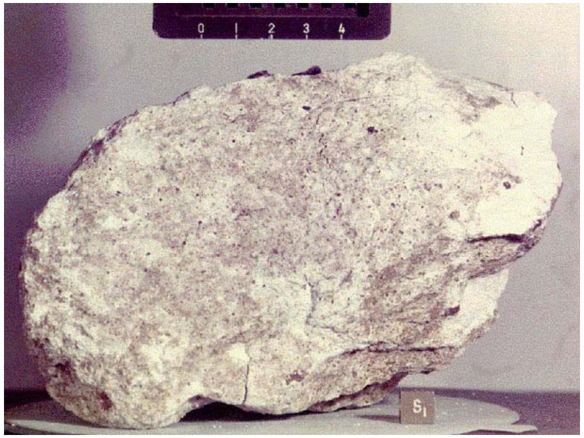
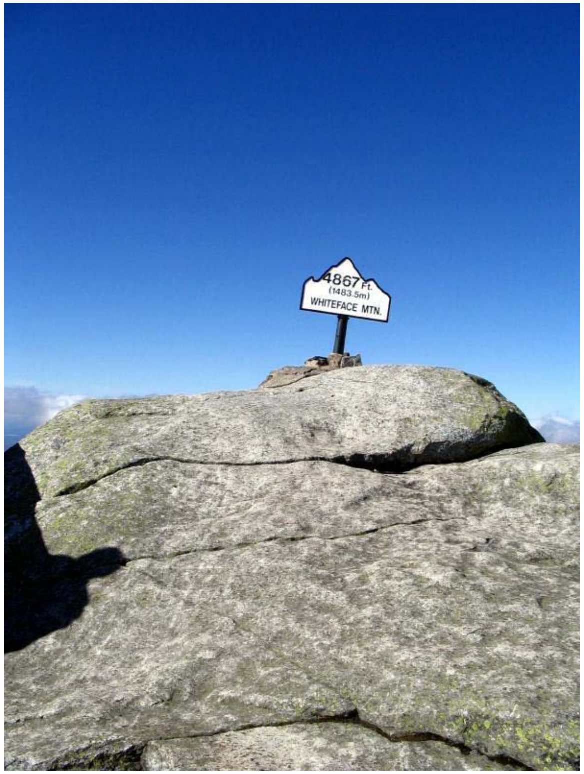
# Today in Astronomy 111: moon rocks

- ☐ The minerals and rocks common on the Moon
- ☐ The Moon's composition
- ☐ Trace elements in minerals
- ☐ Radioisotope dating
- ☐ The age of moon rocks

**Homework #2 is available now; due Friday, 9/16/2011, Dan's office.**

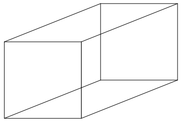
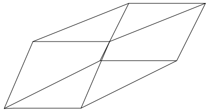




Top: anorthosite boulder, retrieved from the Lunar highlands by the crew of Apollo 16. Bottom: anorthosite boulder, left behind in the Adirondack highlands by Ronald Correia.

# The most abundant silicates

"Mafic" minerals

| | | |
|---|---|---|
| Olivine | Forsterite | $Mg_2SiO_4$ |
| | Fayalite | $Fe_2SiO_4$ |
| Pyroxene<br>Orthorhombic<br><br>or monoclinic<br> | Enstatite | $Mg_2(SiO_3)_2$ |
| | Hypersthene | $MgFe(SiO_3)_2$ |
| | Ferrosilite | $Fe_2(SiO_3)_2$ |
| | Diopside | $CaMg(SiO_3)_2$ |
| | Augite | $Ca[Mg,Fe,Al][Al,Si]_2O_6$ |
| | Hedenbergite | $CaFe(SiO_3)_2$ |

# The most abundant silicates (continued)

“Felsic” minerals

- Feldspar
  - Orthoclase — $KAlSi_3O_8$
  - Plagioclase
    - Albite — $NaAlSi_3O_8$
    - Anorthitite — $CaAl_2Si_3O_8$
- Silica — Tridymite, Cristobalite, Quartz — $SiO_2$

Garnet — $[Mg,Fe,Ca]_3[Al,Cr]_2(SiO_4)_3$

Not really silicates, but considered good friends of the family:

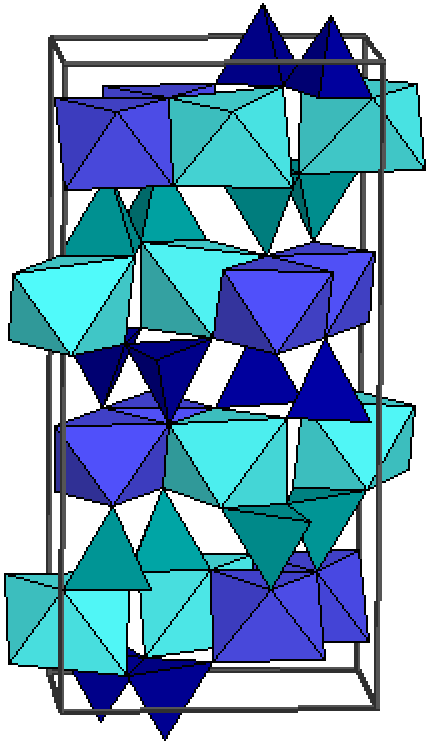
Spinel — $MgAl_2O_4$

Ilmenite — $FeTiO_3$

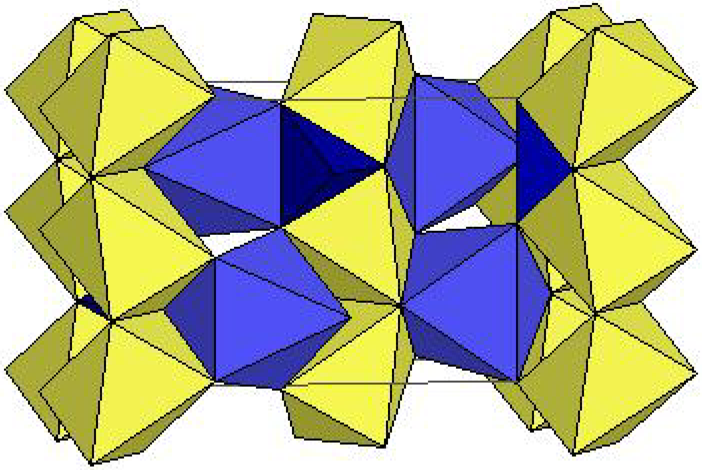
# Crystal structure

In these drawings the tetrahedra are $SiO_4$ units, and the octahedra are back-to-back $SiO_3$ units.

(ortho-) Enstatite



(clino-) Garnet



From Joe Smyth's [mineral-structure database]()

# Common igneous rocks and their major mineral ingredients

Volcanic (**extrusive**) rocks

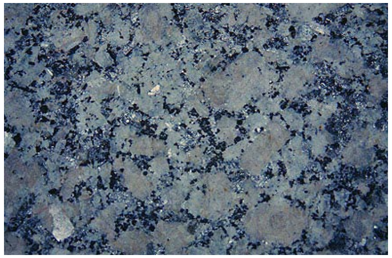
- ☐ Basalt: pyroxenes, plagioclase
- ☐ Andesite: plagioclase, mafic minerals
- ☐ Rhyolite: quartz, orthoclase, plagioclase

Plutonic (**intrusive**) rocks

- ☐ Granite: quartz, orthoclase, plagioclase
- ☐ Diorite: plagioclase, mafic minerals
- ☐ Gabbro: pyroxenes, plagioclase
- ☐ Troctolite: olivines, plagioclase
- ☐ Anorthosite: almost all plagioclase
- ☐ Peridotite: olivines, pyroxenes


Basalt

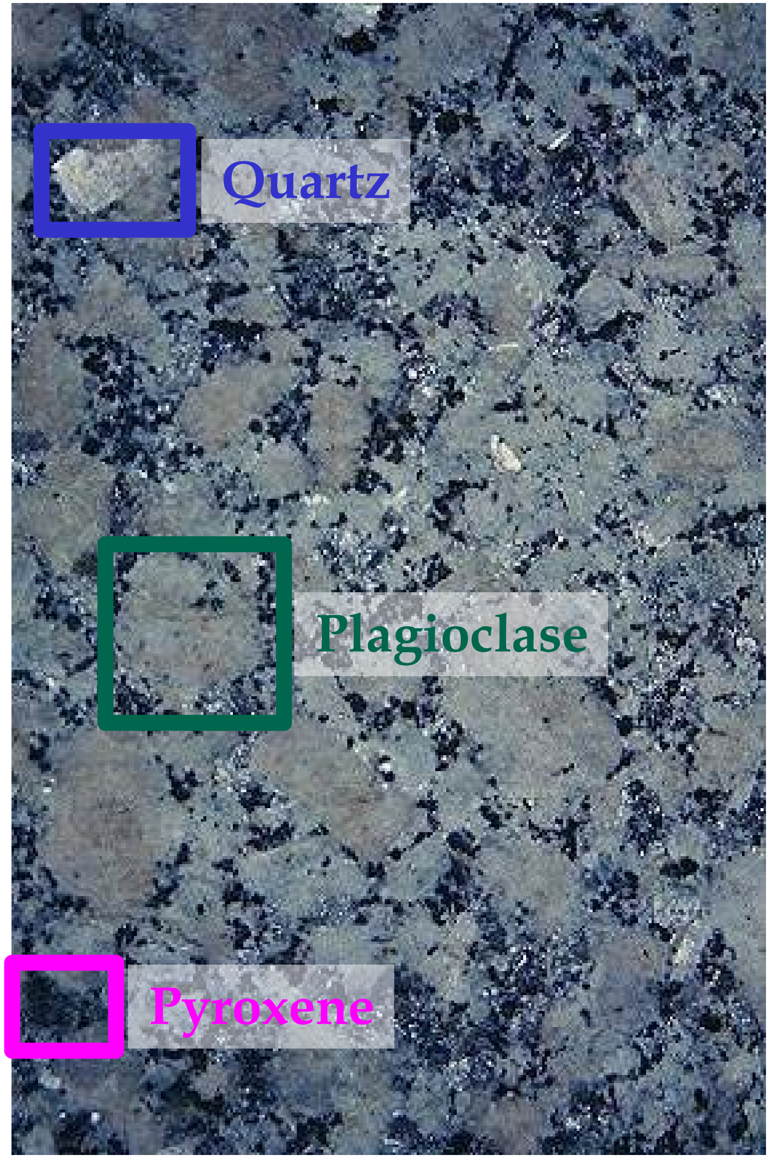

Gabbro


Granite

Images from Volcano World (U.N.Dak.)

# Igneous rocks

Basalt: Devil’s Postpile National Monument, CA.



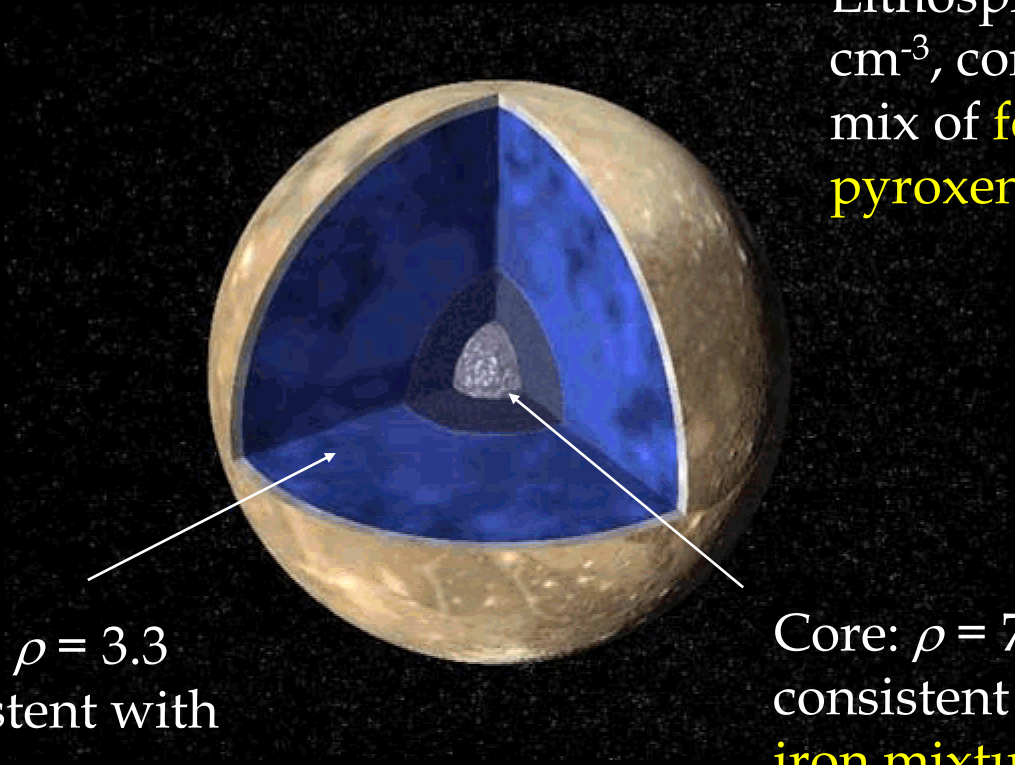
Granite (Volcano World,U.N.Dak.)

# Mineral density

| Mineral (family) |  | Density (gm cm$^{-3}$) |  |
|---|---|---|---|
| Orthoclase | (feldspar) | 2.55 | Felsic minerals |
| Quartz | (silica) | 2.56 |  |
| Albite | (feldspar) | 2.61 |  |
| Anorthite | (feldspar) | 2.76 |  |
| Enstatite | (orthopyroxene) | 3.204 | Mafic minerals |
| Forsterite | (olivine) | 3.227 |  |
| Diopside | (clinopyroxene) | 3.3 |  |
| Augite | (clinopyroxene) | 3.4 |  |
| Hedenbergite | (clinopyroxene) | 3.4 |  |
| Pyrope (Mg garnet) |  | 3.565 |  |
| Spinel |  | 3.578 |  |
| Ferrosilite | (orthopyroxene) | 4.002 |  |
| Fayalite | (olivine) | 4.402 |  |
| Ilmenite |  | 4.786 |  |

# Interior composition of the Moon

From the seismographically-determined distribution of densities and outward appearance.



Lithosphere: $\rho = 3$ gm cm$^{-3}$, consistent with a mix of feldspars and pyroxenes.

Asthenosphere: $\rho = 3.3$ gm cm$^{-3}$ , consistent with olivines and pyroxenes.

Core: $\rho = 7.2$ gm cm$^{-3}$, consistent with a nickel-iron mixture.

# The Moon’s most common surface minerals and rocks

Minerals

- Plagioclase
- Pyroxenes
- Olivines
- Ilmenite (!)
- Others <2%

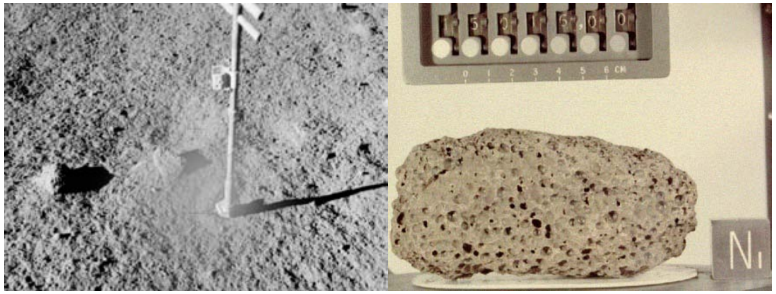
Highland rocks

- Gabbro
- Troctolite
- Anorthosite
- Mixtures of those three

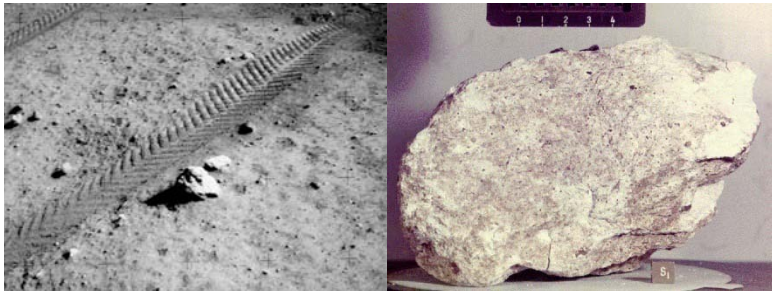
Mare rocks

- Basalt

*Mare basalt (Apollo 15)*



*Highland anorthosite (Apollo 16)*



# What happens to the other elements, besides the "mineral forming" ones?

The basic structure of the minerals is determined by the most abundant nonvolatile elements. What happens to the **trace** elements?

- ☐ If they are isoelectronic and similar in size with any of the constituents of a mineral, a trace-element atom can be **substituted** for the ordinary constituent, during the original freezing and crystallization of the rock. For example, Rb can be found in orthoclase, in place of K.
- ☐ If there isn't a good match, an element may still be incorporated **interstitially**: trapped between several properly-bonded atoms.
- ☐ Except for temperatures near absolute zero, different **isotopes** of a given element behave the same, chemically.
- ☐ The reaction rates for such substitutions can be measured in the laboratory, and used to calculate how much of each trace element would go into each mineral, as a function of temperature.
- ☐ Eminently useful: **radioactive isotopes** of the trace elements.

# Radionuclides, daughters and references

Definitions, first:

- ☐ **Nuclide** is the name we use to refer to the nucleus of an isotope of a given element.
- ☐ Radioactivity involves the decay of a **radionuclide** to a **daughter** nuclide. Most useful if the daughter is rare.
- ☐ A stable isotope of the **daughter** species, one which is not involved in radioactivity, serves as the **reference** nuclide.
- ☐ Suppose that within a given mineral sample, the numbers of these three nuclides are $n$, $d$, and $s$, respectively. Define the **relative abundances** of radionuclide and daughter:

$$N = n/s \quad , \quad D = d/s \quad .$$

These are independent of the amount of material analyzed, since the amount is proportional to $s$.

# Radioactivity

Some nuclides are radioactive, and will transmute into other nuclides over time. If one starts with a bunch of groups of a given nuclide, each group having a total of $n_0$ at $t = 0$, then after a time $t$ the average number remaining in a group is

$$n = n_0 e^{-\lambda t} \quad \xrightarrow[\text{divide by } s]{} \quad N = N_0 e^{-\lambda t} \quad ,$$

where $\lambda$ is the **decay rate** for the radionuclide, a quantity that has usually been measured accurately in the laboratory. $\lambda$ is related to the commonly-quoted **half-life**:

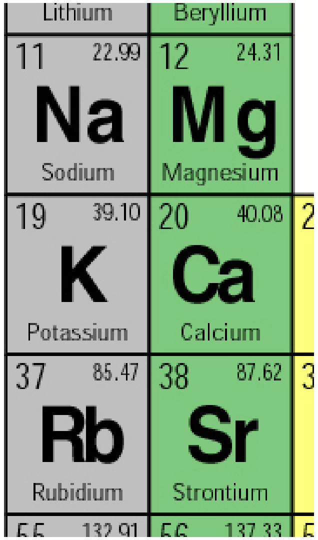
$$\frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} \Rightarrow -\ln 2 = -\lambda t_{1/2} \Rightarrow t_{1/2} = \frac{\ln 2}{\lambda} \quad .$$

# Important example: the Rb-Sr system

- Rubidium is an alkali; it can replace the much-more-abundant sodium and potassium in minerals (e.g. feldspars). It has one stable isotope, $^{85}\mathrm{Rb}$, and one long-lived radioisotope, $^{87}\mathrm{Rb}$.
- Strontium is an alkaline, and can replace magnesium and calcium in feldspars. It has four stable isotopes: $^{84}\mathrm{Sr}$, $^{86}\mathrm{Sr}$, $^{87}\mathrm{Sr}$ and $^{88}\mathrm{Sr}$. $^{87}\mathrm{Sr}$ is fairly rare.
- $^{87}\mathrm{Rb}$ beta-decays into $^{87}\mathrm{Sr}$:

$$^{87}\mathrm{Rb} \rightarrow {}^{87}\mathrm{Sr} + e^- + \bar{\nu}_e + \text{ energy}$$

Commonly used: $$N = \frac{n}{s} = \frac{^{87}\mathrm{Rb}}{^{86}\mathrm{Sr}} \quad , \quad D = \frac{d}{s} = \frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}} \quad .$$

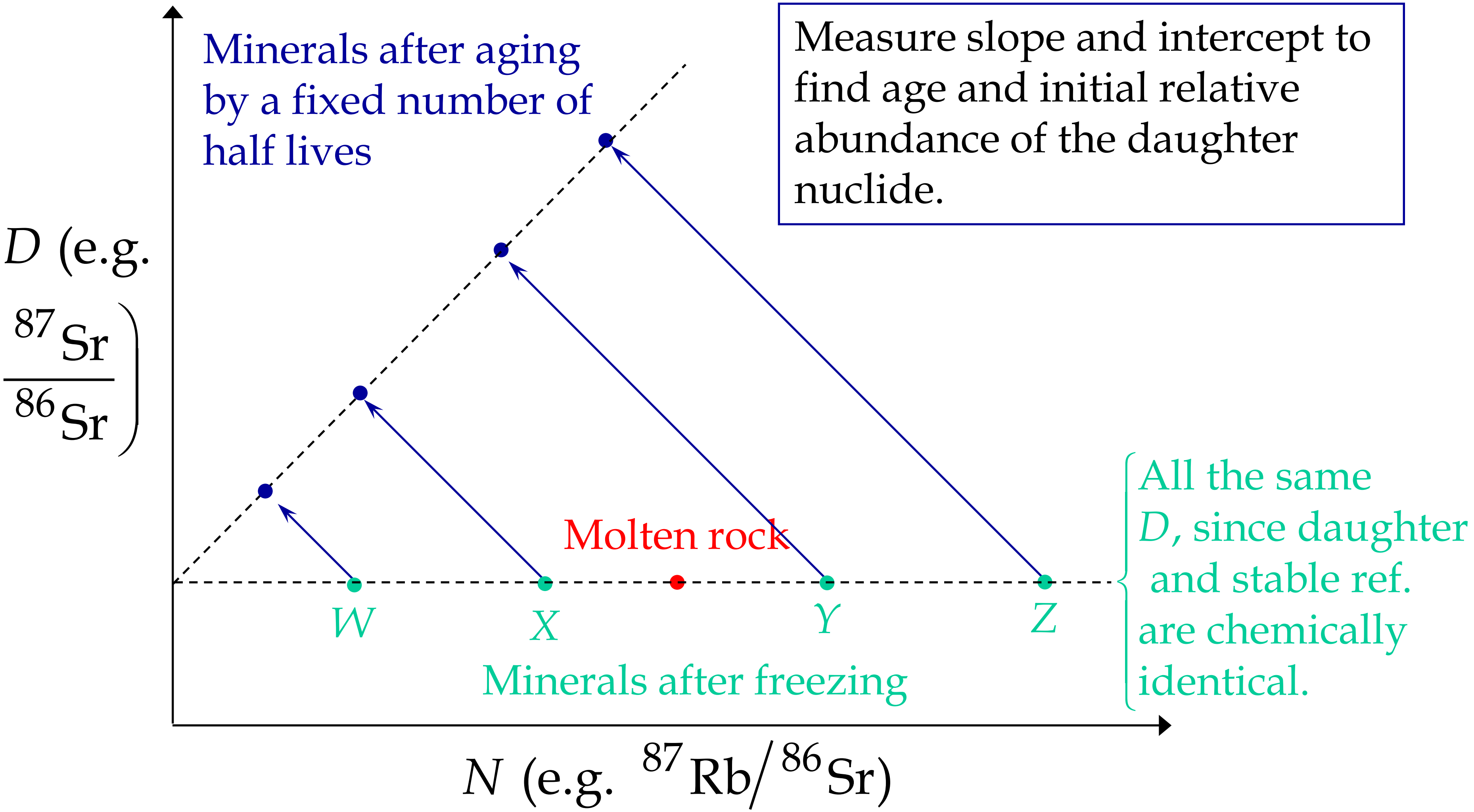


| Lithium | Beryllium |
|---|---|
| 11 22.99<br>Na<br>Sodium | 12 24.31<br>Mg<br>Magnesium |
| 19 39.10<br>K<br>Potassium | 20 40.08<br>Ca<br>Calcium |
| 37 85.47<br>Rb<br>Rubidium | 38 87.62<br>Sr<br>Strontium |

# The use of radionuclides to find out how long ago an igneous rock was last melted

- There are many radioisotopes, with halflives spread from thousands to billions of years, all accurately and precisely measured in the laboratory.
- We can measure the abundances of stable and radioactive nuclides "simply" by taking rocks apart into the minerals of which they are made, and in turn taking the minerals apart into atoms, counting the number for each element and isotope in a **mass spectrometer.**
- This gives values of *N* and *D,* a pair for each mineral. Plot the *D*s against the *N*s: the slope of the resulting line depends upon how many halflives have passed since it froze, and the intercept depends upon the initial relative abundance of the daughter nuclide.

# The use of radionuclides to find out how long ago an igneous rock was last melted (continued)



Measure slope and intercept to find age and initial relative abundance of the daughter nuclide.

Minerals after aging by a fixed number of half lives

Molten rock

$W$ $X$ $Y$ $Z$

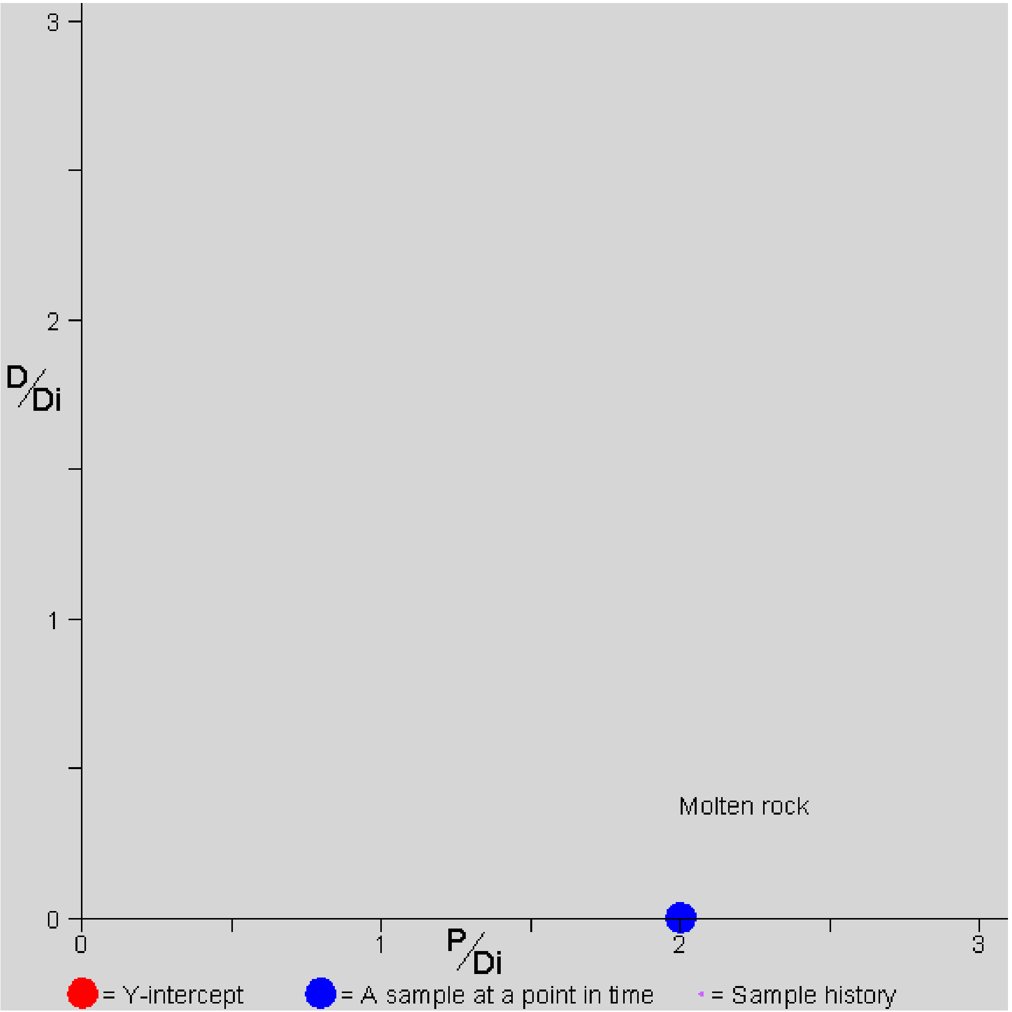
Minerals after freezing

All the same $D$, since daughter and stable ref. are chemically identical.

$D$ (e.g. $\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}$)

$N$ (e.g. $^{87}\mathrm{Rb}/^{86}\mathrm{Sr}$)

# The use of radionuclides to find out how long ago an igneous rock was last melted (continued)



Simulation by [Jon Fleming.](#)

# A simple two-mineral system

Call the initial relative abundances $N_0$ and $D_0$. The relative abundance of daughter nuclides as a function of time is:

$$D = D_0 + \left(N_0 - N\right) = D_0 + N\left(e^{\lambda t} - 1\right) \quad .$$

Suppose we have a rock consisting of two minerals, *A* and *B*, with equal *initial* relative abundances of the daughter nuclide. We can measure the present abundances of *A* and *B:*

$$D_A = D_0 + N_A\left(e^{\lambda t} - 1\right) \quad , \quad D_B = D_0 + N_B\left(e^{\lambda t} - 1\right) \quad .$$

Two equations, two unknowns: $D_0$ and $\lambda$.

This can easily be solved for *t*, in terms of measurable quantities:

$$t = \frac{1}{\lambda} \ln\left(\frac{D_A - D_B}{N_A - N_B} + 1\right) \quad .$$

# Example two-mineral system

The rate at which $^{87}\mathrm{Rb}$ decays into $^{87}\mathrm{Sr}$ is

$$\lambda = 1.39 \times 10^{-11}\ \mathrm{yr}^{-1}$$

Samples of two different minerals from the same plutonic rock from northern Ontario are analyzed in a mass spectrometer, with these results:

| Sample | $^{87}\mathrm{Rb}/^{86}\mathrm{Sr}$ | $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ |
|---|---|---|
| 1 | 0.0755 | 0.7037 |
| 2 | 0.3280 | 0.7133 |

How old is the rock?

# Example two-mineral system (continued)

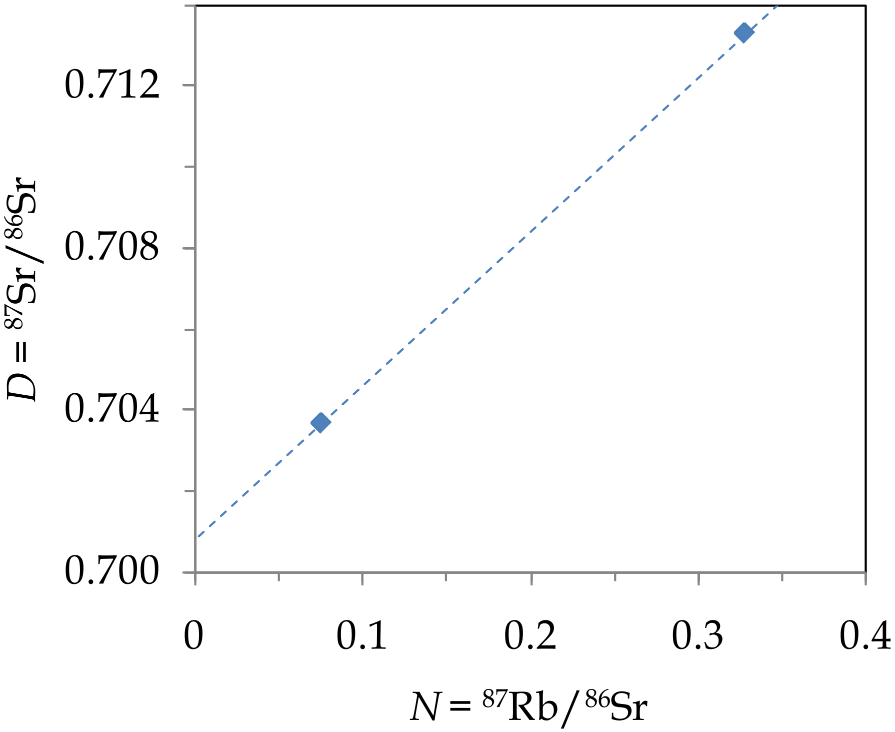
Solution:

$$t = \frac{1}{\lambda}\ln\left(\frac{D_A - D_B}{N_A - N_B} + 1\right)$$

$$= \frac{1}{1.39\times 10^{-11}\ \mathrm{yr}^{-1}}$$

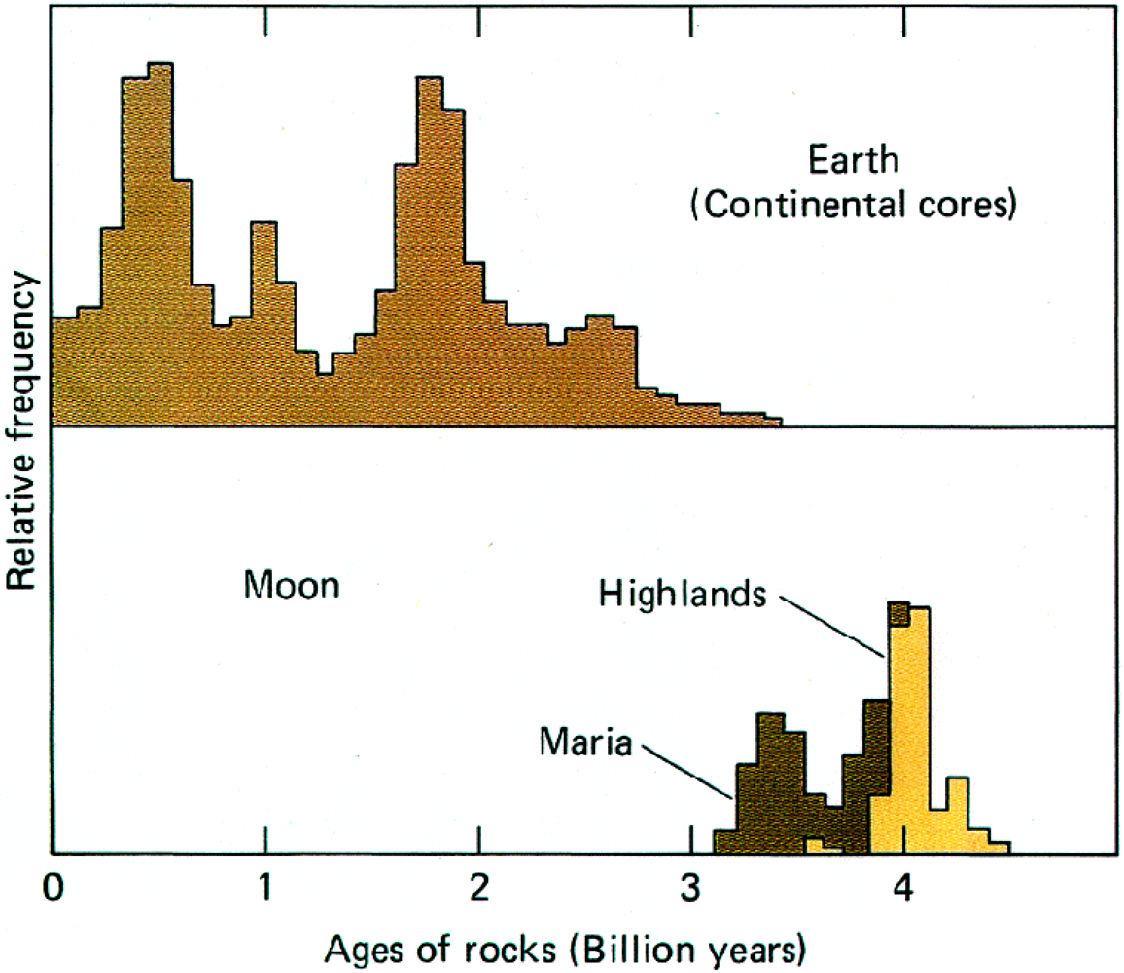
$$\times \ln\left(\frac{0.7133 - 0.7037}{0.328 - 0.0755} + 1\right)$$

$$\boxed{= 2.7\times 10^{9}\ \mathrm{yr.}}$$



The *y* intercept gives the value of *D* that the rock had at the time it froze: $D_0 = d/s = {}^{87}\mathrm{Sr}/{}^{86}\mathrm{Sr} = 0.7008.$

# Results for Earth and Moon



- ☐ The Moon began to solidify about 4.5 billion years ago.
- ☐ The highlands are clearly older than the maria, as the cratering record also shows.
- ☐ The Moon solidified long before the Earth did.

Figure from Jay Frogel.