

# Weathering

## The Origin of Sedimentary Materials

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Remember from early in the term that there are four ways minerals can form:

1. Crystallization from a molten state.
2. Modification of pre-existing minerals by processes acting at or near Earth's surface.
3. Crystallization from solution in water (or other fluids).
4. Modification of pre-existing minerals by exposure to elevated temperature and pressure.

The first of these, highlighted above, was the topic of our exploration of igneous rocks.

As we consider sedimentary rocks we will be concerned with the second two means of mineral formation:

1. Crystallization from a molten state.
2. Modification of pre-existing minerals by processes acting at or near Earth's surface.
3. Crystallization from solution in water (or other fluids).
4. Modification of pre-existing minerals by exposure to elevated temperature and pressure.

Number two refers directly to the process we call **weathering**, or part of it. Number 3 refers, in the context of sedimentary rocks, to the ultimate fate of the by-products of such weathering.

# Weathering Basics

**Weathering** – The set of processes operating at or near Earth’s surface that break down pre-existing (“**source**”) rock and/or its constituent minerals into smaller pieces and/or different minerals from those originally present.

The best way to parse that definition and understand it is to realize that there are two possible outcomes of the processes to which it refers:

- 1) Material can be broken up into smaller pieces (which always happens), and/or
- 2) The original minerals can be changed into new minerals (which does not always happen).

Similarly, we can think of the weathering processes collectively as being of two basic types:

- 1) Those that simply break the source rock into smaller pieces, without any chemical or mineralogical change, and
- 2) Those that cause changes in chemistry and mineralogy, which invariably also lead to reduction in grain size.

The first set of processes we call **mechanical weathering**, the second **chemical weathering**.

# Mechanical Weathering

Simple Reduction in Size of Rocks and  
Their Constituent Minerals

# 1 – Impacts and Abrasion



A.



B.

FIGURE 5-40

(A) Pothole erosion of bedrock in a stream channel, Mt. Fujiama, Japan. (Photo by W. K. Hamblin)

(B) Development of a bedrock channel by pothole erosion, New York. (Photo by P. J. Fleischer)



Though we often hear of a stream eroding rocks, water is really too soft to do much damage alone. Water does transport sedimentary particles that are every bit as hard, at least, as most rocks, and it is the action of this sediment load that actually does most of the work.

Nowhere is this more obvious than in streambeds with potholes. Each hole, regardless of how shallow or deep, has numerous cobbles and pebbles in it, along with sand. When the water is flowing quickly over the potholes it cannot lift the coarsest particles out of the holes, but it can drag them across the bottom.

In eddies, which are very common in fast water, the dragging is in circular paths. The abrasion of the bed that results initiates a shallow pothole. After that, the positions of the potholes partially control where the eddies can form, further dragging the gravel in the bottom of the hole and deepening it. As you can see from the ones in Japan, such holes can get quite deep.

The fine sediment abraded from the hole and from the gravel grains is transported away downstream. What was large rocks has been turned into smaller pieces (mechanically weathered, in other words) and carried away.

Windblown sand is even more efficient than waterborne sediment at abrasion because the air offers less cushion to the individual impacts. Its effects are particularly obvious in deserts, and at different scales.

The principle direction of wind flow in an area is called the **prevailing wind direction**. Individual rocks are often polished on the upwind side into *ventifacts* (right).

Larger bedrock features are often sculpted into streamlined features called yardangs (a Turkish word) that taper lower in the downwind direction.

The Sphinx of Egypt is shaped very much like a yardang and was built by facing a similar bedrock feature with smooth stones. Unfortunately for that interesting little hypothesis, it faces downwind, not upwind.

Ventifact – sandblasted cobble or bolder.



Photo by Mark Wilson, Creative Commons/Wikipedia



Yardang – sandblasted knoll or butte.

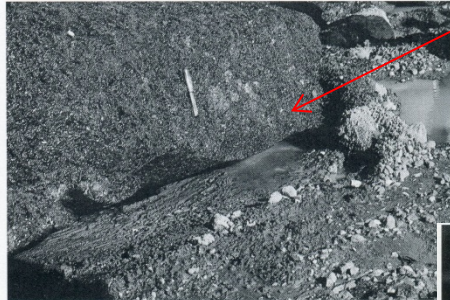


Photo by Michael Welland, from <http://blogs.agu.org/georneys/2011/05/19/geology-word-of-the-week-y-is-for-yardang/> Used under fair use clause of copyright law.

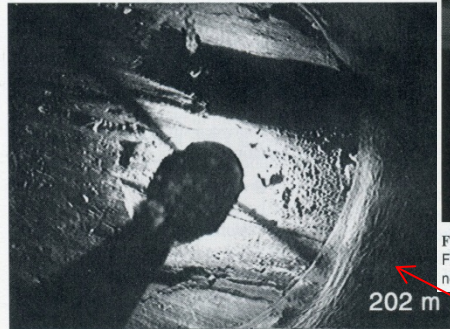


Yardang? – body facing stones removed for repair and cleaning. (Counterargument is that it faces the wrong direction.)





A.



B.

**FIGURE 12-5**  
(A) Basal sliding of the Breidamerkur Glacier, Iceland. Note the small grooves made by ice sliding over subglacial deposits.  
(B) Borehole photo at the base of the Worthington Glacier, Alaska, 202 m below the surface of the glacier. (From Harper and Humphrey, 1995)



**FIGURE 12-35**  
Faceted, polished, and striated cobble from a glacial deposit near Bellingham, Washington.



Glacial ice also typically has rocks of various sizes embedded in its base. The moving glacier plucks and otherwise dislodges the rocks from below and then drags them across the underlying rock as it moves, with predictable results.

In the pictures you can see grooves left in the underlying rock after the ice has melted (12-5A) and below an active glacier, as seen in a borehole through the ice (121-5B)

Of course the rocks being scraped across the bedrock are also abraded in the process as you can see (12-35). This cobble was collected from a pile left at the end of a long-gone glacier.

## 2 – Exfoliation or Unloading or Pressure Release.

When you inflate a balloon the shape is exactly right to balance the internal pressure of the air *inside* the balloon with the internal pressure of the air *outside* the balloon. The elastic balloon stretches at all the right places to make this possible.

When you take the balloon into a higher pressure setting, like the bottom of a pool, the pressure equality inside and outside is maintained by compressing the air inside until it equals the water pressure outside. This changes the *volume* of the balloon, as you can tell from the hand. In the case of a balloon, it also changes the *shape* because the air has a lower density than the water and so is forced into the upper part of the balloon. In a thicker, spherical vessel only the compaction would be apparent.

Rocks deep in the crust are under a much higher **confining pressure** than this balloon, and are compressed as a consequence, even though they are quite solid.

What do you think happened when I brought The balloon *back* to the surface?



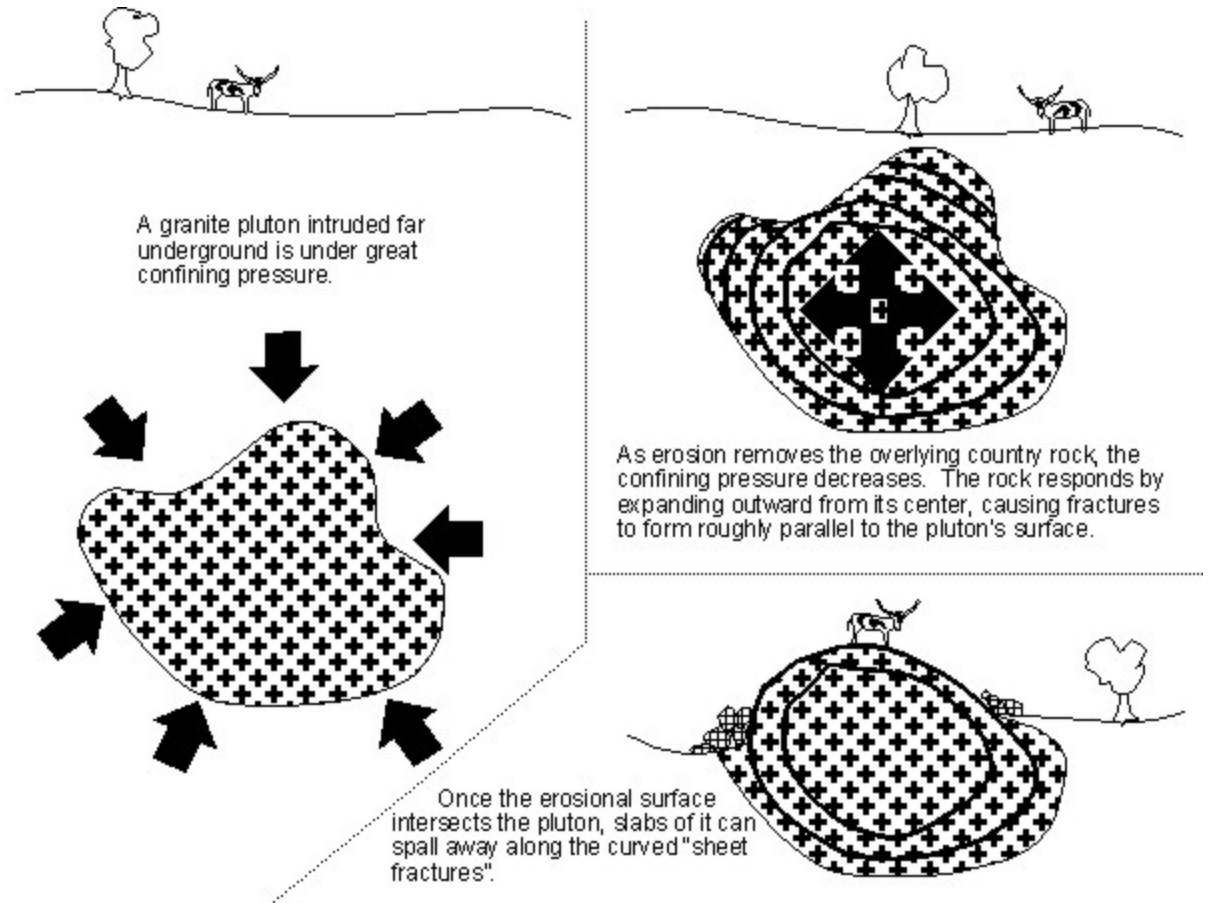
Consider what happens when a granitic pluton that has crystallized 10km deep in the crust is involved in a regional uplift.

Erosion of the overlying country rock brings it closer and closer to Earth's surface (or, to be precise, brings the surface closer and closer to it)

Because it experiences progressively lower confining pressure it can expand, just as the balloon does when we bring it back to the water's surface.

Once it is exposed at the surface the expansion produces fractures within the pluton that are oriented at right angles to any line drawn from its center toward its surface – that is, roughly parallel to the external shape of the pluton, but more regularly rounded.

I'm sure many of you have seen something like this, at least in pictures.









You can find many pictures of my favorite exfoliation dome on Google, but this is one of the best. The outermost concentric crack (joint) in Enchanted Rock, Texas is very obvious under all the thin slabs perched on the hillside. As the shell they belonged to pulled away from the underlying rock it was subjected to internal tension. Think of the increased size of a balloon's rubber as you blow it up – each increase in size makes the rubber shell bigger. The rubber balloon can stretch as it expands, but when you try to stretch rock hard enough it just breaks. In this setting it breaks into polygonal pieces all across its expanse, not unlike the polygonal cracks in columnar basalt. (These, of course, only go through the one shell, not the entire mass.) The next slide illustrates this. When the cracks are open enough to free the individual slabs they can slide down the side of the mountain, and you can see that many have, in fact, accumulated there as **talus** or **scree**.



You'll also see, if you look at the talus carefully, that another type of mechanical weathering is going on here.

All the pieces at the bottom of the hill are *smaller* than those still on the hill, and even smaller the farther down the pile you look. As each new piece slides into the pile the force of the impact breaks it *and* the rocks it hits, *and* the ones they press into, and so on.

And as the piece slides it grinds its base against the rock below, with consequences you can surely imagine.



## (START AT THE BOTTOM!)

3

When the radius of one circle is greater than the radius of another, the *circumference* of the first will also be greater. That is, the length of its arc will be greater. Therefore, if a rock layer moves outward from an exfoliating pluton the same amount of rock will have to be “stretched” into a longer arc. It goes without saying that rocks don’t stretch, but the internal stress still has to be accommodated. Since *elastic* stretching is out of the question, *brittle* fracturing happens instead. The black lines represent cracks in the rock “shell”. The sum of the rock segment lengths plus the crack widths would equal the new circumference of the shell. **The sum of the rock fragment lengths alone would equal the original radius!** The cracks account for the difference.

(Both the expansion and the initial crack widths are highly exaggerated here for effect.)

Photo by Caleb Simpson at <http://organicclimber.com/tag/enchanted-rock/>



2

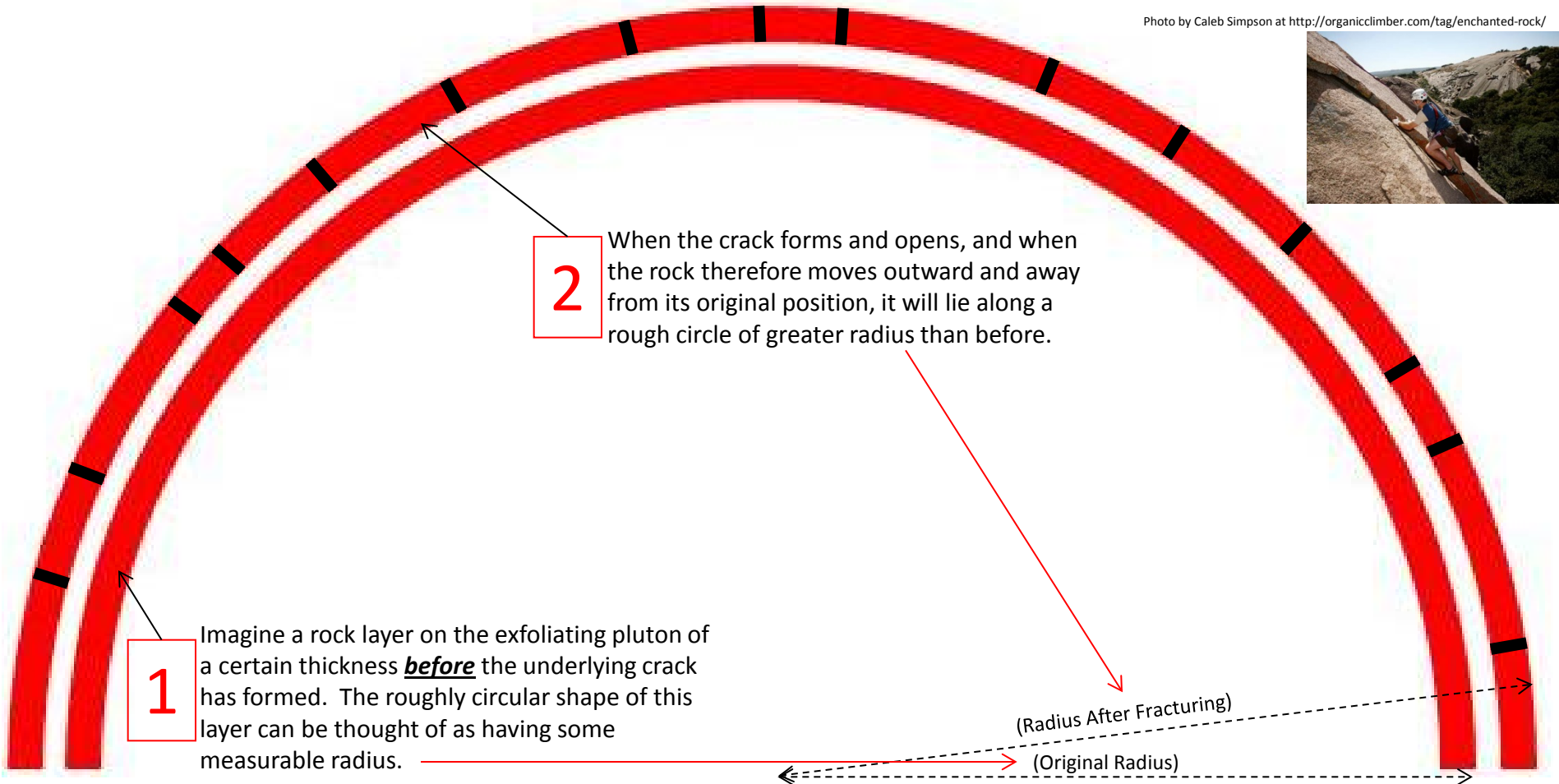
When the crack forms and opens, and when the rock therefore moves outward and away from its original position, it will lie along a rough circle of greater radius than before.

1

Imagine a rock layer on the exfoliating pluton of a certain thickness **before** the underlying crack has formed. The roughly circular shape of this layer can be thought of as having some measurable radius.

(Radius After Fracturing)

(Original Radius)





### 3 – Thermal Expansion and Contraction.

Several years ago my neighbor had his land logged. As usual, at the end of the process the leftover limbs and small trees were bulldozed into piles to be burned, along with many chert cobbles and boulders that were originally scattered on the forest floor.

You can see the consequences of the fire to those rocks. The intense heat made them expand – particularly towards their outsides – and pieces spalled off just as they would during pressure release. (Compare the bottom left photograph with the photo of Enchanted Rock two slides back.)

In addition, the rocks got hot farther inward, and the resulting expansion (and ultimate contraction back to the original size) produced internal stresses that cracked them through.

What were originally solid (and very hard) cobbles and boulders were broken into substantially smaller pieces.

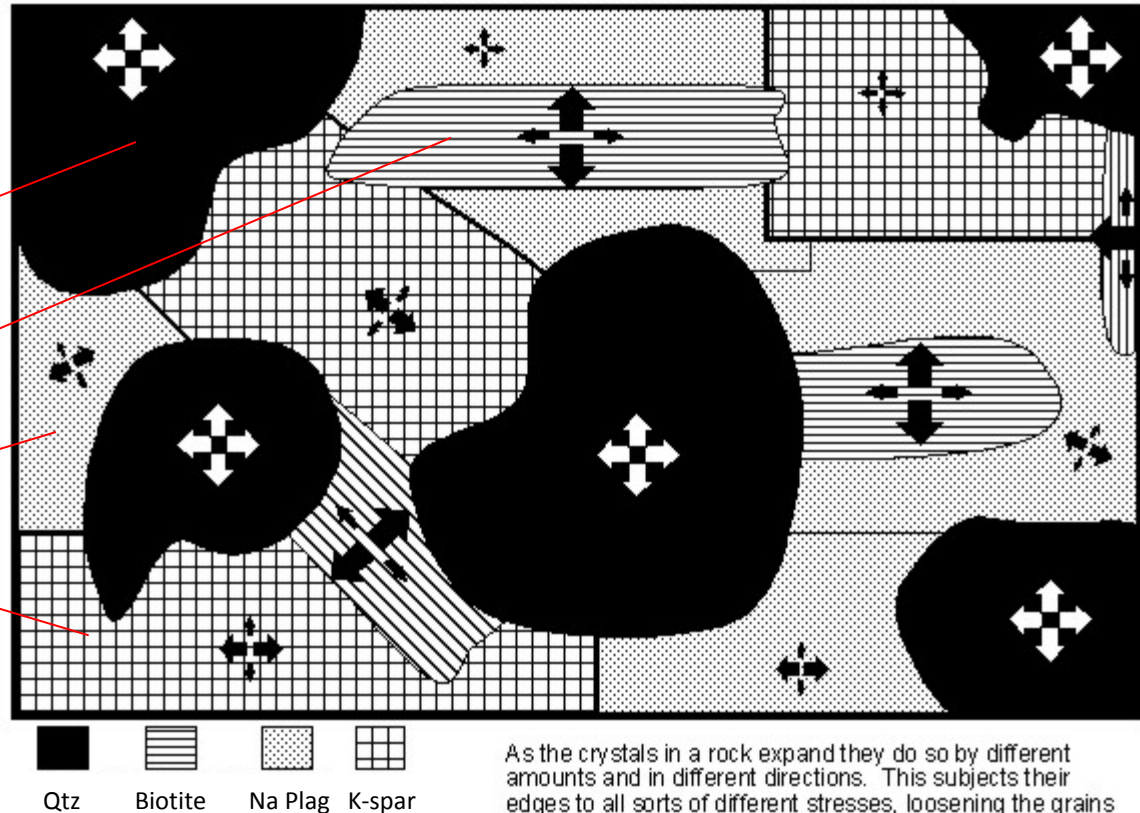
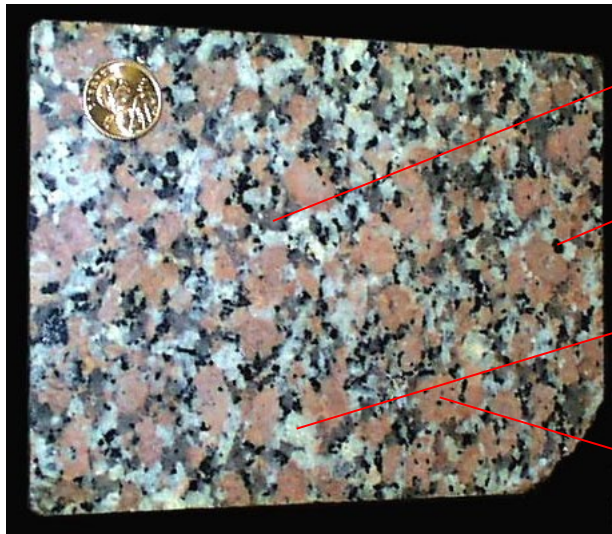


Coin is  
about  
2.5mm in  
diameter



There is some question about whether daily solar heating and cooling of a rock can cause a similar breakdown. When pristine, unweathered pieces of granite were put into a chamber whose temperature could rapidly change from daytime to nighttime temperatures and back, over and over, no evidence of mechanical weathering was seen, even after many years worth of model days and nights.

If the weathering *does* happen in nature then it is because of two different things. First, the sun will obviously heat the outer part of a rock more than the inner part. Second, each mineral within the rock will expand and contract to differing degrees, and most will expand more in some directions than others, as the arrows indicate below. Quartz expands the same in all directions, but micas expand more perpendicular to their sheets than parallel to them, for example. This generates differential stresses at every grain boundary within the rock, pushing and sliding each crystal in different directions at each boundary.



As the crystals in a rock expand they do so by different amounts and in different directions. This subjects their edges to all sorts of different stresses, loosening the grains when they push against at some angle to each other.



Whether pristine granite breaks under the stress of heating and cooling in an artificial low temperature oven, there is good evidence that rocks *do* break when they are naturally heated by the sun and cooled by the night air.

Enchanted Rock is called that because of the ruckus it makes as it heats up in the morning and cools down at night. It groans and creaks and pops, clearly in response to the changing temperature. Perhaps the fact that cracks are already present, and that other weathering phenomena are happening as well allows the thermal expansion and contraction to operate, but operate it does.





## 4 – Freeze/Thaw or Frost Wedging or Frost Action.

Growing ice crystals exert a force on whatever they grow against. You can see sizeable pebbles, an inch or more across, raised off the ground by these thin crystals growing out of the soil pores on a cold morning near my house.



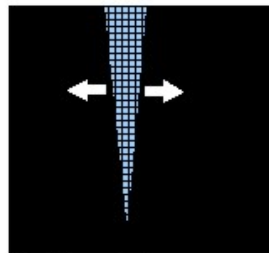
Ice begins to expand just as it begins to form, and the increase in volume is about 9% over a range of about 4°C. (This is why 91% of an iceberg is below the water.)

The short version is that the pressure exerted by the expanding ice in cracks (below) or pores in rock presses on the openings' sides and force them apart. If this happens in a crack repeatedly, with addition of new water periodically, the crack will both widen and deepen. Of course this cannot *start* a crack, only enlarge one that is already there, for example on an exfoliating pluton.

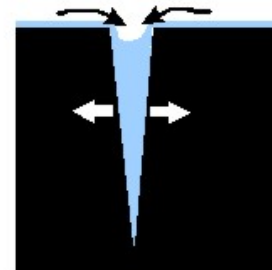
Experimental evidence makes it clear that exactly what happens is not this simple, and some writers question whether this process is important at all. However, they do so by ignoring the evidence of ubiquitous shattered rock in cold-temperate places (see the next slide) and the fact that miners used to work slabs out of quarries by drilling closely spaces holes, filling them with water, plugging the holes, and waiting for winter. It worked like a charm.



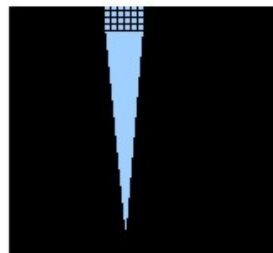
A small crack in a rock fills with water during the daytime. As the water begins to freeze at night, it starts at the top, sealing the crack.



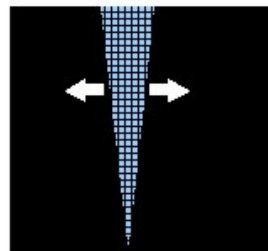
As the water freezes completely, its 9% growth exerts an outward force on the sides of the crack, increasing the size of the crack by a maximum of 9%.



If the ice thaws the next day the resulting water will not fill the crack, which is now both wider and deeper because of its 9% expansion. Dew or rainfall on the rock surface can refill the crack.



The process begins again, this time with a larger initial crack.

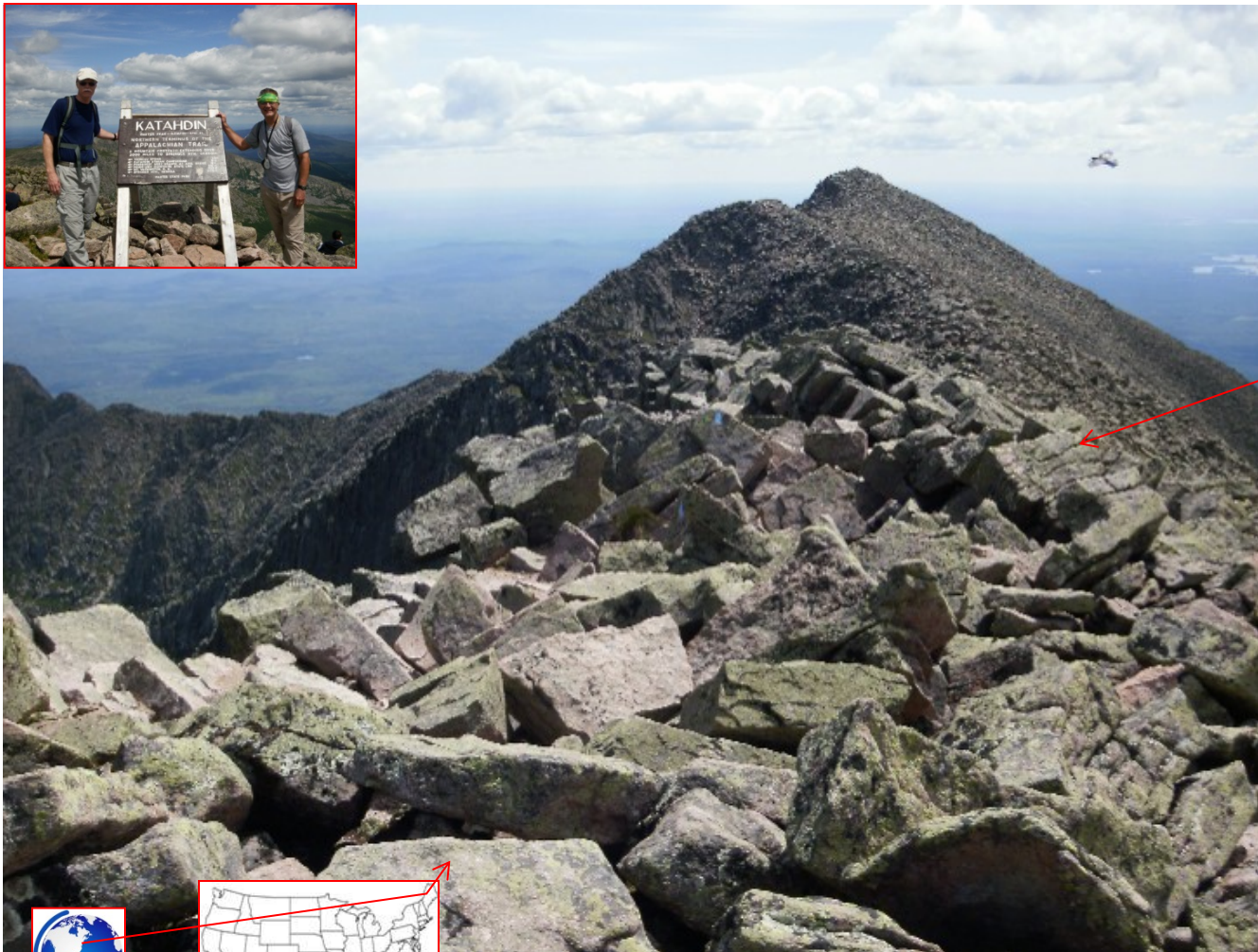


Again the crack expands by as much as 9%. Continued freezing and thawing, particularly with the daily addition of water to keep the crack full, eventually does significant fracturing of the rock.



Though there is abundant evidence for glaciation around Mount Katahdin in Maine, the evidence is all *around* it. The summit was above the ice during the glacial periods of the last few million years, just as the summits of several mountains are above the ice that otherwise covers Antarctica. (Look on Google Maps!)

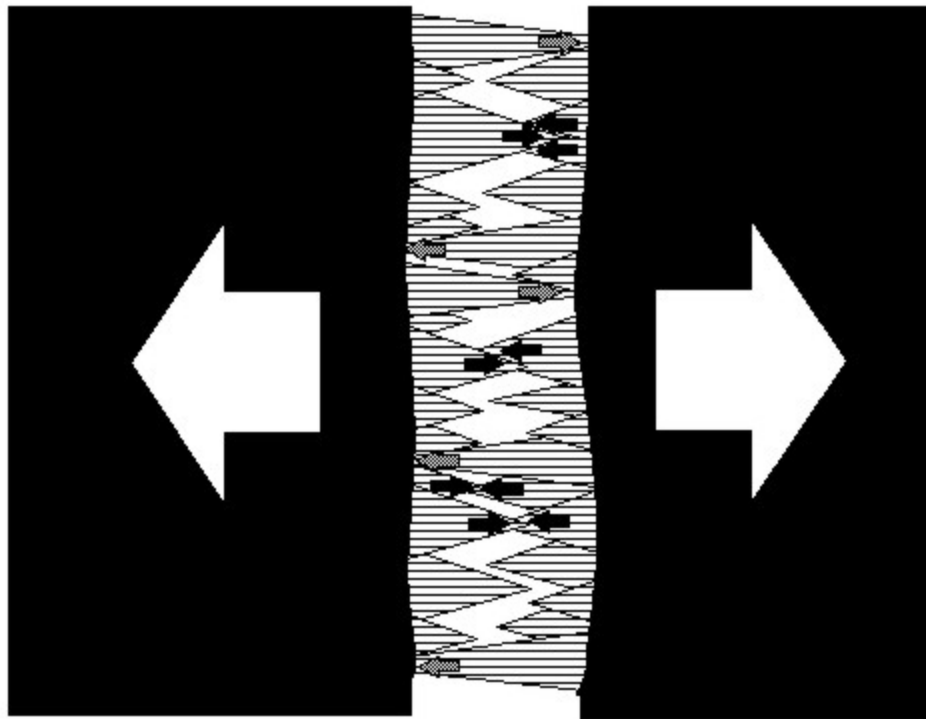
Glaciers are very good at breaking rocks and moving them, but the rocks you see here were not put here by a glacier because the tops of the glaciers were lower than this. So how did they get here? What can we rule out?



- 1) Impacts. These rocks are at the very top of the mountain. Only meteors could impact them here.
- 2) Exfoliation. This is granite, but the glacial and other erosion in this area is so recent that there is no sign of exfoliation of, for example, the sharp granite peak in the background. *Internally* the boulders have layering that might be from exfoliation, but clearly these are fractured as much *across* that layering as along it.
- 3) Thermal expansion and contraction. This is no more common here than it is at, say, Enchanted Rock, where we do not see anything like these piled up on top of the mountain. Also, these rocks are nearly as big as I am. Thermal expansion and contraction should make smaller pieces.
- 4) There are two other means of mechanical weathering that we have not yet covered, but one requires trees, which are conspicuously absent. The other requires abundant groundwater, and there is none at all here. My brother and I were *very* thirsty when we got back down to the closest spring.
- 5) **That leaves frost wedging as the only viable alternative.**

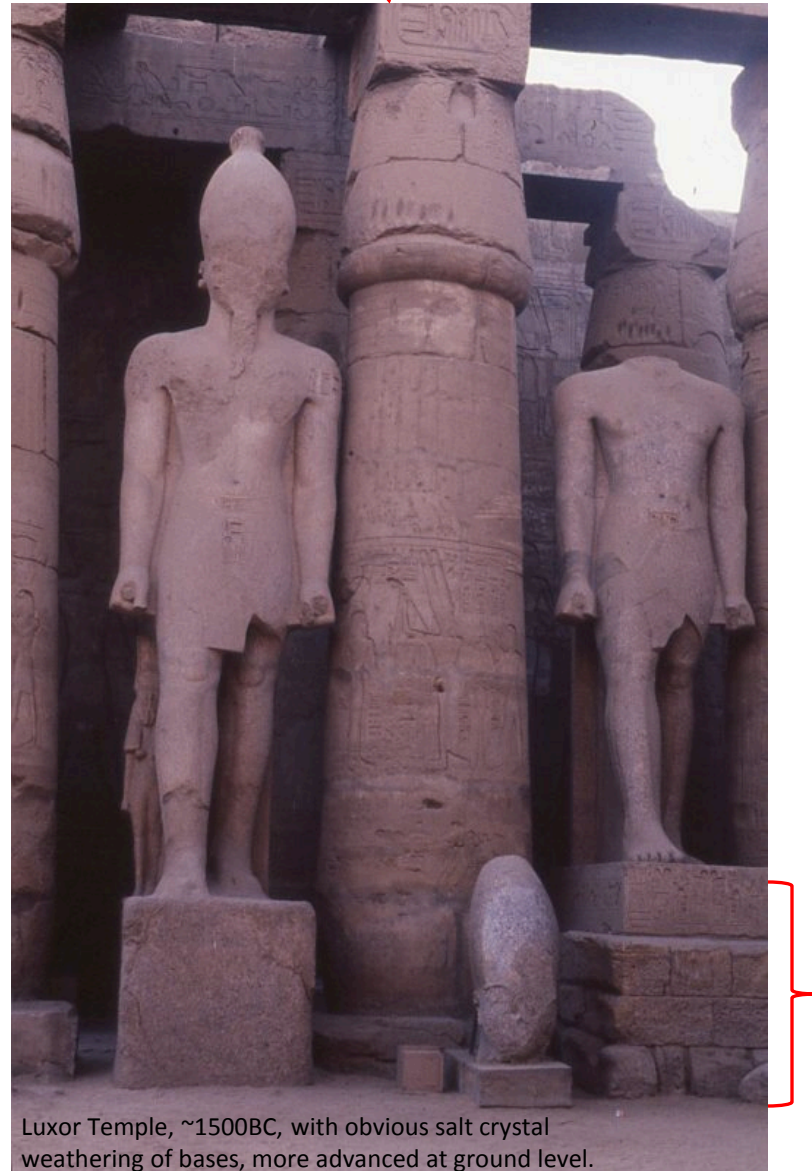
## 5 – Crystal Growth.

This is quite similar to frost action, but the crystals are not ice. Instead they are crystals of “salt” – dissolved material that is usually not NaCl – crystallizing from groundwater in cracks and pores. Otherwise the logic is the same. There is a force of crystallization that accompanies the growth. As long as the crystals grow into the crack they are free to grow as they will, but when they reach the opposite wall (or the crystals growing from it) they begin to push, with familiar consequences.



As crystals grow outward from one wall of a crack they eventually either contact the opposite wall (gray arrows) or the growing ends of other crystals growing from the opposite wall (solid arrows). The sum of all the tiny forces thus generated creates a much larger force pushing the two sides of the crack in opposite directions (white arrows)





Luxor Temple, ~1500BC, with obvious salt crystal weathering of bases, more advanced at ground level.

Al Azhar Mosque, Cairo  
Built 972 AD and houses the  
world's oldest university. Salt  
crystal growth from the  
gypsum-rich groundwater is  
destroying the lower courses  
of limestone blocks.



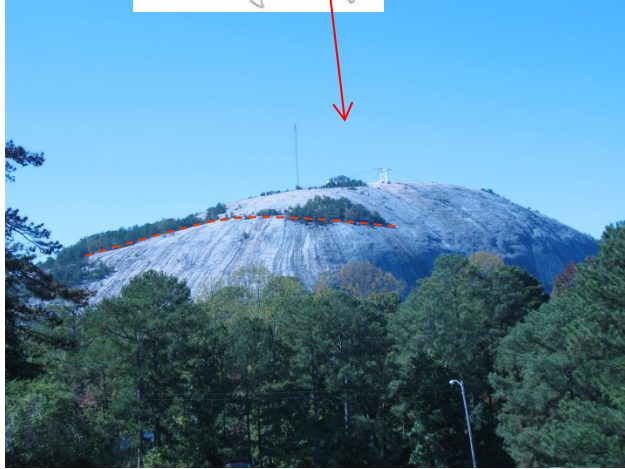


## 6 – Biological Activity.

The trees growing on Stone Mountain are certainly not sending their roots into the solid granite, but rather into exfoliation fractures. The fairly curvilinear trend of the woods suggests there may be a single major crack (and some broken pieces) that has allowed the trees to establish themselves.

The dark stripes down the side of the mountain (and down Enchanted Rock – check and see) are from running water. The exfoliation cracks hold water for extended periods after rain, releasing it very slowly at their lower edge.

The roots of the trees cannot exert a huge amount of pressure on the crack walls, but they do exert a little, and they do take advantage of every slight widening of the crack by other means to increase their diameter. This keeps the cracks open and speeds the process of other weathering mechanisms even if the roots themselves cannot break the rock.







That growing roots do exert *some* force is obvious almost everywhere you look. The sidewalk that goes beside the large magnolia tree on GSW's front campus has been heaved up by the roots growing beneath it.

Some years ago all the heaved sidewalk blocks (for whatever reason) were ground off so people wouldn't trip on them.

The lower picture shows a projection of the original top of the block (long dashed line) along with how much was removed by the grinder (vertical dashed line).

There was not a huge force involved. You could probably lift the block with a strong 2 meter pry bar, but clearly some force was indeed applied.





# Chemical Weathering

## 1 – Hydrolysis

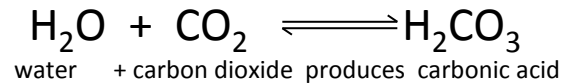
There are numerous types of chemical weathering reactions, but all are variations on one of three themes and the three basic themes are also the most common weathering mechanisms. We begin with hydrolysis.

Judging from the name this process has to do with the action of hydrogen. Hydrogen ions ( $H^+$ ) are what create the reactions we call “acidity” in acids. Surface and near-surface waters and rainwater on Earth are frequently slightly acidic, with the acid coming principally from two sources.

1) Humic, tannic and other organic acids from the decay of organic matter (principally leaves) in soil. The rain that falls on the ground leaches some of this acid before soaking in and interacting with the deeper soil and with bedrock. The  $H^+$  ions it carries are the main reason it accomplishes most of the chemical weathering it does, and it accomplishes a *lot* of chemical weathering. But even before it begins to interact with organic matter on the ground, rainwater already contains a weak acid called

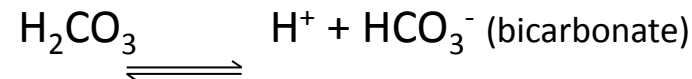
2) Carbonic acid from reaction with atmospheric  $CO_2$ . Gasses “dissolving” in water actually means something a little different than solids “dissolving” in water. Solids have their bonds broken and individual ions are thereby freed into the liquid. Gasses remain as molecules in most cases, spread evenly between the water molecules. A few gasses, including  $CO_2$ , do enter to slight degree into chemical reaction with the water, bonding their molecules to make a more complex compound. When this happens to  $H_2O$  and  $CO_2$  the result is carbonic acid. The next slide elaborates on this reaction and its consequences to acidity.

The basic equation for the reaction is this:



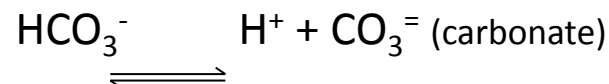
The double arrow indicates that the reaction continues to an equilibrium point and then stops. If some of the products are used up then more are made because the reaction resumes. On the other hand, if some of the CO<sub>2</sub> is removed the reaction operates in the reverse direction and the concentration of carbonic acid is reduced.

Carbonic acid behaves as a weak acid because it dissociates to a small degree to produce H<sup>+</sup> ions by this equilibrium reaction:



Remember that only a little dissolved carbon dioxide actually reacts chemically with water, so the concentration of the acid in rainwater is very low. Furthermore there is a limited dissociation to ions and so the acidity is quite low – the acid is very weak.

It is also true that the bicarbonate dissociates very slightly too, according to the following equation, making an additional tiny amount of H<sup>+</sup> available, but that amount is so small it almost isn't worth mentioning. What *is* worth mentioning is the other product – CO<sub>3</sub><sup>=</sup> -- that ion is **carbonate** and this is the source of that ion in carbonate minerals like **calcite**, the mineral in **limestone**. So we will be revisiting this equation when we talk about limestone.

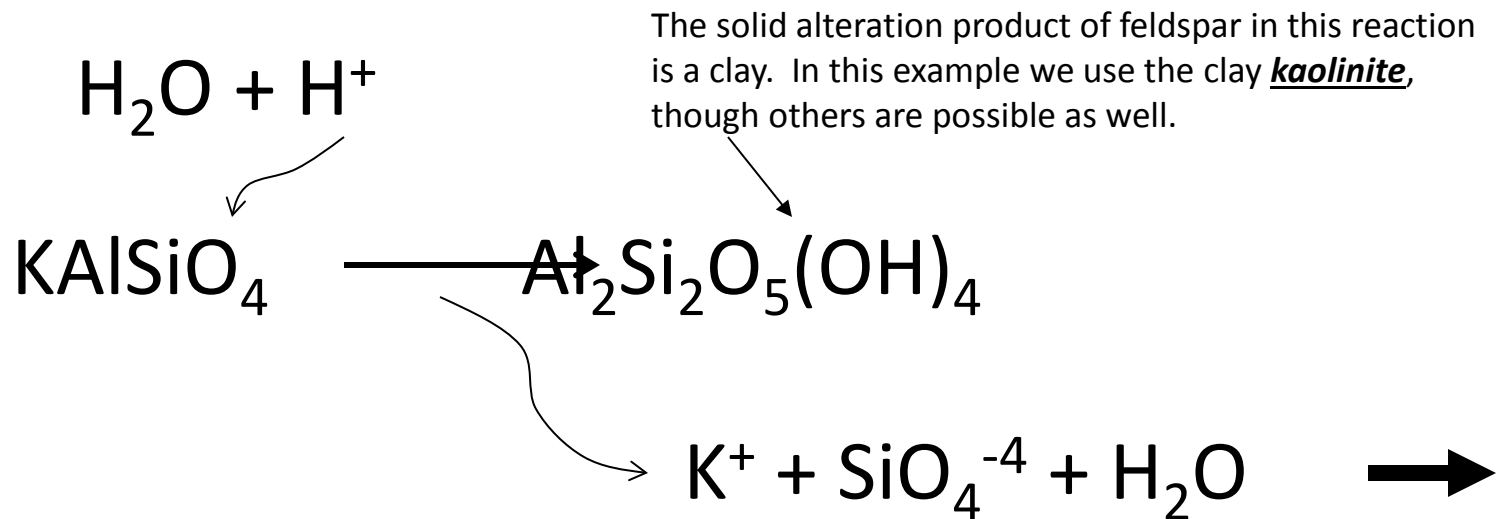


The hydrogen ions from these equations enter into two of the weathering processes we will be examining.

For illustrating weathering by hydrolysis we will use the example of what happens to potassium feldspar, a common constituent mineral of granite.

The formula for K spar is  $\text{KAlSi}_3\text{O}_8$  the Al in the structure makes this an aluminosilicate. Hydrolysis is the predominant weathering mechanism of aluminosilicates, and all the common igneous minerals except olivine and quartz are aluminosilicates. This means that this mechanism (and variations on it) are the most important chemical weathering phenomena on Earth, since most minerals are susceptible.

The  $\text{H}^+$  in an acidic solution does not actually substitute for the cation in this process, but it does interfere with its bond and strip it out of the mineral being weathered. This leaves the remaining chemical structure electrically unbalanced. Without the gory details (that is, without bothering to balance the complex equation), this is fixed by removing  $\text{SiO}_4$  tetrahedra ("silica in solution") from the structure as well, though not in the 1:1 ratio with potassium implied by the simple version below.



The potassium and silicate ions are dissolved in the water and are carried away by it to wherever it goes.

In the previous slide we saw that hydrolysis of potassium feldspar produces a clay mineral (e.g., kaolinite) and potassium ions as products. The clay mineral can become part of sedimentary rock called **mudstone** or **shale**. The ions can become parts of sedimentary rocks as well, but we will put off seeing how this happens. *Do not forget about them because they are as important as the clay when we think about sediments.*

Suppose that instead of K spar that a sodium plagioclase was the mineral being weathered. What would be different about the products? What about if it were a calcium plagioclase? (The formulas for the plagioclase feldspars are virtually the same as for the K spar.)

Hydrolysis, simply defined, is that process by which acidic water strips the major cations and a lesser amount of silica from the crystal structure of an aluminosilicate, turning it into a clay mineral in the process.

All the feldspars, all the micas, all the amphiboles, and most pyroxenes are weathered in this fashion, once they are exposed to rain and atmospheric CO<sub>2</sub> near the Earth's surface.

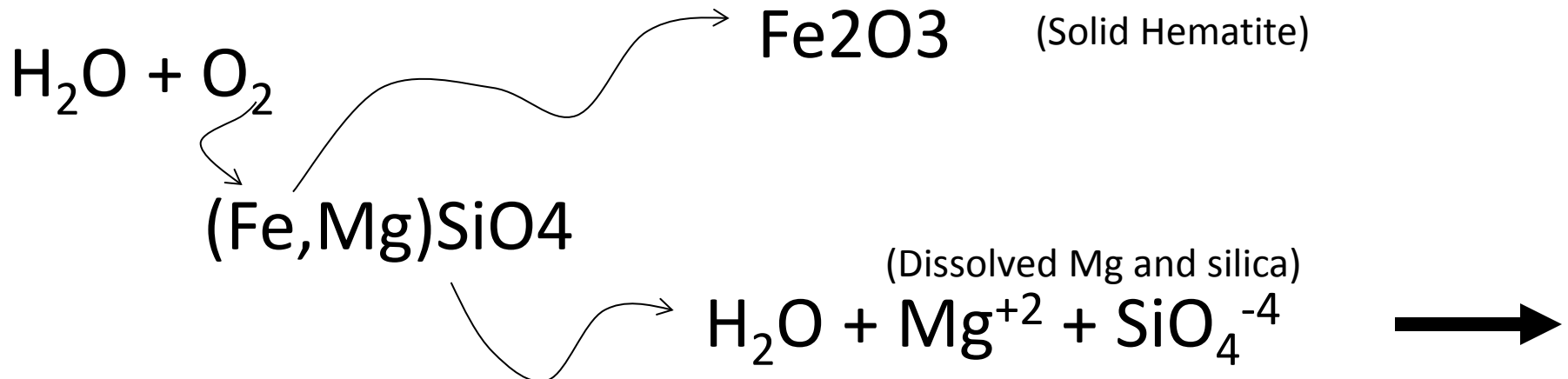
# Chemical Weathering

## 2 – Oxidation

Rainwater, surface waters, and shallow groundwater all have O<sub>2</sub> molecules dissolved in them as well as CO<sub>2</sub> molecules. Unlike the CO<sub>2</sub> the oxygen does not react chemically with the water. The water simply carries it around. If it encounters a mineral with iron in it (or some other metallic cations) the oxygen can weather the mineral by oxidation. You are very familiar with this process.

In oxidation the oxygen carried by the water (which can ionize to O<sup>-</sup> in the presence of reduced iron) is substituted for the original anion in the mineral, creating a new mineral called hematite. The original anion (and soluble cations like Mg<sup>+2</sup>) is carried away by the water, and can become part of sedimentary rocks somewhere else.

As an example we will use olivine, though *all* the ferromagnesian minerals are affected by this process. (If they are also aluminosilicates then they will be hydrolized as well!)



Hematite is the mineral that makes red clay in the South red. You won't have to look far to find some of this very common weathering product.



New Point Church Rd or Pa's Rd near Americus, GA





# Chemical Weathering

## 3 – Solution

A brief recap is in order here.

**Hydrolysis** alters a mineral by stripping its principle cations (and silica) and it leaves a solid residue in the form of a **clay mineral**.

**Oxidation** alters a mineral by removing its anion and placing oxygen in its place. It leaves a solid residue in the form of **hematite**.

The third type of weathering we will examine is called **solution** (or *dissolution*). This process dissolves **ALL** the ions from a mineral, cations and anions alike, and it leaves **no solid residue**. In fact, it leaves a cavity in the remianing rock that we call a *cave* or a *vug*, depending on the size.



Subterranean stream in a limestone cave, Krizna Jama, Slovenia. (Photo by A. N. Palmer)

Some minerals, like halite and gypsum, are highly soluble in fresh water and can simply dissolve in water without any acidity. There are caves in such rocks, but the effects of solution weathering is most common in rocks made of carbonate minerals, including calcite. These require acidic water to weather.

The sedimentary rock limestone and the metamorphic rock marble are both made of calcite (or another carbonate mineral that weathers similarly).

You actually force this type of weathering when you drip acid on a piece of calcite. Nature doesn't make a lot of hydrochloric acid, but any old one will do.

