Goals of Today's Lecture

1. Major themes through the history of Geomorphology
2. Review major trends in modern Geomorphology
3. To discuss some of the fundamental principles of modern Geomorphology
4. To introduce the concept of mass continuity as applied to landscapes

Major themes through the history of Geomorphology

Early contributions to geomorphology

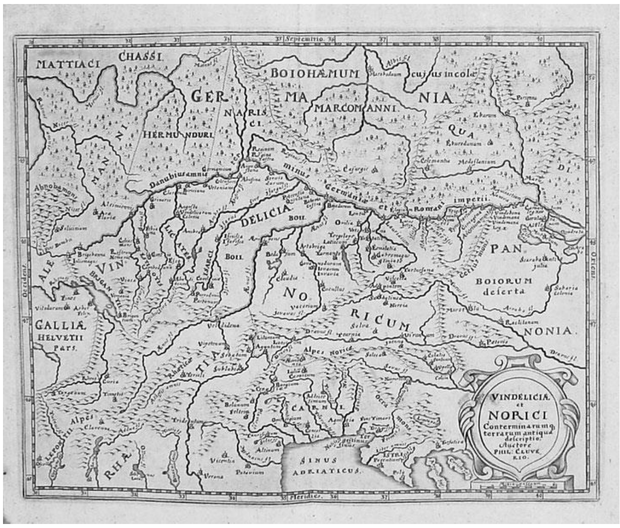
Leonardo da Vinci (1452-1519) studied the topography of the Arno River basin, drew the first contour map of a whole river basin, and believed that rivers carved their valleys and shaped topography.

Italian and French hydraulic engineers developed the study of rivers in the late 17th century to address flooding problems along rivers draining the Alps.

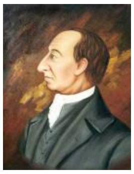
Della Natura de' Fiumi
"The Nature of Rivers"

First Book on Rivers was published by Domenico Gugleilmini in 1697.

The book discusses the nature of rivers and their parts, the motion of water, confluents and estuaries, banks, and materials and application.

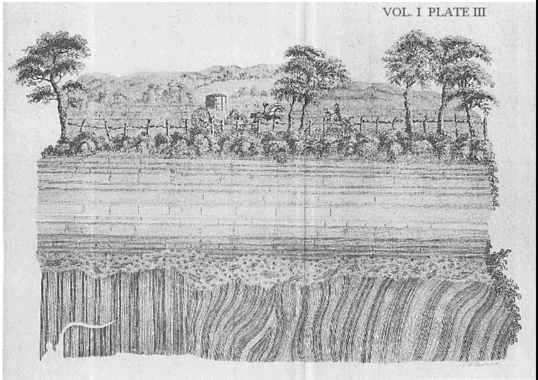


Early contributions: James Hutton



Wrote *Theory of the Earth* in 1795 where he laid the foundation of many of the fundamental principles of Geology. He included chapters on uplift, erosion, and consolidation of rock.

Unfortunately, he did not communicate his ideas very effectively, so they didn't catch on!



See for yourself:
Book 1 of 4 at http://www.gutenberg.org/files/12861/12861-h/12861-h.htm
Book 2 of 4 at http://www.gutenberg.org/files/14179/14179-h/14179-h.htm

Uniformitarianism & catastrophism

Earth 19th century geomorphology was dominated by discussion of whether the landscape evolved (very Darwinian) or whether it was formed by biblical floods. Charles Darwin is thought to have developed his ideas about natural selection and evolution from these discussions.

Uniformitarianism: theory that slow geological processes have occurred throughout the Earth's history and are still occurring today.

Catastrophism: theory that Earth's features formed in single, catastrophic events and remained unchanged thereafter (biblical floods).

By the end of the 19th Century and through most of the 20th century uniformitarianism was accepted and catastrophism was largely rejected.

Yet, the debate continues in some form today where geomorphologists are still piecing together the history of various landscapes across the earth.

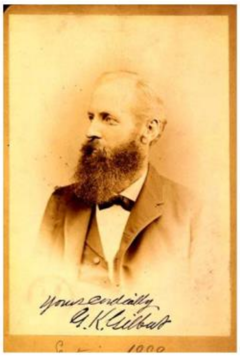
Key contribution:
Charles Lyell, Principles of Geology, published in three volumes in 1830-33

Early 20th century process geomorphology

Geomorphologists first started writing about the connection between geology, **landscapes and the processes that formed them** in surveys of Western North America.

G.K. Gilbert was first to describe the processes that caused landscape evolution. His work systematically discussed **weathering** and **bedrock erosion** (debris production mechanisms) as well as **erosion** and **transport** of sediments in the landscape.

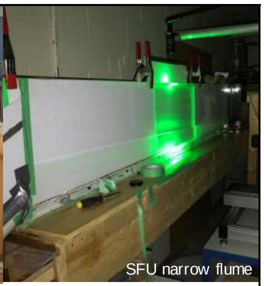
Gilbert linked together climate, erosion and topography, considered how sediments are moved through drainage basins and even did flume experiments.



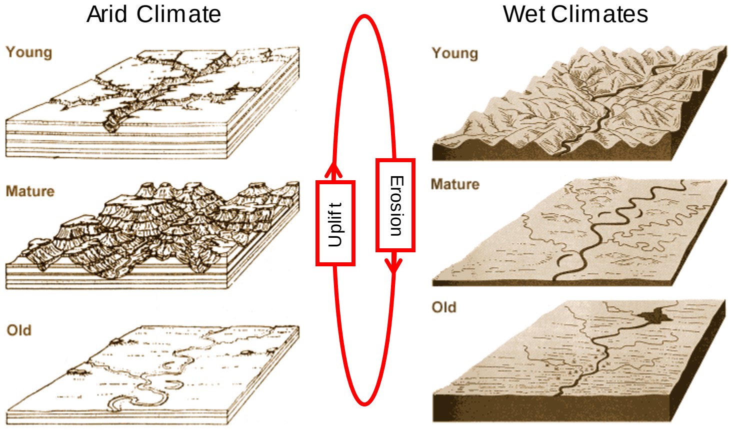
Contributions:
Report on the Geology of the Henry Mountains (1877)
The Transportation of Debris by Running Water (1914)
Hydraulic-Mining Debris in the Sierra Nevada (1917).

Gilbert’s Flume at UC Berkeley

The Transportation of Debris by Running Water (1914)



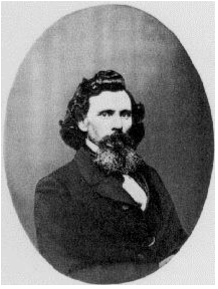
Early 20th century descriptive geomorphology (Geographical Cycle)



Contributions: William Morris Davis, 1889, *The rivers and valleys of Pennsylvania, National Geographic*; William Morris Davis, 1899, *The geographical cycle,* Geographical Journal.

Movie: The Work of Rivers (1935)

Very Davisian!



William Morris Davis

Descriptive geomorphology fell out of favor in the mid-20th century and was replaced by quantitative, process-based geomorphology. This first occurred in aeolian (wind), fluvial (river), and coastal (beach) geomorphology. It later occurred in hillslope geomorphology with the development of computer simulations. More recently it has happened in glacial (ice) geomorphology when glaciologists started to care about predicting landscape evolution.

Return to Catastrophism: J. Haren Bretz and the Channeled Scablands (1920s – now)

Mid-20th century frequency and magnitude of geomorphic processes

There is a competition between the Frequency and Magnitude of geomorphic events

The most frequent events do not do the greatest amount of work (not surprising)

The largest events do the lots of work, but they are infrequent.

Moderately sized transport events do the most geomorphic work in the landscape as a consequence of the frequency of moderate sized events

Persistence wins!

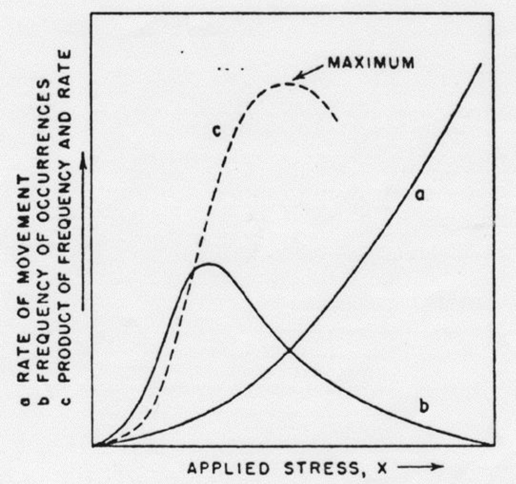


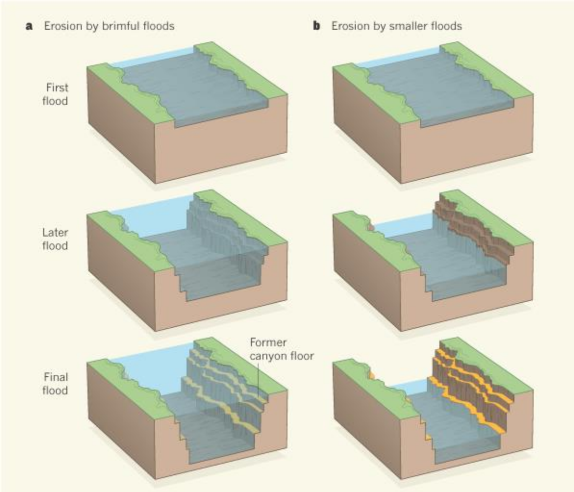
FIG. 1.—Relations between rate of transport, applied stress, and frequency of stress application.

From: Wolman, M. G. & Miller, J. P. (1960). Magnitude and frequency of forces in geomorphic processes. *Journal of Geology*, 68, 54-74.

Erosion of Channeled Scablands: Megaflood or Persistence?

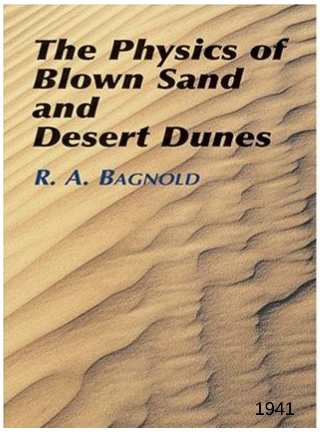
Figure 2 | Moses Coulee. Upstream view along the east wall of Moses Coulee, a canyon in the Channeled Scablands of Washington state.

Moses Coulee, Scablands, WA, USA



Cartoon from Perron and Venditti (Nature, 2016)
Based on modelling from Larsen and Lamb (Nature, 2016)

Mid-20th century application of physics to Earth surface processes

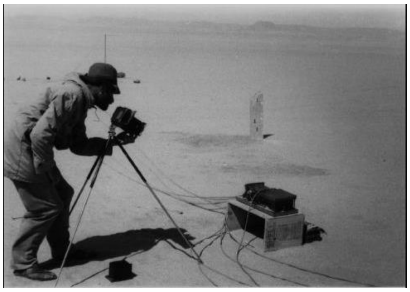


The Physics of Blown Sand and Desert Dunes

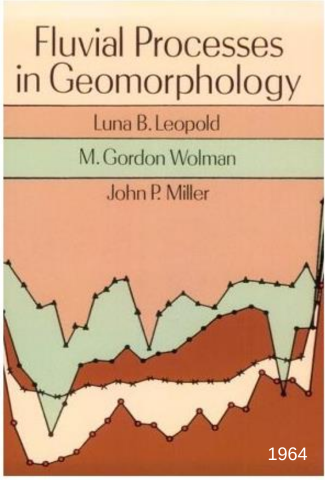
R. A. Bagnold

1941

Bagnold was one of the first to use fundamental physics to explain landscape features. His book remains a standard reference in the field today.



Mid 20th century quantitative fluvial geomorphology



Fluvial Processes in Geomorphology

Luna B. Leopold

M. Gordon Wolman

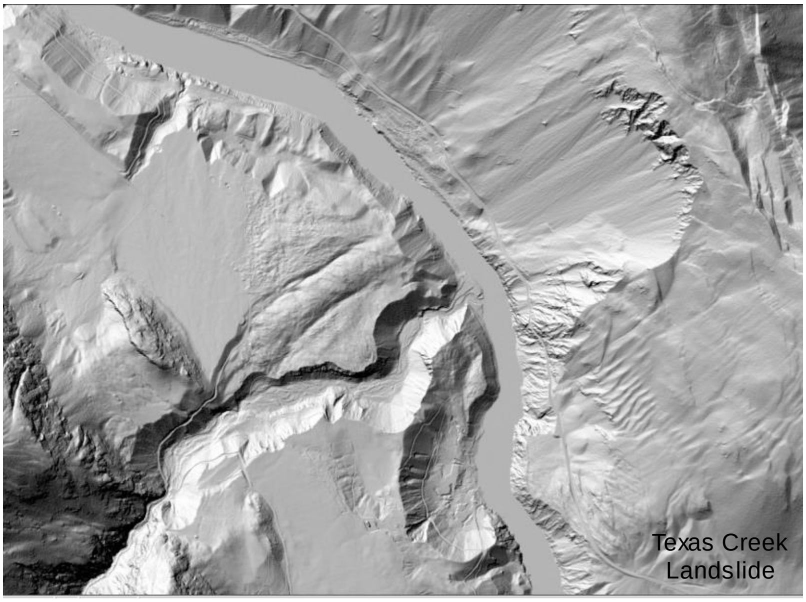
John P. Miller

1964

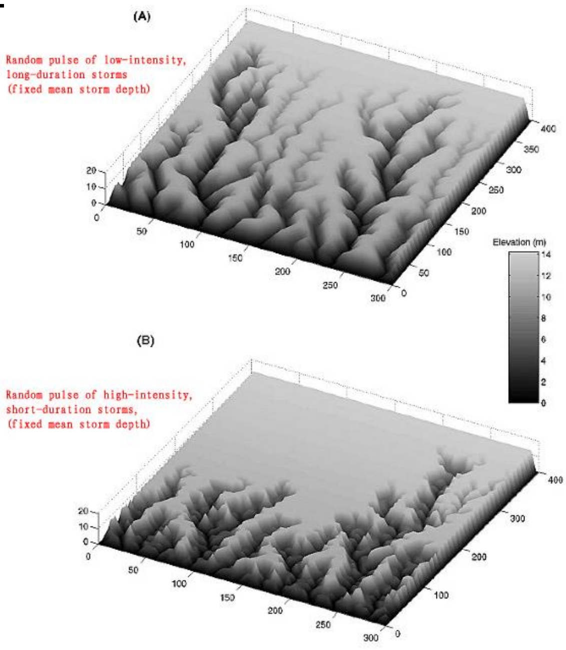
Luna Leopold served as Chief of the Hydrology Section of the USGS in the late 1950s and 1960s where he and several colleagues revolutionized geomorphology by placing it on a firm quantitative and theoretical base.

Current trends in modern geomorphology

Current Trends: Quantitative analysis of topographic relief and hypothesis testing



Current Trends: Computer-generated simulations of geomorphic processes and landscape evolution



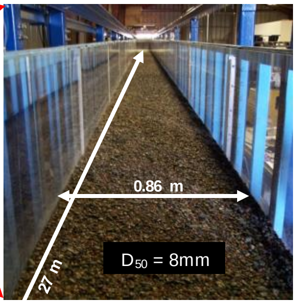
Output from CHILDS (Channel-Hillslope Integrated Landscape Development)

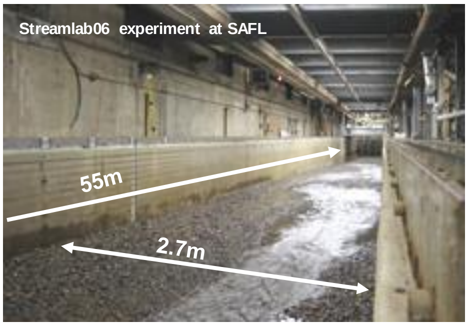
Most recent generation of landscape evolution models

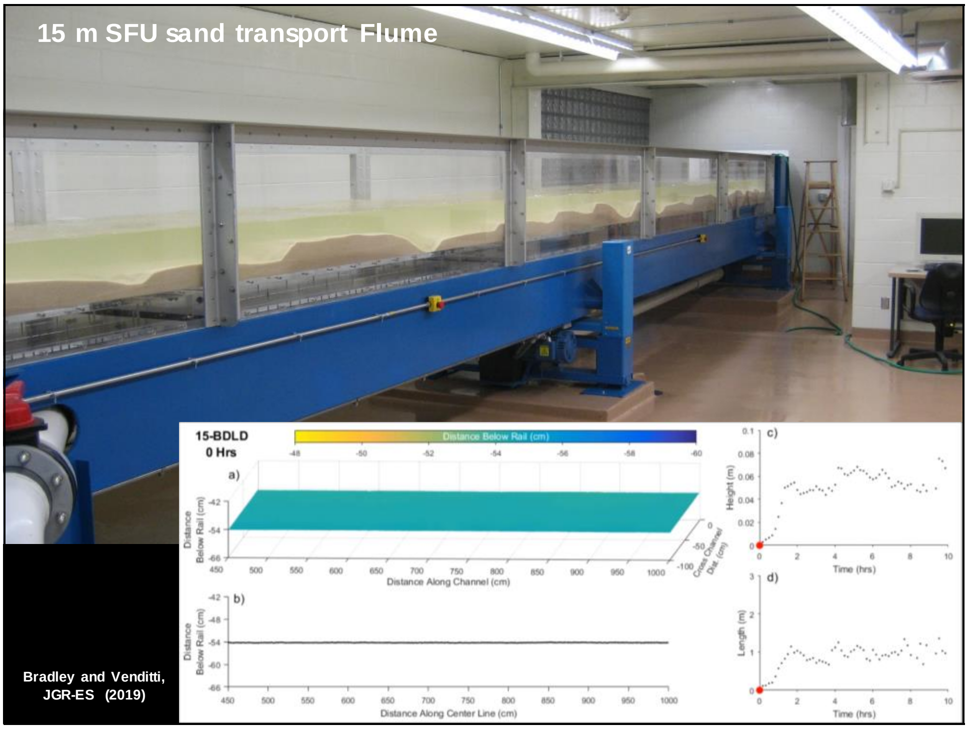
https://landlab.github.io/#/

LANDLAB

Current Trends: Experiments to test models and ideas about landscape processes



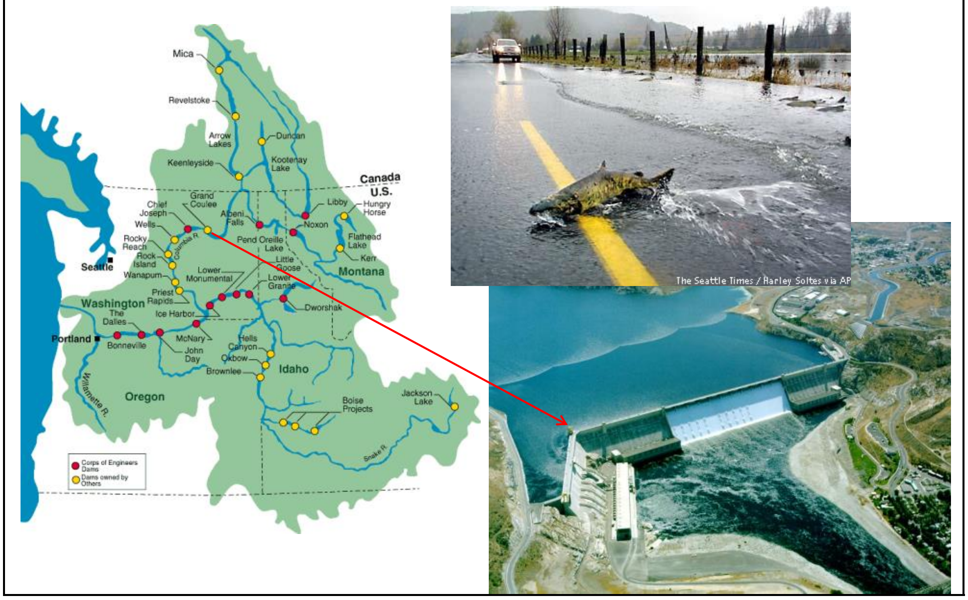




15 m SFU sand transport Flume

Bradley and Venditti, JGR-ES (2019)

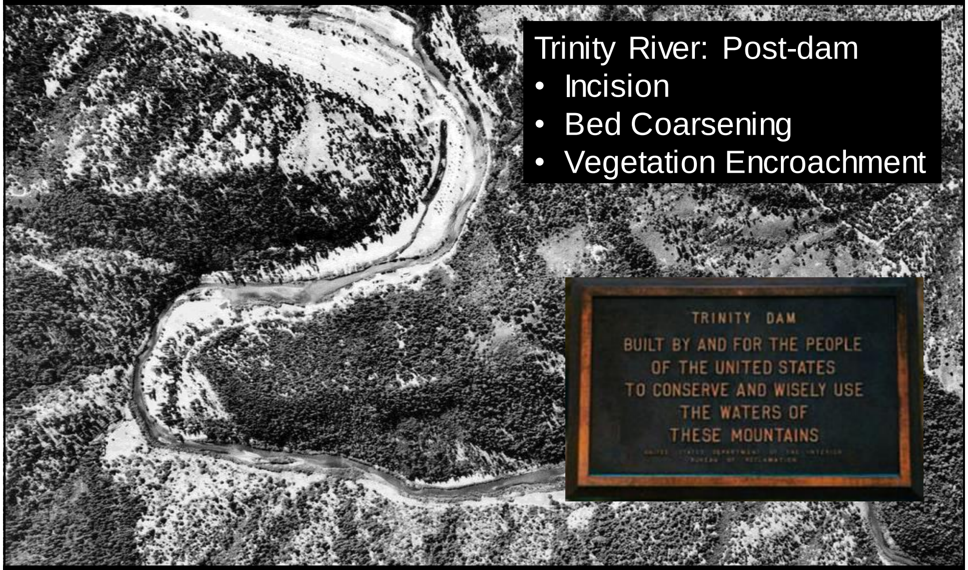
Current Trends: Using geomorphology as a tool to understanding ecologic processes and landuse impacts



Effects of Dam Construction on River Channels

Trinity River, CA: Pre-dam

Effects of Dam Construction on River Channels



Trinity River: Post-dam
- Incision
- Bed Coarsening
- Vegetation Encroachment

Current Trends: Dating the landscape

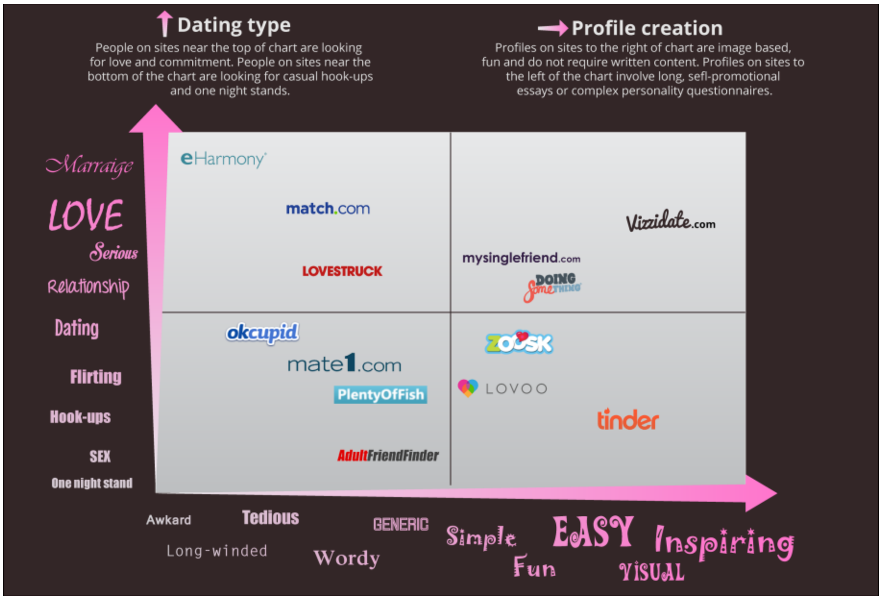

Pachena River, Jeremy Venditti

Lowell Glacier, Brian Menounos

Joshua Tree NP, Jeremy Venditti

How old are these landscapes?

Dating techniques for the rest of the world

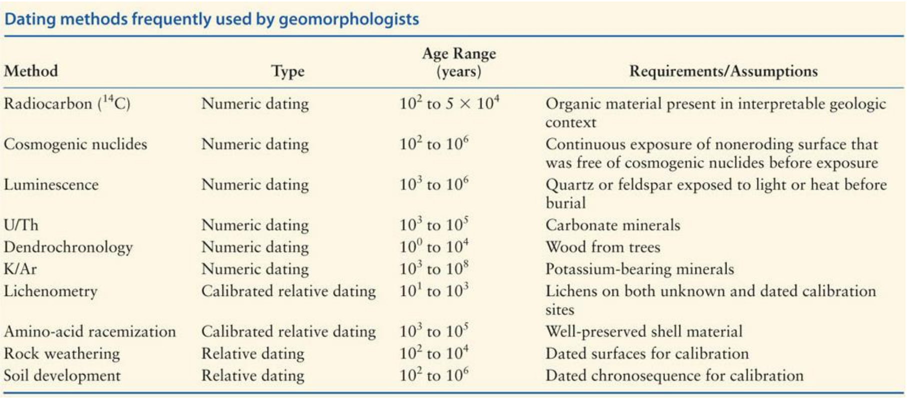

Dating type

People on sites near the top of chart are looking for love and commitment. People on sites near the bottom of the chart are looking for casual hook-ups and one night stands.

Profile creation

Profiles on sites to the right of chart are image based, fun and do not require written content. Profiles on sites to the left of the chart involve long, sefl-promotional essays or complex personality questionnaires.

Dating techniques for Geomorphologists



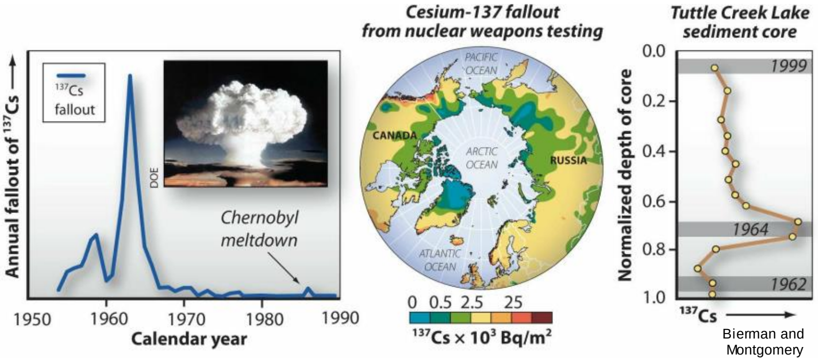
Dating methods frequently used by geomorphologists

Method	Type	Age Range (years)	Requirements/Assumptions
Radiocarbon (^{14}C)	Numeric dating	10^2 to 5×10^4	Organic material present in interpretable geologic context
Cosmogenic nuclides	Numeric dating	10^2 to 10^6	Continuous exposure of noneroding surface that was free of cosmogenic nuclides before exposure
Luminescence	Numeric dating	10^3 to 10^6	Quartz or feldspar exposed to light or heat before burial
U/Th	Numeric dating	10^3 to 10^5	Carbonate minerals
Dendrochronology	Numeric dating	10^0 to 10^4	Wood from trees
K/Ar	Numeric dating	10^3 to 10^8	Potassium-bearing minerals
Lichenometry	Calibrated relative dating	10^1 to 10^3	Lichens on both unknown and dated calibration sites
Amino-acid racemization	Calibrated relative dating	10^3 to 10^5	Well-preserved shell material
Rock weathering	Relative dating	10^2 to 10^4	Dated surfaces for calibration
Soil development	Relative dating	10^2 to 10^6	Dated chronosequence for calibration

Bierman and Montgomery, 2014

There are a wide array of techniques available to determine the age of landscapes, all of which have their own range over which they are accurate.

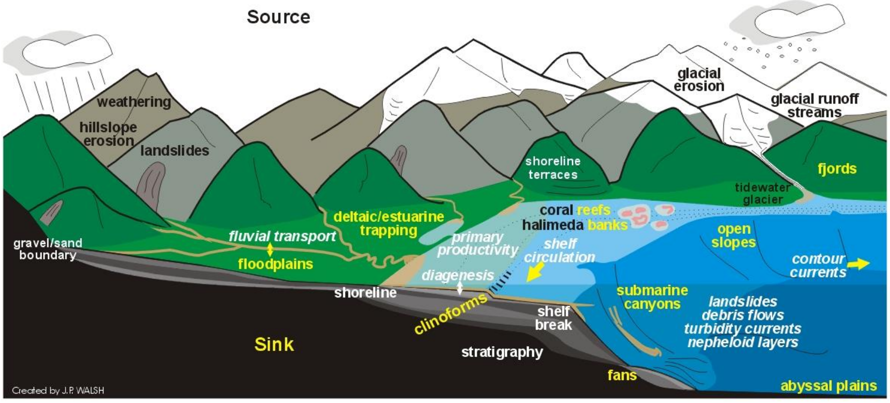
Dating example: Cesium-137 dating of a tsunami deposit



Bierman and Montgomery

Fundamental principles of modern geomorphology

Source to Sink Concept



…Follow the sediment

Equillibrium

Critical concepts:

1. A ***delicate balance*** (equilibrium) exists between geomorphic processes and the landforms that they develop.
2. The perceived balance is created by the forces that drive landform change and the resistance to change.
3. Changes in the driving forces or resisting forces can push a system beyond defined limits (threshold), resulting in landform change.
4. The balance and thresholds are all scale dependent.

Grain-scale → **Hillslope or channel reach scale** → **Drainage basin scale** → **Landscape scale**

Ingredients of the balance

Driving forces:

1. Climate – solar radiation drives the climate system including surface heating, precipitation & wind.

Almost all change in the landscape is controlled by the movement of water in its various forms

2. Gravity – gravitational force ($F_g = mg$) is the force driving water movement and drawing landscape materials to lower elevation.
3. Internal Heat – drives the tectonic system.

Ingredients of the balance

Resisting framework:

1. Lithology – determines both erodibility and the stable products of the weathering process
2. Structure – Faults, crustal warps, folds etc. often have a first order control on surface morphology
3. Internally generated resistance including the mass of particles, bedforms in rivers, vegetation in flows, root cohesion, interparticle cohesion, etc.

Threshold concept

Any system that can be thought of as being in equilibrium must also have a contrasting state of disequilibrium.

The point when the system shifts from one state to the other is a threshold.

Thresholds can be either extrinsic (caused by changes in driving forces) or intrinsic (caused by changes in the resisting forces).

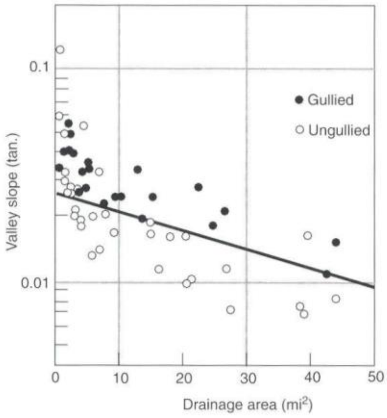


Figure 1.9
Threshold relationship between gullied and ungullied valley floors in several drainage basins of northwest Colorado.
(Patton and Schumm 1975)

From Ritter et al.2002.

Mass continuity applied to landscapes

https://www.youtube.com/watch?v=_brYGS_kYvQ

Mass Continuity

The ***law of conservation of mass*** states that the mass of a closed system will remain constant, regardless of the processes acting inside the system. An equivalent statement is that matter changes form, but cannot be created or destroyed.

Application to the landscape:

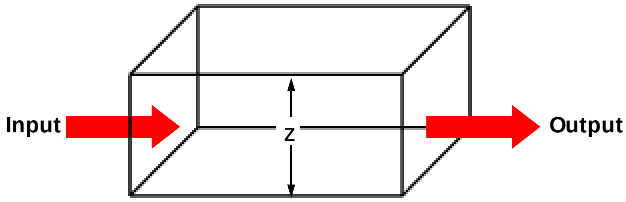
$$\mathbf{I - O = \Delta S}$$

I = Input of sediment

O = output of sediment

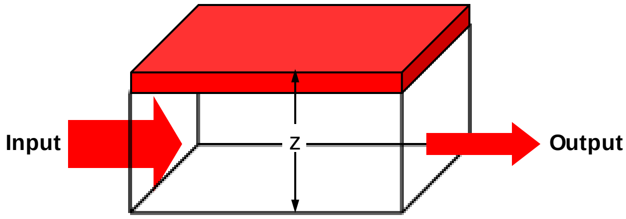
ΔS = change in storage

Mass Continuity



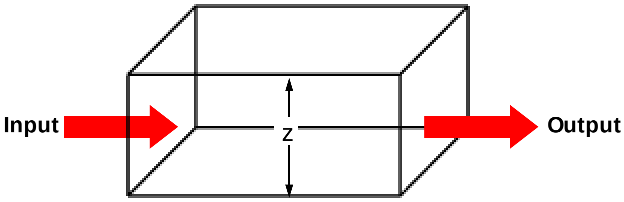
If I = O then ΔS = zero
So z is constant

Mass Continuity



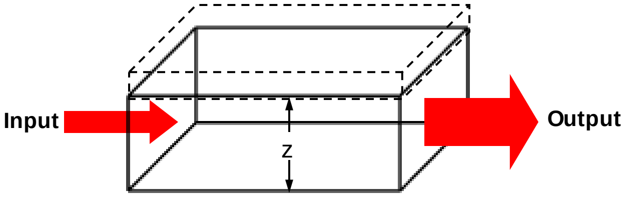
If I > O then ΔS increases
So z must increase

Mass Continuity



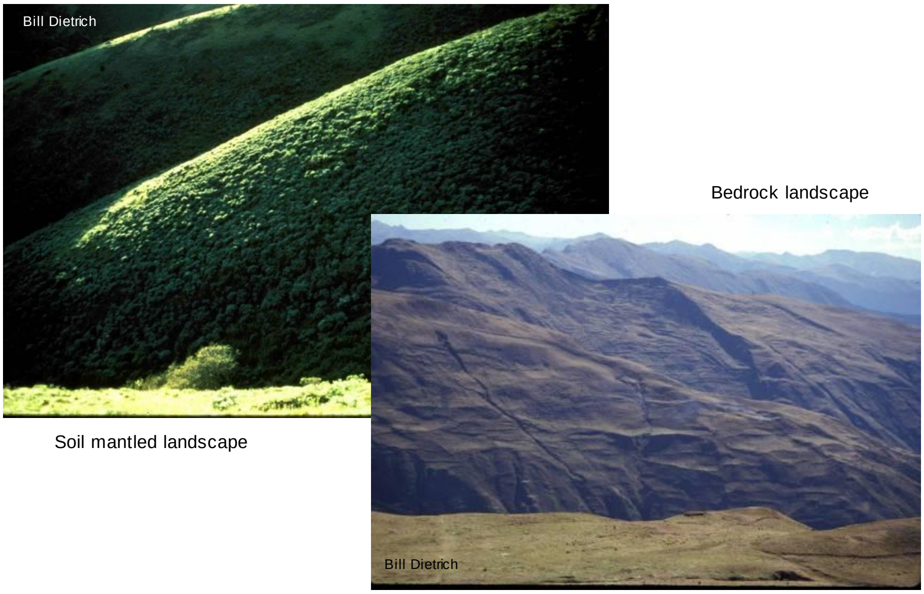
If I = O then ΔS = zero
So z is constant

Mass Continuity



If I < O then ΔS decreases
So z must decrease

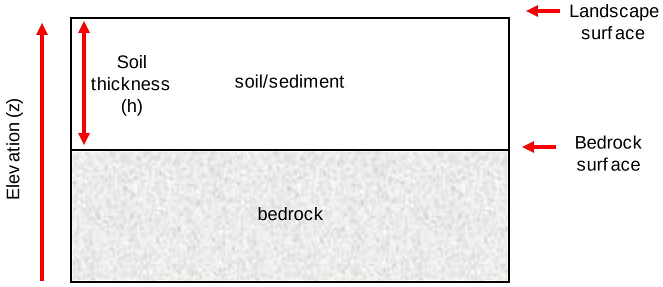
Two types of landscapes



Bedrock landscape

Soil mantled landscape

Conservation of mass for a soil covered landscape

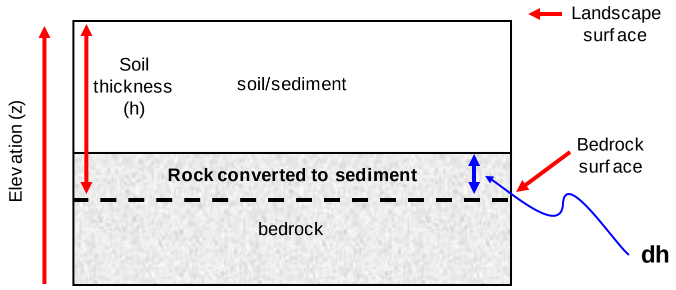


$$\frac{dz}{dt} = 0$$

Which means the change in elevation over some time period

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

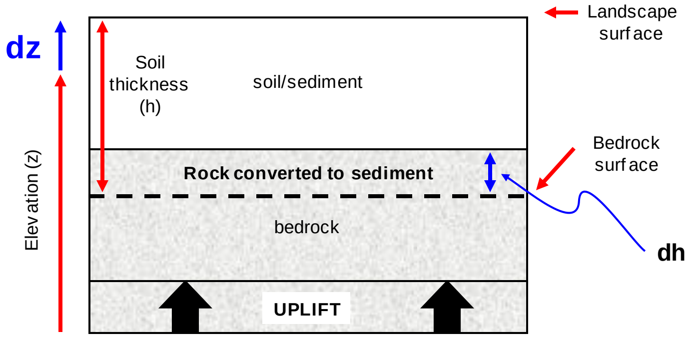
Conservation of mass for a soil covered landscape: Soil production



Weathering produces soil, thickening the profile.

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

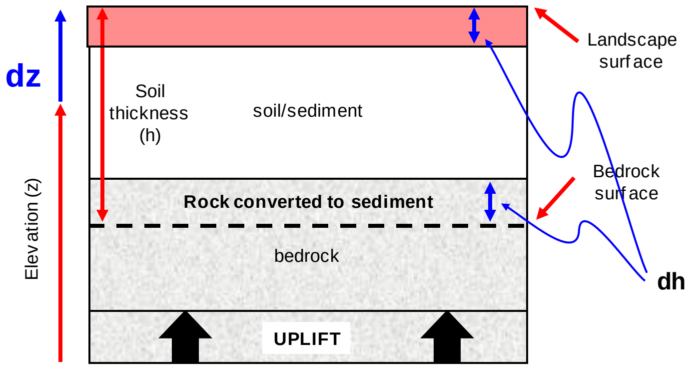
Conservation of mass for a soil covered landscape: Uplift



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.

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

Remember this one!

Conservation of mass for a soil covered landscape: flux divergence

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

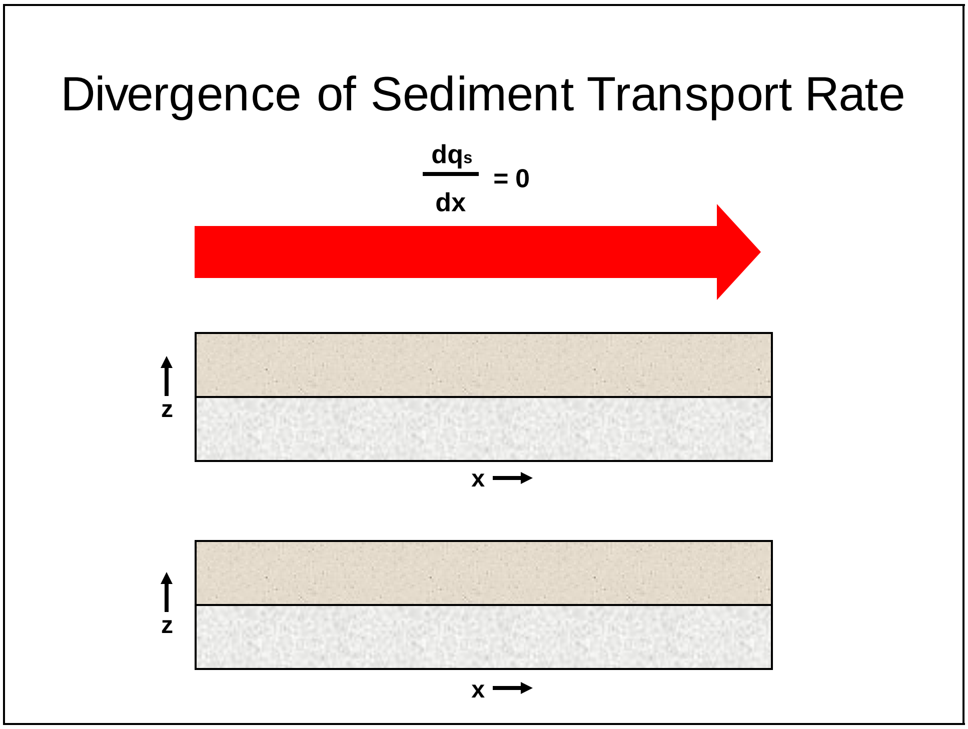
In order to make meaningful predictions of landscape evolution with this equation, we need to use physical laws to replace the soil thickness term (dh/dt).

We do this by writing the following expression:

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

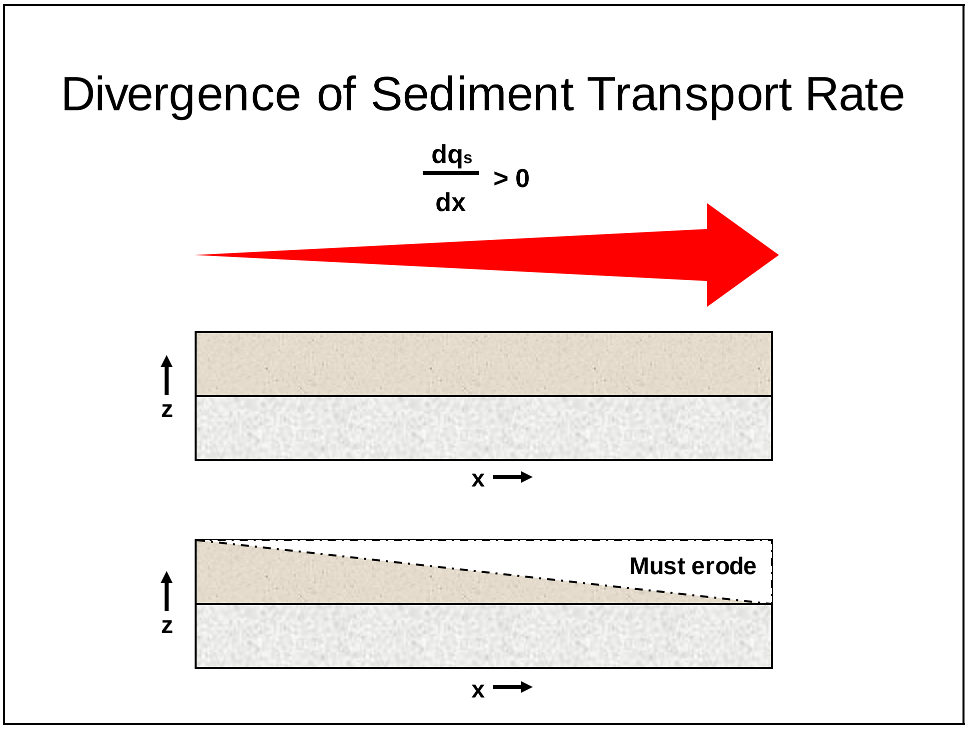
Remember this one!

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

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

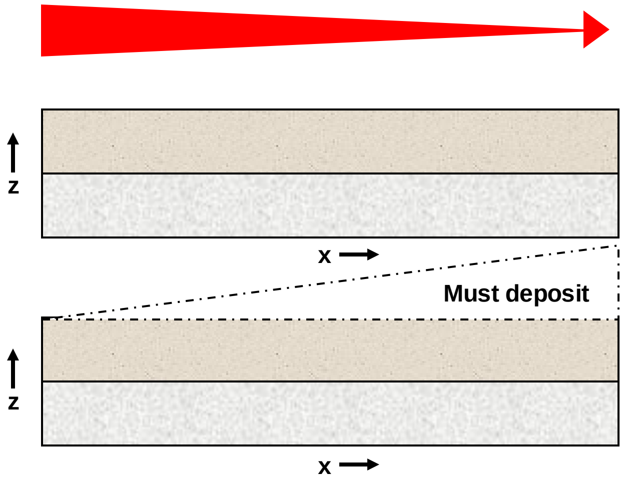


Divergence of Sediment Transport Rate

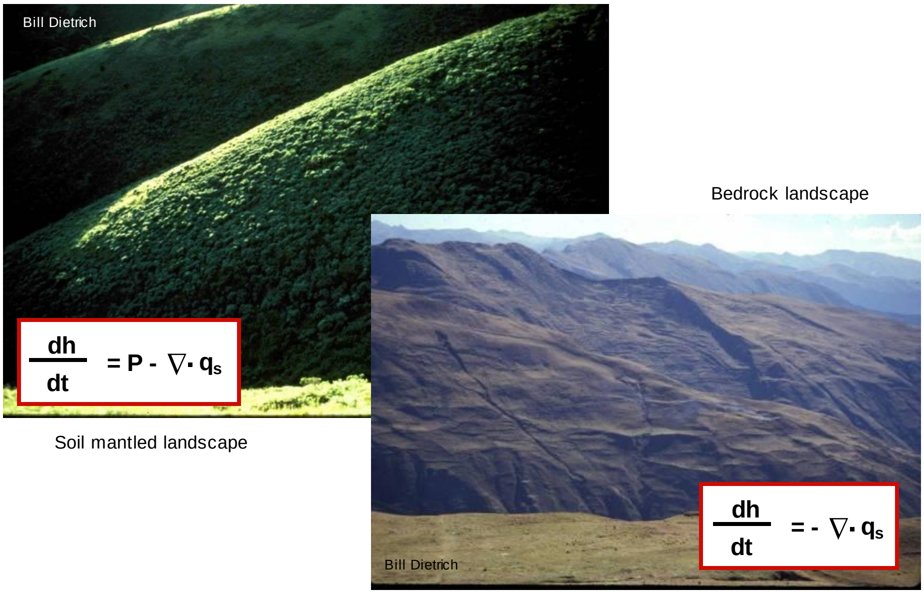
$$\frac{dq_s}{dx} > 0$$

Divergence of Sediment Transport Rate

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



How does this differ for a bedrock landscape?


Bill Dietrich

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

Soil mantled landscape

Bedrock landscape

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

Bill Dietrich

Limiting conditions in landscapes

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

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

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

Inserted into:

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

We get:

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

Remember this one!

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:

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

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

Inserted into:

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

We get:

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

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:

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

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)

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

Remember this one!

or

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

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

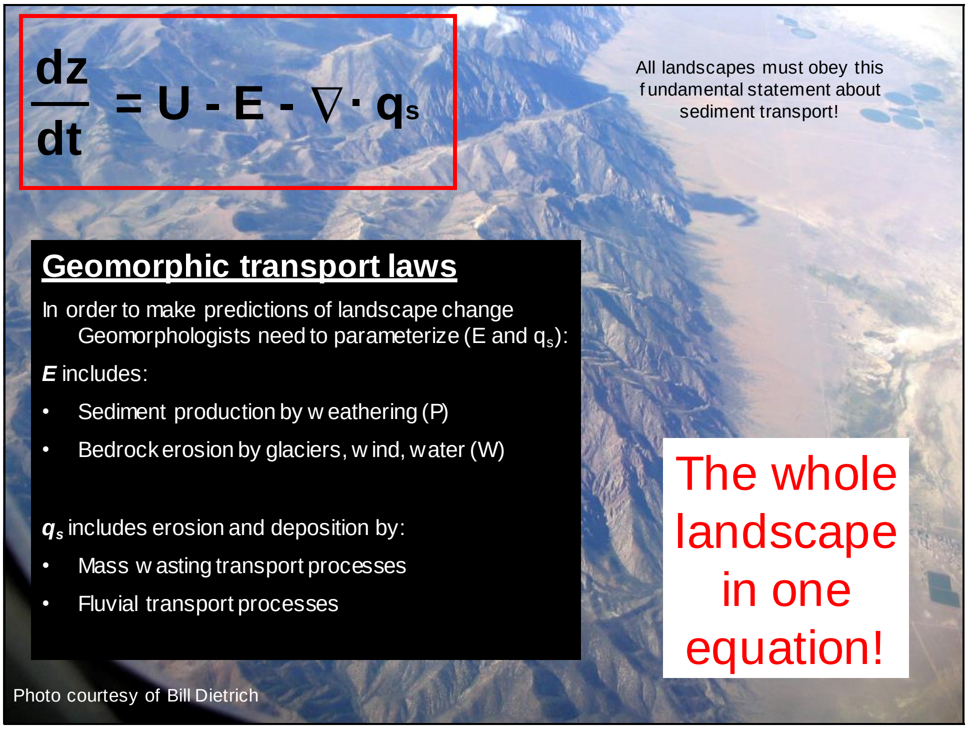
$$\boxed{\frac{dz}{dt} = U - \nabla \cdot q_s}$$

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

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

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

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



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

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 q_s):

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