Landscape Evolution

Summary

- Changes in the landscape are generated by processes of uplift, exhumation and denudation. Geomorphology is the study of landforms and their evolution.
- Exhumation refers to processes that expose rock that lies beneath the surface. Denudation refers to processes that removal and re-deposition of debris.
- Uplift can occur from collisional, extensional, and isostatic mechanisms.
- Collisional uplift generally takes the form of an orogen (mountain chain) along a convergent plate boundary, constructed largely by earthquake motion on thrust faults.
- Extensional uplift occurs when the lithosphere is thinned and brittle surface rocks break apart in normal faults.
- Isostatic uplift takes several forms. The buoyancy of a mantle hot spot may cause the overlying lithosphere to rise. A portion of cool mantle lithosphere, thickened like toothpaste in a plate collision, may drop off into the mantle, being replace by more buoyant asthenosphere.
- Erosion provides positive feedback on mantle flow generating uplift – and uplift can change climate

- The Earth’s surface topography reflects sculpture by different erosional processes and deposition of resulting sediment. Water, ice, and wind are the principal agents that erode the land and transfer sediment toward the ocean basins.
- The principal factors influencing denudation rate are climate, lithology, relief, and time.
- Exhumation rates can be estimated from radioactive decay systems in which the daughter products accumulate only when the rock is cool, and therefore close to the surface. These systems include the accumulation of the noble gas helium from alpha-decay of uranium and thorium, and damage to mineral crystals from alpha particles, called “fission tracks”.
- Another estimate of exhumation rate can be obtained from cosmogenic nuclides, rare isotopes that are generated by the absorption of cosmic rays in the top meter or so of exposed rock.
- Natural denudation processes are constantly changing the character of the landscape, but so, too, are human activities.

- Landscapes evolve through time as tectonic forces raise crustal rocks and erosional agents wear them away.
- Landscapes are constantly adjusting to changes in the factors that control their development and likely are never in a complete state of equilibrium. Hypothetical models for landscape evolution attempt to generalize how uplift and denudation interact.
  - In the ìgeographic cycleî of W. W. Davis, uplift dominates in young landscapes, and denudation becomes more dominant as the landscape matures.
  - The steady-state hypothesis proposes that uplift and denudation remain in balance for long periods of time
- Ancient landscapes with low relief imply long intervals of erosion that slowly lowered the land surface to low altitude. Although not common in modern landscapes, extensive surfaces of low relief are preserved in some ancient rocks
- Silicate weathering and burial of organic carbon remove CO_2 from the atmosphere and place it in long-term storage. Removal of CO_2 from the atmosphere reduces the greenhouse effect and influences world climate. Mountain uplift exerts a strong influence on atmospheric CO_2 levels in Earth history, because uplift exposes fresh rock to chemical weathering

Marble quarry in the Alps, Italy

Landscape Evolution (Geomorphology)

- Uplift
- Erosion
  - Exhumation = exposing rocks
  - Denudation = removing debris & placing elsewhere
- Old idea – two are decoupled
- New Idea – two are closely linked

Uplift controls

- Plate Tectonics
  - Mantle convection
    - Collisional uplift
    - Extensional uplift
    - plumes
- Isostatic uplift
  - Climate connection

New Insight

counter-intuitive idea?

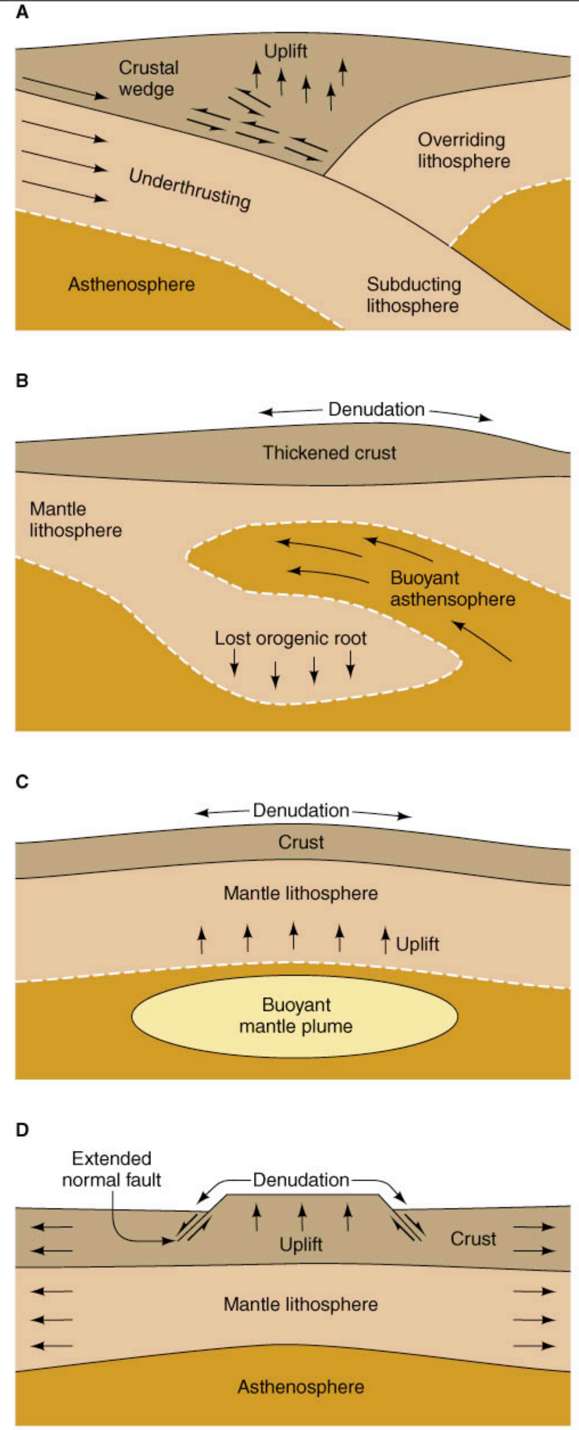
- High mountains affect weather patterns
  - Increase in precipitation (more erosion)
  - Glaciation (more erosion)
- Erosion drives uplift through isostacy
  - Erosion therefore causes mantle flow
- Thus, climate can drive mantle flow
  - Provides a positive feedback on mantle processes
- Climate change due to uplift
  - Changed global circulation
  - Changed CO_2 cycling and storage

Collision zone "crustal wedge"
(Olympic Mtn, Taiwan, Alps)

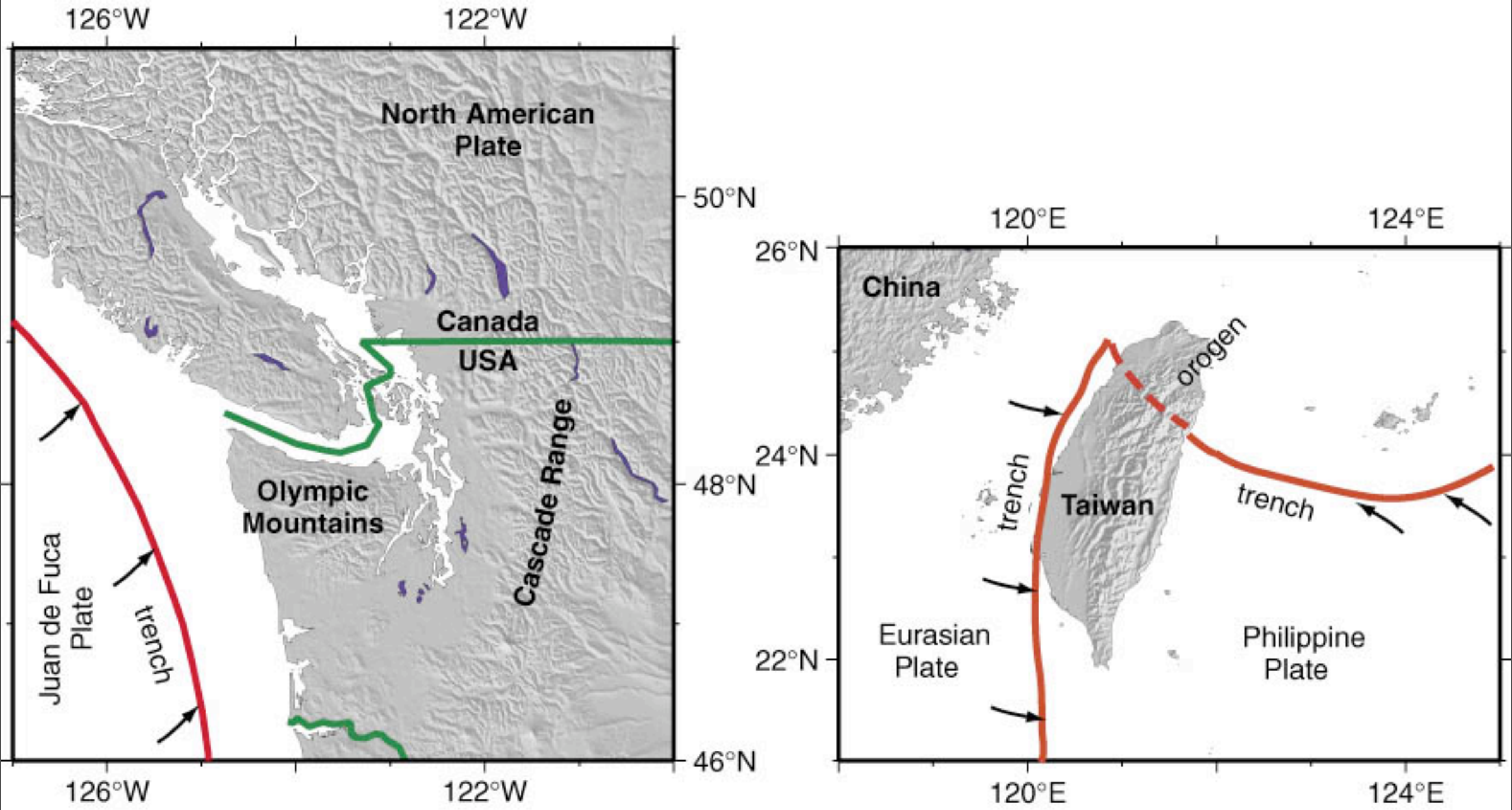
Loss of "lithospheric root"
(Tibet, Altiplano)

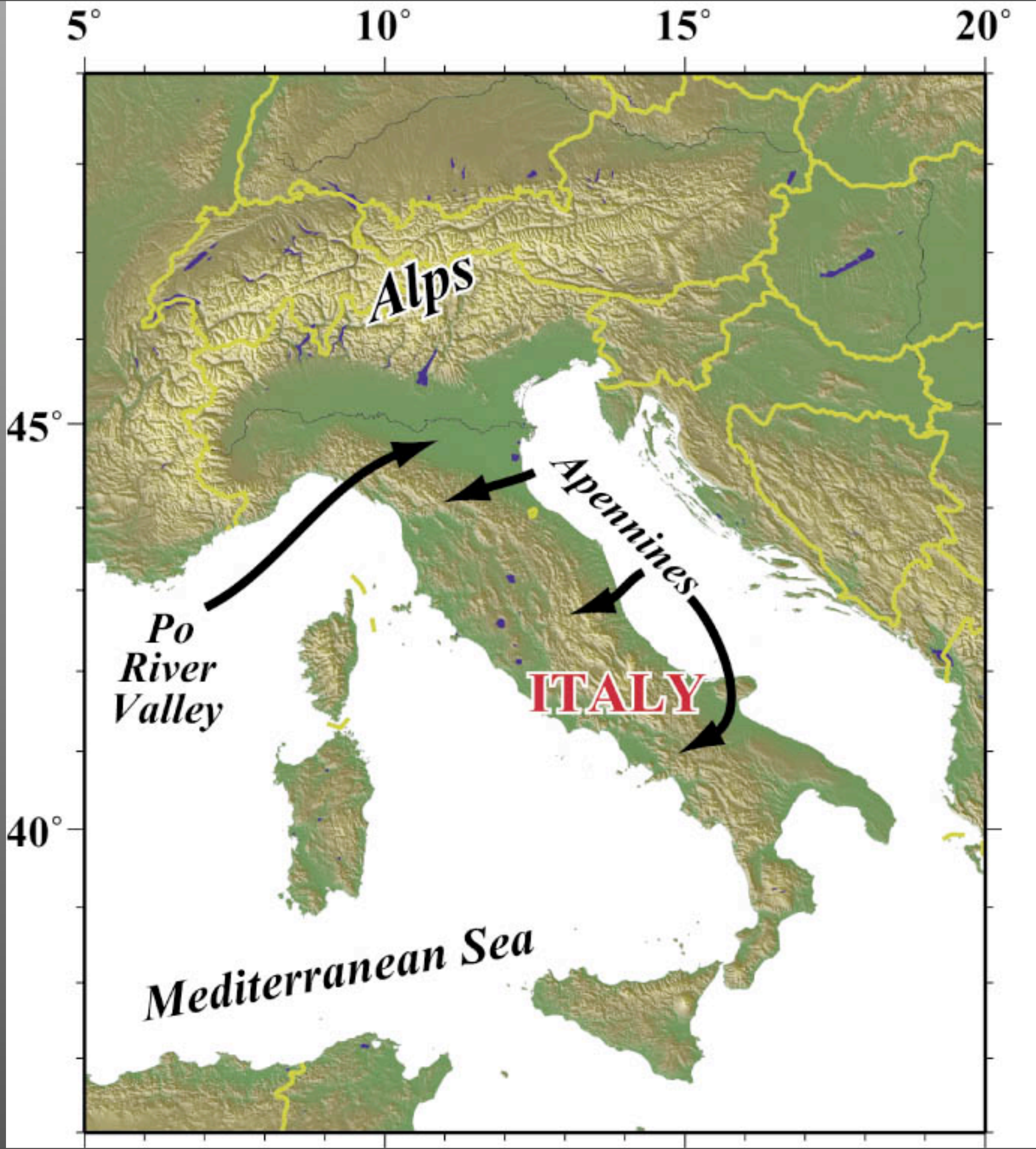
Mantle Plume
(Yellowstone, Africa)

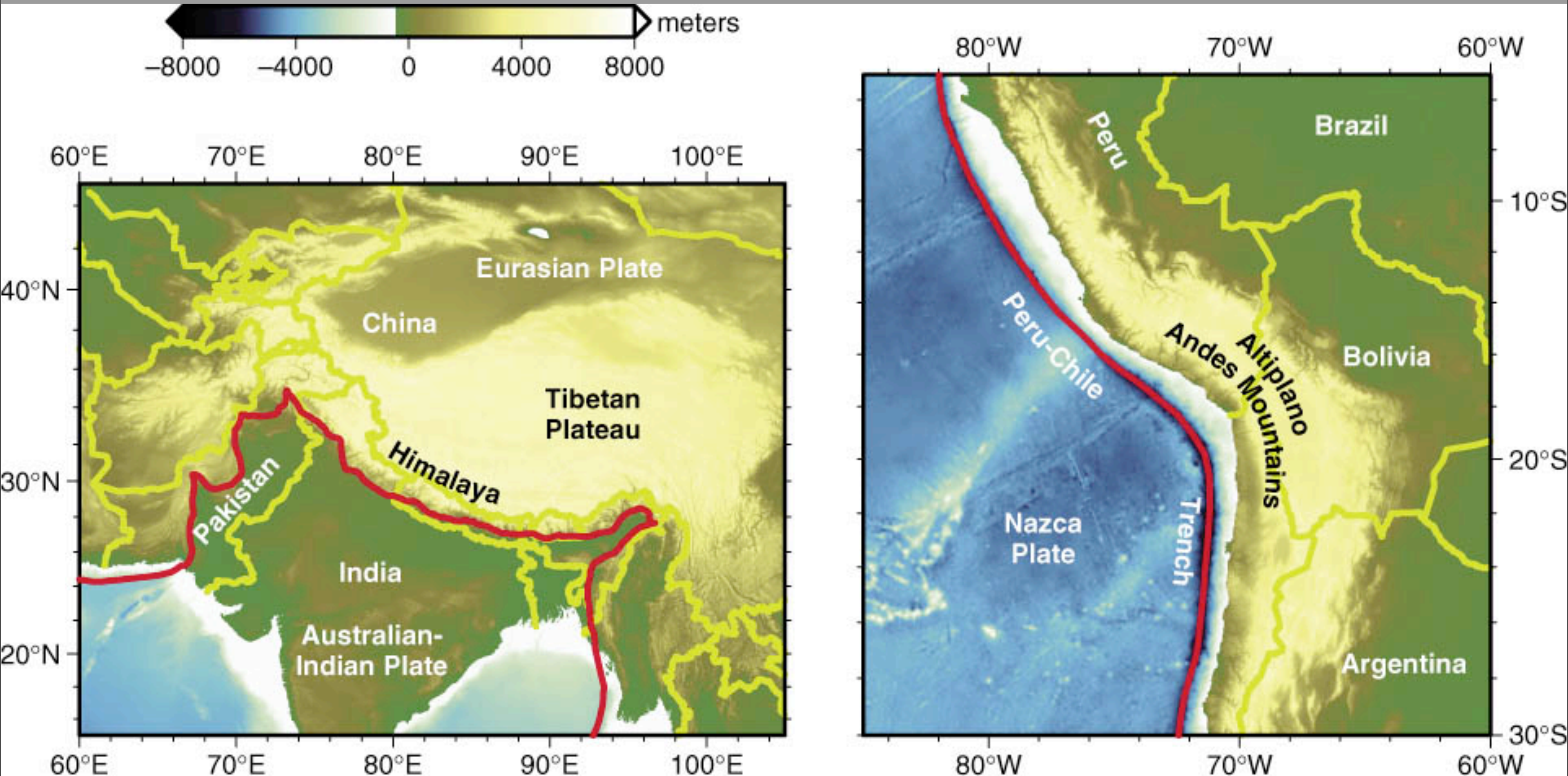
Extensional thinning
(Basin and Range –Nevada)



Examples


126°W
122°W
North American Plate
50°N
Canada
USA
Olympic Mountains
Cascade Range
48°N
Juan de Fuca Plate
trench
46°N
120°E
124°E
26°N
China
orogen
24°N
trench
Taiwan
trench
22°N
Eurasian Plate
Philippine Plate


5°
10°
15°
20°
45°
40°
Alps
Apennines
Po
River
Valley
ITALY
Mediterranean Sea



meters
−8000
−4000
0
4000
8000
60°E
70°E
80°E
90°E
100°E
40°N
30°N
20°N
Eurasian Plate
China
Tibetan Plateau
Himalaya
Pakistan
India
Australian-Indian Plate
80°W
70°W
60°W
10°S
20°S
30°S
Peru
Brazil
Bolivia
Altiplano
Andes Mountains
Peru-Chile Trench
Nazca Plate
Argentina

Figure 12.3

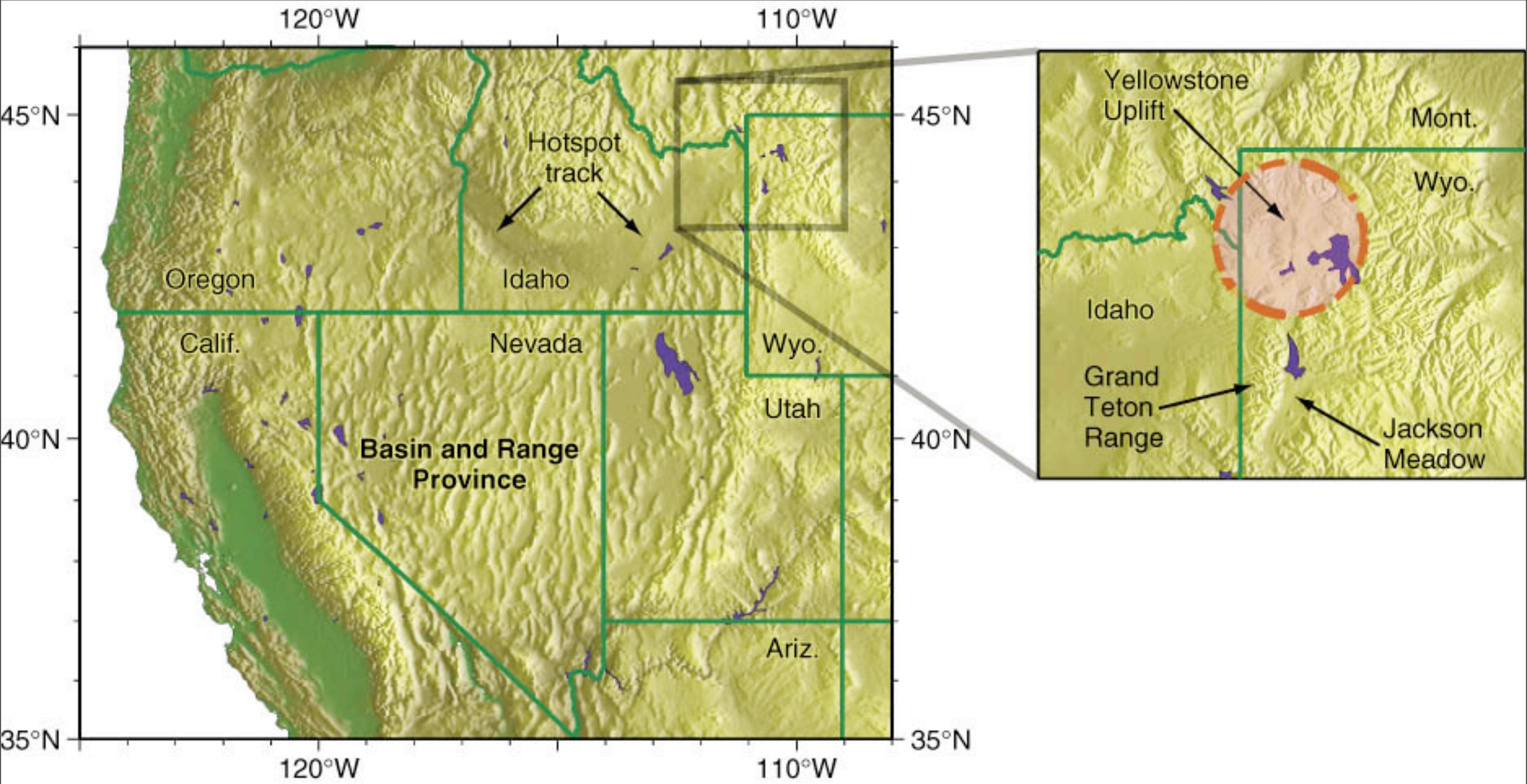
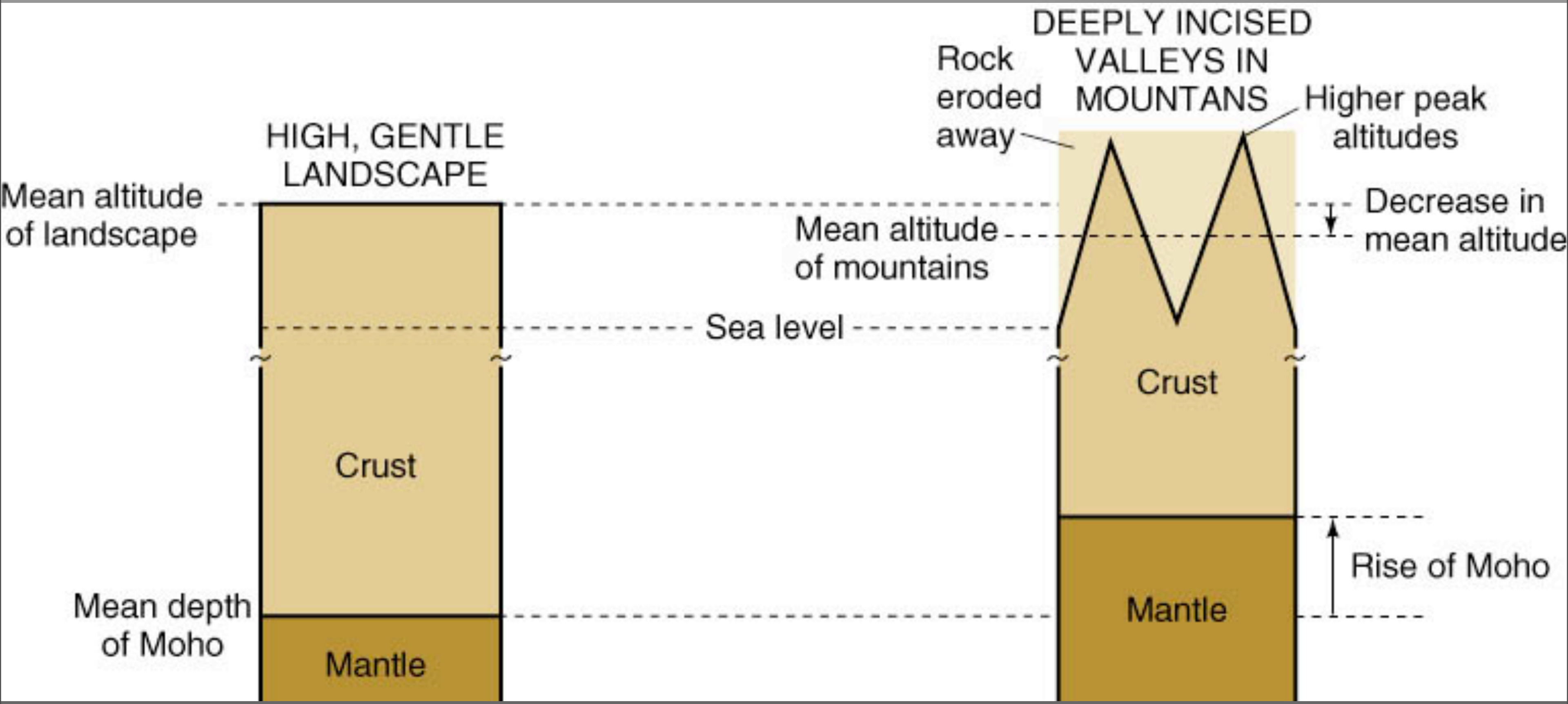
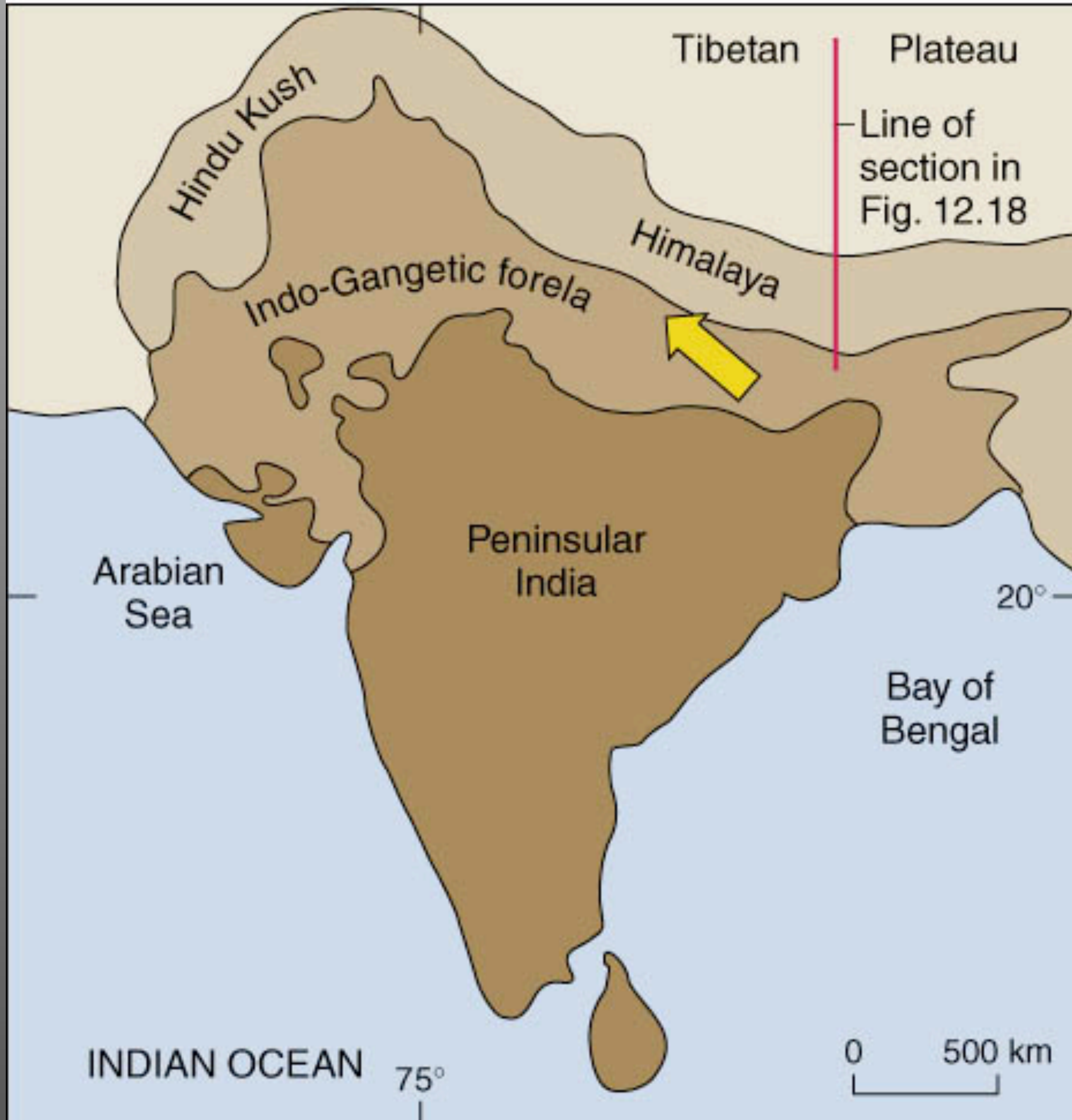

120°W
110°W
45°N
40°N
35°N
Hotspot track
Oregon
Idaho
Calif.
Nevada
Wyo.
Utah
Basin and Range Province
Ariz.
Yellowstone Uplift
Mont.
Wyo.
Idaho
Grand Teton Range
Jackson Meadow

Figure 12.5

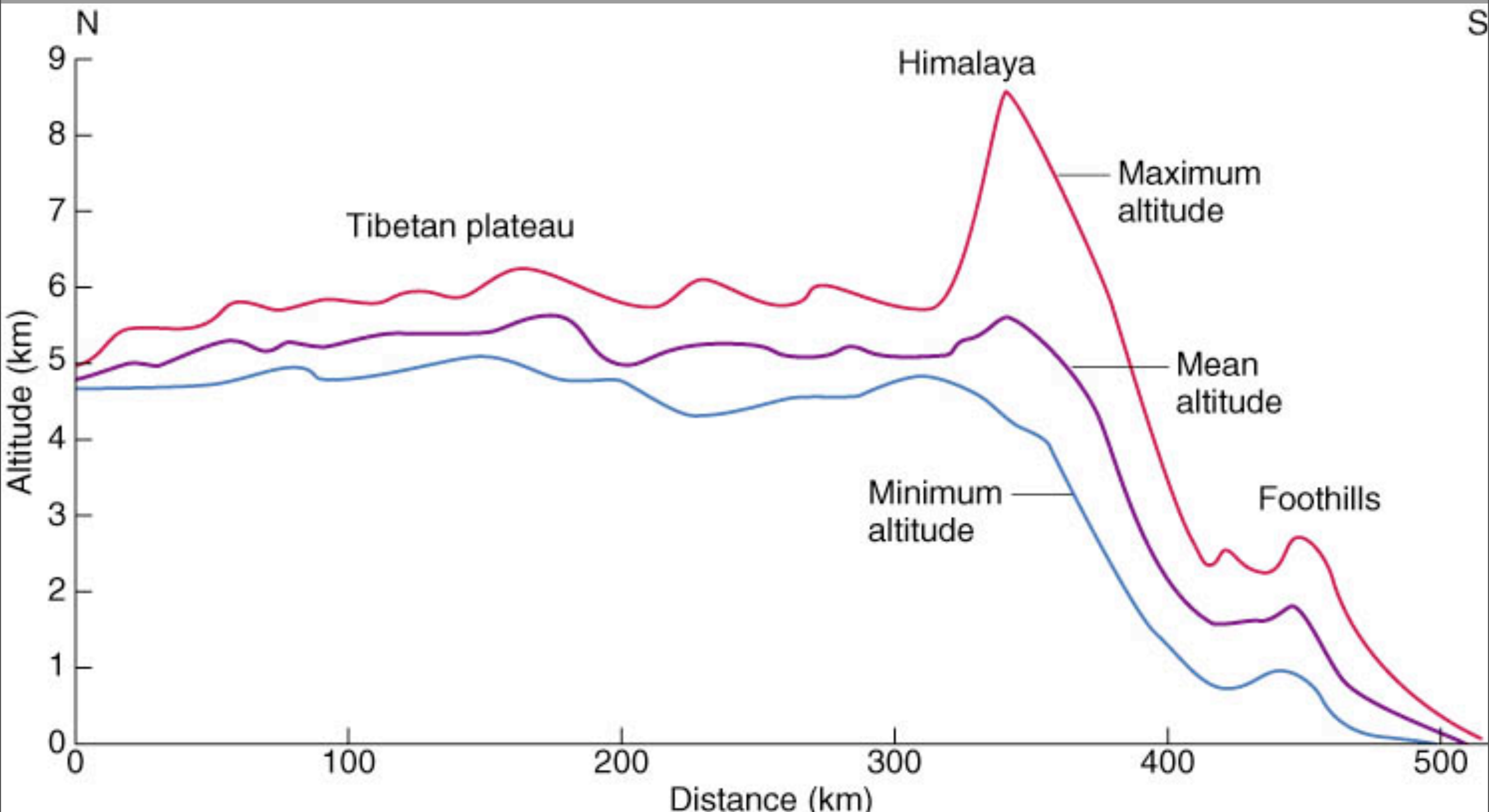
The Climate Connection

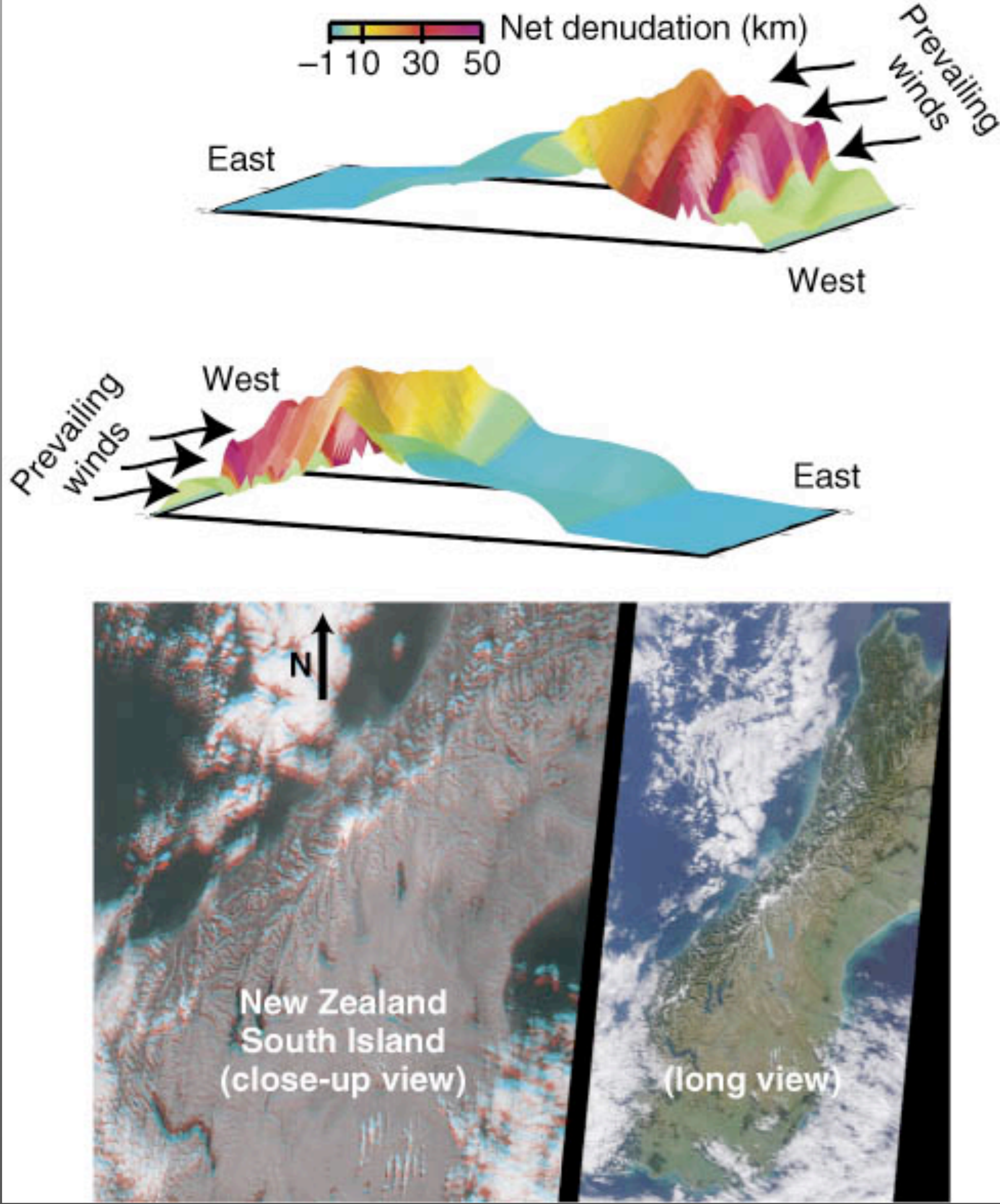

HIGH, GENTLE LANDSCAPE
Mean altitude of landscape
Crust
Mean depth of Moho
Mantle
DEEPLY INCISED VALLEYS IN MOUNTANS
Rock eroded away
Higher peak altitudes
Mean altitude of mountains
Decrease in mean altitude
Sea level
Crust
Rise of Moho
Mantle

B



Tibetan
Plateau
Line of section in Fig. 12.18
Hindu Kush
Himalaya
Indo-Gangetic forela
Arabian Sea
Peninsular India
20°
Bay of Bengal
INDIAN OCEAN
75°
0
500 km


N
S
Himalaya
Maximum altitude
Tibetan plateau
Mean altitude
Minimum altitude
Foothills
Altitude (km)
9
8
7
6
5
4
3
2
1
0
0
100
200
300
400
500
Distance (km)

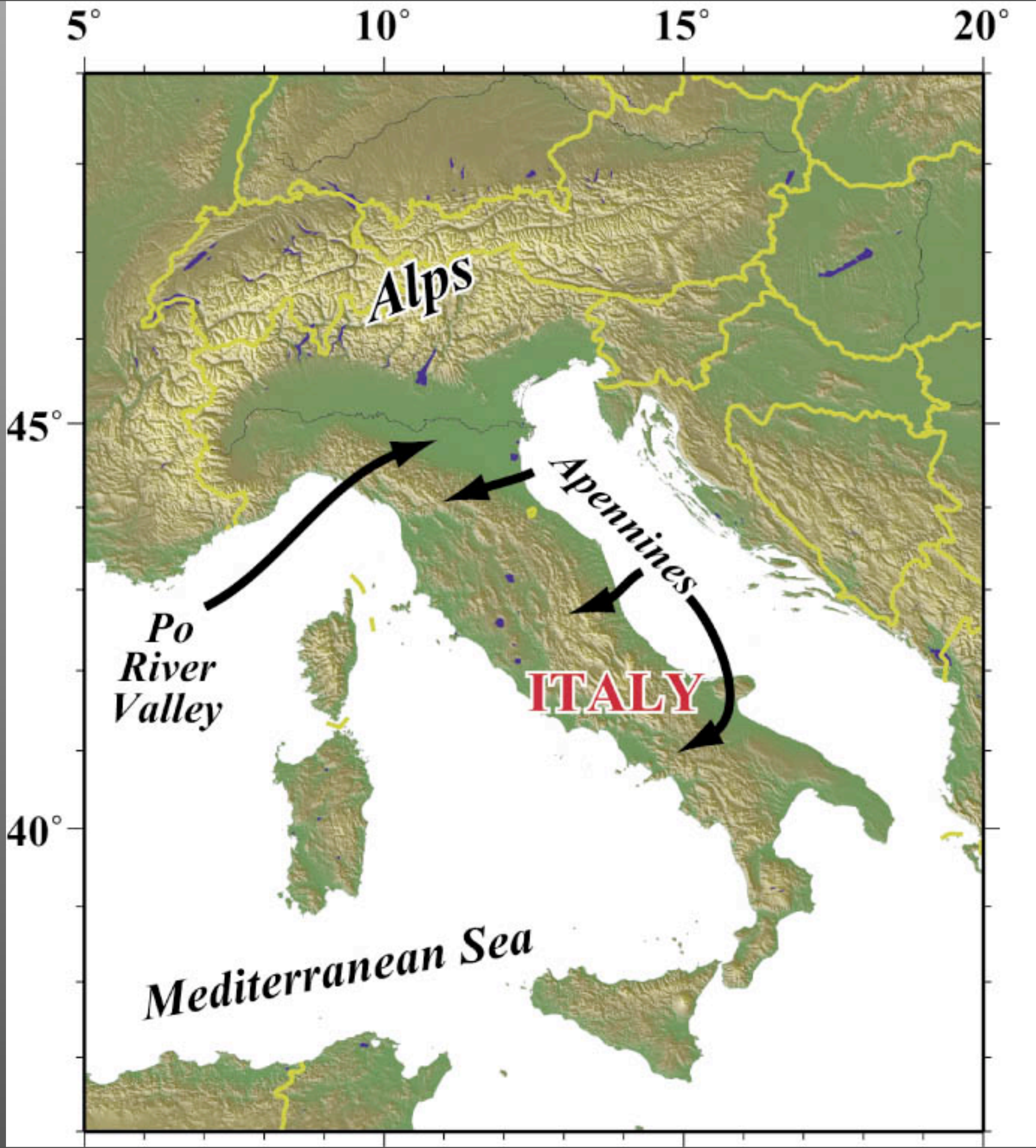

Net denudation (km)
−1 10 30 50
Prevailing winds
East
West
West
Prevailing winds
East
N
New Zealand
South Island
(close-up view)
(long view)

Erosion Controls

- Parent material
- Topography
- Climate
- Organisms
- Time

Calculating erosion

- Exhumation rates
  - Measure rate of rock removal
  - Measure how long rocks have been at the surface
- Denudation rates
  - Measure how much sediment has accumulated over time


5°
10°
15°
20°
45°
40°
Alps
Apennines
Po
River
Valley
ITALY
Mediterranean Sea

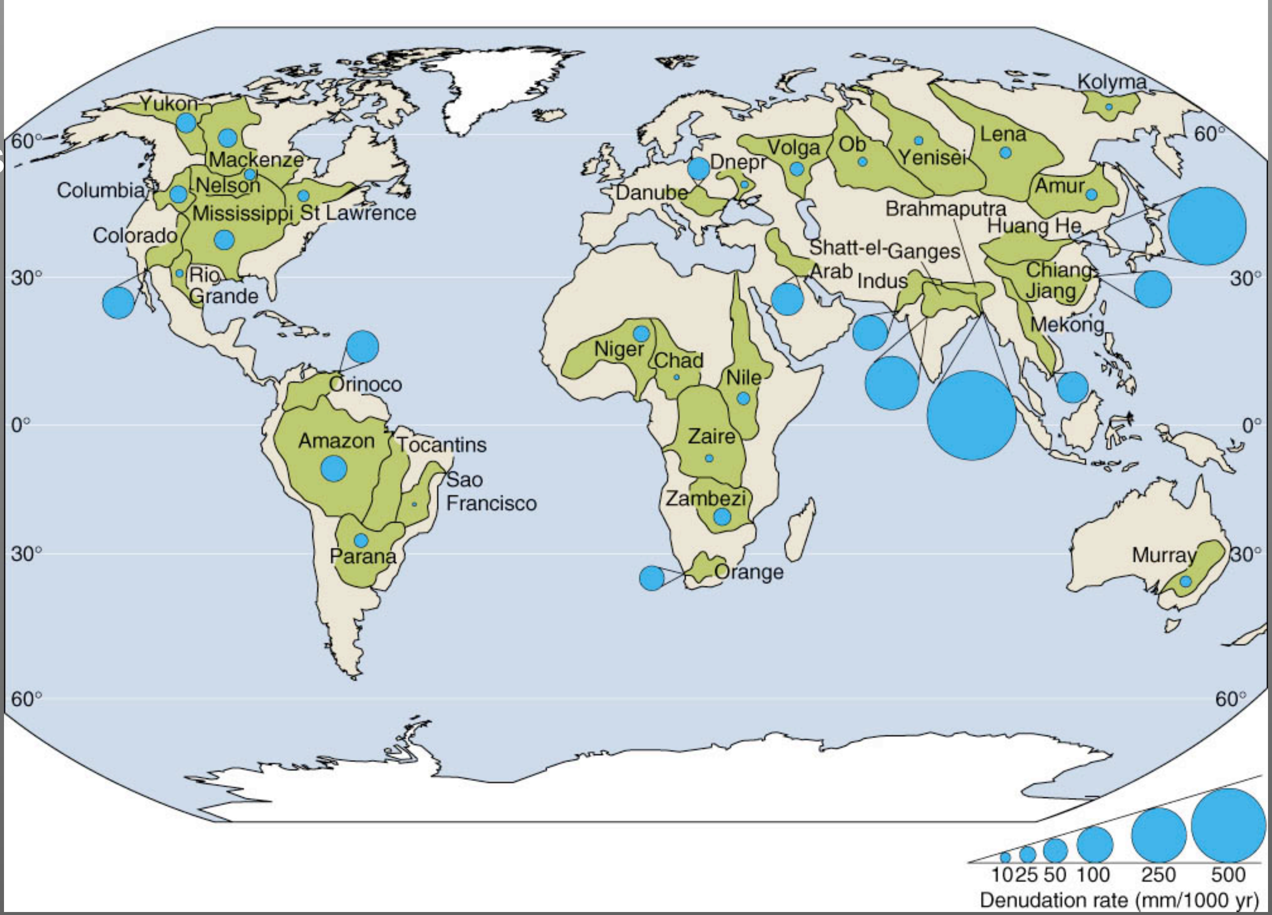
Denudation rates

High

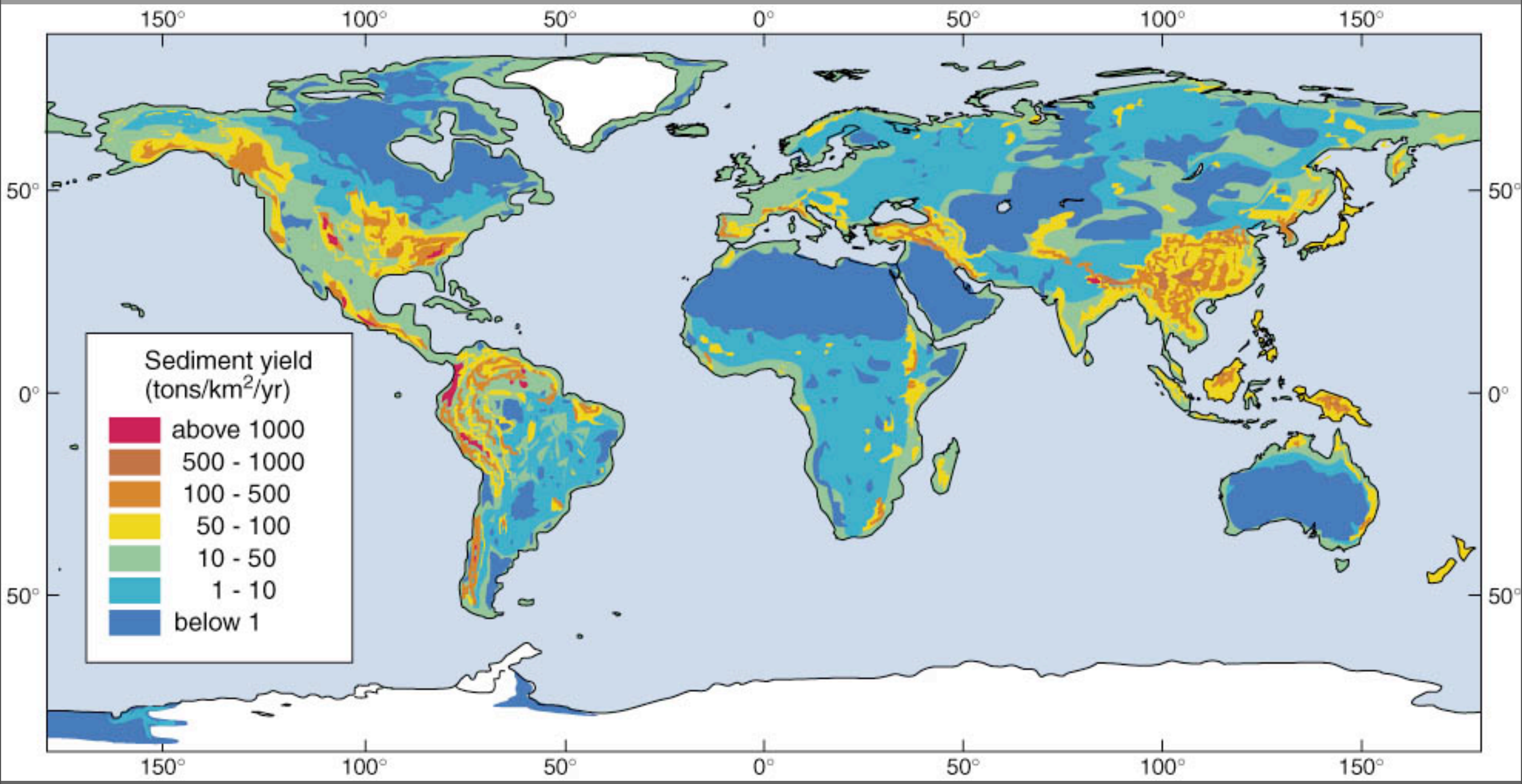
- Humid regions
- High relief regions
- Low vegetation regions
- Glacial regions

Low

- Deserts
- Cold regions



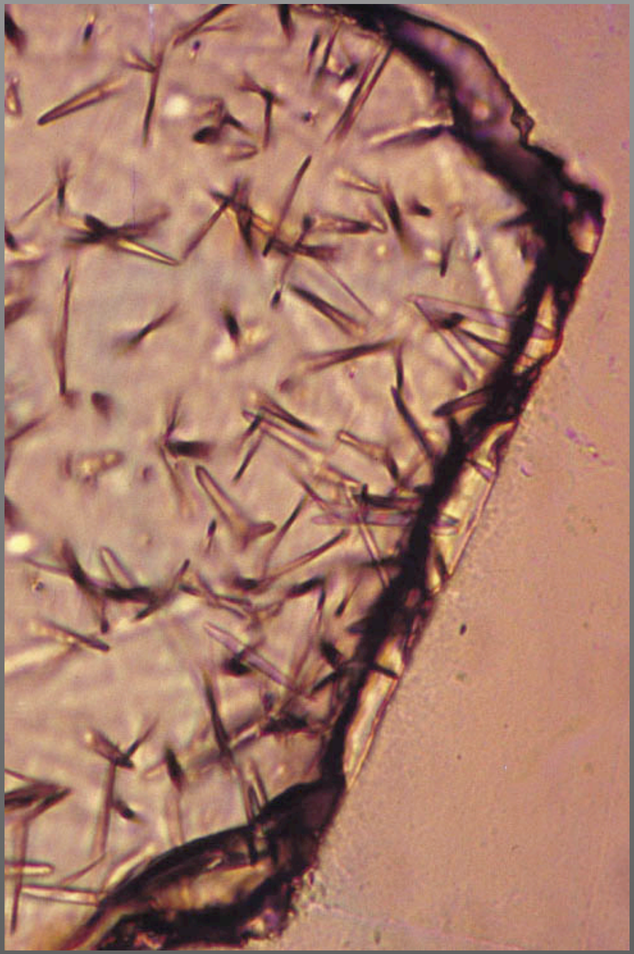
*We are affecting denudation rates!



150°
100°
50°
0°
50°
100°
150°
50°
0°
50°
Sediment yield
(tons/km²/yr)
above 1000
500 - 1000
100 - 500
50 - 100
10 - 50
1 - 10
below 1

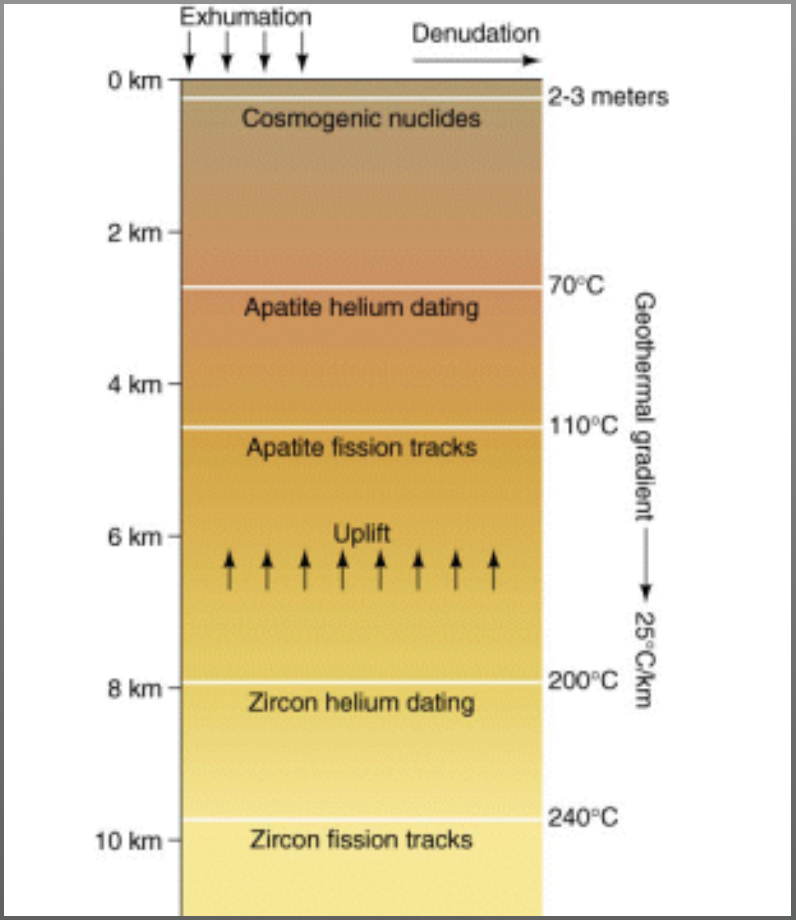
Exhumation rates based on rock removal

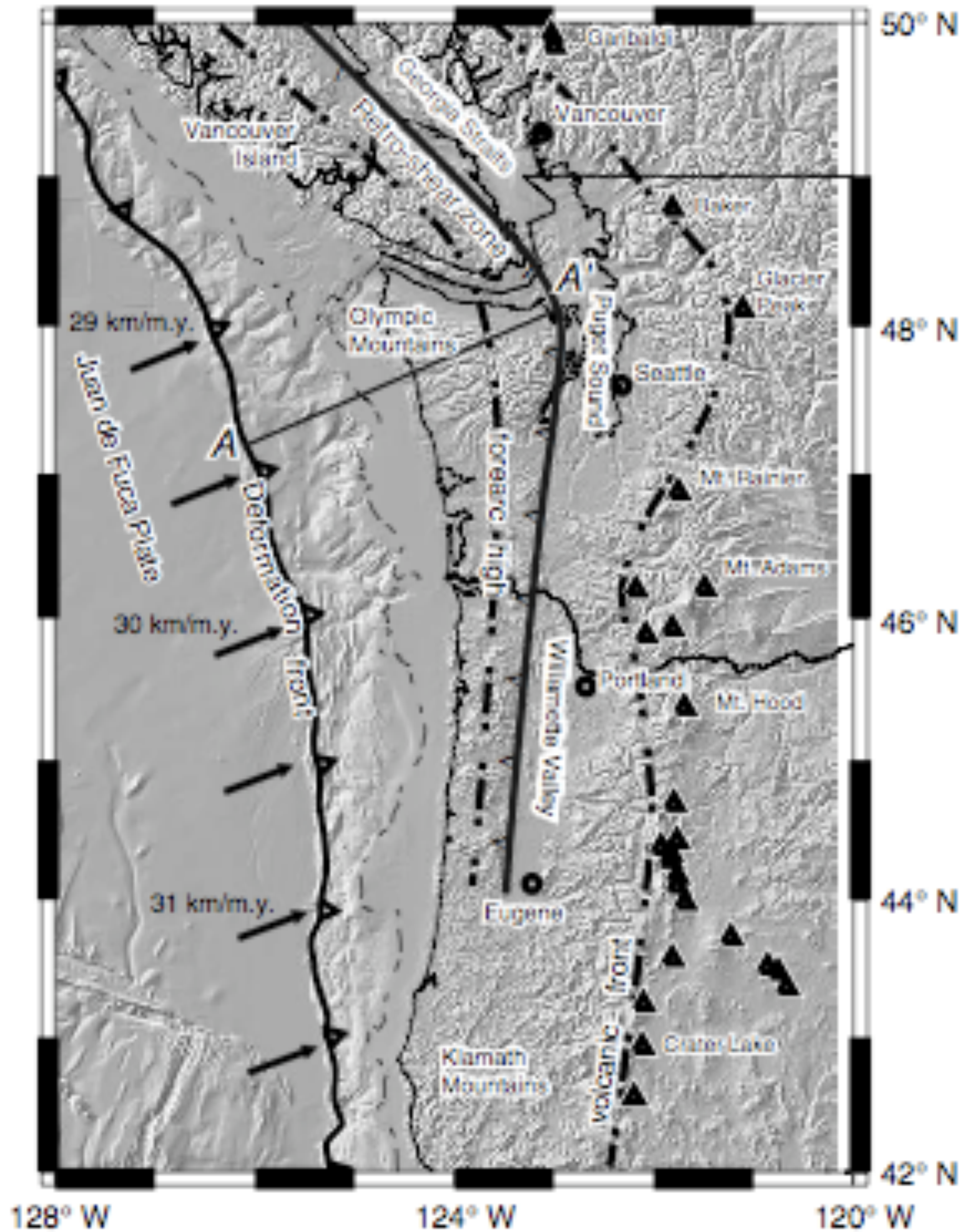
- Fission tracks
  - Spontaneous fission scars minerals
    - at high temps scars heal
    - At low temps scars accumulate
  - Counting fission tracks gives estimate of time since rock cooled through some temperature (depth)



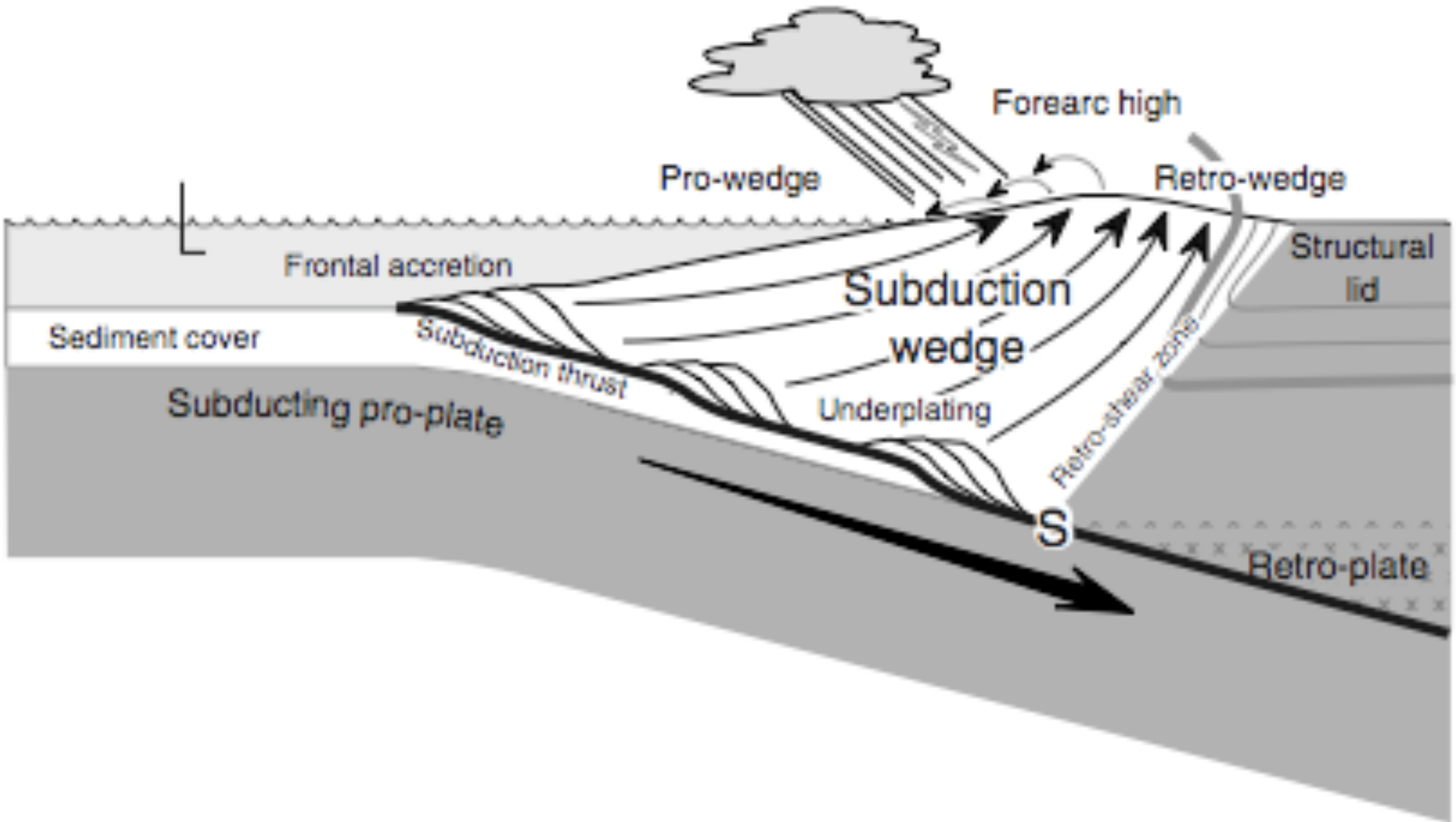
Exhumation rates based on rock removal

- Radioactive decay
  - Some elements in rocks decay
    - At high temperature decay products escape
    - At low temperatures decay products trapped
  - Measuring amount of decay product give estimate of time since rock cooled





50° N
48° N
46° N
44° N
42° N
128° W
124° W
120° W
Garibaldi
Georgia Strait
Vancouver
Vancouver Island
Petrox shear Zone
Baker
Glacier Peak
A'
A
Olympic Mountains
Puget Sound
Seattle
29 km/m.y.
Juan de Fuca Plate
Deformation front
forearc high
Mt Rainier
Mt Adams
30 km/m.y.
Willamette Valley
Portland
Mt. Hood
31 km/m.y.
Eugene
Crater Lake
Klamath Mountains
volcanic front



Forearc high
Pro-wedge
Retro-wedge
Frontal accretion
Structural
lid
Subduction
wedge
Sediment cover
Subduction thrust
Subducting pro-plate
Underplating
Retro-shear zone
S
Retro-plate

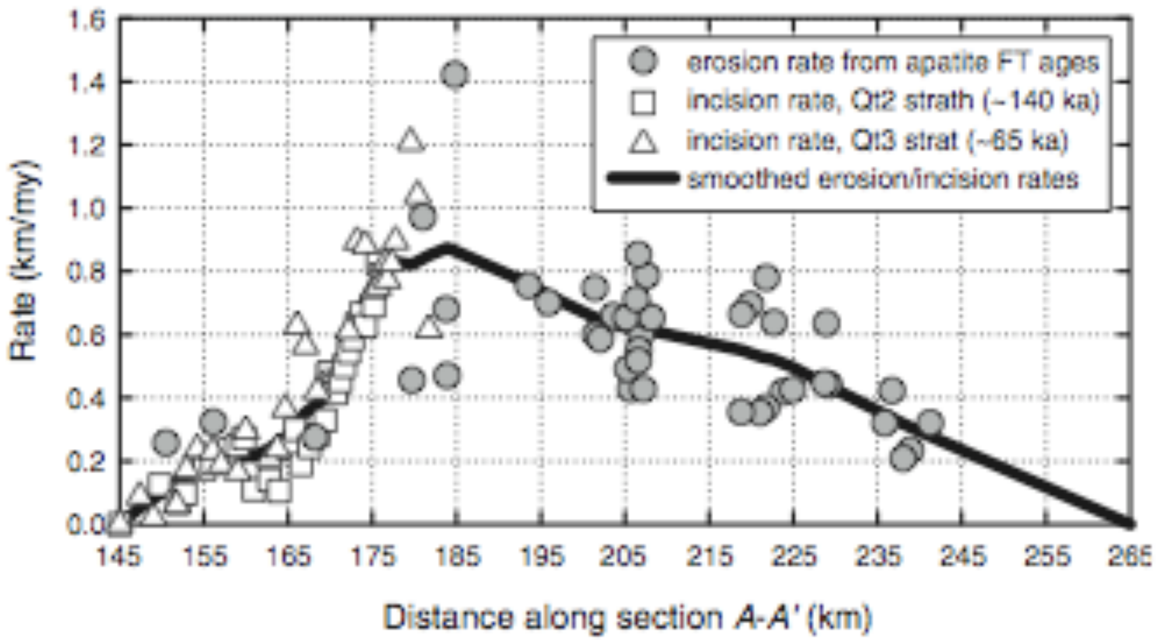
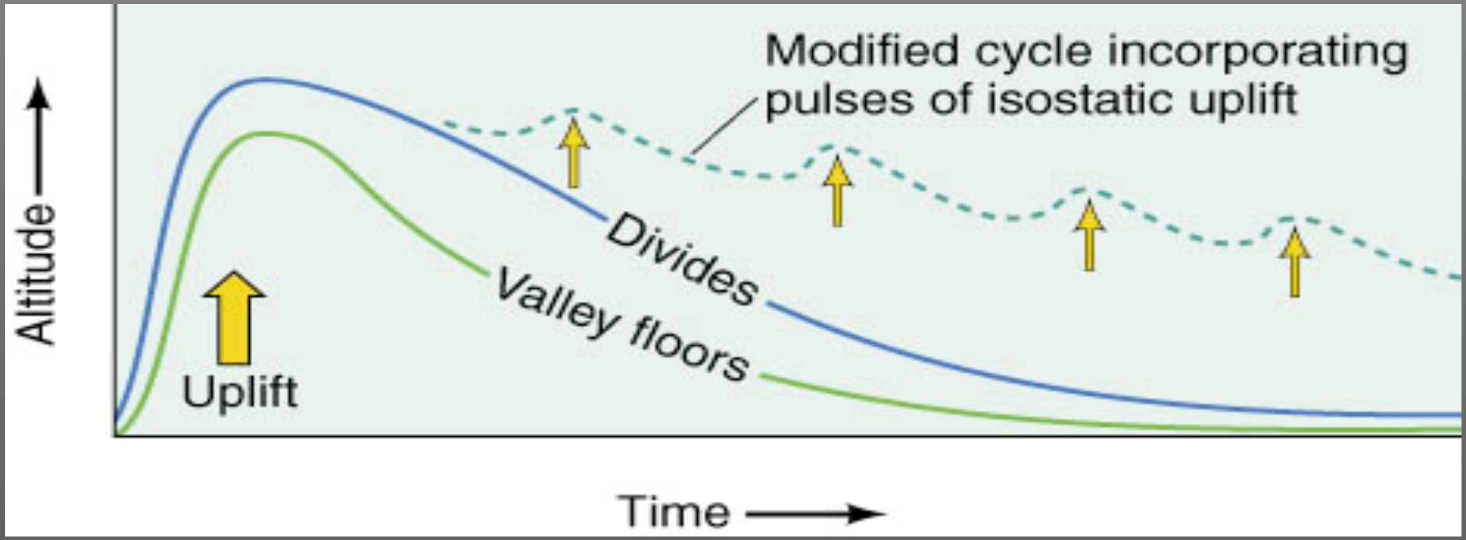


FIGURE 22.2.5 Fluvial incision rates and long-term erosion rates determined from apatite fission-track ages. The fluvial incision rates represent downcutting of the Clearwater River over a timeframe of ~100 ka, whereas the fission-track ages indicate erosion rates over a time frame of ~7 my. The similarity in rates suggests that the pattern and rates of erosion have been steady across this part of the forearc high. The black curve represents a smoothed version of the erosion rate distribution across the high. Integration of this curve indicates that the long-term erosional flux from the forearc high is ~51 km^2/my.

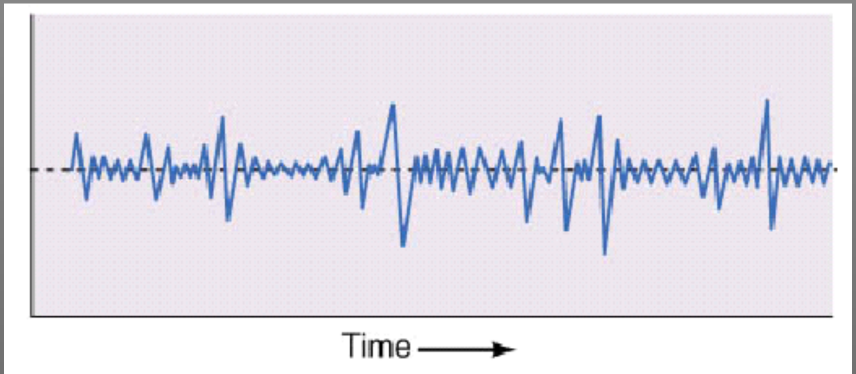
Models of uplift and erosion

- Davis cycle
  - Young landscape = high relief and v-shaped valleys
  - Old landscapes = low relief and broad flat valleys



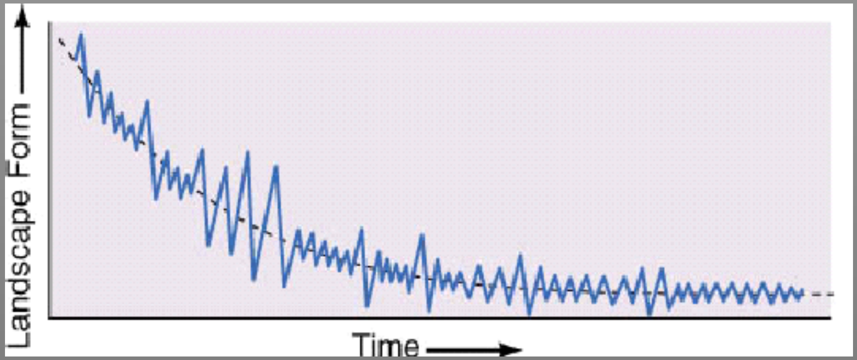
Models of uplift and erosion

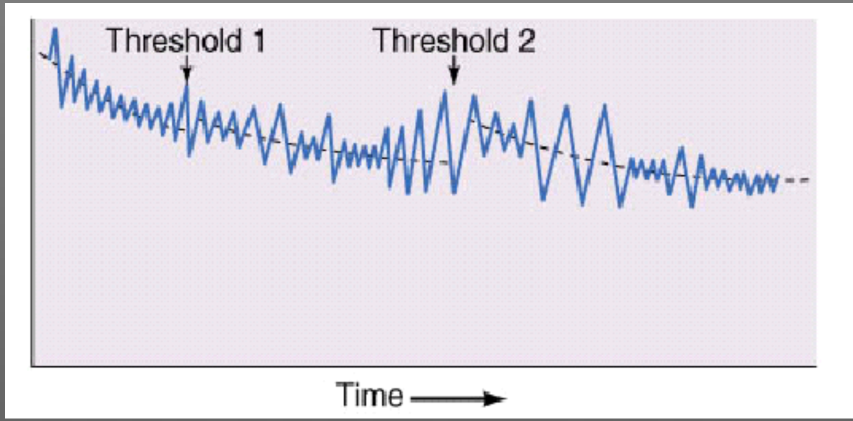
- Steady-State landscapes
  - Theory
    - Over time landscapes reach balance
    - Uplift = erosion
  - Reality
    - Changes in relief
      - Uplift events
      - Sea level change
    - Changes in erosion rates
      - Climate changes
      - Differing lithologies



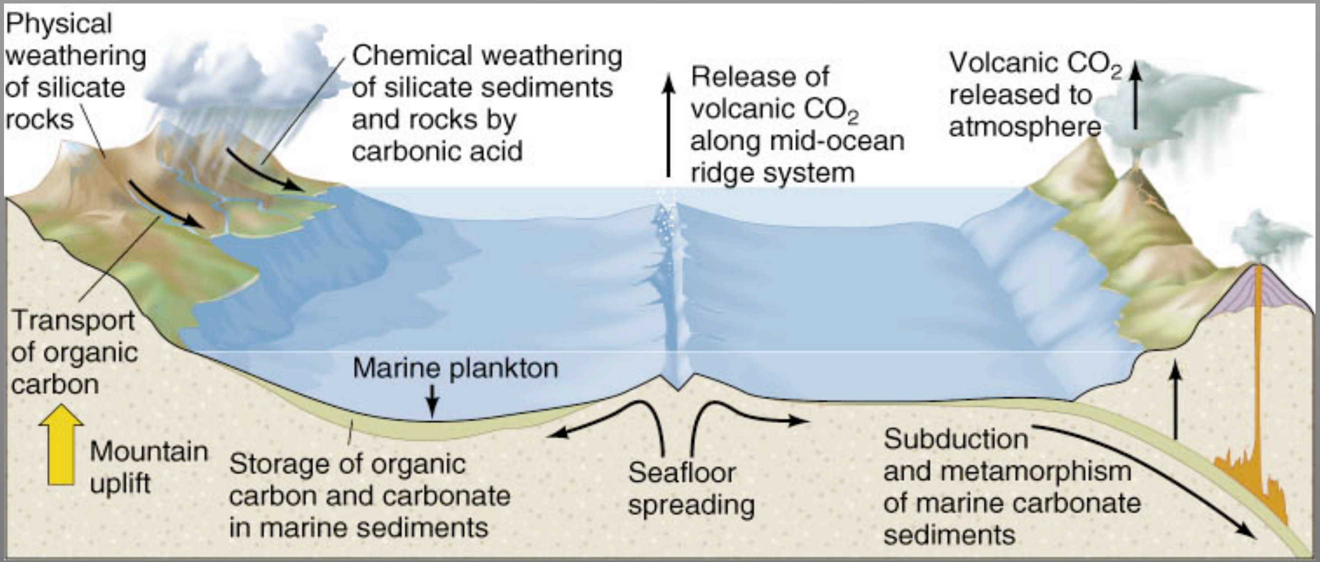
Models of uplift and erosion

- Dynamic equilibrium
  - More erosion or more uplift through time produces
  - Rapid landscape change
    - Small variations don't change the system but over time they accumulate till a THRESHOLD is reached and then the entire system shifts into a new regime





Climate and Plate Tectonics



- CO_2 sources
  - Volcanoes, metamorphism of carbon rich marine rocks
- CO_2 sinks
  - Silicate weathering
  - Organic carbon burial
- Climate change in last 40 my due to uplift?