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Scientific Dating in Archaeology

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1. Age Determination in Archaeology

Relative Age: stratigraphy, typology

Absolute Age: historical data

Age Determination by (natural) Scientific Methods

numerical age (chronometric age)

relative age

2. Age Determination by Scientific Methods

2-1. Numerical Methods

Radiometric Methods

Radioactive Isotope: radiocarbon, potassium-argon, argon-argon, uranium series

Radiation Damage: fission track, luminescence, electron spin resonance

Non-Radiometric Methods

Chemical Change: amino acid, obsidian hydration

2-2. Relative Methods

archaeomagnetism and paleomagnetism, dendrochronology, fluorite

3. Radiometric Methods

3-1.Radioactive Isotopes

The dating clock is directly provided by radioactive decay: e.g., radiocarbon, potassium-argon and uranium-series.

The number of a nuclide (N_t) at a certain time t decreases by decaying into its daughter nuclide. The number of a nuclide (dN) which decay in a short time (dt) is proportional to the total number of the nuclide at time t (N_t):

$$d N_t / dt = -\lambda N_t \qquad (1)$$

where λ: decay constant.

Then, N_t is derived from (1) as

$$N_t = N_0 \exp(-0.693t/T_{1/2}) \qquad (2)$$

Where N_0 is the number of the isotope at t = 0 and $T_{1/2}$ is its the half-life.

Thus,

$$t = (T_{1/2}/0.693)\exp(N_0/N_t)$$

When the values of $T_{1/2}$ and N_0 are known, the time t elapsed from t=0 is easily obtained by evaluating the value N_t.

Radiocarbon Technique is the typical one in which the decrease of the parent nuclide is the measure of dating . On the other hand, the decrease of the parent nuclide and increase of the daughter nuclide or their ratio is the measure of dating in potassium-argon and uranium-series. In principle some other radioisotopes, e.g., ^{26}Al (half-life;730ka), ^{36}Cl (300ka), ^{10}Be (1600ka), ^{32}Si (0.1ka) and ^{41}Ca (100ka), could be available for dating, but not yet in practical use.

1) Radiocarbon Dating (C-14)

Natural carbons consist of ^{12}C, ^{13}C and ^{14}C. Among them only ^{14}C is radioactive and decays to stable nitrogen ^{14}N with a half-life of 5730 years. ^{14}C is produced in the upper atmosphere (maximum at c. 15,000m) by nuclear reaction of ^{14}N with cosmic ray and combined with stable oxygen to form carbon dioxide (CO_2). Since the radioactive and stable CO_2 are mixed uniformly and distributed throughout the atmosphere, the ratio of ^{14}C to ^{12}C (as well as ^{14}C to ^{13}C) is approximately constant at any location in the world. The chemical characteristics of radioactive CO_2 and stable CO_2 are the same, so the ratio of them in the biosphere (plants and animals) and the ocean is close to that in the atmosphere. After the death of plants, animals or shells etc., the exchange of CO_2 between them and atmosphere stops, resulting their content of ^{14}C decreases with a half-life of 5730 years. If we know how much the ratio of carbon isotopes in an organic materials excavated is decreased, the time since the death of them could be estimated.

C-14 year is expressed as xxxx years BP (Before Present or Before Physics), which means xxxx years before 1950. Why "before 1950"? That is because the ratio of ^{14}C to ^{12}C in the atmosphere has been drastically changed due to the nuclear bomb explosions after 1950's.

Conventional Method and Accelerator Mass Spectrometer (AMS) Method

Beta particles emitted from ^{14}C are measured with a proportional counter or a liquid scintillation detector in conventional methods. 1 gram of carbon contains about 50 billion (5×10^{10}) ^{14}C, emitting beta particles of about 68, 42, 23 and 7 per hour, 1000, 5000, 10000 and 20000 years, respectively, after the death of an animal or a plant. It may take fairly long hours (days) to get statistically sufficient data by the conventional method. Carbon isotope ratio must be independently evaluated with a mass spectrometer.

In late 1970’s, accelerator mass spectrometer (AMS), in which ionized atoms are directly counted atom-by-atom, is utilized as a dating tool. Significantly high efficiencies of AMS technique permit the use of sample sizes several orders of magnitude below that with conventional methods (a few milligrams) as well as the reduction of measuring time. Furthermore, the isotope ratio is simultaneously measured in AMS method.

Uncertainty of C-14 year and calendar year

The half life of 5568 years (instead of 5730 years) is used in C-14 dating because "5568 years" was the most reliable half life of ^{14}C when Libby established the C-14 dating method. If we used the half life of 5730 years, C-14 age is about 3 % older than that with the half life of 5568 years. Moreover, it is assumed that ^{14}C concentration has been constant throughout the past. This assumption, however, is not necessarily correct because of, e.g., the inconstancy of C-14 product in the past.

The dendrochronology is a strong tool for converting a C-14 age into a calendar year (calibration of C-14 year). IntCal 98 is the C-14 calibration system established in 1998. A new calibration system, IntCal04, was proposed using the coral stripes in addition to the tree rings. When the C-14 year is calibrated with IntCal98 or IntCal04, it is expressed as xxxx years calBP.

Notes for C-14 Dating

- ♦ Half-life of Radiocarbon
- ♦ Isotope Fractionation
- ♦ Contamination
- ♦ Global Variation of the Relative Radiocarbon Concentration
- ♦ Regional Activities
- ♦ Reservoir Effect
- ♦ Calibration (INtCal98 & IntCal04)

2) Potassium-Argon (K-Ar) and Argon-Argon (Ar-Ar) Dating

3) Uranium-series

3-2. Radiation Damage

The radioactivity plays an essential part in the dating methods applying the radiation damage, but the actual dating signal is a secondary effect of radioactivity:

e.g., luminescence, electron spin resonance and fission track.

Radiations accompanied with the decay of radioactive elements and cosmic rays constantly accumulate electrons in the defects of minerals (e.g. quartz and feldspar). The minerals show luminescence and electron spin resonance (ESR) signal in proportion to the amount of accumulated electrons, thus the time when the accumulation started could be obtained by evaluating the intensity of luminescence or ESR signal. Fission fragments due to the spontaneous fission of ^{238}U cause microscopic tracks in volcanic glass and zircon, the number of which is proportional to the time from the eruption of the volcano.

1) Luminescence Dating (TL, OSL, IRSL)

The irradiated crystals with impurities or dislocations accumulate unpaired electrons in proportion to the amount of absorbed radiation dose. These electrons are evicted and emit visible lights when they are heated or exposed to light. The intensity of emitted light is usually proportional to the amount of trapped electrons, or accumulated dose (PD; paleodose). If annual dose (AD), which the mineral absorbs at the burial location, is known, luminescence age could be easily obtained by dividing the accumulated dose by annual dose (Luminescence Age = PD / AD).

Thermoluminescence (TL) technique is mainly applied to the heated materials such as pottery, burnt stone, kiln and tephra. The technique of Optically Stimulated Luminescence (OSL) can be used for the samples exposed to sunlight such as loess and dune other than heated materials. IRSL technique is a kind of OSL dating in which the stimulation is made by infrared light.

2) Electron Spin Resonance Dating (ESR)

Principle of ESR dating is the same with TL and OSL methods, the amount of trapped electrons being measured with ESR signals.

3) Fission Track Dating (FT)

3-3. Non-Radiometric Methods

1) Obsidian Hydration

2) Amino Acid

4. Relative Methods

The methods in this category need to prepare a standard pattern prior to obtain the age of an unknown sample. The standard pattern is made by the data which are obtained using the samples of known ages.

1) Archaeomagnetism and Paleomagnetism

Archaeomagnetism and paleomagnetism are based on the same principle. The direction of magnetic minerals comes to the same with that of geomagnetism when they are cooled after heating or deposit at a particular time and the direction and the geomagnetic intensity of them are preserved if they are not heated at high temperature (Curie point). If the secular variation of declination and inclination in an area could be available using the archaeological or geological samples of known ages, the measured declination and inclination of a sample with unknown age may suggest the numerical age comparing with the secular variation. To know the numerical age by this method, an accurate secular variation of declinations and inclinations should be prepared prior to the measurement of a sample of interest, which is the same in dendrochronology method.

The polarity of the Earth's magnetic field drastically changed in certain periods of the geological past. This phenomenon is called “event” or “excursion”. Since the “event” observed in a stratum is identified at many locations in the world, it is a big tool to determine the age of a layer in prehistoric sites and the Quaternary. In this case the age of the events have to be known prior to the measurement of the layer.

2) Dendrochronology

The ring pattern of a specimen (tree) is recorded and compared with the master ring pattern. The matching position, where the year-by-year record of the specimen is similar to the same pattern in the master, show the date of the specimen. The master ring pattern is constructed using the modern trees, specimen from buildings, archaeological sites, submerged trees etc.

3) Fluorite

5. General Notes

Careful considerations are needed to use a result of scientific dating to determine the age of archaeological remains. One of them is concerned with the sample used for the measurements and another one is the problems, which belong to the principle and technique peculiar to each dating method.

The most important and critical matter when we use any type of scientific dating technique is whether the age of the measured sample represents the age of the archaeological event or materials of interest. For example, a charcoal is the most suitable sample for C-14 method but is easily carried by water or landslip etc. and sometimes drops into a small pit made by insects or small animals. In some case, stone artifacts or ceramic shards may vertically move up to 1 m or more. In these cases, the C-14 age obtained for a charcoal near the artifact does not show the age of the archaeological materials of interest.

Any scientific dating method is based on a particular principle. The sample used in a measurement, the archaeological object (materials) and the range of age covered by a method are listed in Table 1. The limitation of each technique is not shown here. For example, the age obtained by TL, ESR or Archaeomagnetism shows the latest time when the sample was heated. Therefore, if a ceramic sample was accidentally heated after the firing, the age obtained is not that of the firing but the latest heating. In case of C-14 dating, a result is expressed by calBP or .BP. Even when the data is presented with calBP, we should verify whether the data is calibrated for isotope fractionation and reservoir effect.

It is desirable to use more than two scientific methods for getting more accurate age and to get a conclusion comparing all data and considering archaeological aspects.

Method	Sample	Archaeological Materials	Range (years)
Radiocarbon	Carbon	Organic Material	400 - 500×10^3
K-Ar (Ar-Ar)	Volcanic Rock	Lava	> 10×10^3
U series	Io (^{230}Th)	Stalagmite, Bone, Tooth	10x103 - 300×10^3
Fission Track	Mineral (Zircon, Glass)	Tephra, Lava	> 10×10^3
Luminescence	Mineral (Quartz, Feldspar)	Pottery, Tephra, Burnt Stone, Loess, Alluvium	100 - 1×10^6
Electron Spin Resonance	Mineral (Quartz, Calcite)	Pottery, Tephra, Lava, Burnt Stone, Stalagmite, Bone, Tooth	1×10^3 – 10×10^6
Amino Acid	Amino Acid	Shell, Bone, Coral	5×10^3 – 500×10^3
Obsidian Hydration	Obsidian	Obsidian	10×10^3 – 500×10^3
Archaeomagnetism	Magnetic Mineral	Kiln	< 3×10^3
Paleomagnetism	Magnetic Mineral	Tephra, Alluvium	10×10^3 – 5×10^6
Dendrochronology	Wood	Wood	< 10×10^3
Fluorite	Fluorite	Bone	1×10^3 – 1×10^6
Tephrochronology	Mineral, Volcanic Glass	Tephra	< 200×10^6