Chapter 12: The Changing Face of the Land

Introduction: Earth’s Varied Landscapes (1)

- Uplift:
  - Processes that raise topography.
  - Byproduct of plate tectonics and thermal convection.

- Exhumation:
  - Processes that erode topography.
  - Gradual exposure of subsurface rocks by stripping off (eroding) the surface layers.

Marble quarry in the Alps, Italy
Introduction:
Earth’s Varied Landscapes (2)
- Closely related terms that imply different perspectives on erosional processes.
- Denudation:
  - The transport of eroded material to another location.
- Geomorphology:
  - The study of Earth’s landforms.

Factors Controlling Uplift
- Uplift occurs as a byproduct of mantle convection and plate tectonics.
- We can identify several types of uplift:
  - Collisional uplift.
  - Isostatic uplift.
  - Extensional uplift.

Figure 12.1
Collisional Uplift

- The most natural uplifted landscape would be a long, narrow orogen that forms along a convergent plate boundary.
  - Results from compression of relatively light crustal rock atop a continental plate.
  - When an oceanic plate subducts beneath a continental plate, an orogen can form from a rising wedge of marine sediments scraped from the downgoing plate.
    - The island of Taiwan and the Olympic mountains of Washington State are examples of such orogens.

Figure 12.2

Figure B 12.1
The Himalayan orogen forms the southern border of the Tibetan Plateau, which approaches 1000 km in width. When continents collide, their plate boundaries tend to crumple somewhat, so the lithosphere locally thickens.
Isostatic Uplift

Many geologists argue that the dense mantle lithosphere of a thickened plate boundary can peel off and be replaced by hot buoyant asthenosphere.
- Isostatic uplift would follow.
- Isostatic uplift occurs wherever a hot, buoyant mantle plume rises to the base of the lithosphere, as beneath the Hawaiian Island or Yellowstone National Park.

Isostatic Uplift

Topography elevates locally wherever hot magmas activity creates individual volcanoes.

Extensional Uplift

Extensional uplift occurs in regions where the ascent of hot buoyant mantle at the base of continental lithosphere induces broad uplift and stretching of crust.
Extensional Uplift (2)

- Isostatic uplift can induce short-scale topographic relief by extension and normal faulting.
  - Bathymetric scarps parallel the midocean ridges.
  - The Basin and Range Province (Nevada, Utah, Arizona).
  - Horst-and-graben structures.

Figure 12.4

Figure 12.5
Factors Controlling Denudation

- Climate.
- Lithology.
- Relief.

Climate (1)

- Climate helps determine which surface processes are active in any area.
  - In humid climates, streams may be the primary agent that moves and deposits sediment.
  - In an arid region wind may locally assume the dominant role.
  - Glaciers are largely restricted to high latitudes and high altitudes.

Climate (2)

- Climate controls vegetation cover.
- Climates have changed through time.
- Many modern landscapes reflect former conditions—like glaciation—rather current processes.
Lithology (1)

- Some rock types are less erodible, and thus will produce greater relief and steeper landform.
  - Granite or hard sandstone can maintain steep slopes for a long time.
  - Soft shale easily erodes into low-relief debris.

Lithology (2)

- However, a specific rock type may behave differently under different climatic conditions.
  - Limestone in a moist climate may dissolve and erode into a terrain of sinkholes.
  - In a desert, the same limestone may form bold cliff.
Figure 12.7

Relief (1)
- Relief exerts a strong influence on denudation rates.
- Tectonically active regions with high rates of uplift generate rapid erosion.
- In areas far from active tectonism:
  - Relief typically is low.
  - Erosion rates are much slower.
  - Landscape changes are more gradual.

Relief (2)
- Even in tectonically inactive areas, a rapid change of sea level or small regional isostatic movements may significantly change streams and the landscapes they influence.
The line separating any two major drainage basins is a continental divide.

- In North America, continental divides lies at the head of major streams that drain into the Pacific, Atlantic, and Arctic oceans.

Climate can also influence the location of the divide.

- Prevailing winds may cause one side of a divide to be wetter than the other, and therefore more subject to denudation.

Because continental divides often coincide with the crests of mountain ranges, and because mountain ranges are the result of uplift associated with the interaction of tectonic plates, a close relationship exists between plate tectonics and the location of primary stream divides and drainage basins.
American geographer William Morris Davis (1850-1934) proposed in the late nineteenth century a model called the geographic cycle:

- In the initial stage, “youthful” streams downcut vigorously into the uplifted land surface to produce sharp, V-shape valleys, thereby increasing the local relief.
- The drainage system expands and valleys grow deeper and wider.

As the cycle progresses, streams begin to “mature” and meander in their gentler valleys, and valley slopes are gradually worn down by mass wasting and erosion.

- The final stage, the “old-age” landscape consists of broad valleys containing wide floodplains, stream divides are low and rounded, and the landscape is slowly worn down ever closer to sea level.

Current geomorphologists (geologist who specialize in the shape of the land) have discarded Davis’s landscape cycles.
Steady-State Landscapes (1)

- A landscape that maintains a constant altitude and topographic relief while still undergoing uplift, exhumation and denudation.
- It is not common for a landscape to achieve a steady state because of:
  - A tectonic event that lifts up a landmass.
  - A substantial sea level drop.
  - A climate shift.
  - A stream that erodes downward through weak rock and encounters massive, hard rock beneath.

Steady-State Landscapes (2)

- If rates of denudation and uplift are stable for long periods, the landscape can adjust itself to a steady state.
- A steady state landscape maintains a constant altitude and topographic relief while still undergoing change.
- If uplift ceases altogether, the average rate of change gradually decreases as the land surface is progressively eroded toward sea level.
Rapid landscape Changes: Threshold Effects

- Sudden changes can occur once a critical threshold condition is reached.
- A threshold effect implies that landscape development, rather than being progressive and steady, can be punctuated by occasional abrupt changes.
- A landscape in near-equilibrium may undergo a sudden change if a process operating on it reaches a threshold level.

How Can We Calculate Uplift Rates?

- Three methods are used to calculate uplift rates:
  - Extrapolation from earthquake displacements.
  - Measurement of warped strata.
  - Measurement of river terraces.
Extrapolation from Earthquake Displacements

- Measure how much local uplift occurred during historical large earthquakes.
- Extrapolate the recent rates of uplift back in time.
  - This is based on the risky assumption that the brief historical record is representative of longer intervals of geologic time.
  - Organic processes can supplement historical record.
    - In New Zealand, for instance, lichens grow on newly exposed rock surfaces at a predictable rate for several centuries, providing information about the age of the surface.

Calculation from Warped Strata

- This technique measures the warping (vertical dislocation) of originally horizontal strata of known age.
- For this method, we need to know:
  - The altitude difference between where the stratum is today and where it was at its formation.
  - A radiometric age for the stratum.

Calculation from River Terraces (1)

- Rivers tend to carry material eroded from steep slopes and deposit it along flatter portions of river valleys.
- In an uplift region, a river may form a sequence of abandoned depositional surfaces called river terraces.
- As uplift raises a river valley, the river erodes into its former depositional surface and its terraces are abandoned.
Calculation from River Terraces (2)

- If we can determine the age of the last sediment deposited, abandonment times and uplift rates can be calculated.
- However, interpretation requires some caution.
  - Climate changes can alter streambed erosion rates and cause river terraces to form as well.
  - Measured uplift rates in tectonic belts are quite variable through time.

Radioactive-Decay Techniques (1)

- Some radioactive products, such as fission tracks and radiogenic helium, will not accumulate if the rock is too hot.
  - They are retained only if the rock is cooler than a certain critical temperature, called the closure temperature.
  - Radioactive decay products use thermal energy to escape their host rock.

Radioactive-Decay Techniques (2)

- Each decay product has an independent closure temperature.
- Escape is easier if the decay product is a noble gas, like helium (He) or argon (Ar).
Radioactive-Decay Techniques (3)

- Fission tracks damage the crystalline structure of minerals, but this damage will repair itself by annealing if the temperature is sufficiently high.
- Fission tracks and radiogenic helium do not give reliable ages for the original formation of surface rocks, but rather tells us how many years the rocks have been at or below their closure temperatures.

Cosmogenic Nuclides

- Cosmogenic nuclides are radioactive isotopes that are not present in a rock at its formation, but rather are generated by high-energy subatomic particles emitted by the sun.
  - Their abundance in a surface rock can tell us how long a rock has been exposed to such radiation.
How Can We Calculate Exhumation and Denudation Rates?

- The exhumation rate is equal to the erosion rate.
- Local exhumation rate:
  - The simple ratio “depth over time” estimates the rate at which erosion has stripped off rock that lay atop the present surface.

Denudation Rates

- To calculate long-term denudation rates, we must know how much rock debris has been removed from an area during a specified length of time.
- For areas drained by major streams, the volume of sediment reaching the ocean each year is a measure of the modern erosion rate.
  - We can estimate the volume of sediment deposited during a specific time interval by using drill-core and seismic records of the seafloor.
The highest measured sediment yields are from:
- The humid region of southeastern Asia and Oceania.
- Basins that drain steep, high-relief mountains of young orogenic belts, such as the Himalayas, the Andes, and the Alps.

Low sediment yields are from:
- Deserts.
- The polar and subpolar sectors of the northern continents.

Structural factors also play a role.
- Rocks that are more highly jointed or fractured are more susceptible to erosion than massive rock formation.
- Denudation is surprisingly high in some dry-climate regions, often because the surface lacks a protective cover of vegetation.
World Sediment Yields (3)

- Below a certain vegetation density, erosion rates may increase.
- This threshold effect explains why soil erosion is a serious problem after forested land is cleared for farming or livestock grazing.

World Sediment Yields (4)

- In south-coastal Alaska, as in the most extensively glaciated temperate mountain regions in the world, denudation rates exceed those of comparable-sized nonglaciated basins in other region by factor of 10 or more.
  - Near temperate valley glaciers, both chemical and physical weathering rates tend to be substantially above the global average.

Figure 12.13
Human Impact on Denudation (1)

- Humans increase the rate of denudation by:
  - Clearing forests.
  - Developing cultivated land.
  - Damming streams.
  - Building cities.

Human Impact on Denudation (2)

- In parts of the eastern United States, areas cleared for construction produce 10 to 100 times more sediment than comparable rural areas or natural areas that are vegetated.
- The high Aswan Dam on the Nile River, in Egypt, now intercepts most of the sediment that the Nile previously carried to the Mediterranean sea.

Ancient landscapes of Low Relief (1)

- If changes in plate motion lead to cessation of tectonic uplift, denudation can gradually lower the relief.
- Australia is widely believed to have some of the oldest landscapes of any of the continents.
Ancient landscapes of Low Relief (2)

- Widespread erosional landscapes of low relief and altitude are uncommon.
- This must mean either that:
  - The Earth’s crust has been very active in the recent geologic past, or
  - Such landscapes take an extremely long time to develop.

Figure 12.14

The Carbon Cycle (1)

- The carbon cycle on Earth is driven by plate tectonic motions.
- Uplift and exhumation are among the most important factors in determining the level of CO₂ in the atmosphere.
- Global volcanism adds CO₂ to the atmosphere from Earth’s interior.
The Carbon Cycle (2)

- The global rate of seafloor spreading may control the transfer rate of CO₂ to the atmosphere.
- Another source of atmospheric CO₂, possibly larger than volcanic outgassing, is metamorphism of carbon-rich ocean sediments carried downward in subduction zones.

The Carbon Cycle (3)

- CO₂ is removed from the atmosphere by weathering of surface silicate rocks.
  - Rainwater combines with CO₂ to form carbonic acid (H₂CO₃), and this acid weathers silicate rocks:
    - CaSiO₃ + H₂CO₃ → CaCO₃ + SiO₂ + H₂O
  - Silicate rock + carbonic acid → weathering products + water
The Carbon Cycle (4)

- Land plants synthesize other carbon-based acids in their roots to leach chemical nutrients from rocks.
- Streams transport weathering products to the ocean.
  - There the carbonate and silica are used by marine organisms, and their remains accumulate on the seafloor, stored as sediment.

The Carbon Cycle: An Alternate View

- An alternative hypothesis: uplift could increase the removal rate for atmospheric CO$_2$ because it generates faulting, which exposes fresh, fractured rock to chemical weathering.
  - A trend over the past 100 million years toward cooler global temperatures and reduced atmospheric CO$_2$ has occurred at the same time as the uplift and erosion of several major continental plateaus, including Tibet in central Asia, the Altiplano in South America, and the Laramide uplift (Rocky Mountains) in North America.