Establishing a Relevant Time Scale in Anthropological and Archaeological Research [and Discussion]

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MAN'S IMMEDIATE FORERUNNERS

Establishing a relevant time scale in anthropological and archaeological research

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From time to time, it is desirable to review a given field of research, its methods and accomplishments, and see what further advances in that field may be anticipated. Toward this end, physical and chemical dating methods applicable to anthropological and archaeological problems are reviewed and discussed here, particularly recent innovations, followed by a discussion of the present status of established calibration points in early hominid evolution.

Since the advent of the radiocarbon dating method in 1949, there has been an ever increasing application of physical and chemical methods of dating to anthropological and archaeological problems as new methods of dating have been discovered and as both old and new methods of dating have been improved. There are now available several overlapping methods that may be applied under suitable conditions to yield reasonably precise and accurate dates in the entire time range of hominid evolution, or, from 0 to about 15 Ma. Some of these dating methods can only be applied to the most recent part of this time scale, the last 10000 a or so, but this is most fortunate, because it has permitted the dating with fair accuracy of a number of very important prehistoric events that occurred as human beings emerged from the stone age, developed agriculture, domesticated animals, made pottery, improved grains and other foods, began to mine and smelt metals, and evolved the complex social organization that attended these innovations.

Some dating methods are more precise and accurate than others, because they are based on fewer assumptions concerning the measurable parameters of the methods. It must be kept in mind, however, that primary assumptions are made about every dating method as well as secondary assumptions concerning the history of the sample to be dated during and after its formation. Accuracy, the approach to a true date, is limited by the degree to which the assumptions themselves are met in the application of a given method of dating. The necessary measurements of a method can be made with high precision but still yield low accuracy if the assumptions are not correct.

Figure 1 shows the more important methods of measuring geological time in the range 0–15 Ma and their limits under most conditions. Dashed extensions indicate the ranges of these methods under unusually favourable conditions. The logarithmic scale emphasizes the younger end of this time range, where most rapid change has taken place in human technological and sociological development. These methods are not all of equal potential accuracy, and at the lower or upper limits of any method the accuracy attainable falls to zero. The details of the dating

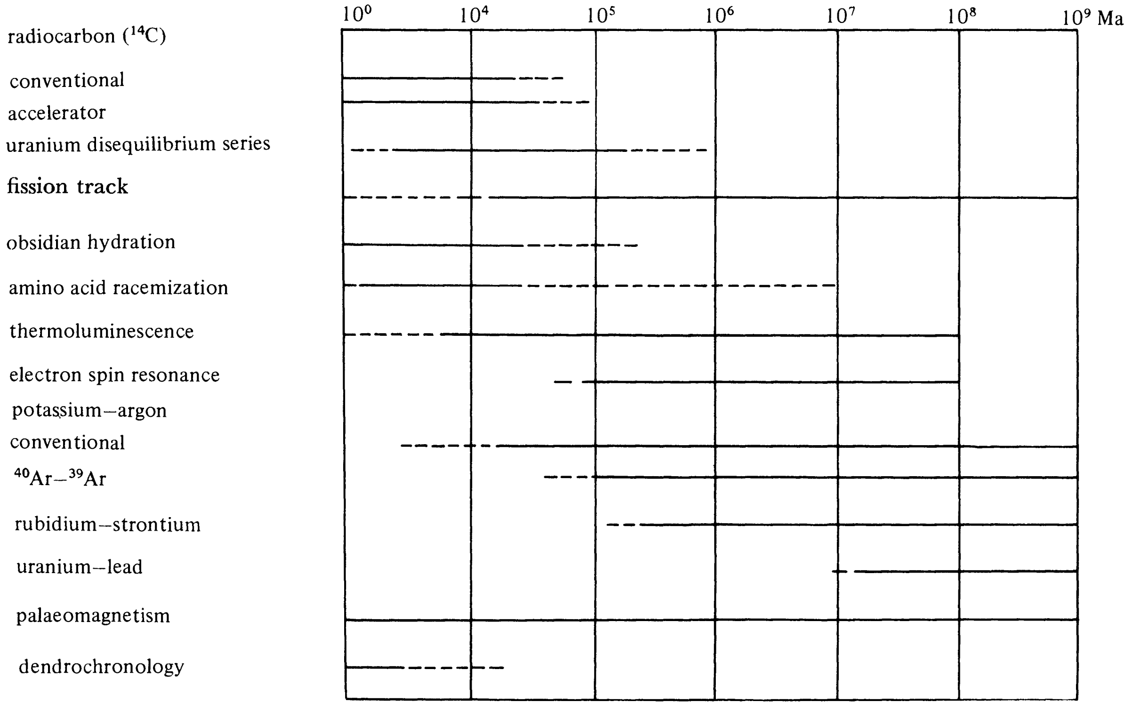

FIGURE 1. The ranges of the most common dating methods used in the calibration of the evolution of the hominids. Dashed lines indicate the ranges of methods under the most favourable circumstance.

methods have been described in a number of books and review articles. Faure (1977) is especially good for descriptions of the carbon-14, uranium disequilibrium series, uranium–lead, rubidium–strontium, potassium–argon and fission track methods. *World Archaeology*, vol. 7, no. 2 (1977) has review articles on amino acid racemization, obsidian hydration and dendrochronology methods as well as on fission track, carbon-14 and potassium–argon methods, together with a description of a new possible method of dating based on the rate of diffusion of fluorine into chipped lithic materials, a method that when developed would both support obsidian hydration dates and be applicable to a much wider variety of lithic materials. McDougall (1968) covers most aspects of thermoluminescence dating methods, while Cox (1973) reviews the history of the development of the geomagnetic time scale. Electron spin resonance research has been going on for more than two decades, but its application to dating geological materials was first described by Zeller *et al.* (1967). Owing to its potential for dating bone directly, the method will be discussed further here.

At the very recent end of the time scale, 0–10000 a, radiocarbon (^{14}C), uranium disequilibrium, amino acid racemization, fission track, obsidian hydration and thermoluminescence, and, to a limit of about 7500 a, dendrochronology, have been applied successfully to appropriate material to yield dates of fair accuracy. In the time scale 10000–75000 a, the K–Ar method can be added to the above methods under favourable conditions. The extreme limit for both obsidian hydration and conventional radiocarbon dating by counting β-emissions of decaying radiocarbon is presently 75000 a. Indeed, except in a few exceptional cases, 50000 a is the virtual limit of the ^{14}C method. Thermoluminescence and electron spin resonance methods have been limited almost entirely to dating pottery or the stones forming ancient hearths in this time range, owing to the fact that these methods can only be used on crystalline material. Nevertheless, these methods have given some very important dates. Obsidian hydration, in theory, should be applicable to fresh glass over a period of several hundreds of thousands of years; however, hydration of volcanic glass results in expansion of the hydrated portion, and thin rinds often exfoliate from the specimen after a period of 60000 to 75000 a, permitting the process to start over again on the freshly exposed surfaces, thus leading to difficulties in obtaining accurate results. Although uranium disequilibrium series and amino acid racemization methods have been extensively used to date events in this time scale and beyond, both methods have inherent difficulties. With uranium disequilibrium series, there are large uncertainties in the assumption that the systems have remained closed to gain or loss of parent and daughter isotopes during the period of time after original isolation from the radioactive source uranium isotopes; and the amino acid racemization method is very temperature-dependent. So, unless there is some way to determine the temperature accurately during the entire period of time that the collagens to be dated have been in existence, the method cannot yield accurate dates. Radiocarbon dates have been used to calibrate racemization dates with great success, but extrapolations beyond the oldest ^{14}C date used for calibration in a given stratigraphic section can only yield approximate amino acid racemization dates, as mean temperatures for older periods of time can only be approximated.

The palaeomagnetic or geomagnetic time scale of the Earth's magnetic reversals has been an important adjunct to geochronological studies. It has been undergoing constant revision as new data are obtained concerning the calibration of the time scale itself and as new short-term reversal events are discovered (Mankinen & Dalrymple 1979). The successful application of the geomagnetic time scale in any given locality and stratigraphic section requires independent calibration by radiometric dating of at least one point, but preferably more, in the local stratigraphy. It requires also that the stratigraphic section to which it is applied be complete; that is, that sedimentation has been continuous in that basin, or, if it has not been continuous, that sufficient calibration points can be made, to correct for discontinuities in the sedimentary record.

Of the above methods applicable to 75000 a, the most important has been and probably will continue to be ^{14}C, owing to the abundance of potentially datable organic carbon-bearing material available in this time range, the relative ease with which the method can be applied, and the high accuracy of the dates obtained. However, because of its importance for dating and its use in calibrating other methods of dating, the uncertainties in the radiocarbon method should be kept in mind. The amount of ^{14}C produced by cosmic ray bombardment of the atmosphere is not constant but varies as a function of changes in the intensity of the magnetic field of the sun. The residence time of ^{14}C in the atmosphere also varies, mostly as a function of climate; but there are other factors affecting the residence time as well. As a result of all of the factors involved, corrections have had to be made to radiocarbon dates of as much as 15% at 5000 a, the uncorrected dates being too young. These corrections have been based first on the careful dating of tree rings, mainly bristle cone pines, back to about 8500 a (the present limit of the pine record) and secondly on the dating of glacial varves beyond 8500 a. As there are uncertainties in the glacial varve record, corrections to ^{14}C dates beyond 8500 a are not as accurate as those younger than 7500 a.

Because of the large amounts of carbon required for old dates and the lack of other suitable material for dating at most sites 50000 a of age and older, there is a rapid drop-off in the number of reasonably accurate dates that have been made beyond this time. A recent technological break-through in radiocarbon dating may soon change this, however. The increased precision and accuracy obtainable in measuring the amount of ^{14}C directly by means of mass spectrometers has been obvious to researchers for many years, even though there is only one atom of ^{14}C for every 10^{18} atoms of normal carbon in contemporaneous organic matter. The problem has lain, not in separating ^{14}C from other lighter carbon isotopes, however, but in separating it from ^{14}N, the nitrogen isotope from which it was formed and into which it decays. These two atoms differ in mass by only one part in 10^5, a mass difference too small for accurate separation by any mass spectrometer. This problem has now been overcome by making use of the different properties that these atoms have when ionized. ^{14}N ions slow down more rapidly than ^{14}C ions when they pass through matter at high energy; thus they may be filtered out. Xenon gas has been used successfully for such a filter. Also, it has been found that negatively ionized nitrogen, $^{14}N^-$, is fragile and quickly destroyed, while negatively ionized carbon is stable; and this property has been utilized in applying Van de Graff tandem generators to accelerate these atoms to high energies. In addition to the greater accuracy obtainable by the direct measurement of radiocarbon, there are other advantages afforded. Whereas large amounts of sample are usually required for β-counting, often 20 g or more, only a few milligrams of carbon are needed for accelerator dating, and the time necessary for a measurement can be very much less, only an hour in some cases. Many carbon-bearing objects heretofore undatable by conventional radiocarbon dating, such as carbon pigment in cave paintings, may now be dated by means of accelerator techniques. Presently the method has been used to date artefacts back to 75000 a, but it may soon be extended to 100000 a. See Bennett (1979) for an excellent review of the method.

Beyond 75000 a, K–Ar dating has so far dominated the dating of archaeological and anthropological events, even though it is limited to use with volcanic rocks. Fission track dating, however, which also is limited to use with volcanic rocks in this time range, is being increasingly applied, and has given support to K–Ar dates, as will be discussed. Another method, formerly used only for rocks of great age, has also been improved recently to the point where it can be used to date igneous rocks in the range of a few hundred thousand years and older. This is the rubidium–strontium method (Rb–Sr) (Radicati di Brozolo *et al.* 1978).

The electron spin resonance (e.s.r.) method has been successfully applied to crystalline substances beyond 75000 a and is also a method in which a major break-through has occurred. As the method is not well known, its general principle will be described. E.s.r. is somewhat similar in basic principles to the well known thermoluminescence dating method. Natural radioactivity in the mineral tears off electrons from nearby atoms by bombardment and produces structural defects. These radiation-induced defects, plus naturally occurring defects produced during growth of the mineral, serve as electron traps for the freed electrons, which attach themselves unstably onto such elements as oxygen and aluminium in the crystal structure, forming radicals. In a non-varying magnetic field, these unpaired electrons precess as they spin around the nuclei, grouping in two energy levels, the electron spin vectors of which are parallel to or anti-parallel to the magnetic field vector. If an alternating magnetic field is oriented perpendicularly to the steady field, it can cause 'spin flips' or transitions from one energy level to the other when the precession frequency of the electrons matches the applied microwave field frequency. Energy is absorbed or emitted when the electron spin vector is flipped from a direction parallel to the steady field or anti-parallel to it, as the case may be, the amount of energy being proportional to the number of unpaired electrons. An e.s.r. spectrometer is used to measure the energy absorbed. The absorption spectrum of the sample is compared with that of a calibration standard and with spectra obtained by treating the sample with known doses of radiation. The absorption spectrum of the natural sample is first measured, then the sample is irradiated with a known dose of gamma rays and the absorption spectrum is measured again. Several more irradiations are made, the natural amount being subtracted each time from the total to determine the amount of increase. Absorption bands that increase linearly with increase of dose are looked for. Linear increase indicates that the traps are not saturated, unsaturated traps being essential to the success of the method. To establish the annual amount of natural radiation in the sample, the content of natural radioactive contamination must be determined. By measuring how many radicals are produced in the sample by a known amount of radiation, the time required to produce the naturally occurring radicals by natural radioactivity may be determined.

Hydroxyapatite is an essential mineral in bone and teeth and is a repository for uranium absorbed shortly after death and burial of the animal from percolating groundwaters. Attempts to date bone by thermoluminescence have failed owing to secondary triboluminescence and chemoluminescence produced upon pulverizing the bone for the experiment. With e.s.r., however, the bone need not be crushed, only cleaned of soft organic material. Experiments performed so far by Ikeya & Miki (1980) have shown the feasibility of using e.s.r. on bone as old as 700 000 a. If further research bears out the great promise of these first results, it may lead to dating such important and heretofore undatable sites as those in South Africa and China.

With the development and perfecting of these dating methods, it is safe to say that in the future all critical points on the time scale will be acceptable only if they have been dated concordantly by more than one method. This is because, when two different dating methods give the same date for a sample, it indicates strongly that the primary and secondary assumptions have been met for each of the methods used for that sample. Without such concordancy or near concordancy by two different methods, any single date by any method must be suspect, even though it appears to have high precision. Replicate dates increase the precision but not necessarily the accuracy of a date. For instance, one of the assumptions of most radioactive decay systems used for dating is that there are no initial daughter isotopes in the materials to be dated, or, if there are, the amounts may be independently determined. If this information is unavailable for a particular sample that contains excess daughter isotopes, the sample will give too old an age; and it matters not how many times the experiment is repeated or how high the precision of the results, the ages obtained will all be too old. Similarly, if some of the daughter isotope is lost from a sample owing to diffusion after the time of formation and before dating of the sample, the sample will appear too young. In a succession of strata where more than one stratum may be dated, confidence in the dates is increased when the dates increase in age downward in the sequence of strata. Even so, the sequence of dates may have systematic errors that impair their accuracy. The precision of a single isotopic date is usually better than ± 5 % and if all assumptions are met this is its accuracy also; but this cannot be known with certainty unless the sample is dated by another method that gives a concordant date.

We may examine, now, the status of some of the dates obtained at various of the important earliest hominid sites that are being used to calibrate hominid evolution. The discussion is confined to hominid dates as there has been little added to the dating of the hominoids, the related apes, since publication of *Calibration of hominoid evolution* (Bishop & Miller 1972).

The ramapithecines are considered by some anthropologists (Pilbeam 1972; Simons 1972) to be the most primitive hominids, although the relationship of the ramapithecines to the more advanced hominids, *Australopithecus* and *Homo*, is not clear. *Ramapithecus* was first discovered in the Siwalik Hills in what is now Pakistan. It has since been found in deposits as far north as Hungary and southwestward in east Africa. Unfortunately, there are very few physically determined dates to calibrate this important early phase of hominid evolution. The oldest dated deposits are those at Fort Ternan, Kenya, where Evernden and Curtis obtained a K–Ar date of 14.0 Ma for a large euhedral biotite book in a tuffaceous bed just below the fossiliferous zone (Bishop *et al.* 1969). Later, Fitch and Miller obtained two K–Ar dates from this same tuff of 14.0 and 14.7 Ma (Bishop *et al.* 1969), confirming the date of Evernden and Curtis. Subsequent studies there, however, have shown that the tuff may be derived from older deposits, so that the vertebrate fauna containing *Ramapithecus* may be much younger (M. H. L. Pickford, personal communication). Fitch & Miller have recently completed a more extensive K–Ar and ^{40}Ar–^{39}Ar dating programme of the Fort Ternon beds, in which they conclude that the *Ramapithecus* beds are indeed approximately 14 Ma old. Their data are questioned by M. H. L. Pickford (personal communication), who is making an independent study of the area.

In the Siwalik Hills of Pakistan, *Ramapithecus* remains have been found with mammalian faunas ranging from Miocene to Pliocene in age. These have been under study for several years by a team headed by Pilbeam. The exact time span of *Ramapithecus* in the strata of the Siwalik Hills is not known, but a fission track date of approximately 9 Ma for a bentonite tuff in these beds, together with geomagnetic data indicating that *Ramapithecus* may be as young as 6 Ma there, shows a total time range of *Ramapithecus* of at least 8 Ma when the Siwalik data are taken in conjunction with the Fort Ternan dates (D. Pilbeam, personal communication).

Except for a few isolated hominid teeth, a significant gap of several million years presently exists in the hominid record between the youngest known *Ramapithecus* remains in the Siwalik Hills section and the oldest known *Australopithecus* bones in Africa. Whatever the relationship is between *Ramapithecus* and *Australopithecus* lies hidden in this gap, and until hominid-bearing volcanic strata of this age are found no calibration points can be determined.

Although the relationship of *Australopithecus* to *Homo* is being hotly debated, a large amount of fossil material of these two genera has been discovered in tuff-bearing strata at several localities along the East African Rift system, which has permitted accurate dating by isotopic methods. Most of the dating has been by the K–Ar and ^{40}Ar–^{39}Ar techniques, but recently some of these K–Ar dates have been supported by fission track dates, and in this support by an entirely different method the overall calibration of hominid evolution has been greatly strengthened.

South African hominid sites have so far not been dated directly by any isotopic method although an attempt to date them by the fission track method was made by Macdougall & Price (1974). The relative ages of the South African sites have been established by the mammalian faunal assemblages (Vrba 1975; White & Harris 1977), some of which have been dated by correlation with isotopically dated deposits in east Africa (White & Harris 1977). In this correlation, and for inter- and intra-basin correlation, the fossil suids have proved particularly useful (White & Harris 1977; Cooke 1976; Cooke & Maglio 1972). Vrba (1975) used the Bovidae in her study, and Cooke & Maglio (1972) showed the potential of the proboscideans for similar purposes, the family of Proboscidea having evolved rapidly over the past 7 Ma.

The oldest trace of *Australopithecus* (?) has been found at Lukeino, West Baringo, Kenya (Pickford 1978). *Australopithecus* has also been found at Lothagam and Kanapoi (Patterson *et al.* 1970; Behrensmeyer 1976), but the K–Ar dates controlling these finds have low accuracy and are stratigraphically remote from the hominid remains themselves and so cannot be used for accurate calibration purposes. All of these finds are probably older than 4 Ma and Lukeino may be as old as 6 Ma.

The oldest abundant *Australopithecus* remains closely associated with K–Ar dated tuffs are in the Laetolil beds at Laetoli, northern Tanzania (M. D. Leakey *et al.* 1976, 1978) and in the Hadar Formation in the Afar Depression of Ethiopia (Aronson *et al.* 1977). The accurate dating of these two deposits is of particular importance in the calibration of hominid evolution for two reasons: first, hominid footprints preserved in tuffaceous strata at Laetoli prove beyond question that hominids were bipedal at this stage of their evolution; and, secondly, on the basis of the hominid material found in both the Laetolil beds and the Hadar Formation, Johanson *et al.* (1978) have established a new species of *Australopithecus*, *A. afarensis*, which they believe is a direct predecessor of both *Homo habilis* and *A. africanus* (Johanson & White 1979).

The K–Ar dates and one ^{40}Ar–^{39}Ar date of the tuffaceous strata in the Laetolil beds were obtained from phlogopite, a magnesian-rich biotite, except for two whole-rock dates from a vogesite lava flow unconformably overlying the beds. Although the phlogopite dates range from 3.4 to 3.8 Ma, R. L. Hay (personal communication) believes that the strata were deposited in a shorter period of time than 400000 a, probably no more than 200000 a, as there are no palaeosols or disconformities in the sequence to indicate breaks in time between strata. All of these K–Ar dates have moderate precision, being based on more than 20% radiogenic argon for each date. An excellent concordant date of 3.55 Ma was obtained by the ^{40}Ar–^{39}Ar incremental heating method on a split of a single large crystal of phlogopite for which K–Ar dates of 3.59 Ma and 3.62 Ma had been determined. This concordance would appear to confirm the validity of these K–Ar dates, but this is not necessarily so. The phlogopite-bearing xenoliths in these Latolil tuffs are holocrystalline and very coarse grained, the average grain size being often more than 1 cm, indicating that they have grown under uniform conditions of temperature and pressure. Such conditions are believed usually to obtain at great depth in the magma chamber. If this is true, ambient ^{40}Ar in the magma could be incorporated in the growing phlogopite crystals. There is a common belief that excess initial ^{40}Ar can be proved by the ^{40}Ar–^{39}Ar method when the isochron is extrapolated to intercept the ^{40}Ar/^{36}Ar ordinate at zero ^{39}Ar. If no excess ^{40}Ar is present, the isochron will intercept the ordinate at 296, the atmospheric ratio of ^{40}Ar/^{36}Ar; but if the mineral has excess initial ^{40}Ar, the isochron is supposed to intercept the ordinate at a value greater than 296. This, however, is true only if the excess ^{40}Ar is not in the same position in the crystal structure as the radiogenic ^{40}Ar. If the excess ^{40}Ar is uniformly distributed through the crystal structure, as it may be if incorporated during the entire growth of the crystal, the isochron will intercept the ordinate at 296, but its slope will be steeper, indicating an erroneously older age. All that has been proven by dating the phlogopite crystal by both K–Ar and ^{40}Ar–^{39}Ar methods is that the K–Ar dates for that crystal are quite precise; the accuracy of the dates will only be demonstrated when the tuff is dated by some other method.

The Hadar hominid-bearing strata in Ethiopia appeared at first to have superbly concordant dates for the BKT$_2$ tuff in the upper part of the section of 2.64 ± 0.03 Ma by K–Ar, the average of seven runs, and 2.61 ± 0.2 Ma by fission track, the average of 20 zircon grains (Aronson *et al.* 1981). This K–Ar date, however, was computed with use of decay constants for potassium that are no longer accepted. When new constants are used, this figure becomes 2.71 Ma, which is still good concordance. The lower part of the Hadar section has a less satisfactory whole-rock basalt date of 3.0 ± 0.05 Ma, the average of six K–Ar determinations of the 'massive black phase' of the Kadado Moumou basalt, and 2.62 ± 0.10 Ma for the 'sugary grey phase', the average of three K–Ar determinations. The black phase appears to be the better material for dating; and the 3 Ma date agrees with the magnetostratigraphy. It appears likely, thus, that the *Australopithecus afarensis* remains in these deposits are less than 3 Ma old. In view of the similarity of the hominids in the Hafar formation and Laetolil beds, it is puzzling that there is such a large difference in the ages of these deposits. The conclusion that hominid evolution was static for over 600000 a during this period cannot be justified until the Laetolil dates are confirmed.

Extensive dating programmes of hominid-bearing strata have been carried out in the Lake Turkana area of northern Kenya and southern Ethiopia, where in the Omo River section of Ethiopia the earliest hominid remains have been found in unit 12 of the Usno Formation and in the slightly younger tuff B member of the Shungura Formation, both dated at over 3 Ma (Howell & Coppens 1976; Howell & Isaac 1976; Brown & Nash 1976; Cerling *et al.* 1979) and about 2 Ma in the lower member of the Koobi Fora Formation of the East Turkana section, Kenya (Leakey 1976; Fitch *et al.* 1978). These areas have been of great importance because of the large amount of hominid fossil material that they contain, cranial and post-cranial, as well as some of the earliest known stone tools and artefacts.

Isotope dating has been difficult in the Koobi Fora beds owing to the fact that all of the tuffs in that sequence have been derived from tuffs first deposited elsewhere then mixed with contaminating older minerals during transport to their present positions. Other problems have also arisen and, as a result, the very important KBS tuff containing early stone artefacts and overlying the remarkably complete skull, KNM-ER-1470, possibly the earliest *Homo*, has been dated no less than 60 times by K–Ar and ^{40}Ar–^{39}Ar techniques, and several times by the fission track method. Dates obtained for this tuff range from 0.52 to 223 Ma (Fitch & Miller 1976; Fitch *et al.* 1978); however, concordant dates by K–Ar and fission track methods indicate the age to be between 1.8 and 1.9 Ma (1.83 Ma, K–Ar (Drake *et al.* 1980); 1.87 Ma, fission track (Gleadow 1980); 1.89 Ma, K–Ar (McDougall 1980)). Using major, minor and trace elements, Cerling (Cerling *et al.* 1980) has correlated the KBS tuff with the tuff H_2 member of the Shungura Formation of the Omo area, for which Drake (Drake *et al.* 1980) obtained an age of 1.87 Ma, the average of four K–Ar dates. This is in good agreement with the concordant dates obtained for the KBS tuff, and these two members, the KBS tuff and tuff H_2, define an isochronous surface which is also well supported by proboscidean and suid fossils (White & Harris 1977; Cooke 1976; Cooke & Maglio 1972) as well as by the magnetostratigraphies in the two areas (Brown & Shuey 1976; Brock & Isaac 1976). By similarity of K–Ar dates, similarity of suids and probscideans, similarity of magnetostratigraphies, and similarity of stone tool and artefact assemblages, this surface can be extended to Olduvai Gorge, bed I. Indeed, it can be named the Olduwan Industrial Complex Surface (Isaac 1976). With this, then, as an accurately dated surface, correlations can be made with considerable assurance (figure 2) and conclusions drawn concerning hominid evolution, one of which is that stone tool and artefact making began before this time, the oldest dated stone artefacts being those found in the tuff D member of the Shungura Formation in the Omo sequence, dated by Brown at approximately 2 Ma (Brown & Nash 1976; Merrick & Merrick 1976; Chevaillon 1976). (Tools have been found in a bed in the Hadar Formation, Ethiopia, that have been tentatively dated at 2.6 Ma (Aronson, personal communication).)

If most of the taxonomic designations by the various workers are correct concerning *Australopithecus afarensis*, *A. africanus*, *A. boisei*, *Homo habilis* and *H. erectus* in the African succession, the

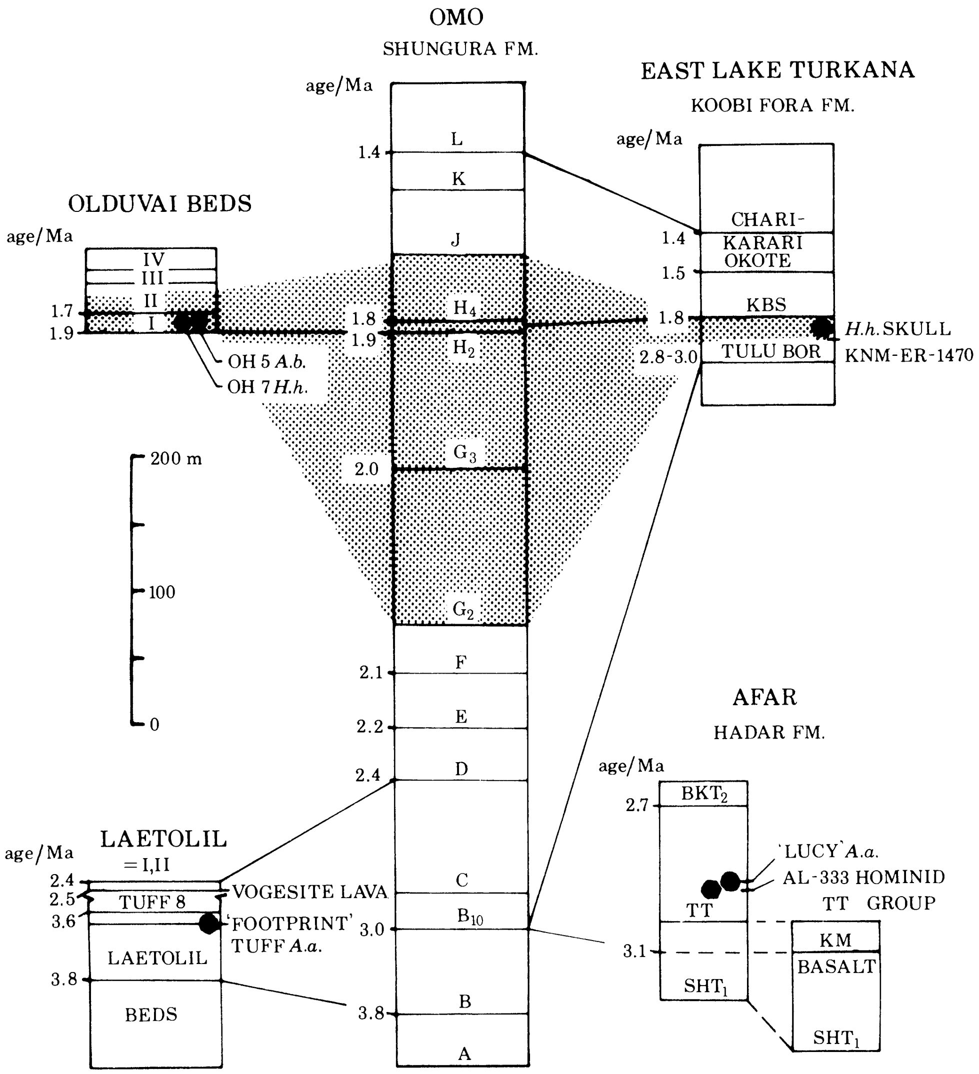

FIGURE 2. Correlations of dated stratigraphic sections at various localities in east Africa. The stippled area shows the biostratigraphic correlation (from Drake *et al.* 1980).

first appearance of *A. africanus* is calibrated by the date for tuff B of the Shungura Formation in the Omo sequence at close to 3 Ma (Brown & Nash 1976). The last appearance of that taxon is calibrated by the date for tuff G in the Shungura Formation at approximately 2 Ma (Brown & Nash 1976) The first appearance of *A. boisei* is calibrated by the date for tuff E in the Shungura Formation of slightly older than 2 Ma (Brown & Nash 1976) and its last appearance above the Middle Tuff at Ileret, East Turkana, cannot be calibrated more closely than that it is older than the Chari-Karari Tuff of 1.4 Ma (Drake *et al.* 1980) and probably close in age to the Koobi Fora Tuff, dated by Fitch & Miller at 1.6 Ma (1976). The first appearance of *Homo* (*habilis*?) is calibrated by the date of approximately 2 Ma for tuff G in the Shungura Formation, which is probably in close agreement with *Homo* below the KBS tuff in the Koobi Fora Formation east of Lake Turkana. *Homo habilis* appears below the KBS tuff in several places in the East Turkana section and possibly as high as tuff L in the Shungura Formation, dated at 1.45 Ma (Brown & Nash 1976). The first appearance of *H. erectus* is calibrated by the date for the Koobi Fora Tuff at Ileret, East Turkana, of 1.6 Ma (Fitch & Miller 1976). This is probably close in time to the first appearance of *H. erectus* in upper bed II at Olduvai, just above the Olduvai event dated at 1.67 Ma (Leakey 1961; Mankinen & Dalrymple 1979). It may also be close in time to the first appearance of *H. erectus* in Java (see below). It is probably significant that the first appearance of stone hand axes in bed II, Olduvai, is almost at the same level as the first *H. erectus*. They appear also in the Peninj beds, dated at between 1.4 and 1.6 Ma (Isaac & Curtis 1974).

The isotopic dating of early hominids in Indonesia and China has not been very successful up to this time. In Indonesia dating has been limited to the K–Ar method, which has been unsatisfactory owing to the fact that most of the volcanic rocks in Java are very low in potassium, and dates obtained from them have as a result relatively high atmospheric argon. At the major hominid sites in Java, no minerals with essential potassium in them occur in the rocks present. Of the minerals composing these rocks, hornblende has the highest amounts of potassium, but it does not exceed 0.3% K.

At Sangiron, where several hominid fossils, mostly cranial fragments, have been found, possibly comprising two genera, *Pithecanthropus* and *Meganthropus* (Jacob 1973), the fossils are older than strata believed to bear tektites, although the tektites have not been found in place in the strata. Zähringer (1963) dated tektites from Sangiron and elsewhere in southeast Asia at 0.73 Ma by K–Ar, which would appear to put a minimum age on these hominids. However, the K–Ar ages of tektites from southeast Asia have been questioned on two counts: first, the ages obtained may not represent the time of emplacement of the tektites in the strata; and, secondly, the tektites may not have lost all of their initial argon during heating in the atmosphere when they fell (Schaeffer 1966), which, if true, would mean they are not as old as they appear to be. Fission track ages of the tektites obtained by Storzer & Wagner (1969), and corrected for annealing of the tracks by grass fires, average 0.7 Ma, making them concordant with the K–Ar dates. Possibly the first question can be discounted also. Tektites identical in composition to those found in southeast Asia on land are found in ocean-bottom cores at the Bruhnes–Matuyama geomagnetic boundary, well dated at 0.73 Ma (Cassidy *et al.* 1969).

A K–Ar date of 0.83 ± 0.04 Ma, the average of four runs, was obtained from pumice closely associated with hominid crania at Sangiron in the Kabuh Formation. The dates were obtained from hornblende in the pumice and ranged from 0.79 Ma to 0.90 Ma, and none of them had less than 98% atmospheric argon (Jacob & Curtis 1971). Recently, a split of one of these samples was run at Berkeley under improved conditions and it yielded a date of 1.2 ± 0.2 Ma, with less than 90% atmospheric argon (unpublished data). This date must be considered superior to the 0.83 Ma figure.

At Modukerto, where part of the cranium of a *Pithecanthropus* (*Homo*) *erectus* infant was found by Duyfjes in 1936 (Koenigswald 1936) a K–Ar date of 1.9 ± 0.4 Ma, the average of two runs, was obtained from hornblende separated from pumice fragments occurring some 50 m below the fossil site (Jacob & Curtis 1971). Again, the very high atmospheric argon content of these two runs, approximately 99%, greatly reduces their precision and accuracy.

In China, at Choukoutien, the site of 'Peking Man' (*Sinanthropus pekinensis*, *Homo erectus*) and some of the earliest known evidence of the use of fire, as well as elsewhere in China, the geological context is unfavourable for isotopic dating, although a uranium–thorium date of 0.21 to 0.5 Ma has been obtained (Chang 1968). No details of this date are given, but it accords roughly with the Second and Third Glacials of Europe, as do the pollen profiles and associated fauna (Chang 1968). Evernden & Curtis obtained a K–Ar date of 380000 a for Mindel II of the

Second Glaciation (Evernden & Curtis 1965) from a tuff on the Lower Main Terrace of the Rhine, which also tends to support an age of approximately 400000–500000 a for the age of *Homo erectus* at Choukoutien and, by mammalian correlation, at Lan-t'ien in east central Shensi.

In conclusion, it appears that very few isotopic dates being used to calibrate the early evolution of the hominids are as accurate as we would like them to be. On the other hand, several have higher 'accuracy' than the taxon designations that they are being used to calibrate. It appears probable that within a few years accurate isotopic dates will be available for calibration of all phases of hominid evolution. The late stages of hominid evolution and social and cultural development are dated better although not nearly as well as anthropologists and archaeologists wish. New improvements to dating techniques will soon help greatly to resolve problems at the younger end of the time scale.

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Discussion

R. BURLEIGH (*Research Laboratory, The British Museum, London, U.K.*). The question of dating and time scales is the key to the ideas being discussed here over the next two days and we should be grateful to Professor Curtis for his clear survey, first of problems and methods (excluding, perhaps deliberately, palaeomagnetism), and secondly of the exact time scales that are now being established for the last 10 Ma. The dates and the time scales will, I am sure, be the basis of much discussion during this meeting and I would like to confine my remarks mainly to a brief commentary on the methods, and especially the potential application, of electron spin resonance (e.s.r.) to dating. If problems relating to the radiation history of the materials dated in this way can be resolved this is a most promising development since it offers the opportunity of making useful comparisons with other methods of dating based on different materials. It may also offer a chance to span the interval between the upper limit of, for example, ^{14}C dating and the lower end of the range of other methods such as K–Ar dating. Many of the methods that are now available to cover this critical period between about 50–100 ka B.P. when modern man, *Homo sapiens sapiens*, finally emerged, face severe technical difficulties, for example those to which thermoluminescence dating of burnt, humanly worked flint is subject, or the uncertainties of amino acid dating. Thus there is great scope for an alternative method that significantly overlaps the methods that are well established but have incomplete coverage within the period of greatest interest, such as the K–Ar and ^{14}C dating. The extension of the range of ^{14}C dating to perhaps as much as 100 ka B.P. by the use of Van de Graaff accelerator techniques (and the possibility of detecting by this means other natural radioisotopes with much longer half-lives, such as ^{10}Be) is also a development of the greatest importance in this context. But one of the advantages of using e.s.r. for dating of, say, bone would be the possibility of being able to date important fossil material directly (A.1 dating in K. P. Oakley's terminology) and I would like to ask Professor Curtis how destructive the use of this method, if it indeed proves workable, would be.

G. H. CURTIS. The method is not destructive in the sense that one is still left with the sample at the end and measurements can be made on it any number of times, but one does have to grind up the bone first of all (a few grams only, though) to do the measurement.

T. Molleson (*British Museum* (*Natural History*), *London SW*7 5*BD*, *U.K.*). Dr Curtis remarked during his paper that fluorine and uranium elements accumulate in bone with time, and Dr Harmon has shown concern that uranium series breakdown should be used for dating fossil bones since we cannot tell when the uranium entered the bone.

It is not at all clear, however, that uranium and fluorine do in fact continue to accumulate in bone. During the process of fossilization of recently buried bone, mineralizing elements are taken up by bone as organic compounds are lost. The levels of fluorine, uranium etc. taken up by the bone reflect the ambient levels of these elements in the ground waters percolating over the bone. Equilibrium is probably reached comparatively rapidly. Once the sediment containing the bone has become indurated, little if any further chemical change can take place in the bone; although, of course, isotopic and amino acid breakdown continue. Bone from indurated impervious sediments can thus be considered a closed system for the purposes of quantitative measurements until rock erosion or excavation bring the buried bone to the surface again.