THE EVOLUTION OF LANDSCAPE

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Summary

Earth's landscape is continually evolving as land uplifted by tectonic and volcanic processes is eroded by water, ice, and wind. On Earth, the dominant landforms have been produced by the action of rivers and glaciers transporting material from mountains to the sea. The amount and proportion of water and ice available for changing the landscape are both sensitive to climatic regime, so that a study of ancient landforms provides a basis for investigating variations in global climate. Similar studies can be applied to the terrestrial planets, and these highlight the unique status of Earth as the only planet with free flowing surface water, one of the key components for the evolution of life.

1. Introduction

Earth's landscape is continually changing. While tectonic and volcanic processes help to raise Earth's surface, the action of wind, sea, rivers, and ice conspires to even out variations in relief and to lower mean surface level. The interaction of these opposing processes and its variation across the globe through time have produced the variety of landforms that characterize today's continents, islands, and ocean floors.

Although volcanic eruptions can construct mountains 1000 to 2000 m high within tens of thousands of years, their impact is localized geographically, and on a global scale, sustained rates of uplift are greatest in zones of active mountain building along compressional plate boundaries. Thus, for the past 25 to 35 million years, the Himalayas and European Alps have been rising at rates of about 400 to 1000 m per million years, while the younger Southern Alps of New Zealand have been growing about ten times faster in the last million years alone. In comparison, the interiors of continents, far removed from mountain chains, appear to have been rising at more modest rates of 10 to 200 m per million years. Since continental interiors also dominate Earth's land area, their mean uplift rate is of the same order as the mean global value including mountain chains.

Different rates of uplift produce large variations in topographic relief and these, in turn, make surfaces vulnerable to denudation and the transport of material from high to low elevations. Landslides provide dramatic examples of rapid mass transport, and a few times each decade, giant collapses can remove as much as 0.1 to 1 km^3 of rock from a single mountainside. However, as with volcanic eruptions, the impact of giant landslides is restricted geographically and becomes insignificant globally when compared with the persistent weathering and erosion of the surface by water, ice, and wind, all of which together are estimated to lower the mean surface level of the continents by about 30 to 70 m per million years, with peak rates of about 1000 (European Alps) to 10 000 m (New Zealand's Southern Alps) per million years in mountain belts.

Figure 1. Glacial scenery along the Ötz Valley in the Austrian Alps.

The effect of glaciers is evident from the tiers of bowl-shaped depressions (cirques), separated by saw-tooth ridges (arêtes). The uppermost cirques still contain glaciers. Source: photo by B. Bauer.

Given the large errors (at least several tens of percent) expected for the different methods for estimating rates of uplift and denudation, their similarities in both mean and peak values suggest that Earth's landscape may have settled to a condition of equilibrium at timescales of 1 to 10 million years. This balance, however, is only relevant to conditions in the Cenozoic, following the intense tectonic activity that produced the Alpine–Himalayan mountain chain. Moreover, the long-term rates fail to describe short-term fluctuations in behavior, especially those associated with changes in climatic regime. Indeed, the most dramatic adjustments on record are those continuing today in response to the Late Cenozoic glaciation, during the peak of which, 18 000 years ago, some 30 percent of Earth's surface was covered with ice.

The last glaciation has had a major influence on the history of geomorphology, the science dedicated to landforms and their development. As with geology (see *Using the Earth to Measure Time*), the foundations of modern geomorphology were laid during nineteenth-century studies in the Northern Hemisphere, especially Europe and the United States. As a result, much emphasis has been placed on the impact of ice and water in denuding mountainous areas and transporting loose material to the oceans. To illustrate the importance of geomorphological processes, therefore, this chapter will focus on the action of rivers and glaciers, rather than of aeolian mechanisms. However, although glacial and post-glacial rates of landscape development are important to understanding a large fraction of Earth's surface morphology in the Northern Hemisphere (Figure 1), it is essential to remember that contemporaneous rates and styles of surface evolution will have varied at equatorial and southern latitudes. In addition, because the surface is still enjoying post-glacial conditions, it is not possible to extrapolate its behavior backwards in time without due regard for variations in climatic condition.

Ice-core studies indicate that, during the past 3 million years, Earth has been subjected to about 30 cycles of major glacial advance and retreat, each lasting for about 100 000 years. With every advance, glacial action extended beyond the poles, pushing temperate climates (dominated by rainfall and river action) further towards the Equator, to regions currently typified by semi-arid conditions; accompanying every retreat, the trend was reversed, with semi-arid and temperate conditions each extending to higher latitudes.

In addition to changing the positions of climatic belts, increased glaciation also locks a greater proportion of surface water into ice, thereby lowering mean sea level and exposing greater areas of continental margin to subaerial denudation. Ice retreat, in contrast, releases surface water and contributes to a rise in sea level. Although the effect of a changing sea level is felt most immediately in coastal regions, it is eventually transmitted upstream along fluvial systems. The net result will be a change in mean rates of denudation and material transport from land to sea.

2. Landscape Changes in the Fluvial Cycle

2.1. River Networks

The primary function of river systems is to carry away the weathered debris and solute material with which they are fed, not only by external material being carried into a river (for example, fragments carried by the wind or dumped by landslides), but also by a river eroding its own bed. Erosion occurs when the river has more kinetic energy than is needed for flowing and for transporting its load; the rate of erosion then depends on the strength of the material comprising the river bed, weaker beds favoring faster rates.

Excess kinetic energy is favored by steeper gradients, and so is more readily available in the mountainous regions where rivers begin, rather than in the shallow coastal plains at their mouths. If the rates of erosion and material transport are proportional to the gradient, a river will naturally evolve a curved longitudinal profile, steep at its source and shallow at its mouth, rather than, for instance, a subhorizontal profile throughout. Such profiles are indeed common and are often parabolic. In addition, mountains are characterized by deformed, metamorphic rocks that are typically more resistant than the sedimentary rocks found in the less-deformed low-lying areas beyond their foothills. The contrasting action of gradient and rock strength further reinforces the trend for mature rivers to establish parabolic longitudinal profiles.

Erosion also concentrates the flow of water along a few, well-defined streams, as opposed to many poorly defined pathways. This produces the system of tributaries that characterize fluvial drainage basins. From even a cursory glance, a river system can be imagined to consist of a large main stream (the “trunk” stream) that is fed by a collection of slightly smaller tributaries (“first-order” streams), the first-order streams, in turn, are fed by smaller streams (“second-order” streams) and so on, each stream being fed by a network of smaller tributaries. In many cases, the number of tributaries of a particular size (for example, second-order streams) is directly related to the number of the next larger streams that they feed (in this case, first-order streams), independent of which pair of successive sizes is being considered (first and second order, second and third order, third and fourth order, and so on). Such a geometrical pattern is termed “scale-independent,” or “fractal,” and indicates that the size of a particular tributary directly controls or is controlled by the size of its own feeding streams.

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Biographical Sketches

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