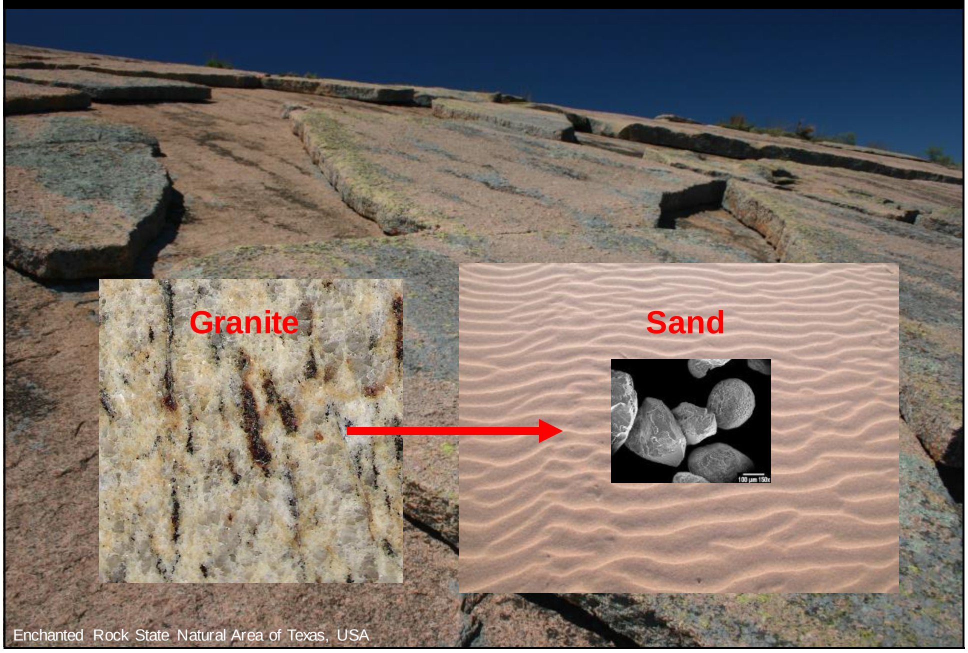
Goals of Today's Lecture

1. To answer the question: Where do landscape materials come from?
2. To examine weathering processes in the context of driving and resisting forces.
3. To consider the soil production function and what it means for agriculture.
4. To briefly examine bedrock erosion (wear) processes in the context of driving and resisting forces.

Where do landscape materials come from?



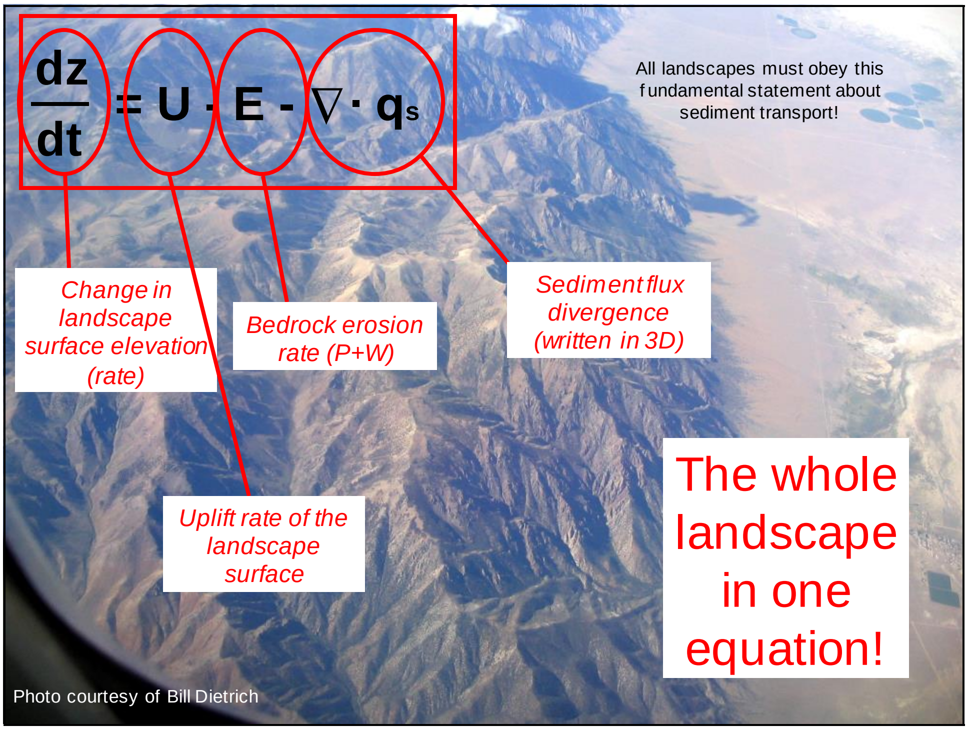
Where do landscape materials come from?

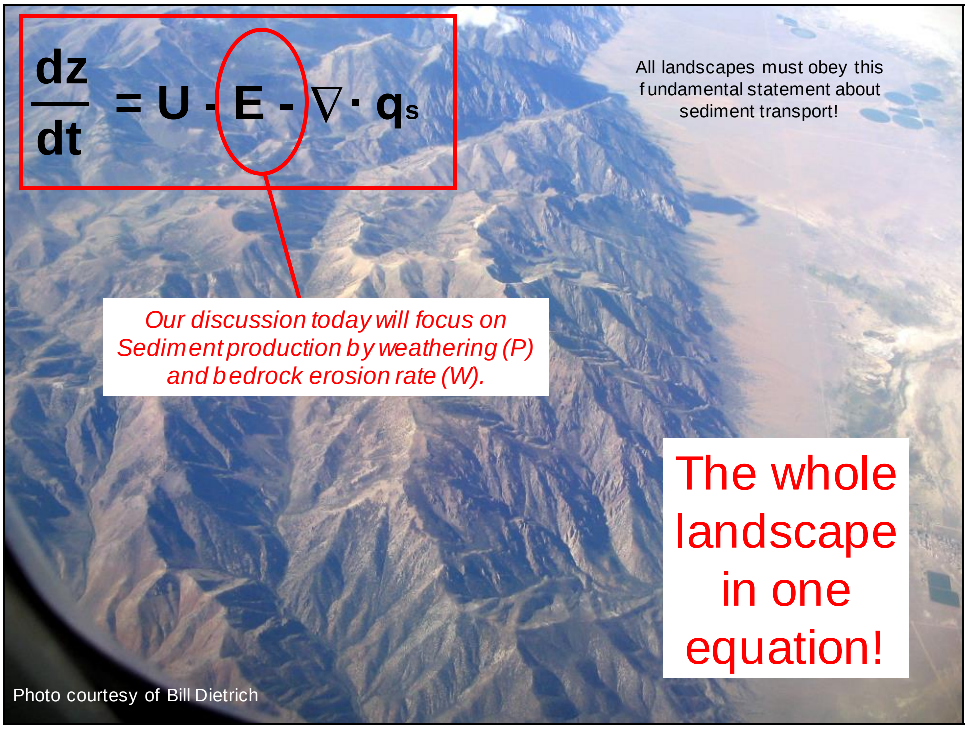
There are two processes that are important:

1) Weathering or Soil **P**roduction: In situ disintegration or breakdown of rock material

2) Bedrock Erosion or **W**ear: Erosion of rock material by water, wind, or ice.

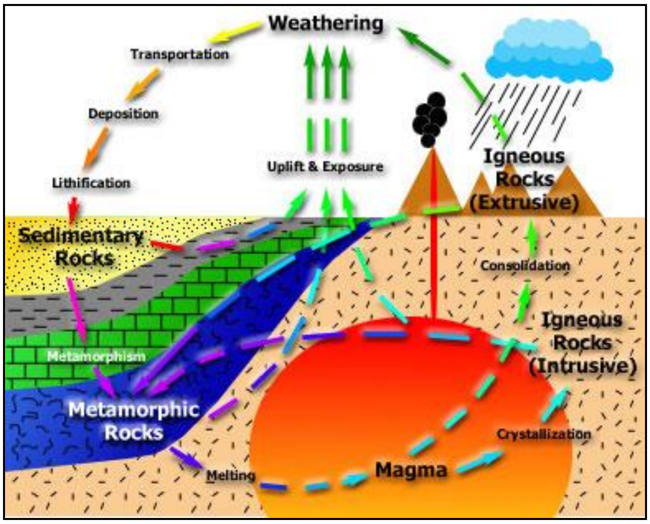
These are not mutually exclusive processes. Only where rock is covered by soil does weathering operate as the sole process. In many environments, both weathering and bedrock erosion are occurring at the same time.



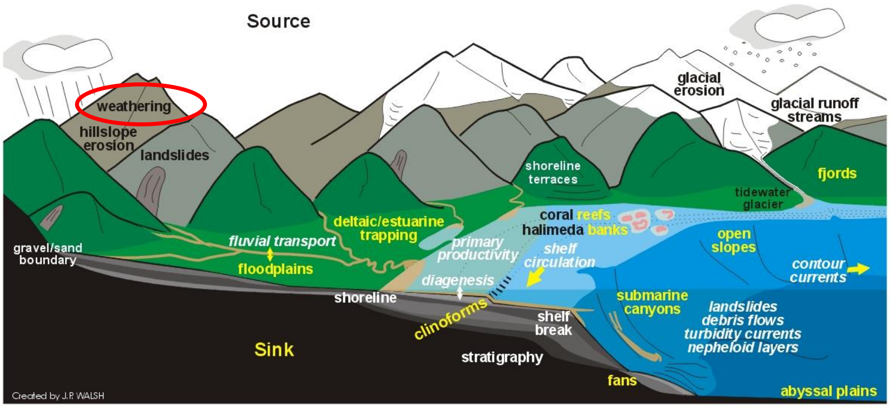

$\frac{dz}{dt} = U - E - \nabla \cdot q_s$
All landscapes must obey this fundamental statement about sediment transport!
Our discussion today will focus on Sediment production by weathering (P) and bedrock erosion rate (W).
The whole landscape in one equation!
Photo courtesy of Bill Dietrich

Weathering

Weathering in the Rock Cycle



Weathering in the Source to Sink Framework



Types of weathering

Physical (Mechanical):

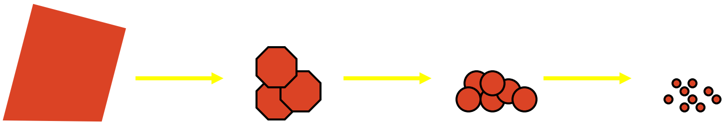
Disintegration of rock into smaller pieces *in situ*

Chemical:

Transformation/decomposition of one minerals to another *in situ*

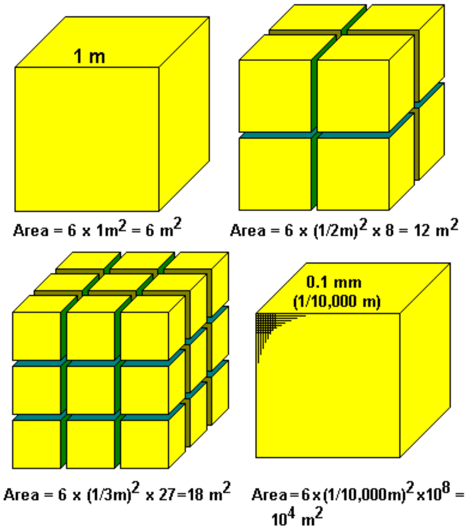
Review different types in textbook.

Mechanical Weathering: no change in chemical composition--just disintegration into smaller pieces



This increases the total surface area exposed to weathering processes.

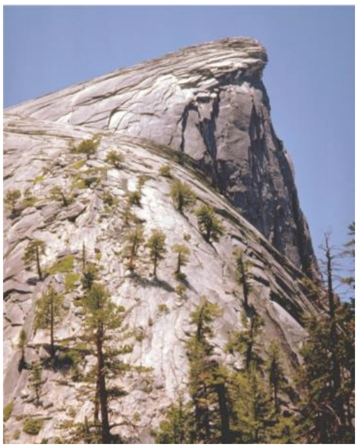
Role of Physical Weathering



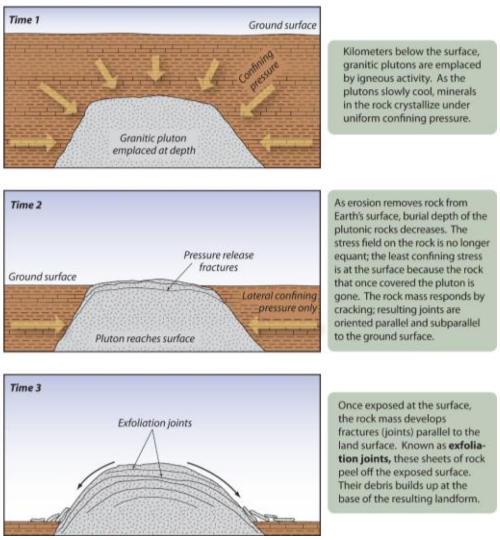
1) Reduces rock material to smaller fragments that are easier to transport

2) Increases the exposed surface area of rock, making it more vulnerable to further physical and chemical weathering

Physical Weathering 1: Exfoliation



Half Dome, Yosemite, CA



Bierman and Montgomery (2019)

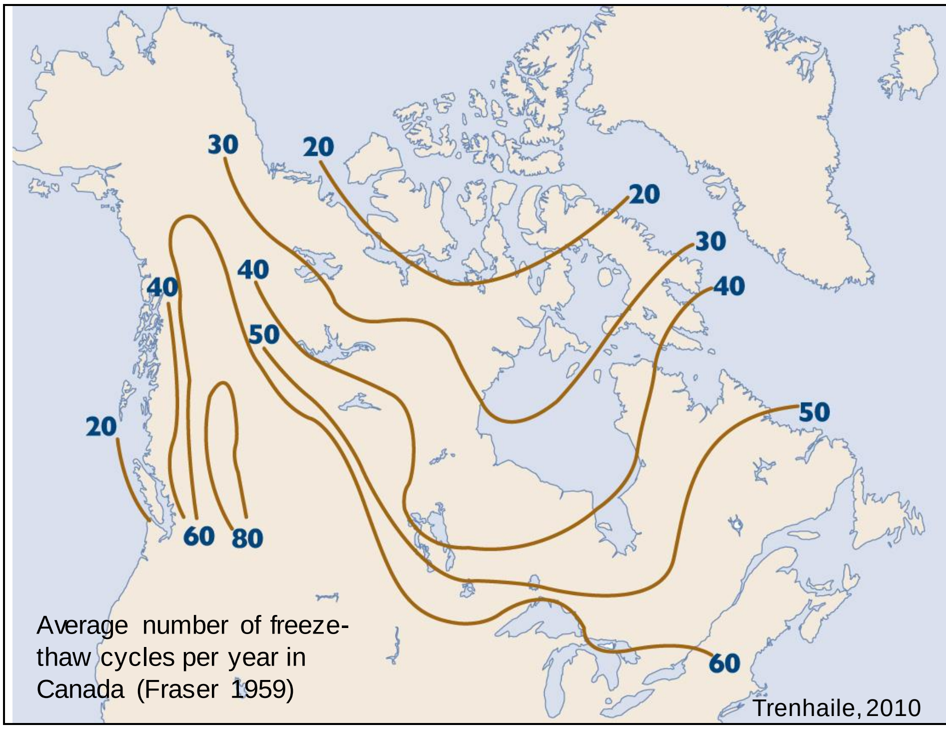
Pressure release weathering

Stone Mountain, GA

Physical Weathering 2: Freeze-Thaw

Frost Wedging: rock breakdown caused by expansion of ice in cracks and joints

Shattered rocks are common in cold and alpine environments where repeated freeze-thaw cycles gradually pry rocks apart.



Average number of freeze-thaw cycles per year in Canada (Fraser 1959)

Trenhaile, 2010

Physical Weathering 3: Thermal Expansion

Thermal expansion due to the extreme range of temperatures can shatter rocks in desert environments.

Repeated swelling and shrinking of minerals with different expansion rates will shatter rocks.

Physical Weathering 4: Salt Crystal Growth

Often thought to be most effective at granular disintegration on exposed rock faces. *Can it split rock?*

Tafoni weathering is common in arid coastal areas where brine is abundant and salt crystallization is possible.

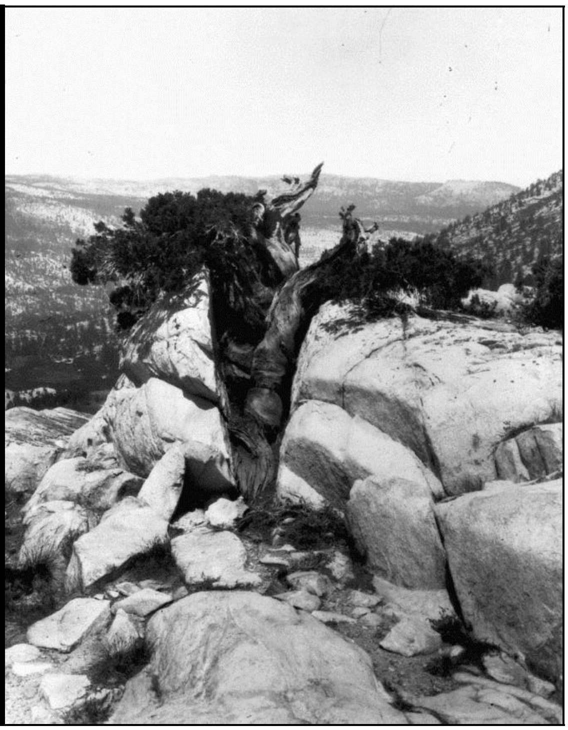
Honey combs, Artillery Rocks, Victoria, Australia (Trenhaile, 2010)

Physical Weathering 5: Biotic

Root Splitting: At large scales, seedlings sprouting in a crevice and plant roots exert physical pressure.

Burrowing animals and insects disturb the soil layer adjacent to the bedrock surface, increasing water infiltration and exposure to other processes.

Photo courtesy USGS DDS21

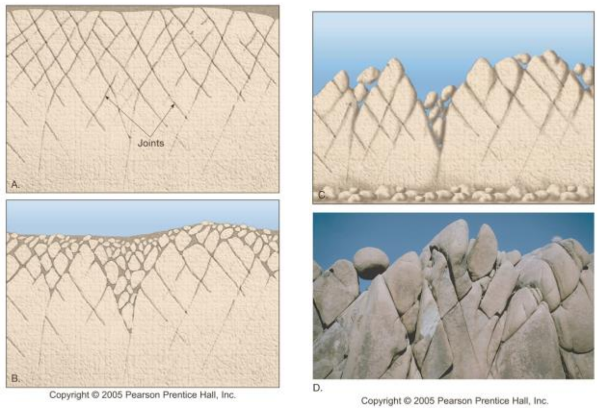


What controls rate of physical weathering?

Resistance to weathering: Rock strength, composition, fracture pattern.

Joints in a rock are a pathway for water – they can enhance mechanical weathering.

The form and density of fractures is controlled by the rock type.



What controls rate of physical weathering?

Driving force of weathering:

1) Exfoliation requires erosion which requires → water
2) Ice crystalization requires → water
3) Salt crystalization requires → water
4) Biota growth requires → water

Physical weathering systems are controlled by the availability of water and thus are climatically controlled.

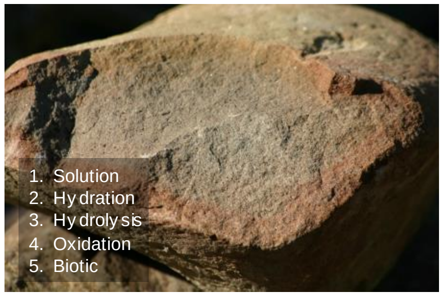
More on this later!

Types of Weathering

Physical (Mechanical):

Disintegration of rock into smaller pieces *in situ*

Chemical:



Transformation/decomposition of one minerals to another *in situ*

Review different types in textbook.

Chemical Weathering: breakdown as a result of chemical reactions.

$$CaCO_3 + CO_2 + H_2O \text{ ---> } Ca^{2+} + 2HCO_3^-$$

Calcium Carbonate — Limestone or marble rock

Carbon dioxide

Water — Carbonic Acid (H_2CO_3)

Calcium

Bicarbonate — Rock that can be carried in solution!

Transformation/decomposition of one mineral into another!

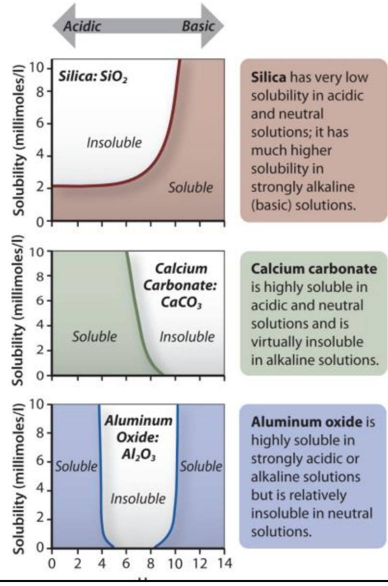
Chemical Weathering 1: Solution

Solution: process by which rock is dissolved in water

Calcium Carbonate *Carbon dioxide* *Water*

$$CaCO_3 + CO_2 + H_2O \rightarrow$$
$$Ca^{2+} + 2HCO_3^-$$

Calcium *Bicarbonate*



Chemical Weathering 2: Hydration

Hydration: attachment of water molecules to crystalline structure of a rock, causing expansion and weakness.

Hydration of Anhydrite

$$Ca_2SO_4 + 2H_20 \rightarrow Ca_2SO_4 \,.\, 2H_20$$

Anhydrite **Water** **Gypsum**

But, many of these reactions are reversible!

Dehydration of gypsum by heating: $Ca_2SO_4 \,.\, 2H_20 \rightarrow Ca_2SO_4 + 2H_20$

So, is this a chemical weathering process?

Chemical Weathering 3: Hydrolysis

Hydrolysis: combination of hydrogen and oxygen in water with rock to form new substances. Carbonation is essentially the same reaction, but with CO_2 instead of H^+.

Feldspar Weathering to Kaolinite:

Feldspar · *Hydrogen Ion* · *Water*

$$2K\,Al\,Si_3\,O_8 + 2H^+ + 9H_2O \rightarrow H_4\,Al_2\,Si_2\,O_9 + 4H_4\,Si\,O_4 + 2K^+$$

Kaolinite · *Disolved silica (acid)* · *Potassium ion*

Most common mechanism for clay formation.

Chemical Weathering 4: Oxidation

Oxidation: Oxygen dissolved in water oxidizes sulfides, ferrous oxides, native metals

Olivine · *Water* · *Oxygen*

$$2Fe\,Si\,O_4 + 4H_2O + O_2 \rightarrow 2Fe_2\,O_3 + 4H_4\,Si\,O_4$$

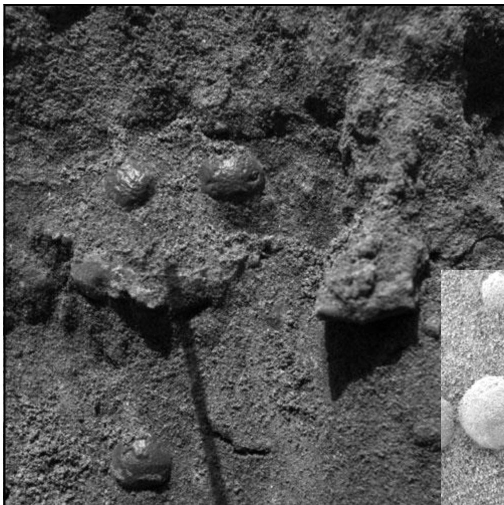
Hematite · *Disolved silica (acid)*

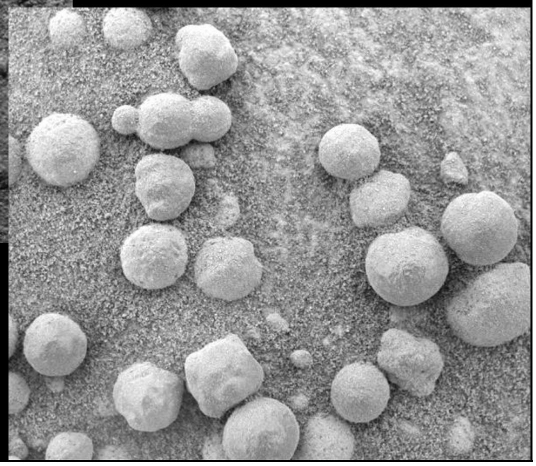
Hematite

Oxidation Weathering?

or

Aqueous Mineralization?





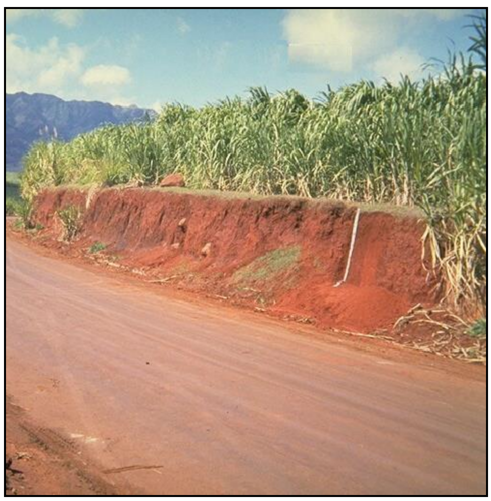
"Blueberries" (hematite spheres) on a rocky outcrop at Eagle Crater.

Images from Mars rover Opportunity, NASA

Chemical Weathering: 5. Biotic

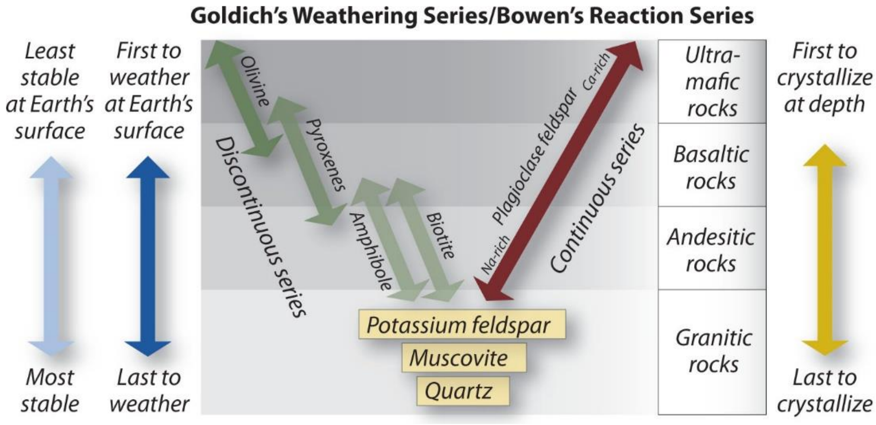
Plants and animals cause chemical weathering through release of acidic compounds or hydrogen (H^+).

Thus, biota provide the reactant that causes chemical weathering and may also provide a conduit that feeds water and reactants into fissures and cracks, but does not dissolve rock in any constitutive way.



What controls rate of chemical weathering?

Resistance to weathering is controlled by rock type.



Bierman and Montgomery (2019)

Typical Chemical Weathering Products

+ H_2CO_3 (acid)

↓

Typical Chemical Weathering Products

+ H_2CO_3 (acid)

↓

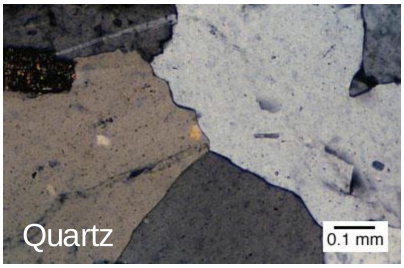
Calcite to …….

+ anything

↓

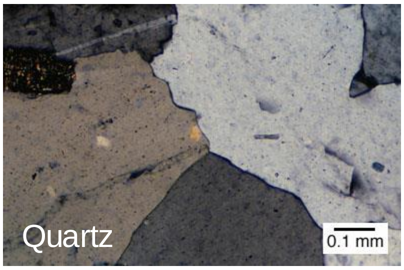
Nothing solid

Typical Chemical Weathering Products



+ **anything**

↓



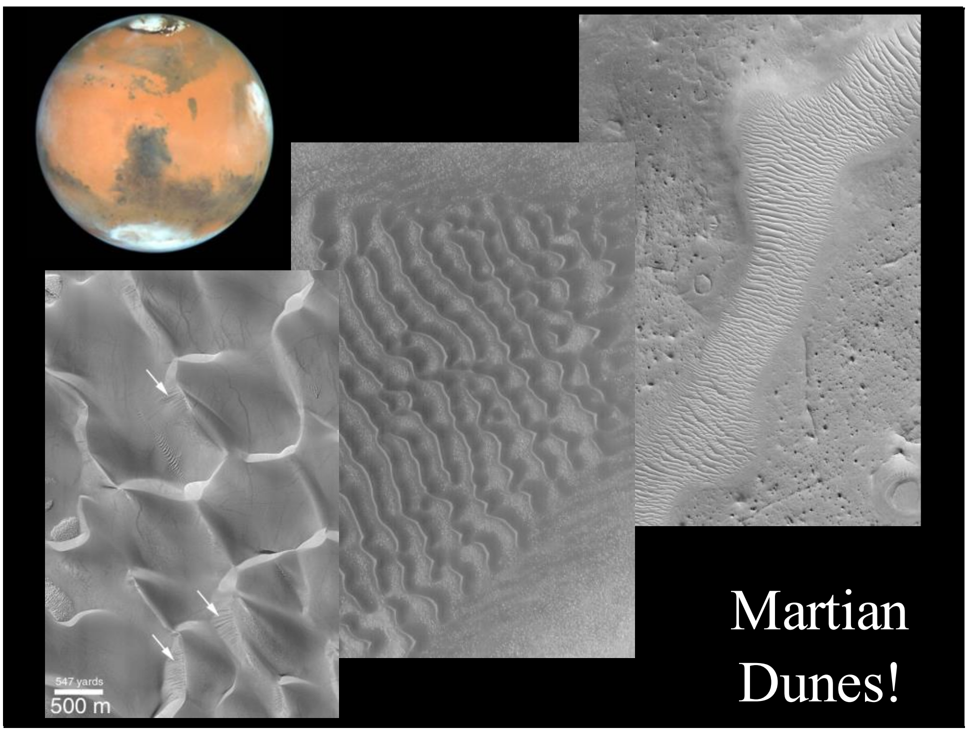
What controls rate of chemical weathering?

Water is main driving force:

- Dissolution → Many ionic and organic compounds dissolve in water (Silica, K, Na, Mg, Ca, Cl)
- Hydration and Hydrolysis → both require water
- Acid Reactions → Require water
  - Water + carbon dioxide ←→ carbonic acid
  - Water + sulfur ←→ sulfuric acid
  - Water + silica ←→ silica acid

Why is sand so prevalent at Earth's surface?

Mean Lifetime of a 1mm crystal at surface (in years)	
Quartz	34,000,000
Kaolinite	6,000,000
Muscovite	2,600,000
Microcline (Alk. Feldspar)	921,000
Albite (Sodium Plagioclase)	575,000
Sandine (Alk. Feldspar)	291,000
Enstatite (Pyroxene)	10,100
Diopside (Pyroxene)	6,800
Forsterite (Olivine)	2,300
Nepheline (Amphibole)	211
Anorthite (Calcium Plagioclase)	112

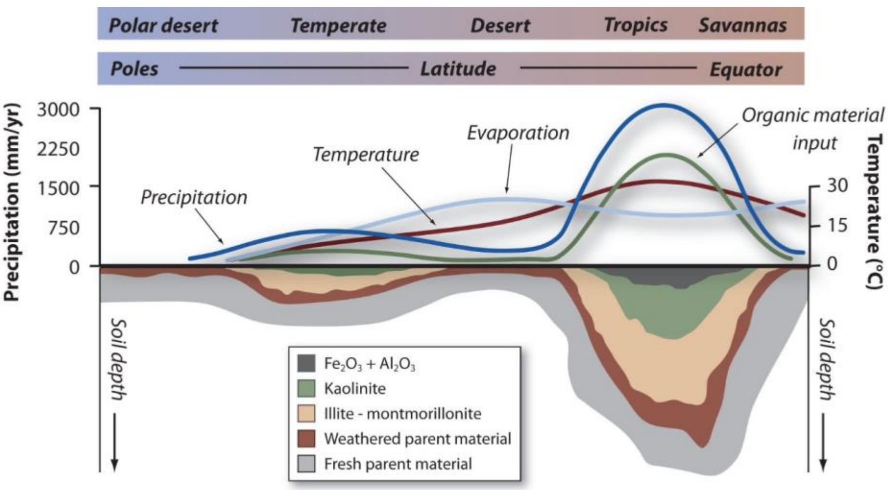


Meanwhile…Back in the real world

Mechanical and chemical weathering work together to break down the landscape into materials that can be easily transported.

- Fracturing, disintegration caused by mechanical weathering exposes more surface area.
- Greater surface area, means more places for chemical action to occur.
- Disturbances by biota are one of the primary ways in which weathered bedrock is churned up to form soil.

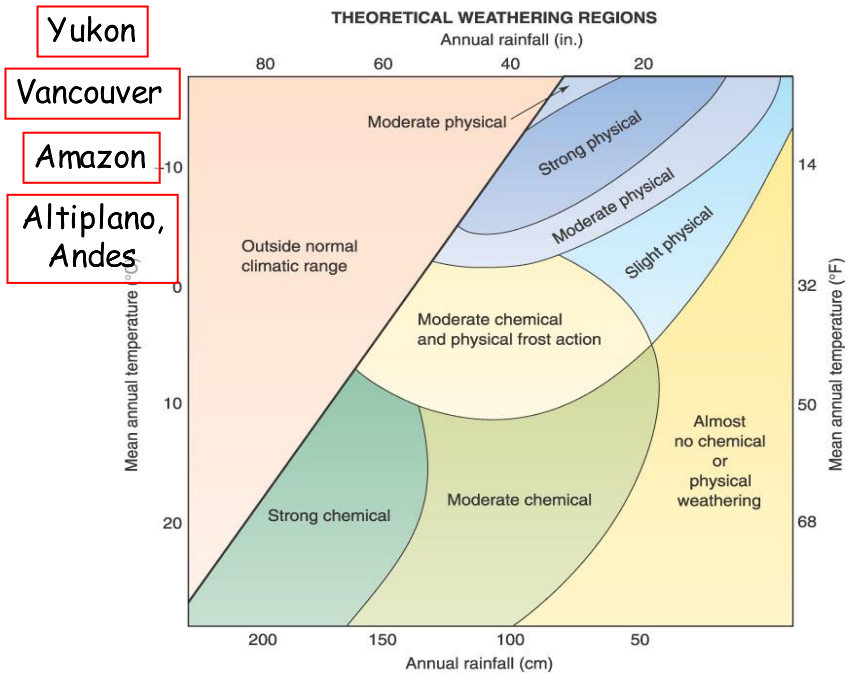
Linkage between climate and weathering



Mechanical weathering
Enhanced where there are frequent freeze-thaw cycles

Chemical weathering
Most effective in areas of warm, moist climates – decaying vegetation creates acids that enhance weathering
Least effective in polar regions (water is locked up as ice) and arid regions (little water)

Bierman and Montgomery (2019)



Summary: Driving and resisting forces

Driving forces behind weathering are all related to the climate.

Most weathering processes require water to occur.

Temperature variability is a driving force, but only where there is lots of variation. Heat doesn't cause weathering and neither does cold.

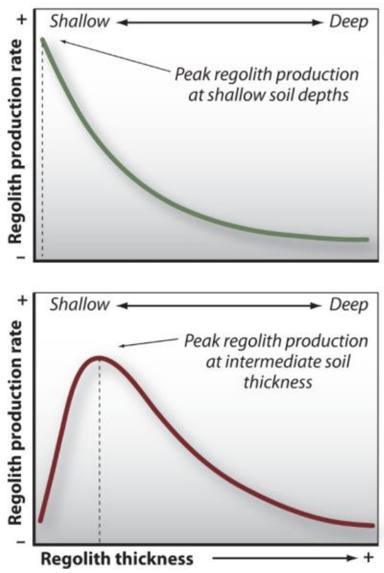
Plant growth may be a driving force.

Resisting forces are all about the rock type. Some rocks take longer to weather because they are made of stronger minerals.

Resistance to weathering is also dependent on rock integrity. Fractures rock will let water and acids inside.

Soil Production Function

How can we predict P?



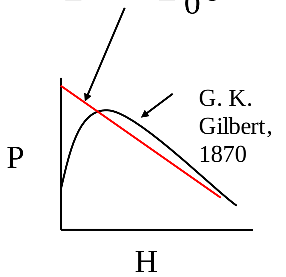
In many landscapes, the rate of **regolith production** from bedrock weathering exhibits an exponential decrease with increasing regolith depth. In this case, the maximum rate of regolith production occurs under little to no cover because thicker regolith cover reduces the ability of regolith-producing processes to reach fresh bedrock parent material.

In landscapes where the rate of regolith production is more strongly controlled by regolith water content, the regolith production function may exhibit a maximum at an intermediate cover thickness. Regolith production rates drop where regolith is thin because the regolith/rock interface there is often dry.

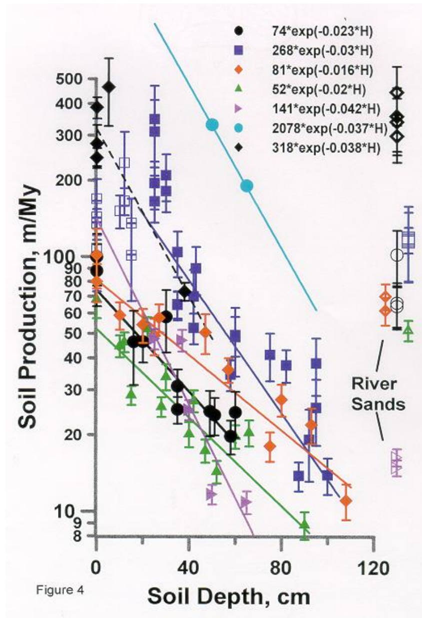
Bierman and Montgomery Textbook

Soil Production Function

$$P = P_0 e^{-\alpha H}$$



An exponential decay in the soil production rate with soil depth for a given climate and rock type.

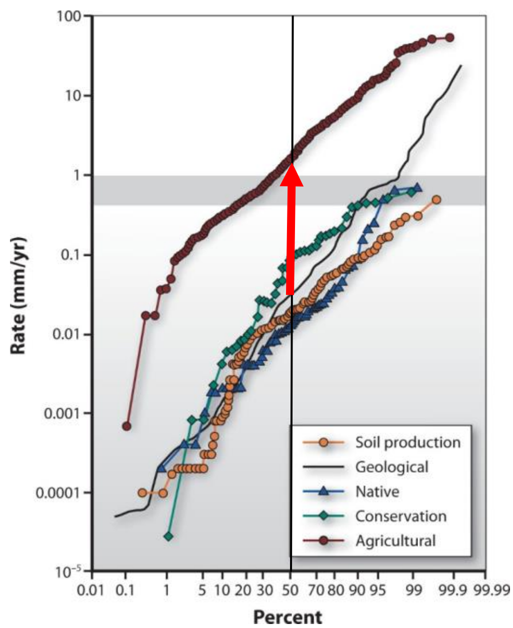


Heimsath, et al., 1997, Nature.

A practical reason to know the soil production rate

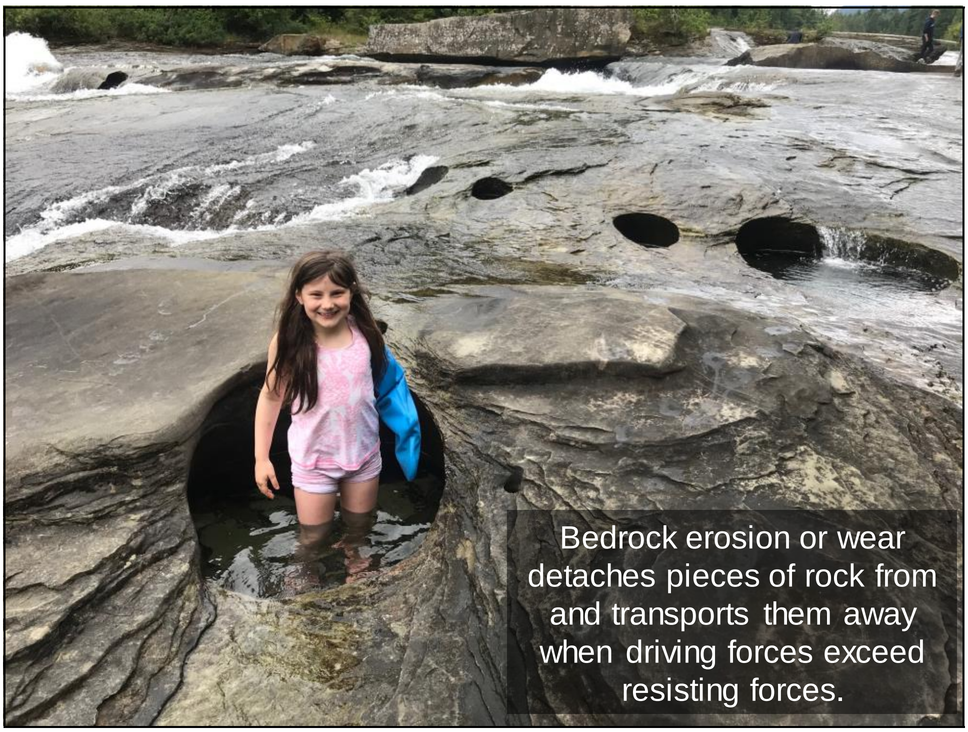
Lynn Betts, USDA-NRCS

USDA-NRCS



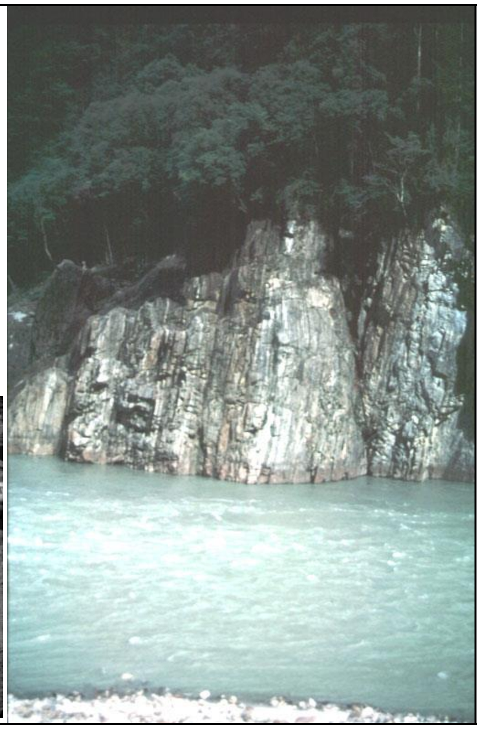
Bierman and Montgomery Textbook

Bedrock Erosion Processes



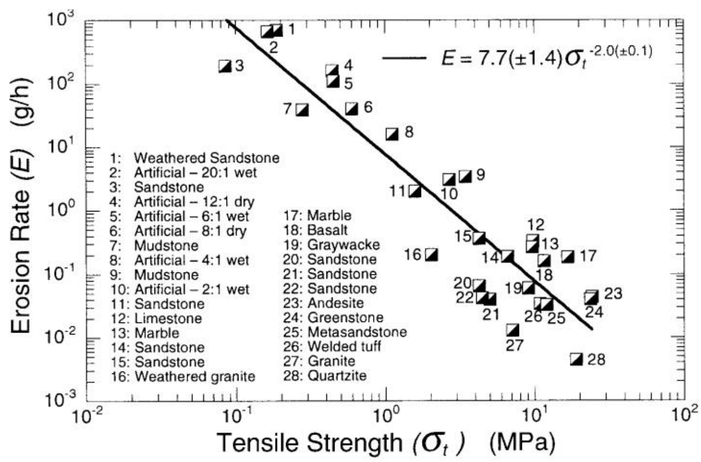
Erodibility

Resistance to erosion: There is 5 order of magnitude range in bedrock erodiblity



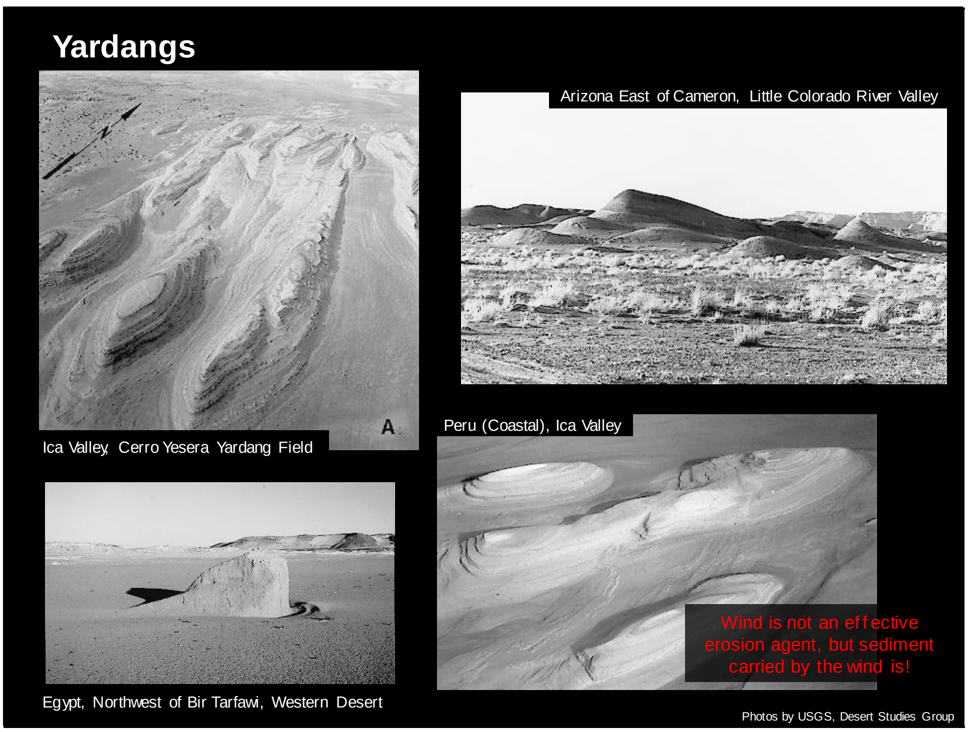
Sediment and rock strength controls on river incision into bedrock

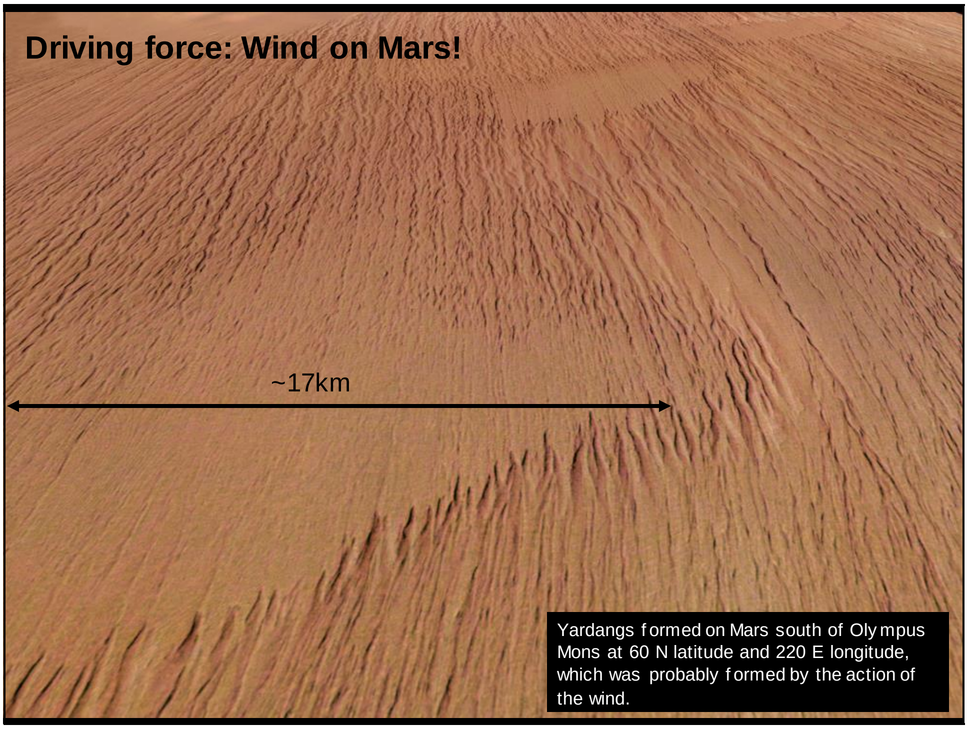
Leonard S. Sklar
William E. Dietrich
Department of Earth and Planetary Science, University of California, 307 McCone Hall, Berkeley, California 94720-4767, USA



Erosion varies inversely as the square of the rock strength.


Driving force: Water
Water is not an effective erosion agent, but sediment carried by the water is!
Near Banff Springs Hotel, Alberta


Yardangs
A
Ica Valley, Cerro Yesera Yardang Field
Arizona East of Cameron, Little Colorado River Valley
Peru (Coastal), Ica Valley
Egypt, Northwest of Bir Tarfawi, Western Desert
Wind is not an effective erosion agent, but sediment carried by the wind is!
Photos by USGS, Desert Studies Group


Driving force: Wind on Mars!
~17km
Yardangs formed on Mars south of Olympus Mons at 60 N latitude and 220 E longitude, which was probably formed by the action of the wind.


Driving force: Ice
Yosemite NP
Glacial grooves caused by the Wisconsin glaciation at Kelleys Island, Ohio
Ice is not an effective erosion agent, but sediment carried by the ice is!
http://www.yosemite.ca.us/library/geologic_story_of_yosemite/final_evolution.html

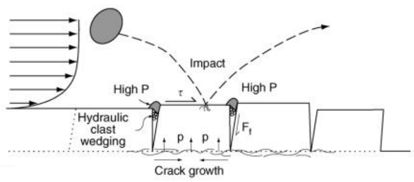

Driving force: Ice (Avalanche)

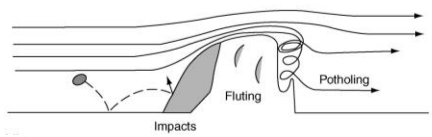

Driving force: Sediment flow
Debris flow track on West Coast of Vancouver Island nr. Bamfield, BC

Bedrock Erosion Processes (in rivers)

Plucking

Abrasion

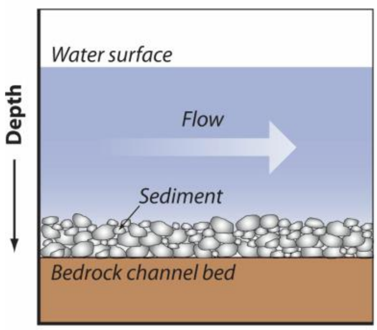


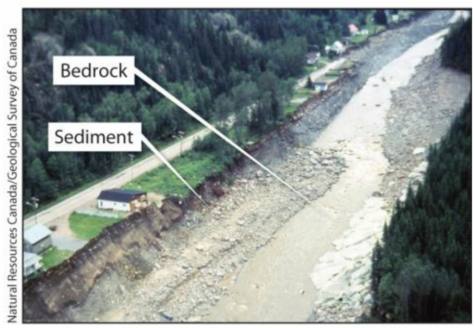


Whipple, DiBiase and Crosby, 2013

Tools and Cover Effect (in all flows)

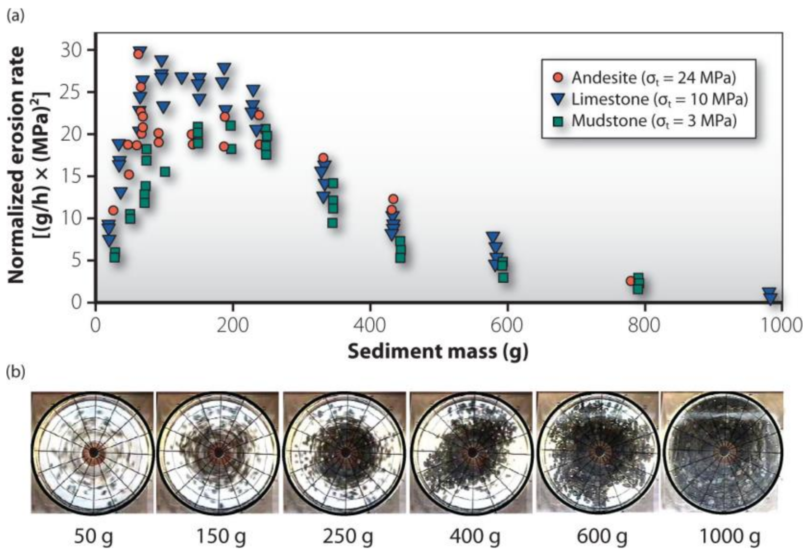
River channels are underlain by both rock and sediment. In order for the river to incise into the underlying bedrock, it must first entrain sediment from the channel bed. Bedrock cannot be eroded until its sediment cover is in motion.





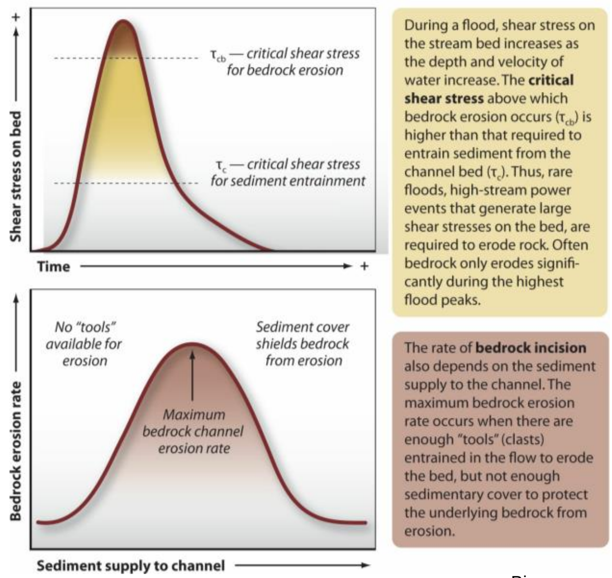
Bierman and Montgomery, 2014

Tumbler experiments Sklar and Dietrich (2001)



Bierman and Montgomery, 2014

How can we predict W?



Bierman and Montgomery, 2014

Plucking or abrasion potholes?