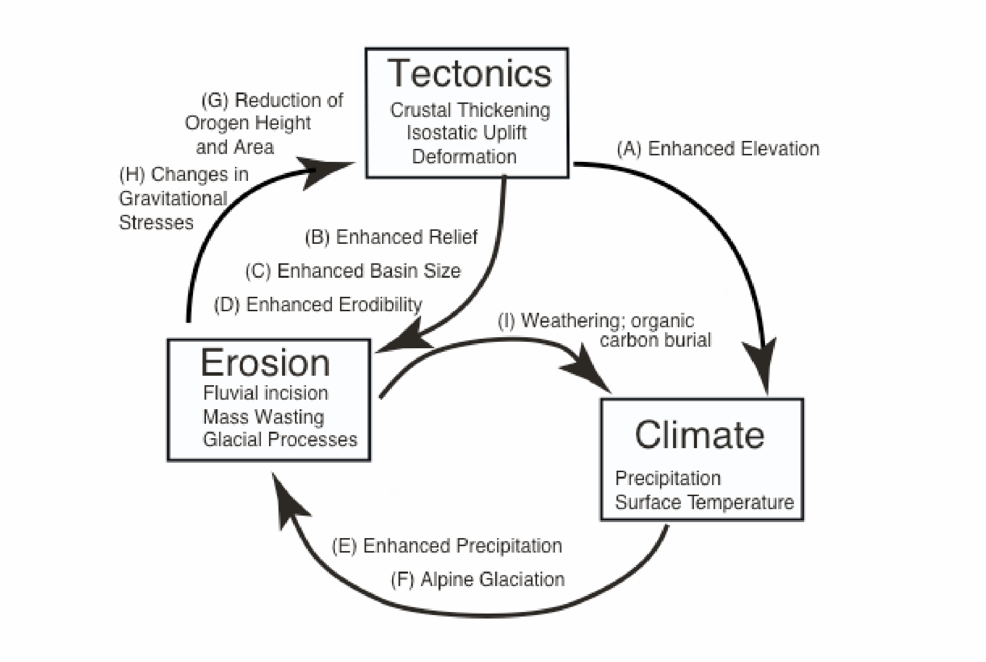

Figure 1: Interactions and feedback pathways for tectonics, climate and erosional processes.

Recent Scientific Advances and this Volume

The papers collected in this volume reach across fields that have experienced rapid advances in the last 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., 2006). 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. (2006) and Hermann and Braun (2006) are contributions that quantify and parameterize geomorphic processes, and provide important progress towards 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 re-organization 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., 2006), analytical solutions (Roe et al., 2006), and numerical models (Stolar et al., 2006).

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 meso-scale 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 (2006) reviews a new model that provides a simplified prediction of how stable atmospheric flow interacts with topography to produce precipitation. Barros et al. (2006) and Anders et al. (2006) 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 co-evolve through time even at limited spatial scales. The linear theory of Smith (2006) 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 and apatite, and $^{40}Ar/^{39}Ar$ dating of micas and feldspars, 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 the 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 (2006) provide an example of this approach, using $^{40}Ar/^{39}Ar$ 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. (2006) measure isotopic compositions of smectites across the western US and use these results to argue that the Rocky Mountains have been elevated since at least 50 Ma.

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