On steady states in mountain belts

Sean D. Willett
Department of Earth and Space Sciences, University of Washington, Seattle, Washington, 98195, USA
Mark T. Brandon
Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06520, USA

ABSTRACT

The dynamic system of tectonics and erosion contains important feedback mechanisms such that orogenic systems tend toward a steady state. This concept is often invoked, but the nature of the steady state is commonly not specified. We identify four types of steady state that characterize the orogenic system and illustrate these cases by using numerical-model results and natural examples. These types are (1) flux steady state, (2) topographic steady state, (3) thermal steady state, and (4) exhumational steady state: they refer to the erosional flux, the topography, the subsurface temperature field, and the spatial pattern of cooling ages, respectively. Models suggest that the topography will reach a steady mean form at the scale of an orogenic belt, but perfect topographic steady state is unlikely to be achieved at shorter length scales. Thermal steady state is a precondition for exhumational steady state and in the case of temperature-dependent deformation, topographic steady state. Exhumational steady state is characterized by reset age zones spatially nested according to closure temperature, as illustrated in natural systems from New Zealand, the Cascadia accretionary margin, and Taiwan.

Keywords: orogeny, exhumation, fission-track dating, landscape evolution, steady-state processes.

INTRODUCTION

The high elevation of active convergent mountain belts represents a balance between the tectonic processes that create topography and the erosional surface processes that destroy it. This orogenic system represents a dynamic system with negative feedback, such that the system tends toward a stable or steady state (Adams, 1980; Jamieson and Beaumont, 1988). Foremost among these feedback mechanisms is the dependence of erosion rate on relief and elevation. Increased relief in mountain belts leads to enhanced erosion through the relief dependence of major erosional mechanisms such as fluvial incision and mass wasting (Ahnert, 1970). Increased elevation leads to higher erosion rates by orographically enhancing precipitation rates (Barry, 1981) and by permitting the development of alpine glaciers (Hallet et al., 1996).

Geomorphologists have long recognized the importance of erosional feedback. The recognition of steady landforms, such as graded river channels, can be traced to Gilbert (1877), and by the 1970s concepts of steady or equilibrium landforms became widely accepted (Hack, 1960; Chorley, 1962; Schumm and Lichty, 1965; Penck, 1953; Howard, 1965, 1982). The importance of time and space scales to the stability of landforms, as well as overuse of equilibrium, led to some confusion with terminology (Howard, 1988; Phillips, 1992). Nonetheless, the important hypothesis emerged that steady-state landforms are indicative of steady tectonic uplift (Hack, 1976), although the ability of a system to reach steady state depends on the system response time to tectonic or climatic change (Howard, 1982; Kooi and Beaumont, 1996; Whipple, 2001).

With knowledge of the thermal state of the crust, important constraints on erosion rates and the stability of landforms are available from low-temperature thermochronometers, such as fission-track dating of apatite and zircon (Gleadow and Brown, 2000) and U-Th/He dating of apatite (Farley, 2000). Constant erosion rates determined over different age ranges from independent thermochronometers or single thermochronometers distributed in elevation can be interpreted as representative of one type of steady state (Brandon et al., 1998; Batt et al., 2000; Gleadow and Brown, 2000).

Steady states for topography and erosional processes are important because these represent the stable states toward which the dynamic tectonic-erosion system evolves. In addition, many modeling studies are developed in the context of a steady state (Koons, 1989; Stuwe et al., 1994). Even if a mountain belt never reaches a steady state, the degree to which it approaches steady state provides a measure of its maturity. To fully exploit these principles, we must address two interrelated questions regarding the characteristics of steady-state systems. First, how do we define and recognize steady state in terms of topography, cooling ages, or other measures of erosion in mountain belts? Second, what are the space- and time-scale dependencies, or interdependencies of various steady states?

We address these questions by presenting a model for the space and time evolution of topography and cooling ages exposed at Earth's surface in a convergent orogenic mountain belt. Our model is based on numerical models of coupled crustal deformation, landscape evolution, and erosion, details of which were presented elsewhere (Willett, 1999; Willett et al., 2001); we focus here on concepts, definitions, and intuitive understanding of the orogenic system.

CONVERGENT OROGEN MODEL

Although the concept of a steady-state topography is applicable to the full range of tectonic settings, in this paper we restrict our analysis to convergent orogenic belts, where there is a strong feedback between the high rates of rock uplift and erosion. We assume that the process of orogenesis is described by a model of crustal accretion associated with plate subduction (Fig. 1). Material accreted from the subducting plate can consist of sediment or continental crustal basement, depending on the tectonic setting. The important characteristic is that crustal deformation is driven by a mass flux F_A (Fig. 1) of material from the pro-plate (left in Fig. 1) into the orogen (right in Fig. 1). During convergent orogenesis, a positive accretionary flux, F_A, leads to surface uplift and an increase in erosional flux, F_E. As these fluxes approach equality, physical characteristics of the system approach steady values.