Dating for Anthropology

Radiocarbon dating is limited to the analysis of archaeological samples because of its relatively short half life $T_{1/2} = 5730$ y. For dating samples with older history - geological samples for exploring earth history, paleontological samples for studying the origin and evolution of life, or anthropological samples for exploring the origin and early development of mankind – other methods are typically used involving longer-lived radionuclides.

Most frequently used radionuclide methods are:
- potassium-argon method: $>10\,000$ y
- uranium series method: $>10\,000 - 1\,000\,000$ y
3.7. Potassium-Argon Dating

$^40\text{K}$ has unusual decay mode
- e$^-$-capture to 1. excited state in $^40\text{Ar}$ (11%)
- $\beta^-$-decay to $^40\text{Ca}$ (89%)

$^40\text{K}$ is very long-lived
$T_{1/2}=1.28\times10^9 \text{ y}$

$^40\text{K}$ is in body material and in rock content,
$^40\text{Ar}$ is noble gas with no chemical reactivity
$^40\text{Ca}$ cannot be distinguished from natural Ca content
$^{40}\text{Ar}/^{40}\text{K}$ time-relation

$$N(\ ^{40}\text{Ar} \ ) = 0.11 \cdot N(\ ^{40}\text{K} \ ) \cdot (e^{\lambda \cdot t} - 1)$$

for $^{40}\text{K}$ decay: $\lambda = 5.4 \cdot 10^{-10}$ $\text{y}^{-1}$

$$\frac{N(\ ^{40}\text{Ar} \ )}{N(\ ^{40}\text{K} \ )} = 0.11 \cdot (e^{\lambda \cdot t} - 1)$$

build-up of $^{40}\text{Ar}/^{40}\text{K}$ abundance ratio in material

anthropological time range $T_{1/2} = 1.28 \cdot 10^9$ $\text{y}$
The chemical or physical analysis of this ratio gives the age of the sample. Minerals (bone material) contain \(\sim 2\%-10\%\) of potassium with \(\sim 0.021\%\) of \(^{40}\text{K}\). \(^{40}\text{Ar}\) must be released and can be counted by mass spectrometry.
Problem: zero-point

$^{40}\text{K}$ is in mineral material since the original formation
- for rock material dating back to geological formation since $^{40}\text{Ar}$ remains trapped
- for volcanic material dating back to last activity since $^{40}\text{Ar}$ is released in melting process
- for organic material dating back to mineralization since organic material is porous and releases $^{40}\text{Ar}$
Zero-point in $^{40}$Ar counting

Possibly reflected in two step $^{40}$Ar release yielding two different dates, one for the second melting and one for the first melting period of rock.
Volcanic dating

Potassium Argon method is often applied to material embedded in volcanic layers. dating the material above and below the sample gives age range information.
Release and analysis of $^{40}$Ar

To count $^{40}$Ar nuclei the argon must be released from rock sample!

Typical analysis techniques require
- melting the sample
- catching the released gas
- ionizing the argon gas
- selecting the gas atoms by mass spectrometry

error sources:
- loss of $^{40}$Ar due to diffusion → simulates low age
- infusion of atmospheric $^{40}$Ar → simulates large age
  (measurement of $^{36}$Ar content in sample)
Efficiency of $^{40}$Ar counting

Suppose you have a 10g sample which is 3.2 Million years old, that sample contains $\sim <1g$ K $\Rightarrow \sim 0.00021g$ $^{40}$K

How many $^{40}$Ar atoms have been generated by decay?

\[
40g \equiv 6.023 \cdot 10^{23} \; ^{40}K \; \text{atoms}
\]

\[
0.00021g \equiv \frac{6.023 \cdot 10^{23} \cdot 0.00021g}{40g} = 3.16 \cdot 10^{18} \; ^{40}K \; \text{atoms}
\]

\[
N(\; ^{40}Ar) = N_0(\; ^{40}K) - N_t(\; ^{40}K) = N_0(\; ^{40}K) \cdot \left(1 - e^{-\lambda \cdot t}\right)
\]

\[
N(\; ^{40}Ar) = 3.16 \cdot 10^{18} \cdot \left(1 - e^{-\frac{\ln 2}{1.28 \cdot 10^9 y} \cdot 3.2 \cdot 10^6 y}\right)
\]

\[
N(\; ^{40}Ar) = 3.16 \cdot 10^{18} \cdot (1 - 0.99827) = 5.47 \cdot 10^{15} \; ^{40}Ar \; \text{atoms}
\]

Number of $^{40}$K basically constant (within uncertainties)
Laser Heating Technique

Release by laser heating. Released $^{40}$Ar atoms can also be counted using mass spectrometer techniques.

Main advantage of laser heating is the high spatial resolution $\sim \mu$m!
Dating the Ashes by counting Atoms
40\text{Ar}/40\text{K} Method

Age is determined by ratio of 40\text{Ar} and 40\text{K} abundance in sample.

\[ t = \frac{1}{\lambda} \ln \left( 9.09 \cdot \frac{N(40\text{Ar})}{N(40\text{Ar})} + 1 \right) \]

40\text{Ar} is easily released, 40\text{K} must be detected by measuring characteristic \( \gamma \)-activity with \( E_\gamma = 1.461 \) MeV

\[ A_\gamma (40\text{K}) = 0.11 \cdot \lambda \cdot N(40\text{K}) \]

Sensitivity is limited by characteristic activity
Example: $^{40}\text{K}$ counting

Minerals (bone material) contain $\sim 2-10\%$ of $\text{K}$ with $\sim 0.021\%$ of $^{40}\text{K}$.

You have $10\text{ g}$ of sample material

$\Rightarrow 1\text{ g K} \Rightarrow \sim 0.00021\text{ g}^{40}\text{K}$

$40\text{ g} \equiv 6.023 \cdot 10^{23} \ 40\text{K atoms}$

$0.00021\text{ g} \equiv \frac{6.023 \cdot 10^{23} \cdot 0.00021\text{ g}}{40\text{ g}} = 3.16 \cdot 10^{18} \ 40\text{K atoms}$

$A_\gamma (^{40}\text{K}) = 0.11 \cdot \frac{\ln 2}{1.28 \cdot 10^9 \gamma} \cdot 3.16 \cdot 10^{18} = 1.9 \cdot 10^8 \gamma / \gamma$

with $1\gamma \approx \pi \cdot 10^7 \text{s}$

$A_\gamma (^{40}\text{K}) = 6 \gamma / \text{s}$

Typical detection efficiency is $\sim 1\% \Rightarrow N_\gamma = 0.06 \gamma / \text{s}$

To achieve significant statistics of $10\%$ ($100\pm10$)

You need to count for $t = 100/0.06 = 1666 \text{ s} \approx 1/2 \text{ h}$
Problems of $^{40}\text{K}$ activity counting

- Significant $^{40}\text{K}$ background in laboratory environment (concrete)
  Count rate $\sim 1$ event/s $\Rightarrow$ heavy shielding required
- Good statistics requires long counting time and $>10$g sample size
- Uncertainties due to different counting methods for $^{40}\text{K}$ and $^{40}\text{Ar}$ (different efficiencies in producing $^{40}\text{Ar}$ ions and detecting $^{40}\text{K}$ $\gamma$-radiation.)

Development of alternative method using identical techniques $\Rightarrow$ $^{39}\text{Ar}/^{40}\text{Ar}$ counting
**$^{39}\text{Ar}/^{40}\text{Ar}$ Method**

Method has advantage of parallel counting of $^{39}\text{Ar}$ and $^{40}\text{Ar}$ atoms in mass analyzer $\Rightarrow$ identical efficiencies, reduced uncertainties!

**Problem of generating $^{39}\text{Ar}$ and relating it to $^{40}\text{K}$**

Fixed ratio of stable $^{39}\text{K}$ and radioactive $^{40}\text{K}$ isotopes

$$Z=19 \begin{array}{ccc}
^{39}\text{K} & 39\text{K} & 93.2581 \\
^{40}\text{K} & 40\text{K} & 0.0117 \\
^{41}\text{K} & 41\text{K} & 6.7302
\end{array}$$

Conversion of $^{39}\text{K}$ into $^{39}\text{Ar}$ by neutron activation:

$$^{39}\text{K}(n,p)^{39}\text{Ar}$$
Standard Reactor Techniques

Conventional TRIGA reactor
Neutron flux of $F_n \sim 10^{14} \text{ n s}^{-1} \text{ cm}^2$

http://geology.cr.usgs.gov/facilities/gstr/
Conversion rate $^{39}\text{K} \Rightarrow ^{39}\text{Ar}$

\[ Y(^{39}\text{Ar}) = \sigma_{^{39}\text{K}(n,p)} \cdot F_n \cdot N(^{39}\text{K}) \]

1 g of $^{39}\text{K} \Rightarrow N(^{39}\text{K}) = 1.544 \cdot 10^{22}$

\[ \sigma_{^{39}\text{K}(n,p)} \approx 1 \text{mb} = 10^{-27} \text{cm}^2 \]

\[ F_n \approx 10^{14} \text{ n s}^{-1} \text{ cm}^{-2} \]

\[ Y(^{39}\text{Ar}) = 10^{-27} \text{ cm}^2 \cdot 10^{14} \text{n s}^{-1} \text{ cm}^{-2} \cdot 1.544 \cdot 10^{22} \]

\[ Y(^{39}\text{Ar}) = 1.55 \cdot 10^{9} \text{ s}^{-1}; \]

Full conversion would take quite a long time, a 1 hour generation of measurable $^{39}\text{Ar}$ content is sufficient to produce the measurable amount of $N(^{39}\text{Ar})=5.5\cdot10^{12}$!
39Ar/40Ar Method

Neutron flux dependent parameters are typically determined by using well known 39K standard sample ⇒ relative measurement

Advantages:
- Parallel release of 39Ar and 40Ar by heating
- Parallel separation of 39Ar and 40Ar in mass spectrometer
- Parallel counting in identical detector systems

\[ t = \frac{1}{\lambda} \cdot \ln \left( \frac{N(40Ar)}{N(39Ar)} \cdot J_n - 1 \right) \]

\[ J_n = F_n \cdot \sigma^{39K(n,p)} \cdot t_{irr} \cdot \frac{N(39K)}{N(40K)} \]

J\textsubscript{n} determined with a standard sample that is exposed to parallel treatment

Hornblende (mineral) from the McClure Mountains, Colorado (a.k.a. MMhb-1).
Example 1: The cradle of mankind

Ex Africa Semper Aliquid Novi
(Always something new out of Africa)

Pliny the Elder
The Olduvai Gorge

Olduvai Gorge is an archaeological site located in the eastern Serengeti Plains in northern Tanzania. The gorge is a very steep sided ravine roughly 30 miles long and 295 ft. deep. Exposed deposits show rich fossil fauna, many hominid remains belong to the one of the oldest stone tool technologies, called Olduwan. The time span of the objects recovered date from 2,100,000 to 15,000 years ago.
fossil samples from Olduvai site

Australopithecus boisei
1.8 million years

post-cranial remains of homo erectus:
0.5 million years

mineralized fossil
Hadar, Ethiopia

Danakil Rift Valley

Lucy

australopethicus afarensis
3.5 Million years
The Discovery of Lucy
Chronology of Evolution

Principal fossil-find sites in East Africa: U = Usno Formation (Omo Basin); S = Shungura Formation (Omo Basin); I = Ileret (East Rudolf); Kf = Koobi Fora (East Rudolf); L = Lothagam; Ka = Kanapoi; Na = Napak; B = Bukwa; Ng = Ngorora (Baringo Basin); R = Rusinga Island; So = Songhor; F = Fort Ternan; Ko = Koru; P = Peninj (Natron Basin); O = Olduvai Gorge.
Hominoid chronology derived from the K-Ar dating method. Data charted here for thirteen sites are presented in column form with data points to the left recording K-Ar age determinations while lettered markers to the right suggest the hominin's likely age inferred from site stratigraphy relative to the dated regions. Hominoid species are listed here together with source of K-Ar analysis, plus related references (in parentheses).


Bukwa: d. Limnopithecus legetet. Lava above and below the fossiliferous sediments (26).

Songhor: e. Limnopithecus species (legetet and macinnnesi), Dryopithecus (Proconsul) species (africanus, nyasae and major), Dryopithecus species (gordoni and vancouveri). Mica from near the base of tuffs that yield the bulk of the mammalian fauna (25, 26).

Koro: f. similar to Songhor material. Biotite related tuff (25, 26).

Napak: g. Limnopithecus species (legetet and macinnnesi), Dryopithecus (Proconsul) major. Mica from tuff (level 1) (26).

Rusinga Island: h. Limnopithecus species (legetet and macinnnesi), Dryopithecus (Proconsul) species (africanus, nyasae and major). Lava rich in melanepheline, overlying fossil horizon, Nepheline separate underlying fossil horizon (27).

Fort Ternan: i. Ramapithecus wickeri, Limnopithecus species, Dryopithecus species. Biotite from tuff horizon immediately underlying the fossiliferous strata and an overlying phonolite lava (26). The $^{40}$Ar/$^{39}$Ar 'age spectrum' technique was used for the phonolite study.

Ngorora: j. Hominid, the find represented only by the crown of a single molar. Underlying lavas and 'derived' feldspars in the sediments (28).

Lothagam: k. Australopithecus africanus (hominid mandibular fragment). A basalt sill intrusive into the middle faunal level, Lothagam 2, which lies well above the hominin fossil level (29, 30).

Omo (Usno Formation): l. Australopithecus species of two lineages: (i) a robust series, similar to the Olduvai genus, boisei and (ii) a gracile series comparable with the genus, aficanus.

Glass from an underlying tuff (29, 31).

Omo (Shungura Formation): m. similar to Usno Formation material. Feldspar from a series of tuffs two of which bracket the fossiliferous zone (31).

East Rudolf: n. Homo (species indeterminate) (cranium 1470); o. Australopithecus boisei (see Plate 4.2). Sanidine feldspar phenocrysts extracted from a sediment termed the KBS Tuff of the Koobi Fora formation. Hominid n was found in the Karari Escarpment area while hominid o originates from the lower tuff of the Ilveret area. The $^{40}$Ar/$^{39}$Ar 'age spectrum' technique was used for the KBS tuff material (32–34). Stratigraphical relationships and fauna of these deposits are discussed in references 35–38 while the most recent hominid finds and their genus attributions are discussed in references 39 and 40.

Olduvai Gorge: p. Homo habilis (type cranium H.7) Australopithecus boisei. Several anorthoclase extracts from different strata of a volcanic tuff, Bed I (16, 41–43). q. Homo erectus (cranium, H.9, on Bed II). Continued representation of this Homo species is found throughout the Middle Pleistocene, in Beds III and IV. Post cranial remains of Hominid, H.28, from the latter is illustrated in Plate 4.3. Biotite from Middle or Lower Bed II (16, 44–46). A more recent anorthoclase K-Ar marker date is recorded, related to the tool industry transition of a developed Oldoway form to early Acheulian.

Natron Basin (Humbu Formation): r. Australopithecus species in the robust group (the Peninj mandible), though there are strong Homo affinities when compared with the cranium, (II.9) from Olduvai (labelled q above). Olivine basalt overlying the fossil stratum (47). Basalt flow underlying the fossil stratum, in the upper part of the Sambu lavas (48).
Footprints of our Ancestors?
3,500,000 years ago, our very remote ancient ancestors walked through a landscape very like that which we see today. On one particular day the volcano Sadiman puffed out a lot of gray ash, which covered the plains. A rain shower dampened and settled the ashes, so that the local animals left their crisp, clear tracks when they walked. Through this desolated grey landscape, traveled three hominids walking on two legs. A large, medium sized and small individual walked together. Some days later, a fresh ash fall buried the tracks, until they were excavated in 1978. How do we know the age of the footprints?