Dating of samples and planetary surfaces

- What is the age of the solar system ?
- Did the various bodies in the solar system form at the same time ?
- What is the age of the surface rocks or of geological formations on different planets ?
- What is the spread of ages found on a single planet ?

A rose-red city half as old as Time.
One billion years ago the city's age
Was just two-fifths of what Time's age will be
A billion years from now. Can you compute
How old the crimson city is today ?
John William Burgon

Radioactive dating: Rb-Sr method

Rubidium and strontium are trace elements in natural rocks. Rb can replace K or Na in the crystal lattice, Sr can replace Ca. Rubidium has a radioactive isotope that decays into a strontium isotope by β-decay.

$^{87}\mathrm{Rb} \rightarrow {}^{87}\mathrm{Sr} + e^-$ half-life $T_{1/2} = 48.8$ Gyr decay constant $\lambda = \ln(2)/T_{1/2}$

Over geological time t after the formation of a rock, the concentration of ^{87}Rb decreases and that of ^{87}Sr increases

$[^{87}\mathrm{Rb}]_t = [^{87}\mathrm{Rb}]_o\, e^{-\lambda t}$ $[^{87}\mathrm{Sr}]_t = [^{87}\mathrm{Sr}]_o + [^{87}\mathrm{Rb}]_o\,(1 - e^{-\lambda t}) = [^{87}\mathrm{Sr}]_o + [^{87}\mathrm{Rb}]_t\,(e^{\lambda t} - 1)$

Because isotope ratios can be measured much more precisely than absolute abundance, it is useful to normalize all concentrations with that of a reference isotope, ^{86}Sr, which is stable and not produced by decay, so that it does not change with time:

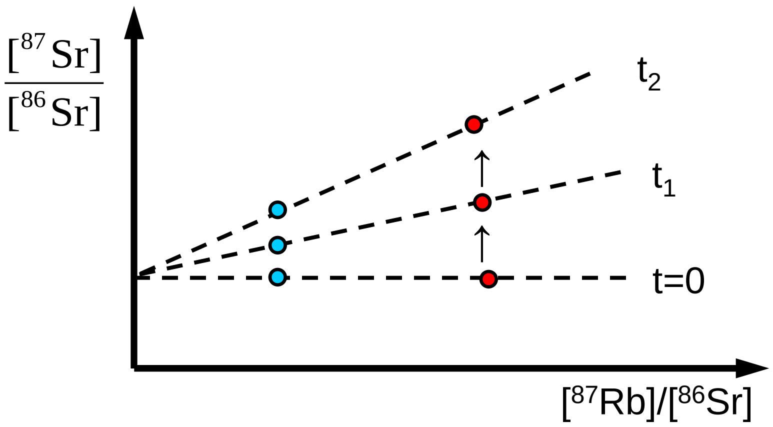
$$\frac{[^{87}\mathrm{Sr}]_t}{[^{86}\mathrm{Sr}]} = \frac{[^{87}\mathrm{Sr}]_o}{[^{86}\mathrm{Sr}]} + (e^{\lambda t} - 1)\frac{[^{87}\mathrm{Rb}]_t}{[^{86}\mathrm{Sr}]} \qquad \text{[Eqn. 1]}$$

$$y = y_o + \mathrm{const} * x$$

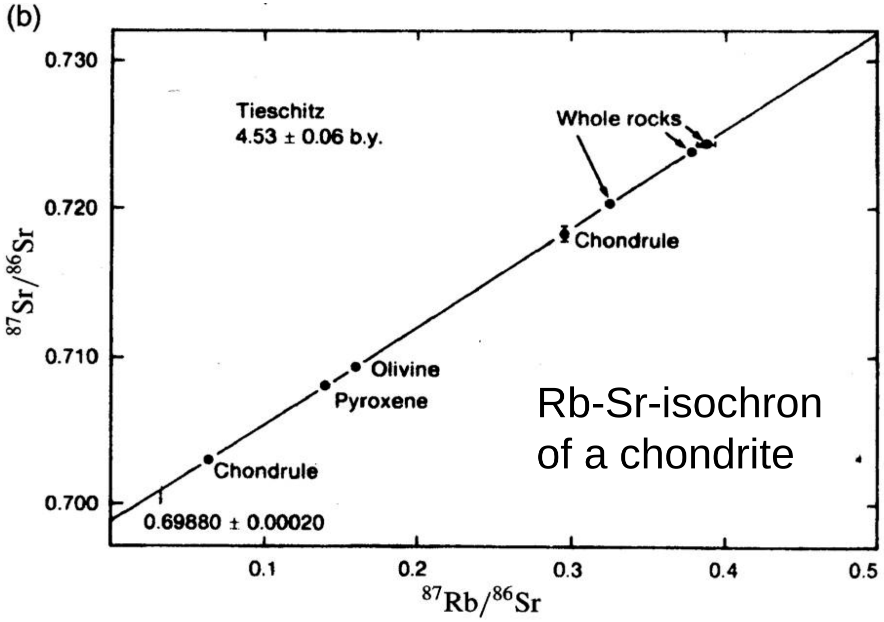
When a rock forms from a magma (or solid bodies from the protoplanetary nebula), the source material is well mixed, but during this process it becomes differentiated. The absolute and relative concentrations of Rb and Sr will be different in different mineral grains, in different batches of magma erupted from a magma chamber at different times or in different protoplanets formed from the nebula. The different minerals in a piece of rock, different lava flows coming from the same magma source, or different protoplanets, form a suite of samples with a common origin (cogenetic suite).

Rb-Sr method

Because the different isotopes of an element behave chemically almost identically, different samples of a suite may have different concentrations of Sr and Rb, but their isotope ratios are initially the same. As time progresses, the $^{87}Sr/^{86}Sr$-ratio will grow strongly in a sample with a high Rb/Sr-ratio and weakly in a sample with a low Rb/Sr-ratio.

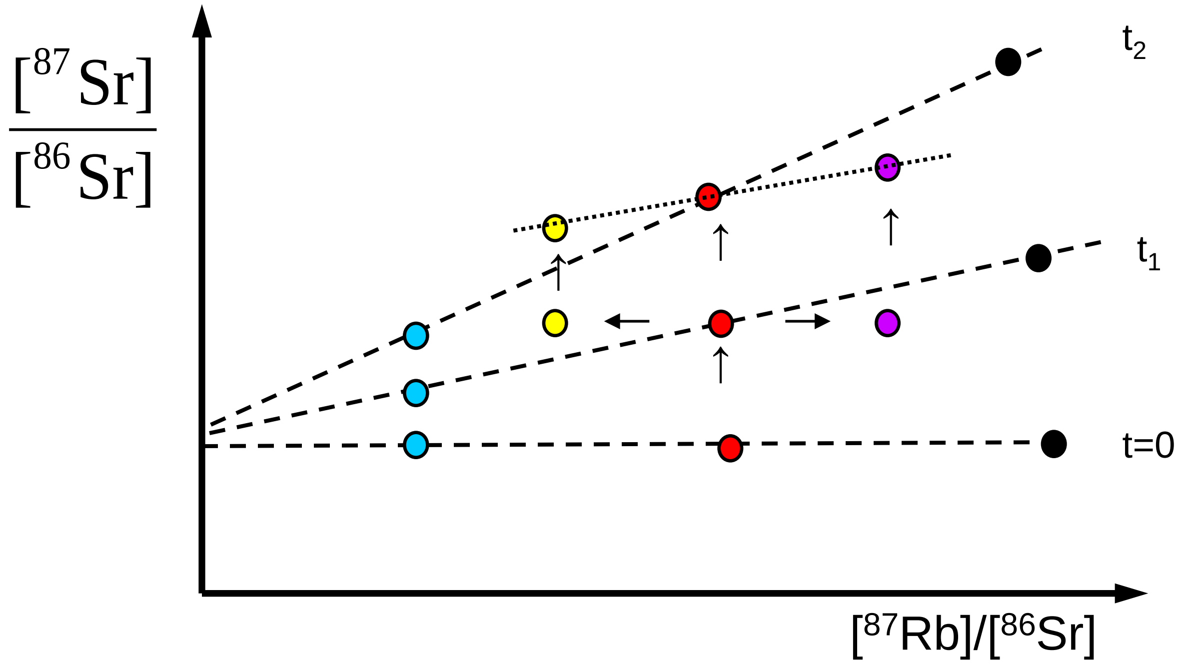


The age is obtained by measuring the isotope ratios of several samples of a suite and by calculating the best-fitting linear regression to eqn. 1 on slide 3.2. With the known value of λ the age is obtained from the constant of proportionality (the slope of the regression line, called **isochron**). An important condition is that the different samples formed **closed systems,** i.e. there was no chemical exchange with the environment after their formation.



Rb-Sr-isochron of a chondrite

Dating a second step of differentiation



At t=0 a reservoir (e.g. protosolar nebula) splits up into several bodies (planets). At a later time t_1 the red one differentiates into different sub-samples (yellow, red and pink) with different Rb/Sr-ratios. Their $^{87}Sr/^{86}Sr$ ratio is the same at t_1, because they are all drawn from the same reservoir. However, subsequently it will evolve differently because of the different Rb concentrations. The slope connecting these three samples at t_2 indicates the time lapse between t_1 and t_2, i.e., the age of the second differention event. When we want to use the samples from the „red planet“ in order to date the first event, we must „remix“ them and use them together with data from the other planets (blue and black). If we used at t_2 the blue, yellow and black points, they do not fall on a straight line.

Pb-Pb method

The lead-lead method of dating makes use of two decay series, both starting at an isotope of uranium and ending at a lead isotope.

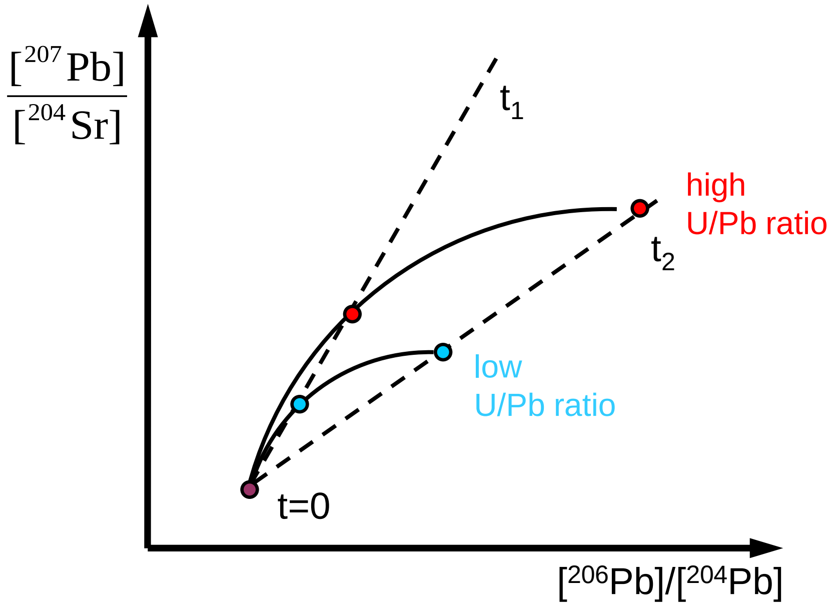
$^{238}U \rightarrow ... \rightarrow {}^{206}Pb \quad (T_{1/2} = 4.46 \text{ Gyr})$ $^{235}U \rightarrow ... \rightarrow {}^{207}Pb \quad (T_{1/2} = 0.704 \text{ Gyr})$

$$\frac{[^{207}\mathrm{Pb}]_t}{[^{204}\mathrm{Pb}]} = \frac{[^{207}\mathrm{Pb}]_0}{[^{204}\mathrm{Pb}]} + \frac{e^{\lambda_{235}t}-1}{e^{\lambda_{238}t}-1}\,\frac{[^{235}\mathrm{U}]_t}{[^{238}\mathrm{U}]_t} \times \left(\frac{[^{206}\mathrm{Pb}]_t}{[^{204}\mathrm{Pb}]} - \frac{[^{206}\mathrm{Pb}]_0}{[^{204}\mathrm{Pb}]}\right) \qquad \text{[Eqn. 2]}$$

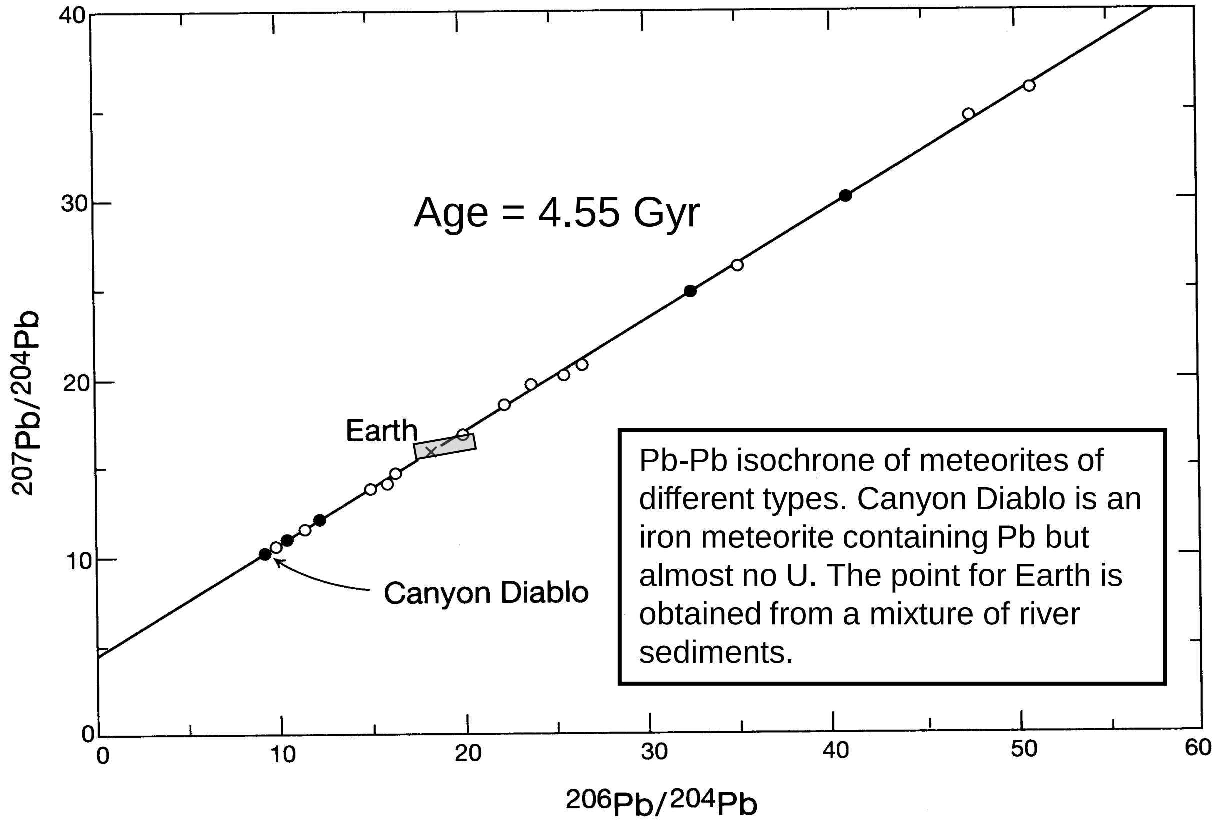
$$y = y_o + \text{const} * (x - x_o)$$

$R = [^{235}U]/[^{238}U] = 1/137.9$ (today)

At a given time, R is the same for all samples. Because of the short half-life of ^{235}U, the $^{207}Pb/^{204}Pb$-ratio grew rapidly early on, but grows more slowly in more recent times. Again, samples from a cogenetic suite fall on an isochron, whose slope relates to the age through eqn. 2. With this method only isotopes ratios of a single element need to be measured.



Age of meteorite parent bodies



Pb-Pb isochrone of meteorites of different types. Canyon Diablo is an iron meteorite containing Pb but almost no U. The point for Earth is obtained from a mixture of river sediments.

Most meteorites (of various types) fall on a single Pb-Pb isochron. A representative mixture of terrestrial rocks falls on the same line. The various meteorite parent bodies and the Earth (or the protoplanets that built the Earth) formed at the same time. The age of the isochron, ≈ 4.55 Gyr, is taken as the time of formation of the entire solar system.

It marks the time when the different bodies in the solar system separated, with no or very limited chemical exchange between them thereafter.

Radioactive dating of individual samples from the solar system

Some parts of a body in the solar system can be younger than the body as a whole. For example, an individual rock on Earth is younger than the Earth, because after formation the Earth continued to differentiate internally. The age of the individual sample is obtained by dividing it up into sub-samples (e.g. into the various minerals forming a rock) and determine an isochron for this suite. The following characteristic ages are obtained using different radioactive dating techniques:

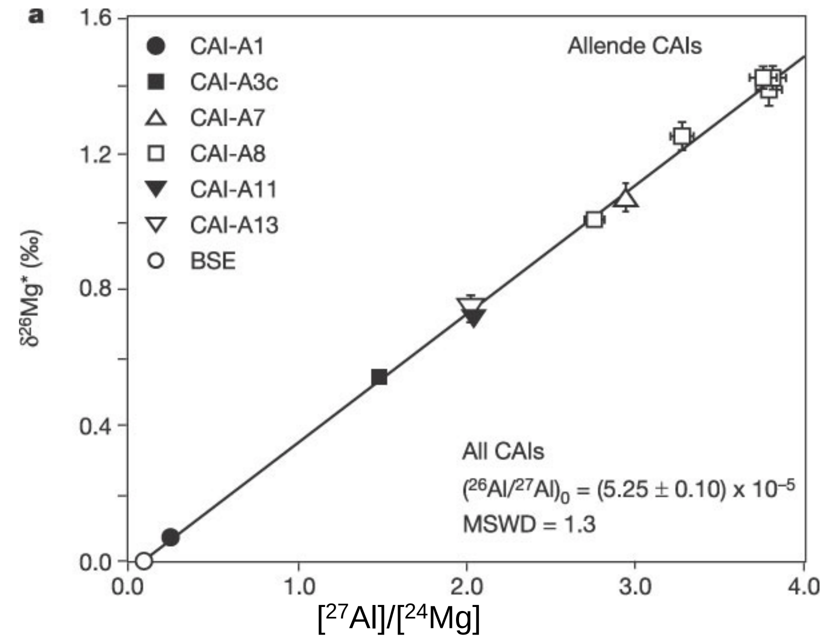
Chondritic / iron meteorites:	4.55 Gyr
HED meteorites (Vesta ?)	4.5 Gyr
Oldest terrestrial mineral grains (zircons):	4.4 Gyr
Oldest terrestrial rocks:	4.0 Gyr
Lunar highland rocks:	4.5 – 3.9 Gyr
Lunar Mare rocks:	3.9 – 3.1 Gyr
SNC meteorites (Mars?)	4.3 – 0.2 Gyr
Average terrestrial continental crust:	≈ 2.5 Gyr
Terrestrial oceanic crust:	0.0 – 0.2 Gyr

High resolution dating of early events

Short-lived (now extinct) radioactive isotopes were present when the solar system formed. Example:

$^{26}Al \rightarrow {}^{26}Mg + e^-$ $T_{1/2} = 720{,}000$ yr.

In so-called calcium-aluminium rich inclusions (CAIs) in the chondritic Allende meteorite, the ratio $[^{26}Mg]/[^{24}Mg]$ correlates linearly with the Al/Mg-ratio. It shows that ^{26}Al was incorporated into the CAIs and created by decay of the excess ^{26}Mg.

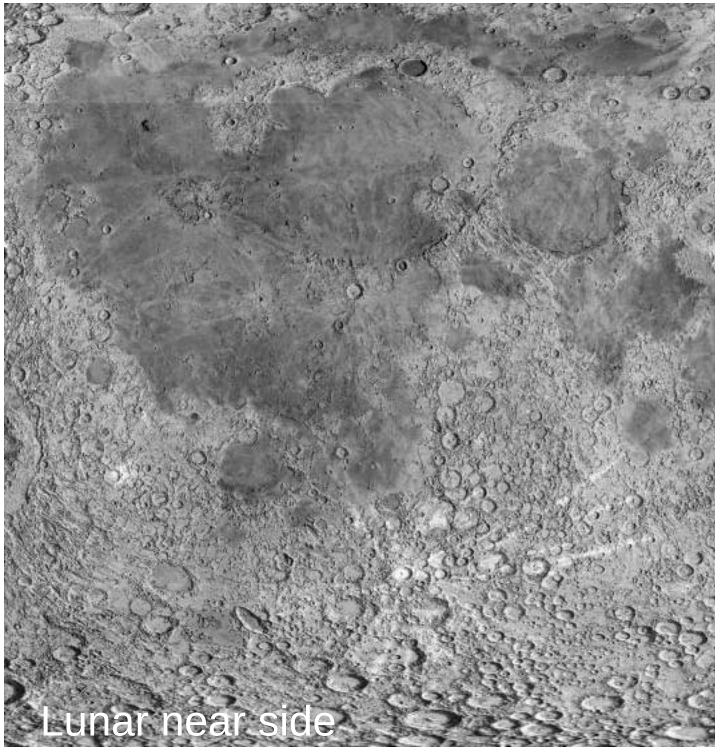


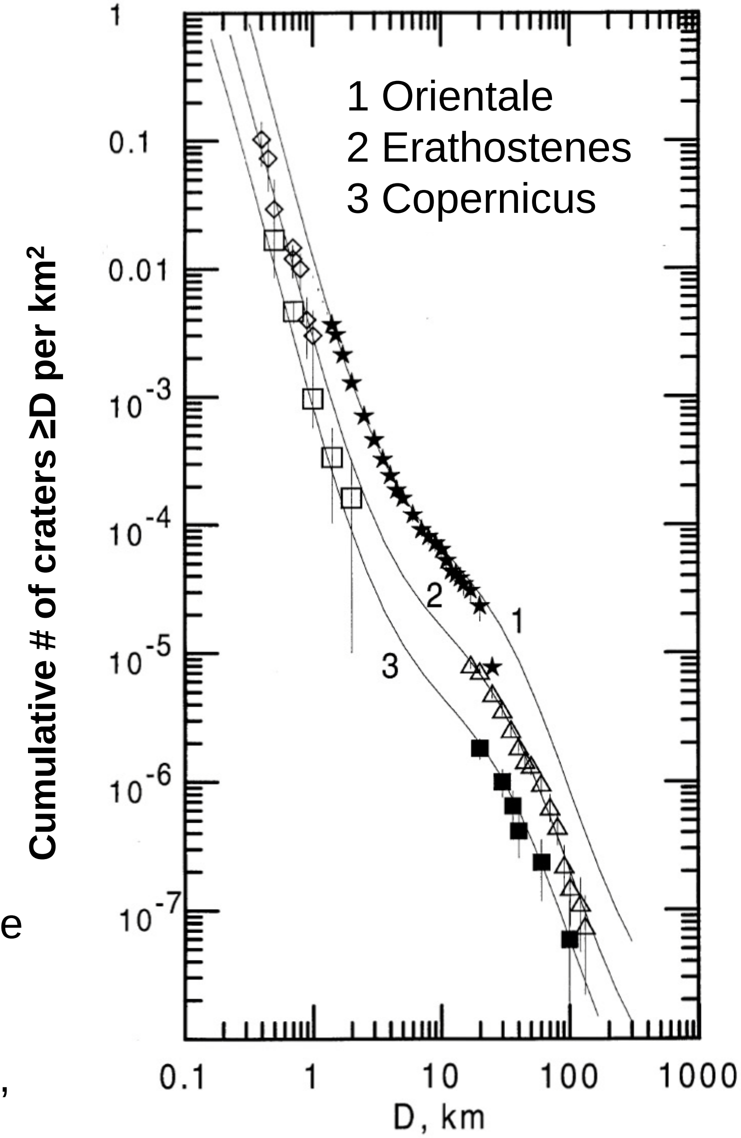
Conclusions

(1) CAIs represent the first condensation products in the solar nebula, which were later included into chondritic meteorites,

(2) The nucleosynthesis, which created some of the heavy elements of which the terrestrial planets are formed, occured not more than a few Myr before the solar system formed (otherwise ^{26}Al would have no longer been present). Perhaps a supernova explosion occured ~ 5 Myr before the CAIs condensed, blowing heavy elements (among them ^{26}Al) into space, triggering at the same time the gravitational collapse of the protosolar gas cloud.

Surface ages from cratering statistics





All solar system bodies a subject to a continuous flux of impactors. On most planets erosion is much less active than on Earth and impact craters survive for billions of years, unless the planetary surface is changed by internal processes (volcanism). The **crater density** of a geological unit allows to date it, at least in a relative sense.

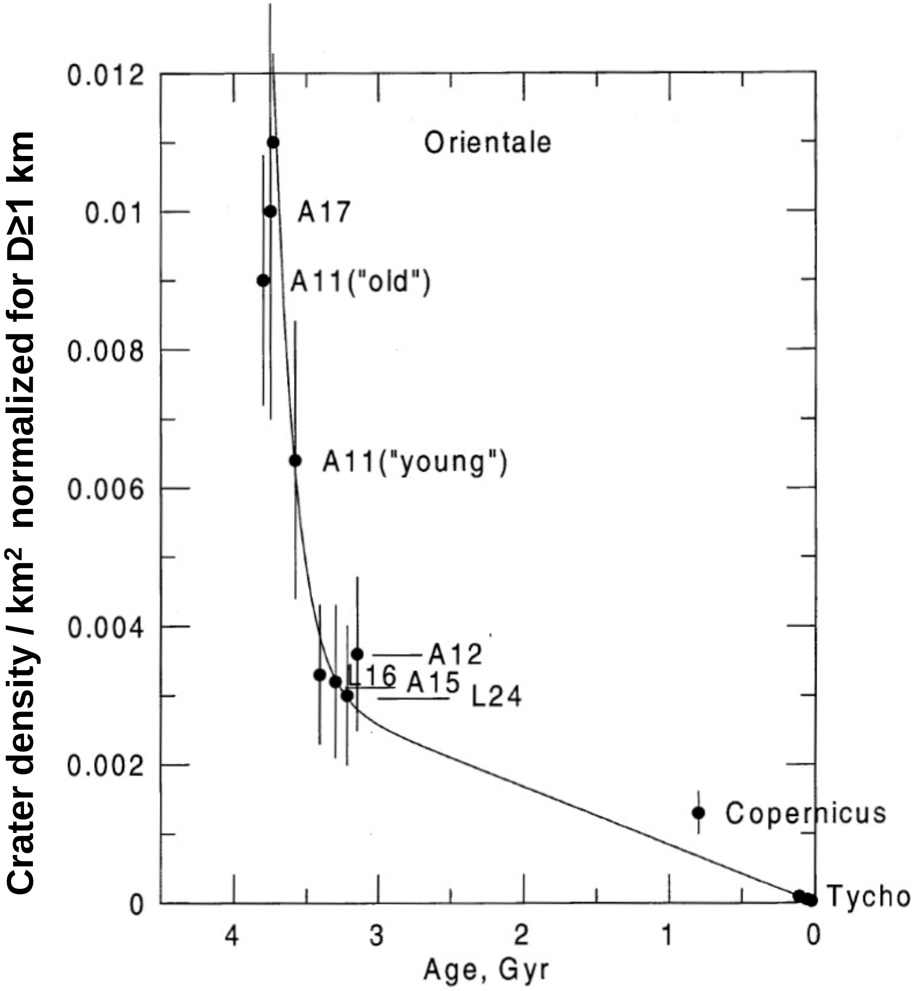
Christensen et al., Planetary Interiors and Surfaces, June 2011

Cratering density versus age

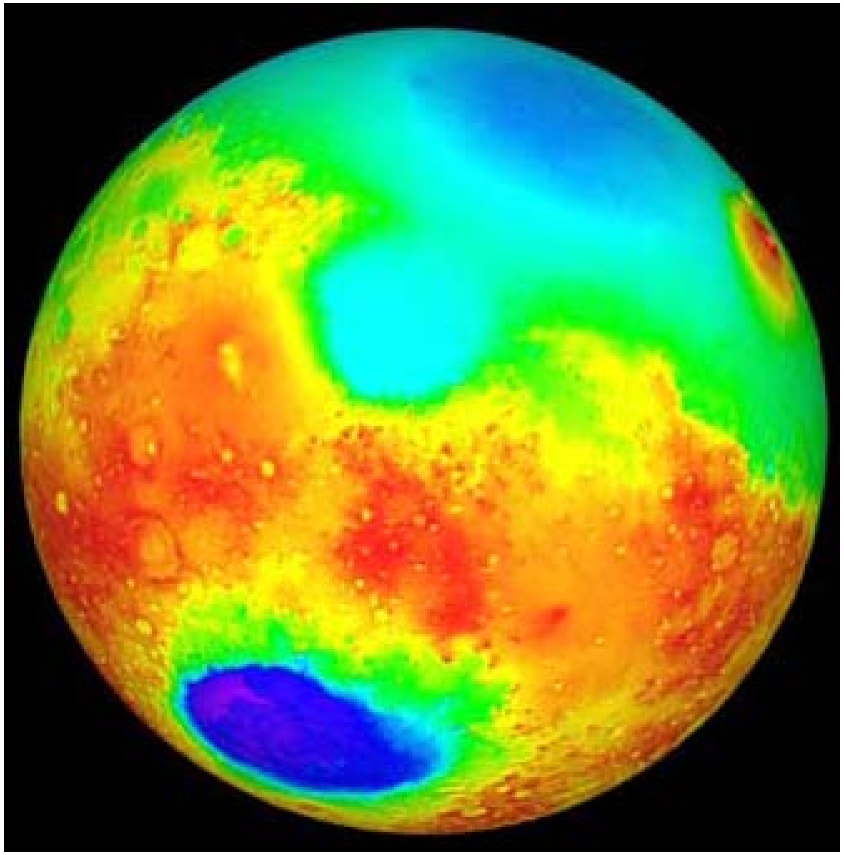
Radiometrically dated samples from the moon allow to associate an absolute age with a certain crater density. The relation is non-linear because the flux of impactors was higher before 3.5 Gyr, but seems to stay at a nearly constant level since.

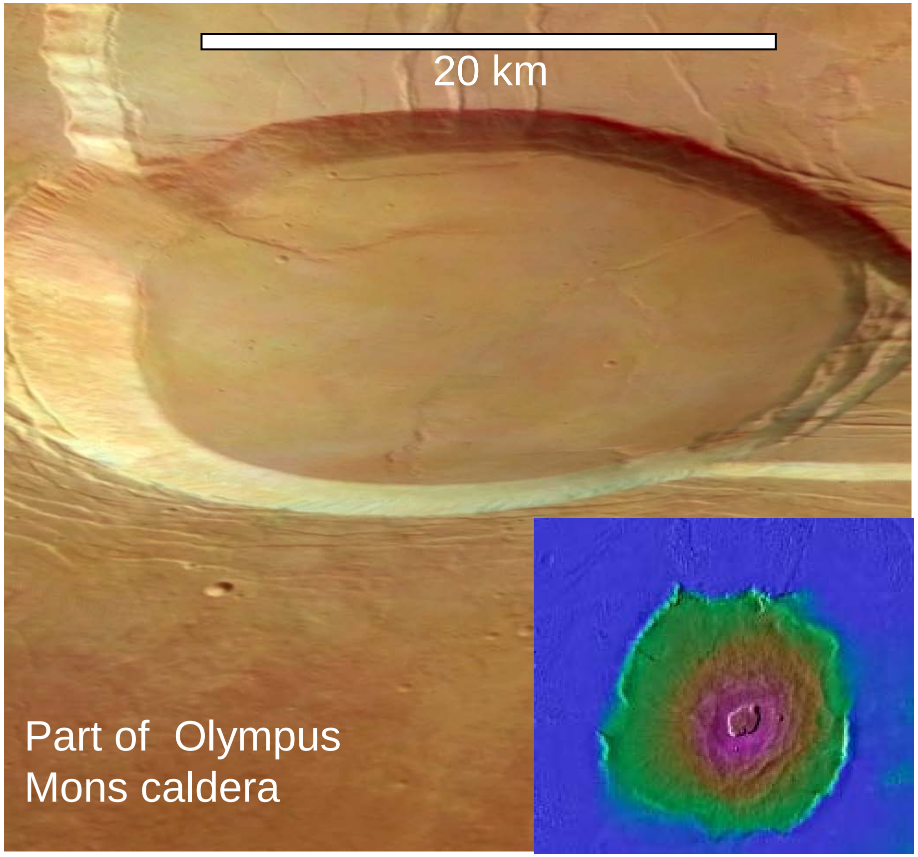
With this calibration, absolute ages have been determined also for other planetary surfaces from the crater density. However, a correction for the different fluxes of impactors in different parts of the solar system must be made (based on theoretical considerations), which adds to the uncertainty.

The uncertainty is probably a factor of two for young ages (≤ 1 Gyr), but relatively less for old ages because of the variation of impactor flux between 4.5 and 3.5 Gyr.



Example: Cratering density ages on Mars





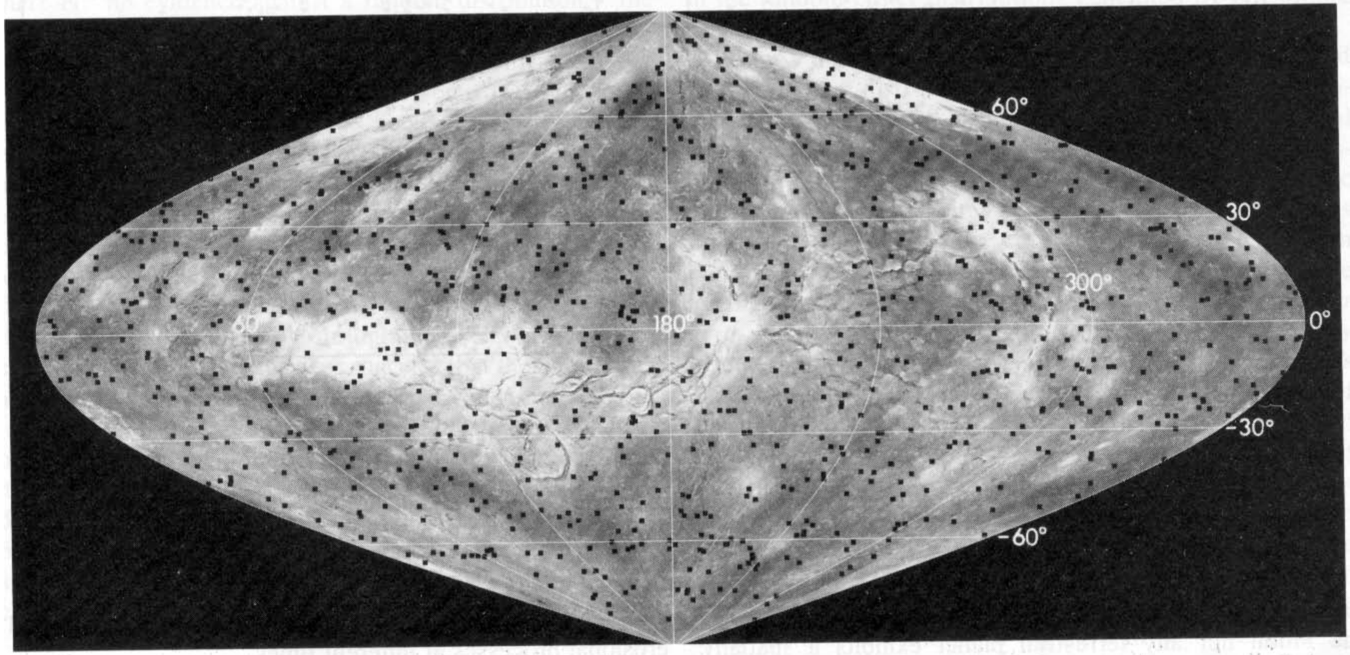
Southern Highlands: > 3.8 Gyr

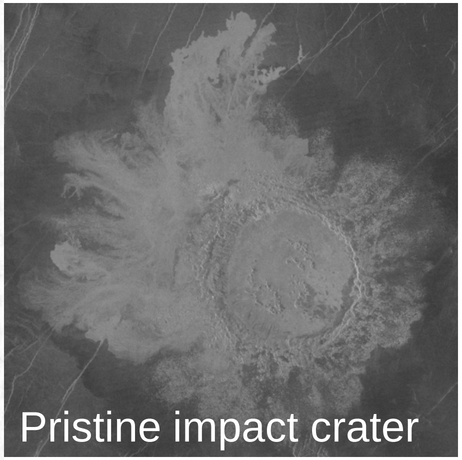
Northern Lowlands: ≈ 3.0 Gyr

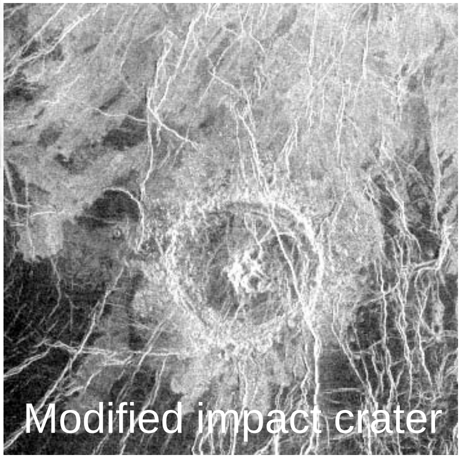
Large volcanoes: mostly 3 -1 Gyr

Olympus Mons caldera: 100-200 Myr, some small flank regions 4 Myr (HRSC camera!)

Example: Crater density on Venus

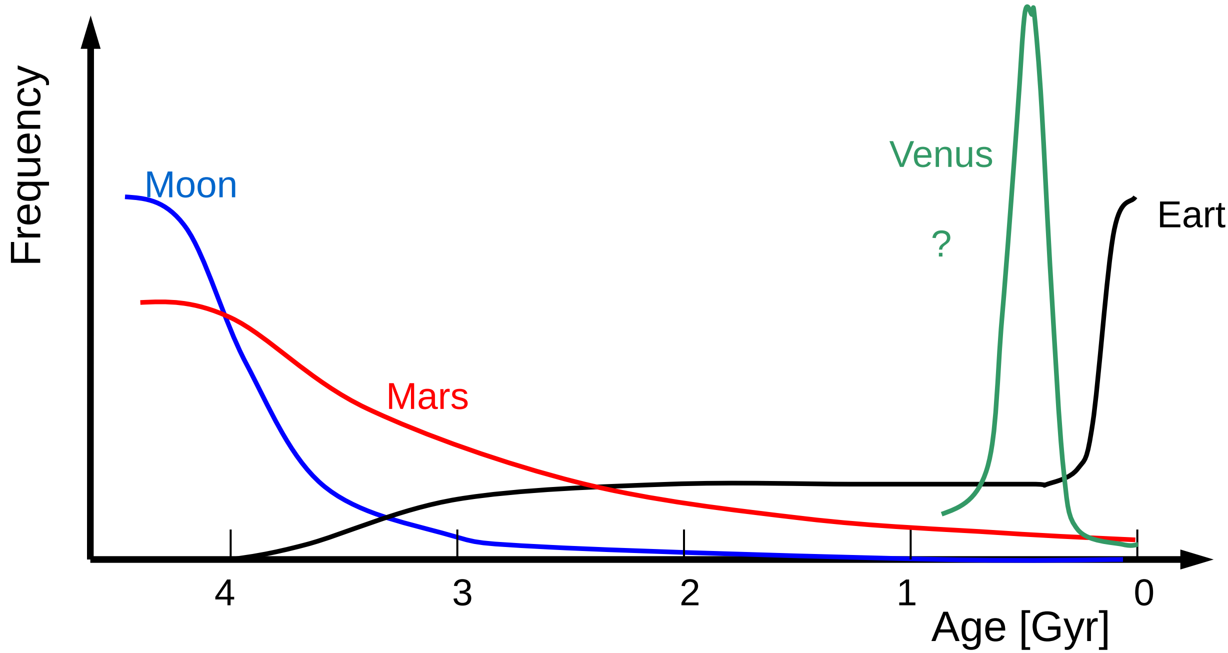



Pristine impact crater


Modified impact crater

Only large impactors can penetrate the dense atmosphere of Venus: no small craters, limited statistics. Approximately 1000 impact craters identified on Magellan radar images. Their distribution is uniform: all parts of the Venusian surface seem to have the same age (very different from Earth!). Their density requires an age of 600 200 Myr (young for a planetary surface!). It seems that a relatively short, global event re-surfaced Venus at this time.

Surface ages for different planets



Schematic age frequency distribution of surface units on the terrestrial planets