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# 15 Chronometric techniques for the Middle Pleistocene

*A brief outline is given of the following dating techniques: potassium-argon, uranium-series, fission track, luminescence (TL and OSL), electron spin resonance (ESR), amino acid racemization (AAR), obsidian hydration, and geomagnetic reversal stratigraphy. Oxygen isotope chronostratigraphy is also mentioned, both in respect of fossil marine microfauna and in respect of ice obtained by means of long cores extracted from the polar ice caps; recent revisions to the astronomically-based dating of oxygen isotope stages beyond Stage 16 are indicated as well as to the potassium-argon dating of reversal stratigraphy, the Brunhes-Matuyama transition now being placed at 0.78 Myr ago.*

## 1. Introduction

The various techniques that are briefly outlined here may be conveniently grouped into those based on radioactive decay or build-up (potassium-argon; uranium-series; calcium-41), on the effects of radioactivity (fission tracks; luminescence; electron spin resonance), and on chemical change (amino acid racemization; obsidian hydration). All these are processes intrinsic to the sample. In addition there are the time scales provided by geomagnetic reversals and by astronomical calibration of the oxygen isotope chronostratigraphy; for convenience of reference some detail of these are given including mention of the recent slight lengthening of both at the beginning of the Middle Pleistocene.

Of the chronometric techniques of interest for the earliest occupation of Europe it is the potassium-argon and fission track techniques that are the most well-developed, followed by uranium-series (to the extent that the occupation was subsequent to that technique's limit of around 500 Kyr). Since these are only applicable in certain geological regions there is strong interest in the use of electron spin resonance (ESR) and luminescence; neither have been much tried archaeologically beyond several 100 Kyr, but ESR should encompass a million years without difficulty and there are indications that, unexpectedly, luminescence may reach beyond half-a-million. Both of the chemical change techniques are handicapped by their strong dependence on environmental conditions and when a number of glacial/interglacial cycles are encompassed within the burial period the strong temperature-dependence is a particular drawback.

The possibility of using calcium-41 is still highly problematic, and radiocarbon dating, while very powerful in later periods, has too short a limiting range to be relevant; effectively it is *c.* 40 Kyr BP at present and highly unlikely ever to exceed *c.* 70 Kyr BP.

## 2. Potassium-argon dating

### 2.1. Basis

With its enormous range (*c.* 10 Kyr to around 400 Myr) this technique has been, and is, of crucial importance. It is based on the accumulation, in volcanic lava and ash, of argon-40 produced from the slow radioactive decay of any potassium-40 present (potassium-40 is a naturally-occurring isotope of potassium). The event dated is the volcanic eruption; during this, and while lava is molten, previously accumulated argon (a gas) is released thereby setting the radioactive clock to zero. The age is derived from the measured ratio of argon-40 to potassium-40.

*Argon-argon dating* has the same basis but employs an advantageous technique. One advantage is that potassium and argon are determined on exactly the same sub-sample thereby avoiding possible errors due to inhomogeneity; another advantage is that the argon can be gradually released by stepwise heating of the sample and an age can be determined at each step. Constancy in age (an 'age plateau') is indicative of reliability. Effects causing the age to be erroneously too low are those which give rise to release of accumulated argon during burial such as mineral alteration (due to weathering), or secondary heating; on the other hand incomplete release at time-zero of previously-accumulated argon would give rise to an age that is erroneously too old, as also the presence of absorbed atmospheric argon. Because of differential argon release at different stages of the heating these interfering effects manifest themselves through upset to the age plateau; analysis by the *isochron technique* is also diagnostic.

Use of a laser for heating permits dating of single grains (of the order of 1 milligram or less). This allows potassium-rich grains only to be selected; also older, contaminating grains to be detected and avoided.

### 2.2. Application

Obviously the important question is the relationship between the human occupation and the volcanic products that are dated. Where two layers of lava, or ash, bracket the archaeology there is no problem (except, sometimes, a rather wide bracket). A recent example where the question of association is critical is the 1.8-1.6 Myr ages for hominid cranial material from Java (Swisher *et al.*, 1994); whereas the dating of the hornblende crystals is not in doubt, excellent age plateaux and isochrons having been obtained, the association of the crystals with the fossils is indirect.

More relevant to Europe is the date of 0.73 Myr ago obtained for the Italian site of Isernia (Sevink *et al.*, 1981; Coltorti *et al.*, 1982); one should note here that neither of the determinations utilised the advantageous argon-argon technique, though the agreement between two laboratories using different minerals is suggestive of reliability. However without the evidence of an age plateau the possibility cannot be ruled out that in both cases the age obtained was erroneously in excess because of incomplete removal of argon at time-zero.

## 3. Uranium-series

### 3.1. Basis

An eventual decay product (a 'daughter') of naturally-occurring uranium-238 is thorium-230 and when the former is present in newly-formed crystals the gradual build-up of the latter can be used for dating. The most widespread application is to cave speleothems (stalactites, stalagmites and flowstones); newly-formed calcite (calcium carbonate) contains only uranium-238 and its daughter uranium-234; thereafter there is build-up of thorium-230 according to its half-life of 75.4 Kyr and the ratios between these three allow the age to be determined. In some circumstances the ratio between the two uranium isotopes can be used for dating – on a much longer timescale. There is also another naturally-occurring isotope of uranium, uranium-235, and build-up of its daughter protactinium-231 (half-life, 34.3 Kyr) can be used for shorter range dating, usually in combination with thorium-230.

The traditional measurement technique is by *alpha spectrometry*. This requires between a few grams and a few tens of grams of sample; the upper age limit is around 350 Kyr. A much superior approach, very much more expensive and demanding of expertise, is by *thermal ionisation mass spectrometry* (TIMS); sample weights can be lower by a factor of 10 and in good circumstances the age range can be from a few hundred years to about 500 Kyr. *Gamma spectrometry* can also be used, with the advantage of being able to measure a whole specimen (e.g. the Arago cranium), but with the serious disadvantages of increased uncertainty and decreased reliability.

### 3.2. Application

There has been widespread application to speleothems but also, with varying degrees of success, to spring-deposits, marl, caliche, calcrete, molluscan shells, ratite egg shells (e.g. ostrich), and teeth (particularly the enamel). Application to bone has long been tried but, with exceptions, the data have been problematic. Coral is an excellent material; although not of direct archaeological interest, with the high accuracy obtainable using the TIMS technique it has a very important role in extending carbon-14 calibration beyond the tree-ring limit.

Sample purity is one important question; particularly with the sample-types just mentioned, but also with speleothems too, there is the possibility that detrital grains (containing thorium-230) were incorporated at crystal formation thereby making the apparent age erroneously too old; various methods, including the isochron technique, are employed to deal with such 'dirty calcite'. Two other interfering effects are recrystallisation and secondary deposition (overgrowth) – both are detectable through microscopic examination of thin sections. Recrystallisation allows mobilisation of uranium and thorium; this is one form of 'open system' in which the age is distorted by loss or gain. In general, an indication that 'closed system' conditions have not existed is given by an unacceptable spread in coeval samples. Because aragonite is intrinsically unstable (converting to calcite) any such samples, unfortunately rather rare, are their own proof of integrity.

## 4. Calcium-41 and other radioisotopes

The effective *c.* 40 Kyr BP limit of carbon-14 inevitably prompts the question as to whether there is another cosmogenic radioisotope with a half-life more appropriate for the Middle Pleistocene. Some possibilities (with half-lives given in parenthesis) are: aluminium-26 (720 Kyr); beryllium-10 (1500 Kyr); calcium-41 (*c.* 100 Kyr); chlorine-36 (300 Kyr). Although there is some possibility of using aluminium-26 and beryllium-10 for sediment cores, it is only calcium-41 that holds any prospect for archaeological application, on account of its occurrence in bone. However, whereas carbon-14 is formed in the upper atmosphere and is spread, through forming carbon dioxide, more or less uniformly through the biosphere and the oceans, calcium-41 is formed from non-radioactive calcium-40, in the top metre or so of soil and although it enters bones via plant life there is no mechanism for spreading worldwide; hence local variations influenced by soil history are to be expected and so the time-zero level is uncertain. A further problem is the difficulty of measurement, even using accelerator mass spectrometry.

## 5. Fission tracks

As with potassium-argon the main involvement is through application to volcanic material with which human remains have been associated. Existing tracks in minerals of such material are erased by the heating inherent in the volcanic eruption. Thereafter spontaneous nuclear fission of uranium-238 in the mineral causes gradual re-accumulation; the tracks can be counted using an optical microscope and hence, after determining the content of uranium and the sensitivity of the mineral for track acquisition, the time that has elapsed since the eruption can be evaluated. Some suitable minerals are zircon, obsidian, mica, sphene and apatite; however, attempts to date the apatite component of bone and teeth have so far met with difficulty.

Application in recent archaeology is usually ruled out by sparsity of tracks; for the Middle Pleistocene the more likely problem to be encountered is *fading*, i.e. some loss of tracks with time. Several techniques have been developed to deal with this, among them the *plateau correction method.* In this, there are successive annealings of increasing stringency and after each a measurement is made of the ratio of the number of 'as found' tracks remaining in one portion to the number of artificially-induced tracks remaining in another portion. Track size is another parameter that is useful.

As with laser dating of single grains by the potassium-argon technique it has the strong advantage of utilising only a few grains, thereby minimising contamination risks. The main application has been to hominid evolution in East Africa.

## 6. Luminescence dating

### 6.1. Basis

This comprises thermoluminescence (TL) and optical dating, the latter utilising optically-stimulated luminescence (OSL). These methods are based on the cumulative effect of nuclear radiation on the position of electrons in the crystal structure of certain minerals, mainly quartz and feldspar.

The nuclear radiation is provided by trace amounts of potassium-40, rubidium-87, thorium and uranium that are naturally present in the sample and its surroundings. The dating signal is obtained, in the case of TL, by heating grains extracted from the sample and measuring the light emitted by means of a highly sensitive photomultiplier; in the case of OSL the luminescence is obtained by shining light on the grains; lasers and halogen lamps can be used, and also, except with quartz, infrared-emitting diodes – in which case the luminescence may be termed IRSL.

The TL technique was first used in application to pottery, the event dated being the firing by the ancient potter (thereby setting to zero the previously accumulated TL). Subsequently it was extended to stalagmitic calcite (which has zero TL at formation) and to burnt flint. The latter application, along with the ESR dating of tooth enamel, has had particularly important impact on hypotheses concerning the relationship between anatomically-modern humans and Neanderthals. The OSL signal from quartz and feldspar, and to a lesser extent the TL signal, can also be set to zero by exposure to daylight; this occurs during transportation and deposition of windblown sediment (such as loess and sand) and similarly, but less effectively, for waterlain sediment. In the latter case use of OSL is particularly advantageous compared to TL.

For either method it is necessary to evaluate the *dose-rate* of nuclear radiation that the sample has been receiving during burial. This is done partly by radioactive analysis in the laboratory and partly by on-site measurement (of the penetrating gamma radiation that reaches the sample from its surrounding soil and rock, up to a distance of about 0.3 m). It is also necessary to estimate the water content of sample and soil/rock – because any water present attenuates the nuclear radiation.

### 6.2. Application

The age range is highly dependent on sample-type, technique, and site; at present several hundred thousand years is a typical upper limit for flint, quartz, calcite, and sediment; however if some types of feldspar are present in the latter there is a tendency for the age to be underestimated, particularly beyond 50 Kyr. This is through signal instability *(fading)* and the so-called '100 Kyr barrier' in European and Chinese loess has been the subject of much discussion and technological research; on the other hand for loess from Alaska and New Zealand TL ages up to 800 Kyr have been reported (Berger 1992).

With flint and quartz the age range limitation arises from saturation rather than fading; hence sites of low radioactivity (i.e., low dose-rate) are advantageous. The Middle Pleistocene potential of quartz has been demonstrated by Huntley *et al.* (1993; 1994) who have obtained consonant TL ages up to 800 Kyr for a succession of high sea level dune sands in Australia. Another approach to long range dating with quartz is use of the 'red TL peak'; this peak does not suffer from saturation and hence can be used irrespective of the level of site radioactivity. On the other hand it is applicable to volcanic products rather than sediment; a consonant age has been reported (Miallier *et al.*, 1994) for pumice dated at 580 Kyr ago by potassium-argon.

It is to be noted that Russian (and some other) workers have long been obtaining million-year ages for sediments and regard the approach of the rest of the luminescence community as being on the wrong track (see, for instance, Slukov *et al.*, 1993); this view is reciprocated.

Except at the limits of the technique the accuracy attainable is usually in the range 5-10% of the age. The ultimate barrier to better accuracy is uncertainty about the average dose-rate during the burial period; because of geochemical leaching the radioactivity may be different from that measured today and likewise the water content because of climatic fluctuation. As mentioned above the water absorbs a proportion of the radiation flux and hence sites which have always been bone-dry are advantageous.

Collection of sediment samples is best done by a laboratory specialist as special precautions need to be taken in order to avoid the slightest exposure to daylight. The usual approach is to drive a short steel tube (about 5 cm diameter by 10 cm long) into the section, the exposed ends being discarded during laboratory processing (in very subdued red light); if the sediment is consolidated then a lump can be taken and the surface scraped off in the laboratory. The hole made for extraction of sample is used for measurement of the gamma-ray dose-rate, either with a portable gamma spectrometer (taking an hour), or, by burial of a small capsule filled with a highly-sensitive thermoluminescence powder (for upwards of several months, preferably a year).

## 7. Electron Spin Resonance (ESR)

This is yet another way of measuring the cumulative effect of nuclear radiation. Its principal archaeological applications have been to tooth enamel and to stalagmitic calcite. In time range ESR reaches back to several million years ago; its lower limit is a few thousand years. As with all techniques, careful selection of measurement parameters is necessary for valid results.

The above remarks about dose-rate evaluation are applicable but with additional complexity in the case of tooth enamel, due to uranium migration into the tooth. Because of this two ages are quoted, these being based on the two assumptions about the timing of the uranium ingress: *early uptake* (EU) and *linear uptake* (LU). If the internal radiation flux is dominant the EU age will be substantially lower than the LU age (but never lower than by half) whereas if the flux is predominantly from the burial soil the difference is unimportant. Large teeth (e.g. elephant, mammoth) are preferred; usually separate determinations on about a dozen samples are averaged.

Because the uranium-series technique is also affected by uranium migration, but to a different degree, it is possible to eliminate the uptake uncertainty by applying both techniques to the same sample. Obviously this doubles the work and there is also limitation in accuracy – to about ±10% of the age, whereas the accuracy for a 'straight' ESR date if a particular uptake model is assumed is a little better than for luminescence, though similarly limited by uncertainty about average water content.

## 8. Amino Acid Racemization (AAR)

The dating is based on the slow conversion within a protein molecule of an amino acid (such as aspartic) from its **L** form, at formation, to its **D** form, until an equilibrium mixture of the two is reached. Epimerization of isoleucine is another reaction utilised, notably in the dating of ostrich eggshells. These processes are strongly influenced by environmental conditions, temperature in particular. Site-by-site calibration against radiocarbon is usual and for good reliability the samples used for this should be of the same type and same preservation condition as the ones being dated.

In early application the technique acquired a reputation for unreliability, particularly in application to poorly preserved bone. However good reliability is now being obtained by careful selection of sample types (such as ostrich eggshell as mentioned above, well-preserved bone, and tooth enamel), strict attention to the validity of the radiocarbon dates used for calibration, and more stringent laboratory procedures. Using aspartic acid the last 50-100 Kyr can be covered and, using the epimerization of isoleucine, reaching half-a-million years is feasible. Besides extension of age range another advantage over radiocarbon is the comparative ease of measurement and hence lower cost – so that an archaeologist can undertake a much wider sampling of site than could be afforded using radiocarbon only.

In the context of the Middle Pleistocene it is particularly important to keep in mind the strong influence of temperature; it is not only necessary to measure the present-day value at the site but also to estimate the temperature history of the site through whatever glacials and interglacials have occurred during the burial period. Even only as far back as the last interglacial this introduces added uncertainty and it becomes appropriate to calculate ages on the basis of different temperature scenarios (see, for example, Miller *et al.* 1993). An alternative approach to calibration, particularly in the case of shells, is *amino-stratigraphy;* characteristic (**D/L**) ratios are established as being representative of particular climatic phases, it being important to keep in mind that **D** to **L** conversion rates for shell are species-specific as well as environmentally dependent. A recent application to sites extending into the Middle Pleistocene of northwestern France has been reported by Bates (1993).

## 9. Obsidian Hydration

This too is a chemical process strongly influenced by environmental conditions, particularly temperature. It is based on the slow formation of hydration rims on freshly-cleaved obsidian. Until the late 1970's the favoured approach was by regional calibration using known-age samples. Since then the emphasis has been on obtaining absolute ages independent of other techniques or archaeological chronology. This approach requires two major evaluations in addition to measurement of the hydration rim itself: (i) the effective burial temperature and (ii) laboratory measurement (at elevated temperature and pressure) of the rim growth-rate for each type of obsidian that is dated.

Dates have been reported in the age range from 200 to 100,000 years ago. Growth-rates vary widely between different parts of the world; the comparatively rapid hydration rates in tropical countries allow more recent dating than in Arctic regions.

## 10. The Geomagnetic Reversal Time Scale (GRTS)

A fossilised record of the direction of the past geomagnetic field (generated through dynamo action in the earth's molten core) is provided by the weak but permanent magnetisation that is acquired by lava as it cools down, likewise for baked clay and heated stones; sediment may also acquire a fossilised record during deposition (under suitable conditions) or during subsequent consolidation. This latter type of magnetisation is even weaker and it is less robust, being vulnerable both to disturbance and to 'overprinting' during later periods when the field may have a different direction; however various magnetic 'cleaning' techniques can be used to eliminate such overprints and so determine the primary direction. Sediment has the strong advantage of giving a much more continuous record than lava; on the other hand, particularly when the magnetisation is acquired during consolidation, it may be the average direction over several hundred years that is recorded, thereby smoothing-out rapid changes as well as introducing a time lag.

Roughly every million years there is a reversal of the direction of the field on the earth's surface; this follows a dying-down of the earth's dynamo, there being a 50:50 chance of it starting up in the opposite direction to formerly. The sequence of such reversals is the basis of the magnetic time scale (alternatively called the *Geomagnetic Polarity Time Scale* – GPTS). The major reversals are known as *chrons* (e.g. the Matuyama chron; this reversed chron preceded the present 'normal' polarity Brunhes chron); there have also been shorter episodes of changed polarity and these are known as *subchrons* (e.g. the Jaramillo; this normal subchron lasted about 60 Kyr and occurred near the end of the Matuyama).

In earlier terminology classifications such as 'aborted reversals', 'excursions', and 'events' were used. These tended to be used for episodes of directional instability and they were not necessarily worldwide; localised episodes occur when, during a period of weak main dynamo, the field from electrical eddies near the surface of the molten core gain dominance; however such situations usually result in violent changes of direction which stop short of reversal. The effects of physical disturbance to the sediment may be mistaken for such an episode and such confusion is one of the factors that make it important to interpret the magnetic record conservatively. Such effects may also be misinterpreted for the occurrence of a reversal too and when a reversal is being inferred there should always be full publication of the magnetic data so that assessment of the strength of the evidence, and perhaps later reassessment, can be made. A case in point is the Italian site of Isernia mentioned earlier for which, to this author's knowledge, there has still been no proper publication of the magnetic data more than a decade after it being tentatively reported that the fossil-bearing sediment was deposited during the Matuyama chron. Until the data are presented this assignment should be treated with strong reservation.

At one time it was hoped that weaker variations in direction than the above might be effective in dating Palaeolithic sediments but it is only over the last few thousand years that these secular variations have proved useful and even then, mainly for pottery kilns and hearths rather than sediments. Such dating is usually categorised as archaeomagnetism rather than palaeomagnetism.

The chronology of the various chrons and subchrons is based primarily on potassium-argon dating of the lava in which the magnetic direction was recorded and until recently the accepted ages were those given by Mankinen and Dalrymple (1979); however re-evaluations (e.g., Baksi *et al.* 1992; Baksi 1993; Spell and McDougall 1992) indicate a slight lengthening of the timescale so that the Brunhes-Matuyama boundary is now placed at 0.78 Myr (rather 0.73 Myr), the Jaramillo subchron from 0.99 to 1.05 Myr (rather than 0.90-0.97 Myr), and the Olduvai subchron from 1.78 to 2.02 Myr ago (rather than 1.67-1.87 Myr).

Because the succession of reversals is also recorded in the sediment cores from which oxygen isotope variations are obtained, the chrons and subchrons can also be dated astronomically (see below). In fact the revisions mentioned above were subsequent to, and in agreement with, the astronomically-based indications obtained by Shackleton *et al.* (1990).

Loess (notably in China) also carries both a magnetic record and a climatic record; the latter is manifested as variation in magnetic susceptibility on account of loess having a lower susceptibility than the intervening palaeosols.

## 11. Oxygen Isotope Chronostratigraphy

This chronostratigraphy is based on the climatic dependence of the isotope ratio (oxygen-18 to oxygen-16) in marine fossil microfauna, studied in long cores taken from the ocean floor. The ratio is primarily influenced by

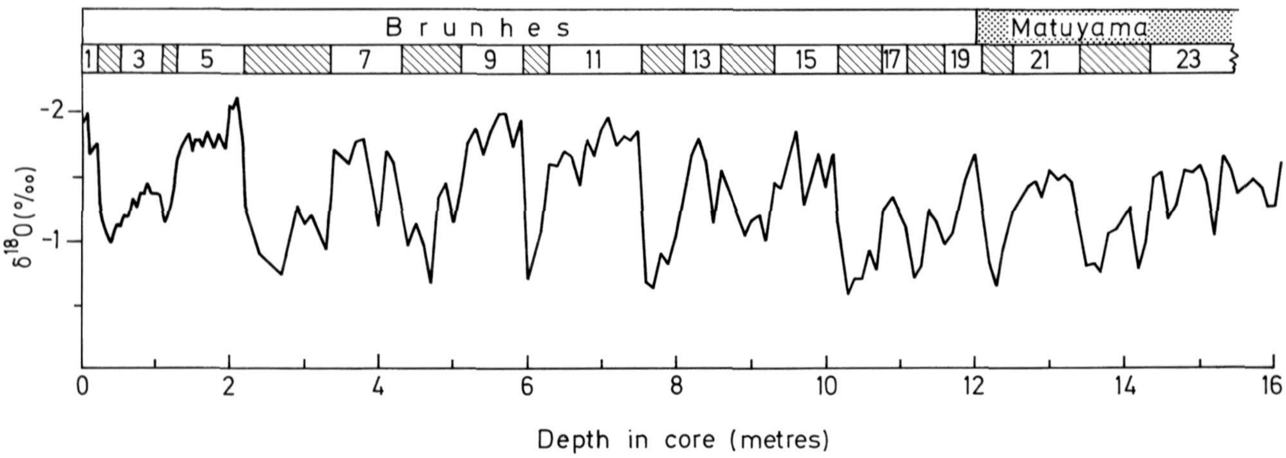


Fig. 1. Oxygen isotope variation in the microfaunal remains of core V28-238 from the Pacific (redrawn from Shackleton and Opdyke 1973; 1976). The vertical scale indicates the deviation (in parts per thousand) of the oxygen-18 content from a standard; the more negative the deviation the warmer the climate. Dates for the stages are given in Table 1. Using longer cores many more stages than shown here have now been identified. Essentially the same pattern of variation is found in cores obtained elsewhere around the world, in agreement with the interpretation of the variations as primarily reflecting the amount of water locked up in the polar ice caps and in glaciers. Magnetic measurements on the sediment in this and other cores indicate that the Brunhes-Matuyama transition occurred during Stage 19.

the amount of water locked up in polar ice caps and glaciers; hence it reflects worldwide climate. Figure 1 is an example of the variations found and it also indicates the succession of cool and warm stages defined on the basis of the ratio; warm stages have odd numbers and cool stages have even. The same pattern of variation has been found in ocean cores from different parts of the world and the correlation with it of continental climate is evidenced in various ways, e.g. magnetic susceptibility variations, pollen frequency variations in peat bogs; pollen indications in ocean cores.

Table 1. Oxygen isotope stage: commencement ages (in Kyr).

| Stage | Age | Stage | Age |
|---|---|---|---|
| 1 | 12 | 11 | 423 |
| 2 | 24 | 12 | 478 |
| 3 | 59 | 13 | 524 |
| 4 | 71 | 14 | 565 |
| 5 | 128 | 15 | 620 |
| 6 | 186 | 16 | 659 |
| 7 | 245 | 17 | 712 (689) |
| 8 | 303 | 18 | 760 (726) |
| 9 | 339 | 19 | 787 (736) |
| 10 | 362 | 20 | 810 (763) |
| | | 21 | 865 (790) |

Note: For Stages 1-16 the ages are as given in the SPECMAP calibration of Imbrie *et al.* (1984); for Stages 17-21 the ages are from Bassinot *et al.* (1994) with the SPECMAP ages given in parenthesis; for Stages 1-16 the revised ages do not differ from SPECMAP ages by more than 5 Kyr.

Isotope variations indicative of climate are also found in long cores drilled into the polar ice caps; these show more detail than the marine cores and there is indication that there is correlation with European interstadials.

As mentioned above the remanent magnetisation of the sediment in the ocean cores allows correlation with the geomagnetic reversal time scale and hence the absolute dating by potassium-argon of the lavas in which the elements of the reversal sequence are observed can be transferred to the cores and hence to the stages. However now that it has been established that there is good correlation between the climatic pattern indicated by the isotope ratio and the Milankovitch astronomical predictions based on changes in the earth's orbital motion (eccentricity of the orbit around the sun; obliquity of the ecliptic; precession of the equinoxes) the succession of stages can be dated astronomically and hence with better accuracy – to the order of around 5 Kyr.

## 12. Concluding remarks

An important characteristic of the foregoing techniques is that they are absolute, in the sense of giving ages in calendar years that are based essentially only on laboratory measurements; excepting the magnetic time scale and amino acid in its calibrated form, they are independent of any other chronology, archaeological or otherwise.

Certainly some give rather wide error limits and there have been cases of unreliability and adjustment but the importance of their independence should not be undervalued. In the long run the "so-called absolute dating methods" (Roebroeks 1994: 303) will give a firmer foundation to the understanding of human development than biostratigraphy; powerful and important though the latter may be it is the mercy of regional non-synchroneity when used on between-region basis. In particular it should be an urgent priority to confirm by chronometric dating the validity of the 'vole clock' (Gamble 1994: 275) as a half-million year time marker throughout Europe.

Criticisms of the chronometric techniques are often in respect of results obtained in a technique's infancy and/or results not properly published; sometimes also unreliability stems from poor association of the samples used with the archaeology. Such criticisms do less than justice to the present state-of-the-art of potassium-argon dating (in its single grain argon-argon mode) and to mass-spectrometric uranium-series dating (TIMS); the former now has the remarkable achievement of reducing error limits in million-year samples to a few percent and the latter of being a basis for calibrating radiocarbon ages. Although the techniques of luminescence and ESR are not yet fully developed their contribution has already been of critical importance in the understanding of the origin of modern humans (e.g., Aitken and Valladas 1992; Schwarcz and Grün 1992). The further progress of these more widely applicable techniques needs the continued stimulation of application and during that necessary phase there will inevitably be some results later shown to be unreliable. But it is in the long term interests of archaeologists to tolerate these – and to minimise their impact by ignoring results not properly published in a fully-refereed journal, with due assessment of reliability. Ultimately it is only thanks to chronometric techniques that it is possible to make any estimate of the pace of human development and the order of events on a worldwide basis.

This paper has attempted only the briefest outline of the techniques concerned; further details, and more references to original papers, can be found elsewhere (for instance, Aitken 1990; Smart and Frances 1991; Taylor and Aitken 1995).

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