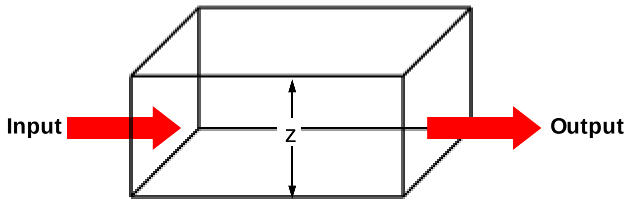
Goals of Today's Lecture

1. To review mass continuity principles applied to geomorphology
2. Establish the mechanisms that drive landscape uplift
3. Examine the linkages between the uplift of mountains, the development of topographic relief, and climate
4. Examine a class of landforms that are controlled primarily by local structural geology and igneous activities (if time permits; if not see textbook).

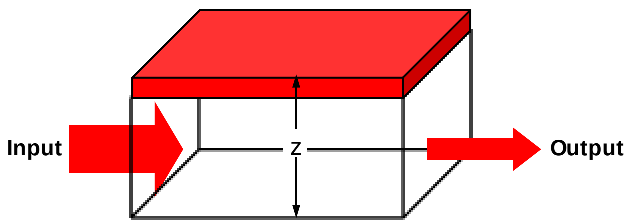
Review of Mass Continuity Applied to Geomorphology

Mass Continuity



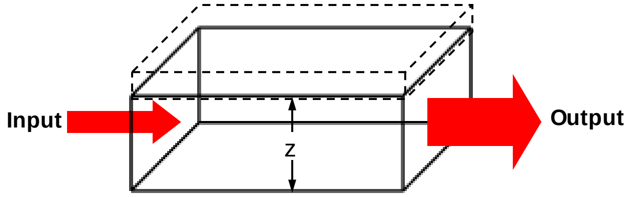
If I = O then ΔS = zero
So z is constant

Mass Continuity



If I > O then ΔS increases
So z must increase

Mass Continuity



If I < O then ΔS decreases
So z must decrease

Why are some landscapes bedrock dominated and others soil mantled?

Weathered material is stored on the landscape.

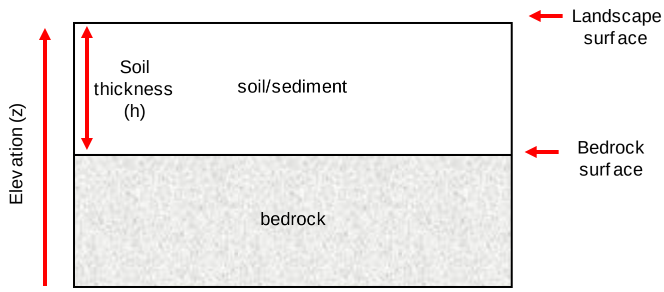
All weathered material is stripped from the landscape, with no storage.

Two types of landscapes

Soil mantled landscape

Bedrock landscape

Conservation of mass for a soil covered landscape

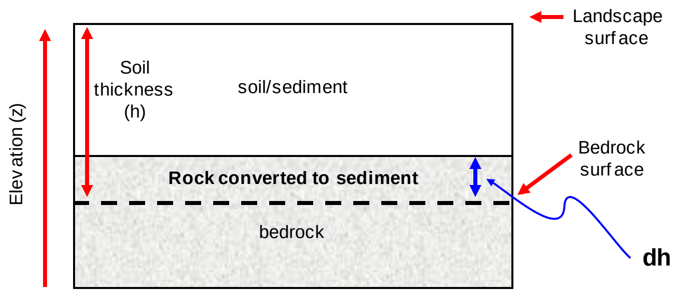


$$\frac{dz}{dt} = 0$$

Which means the change in elevation over some time period

$$\frac{\Delta z}{\Delta t} = 0$$

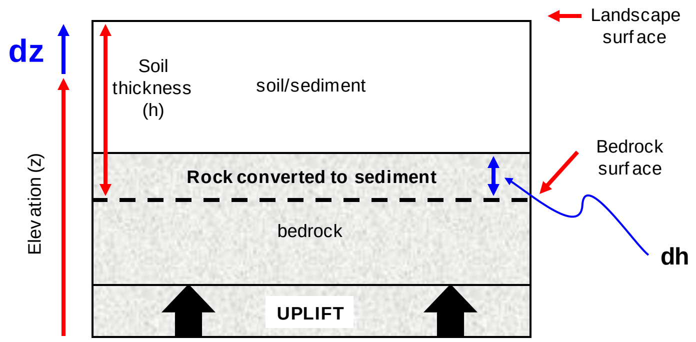
Conservation of mass for a soil covered landscape: Soil production



Weathering produces soil, thickening the profile.

$$P = \frac{\text{Converted Rock}}{dt} \qquad \frac{dz}{dt} = \frac{dh}{dt} - P$$

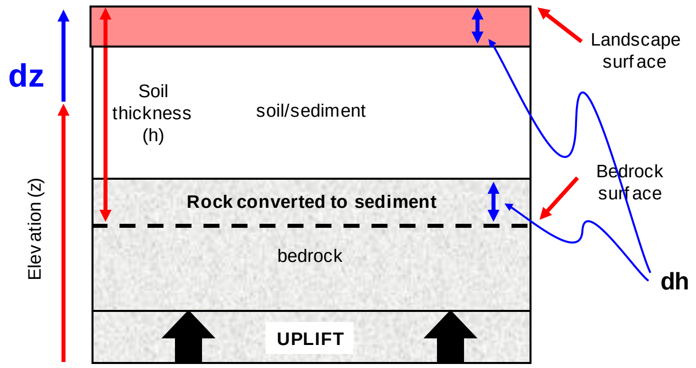
Conservation of mass for a soil covered landscape: Uplift



If the landscape also undergoes regional uplift:

$$U = \frac{\text{Uplift}}{dt} \qquad \frac{dz}{dt} = U + \frac{dh}{dt} - P$$

Conservation of mass for a soil covered landscape: Deposition



If there is deposition of material on the surface, by whatever process, dz and dh will increase further.

$$\frac{dz}{dt} = U + \frac{dh}{dt} - P$$

Remember this one!

Conservation of mass for a soil covered landscape: flux divergence

$$\frac{dz}{dt} = U + \frac{dh}{dt} - P$$

In order to make meaningful predictions of landscape evolution with this equation, we need to use physical laws to replace the soil thickness term (dh/dt).

We do this by writing the following expression:

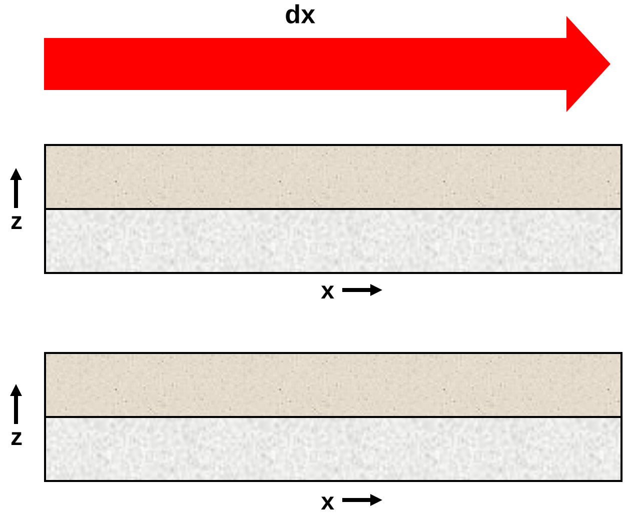
$$\frac{dh}{dt} = P - \nabla \cdot q_s$$

Remember this one!

The change in soil thickness with time is equal to the rate at which rock is converted to soil minus the change in sediment flux over a landscape element or the **sediment flux divergence**.

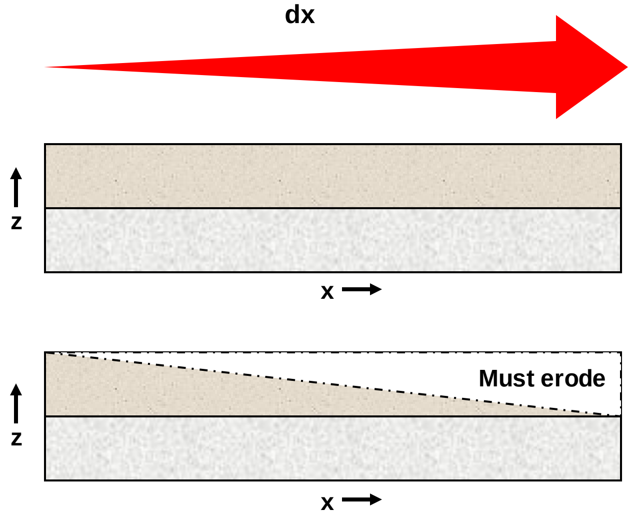
Divergence of Sediment Transport Rate

$$\frac{dq_s}{dx} = 0$$



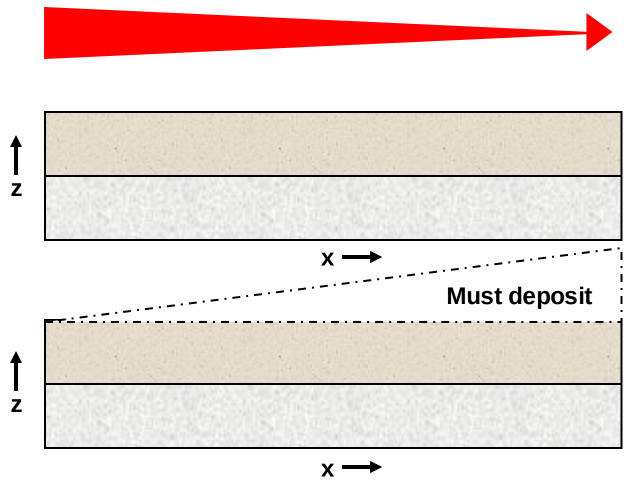
Divergence of Sediment Transport Rate

$$\frac{dq_s}{dx} > 0$$



Divergence of Sediment Transport Rate

$$\frac{dq_s}{dx} < 0$$



Limiting conditions in landscapes

If a landscape is completely covered by sediment, we can write:

$$\frac{dh}{dt} = P - \nabla \cdot q_s$$

Inserted into:

$$\frac{dz}{dt} = U + \frac{dh}{dt} - P$$

We get:

$$\frac{dz}{dt} = U - \nabla \cdot q_s$$

Remember this one!

This is a transport-limited landscape. Where the amount of material removed from the landscape is not controlled by the supply of new material from bedrock

How much bedrock is converted to soil/sediment is not important, because no bedrock is exposed at the surface!

Limiting conditions in landscapes

If bedrock is exposed at the surface of the landscape, the changes in the thickness of the soil are related to the transport rate:

$$\frac{dh}{dt} = - \nabla \cdot q_s$$

This is a weathering - limited landscape. Where the amount of material removed from the landscape is controlled by weathering processes

Inserted into:

$$\frac{dz}{dt} = U + \frac{dh}{dt} - P$$

We get:

$$\frac{dz}{dt} = U - P - \nabla \cdot q_s$$

Remember this one!

The rate of landscape erosion becomes dependent on the rate at which bedrock is converted to soil/sediment

Limiting conditions in landscapes

If bedrock is exposed at the surface of the landscape, the changes in the thickness of the soil are related to the transport rate:

$$\frac{dz}{dt} = U - P - \nabla \cdot q_s$$

This is a detachment - limited landscape. Where the amount of material removed from the landscape is controlled by weathering processes and corrasion by flows

But, if the bedrock at the surface is exposed to flow (water, ice, sediment)

$$\frac{dz}{dt} = U - P - W - \nabla \cdot q_s$$

Remember this one!

or

$$\frac{dz}{dt} = U - E - \nabla \cdot q_s$$

Remember this one!

The rate of landscape erosion becomes dependent on the rate at which bedrock is converted to soil/sediment and the rate at which it is worn down by flows (corrasion)

Types of landscapes

Transport-limited landscape: Where the amount of material removed from the landscape is not controlled by the supply of new material from bedrock

$$\frac{dz}{dt} = U - \nabla \cdot q_s$$

Weathering-limited landscape: Where the amount of material removed from the landscape is controlled by weathering processes

$$\frac{dz}{dt} = U - P - \nabla \cdot q_s$$

Detachment-limited landscape: Where the amount of material removed from the landscape is controlled by weathering processes and corrasion by flows

$$\frac{dz}{dt} = U - P - W - \nabla \cdot q_s$$

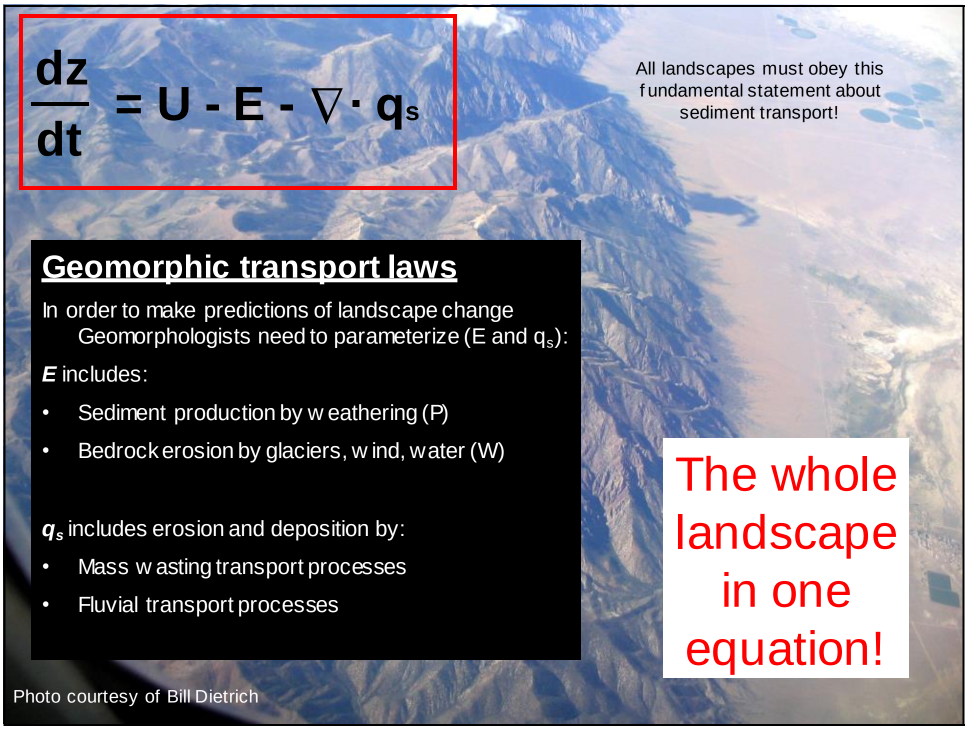
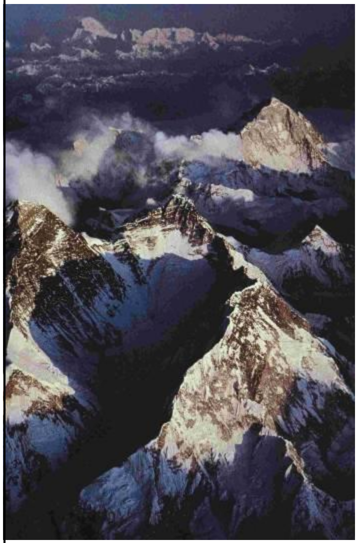


Photo courtesy of Bill Dietrich

Mechanisms that drive landscape uplift

What controls the height and width of mountains?



Himalayas

Cerro do Mar, Brazil

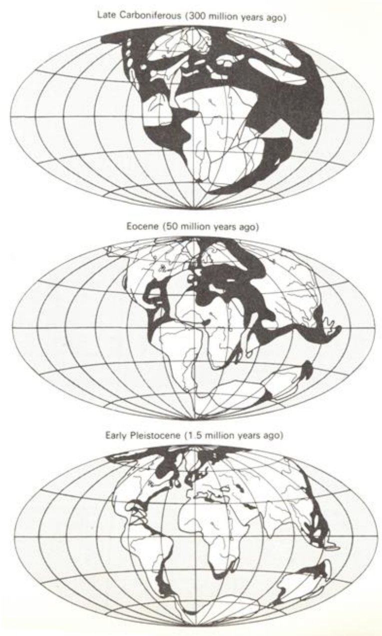
Theory of Plate Tectonics

1. Wegner's continental drift hypothesis
2. Plate convergence and spreading
3. Mantle convection cells

Continental Drift

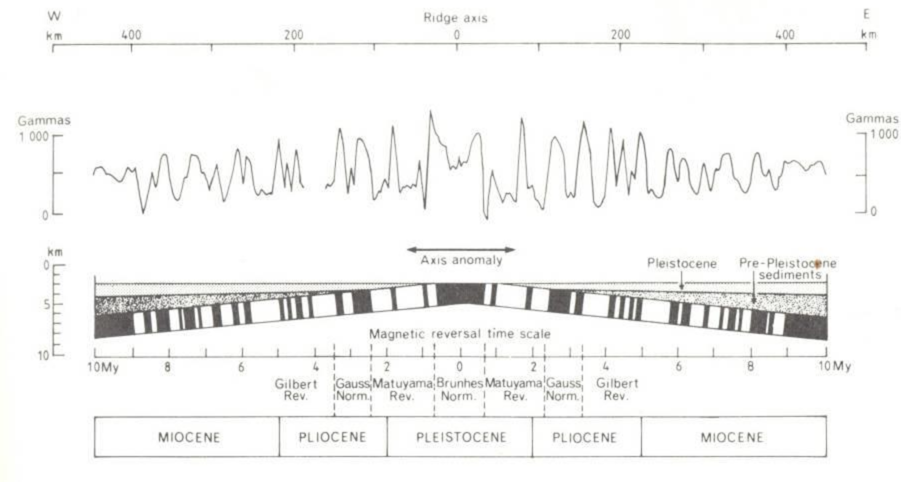
Concept proposed by Alfred Wegner (*The origins of Continents and Oceans*, 1937) to explain glacial history of the southern continents. In particular, he was intrigued by tropical fossils found in Antarctica.

Wegner's theory was based on the apparent 'fit' between S. America and Africa, the similarity of rock formations on either side of the Atlantic and glacial groves carved in rocks in the tropics.



Selby, 1985, pg. 40

Further evidence of Continental Drift: Sea Floor Spreading

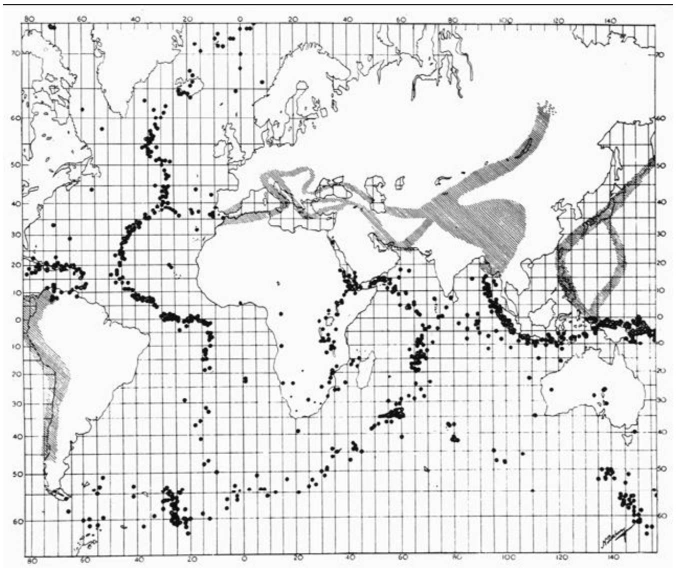


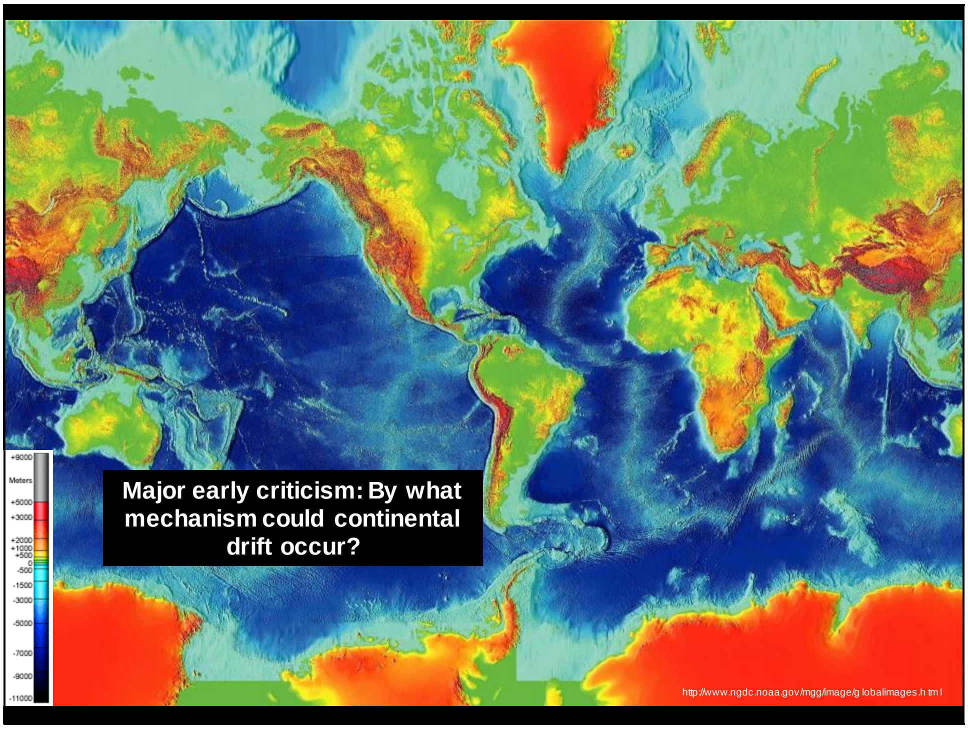
Magnetic anomalies along Pacific-Antarctic Oceanic Ridge (Selby, 1985)

Further evidence of Continental Drift: Earthquake distribution

Concentration of earthquakes along plate boundaries.

J.P. Rothé (1954, Royal Society of London)



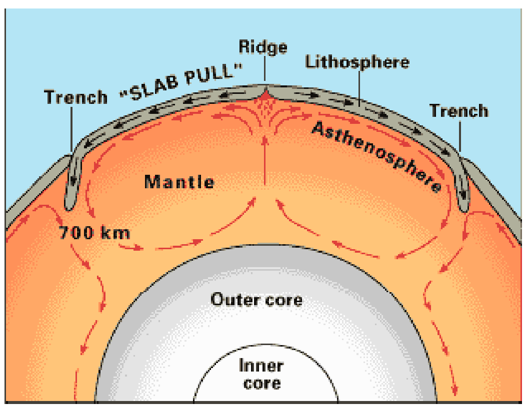


Mantle convection

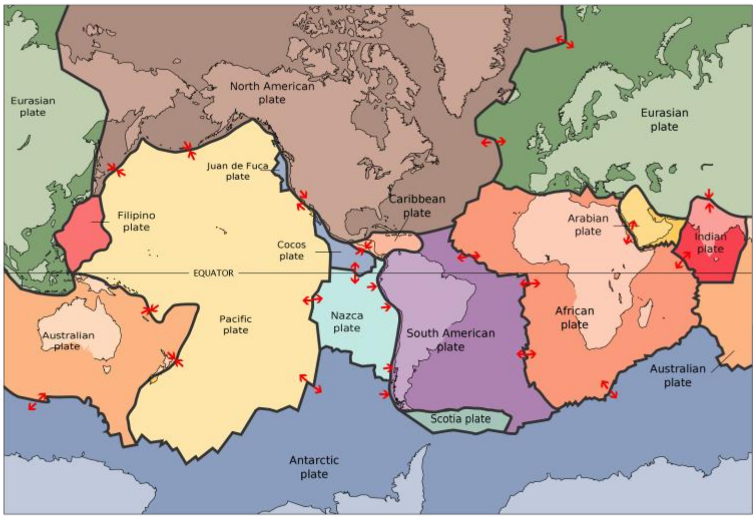
In the early 1960's Harry Hess of Princeton University suggested the magma that composed the mantle undergoes convection.

Convection is the process where heated fluid rises and cooled fluid falls. This establishes convection cells in the mantle.

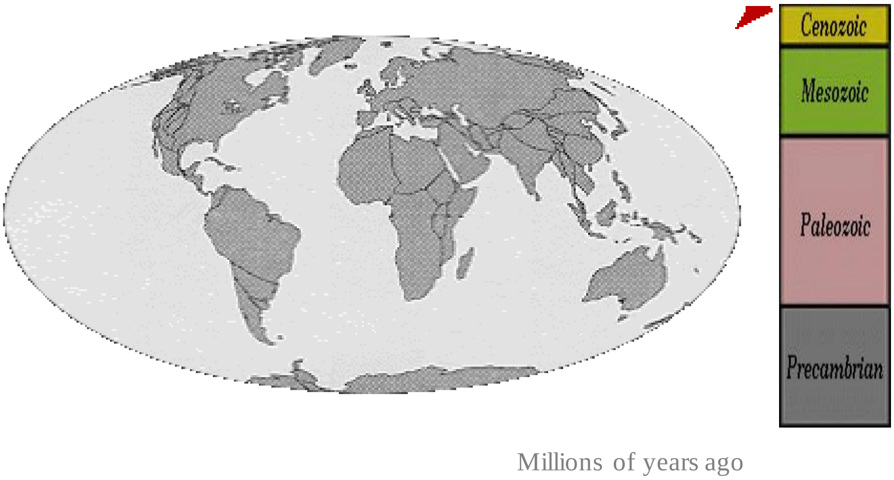
Spreading plates form at rising limbs of convection cells and convergent boundaries are formed by magma that has cooled after a trip to the surface.



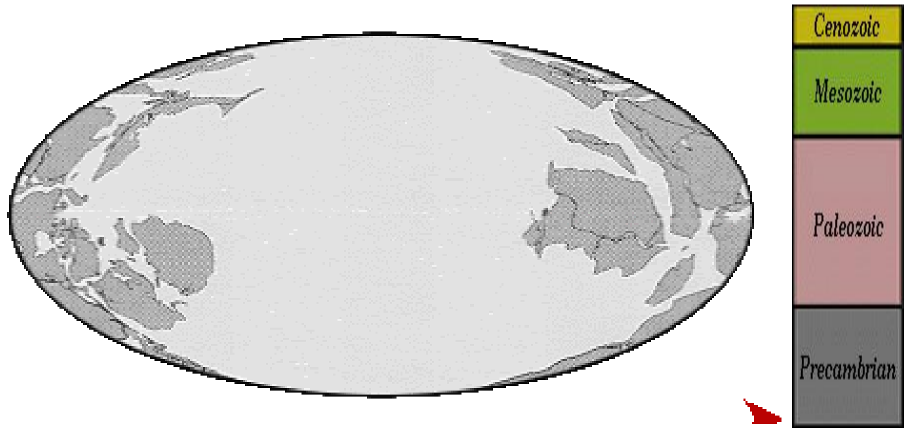
Modern Plate Tectonics



Surface of Earth is composed of moving internally rigid plates which separate at divergent zones (spreading) and meet at convergent zones (subduction and mountain building)



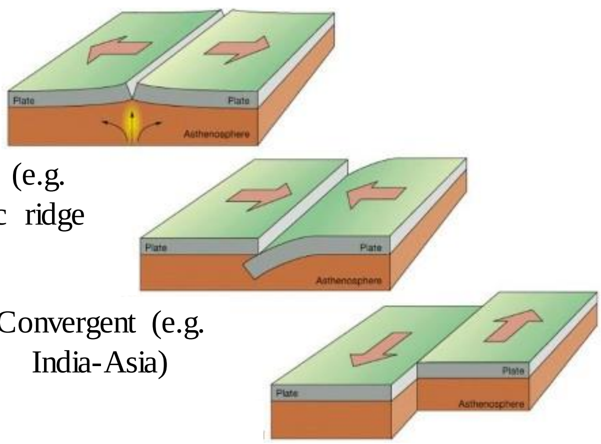
http://www.ucmp.berkeley.edu/geology/tectonics.html



Millions of years ago

http://www.ucmp.berkeley.edu/geology/tectonics.html

Types of tectonic plate boundaries



Divergent (e.g. mid-Atlantic ridge

Convergent (e.g. India-Asia)

Transverse (e.g. San Andreas Fault)

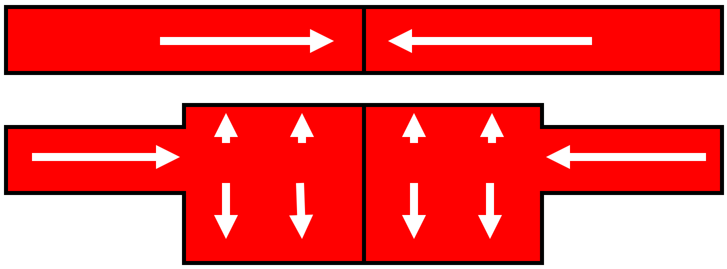
Which one forms mountains?

What controls rates of uplift?

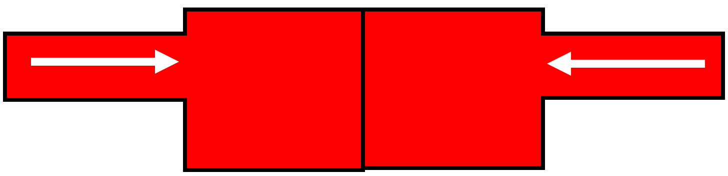
The classical view of orogen development suggests that uplift is controlled by mantle convection cells.

But recent work has suggested this is insufficient to produce increases in topographic relief!

It can be shown mathematically that two colliding continents will force a thickening of the crust. But a large portion of that thickening builds a mountain root.

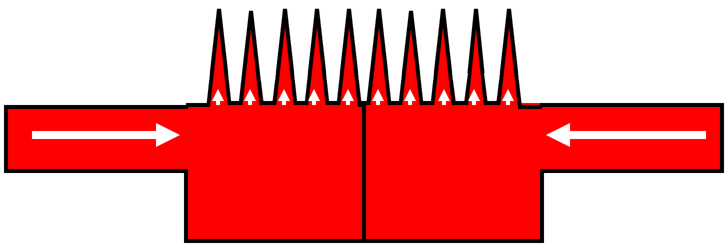


What controls rates of uplift?

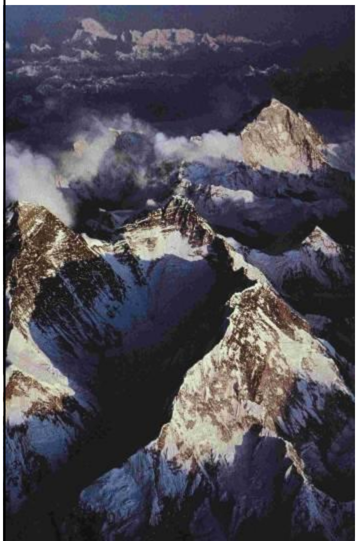


A simple force balance shows that the orogen will become static. Uplift will cease unless something unbalances the system.

Mantle convection forces are rather static, but erosion of the land mass will allow buoyant forces to lift the landscape surface!



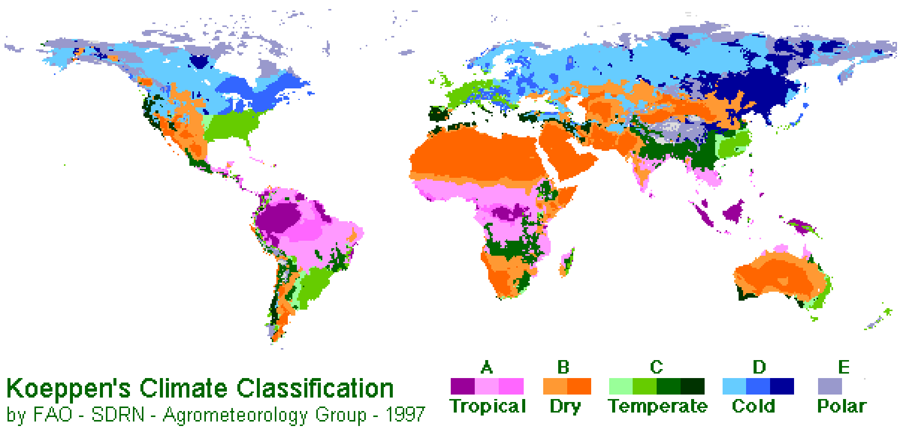
What controls the height of mountains?



Himalayas

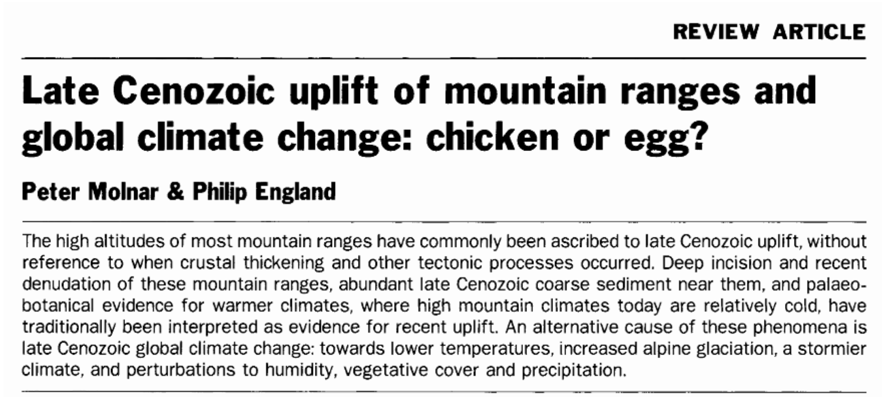
Cerro do Mar, Brazil

What controls erosion rates?



Climate controls amount of runoff, temperature influenced geochemical reactions, freezing and thawing, influence of wind, and the amount of biotic activity.

This week's reading



REVIEW ARTICLE

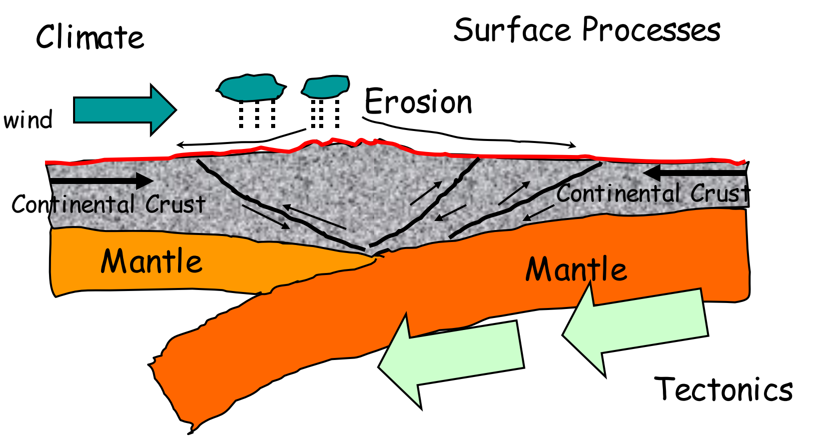
Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg?

Peter Molnar & Philip England

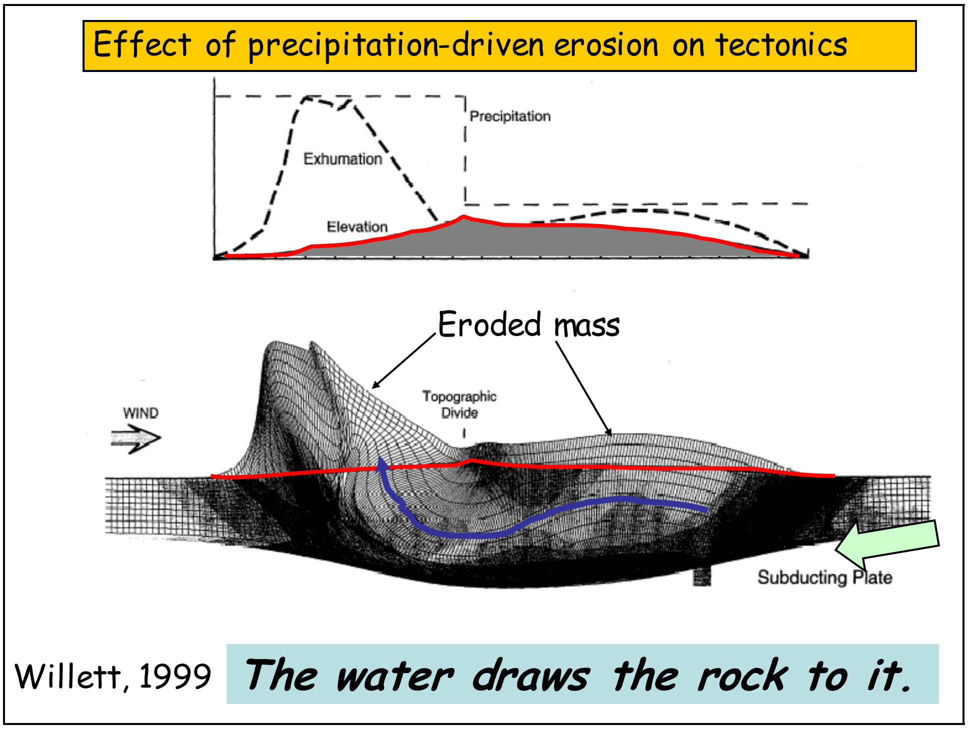
The high altitudes of most mountain ranges have commonly been ascribed to late Cenozoic uplift, without reference to when crustal thickening and other tectonic processes occurred. Deep incision and recent denudation of these mountain ranges, abundant late Cenozoic coarse sediment near them, and palaeo-botanical evidence for warmer climates, where high mountain climates today are relatively cold, have traditionally been interpreted as evidence for recent uplift. An alternative cause of these phenomena is late Cenozoic global climate change: towards lower temperatures, increased alpine glaciation, a stormier climate, and perturbations to humidity, vegetative cover and precipitation.

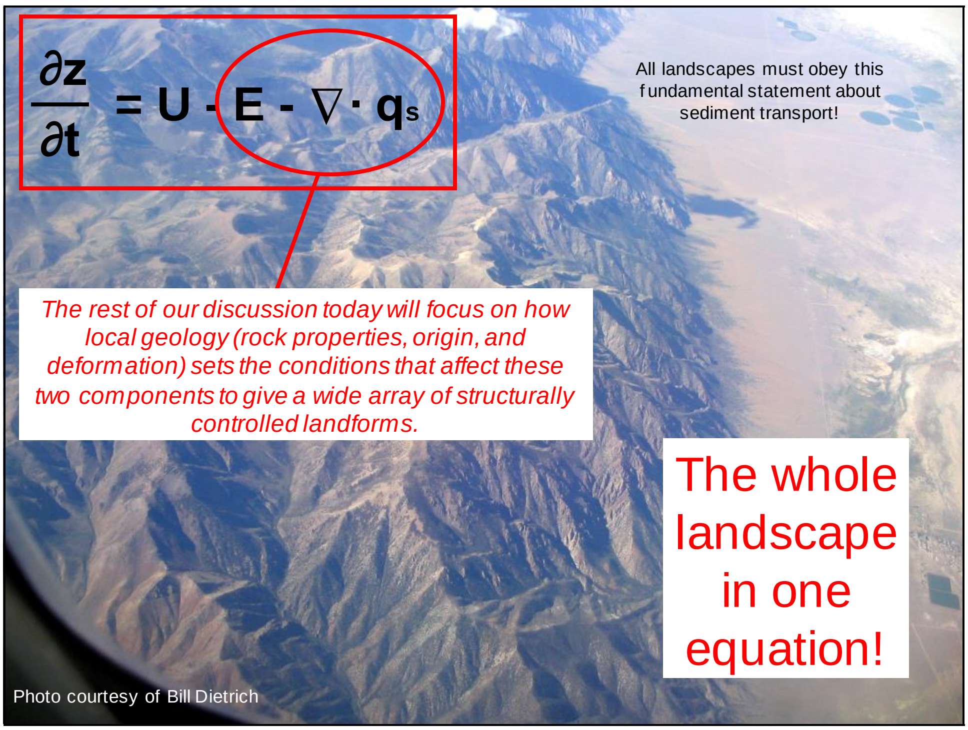
First research article to draw the explicit link between climate and mountain uplift.

Evidence from numerical modeling: Linkages among climate, tectonics, surface processes and topography



Modified from Willett, 1999. JGR


Effect of precipitation-driven erosion on tectonics
Precipitation
Exhumation
Elevation
Eroded mass
Topographic Divide
WIND
Subducting Plate
Willett, 1999
The water draws the rock to it.


$\frac{\partial z}{\partial t} = U - E - \nabla \cdot q_s$
All landscapes must obey this fundamental statement about sediment transport!
The rest of our discussion today will focus on how local geology (rock properties, origin, and deformation) sets the conditions that affect these two components to give a wide array of structurally controlled landforms.
The whole landscape in one equation!
Photo courtesy of Bill Dietrich

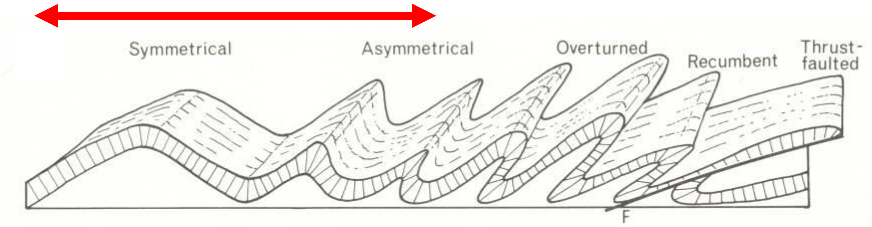
Expressions of Tectonics
at Earth's Surface

Expressions of Tectonics at Earth's Surface

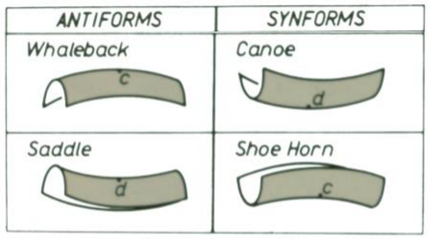
- Tectonics provides the mechanisms for mega-scale mountain uplift, but at the scale of individual mountains or groups of mountains, there are distinctive expressions of tectonic activity that control land form.
- These expressions include ***faults*** and ***folds***, which may have been altered by erosion since tectonic activity.
- Another control on local scale landscape evolution is igneous activity which includes various types of ***volcanoes***, ***lava flows***, and ***intrusion of plutons*** that may be exposed at earth's surface by erosion.
- Together, these expressions of tectonic activity enforce a first order control on the landscape at the local scale.

Definitions: Types of Folds

Anticline



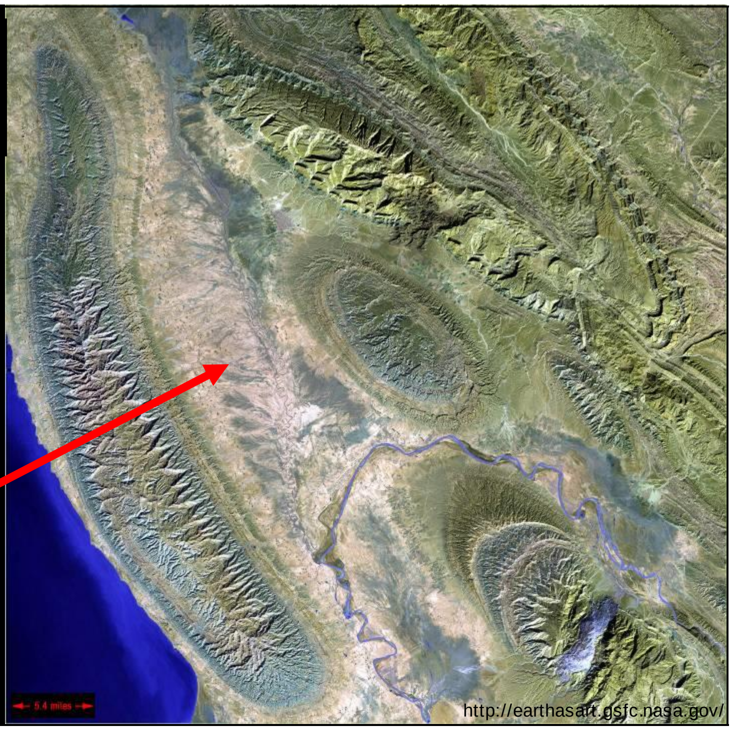
Syncline



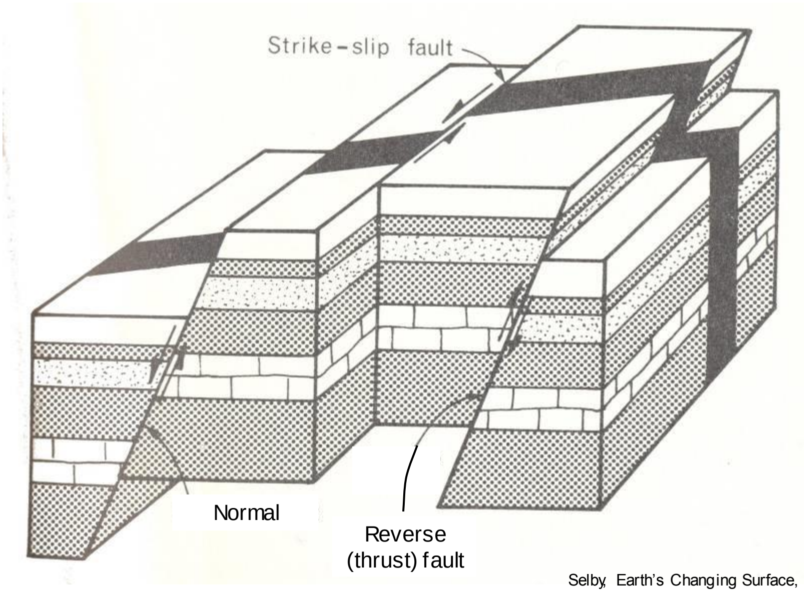
Selby, Earth's Changing Surface, 1985.

Anticlines exposed by erosion Zagros Mountains, Iran.

Syncline filled with sediments

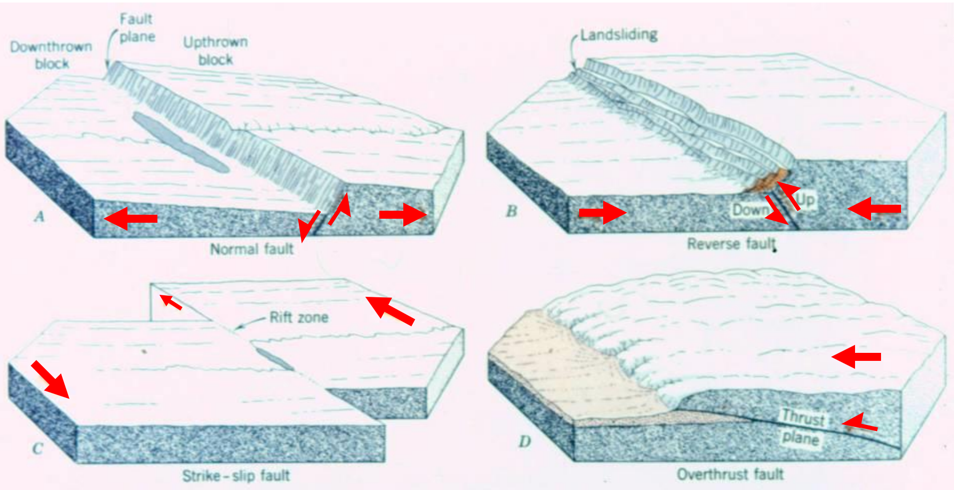


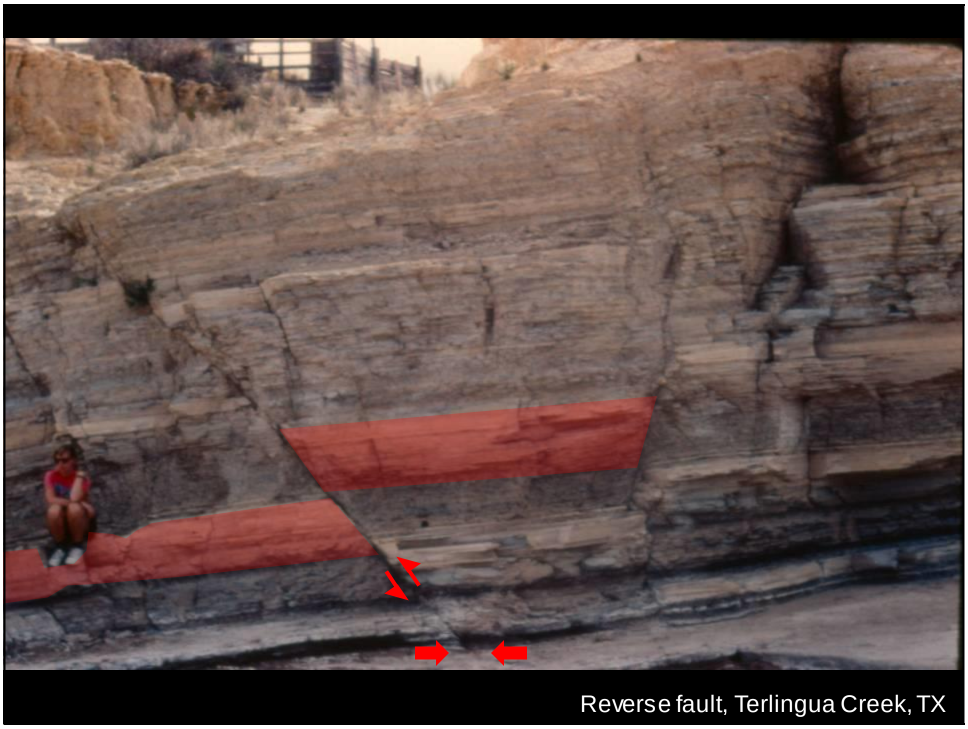
Definitions: Types of faults

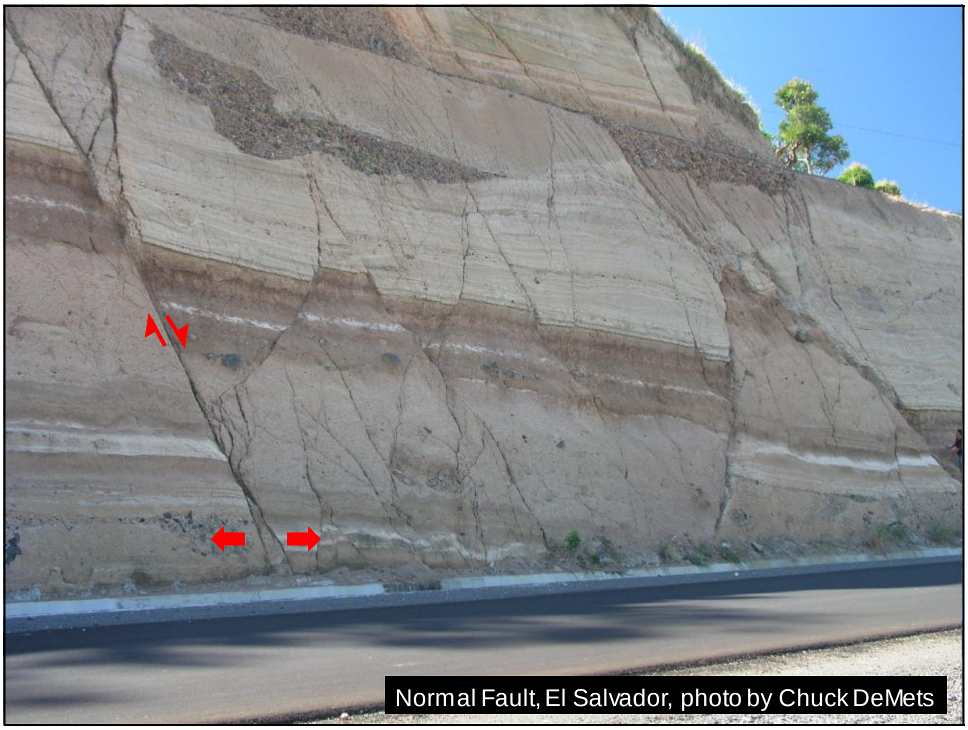


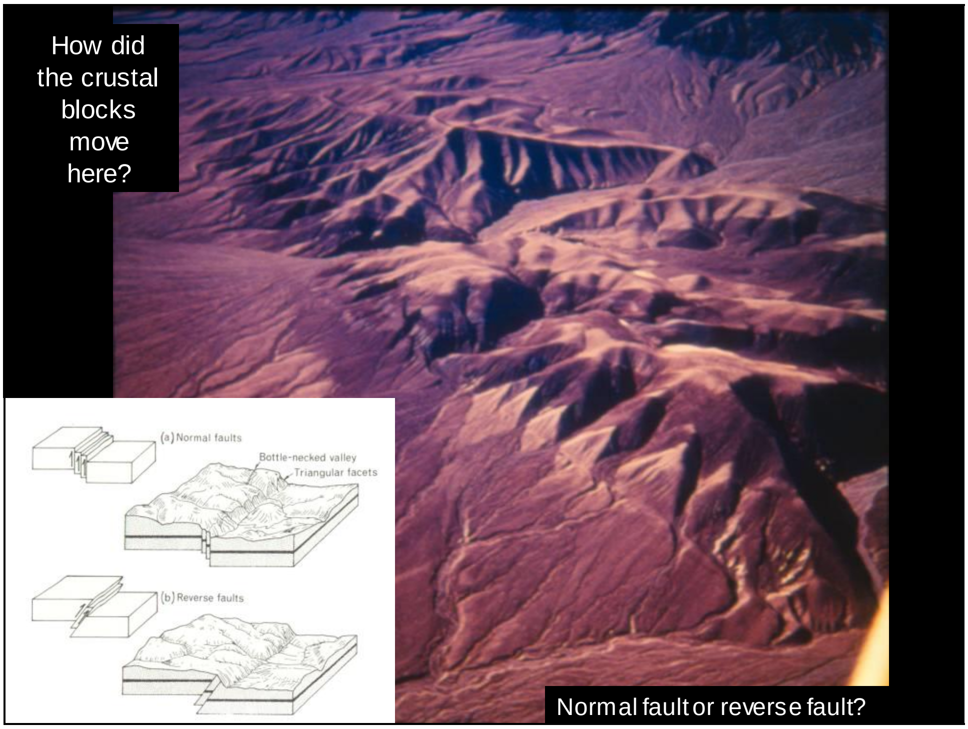
Selby, Earth's Changing Surface, 1985.

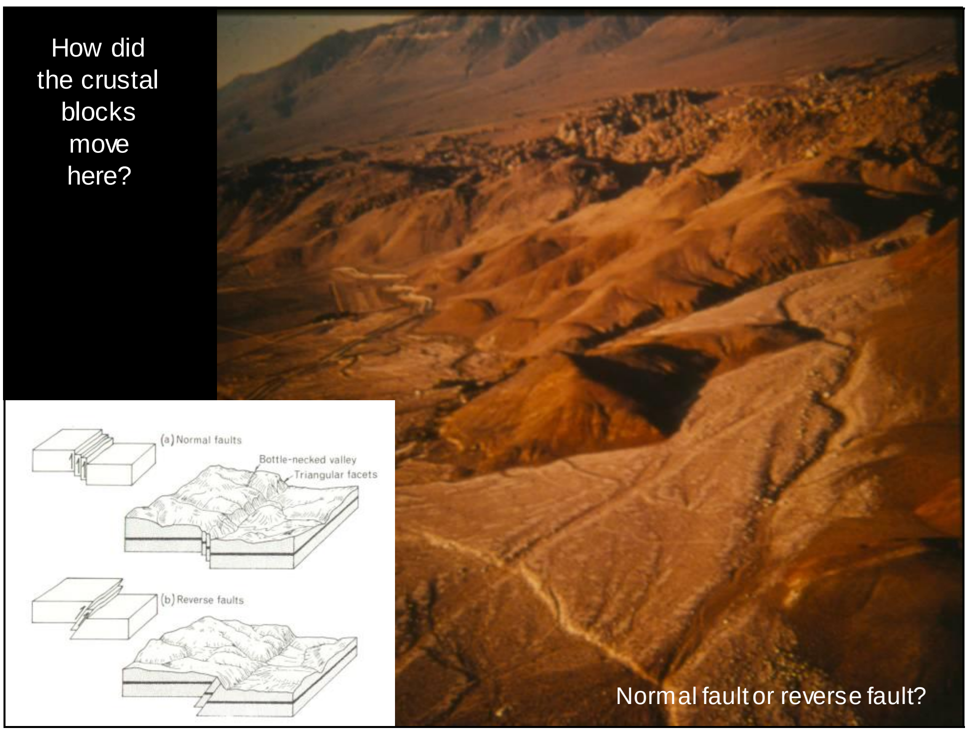
Definitions: Types of faults




Reverse fault, Terlingua Creek, TX


Normal Fault, El Salvador, photo by Chuck DeMets

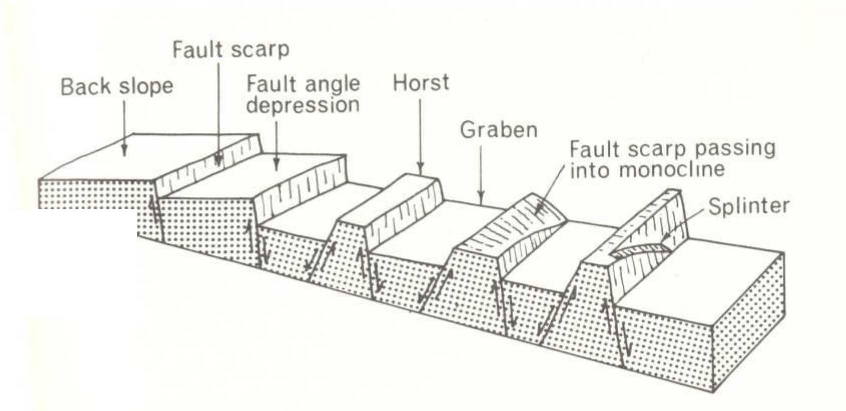

How did the crustal blocks move here?
(a) Normal faults
Bottle-necked valley
Triangular facets
(b) Reverse faults
Normal fault or reverse fault?


How did the crustal blocks move here?
(a) Normal faults
Bottle-necked valley
Triangular facets
(b) Reverse faults
Normal fault or reverse fault?

Strike-slip fault, San Andreas. CA

Overthrust fault, Near Banff, AB

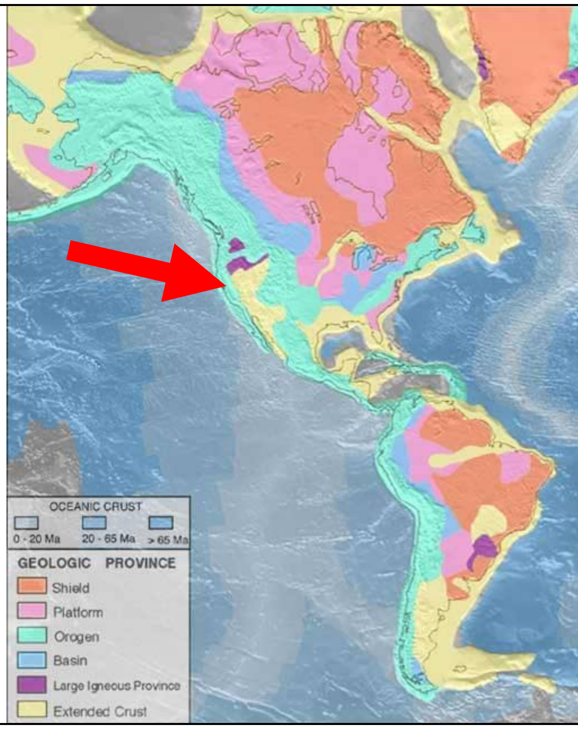
Combinations of faults: Horst and Grabens

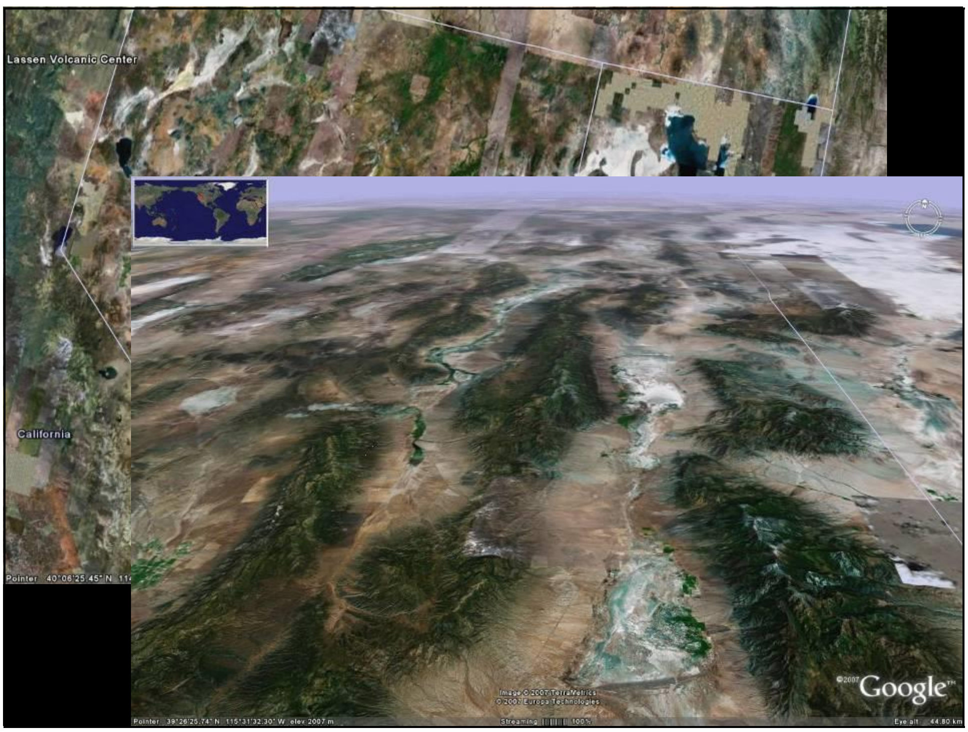


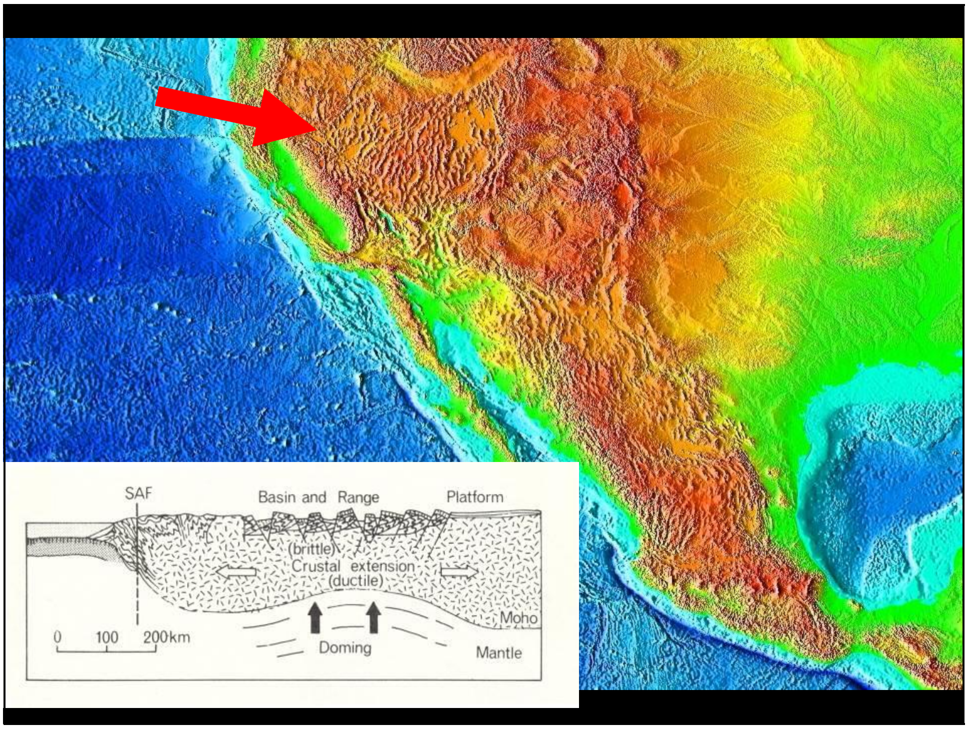
Basin and Range Geologic Province

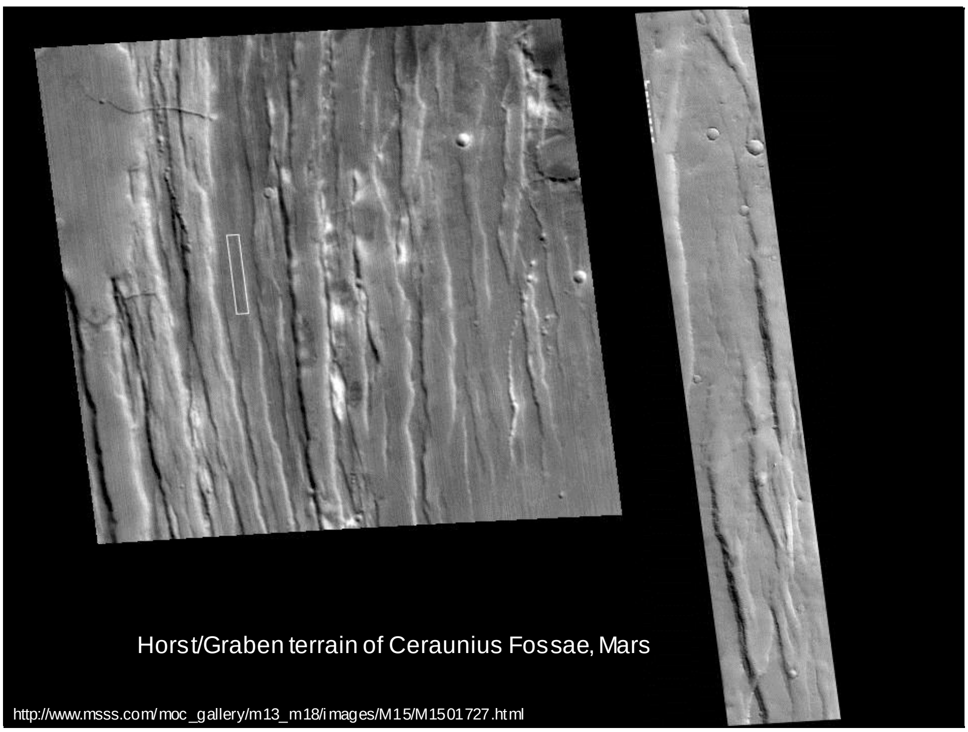
Portion of western NA plate crust that has undergone extension and upwarping

Composed a horst/graben field that covers most of the western desert and includes the Great Basin









Horst/Graben terrain of Ceraunius Fossae, Mars

http://www.msss.com/moc_gallery/m13_m18/images/M15/M1501727.html

Expressions of Igneous Activity at Earth's Surface

Surface Expression of Igneous Activity

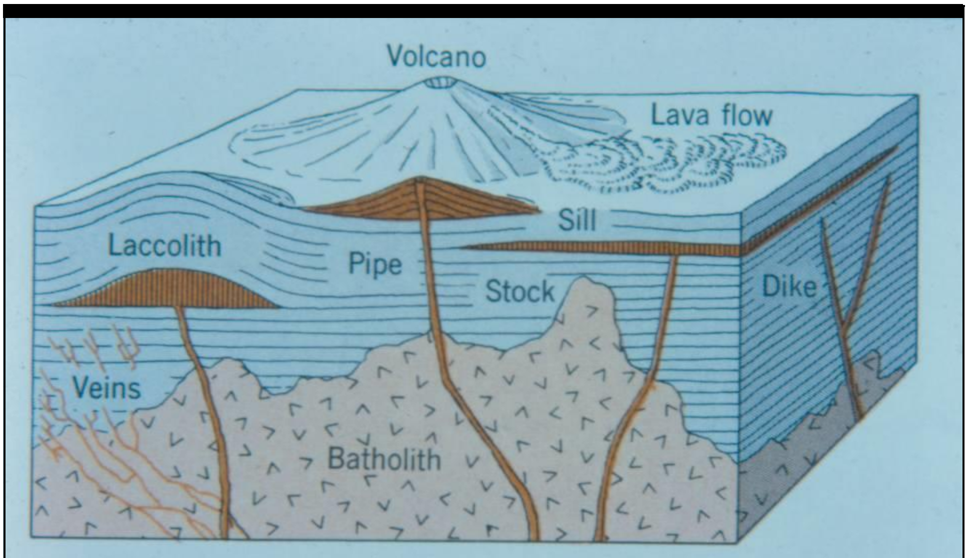
As geomorphologists, we are primarily interested in the shapes produced by volcanic activity at the earth's surface.

Puu Oo, a type of spatter cone, Kilauea, Hawaii

Types of Surface Expression of Igneous Activity

1) Extrusive: volcanic or depositional landforms
   - Lava flows, ejecta, ash, volcanoes

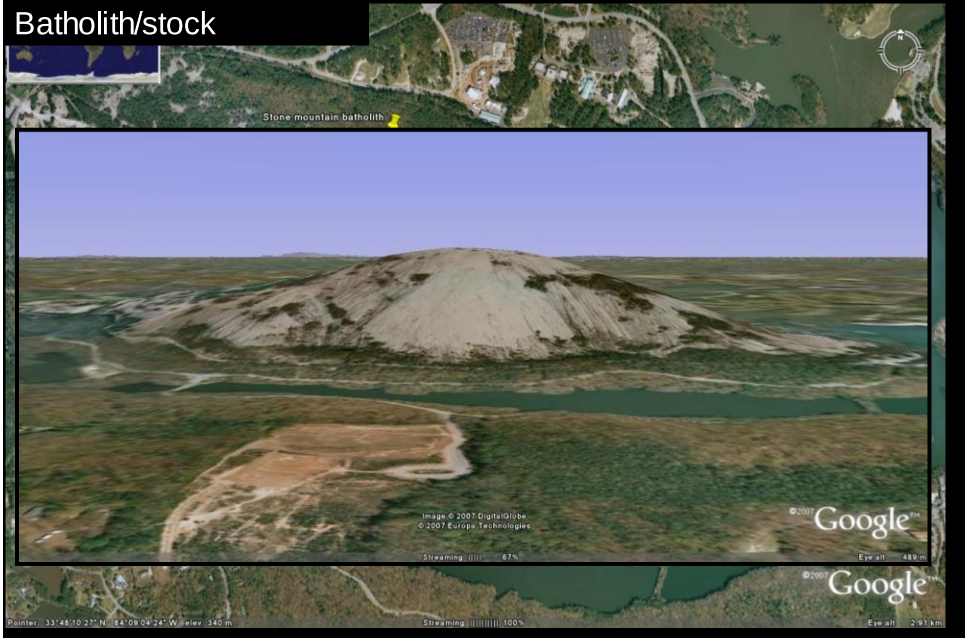
2) Intrusive: igneous landforms exposed by erosion
   - Batholiths, domes, dykes, sills



Igneous rock bodies.

Magma that was forced to surface and cooled is **extrusive**.
Magma rose within the crust and cooled is **intrusive**.

Batholith/stock



Stone mountain, GA

Dike

Volcanic neck with radiating dike, Shiprock, NM

Types of extrusion

1. **Lava flows**
2. **Pyroclastics**
3. **Ashflows**

Most extrusions are some combination of all three types of flow

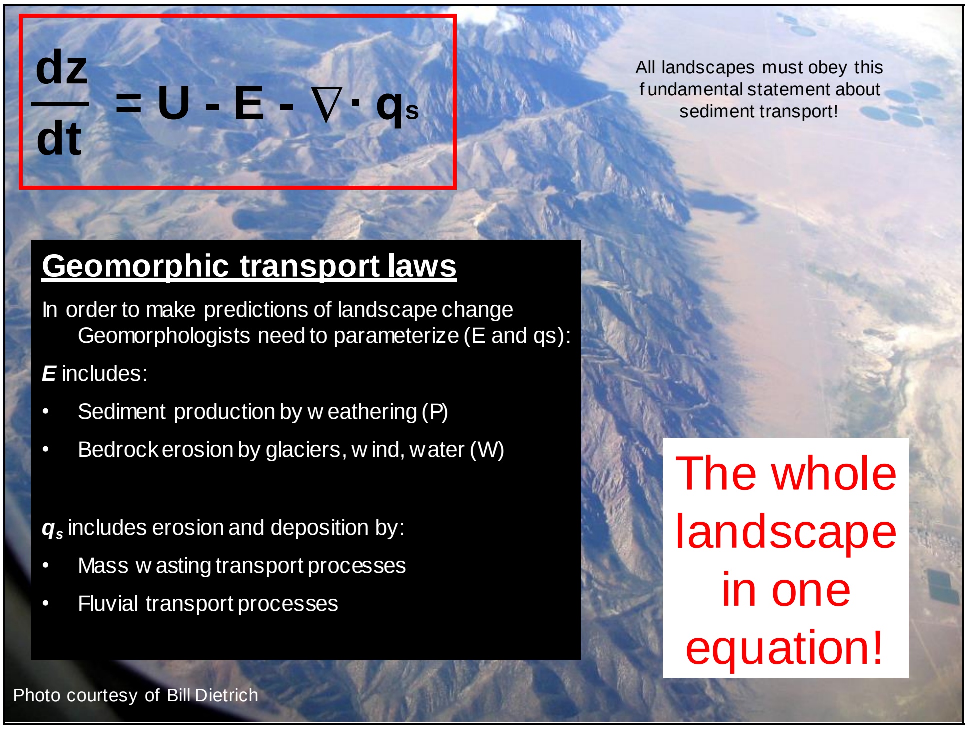
Pyroclastic flows descend the south-eastern flank of Mayon Volcano, Philippines

What controls the surface expression of volcanism?

Characteristics of the magma

1. ***Composition of magma:*** Silica content controls the viscosity of the magma and, consequently likelihood that lava will flow and explosiveness. Basalt 50% SiO_2; Andesitic 60% SiO_2; Rhyolitic 70% SiO_2). More SiO_2 makes or more viscous flows
2. ***Magma Temperature:*** Also controls viscosity; hotter magma is less viscous. Melting point of Basalt → 1100ºC. Melting point of Rhyolite → 650-700ºC.
3. ***Gas Content:*** Controls explosiveness and, ultimately, deposition patterns and flow types

Geomorphology of lava flows


$\frac{dz}{dt} = U - E - \nabla \cdot q_s$
All landscapes must obey this fundamental statement about sediment transport!
Geomorphic transport laws
In order to make predictions of landscape change Geomorphologists need to parameterize (E and qs):
E includes:
• Sediment production by weathering (P)
• Bedrock erosion by glaciers, wind, water (W)
q_s includes erosion and deposition by:
• Mass wasting transport processes
• Fluvial transport processes
The whole landscape in one equation!
Photo courtesy of Bill Dietrich