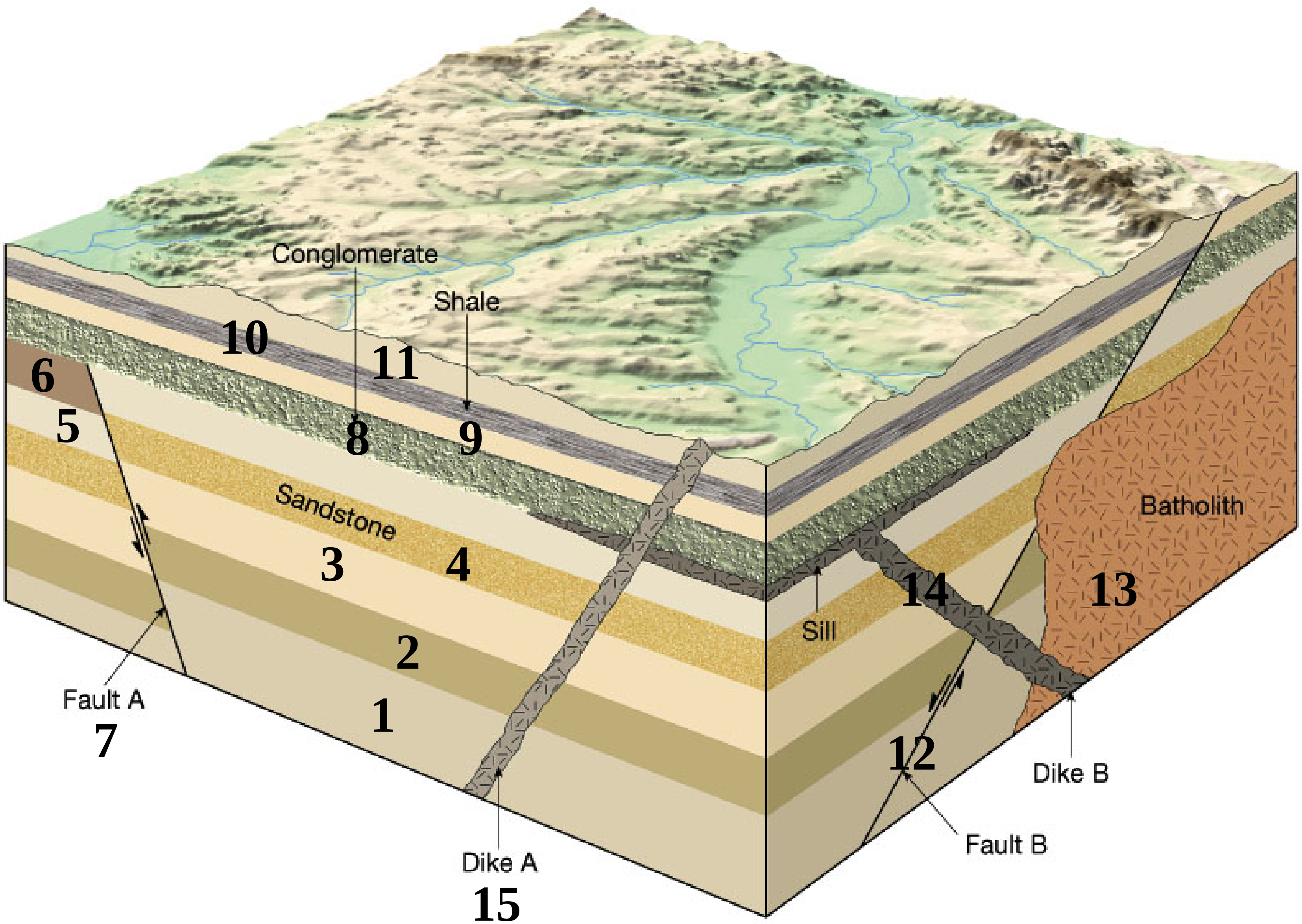
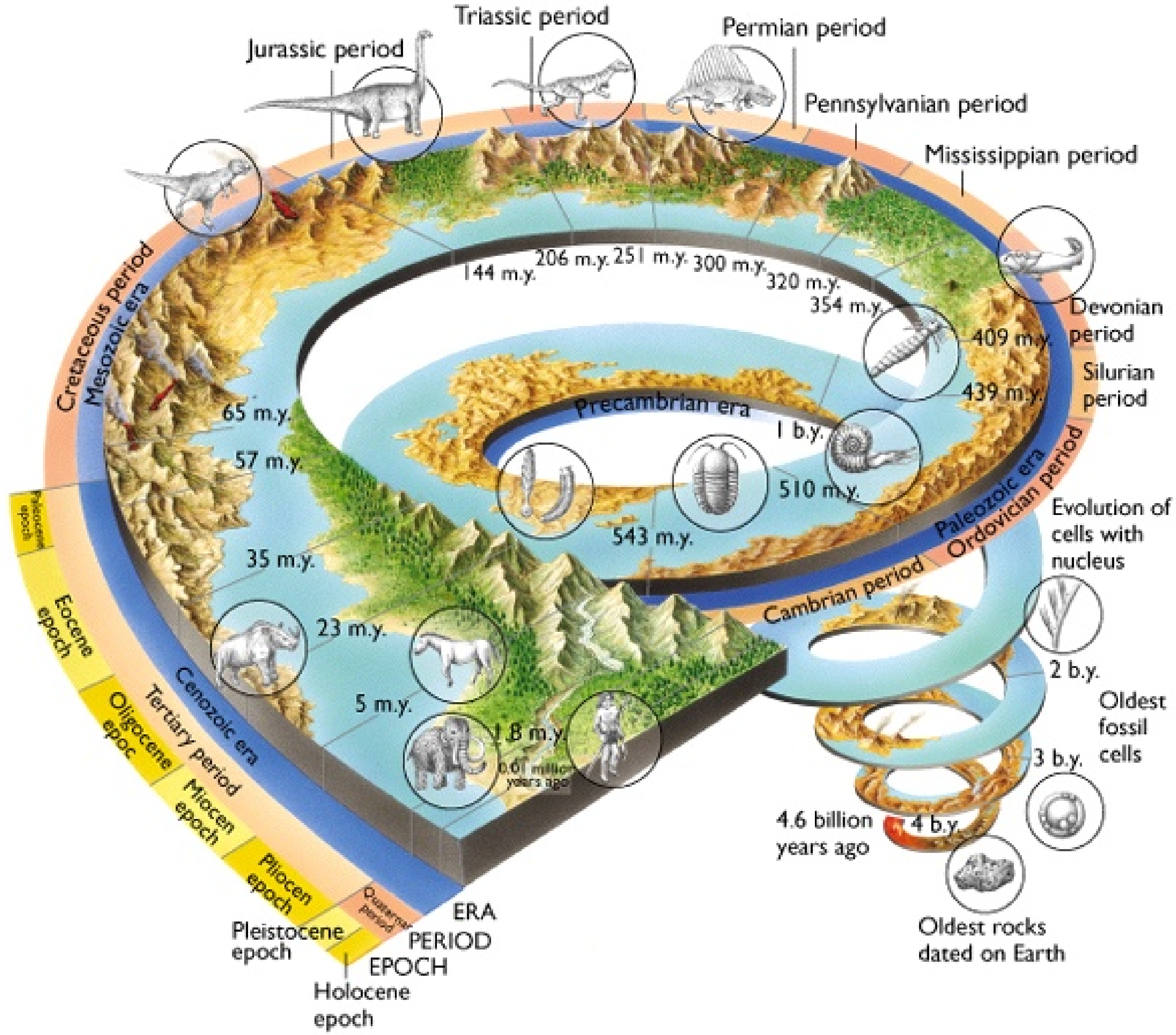
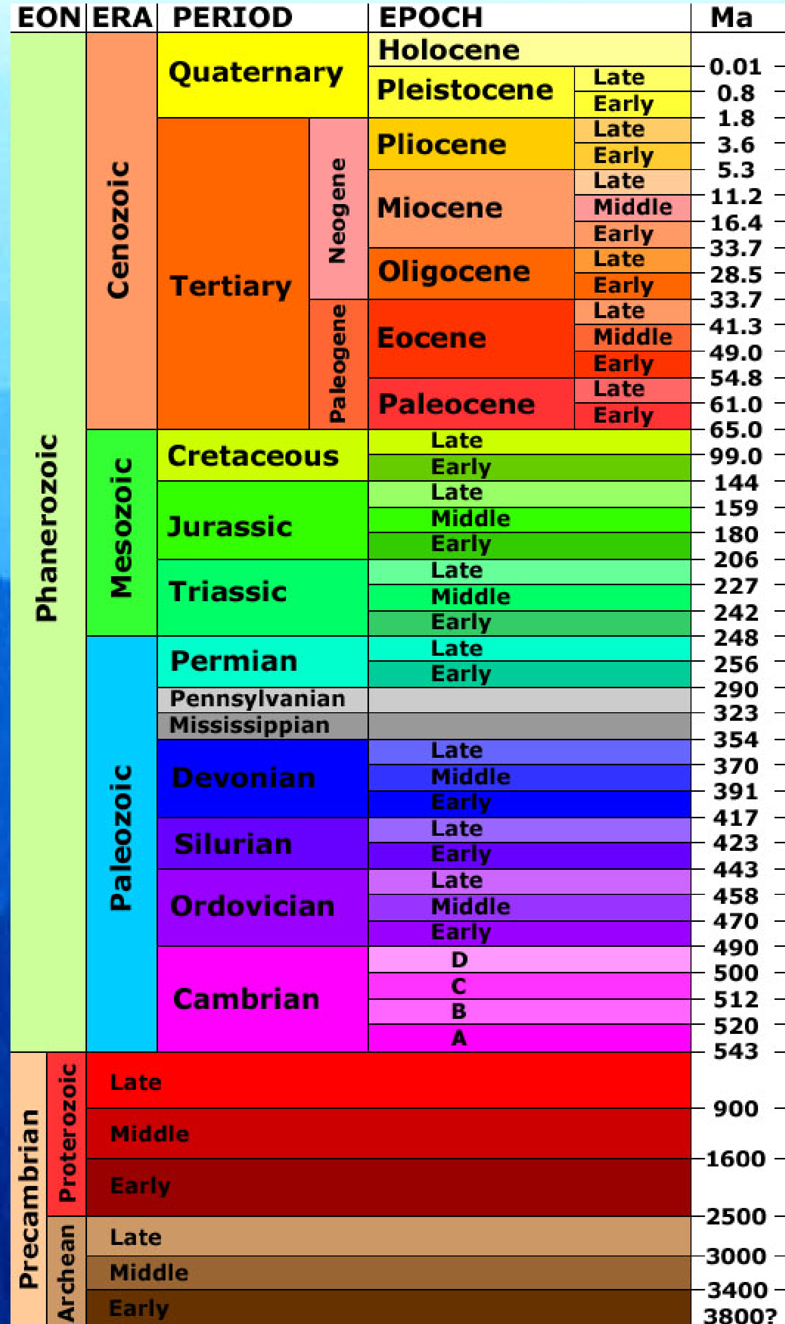
Geologic Time

How can we decipher 4.5 Billion Years of Earth History?


Conglomerate
Shale
10
11
6
5
8
9
Sandstone
3
4
Batholith
14
13
Sill
2
1
Fault A
7
12
Dike B
Fault B
Dike A
15


Jurassic period
Triassic period
Permian period
Pennsylvanian period
Mississippian period
Cretaceous period
Mesozoic era
144 m.y.
206 m.y.
251 m.y.
300 m.y.
320 m.y.
354 m.y.
Devonian period
409 m.y.
Silurian period
439 m.y.
Precambrian era
1 b.y.
65 m.y.
57 m.y.
510 m.y.
Paleozoic era
Ordovician period
Evolution of cells with nucleus
543 m.y.
35 m.y.
Cambrian period
Paleocene epoch
Eocene epoch
23 m.y.
2 b.y.
Cenozoic era
Tertiary period
Oligocene epoc
5 m.y.
Oldest fossil cells
1.8 m.y.
0.01 million years ago
3 b.y.
Miocene epoch
4.6 billion years ago
4 b.y.
Pliocen epoch
Quaternary period
ERA
PERIOD
EPOCH
Pleistocene epoch
Holocene epoch
Oldest rocks dated on Earth

The Scale


EON
ERA
PERIOD
EPOCH
Ma
Phanerozoic
Cenozoic
Quaternary
Holocene
Pleistocene
Late
Early
Tertiary
Neogene
Pliocene
Late
Early
Miocene
Late
Middle
Early
Oligocene
Late
Early
Paleogene
Eocene
Late
Middle
Early
Paleocene
Late
Early
Mesozoic
Cretaceous
Late
Early
Jurassic
Late
Middle
Early
Triassic
Late
Middle
Early
Paleozoic
Permian
Late
Early
Pennsylvanian
Mississippian
Devonian
Late
Middle
Early
Silurian
Late
Early
Ordovician
Late
Middle
Early
Cambrian
D
C
B
A
Precambrian
Proterozoic
Late
Middle
Early
Archean
Late
Middle
Early
0.01
0.8
1.8
3.6
5.3
11.2
16.4
33.7
28.5
33.7
41.3
49.0
54.8
61.0
65.0
99.0
144
159
180
206
227
242
248
256
290
323
354
370
391
417
423
443
458
470
490
500
512
520
543
900
1600
2500
3000
3400
3800?

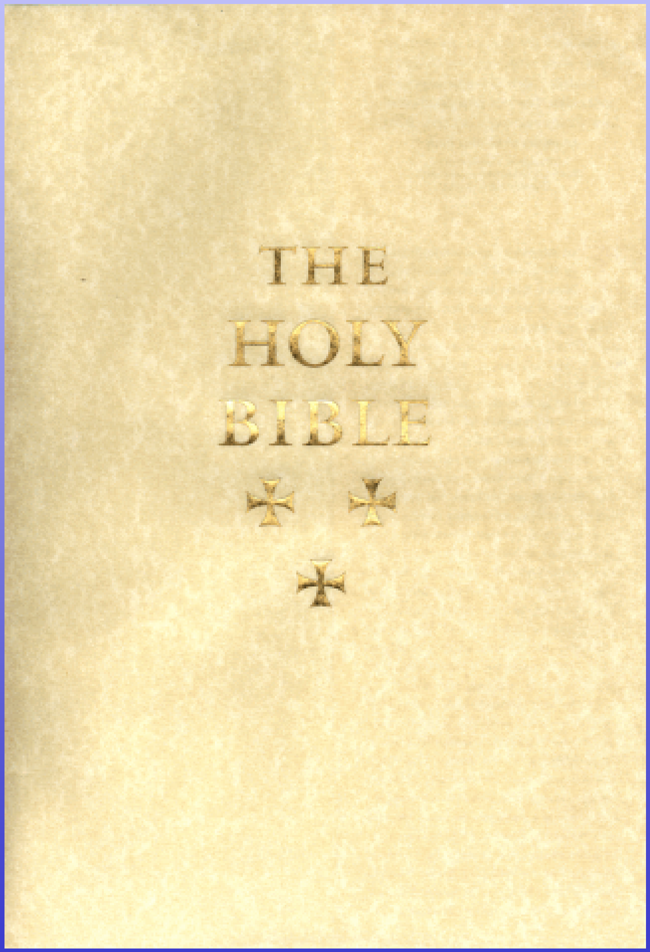
Major Intervals

- Eons- Hadean, Archean, Proterozoic, Phanerozoic
- Eras- Paleozoic, Mesozoic & Cenozoic
- Periods; Ediacaran, Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, Paleogene, Neogene
- Epochs and Stages- further breakdowns of time.

How did Science Arrive at 4.5 Billion?

- A brief history of Age Determination
- Early Philosophers (not scientists) thought the Earth was without beginning or end.
- Of course people have always been interested in questions like these.

Early Quantitative Events



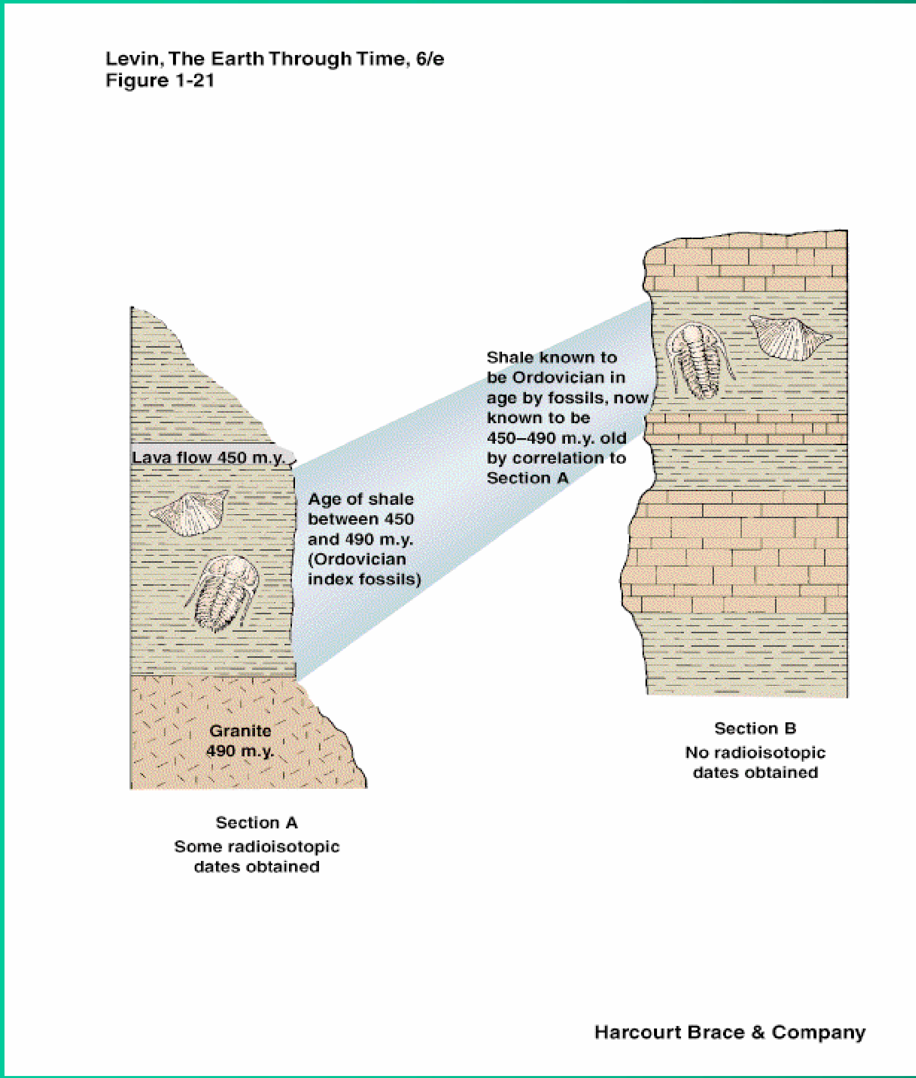
- Archbishop Ussher (1600's)
- Calculated the age based on the post-Adamite generations
- Arrived at ~6000 years.
- Scholarly work, but not scientific.
- Later Scholar determined it was Oct 23, 4004 BC at 9 a.m.

Fossils Were Attributed to the Noachian Flood

Scientific Determinations

- Most Naturalists of the 1700-1800's were also clergymen.
- They realized that the Ussherian estimate was wrong by examining the evidence.
- They also realized that there was no evidence of a Global flood such as the Noachian flood and concluded it was probably a borrowed myth from the Sumerian Epic of Gilgamesh.

The Fossil Record & The Flood

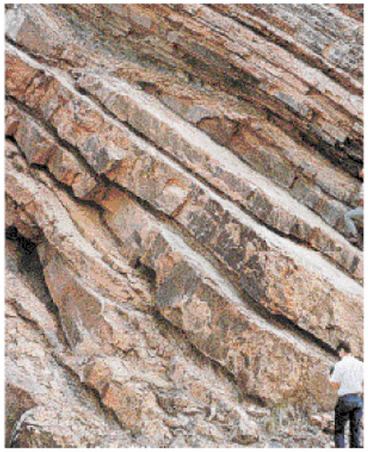


- **It was logical to assume that a global flood left the fossils.**
- **Unfortunately, floods are choatic and tend to create a mess.**
- **Naturalists who studied the fossil record realized that it contained an orderly sequence that was completely at odds with the notion of a global flood.**

Scientific Evidence for the Age of the Earth

- Nicolas Steno's 3 Principles of Geology
- ***Original Horizontality***
- ***Superposition***
- ***Cross-Cutting relationships***

Levin, The Earth Through Time, 6/e
Figure 1-3



Harcourt Brace & Company

Hutton and the Age of the Earth

- "The Earth has no vestige of a beginning and no prospect of an end"
- Hutton watched things like sand being deposited and realized it would take a LONG time to build up a layer of sandstone such as he saw in Scotland.
- Hutton coined the term "Uniformitarianism".

Lyell and Fossils

- Charles Lyell looked at the evolution of marine mollusks in the Cenozoic sediments and arrived at 80 million years
- Not too bad since the current estimate is 65 Ma.
- What’s important is that Lyell, like Darwin viewed Geology as Deep time.

Age Determinations

- Comte de Buffon 1707-1788
  - Noted the Similarities between humans and apes about 100 years before Darwin.
  - Questioned the idea of a 6000 year old earth
  - Manufactured Cannonballs and estimated the age of the earth based on how long it took cannon balls to cool from a molten state.

Joly and the Age of the Earth

- Joly was a Irish Scientist of the 1800's.
- He examined the amount of salt in the ocean and calculated how long it would take the oceans to get that salty.
- His estimate was that the earth was more than *90 million* years old.

Lord Kelvin's Mathematics

$$t_0 = \frac{(T_1 - T_0)^2}{\pi\kappa\left(\frac{\partial T}{\partial y}\right)_0^2}$$

Let's solve using reasonable parameters.

$\left(\frac{\partial T}{\partial y}\right)$ Geothermal gradient

κ Thermal diffusivity

$T_1 - T_0$ Assumed temperature difference past to present

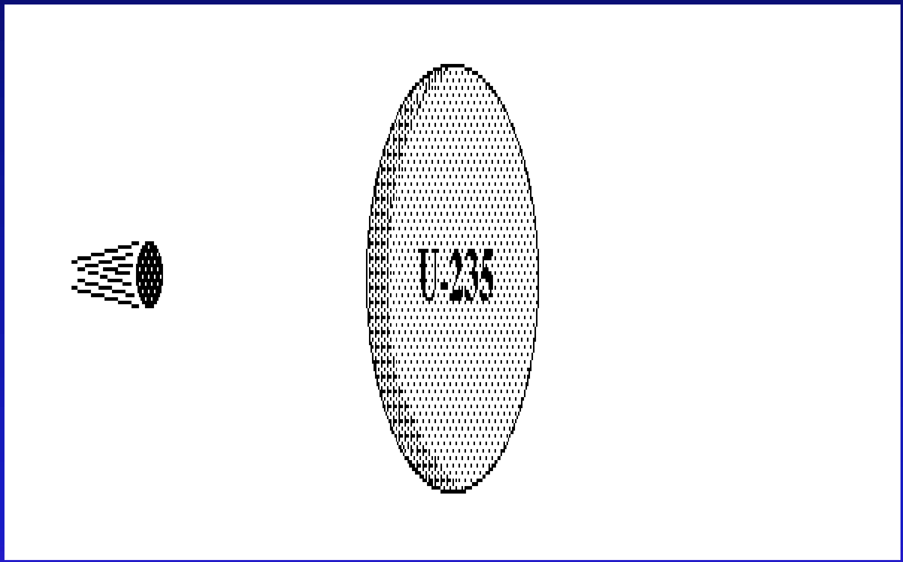
Lord Kelvin and the Age of the Earth

- Lord Kelvin was perhaps the most influential scientist of the 19th century and he was a contemporary of Darwin and Joly.
- He calculated the age of the Earth based on the time it took for the Earth to cool from a molten start.
- His estimate, very precise and mathematical was 24-40 million years.

Lord Kelvin's Estimate

- Lord Kelvin's Estimate for the age of the Earth held sway with much of the Scientific community.
- Charles Darwin and Joly were notable scientists who thought that Kelvin had made a mistake, but they could not figure out how. Darwin, in particular thought the Earth must be very much older than either Joly or Kelvin.
- In the late 1800's three notable French scientists would make a discovery that would topple Lord Kelvin's estimate and vindicate Darwin.

Radioactivity



Marie Curie

Pierre Curie

Henri Becquerel

Won the Nobel Prize for their discovery of radioactivity.

Why was this important?

Radioactive Decay gives off Heat!

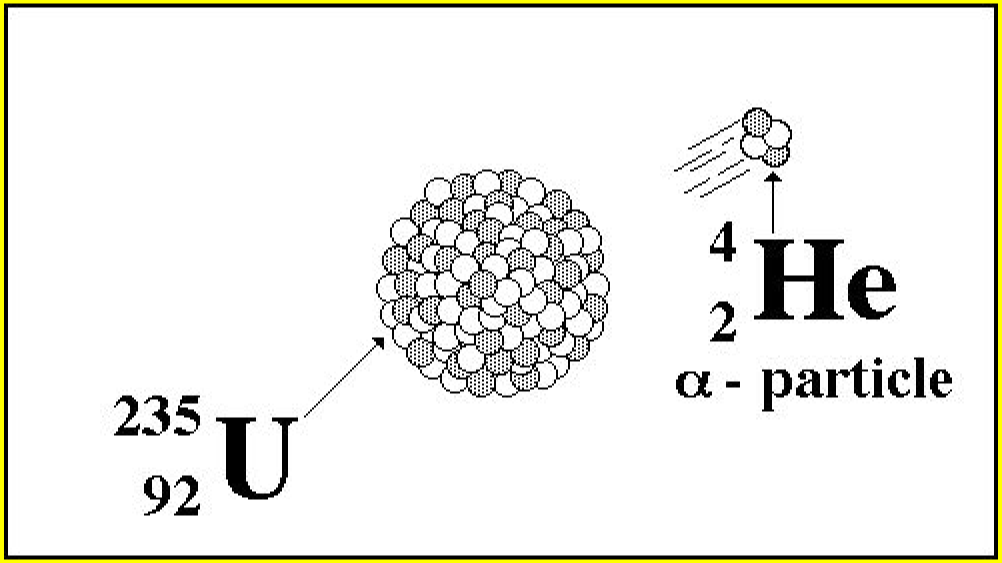
- *Of course, Lord Kelvin did not know about radioactive decay because it was not discovered until long after he made his initial estimates for the age of the Earth. He did learn of the discovery before his death in 1907.*
- *The problem with Kelvin's calculations arose because the Earth had a constant supply of additional heat from radioactive decay.*

The Importance of Decay in Age of Earth Determinations

- **Not only does radioactive decay give off heat, but it occurs (for each different element) at a constant rate.**
- **The rate of decay for radioactive elements is known as their <u>half-life.</u>**
- **Because the rate is constant, radioactivity provides geologists with a natural clock!**

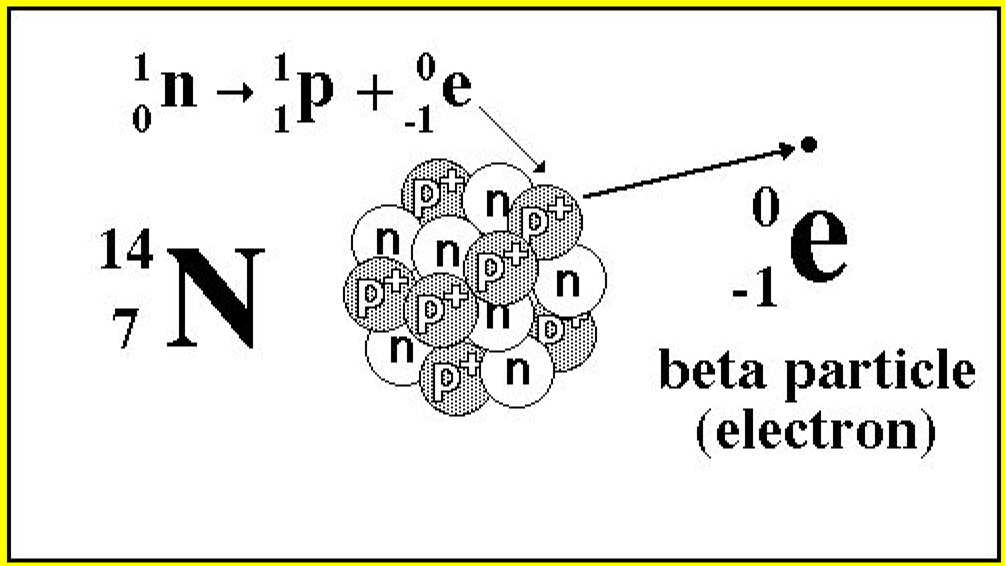
Principles of Radioactive Decay

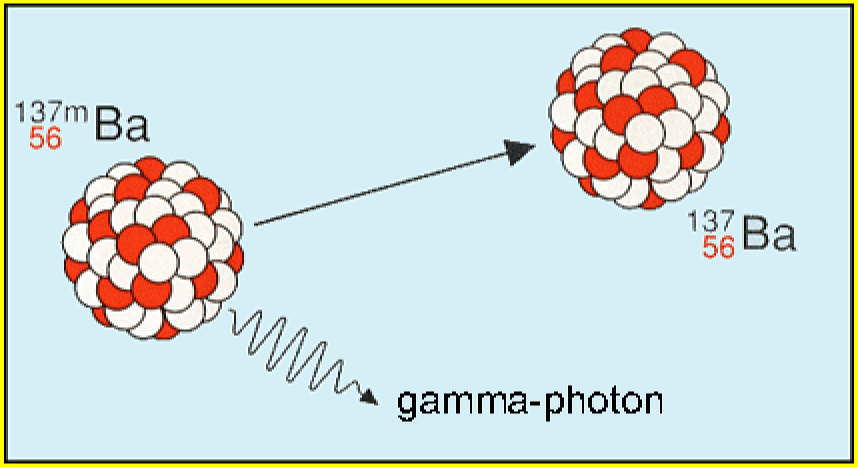
1. Radioactive decay is a spontaneous and random process.
2. Statistically speaking, decay proceeds at a constant rate.
3. This rate is called the <u>½ life</u> of an isotope and represents the time taken for ½ the unstable <u>parent</u> isotopes to decay to stable/unstable <u>daughter</u> isotopes.
4. Because of 2 & 3, we can use the decay of certain isotopes to 'date' rocks.
5. Types of decay & radiation (alpha, beta and gamma)
    a. alpha-decay: + charged Helium (atomic weight of 4 and number 2
    b. Beta-decay: electron released during the fission of a neutron.
    c. Gamma radiation: electromagnetic waves emitted during decay with ultrahigh frequencies.



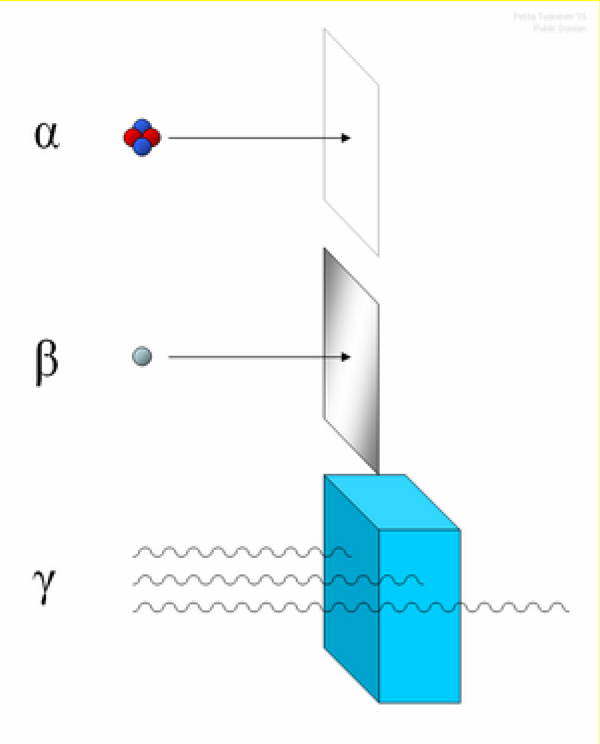
Uranium-235 scheme

Carbon-14 scheme





Note Gamma radiation is a process by which an atom loses energy (it does not change mass or number), but its total energy is decreased.



Alpha-decay particles are stopped by a sheet of paper. Beta particles by an aluminum sheet, gamma particles energy is diminished by lead shielding.

Derivation of the ½ Life from first principles

N=number present at time t, N_0 is the original number present, Lambda is a constant, t=time. We can set up an equation as follows

$$N(t) = N_0 e^{-\lambda t}$$

If we start off with a certain number, then at some time our initial amount N_0 will be reduced by ½.

$$N(0.5t) = N_0 * 0.5$$

This will in essence, we know that ½ of the original number will be present when:

$$e^{-\lambda t^{\frac{1}{2}}} = \frac{1}{2}$$

Remove the exponent by taking ln of both sides:

$$-\lambda t^{\frac{1}{2}} = \ln(\frac{1}{2})$$

$$-\lambda t^{\frac{1}{2}} = \ln(1) - \ln(2)$$

We know that ln(1)=0 so we can simplify to:

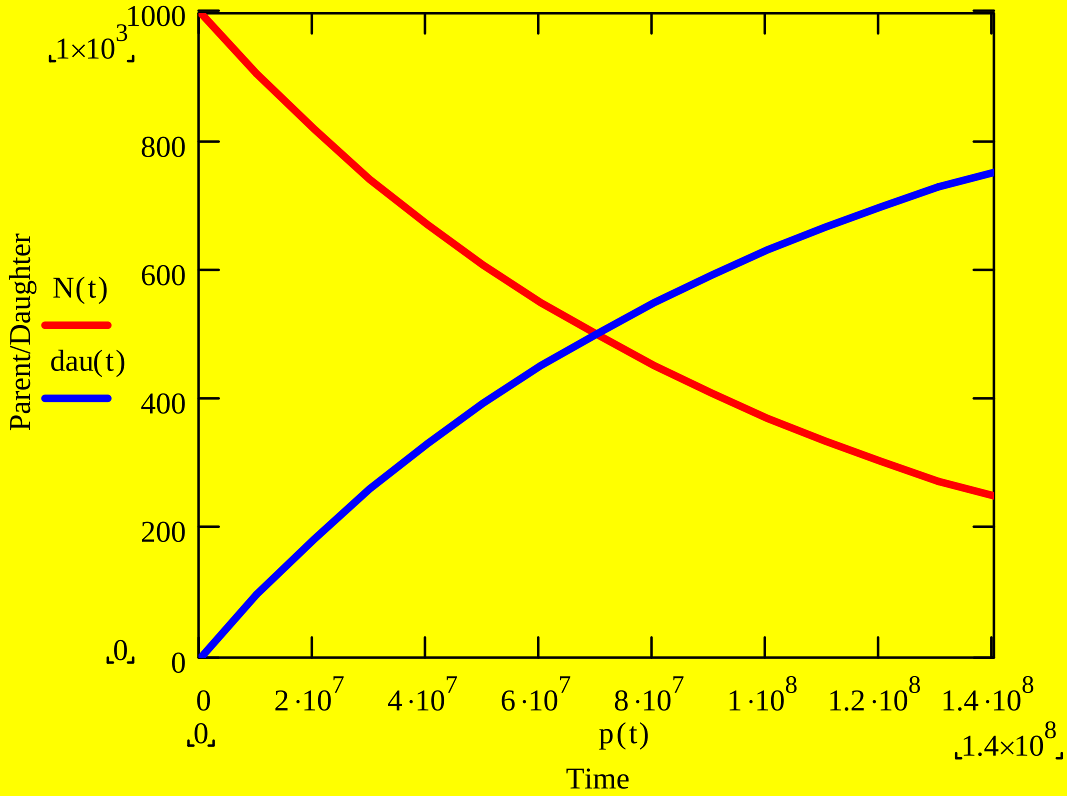
$$-\lambda t^{\frac{1}{2}} = -\ln(2)$$

Isolate the half life on one side to get:

$$t^{\frac{1}{2}} = \frac{\ln(2)}{\lambda}$$

Sample Problem:

Suppose that element X decays to element Y with a decay constant of $1*10^{-8}$. Graph the amount of X versus Y through time.



Calculate the ½ life

$$t^{\frac{1}{2}} = \frac{\ln(2)}{\lambda}$$

Half life= 6.931 x 10^7 years

Different Isotopic Dating Methods and their uses

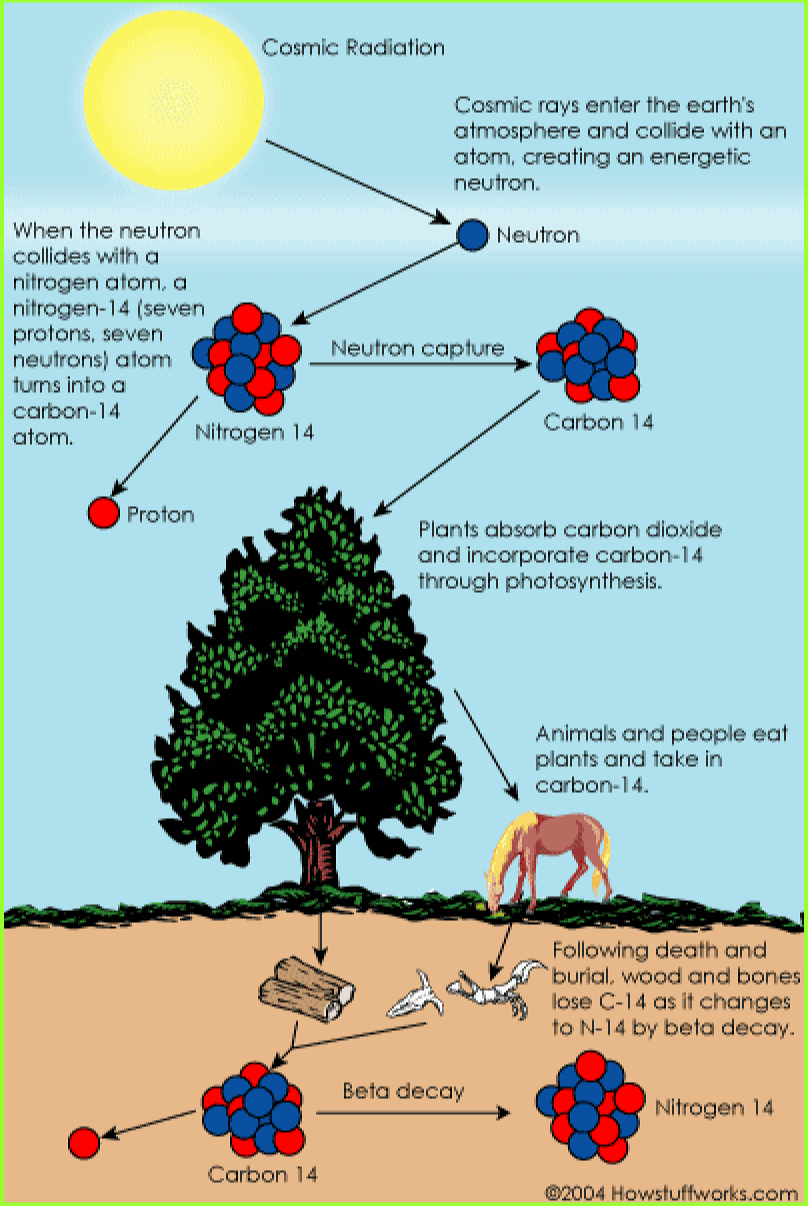
- C-14 decays to Nitrogen 14 5730 years
- U-238 decays to Pb-206 4.47 Ga
- U-235 decays to Pb-207 704 Ma
- U-234 decays to Th-230 248 Ka
- Th-232 decays to Pb-208 14 Ga
- Rb-87 decays to Sr-87 48.8 Ga
- K-40 decays to Ar-40 and Ca-40 1.251 Ga

Assumptions in Radiometric Dating

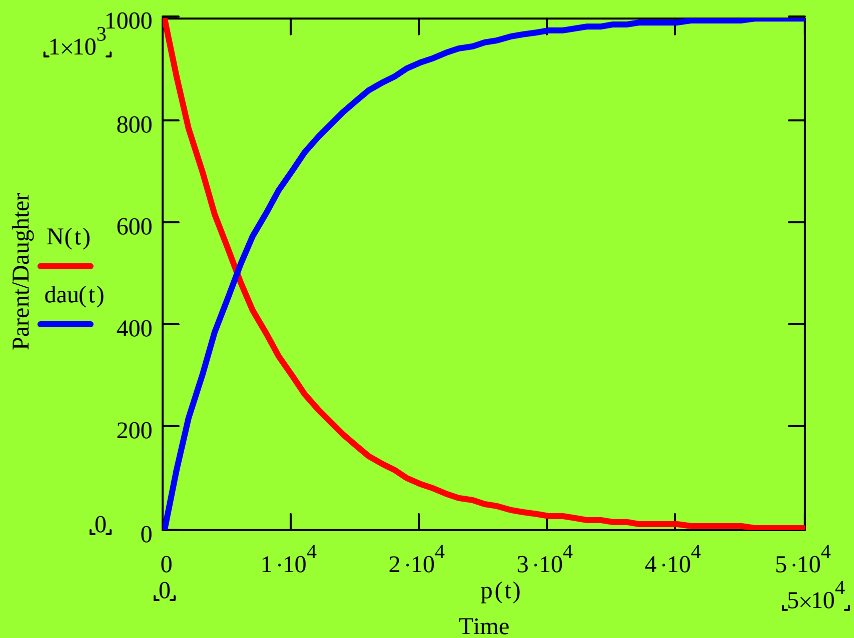
- The system remains closed during the time period of interests
  - No daughter gained, lost or incorporated into the rock at the outset.
  - No parent gained or lost
  - Decay rates are constant

Carbon-14 dating

- Useful only on organic matter (as material becomes older, recent contamination becomes problematic).
- C-14 in the atmosphere is incorporated into living tissues. The system is open until the organism dies. At that point, the C-14 in the organism begins to decay.
- C-14 in the atmosphere is also dependent on the earth's magnetic field and fluctuations. Corrections must be made to C-14 dates.



C-14 dating is effective for organic materials younger than ~50,000 years. Why?



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A look at Some Information we can get from Radiometric dating

- Different systems become closed/open under different conditions.
- Different minerals within the same rock close/open under different conditions.
- That information is useful in determining the history of the rock.

Types of Rocks that can be dated

- Igneous Rocks- All types, multiple methods.
- Metamorphic Rocks- Most types, multiple methods
- Sedimentary rocks- More limited via multiple methods.

Igneous Rocks

- For igneous rocks, we may want to know ‘how old is this rock’?
- Think about igneous bodies. Small bodies (dykes, sills and stocks) will cool quickly whereas plutons may cool slowly.
- What is it that we want to know?

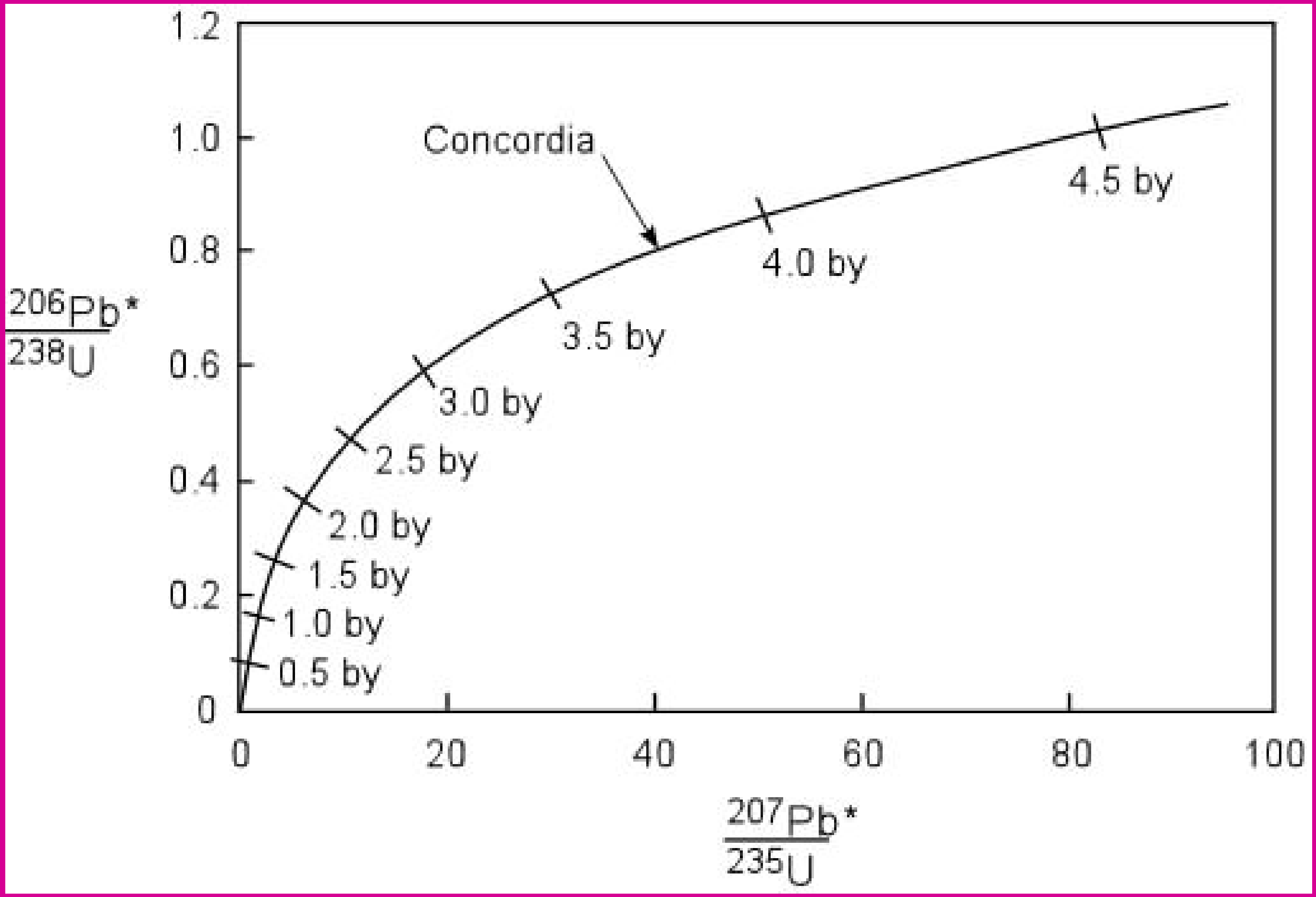
Crystallization Age

- Suppose we want to know the crystallization age of an igneous rock.
- A preferred method is U-Pb because the system is robust (hard to disturb) and precise (small errors).

U-Pb Dating Concordia

- U-Pb dating makes use of the fact that ^{235}U and ^{238}U are both radioactive, but decay at different rates.
- U-238 decays to Pb-206 4.47 Ga
- U-235 decays to Pb-207 704 Ma
- The older the rock, the more 'enriched' in ^{238}U relative to ^{235}U. This dual-system provides a 'check' into the assumptions of parent/daughter loss.
- Let's look at how!

Concordia Plots

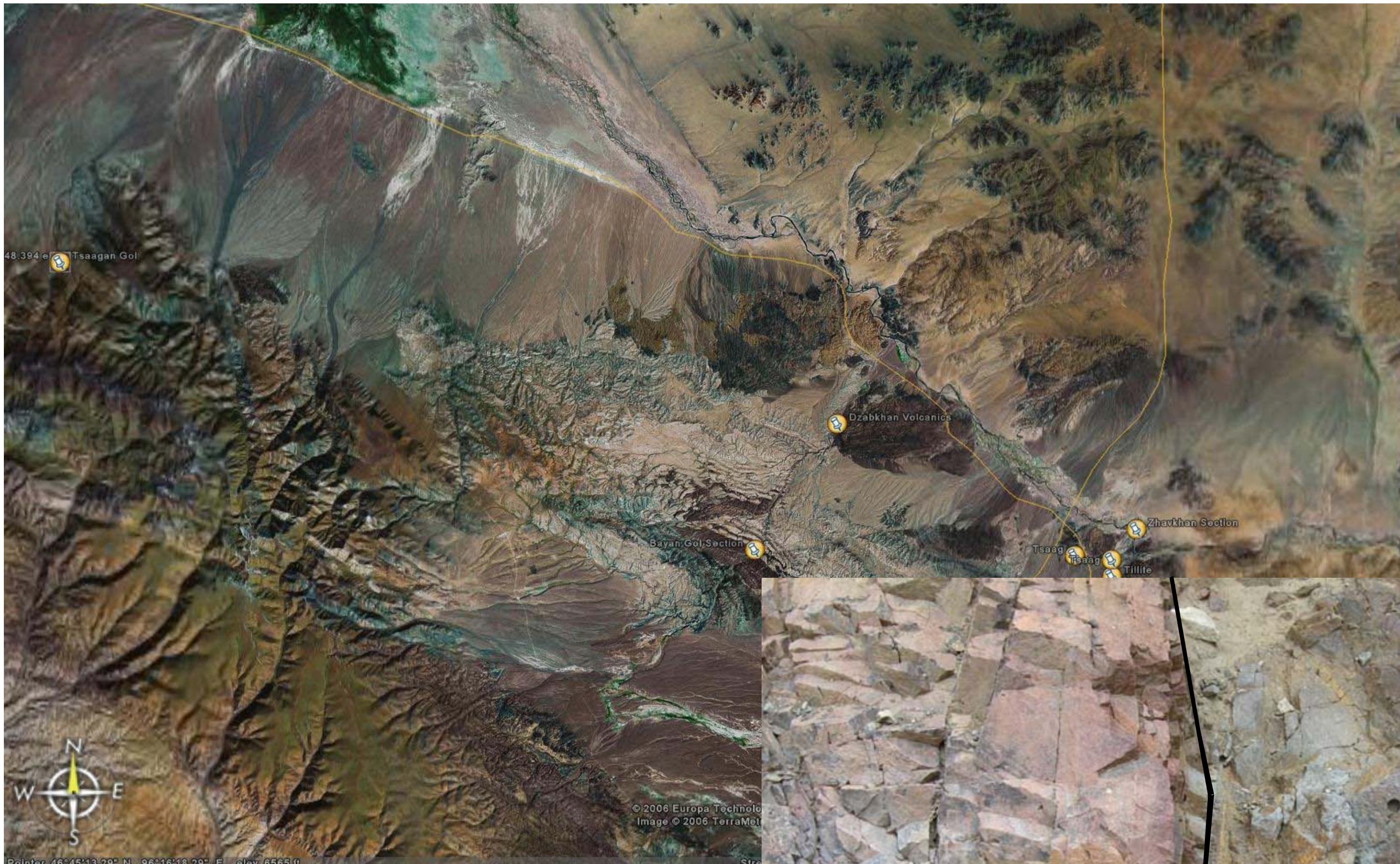


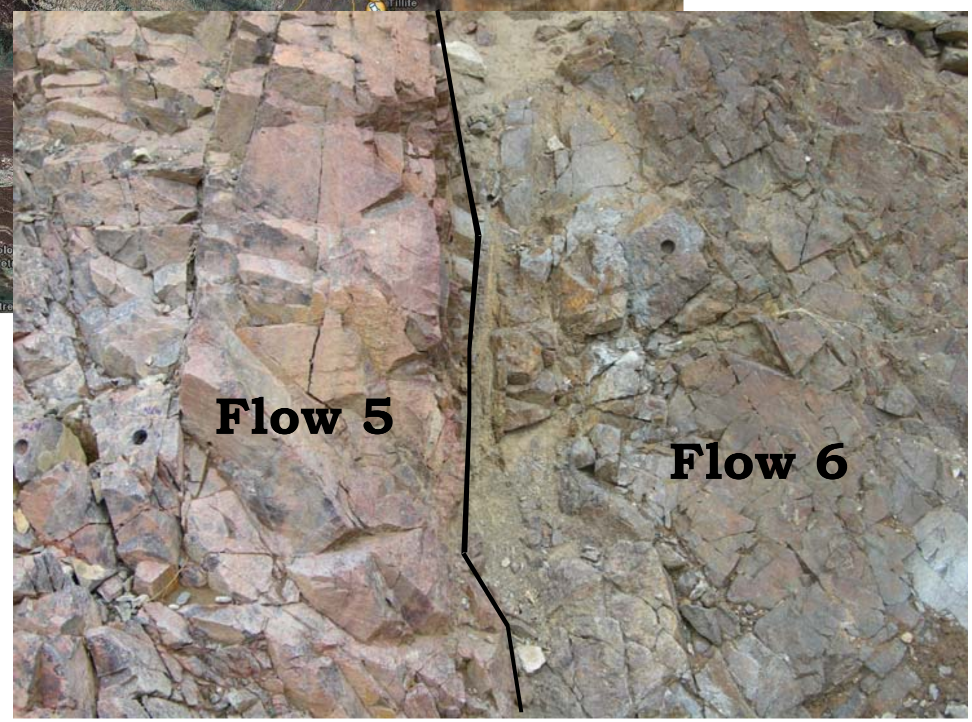
Concordia

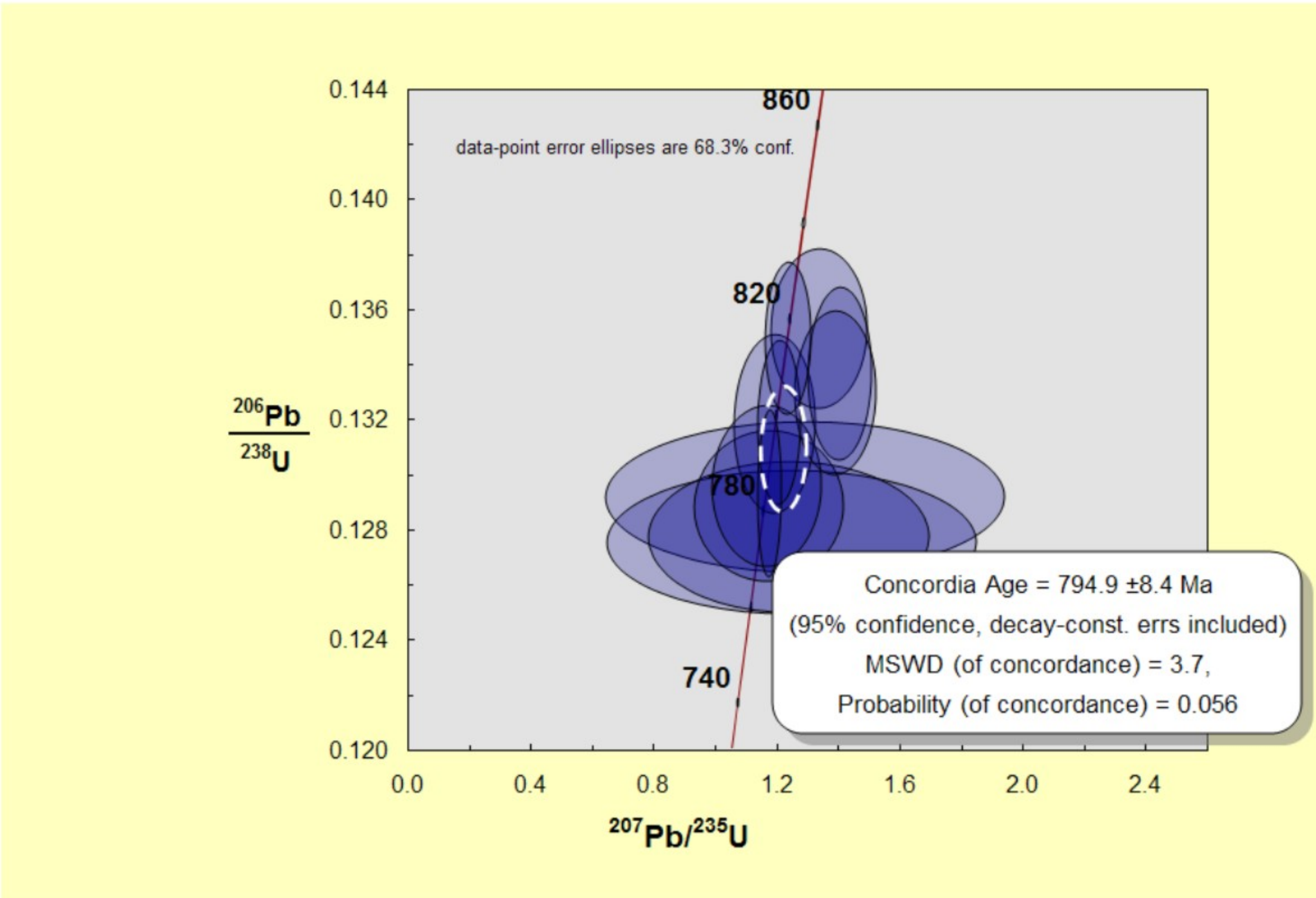
- An age determination that falls on the line (within errors) is called a concordant age. Such an age determination shows no loss of either parent/daughter from the system nor does it show any gain of parent/daughter from the system.
- A concordant age has acted as a closed system.

An Example

- Igneous rocks from the Dzabkhan microcontinent now in Mongolia
- U-Pb zircons extracted from the volcanic rocks.


Tsaagan Gol
Dzabkhan Volcanics
Bayan Gol Section
Zhavkhan Section
Tillite
N
W
E
S


Flow 5
Flow 6

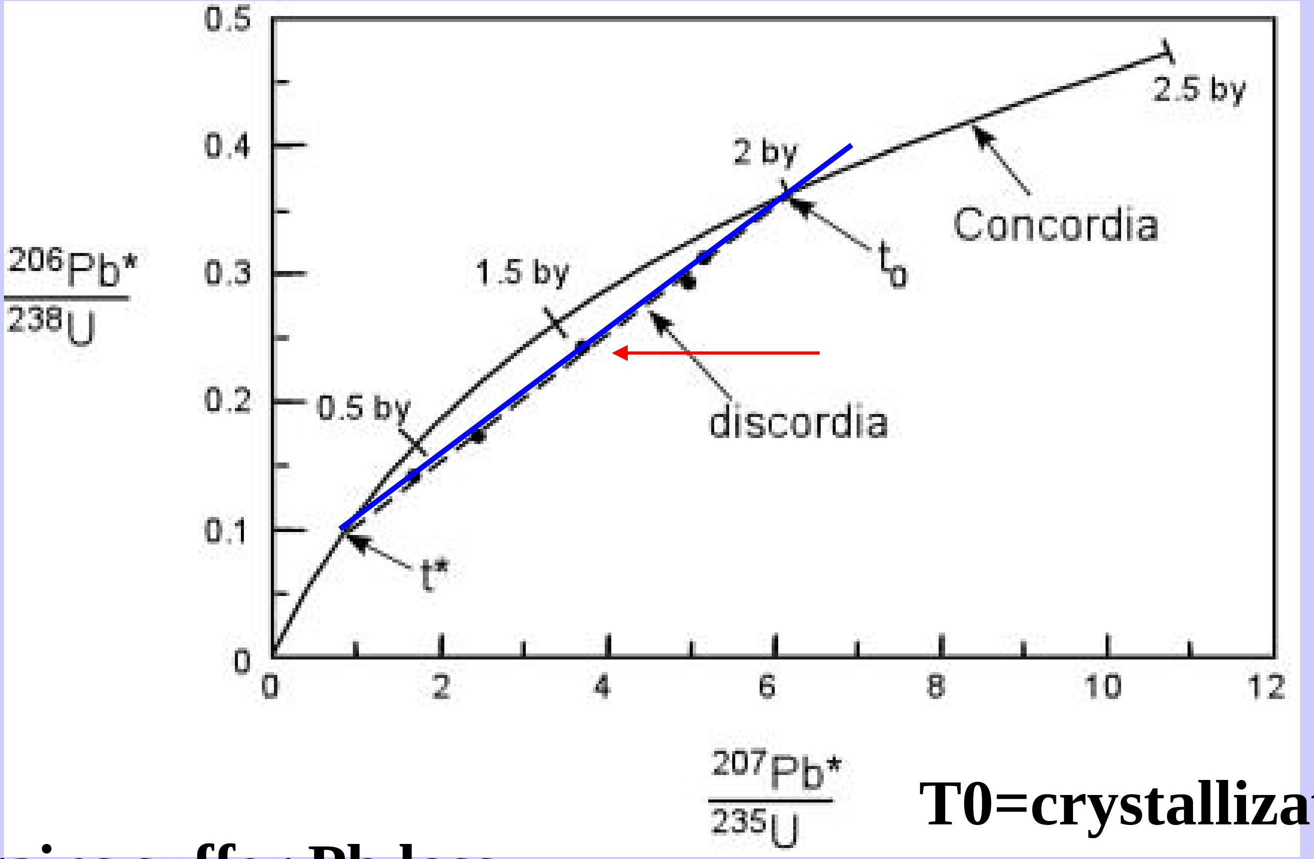


data-point error ellipses are 68.3% conf.
860
820
780
740
0.144
0.140
0.136
0.132
0.128
0.124
0.120
0.0
0.4
0.8
1.2
1.6
2.0
2.4
206Pb/238U
207Pb/235U
Concordia Age = 794.9 ±8.4 Ma
(95% confidence, decay-const. errs included)
MSWD (of concordance) = 3.7,
Probability (of concordance) = 0.056

What happens if Concordant ages are not found?

1. **If ages are not concordant, then it is likely that lead loss has occurred (this is far more common than U-gain.**
2. **Does this make the age useless? Not quite since the information can be used to estimate the event responsible for lead loss and it is also possible to estimate the age of the rock.**
3. **How?**

Discordia



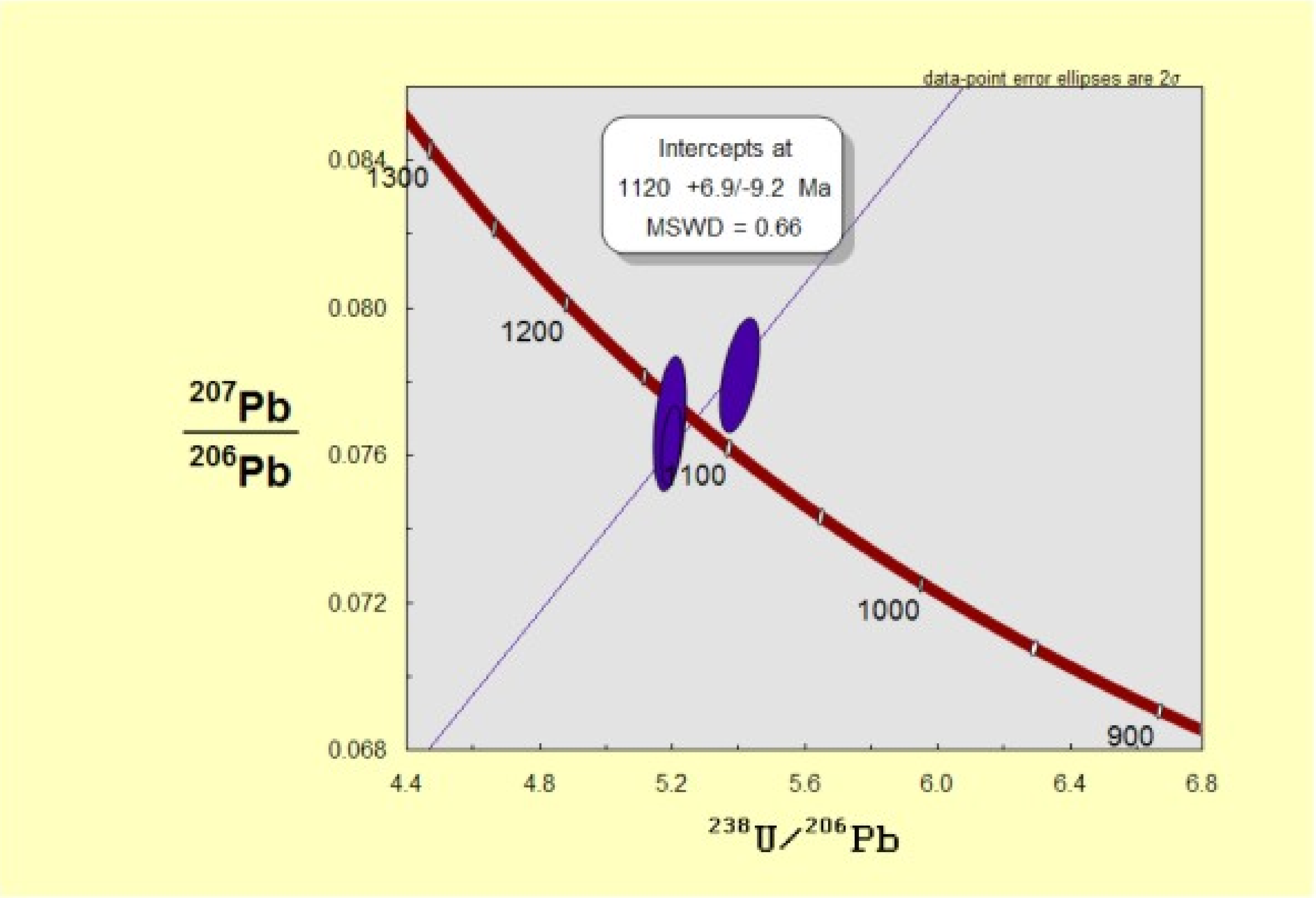
T0=crystallization age

Grains suffer Pb loss

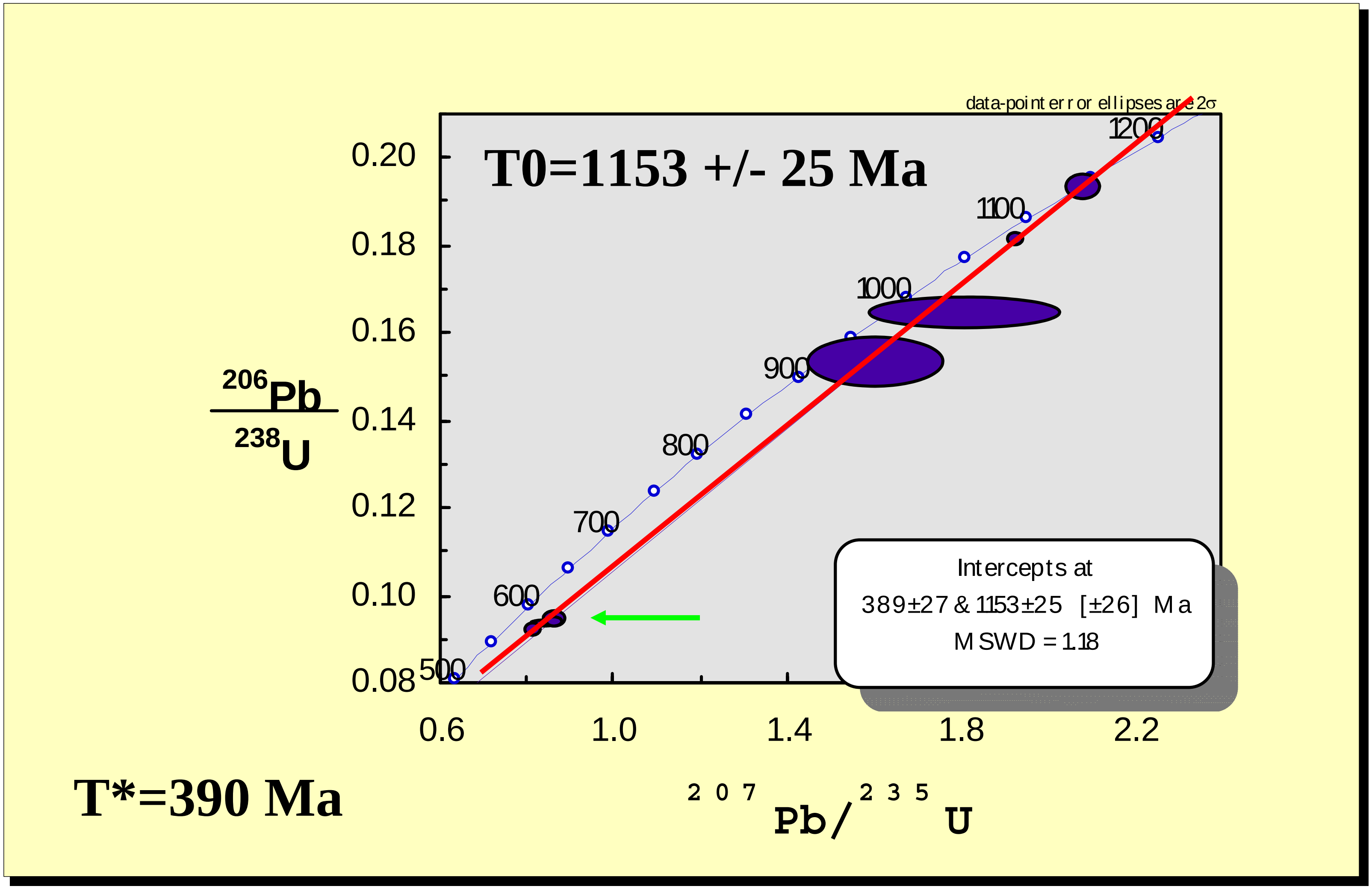
T*=lead loss event

A real life example

- From the Harohalli dikes in southern India.
- The dikes show evidence of both concordant and discordant zircons.



Concordant Zircons yield an age of 1120 Ma



A more complicated discordia!

What causes Discordia?

- Most often attributed to younger metamorphic or igneous events.
- When looking at discordant ages, one should keep in mind the history of the region.

The example

- Note that the t0 value is within statistical error of our concordia age.
- The t* age is 390 Ma and we might accept this as the age of the Pb-loss event but:
  - There are no zircons younger than ~590 Ma
  - There is no 390 Ma event in India that might cause this
  - At ~600 Ma there is a metamorphic event and this is likely the source of the lead loss.

K-Ar Dating

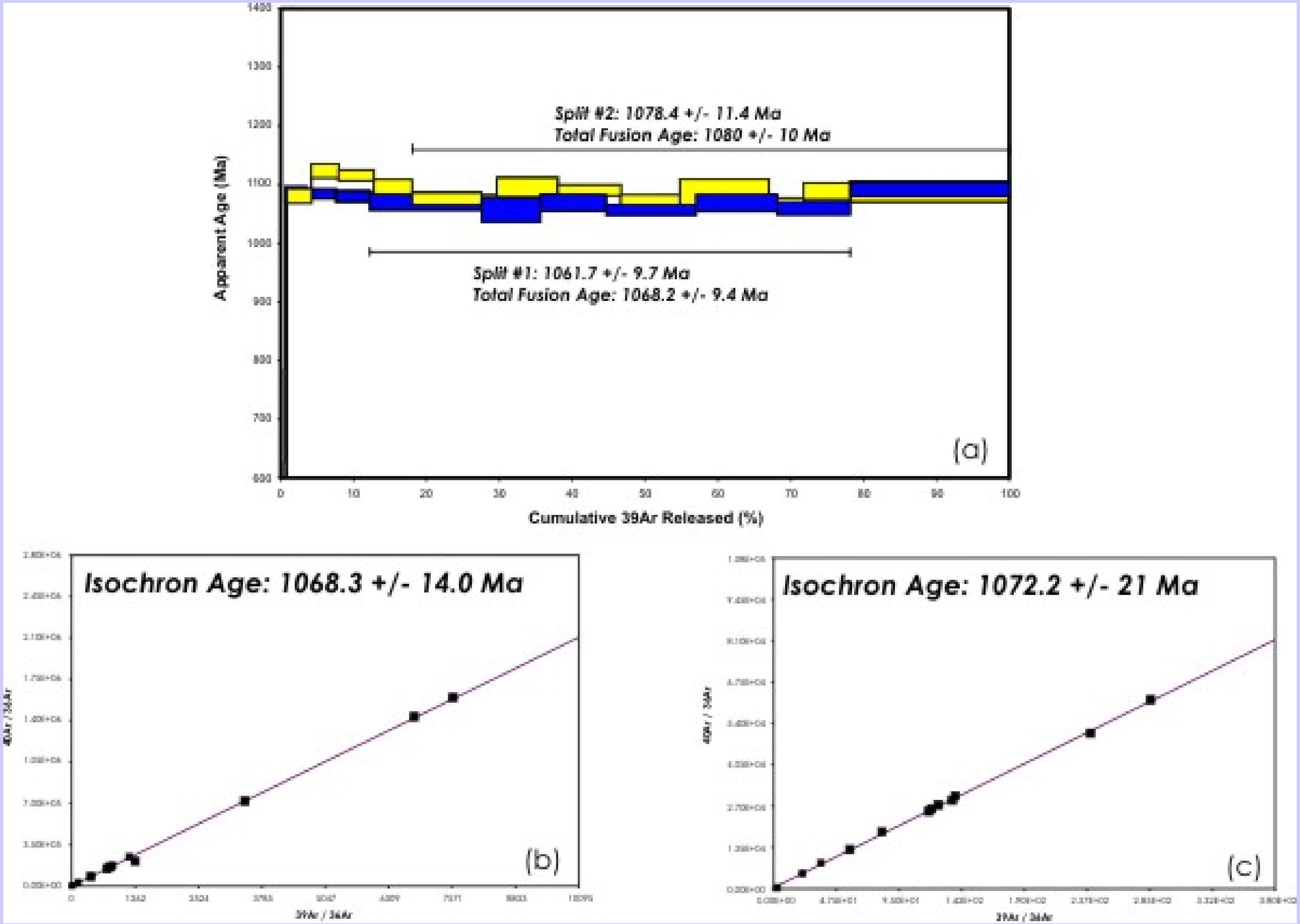
- The potassium-argon system is particularly useful for looking at cooling histories.
- Different minerals, hornblende, biotite and feldspar ‘close’ at different temperatures.
- Hornblende closes at ~500 C
- Biotite closes at ~350 C
- Feldspar closes between 100-200 C (depending on size of the crystal)

K-Ar dating

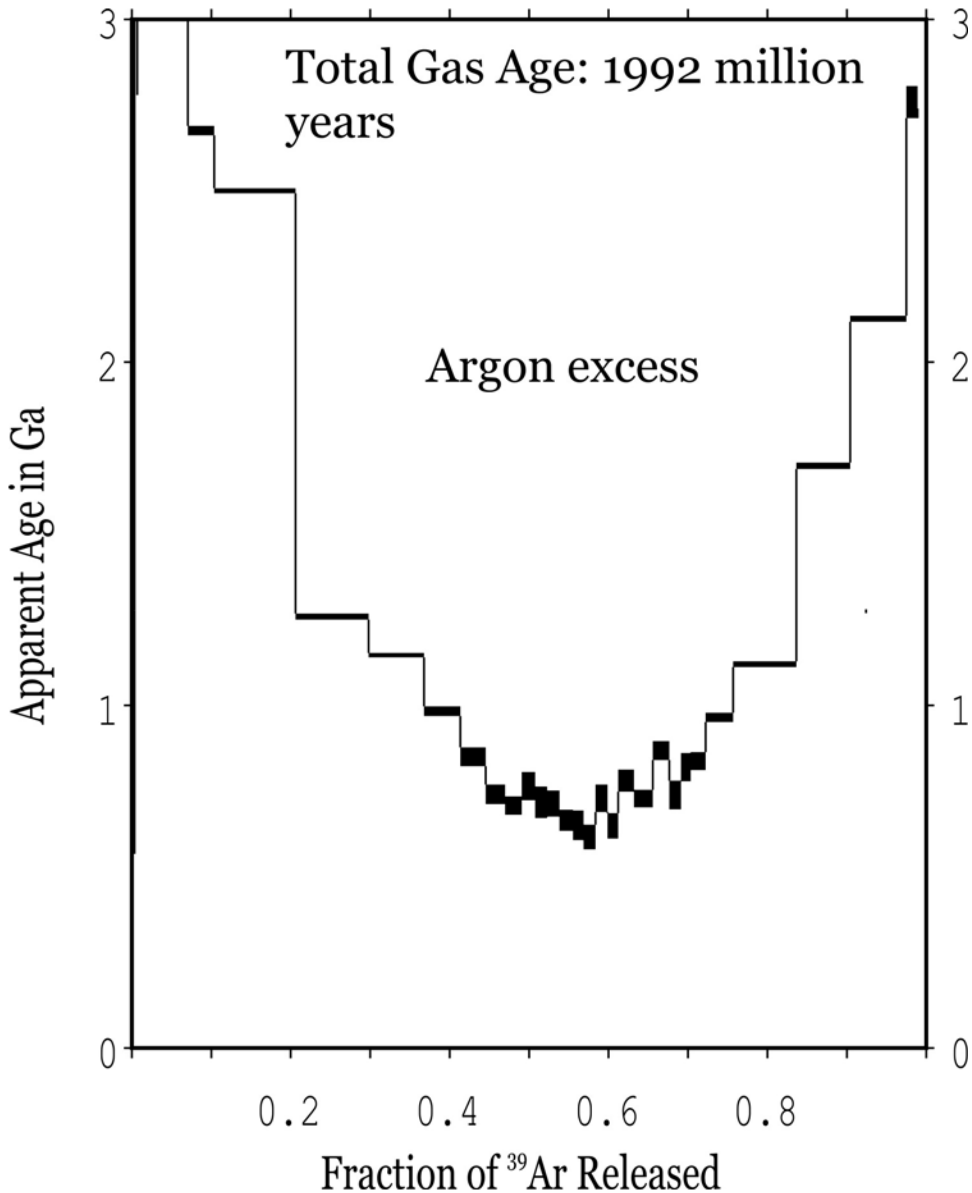
- Like U-Pb, we want to know if daughter loss or parent gain has occurred.
- K-Ar dating (the old fashioned way) yields an integration of the crystal and thus is problematic in determining loss/gain.
- A variant of K-Ar called Ar-Ar dating allows loss/gain to be visualized
- The method uses a stepwise release of radiogenic material that reveals loss/gain of daughter product within the system
- Called plateaus, an undisturbed crystal will show a flat profile. A disturbed crystal will show a gradient.

Flat Spectrum

- Real life example, the Majhgawan kimberlite of India
- Disturbed spectrum from Madagascar



Split #2: 1078.4 +/- 11.4 Ma
Total Fusion Age: 1080 +/- 10 Ma
Split #1: 1061.7 +/- 9.7 Ma
Total Fusion Age: 1068.2 +/- 9.4 Ma
Apparent Age (Ma)
Cumulative 39Ar Released (%)
(a)
Isochron Age: 1068.3 +/- 14.0 Ma
(b)
Isochron Age: 1072.2 +/- 21 Ma
(c)



A very disturbed age!

1. **Total gas age= K-Ar age would yield 1992 Ma.**

2. **We see that excess daughter is present in the crystal yielding some ages older than the earth!**

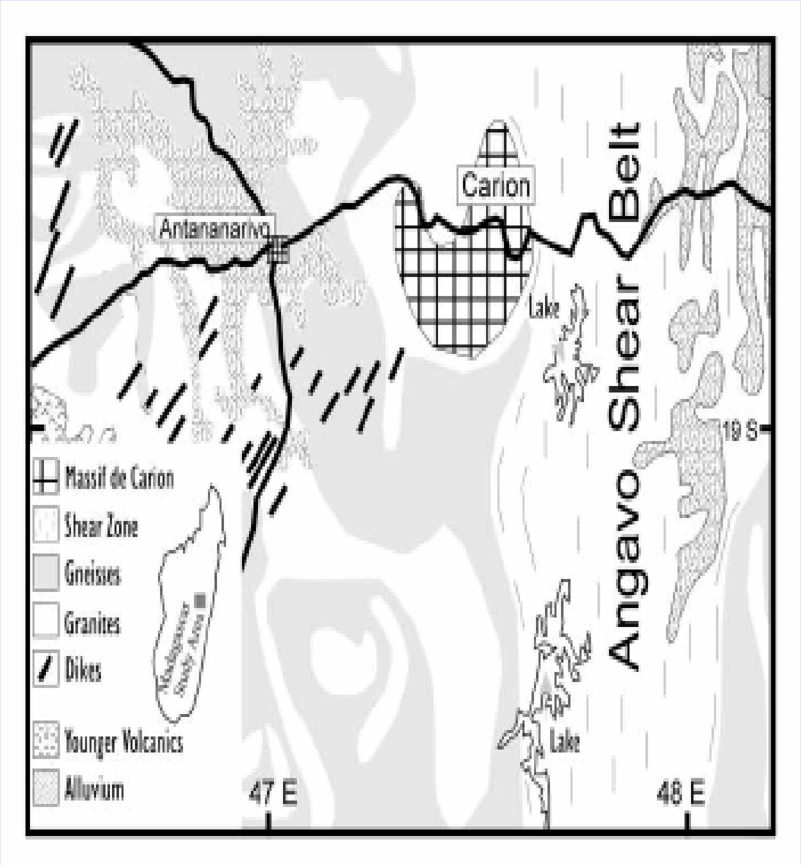
3. **The lowest ages would indicate ~600 Ma, but the sample is too disturbed to be sure!**

What about Slowly Cooled Rocks?

- Zircon, the most common mineral used in U-Pb dating ‘closes’ (i.e. loses no daughter nor gains parent) at a temperature of ~800-850 Celcius.
- Large granitic plutons may take millions of years to cool.
- Suppose we are interested in the cooling history of the pluton?

Real Life Example

- The Carion pluton near Antananarivo, Madagascar
- Carion is a granitic pluton and contains the minerals, zircon, hornblende, biotite and K-feldspar.



The Data

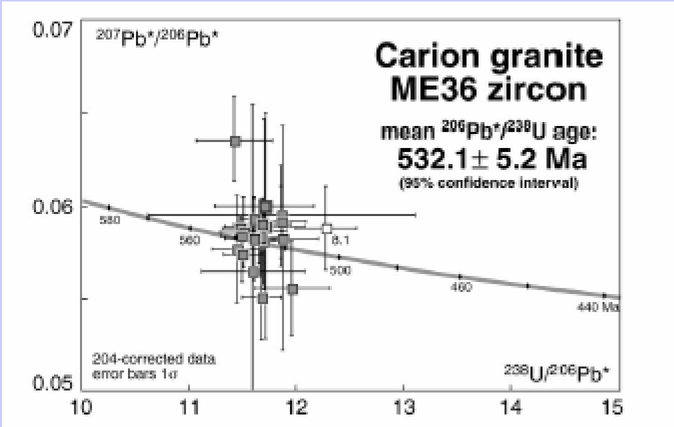
Zircon Age: 532.1 +/- 5.2 Ma

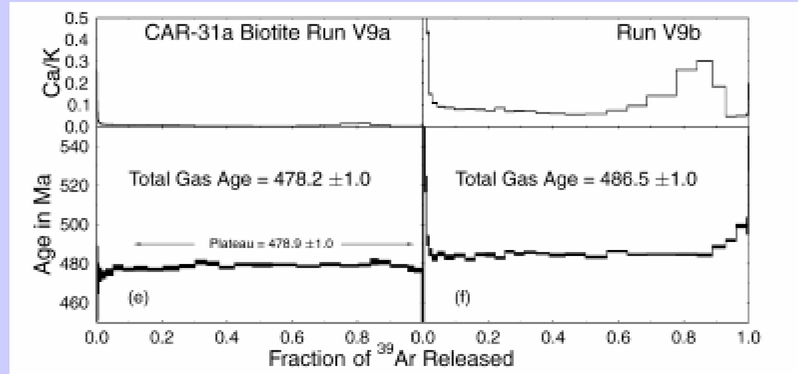
Hornblende Age: 512.2 +/- 1.3 Ma

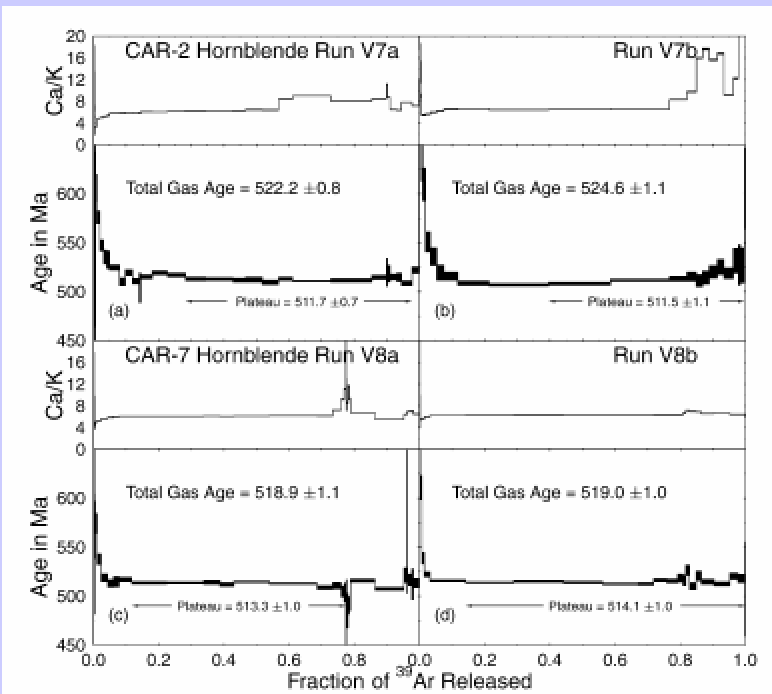
Biotite Age: 478.9 +/- 1.0 Ma

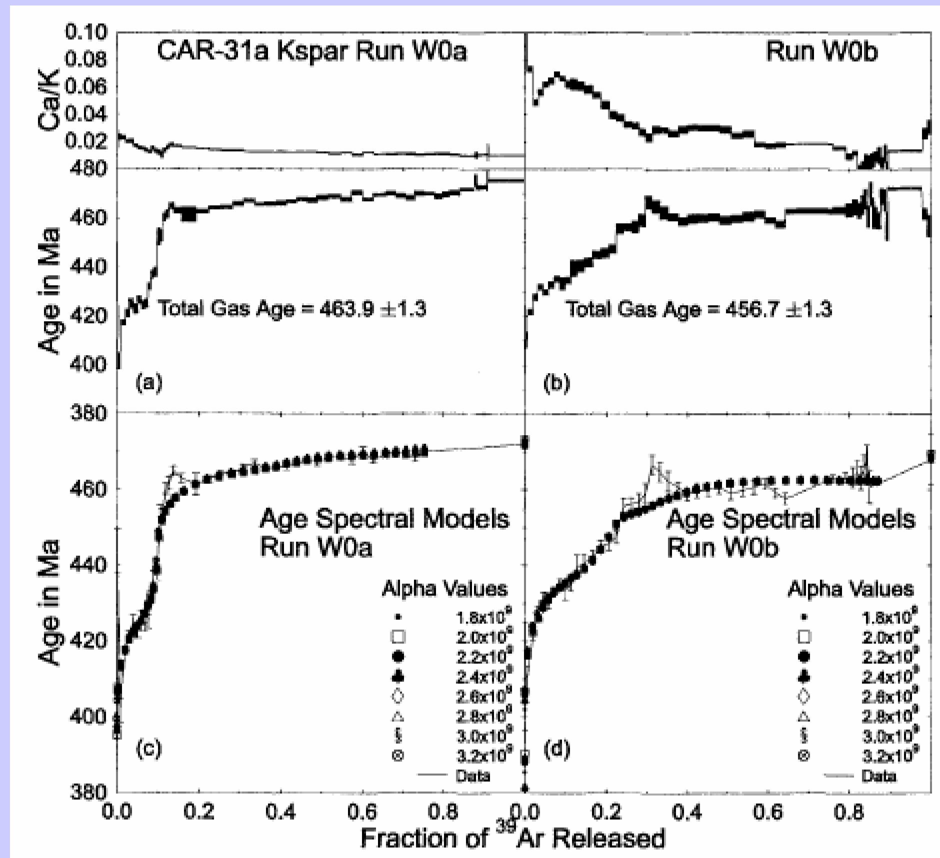
K-Spar 1 Age: 435.0 +/- 10 Ma

K-spar 2 Age: 410 +/- 10 Ma

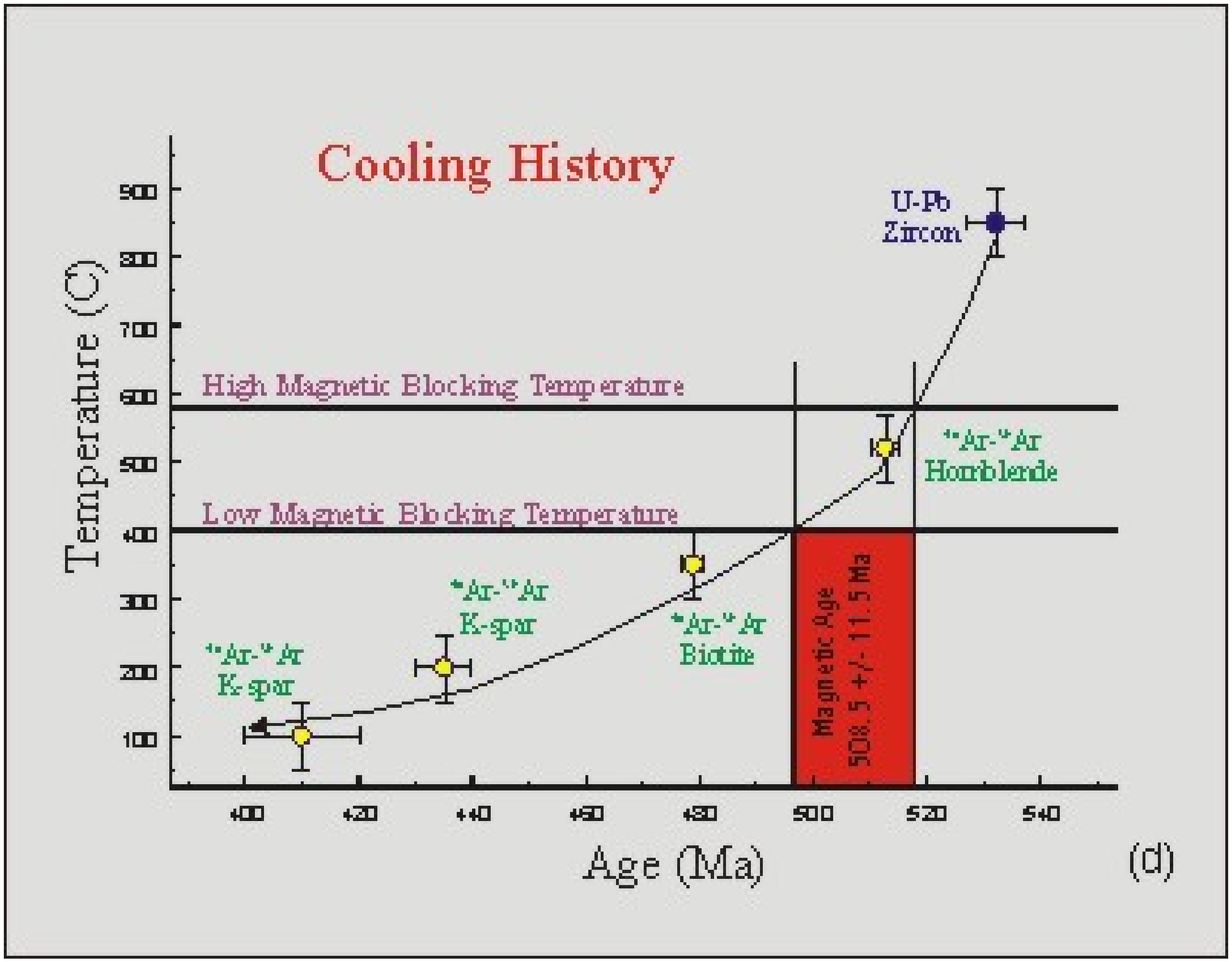

Carion granite
ME36 zircon
mean $^{206}Pb^*/^{238}U$ age:
532.1± 5.2 Ma
(95% confidence interval)
$^{207}Pb^*/^{206}Pb^*$
$^{238}U/^{206}Pb^*$
204-corrected data
error bars 1σ
0.07
0.06
0.05
10
11
12
13
14
15
580
560
500
460
440 Ma


CAR-31a Biotite Run V9a
Run V9b
Ca/K
Age in Ma
Total Gas Age = 478.2 ±1.0
Total Gas Age = 486.5 ±1.0
Plateau = 478.9 ±1.0
(e)
(f)
Fraction of ^{39}Ar Released


CAR-2 Hornblende Run V7a
Run V7b
Ca/K
Age in Ma
Total Gas Age = 522.2 ±0.8
Total Gas Age = 524.6 ±1.1
Plateau = 511.7 ±0.7
Plateau = 511.5 ±1.1
(a)
(b)
CAR-7 Hornblende Run V8a
Run V8b
Total Gas Age = 518.9 ±1.1
Total Gas Age = 519.0 ±1.0
Plateau = 513.3 ±1.0
Plateau = 514.1 ±1.0
(c)
(d)
Fraction of ^{39}Ar Released


CAR-31a Kspar Run W0a
Run W0b
Ca/K
Age in Ma
Total Gas Age = 463.9 ±1.3
Total Gas Age = 456.7 ±1.3
(a)
(b)
Age Spectral Models
Run W0a
Age Spectral Models
Run W0b
Alpha Values
1.8x10⁹
2.0x10⁹
2.2x10⁹
2.4x10⁹
2.6x10⁹
2.8x10⁹
3.0x10⁹
3.2x10⁹
Data
(c)
(d)
Fraction of ^{39}Ar Released

Cooling History

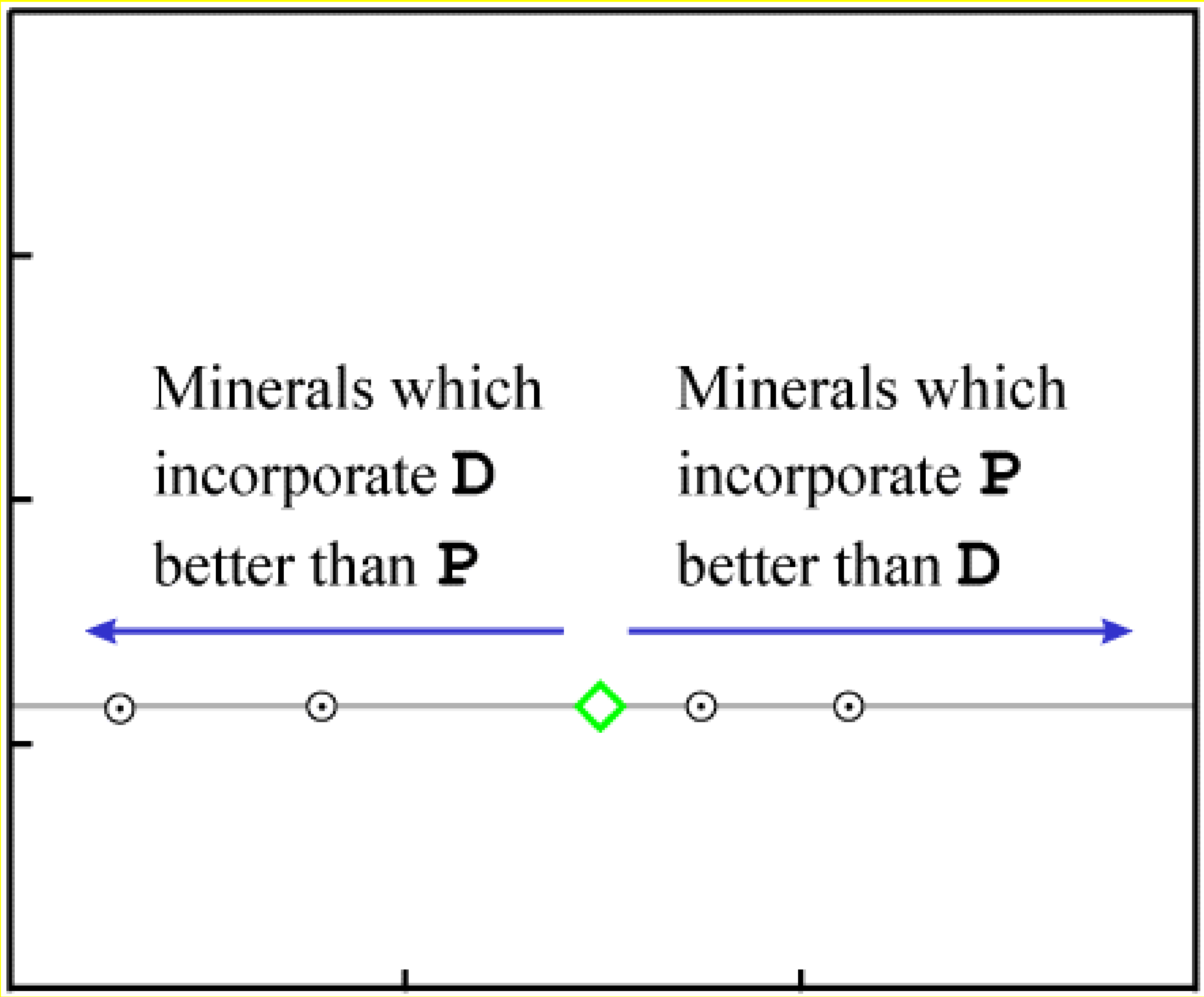


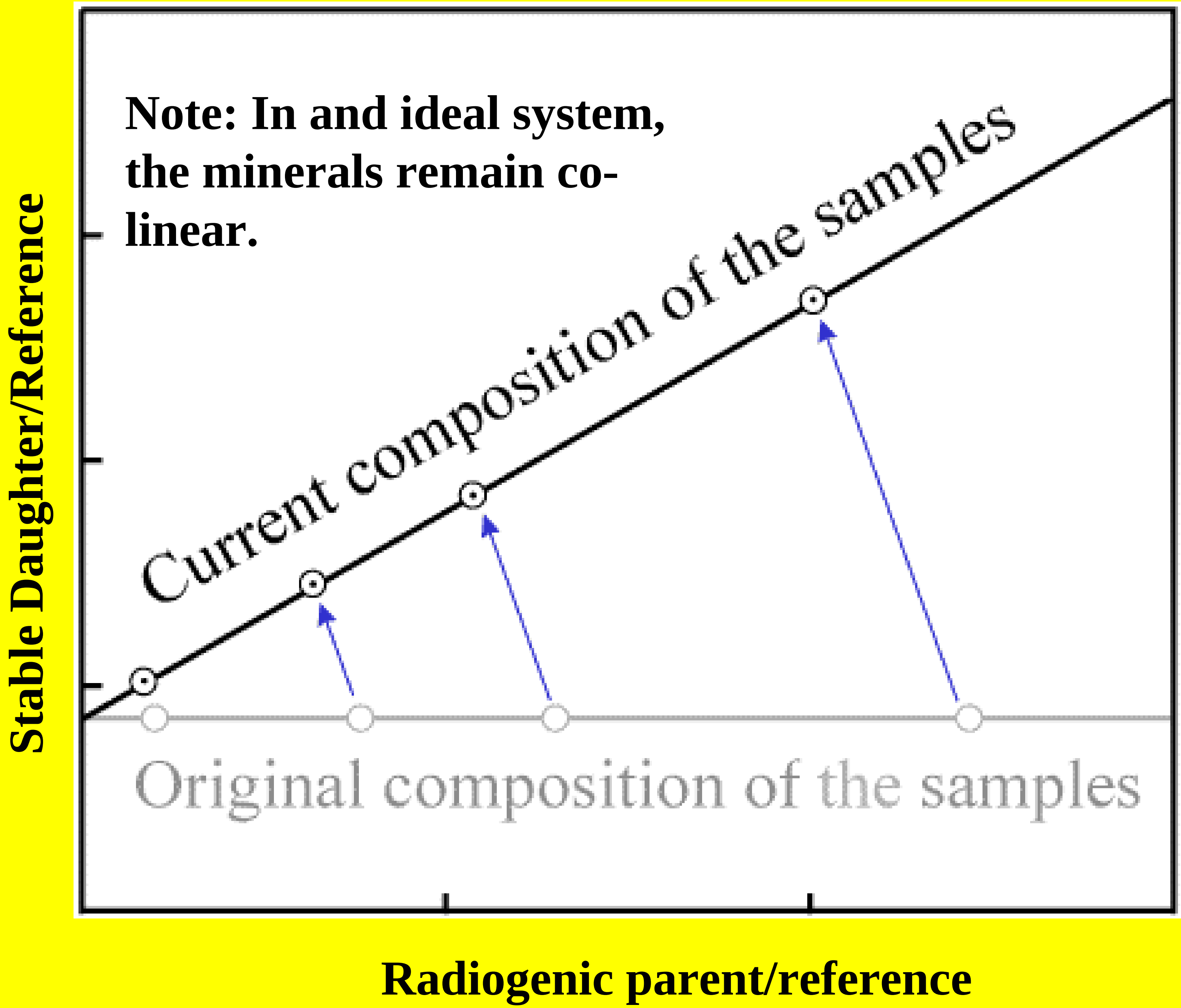
Isochrons

- Another way to detect disturbances in isotopic systems is through the use of isochron dating.
- Isochron- Same time!
- Let’s look at the evolution of an isochron.

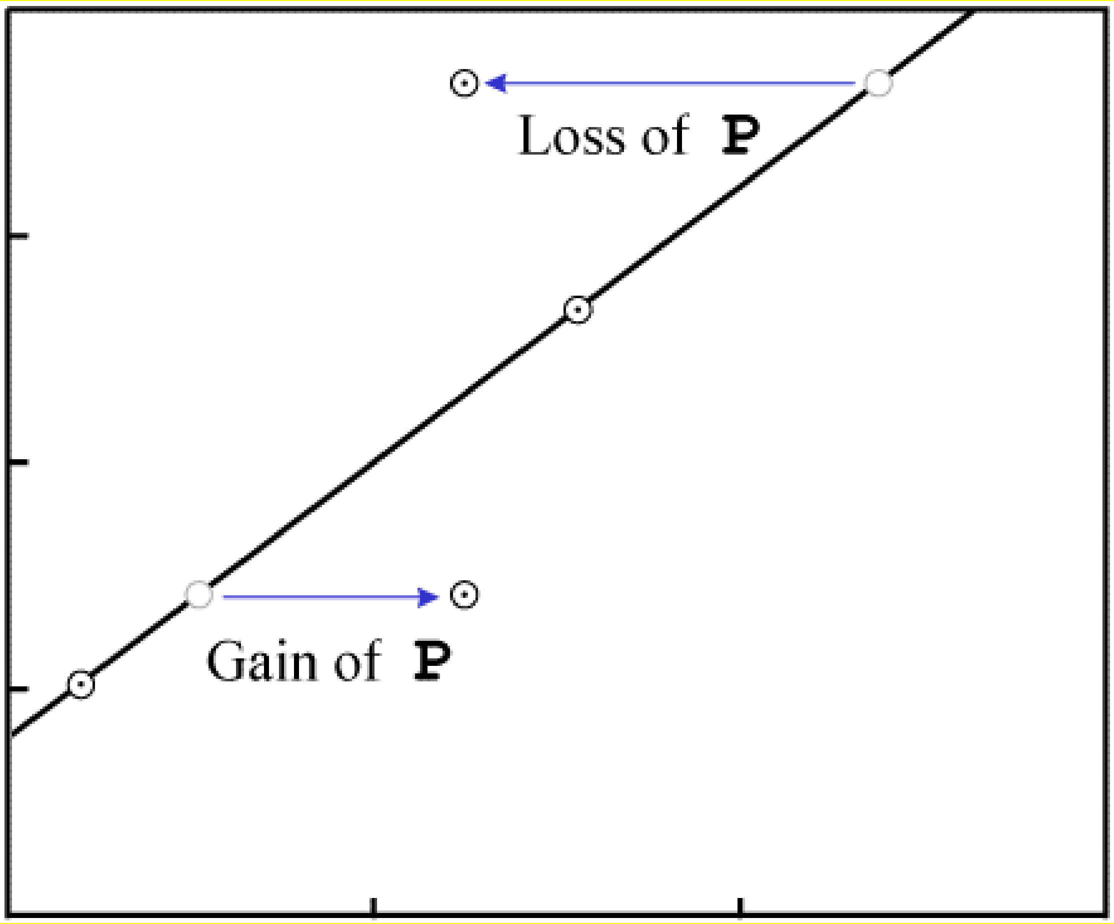
Isochron Dating

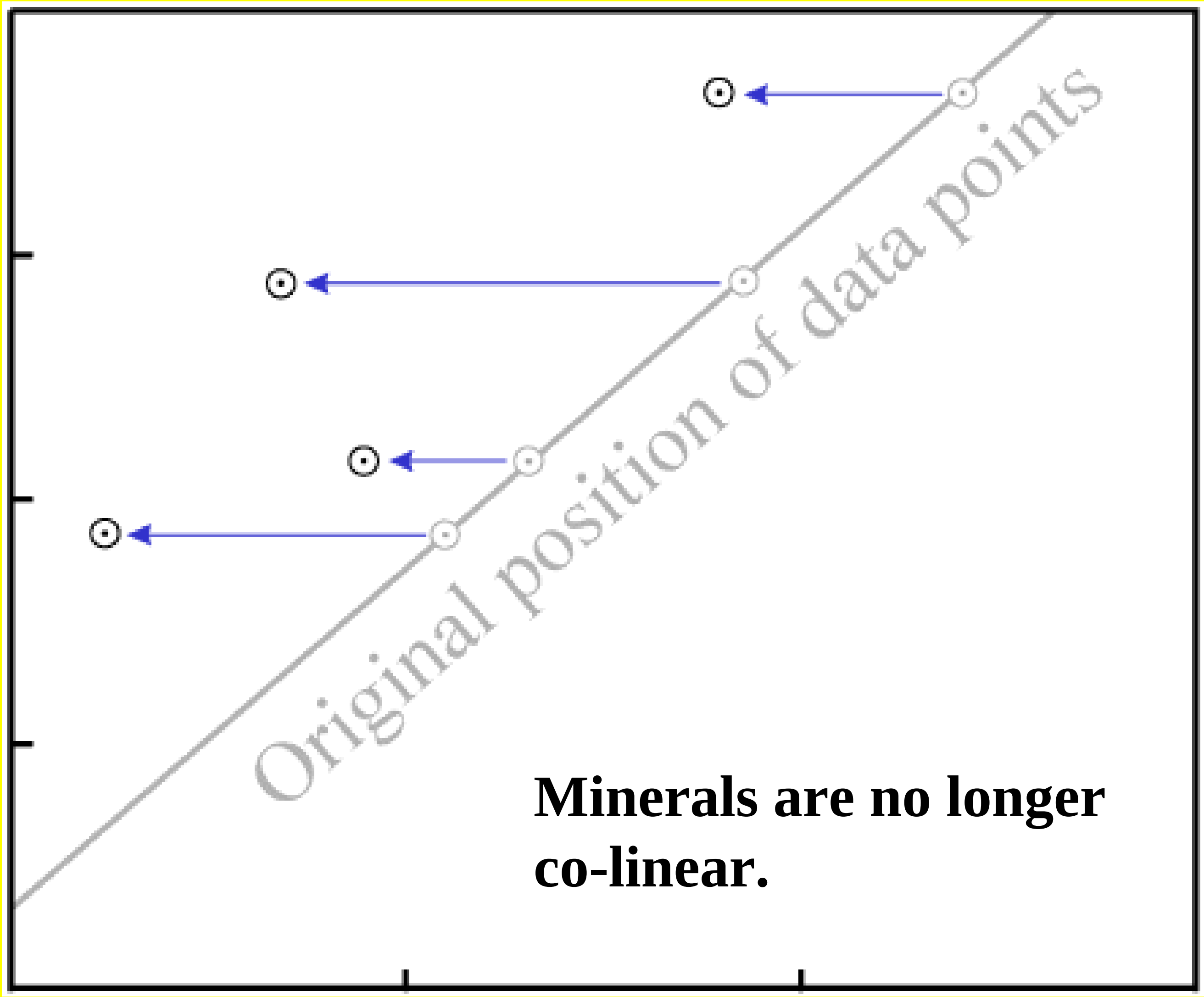
- Suppose we have a rock with a suite of minerals.
- These minerals (due to bonding, atomic size etc) will incorporate different amounts of parent/daughter into their crystals.
- Each will then evolve during decay in a slightly different manner.


Minerals which incorporate D better than P
Minerals which incorporate P better than D

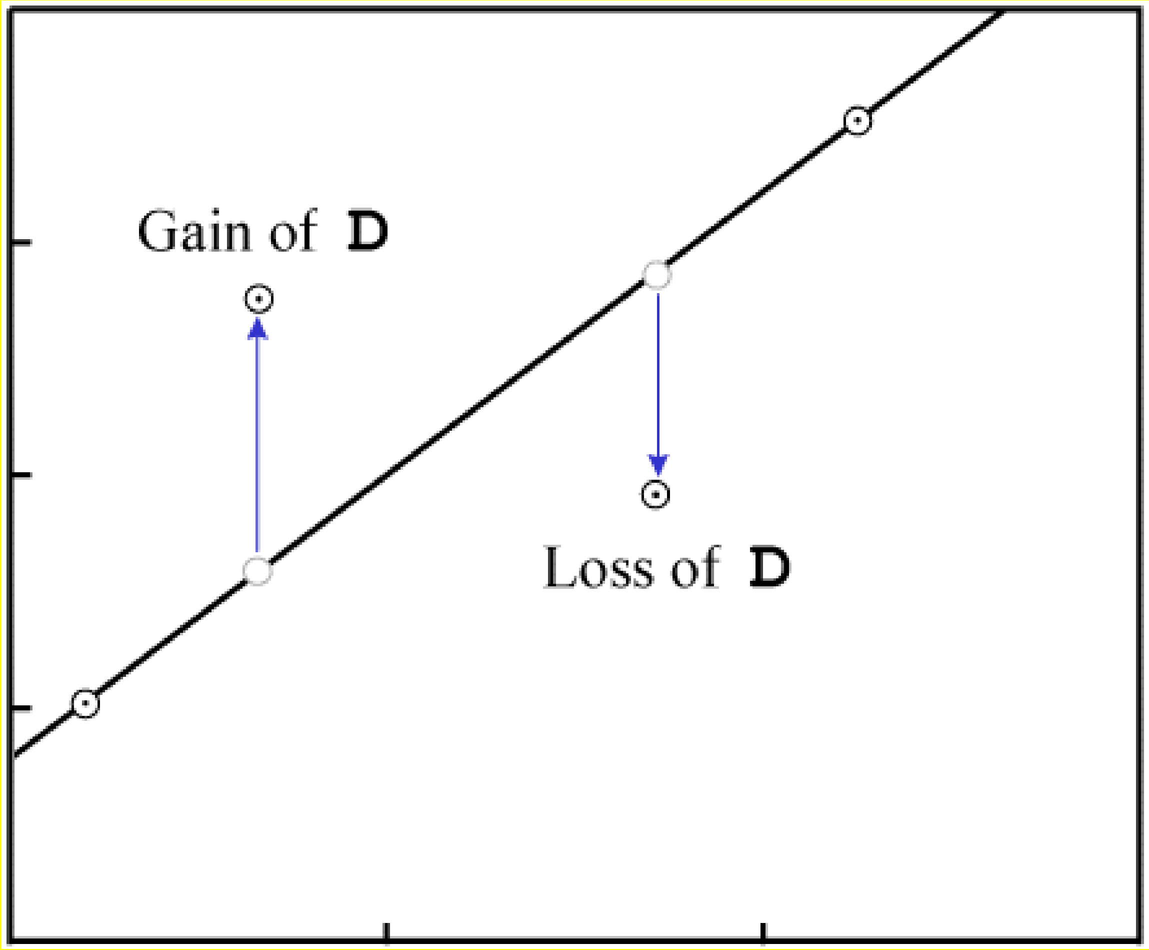

Note: In and ideal system, the minerals remain co-linear.
Current composition of the samples
Original composition of the samples
Stable Daughter/Reference
Radiogenic parent/reference

What about Disturbed Systems?

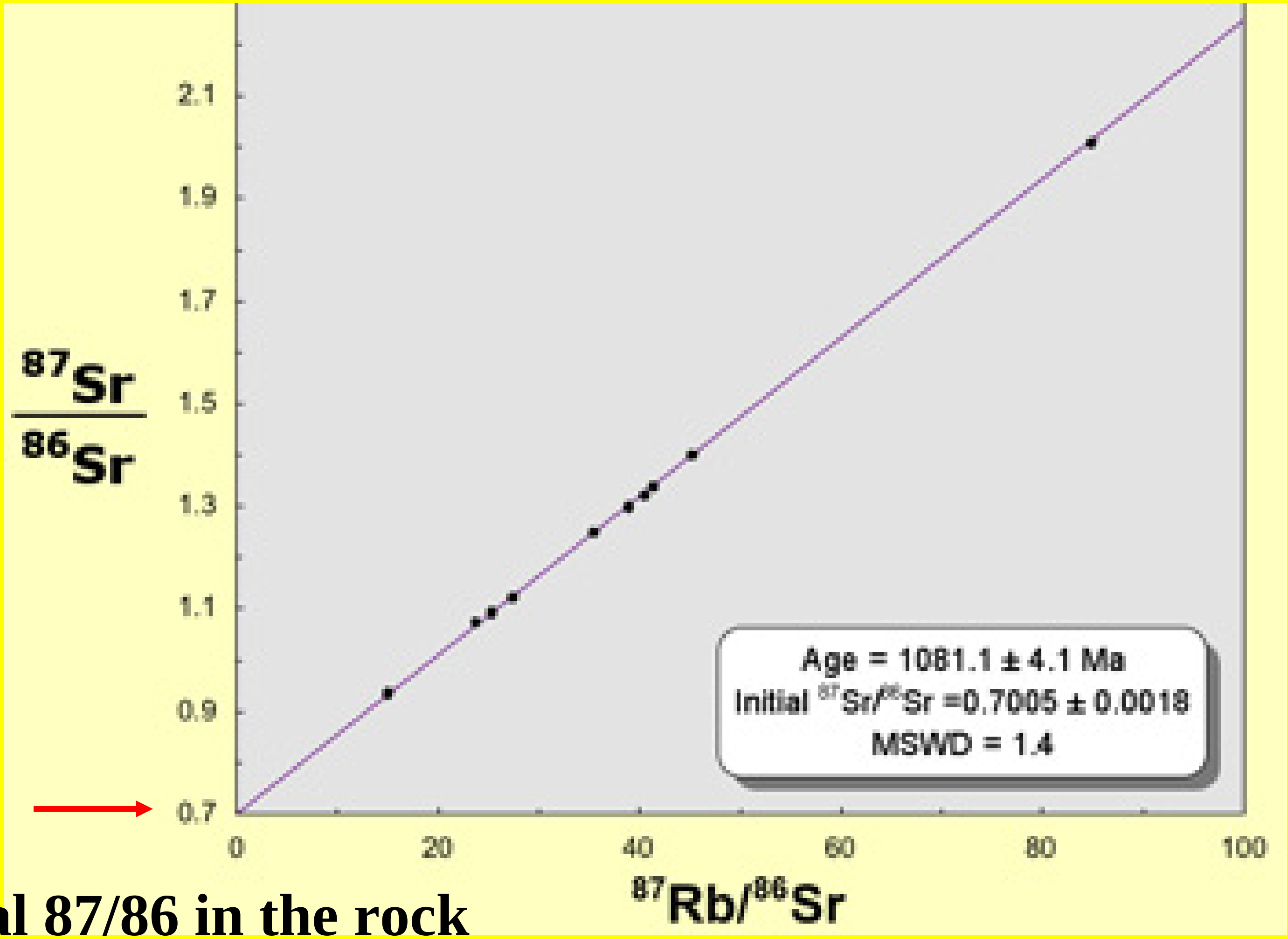



Original position of data points
Minerals are no longer co-linear.

The same problem exists if daughter amounts change



If the minerals are co-linear, we can determine the age because they will all lay along the same time-evolutionary trend AND the ratio of initial daughter in the system! Brilliant!



Initial 87/86 in the rock

Dating Metamorphic Events

- The same systems (U-Pb, Ar-Ar, Rb-Sr) can be used to date metamorphic events.
- Recall that discordia plots are often the result of younger metamorphic events
- New minerals grow during metamorphism and can be dated.

Sedimentary Rocks and Concordia

- Suppose we want to know the age of a sedimentary rock.
  - Sedimentary rocks typically don’t form with radiometric clocks set at zero (they incorporate minerals from parent rocks).
  - In some cases, sedimentary rocks will incorporate small amounts of ‘new’ radiogenic material

Pb-Pb Dating of Limestone

- A new technique is to look at Uranium decay chains in limestone. Pb-Pb dating is a variant of U-Pb dating.
- Can work, but often gives huge errors.
- Developing technique may prove useful.

Detrital Zircons

- A technique that is widely used in dating sedimentary beds is detrital zircon dating.
- Rocks with zircon weather and zircon is resistant to breakdown. Thus, these zircons are found in many sandstones.
- Dating these zircon populations can tell us:
  - Provenance of sediments (source)
  - Maximum age of sediments (they must be younger than the youngest zircon found in them.

Real Life Example: Vindhyanchal Basin India

Bhander-Rewa Detrital Zircon Ages (Rajasthan)