K-Ar and $^{40}Ar/^{39}Ar$ dating of the hominid-bearing Pliocene-Pleistocene sequence at Koobi Fora, Lake Turkana, northern Kenya

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ABSTRACT

In the Koobi Fora region, east of Lake Turkana, northern Kenya, there occurs a sequence ~500 m thick of lacustrine, fluvial, and deltaic sediments that contains abundant vertebrate fossils, including hominids, as well as stone tools. Rhyolitic tuffs within the sedimentary sequence have facilitated stratigraphic mapping. Some of the tuffs contain pumice clasts, from which anorthoclase phenocrysts have been separated, providing ideal material for K-Ar and $^{40}Ar/^{39}Ar$ dating. Seven tuffs have been dated, generally yielding concordant ages on multiple samples from each tuff. Results are consistent with the stratigraphic sequence. The $^{40}Ar/^{39}Ar$ age spectra give nearly ideal flat patterns, indicating that the feldspars have remained undisturbed since crystallization and cooling, with no evidence of thermal overprinting. As the pumice clasts are considered to have been deposited very soon after their eruption, the measured ages provide a close approximation to that of deposition of the tuffs.

The Moiti Tuff, ~30 m above the base of the sequence, has a maximum age of 4.10 ± 0.07 Ma. The Toroto Tuff, some 70 m higher in the sequence, is very securely dated at 3.32 ± 0.02 Ma. Stratigraphically higher tuffs and their ages include the Ninikaa Tuff, 3.06 ± 0.03 Ma; the KBS Tuff, 1.88 ± 0.02 Ma; the Malbe Tuff, 1.86 ± 0.02 Ma; the Chari Tuff, 1.39 ± 0.02 Ma, and the Silbo Tuff, 0.74 ± 0.01 Ma, near the top of the sequence. The geochronology and geological data indicate at least three hiatuses in the sequence, each on the order of 0.5 to 0.7 Ma duration. Conventional K-Ar age measurements on basalts from the basin margin suggest that deposition of the Koobi Fora Formation began no earlier than ~4.3 Ma ago in the early Pliocene.

These results provide a well-documented numerical time framework for the sedimentary sequence in the Koobi Fora region and for the hominids and other fossils contained therein. Most of the hominid fossils, including forms assigned to the *Homo* lineage and a coexisting *Australopithecus* lineage, occur within sediments deposited in the basin over the interval from ~2.0 to 1.4 Ma ago in the late Pliocene and early Pleistocene.

INTRODUCTION

The Pliocene to Pleistocene sedimentary sequence exposed adjacent to the eastern shores of Lake Turkana in the vicinity of Koobi Fora, northern Kenya (Fig. 1), has been the focus of intensive study since its potential importance was recognized by R.E.F. Leakey in 1967. The sequence is of significance because of the abundance of vertebrate fossils, including hominids, as well as artifacts, that have been recovered from it. The hominid fossils have provided important information relating to the evolution of man. Considerable effort therefore has been devoted to the establishment of a numerical time scale for the sequence at Koobi Fora

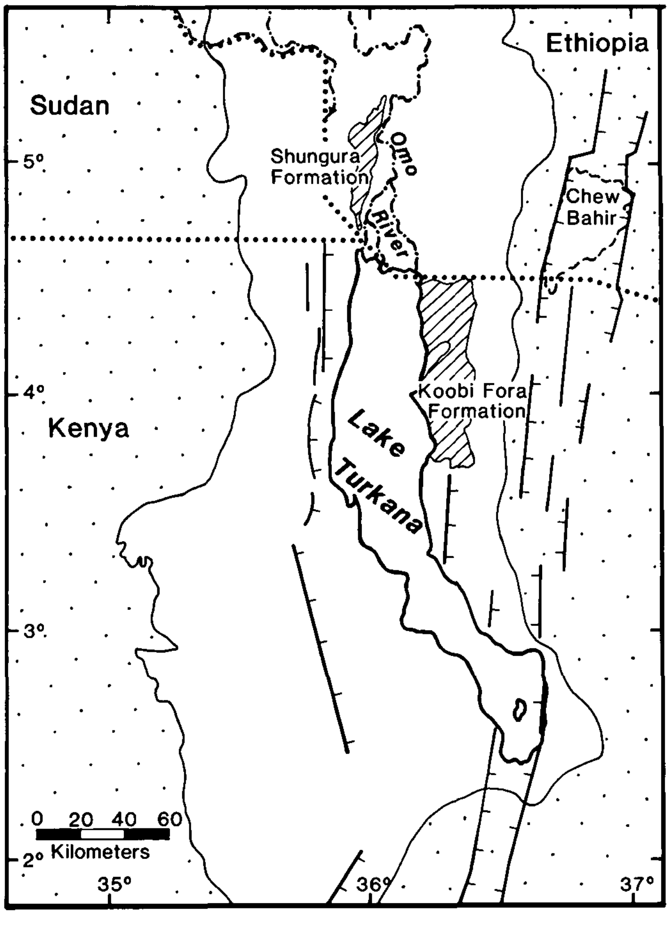

Figure 1. The Lake Turkana region, showing outcrop of the Koobi Fora Formation and the Shungura Formation. Some of the lineaments and faults (bars on downthrown side) associated with rifting are indicated. Area that drains into Lake Turkana is blank.

Additional tabular material for this article may be secured free of charge by requesting Supplementary Data 85-07 from the GSA Documents Secretary.

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over the past 15 yr. Methods used have included isotopic dating by the K-Ar and $^{40}Ar/^{39}Ar$ techniques and fission track dating, as well as relative dating methods involving biostratigraphy and magnetostratigraphy.

The physical dating results from various laboratories on rhyolitic tuffaceous beds within the sequence in the Koobi Fora region have been conflicting and have given rise to much controversy. This paper presents the results of K-Ar and $^{40}Ar/^{39}Ar$ dating of alkali feldspars separated from pumice clasts found within the tuff beds at Koobi Fora. In addition, K-Ar ages have been measured on some samples of basalt that form the local basement to the sedimentary sequence. These new measurements yield a generally consistent and coherent set of precise ages, demonstrating that deposition began possibly as early as 4.1 Ma ago in the Pliocene and continued, intermittently, until at least 0.7 Ma ago in the Pleistocene.

GEOLOGICAL SETTING

Lake Turkana lies in a large asymmetric graben structure, the Turkana Depression, situated between the Kenyan and Ethiopian topographic domes within the eastern (Gregory) rift of the East African Rift System (Baker and others, 1972), which extends southward from the Red Sea for $\sim$3,000 km. The rift system mainly cuts crystalline continental crust that yields late Precambrian to early Paleozoic isotopic ages (Cahen and Snelling, 1966), typical of the Mozambique orogenic belt. Rifting clearly is related to lithospheric plate adjustments (McKenzie and others, 1970), and commonly it has been suggested that the East African Rift System provides a good example of a new plate boundary developing within a continental block. Baker and others (1972) and King (1978) showed that uplift in East Africa began in the Mesozoic to early Cenozoic, with subsequent tensional faulting occurring intermittently from about middle Cenozoic time until the present, resulting in formation of the rifts. Widespread and voluminous volcanism associated with the uplift and rifting is mainly of alkaline character, ranging from basalt to phonolite, trachyte, and rhyolite.

The Turkana Depression was an effective trap for sediments during the Pliocene and Pleistocene. This paper is concerned with the Kubi Algi, the Koobi Fora, and the Guomde Formations, as defined by Bowen and Vondra (1973), in the Koobi Fora region east of Lake Turkana (Fig. 1). North of Lake Turkana in the Omo River Valley, the Shungura Formation crops out over a wide area (Fig. 1). It was laid down over a similar time interval, within a closely related depositional system (Cerling and Brown, 1982).

Brown and Cerling (1982) recently demonstrated that the Koobi Fora Formation makes up most of the sequence in the Koobi Fora region. The Koobi Fora Formation is exposed over an area of about 80 km by 40 km (Fig. 2) and accumulated within a basin developed upon a local basement of volcanic rocks (basalts, silicic lavas, ignimbrites) and sediments of Miocene to Pliocene age (Savage and Williamson, 1978; Fitch and Miller, 1976). The Koobi Fora Formation is nearly flat-lying and consists mainly of sands, silts, and clays deposited in a range of fluvial, deltaic, and lacustrine environments, not unlike those prevailing around Lake Turkana today. It is now known to be at least 475 m thick (Cerling and Brown, 1982) and is overlain by the Guomde Formation, which is as much as $\sim$40 m thick (Bowen and Vondra, 1973).

Much effort has been directed toward working out the stratigraphy within the Koobi Fora region, made difficult because of discontinuous exposure, short sections, and marked facies variations. Behrensmeyer (1970) first recognized rhyolitic tuffs within the sequence, and these tuffs were utilized in the erection of a stratigraphic framework for the deposits. Bowen and Vondra (1973), Vondra and Bowen (1976, 1978), and Findlater (1976, 1978a, 1978b) thus developed a stratigraphic nomenclature and produced geologic maps, based mainly upon correlation throughout the basin of some of the tuffaceous marker beds. Problems with some of the mapping and correlations became evident from paleontological studies using vertebrates, mainly Suidae (White and Harris, 1977; Harris and White, 1979), and also from studies of molluscs (Williamson, 1982).

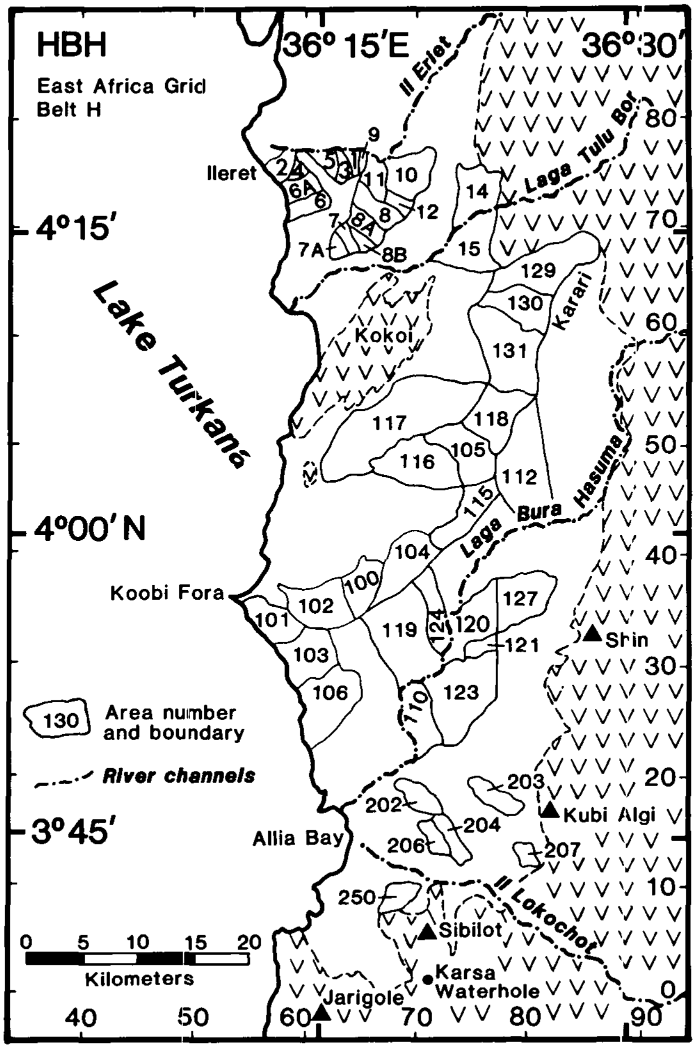

Figure 2. The Koobi Fora region, showing locations of paleontological collection areas within the Koobi Fora Formation. The local basement, dominantly volcanic, is indicated by pattern.

Cerling and others (1979) showed that an earlier correlation of tuff at two localities in the Koobi Fora region was incorrect on the basis of differences in the chemical composition of volcanic glass from pumices in the tuffs. Furthermore, using these geochemical fingerprinting techniques, they proposed that three tuff beds in the Koobi Fora Formation could be correlated with specific tuffs in the Shungura Formation in the Omo River Valley, where the stratigraphy is relatively straightforward. Correlations between at least two pairs of these tuffs had been suggested previously (Brown and Nash, 1976; Brown and others, 1978). Further miscorrelations of tuffs within the Koobi Fora region subsequently were documented, and additional correlations with tuffs in the Shungura Formation were proposed (Cerling and Brown, 1982; Brown and Cerling, 1982). Using established nomenclature where possible, but defining and naming a number of additional tuff beds in the Koobi Fora region, a modified stratigraphy was produced by Cerling and Brown (1982) and Brown and Cerling (1982), essentially as shown in Figure 3.

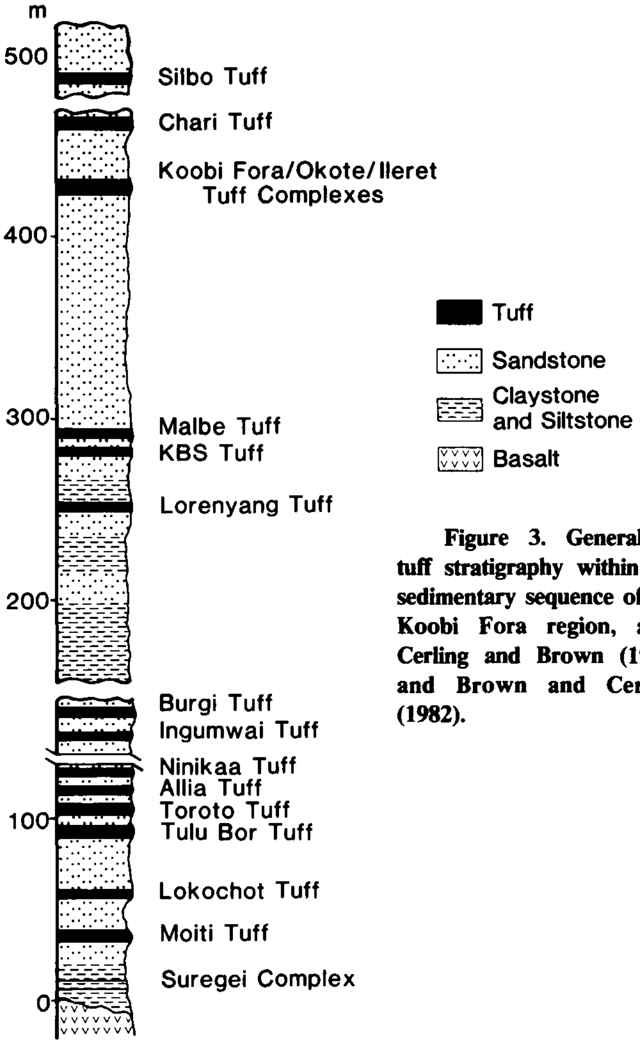

Figure 3. Generalized tuff stratigraphy within the sedimentary sequence of the Koobi Fora region, after Cerling and Brown (1982) and Brown and Cerling (1982).

During the present study, inconsistencies with the earlier interpretations of the stratigraphic sequence at Koobi Fora also became apparent. In contrast, there are no conflicts with the revised stratigraphy of Cerling and Brown (1982), which is used throughout the paper.

At least 40 rhyolitic tuff beds are now recognized within the Pliocene-Pleistocene sequence in the Koobi Fora region (Cerling and Brown, 1982). The more continuous tuff beds not only can be used for correlation throughout the basin, but in principle also can be used for dating by isotopic methods because of their igneous origin. Vondra and Bowen (1976, 1978) and Findlater (1976, 1978a) stressed that most of the tuffs are reworked, as they were deposited from water. Findlater nevertheless emphasized that the time between explosive eruption of the tuffs and their subsequent deposition in the basin is likely to have been very short, so that dating of the tuffs should provide excellent control on the age of deposition. Part of the evidence for this is that the tuffs usually have very sharp lower boundaries with the normal detrital sediments. Most tuffs range from a few centimetres to ~2 m in thickness, but individual beds may vary considerably in thickness even over short distances. They are composed mainly of rhyolitic glass shards together with varying proportions of detrital material.

In some tuffs, rounded pumice clasts occur, often concentrated within what are interpreted as local stream channels. Geochemical data show that in most cases these pumices are products of the same explosive volcanic eruptions that produced the tuffs (Cerling and others, 1979; Cerling and Brown, 1982). The clasts range in size from ~1 cm to ~60 cm in diameter. They commonly contain phenocrysts of alkali feldspar (anorthoclase), ideal for K-Ar and $^{40}Ar/^{39}Ar$ dating. Feldspars from the pumice clasts thus have been used to date the tuffs. Although K-Ar ages have been measured successfully on glass from some of these beds (Drake and others, 1980), it was not used in this study, because such glasses, especially when altered, tend to leak radiogenic Ar readily.

PREVIOUS DATING

Soon after tuffs were discovered within the sequence at Koobi Fora, it was recognized that they might be utilized for isotopic dating purposes to provide numerical age control (Fitch and Miller, 1970). Fitch and Miller (1976) published results in summary form of a large program of dating, mainly using the $^{40}Ar/^{39}Ar$ method on alkali feldspars separated from pumices within the tuffs. These results are characterized by much scatter. For example, feldspar concentrates from 7 pumice samples from the Karari Tuff yielded apparent $^{40}Ar/^{39}Ar$ total fusion ages ranging from 0.61 ± 0.30 Ma to 1.39 ± 0.11 Ma, typically with <15% of the Ar being radiogenic. An even larger range of age was reported for feldspars from pumices in the KBS Tuff. The $^{40}Ar/^{39}Ar$ age spectra measured on individual feldspars from pumices throughout the sequence were stated to be complex and discordant. Fitch and Miller ascribed the large scatter in both types of data to problems of contamination by detrital feldspar, leading to old apparent ages, and to variable loss of radiogenic Ar owing to thermal overprinting, causing young apparent ages.

Data in the present paper confirm that contamination by old detrital components can be a problem, but no evidence is found for significant loss of radiogenic Ar from any of the feldspars analyzed, as the $^{40}Ar/^{39}Ar$ age spectra are relatively simple and concordant. It is concluded, therefore, that the large spread of results reported by Fitch and Miller (1976) must result from experimental difficulties or error estimations that do not properly reflect the uncertainties in the actual measurements.

Other dating studies (Curtis and others, 1975; Fitch and others, 1976; Hurford and others, 1976; McDougall and others, 1980; Gleadow, 1980; Drake and others, 1980; McDougall, 1981) are most conveniently discussed with the new results from the relevant stratigraphic units (see below).

Some success was achieved in defining a magnetostratigraphy within the Koobi Fora Formation (Brock and Isaac, 1974, 1976; Hillhouse and others, 1977). The hope, however, that comparison of the paleomagnetic data with the geomagnetic polarity time scale would provide independent evidence for the age of the sequence and thus help to resolve some of the dating problems was not fulfilled.

ANALYTICAL METHODS AND DATA HANDLING

The basalt samples collected were all examined in thin section under the petrographic microscope to ensure that only fresh rocks, essentially free of alteration, were used for dating. Samples in which groundmass glass was obviously altered or devitrified were rejected; only samples in which the glass appeared to be fresh and isotropic were accepted for dating. Even apparently fresh glass, however, may leak radiogenic Ar, so that in general the measured ages should be regarded as minimum ages. The basalt samples dated were measured by the conventional K-Ar method only.

Pumice clasts from the tuffs normally were trimmed to remove at least the outer 1 cm prior to crushing the remaining material; this was done to minimize contamination from detrital material. Where only small pumices were available, the surface was cleaned with a wire brush and scraped with a knife prior to crushing. In most cases, a concentrate of feldspar was obtained initially by panning with water, as the light pumiceous material floated. The feldspar concentrate coarser than 1 mm was used for further purification, although sometimes it was necessary to include grains as small as 0.5 mm when the amount of sample available was limited. After crushing, usually to 150–350 μm, further purification was achieved with heavy liquids and magnetic separation. A 3-min ultrasonic bath in 7% HF commonly was used to remove traces of adhering glass and groundmass from the feldspar. Feldspar concentrates of >99% grain purity usually were obtained. The feldspars were limpid, free of alteration, and optically homogeneous. As reported previously (McDougall and others, 1980), X-ray diffraction measurements on some feldspars confirmed that they are structurally close to the sanidine-high albite series and can be classified as anorthoclases. No evidence for significant unmixing was found. Polysynthetic twinning on a very fine scale is well developed in some crystals.

All samples were measured by the conventional K-Ar dating method, and a selected minority of the feldspars also was measured by both the $^{40}Ar/^{39}Ar$ total fusion and age spectrum techniques. As a check on the underlying assumptions, a number of samples from the same or related stratigraphic levels normally were dated.

In the $^{40}Ar/^{39}Ar$ dating method, $^{39}Ar_K$ is produced from ^{39}K in the sample by fast neutrons in a nuclear reactor. After irradiation, Ar is extracted from the sample in a high vacuum system and analyzed isotopically, effectively allowing simultaneous determination of K and Ar (Merrihue and Turner, 1966). The ratio of radiogenic Ar ($^{40}Ar^*$) to $^{39}Ar_K$ is proportional to age. The Ar can be released in stages by stepwise heating, commencing at a temperature well below that of fusion, and the gas evolved in successive steps analyzed to provide a series of apparent ages. A plot of age versus fraction of ^{39}Ar released, known as an age spectrum, may be interpreted in terms of the distribution of $^{40}Ar^*$ in the sample, from which conclusions may be drawn as to whether or not the K-Ar system has been disturbed subsequent to crystallization of the sample (Turner, 1968).

In the conventional K-Ar method, separate aliquants of the sample were used for measurement of K by flame photometry and for measurement of Ar by isotope dilution with ^{38}Ar as the tracer. As noted previously (Webb and McDougall, 1967; McDougall and others, 1980), it is difficult to extract Ar quantitatively from high-temperature alkali feldspars. Empirically, it was found necessary to heat the feldspars at a temperature of ~1600 °C for at least 40 min to obtain full recovery of the Ar. Heating was by radio-frequency induction, with the sample contained in a Mo crucible inside a water-cooled, silica glass bottle attached to the vacuum system.

Virtually all of the Ar isotopic analyses on gas extracted from the feldspars in both the K-Ar and $^{40}Ar/^{39}Ar$ dating methods were done using a VG-Isotopes MM1200 mass spectrometer operated statically. Peak hopping was employed, and data were taken on-line with a Hewlett-Packard 1000 computer in which all data handling and calculations were done within minutes of completion of the analysis. For the basalts, most of the Ar isotopic analyses were done on an AEI MS10 mass spectrometer also linked to the HP1000 computer.

Irradiation techniques closely followed those described previously (McDougall, 1981). The flux monitor used was GA1550 biotite (K = 7.70%; $^{40}Ar^* = 134.3 \times 10^{-11}$ mol/g; K-Ar age = 97.7 Ma) (McDougall and Roksandic, 1974), located in a small sealed cylindrical canister centrally within a larger machined canister in which was packed the unknown sample. Irradiation times ranged from 20 to 30 hr in a fast neutron flux of about 4×10^{12} neutrons/cm^2/s in HIFAR reactor. All samples were irradiated within a Cd shield, 0.2 mm thick, to keep the $(^{40}Ar/^{39}Ar)_K$ correction factor acceptably small, usually <0.03. This correction factor was measured in each irradiation, but the Ca correction factors used were those reported by Tetley and others (1980) for HIFAR: $(^{39}Ar/^{37}Ar)_{Ca} = 7.27 \times 10^{-4}$; $(^{36}Ar/^{37}Ar)_{Ca} = 3.06 \times 10^{-4}$.

After irradiation, a small aliquant of the sample normally was employed for direct measurement of a $^{40}Ar/^{39}Ar$ total fusion age. The bulk of the feldspar was used for the measurement of a $^{40}Ar/^{39}Ar$ age spectrum. Temperature at each step was monitored with a thermocouple located in an insert in the bottom of the Mo crucible, and also by optical pyrometer. The relative temperature increments between successive steps were controlled to ~10 °C, but the actual temperature given for each step probably was not known to better than ~±30 °C, because of temperature gradients in the crucible. Heating time at each step was 40 min. Following purification of the Ar released at each step, the gas was transferred directly to the mass spectrometer and isotopically analyzed immediately. Background in the mass spectrometer was measured prior to each gas analysis but was negligible in virtually all cases, even though the gas amounts being measured were small, usually about 10^{-12} mol ^{40}Ar. Sensitivity of the mass spectrometer was about 3.5×10^{-15} mol/mV, using a 10^{11}-ohm resistor in the electrometer. Blank from the Ar extraction line for each step was on the order of 2×10^{-13} mol ^{40}Ar, but as this was rather variable, blank correlations were not applied to the data. The Ar blank generally was atmospheric in composition.

Errors are quoted at the level of one standard deviation according to procedures described previously (McDougall and Schmincke, 1977; Dalrymple and Lanphere, 1971). Where replicate K-Ar measurements were made, the mean age has a minimum assigned error of 1%, as the uncertainties associated with measurement of K and calibration of the ^{38}Ar tracer are of this order. Ages quoted in the tables of data are calculated on the assumption that the nonradiogenic Ar in the sample has the composition of atmospheric Ar with $^{40}Ar/^{36}Ar = 295.5$.

The $^{40}Ar/^{39}Ar$ step heating results from a sample are displayed as an age spectrum. In the ideal case of an igneous sample that has remained thermally undisturbed since crystallization and cooling, the $^{40}Ar^*/^{39}Ar_K$ ratio of the gas fractions, released successively by diffusion from the sample during the laboratory step heating experiment, will be essentially constant. All of the steps in the age spectrum thus will have concordant ages to within the errors, and this would constitute an ideal flat pattern or plateau. If the measured age of a particular gas fraction differs by more than twice its associated error from the age of the plateau, it may be excluded. A plateau often may be identified even in a somewhat discordant age spectrum.

It is also useful to plot data from each step heating experiment on a $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ correlation diagram. These ratios, the inverse of those commonly used, minimize effects of correlation of errors (Roddick and others, 1980; Radicati di Brozolo and others, 1981). If a good straight line is defined, as would be the case when the age spectrum shows an ideal flat pattern, it can be interpreted in terms of a mixing line between nonradiogenic Ar, represented by a point on the ordinate, and Ar derived from K, represented by a point on the abscissa. The respective intercepts define these two end members. The $^{39}Ar_K/^{40}Ar$ intercept value is inversely proportional to age. Such an analysis allows derivation of the composition of the non-radiogenic Ar independently of assumptions and allows an objective assessment of the scatter of data. Regression techniques are essentially those of York (1969). The MSWD is a goodness of fit parameter; if this exceeds a value of ~ 2.5, then scatter about the line is greater than can be accounted for by experimental error alone (Roddick, 1978).

The K decay constants and ^{40}K abundance used in all calculations are those recommended by the IUGS Subcommission on Geochronology (Steiger and Jäger, 1977). Results based upon the K-Ar dating method published earlier than 1977 used a different set of decay constants; these

TABLE 1. POTASSIUM-ARGON AGES ON WHOLE ROCK BASALT SAMPLES, KOOBI FORA REGION, NORTHERN KENYA

Lab. no.	K (wt %)	Radiogenic ^{40}Ar (10^{-11} mol g^{-1})	$\frac{100 \text{ rad. } ^{40}\text{Ar}}{\text{total } ^{40}\text{Ar}}$	Calculated age (Ma) ± 1 s.d.
Karsa Waterhole, HBH711012, photo 1553/047-043*†				
78-1025	0.804,0.803	0.554	29.2	3.97 ± 0.05
78-1023	0.829,0.826	0.625	43.8	4.35 ± 0.05
78-1024	0.970,0.964	2.457	81.7	14.6 ± 0.2
Kokoi Horst, HBH628591 (81-113), HBH629591 (81-114), HBH597541 (81-119)				
81-113	0.684,0.685	0.730	38.2	6.14 ± 0.07
81-114	0.649,0.646	0.603	38.3	5.37 ± 0.06
81-119	0.721,0.721	0.731	25.3	5.83 ± 0.08

$\lambda_e + \lambda'_e = 0.581 \times 10^{-10} a^{-1}$; $\lambda_\beta = 4.962 \times 10^{-11} a^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol mol^{-1}.

*Grid reference is to East Africa metric grid, zone H. Map series Y633, sheets 5 and 13, edition 1 GSGS, scale 1:100,000, 1960.

†Aerial photographs taken in December 1970 by Hunting Surveys, London. Photograph number indicated, and coordinates following refer to millimetres from left edge and top edge of 23-cm square prints, respectively.

ages must be increased by ~2.7% to make them comparable with those reported here. To minimize confusion, results normally are quoted as originally given, but where the revised age also should be available, it is given in parentheses.

Reference to the geological time scale is sometimes useful. Following Berggren (1981), and adjusting to the recommended decay constants, the Oligocene-Miocene boundary has an age of ~24 Ma, the Miocene-Pliocene boundary an estimated age of 5.5 Ma, and that of the Pliocene-Pleistocene boundary an age of 1.7 Ma.

RESULTS AND DISCUSSION

Results of conventional K-Ar and ^{40}Ar/^{39}Ar age measurements are given in Tables 1 through 8 and Tables A, B, C,[1] and these data are discussed in stratigraphic order from oldest to youngest. A number of determinations have been made on volcanic rocks from the margin of the Koobi Fora basin, but only some of these are discussed here, specifically, those from relatively young basalts.

Basalts

Basaltic lavas are widely distributed in the Koobi Fora region, and, as no lava flows have been mapped within the Koobi Fora Formation, it is argued that their eruption ceased before deposition of the sediments began. Dating of basalts thus provides some age control on the time of initiation of deposition. Results of conventional K-Ar dating of several of these basalts are given in Table 1.

At Karsa Waterhole, near the southeastern margin of the basin (Fig. 2), good exposures of basalt occur. The stratigraphically lowest flow, well-exposed in a cliff section, is at least 4 m thick and is spheroidally weathered. A sample (78-1024) from this flow yielded an age of 14.6 ± 0.2 Ma, middle Miocene. Overlying an erosional surface developed on the older basalt and on locally preserved gravels, there occurs a relatively fresh, hackly jointed basalt flow >7 m thick, a sample (78-1023) from which gave a K-Ar age of 4.35 ± 0.05 Ma. This basalt sample is well crystallized, with only a few percent of pale brown, fresh, isotropic glass and minor mineraloid. Another sample (78-1025) of basalt from a columnarly jointed outcrop on the south side of the waterhole gave a measured age of 3.97 ± 0.05 Ma. As this sample probably is from the same flow as is sample 78-1023, the younger apparent age is interpreted as indicating some loss of radiogenic Ar from the abundant (~20%) iron-oxide–charged, intersertal mesostasis that occurs within it. Sediments of the Koobi Fora Formation crop out ~1 km west of Karsa Waterhole, so that the K-Ar age of basalt sample 78-1023, which is regarded as the most reliable age, indicates that their deposition began subsequent to 4.3 Ma. Earlier conventional K-Ar ages of 3.8 ± 0.4 Ma (3.9 Ma) for two basalts near the eastern margin of the Koobi Fora basin (Fitch and Miller, 1976) are similar to the age of the younger basalt at Karsa Waterhole.

Basalt lava flows also are exposed in the Kokoi Horst, an area rising as much as ~130 m above the adjacent landscape between Koobi Fora and Ileret (Fig. 2). This horst exposes the local basement upfaulted relative to the surrounding sediments of the Koobi Fora Formation (Bowen and Vondra, 1973; Vondra and others, 1971). The basalt lavas have low dips, although locally, adjacent to faults, they are dragged up to near vertical. Three basalt samples collected from the Kokoi were dated. Samples 81-113 and 81-114 gave measured ages of 6.1 ± 0.1 and 5.4 ± 0.1 Ma, respectively (Table 1); they were collected from a small valley on the northwest flanks of the Kokoi near the road. These two samples are ~150 m apart laterally, and at both localities the basalt is overlain by sediments. Faulting has also disturbed the sediments, so that some uplift has occurred after sedimentation. The third sample (81-119), which yielded an age of 5.8 ± 0.1 Ma, was collected adjacent to the shore of Lake Turkana, 6 km south-southwest of the previously discussed locality. These results are accepted as reliable minimum ages for the basalts; the spread in apparent age may reflect variable Ar loss from the abundant (10% to 25%) glass or mesostasis present in the samples, especially as samples 81-113 and 81-114 are from the same or adjacent flows. A substantially younger K-Ar age of 3.6 ± 0.4 Ma (3.7 Ma) was reported by Fitch and Miller (1976) for a basalt (FM 7052) from the Kokoi, but the actual locality was not given.

The results from Karsa Waterhole and Kokoi emphasize the importance of late Miocene to early Pliocene basaltic volcanism in the Koobi Fora region. It is inferred that this volcanism ceased no earlier than 4.3 Ma ago, prior to commencement of deposition of sediments of the Koobi Fora Formation.

Moiti Tuff

The Moiti Tuff lies ~30 m above the base of the sedimentary sequence (Fig. 3) and is the lowest tuff recognized at present in the Koobi Fora Formation (Cerling and Brown, 1982). It crops out extensively in the southern part of the Koobi Fora region east of Allia Bay as a tuff of variable thickness ranging to ~5 m. The Moiti Tuff commonly contains small pumice clasts, although in one locality some pumices as much as 20 cm across were found. Feldspar was separated from three of these larger pumices, but sufficient concentrate was obtained in each case to permit only conventional K-Ar ages to be measured.

The apparent ages range from 4.01 ± 0.04 Ma to 4.15 ± 0.06 Ma (Table 2). The mean measured value of 4.10 ± 0.07 Ma could be accepted as a reasonably precise estimate for the age of crystallization and cooling of the feldspars in the pumice clasts, and thus as a maximum age for deposition of the Moiti Tuff. The spread of 3.3% in the measured K-Ar ages, however, is somewhat greater than expected from experimental error alone, suggesting the presence of some other source of error. The effect of contamination by old detrital feldspar could be very large. For example, calculations show that contamination by only 0.1 wt% K-feldspar 460 Ma old, typical of the detrital feldspar in the Koobi Fora Formation (McDougall and others, 1980), would increase the apparent age by ~1.4 Ma. Inasmuch as this effect is so large, it seems unlikely that the feldspar concentrates from three separate pumices could be contaminated so uni-

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[1] Tables A, B, and C may be obtained by requesting Supplementary Data 85-07 from the GSA Documents Secretary. These tables contain the analytical data for all the ^{40}Ar/^{39}Ar age measurements.

TABLE 2. POTASSIUM-ARGON ANALYTICAL DATA ON ANORTHOCLASE PHENOCRYSTS SEPARATED FROM PUMICE CLASTS FOUND WITHIN THE MOITI TUFF AND THE TOROTO TUFF IN THE SOUTHERN PART OF THE KOOBI FORA AREA, EAST OF LAKE TURKANA, NORTHERN KENYA

Lab. no.	K (wt %)	Weight used in Ar extraction (g)	Radiogenic ^{40}Ar (10^{-11} mol g^{-1})	$\frac{100 \text{ Rad. } ^{40}\text{Ar}}{\text{Total } ^{40}\text{Ar}}$	Calculated age (Ma) ± 1 s.d.	Average age (Ma) ± 1 s.d.
Toroto Tuff, area 207, south of Kubi Algi, HBH788128, photo 1729/036-159*†						
81-106	4.302,4.318	1.502 1.002	2.426 2.509	87.4 86.5	3.24 ± 0.03 3.35 ± 0.04	3.30 ± 0.08
81-107	4.375,4.372	1.001 1.001	2.538 2.549	87.1 89.1	3.34 ± 0.04 3.36 ± 0.04	3.35 ± 0.03
81-109A	4.131,4.301	1.001	2.488	86.1	3.33 ± 0.04	3.33 ± 0.04
81-109B	4.362,4.365	1.007	2.507	89 8	3.31 ± 0.04	3.31 ± 0.04
Toroto Tuff, area 204, east of Allia Bay, HBH737138, photo 1575/173-152						
78-1073A	4.247,4.276	1.954 1.504	2.460 2.423	80.5 88.2	3.33 ± 0.04 3.28 ± 0.04	3.30 ± 0.04
78-1073B	4.346,4.305	1.977 2.076	2.534 2.517	86.9 48.9	3.37 ± 0.04 3.34 ± 0.04	3.36 ± 0.04
78-1075A	4.250,4.294	1.626	2.478	88.6	3.34 ± 0.04	3.34 ± 0.04
78-1075B	4.347,4.316	2.061	2.500	74.0	3.32 ± 0.04	3.32 ± 0.04
81-100	4.202,4.269	0.745	2.440	91.2	3.32 ± 0.06	3.32 ± 0.06
81-103	4.310,4.335	1.501 1.284	2.745 2.662	91.4 89.2	3.66 ± 0.04 3.55 ± 0.04	3.60 ± 0.08
Moiti Tuff, 6 km northeast of Sibilot, ~HBH760085, photo 199/131-119						
82-304	3.744,3.844	0.378	2.731	79.0	4.15 ± 0.06	4.15 ± 0.06
83-1	3.971,3.989	0.601 0.501	2.874 2.837	84.7 82.7	4.16 ± 0.04 4.10 ± 0.04	4.13 ± 0.04
83-2	4.006,4.032	0.700 0.701	2.821 2.780	91.0 85.3	4.04 ± 0.04 3.98 ± 0.04	4.01 ± 0.04

$\lambda_e + \lambda'_e = 0.581 \times 10^{-10} a^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10} a^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol mol^{-1}

Toroto Tuff mean ages area 207 = 3.32 ± 0.02 Ma; area 204 (excluding 81-103) = 3.33 ± 0.02 Ma; over-all mean age (excluding 81-103) = 3.33 ± 0.02 Ma. Most concentrates in size range 170–350 μm or 200–400 μm.

Moiti Tuff mean age: 4.10 ± 0.07 Ma. Concentrates in size range 200–700 μm.

*†See footnote to Table 1 for explanation.

formly as to yield nearly concordant ages. Although the possibility of very minor contamination by old detrital feldspar cannot be ruled out, the present results are thus interpreted as indicating that the pumices within the Moiti Tuff may have formed ~4.10 ± 0.07 Ma ago in the early Pliocene. Additional samples should be measured to help clarify the situation.

Toroto Tuff

The Toroto Tuff was defined and named by Cerling and Brown (1982). It crops out in areas 207 and 204 in the southern part of the Koobi Fora region (Fig. 2). In both areas, which are ~5 km apart, the Toroto Tuff is ~2 m thick and is the middle tuff of a group of three occurring within ~15 m of section, ~100 m above the base of the sequence (Fig. 3). Anorthoclase was separated from pumice clasts found locally within the Toroto Tuff. For three of the pumices, two feldspar separates were prepared; that labeled "A" was from feldspar crystals >1 mm in size, and that labeled "B" was from crystals between 0.5 and 1 mm.

Three pumice clasts from the Toroto Tuff at its type locality in area 207 yielded four anorthoclase concentrates that were measured by the conventional K-Ar method. The ages obtained are concordant, with a mean of 3.32 ± 0.02 Ma (Table 2). From the correlative of the Toroto Tuff in area 204, six anorthoclase concentrates were obtained. Of the 6 feldspars, 5 yield concordant K-Ar ages with a mean value of 3.33 ± 0.02 Ma, indistinguishable from that obtained at the type locality. The K contents of the feldspars from the two areas also are similar. Anorthoclase 81-103 gave a significantly older apparent age of 3.60 ± 0.08 Ma, which is interpreted as being anomalously old, presumably because of the presence of minor detrital feldspar in the concentrate. Excluding this last result, the over-all mean K-Ar age on feldspars separated from 6 separate pumice clasts from the Toroto Tuff in the two areas is 3.32 ± 0.02 Ma.

Age spectra were measured on two of the feldspars; results are given in Table A and shown in Figures 4 and 5. Both spectra exhibit nearly ideal flat patterns, with ages measured on individual gas fractions virtually all agreeing with one another to within the errors (Fig. 4). The excellent plateaus and lack of structure in the age spectra are interpreted as indicating that the anorthoclases have not been thermally disturbed since their crystallization and cooling. The plateau ages, incremental total fusion ages, and the ages derived by regression of data in the $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ correlation diagrams (Fig. 5) are indistinguishable from one another and from the directly measured $^{40}Ar/^{39}Ar$ total fusion ages and the conventional K-Ar ages (Table 3). Note that the regressions fit to within experimental error, and that the composition of the nonradiogenic Ar component in the samples, as derived from the regressions, is not significantly different from that of atmospheric Ar. The concordance of all of these results is accepted as very strong evidence that the cooling of the feldspars occurred 3.32 ± 0.02 Ma ago in the early part of the late Pliocene. This age is interpreted as recording the time when explosive volcanism produced the material that soon thereafter was deposited in the Koobi Fora region as the Toroto Tuff.

A number of K-Ar and $^{40}Ar/^{39}Ar$ age measurements reported by Fitch and Miller (1976) on glass shards from tuff, or feldspar from pumices in tuff, at or above the stratigraphic level of the Toroto Tuff, yielded a spread of results. Fitch and Miller gave preferred values of 3.9 and 4.5 Ma for two tuffs subsequently named the "Hasuma and Allia Tuffs" by Findlater (1978b). In the light of new data presented here, these earlier results are anomalously old.

Ninikaa Tuff

The Ninikaa Tuff was defined and named by Brown and Cerling (1982) as the uppermost of three tuffs found in a section ~10 m thick

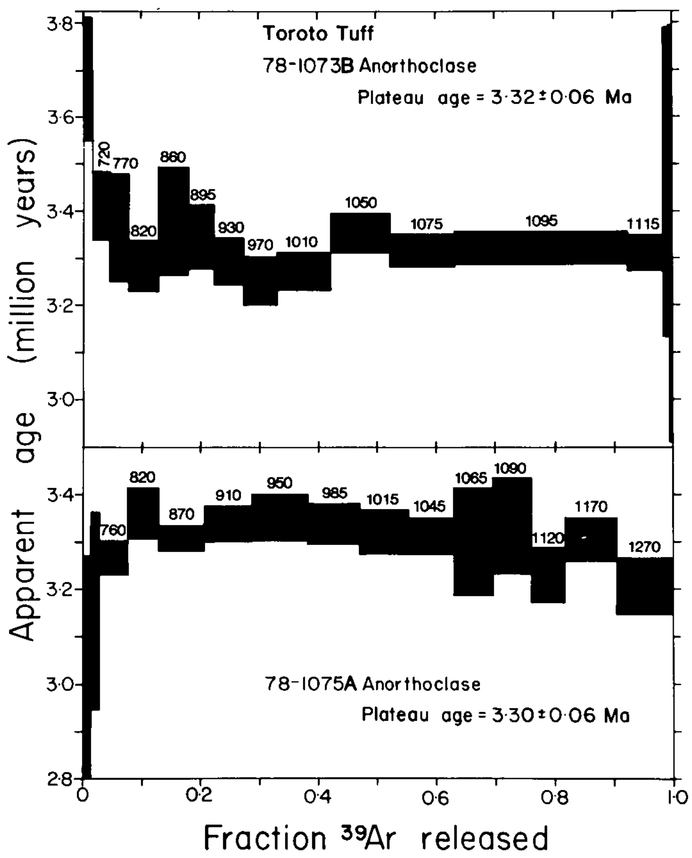

Figure 4. Age spectra for anorthoclase from pumice clasts in the Toroto Tuff. Data plotted against fraction ^{39}Ar released. Uncertainty of the age for each step at the level of one standard deviation indicated by thickness of bar. Temperature at which gas released shown for each step.

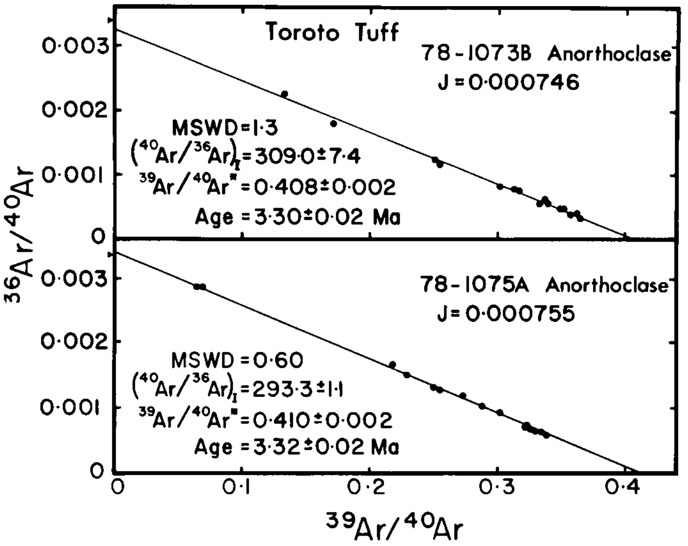

Figure 5. Correlation diagram showing Ar isotopic composition for each gas fraction of each step heating experiment on anorthoclase from pumice clasts in the Toroto Tuff. A best-fit straight line for each experiment is shown. Intercept on ordinate indicates composition of trapped Ar, and intercept on abscissa gives composition of the K-derived Ar, the inverse of which is proportional to age. Small triangle on ordinate represents isotopic composition of atmospheric Ar.

within area 116 in the central part of the Koobi Fora region. This tuff previously had been regarded as a correlative of the Tulu Bor Tuff, which has its type locality in area 129, ~25 km to the north-northeast. The two tuffs, however, are chemically different from one another (Brown and Cerling, 1982). In Figure 3, the Ninikaa Tuff is shown to lie above the Allia Tuff because of the isotopic ages obtained (see below), and because a sample from a tuff mapped as the Hasuma Tuff, ~25 m above the Tulu Bor Tuff in area 204 and therefore above the Toroto and Allia Tuffs, is

TABLE 3. SUMMARY OF ^{40}Ar/^{39}Ar AGES DERIVED FROM MEASUREMENTS ON ANORTHOCLASE FROM PUMICE CLASTS IN TUFFS, KOOBI FORA REGION, NORTHERN KENYA

Lab. no.	K-Ar age (Ma) ± 1 s.d.	^{40}Ar/^{39}Ar total fusion (Ma) ± 1 s.d.	Incremental total fusion (Ma) ±1 s.d.	Data used in regression	Plateau age (Ma) ± 1 s.d.	^{36}Ar/^{40}Ar versus ^{39}Ar/^{40}Ar regression		
						Age (Ma) ± 1 s.d.	(^{40}Ar/^{36}Ar)$_I$ ± 1 s.d.	MSWD
Silbo Tuff, northwest of Shin								
81-152	0.74 ± 0.01	0.73 ± 0.02	0.72 ± 0.02	All data	0.72 ± 0.02	0.71 ± 0.01	298.9 ± 4.9	0.65
Chari Tuff, areas 131 and 1								
79-8	1.45 ± 0.05	1.39 ± 0.06	1.40 ± 0.06	All data	1.40 ± 0.06	1.36 ± 0.02	305.3 ± 4.0	3.94
				Exclude 1130° step	1.39 ± 0.06	1.37 ± 0.01	300.5 ± 2.6	1.54
81-144	1.38 ± 0.03	-	1.37 ± 0.03	All data	1.37 ± 0.03	1.39 ± 0.03	295.0 ± 5.9	9.56
				Exclude 1155° step	1.36 ± 0.03	1.35 ± 0.01	296.6 ± 2.0	0.86
78-1060	1.38 ± 0.02	1.41 ± 0.01	1.38 ± 0.03	All data	1.38 ± 0.03	1.36 ± 0.02	296.6 ± 5.8	12.25
				Exclude 790°, 960°, 1100°, 1220° steps	1.37 ± 0.03	1.36 ± 0.01	295.1 ± 2.0	1.35
78-1064	1.40 ± 0.01	1.39 ± 0.01	1.40 ± 0.04	All data	1.40 ± 0.04	1.39 ± 0.02	299.8 ± 3.0	9.45
				Exclude 620°, 850°, 920°, 1140° steps	1.38 ± 0.05	1.38 ± 0.01	295.6 ± 1.7	2.37
Malbe Tuff, areas 112 and 105								
79-17	1.87 ± 0.02	1.85 ± 0.02	1.84 ± 0.03	All data	1.84 ± 0.03	1.86 ± 0.02	291.7 ± 5.9	3.06
81-196	1.83 ± 0.02	1.85 ± 0.01	1.84 ± 0.02	All data	1.84 ± 0.02	1.86 ± 0.03	290.7 ± 2.1	1.69
				Exclude first step	1.85 ± 0.02	1.86 ± 0.01	292.3 ± 1.8	1.07
Ninikaa Tuff, area 116								
81-123	3.05 ± 0.05	3.00 ± 0.02	3.02 ± 0.03	All data	3.02 ± 0.03	3.01 ± 0.02	296.4 ± 4.2	2.60
				Exclude last 3 steps	3.01 ± 0.03	3.01 ± 0.01	295.2 ± 2.7	1.07
Toroto Tuff, area 204								
78-1073B	3.36 ± 0.04	3.32 ± 0.04	3.33 ± 0.06	All data	3.33 ± 0.06	3.30 ± 0.02	309.0 ± 7.4	1.26
				Exclude 660° step	3.32 ± 0.05	3.31 ± 0.02	298.7 ± 8.4	1.07
78-1075A	3.34 ± 0.04	3.35 ± 0.04	3.30 ± 0.06	All data	3.30 ± 0.06	3.32 ± 0.02	293.3 ± 1.1	0.60

geochemically similar to the type Ninikaa Tuff (Brown and Cerling, 1982).

The Ninikaa Tuff is ~1.5 m thick in its type locality, where it contains small (5–10 cm) pumice clasts locally, and some of these are rich in anorthoclase phenocrysts. Rarely, pumices as much as 25 cm in diameter are found, often rather friable and partly calcified. Anorthoclase was separated from nine pumice clasts from this tuff in area 116; results of conventional K-Ar age measurements are given in Table 4. Note that the measured K contents of the feldspars show an unusually large spread from 4.2% to 5.0%.

The measured conventional K-Ar ages range from 3.05 ± 0.03 Ma to 3.18 ± 0.05 Ma, a spread of ~4%, considerably greater than can be accounted for by experimental error alone. This may be because the pumices are of more than one age or because of contamination by small but variable amounts of old detrital feldspar. Whatever the reason for the spread in the apparent ages, the tuff must have an age equal to or less than that of the youngest anorthoclase found in pumice within the tuff. Of the 9 feldspar samples, 4 have concordant ages with a mean of 3.06 ± 0.01 Ma, which is accepted as a maximum age for the Ninikaa Tuff and may well closely approximate the age of deposition of the tuff. Interestingly, these four samples with concordant ages exhibit the full range of K contents, perhaps indicating that the explosive event involved a magma body or system that was compositionally zoned. The mean K-Ar age calculated from all 9 feldspars is 3.11 ± 0.05 Ma.

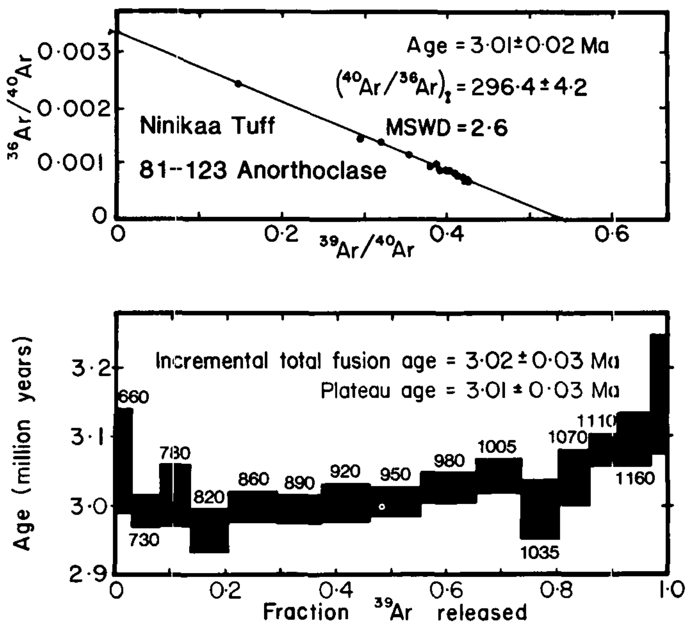

Figure 6. Age spectrum and correlation diagram for anorthoclase from a pumice clast in the Ninikaa Tuff.

One anorthoclase concentrate (81-123) was measured by the $^{40}Ar/^{39}Ar$ dating technique. The directly determined $^{40}Ar/^{39}Ar$ total fusion age was 3.00 ± 0.02 Ma, compared with a value of 3.02 ± 0.03 Ma derived by combining results from all of the gas fractions of the step heating experiment (Table A). The age spectrum (Fig. 6) shows a well-developed plateau over >80% of the gas release, with slightly greater apparent ages for the last 3 steps, making up ~14% of the Ar. The plateau age, calculated by excluding the last 3 steps, is 3.01 ± 0.03 Ma, indistinguishable from the age derived using results from all steps (3.02 ± 0.03 Ma). Similar ages were obtained from regression of data plotted on a $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ correlation diagram, whether or not results from the last 3 gas fractions are included (Fig. 6 and Table 3). The composition of the nonradiogenic Ar component, derived from the regressions, is not significantly different from that of atmospheric Ar. The $^{40}Ar/^{39}Ar$ step heating experiment indicates that sample 81-123 has not been thermally disturbed since its crystallization and cooling ~3.02 ± 0.03 Ma ago, an age that agrees to within the errors with the conventional K-Ar age of 3.05 ± 0.05 Ma for this anorthoclase feldspar.

Overall, the $^{40}Ar/^{39}Ar$ data on one sample and the conventional K-Ar results on a number of feldspars are interpreted as indicating that the

TABLE 4. POTASSIUM-ARGON ANALYTICAL DATA ON ANORTHOCLASE PHENOCRYSTS SEPARATED FROM PUMICE CLASTS FOUND WITHIN THE NINIKAA TUFF, AREA 116, KOOBI FORA, EAST OF LAKE TURKANA, NORTHERN KENYA

Lab. no.	K (wt %)	Wt used in Ar extraction (g)	Radiogenic ^{40}Ar (10^{-11} mol g^{-1})	$\frac{100 \text{ rad. } ^{40}Ar}{\text{Total } ^{40}Ar}$	Calculated age (Ma) ± 1 s.d.	Average age (Ma) ± 1 s.d.
78-1033	4.965, 4.955	1.299	2.676	92.0	3.11 ± 0.03	3.11 ± 0.03
79-21	4.398, 4.447	0.803 1.203	2.442 2.419	68.6 69.6	3.18 ± 0.04 3.15 ± 0.04	3.17 ± 0.04
79-278	4.510, 4.498	1.980 2.051	2.432 2.454	84.6 78.6	3.11 ± 0.03 3.14 ± 0.03	3.12 ± 0.03
81-122	5.024, 5.013	1.503 1.501	2.741 2.732	92.4 93.0	3.15 ± 0.03 3.14 ± 0.03	3.14 ± 0.03
81-123	4.545, 4.595	1.502 1.503 1.499 1.527	2.468 2.362 2.419 2.424	76.8 77.1 77.3 76.7	3.11 ± 0.04 2.98 ± 0.04 3.05 ± 0.04 3.06 ± 0.04	3.05 ± 0.05
81-125	5.031, 5.015	1.000 1.002	2.659 2.678	91.6 91.7	3.05 ± 0.03 3.07 ± 0.03	3.06 ± 0.03
81-127	4.156, 4.188	1.506 1.506	2.217 2.221	73.4 73.4	3.06 ± 0.04 3.07 ± 0.04	3.06 ± 0.04
81-128	4.804, 4.788	1.516 1.508	2.664 2.617	87.7 87.5	3.21 ± 0.03 3.14 ± 0.03	3.18 ± 0.05
81-129	4.501, 4.528	1.610 1.507	2.374 2.408	73.7 75.4	3.03 ± 0.03 3.07 ± 0.03	3.05 ± 0.03

$\lambda_e + \lambda'_e = 0.581 \times 10^{-10} a^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10} a^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol mol^{-1}.
Mean age = 3.11 ± 0.05 Ma. Mean age (excluding 79-21, 81-128) = 3.08 ± 0.04 Ma.
Size fraction of mineral separates was mainly 150–350 μm.
Locality: HBH713460, photo 1589/057-108, see footnote to Table 1 for explanation.

age of the Ninikaa Tuff is equal to or slightly younger than 3.06 Ma, assuming that deposition of the tuff occurred very soon after eruption. An estimate of age of 3.06 ± 0.03 Ma is given, based upon the mean of the 4 youngest K-Ar ages but with an increased error to allow for the fact that uncertainties in calibration of ^{38}Ar tracer and K standards are in this order.

The only previously published information on the numerical age of the Ninikaa Tuff was given by Fitch and Miller (1976) and Fitch and others (1978). They reported measurements on two feldspar concentrates from pumice clasts (FMA 255, FMA 301) found within a tuff in area 116, then regarded as a correlative of the Tulu Bor Tuff. A directly measured ^{40}Ar/^{39}Ar total fusion age of FMA 255 was given as 3.37 ± 0.07 Ma (3.46 ± 0.07 Ma). The ^{40}Ar/^{39}Ar age spectrum obtained for this sample is essentially flat when the quoted error for each step is taken into account, but Fitch and Miller (1976) interpreted the results as indicating the presence of at least three "age components"; two primary age components of ~4 Ma and ~3.1 Ma were thought to be identifiable from the age spectrum. They suggested that the best estimate of age for the younger juvenile component and for the tuff was 3.18 ± 0.09 Ma (3.26 ± 0.09 Ma), the apparent age for one of the gas fractions in the step heating experiment. For the other sample of feldspar (FMA 301), Fitch and others (1978) reported no primary data but showed a ^{40}Ar/^{39}Ar versus ^{39}Ar/^{36}Ar correlation diagram on which 8 data points from a step heating experiment are well aligned. An age of 3.19 ± 0.08 Ma (3.28 ± 0.08 Ma) was derived by regression analysis and described as a good date from an ideal dating sample. This age is ~7% greater than the ^{40}Ar/^{39}Ar age found for feldspar from a pumice in this same tuff in the present study.

KBS Tuff

The age of the KBS Tuff has been the subject of much debate and controversy over the past decade owing to the disconcertingly large range of numerical values reported (Fitch and Miller, 1970, 1976; Fitch and others, 1974, 1976; Curtis and others, 1975; Hurford and others, 1976; Drake and others, 1980). As the KBS Tuff contains stone tools locally at its base, and because many of the hominid fossils at Koobi Fora have been found within a few tens of metres of this bed, resolution of these problems became a major concern. Conventional K-Ar ages and ^{40}Ar/^{39}Ar age spectra from this laboratory thus were published earlier (McDougall and others, 1980; McDougall, 1981). Data from the type locality of the KBS Tuff in area 105, and from a correlative in area 131, yielded a mean K-Ar age of 1.89 ± 0.02 Ma on 7 feldspar separates from pumices. The ^{40}Ar/^{39}Ar age spectra on 3 of these feldspars showed excellent plateaus with no evidence of disturbance and a mean age of 1.88 ± 0.02 Ma. These results served to confirm some previous K-Ar data of Drake and others (1980) but are more precise. In addition, Gleadow (1980) gave a mean fission track age of 1.87 ± 0.04 Ma for zircons separated from KBS Tuff pumices. New measurements on feldspars separated from pumice clasts within tuff correlated with the KBS Tuff in areas 129 and 15 in the northern part of the basin (Fig. 2) are reported here.

Pumice clasts as much as ~15 cm in diameter were found weathering out of tuff in area 129, ~1 km north of site FxJj33 and ~1.7 km north of where the road on Karari Ridge turns west toward Ileret. On the geologic maps of Vondra and Bowen (1976, 1978) and Findlater (1978b), it appears that the tuff is stratigraphically approximately at the level of the KBS Tuff. Anorthoclase separates from 3 pumice clasts yielded K-Ar ages in the range 1.85 to 1.91 Ma (Table 5), with a mean age of 1.87 ± 0.03 Ma. The measured ages and the K content of the anorthoclases are indistinguishable from those obtained previously on the KBS Tuff (McDougall and others, 1980). Glass separated from two of the pumices used for the age measurements is very similar in composition to that found for glass from the KBS Tuff in its type locality (F. H. Brown, 1982, written commun.).

Feldspars were separated from three partly calcified pumice clasts collected from a tuff in area 15. This exposure is shown on the geologic map of Findlater (1978b) as lying within a small faulted block at about the KBS Tuff stratigraphic level. The feldspars gave concordant K-Ar ages with a mean of 1.87 ± 0.01 Ma (Table 5), entirely consistent with the previously measured age of the KBS Tuff. Geochemical studies on glass from the tuff at this locality confirmed that it has a composition essentially identical to that of the KBS Tuff (Brown and Cerling, 1982).

These 6 new results from areas 129 and 15 yield a mean age of 1.87 ± 0.02 Ma. Combining the K-Ar data measured in this laboratory on all 13 feldspars from the KBS Tuff and its correlatives in areas 105, 131, 129, and 15, a mean age of 1.88 ± 0.02 Ma is obtained. This is regarded as the best current estimate for the age of the KBS Tuff. The evidence is strong that the previous estimates for the age of the KBS Tuff of ~2.6 Ma (Fitch

TABLE 5. POTASSIUM-ARGON AGE DATA ON ANORTHOCLASE SEPARATED FROM PUMICE CLASTS WITHIN CORRELATIVES OF THE KBS TUFF IN AREAS 129 AND 15, KOOBI FORA REGION, NORTHERN KENYA

Lab. no.	K (wt %)	Radiogenic ^{40}Ar (10^{-11} mol g^{-1})	$\frac{100\text{ rad. }^{40}\text{Ar}}{\text{Total }^{40}\text{Ar}}$	Calculated age (Ma) ± 1 s.d.	Average age (Ma) ± 1 s.d.
Area 129, ~HBH827653, photo 1753/195-136*†					
81-230	5.130, 5.183	1.673 1.676	79.0 80.2	1.870 ± 0.024 1.873 ± 0.024	1.87 ± 0.02
81-231	5.217, 5.218	1.671 1.678	81.2 81.1	1.846 ± 0.020 1.853 ± 0.020	1.85 ± 0.02
81-232	5.206, 5.205	1.721 1.709	71.0 70.0	1.906 ± 0.023 1.892 ± 0.020	1.90 ± 0.02
Area 15, ~HBH708717, photo 1522/047-060					
81-234	5.160, 5.180	1.707 1.675	80.4 79.8	1.903 ± 0.020 1.867 ± 0.020	1.89 ± 0.02
81-235	5.181, 5.147	1.674	83.0	1.868 ± 0.021	1.87 ± 0.02
81-238	5.210, 5.197	1.677	83.6	1.857 ± 0.020	1.86 ± 0.02

$\lambda_e + \lambda'_e = 0.581 \times 10^{-10} a^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10} a^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol mol^{-1}.
Feldspar concentrates have grain size 150 to 350 μm. Mean age: area 129 = 1.87 ± 0.03 Ma; area 15 = 1.87 ± 0.01 Ma.
For area 129 samples, 1.80g of feldspar used in Ar extractions.
For area 15 samples, 1.50g of feldspar used in Ar extractions.
*†See footnote to Table 1 for explanation.

and Miller, 1970; Fitch and others, 1974), subsequently revised to ~2.4 Ma (Fitch and Miller, 1976; Fitch and others, 1976; Hurford and others, 1976), are incorrect.

Malbe Tuff

Cerling and others (1979) recognized that a tuff cropping out in area 105-East, now designated as area 112, is compositionally distinct from the KBS Tuff, with which it had been correlated by Findlater (1978b). This is the Malbe Tuff, which lies ~15 m above the KBS Tuff in the eastern part of area 105 (Cerling and Brown, 1982). The type locality is in area 112 beside the Kolom Malbe, and here this tuff contains abundant pumice clasts. McDougall and others (1980) and Drake and others (1980) presented K-Ar data on feldspar from pumices from the type locality of the Malbe Tuff without distinguishing it from the KBS Tuff.

For the present study, additional samples were dated from the Malbe Tuff at its type locality, and from a tuff in the eastern part of area 105 at the so-called "Lucas site," correlated with the Malbe Tuff (Cerling and Brown, 1982).

The new K-Ar results on 3 feldspars from pumices collected from the type locality are concordant with a mean of 1.86 ± 0.02 Ma (Table 6). Similarly, data from 3 feldspars from the eastern part of area 105 are concordant and provide an average of 1.85 ± 0.02 Ma (Table 6). The over-all mean of the 6 new K-Ar ages is 1.85 ± 0.02 Ma, not significantly different from the mean K-Ar age of 1.88 ± 0.01 Ma calculated from the previous K-Ar results of McDougall and others (1980) and based on measurements on 7 feldspars from pumices in the Malbe Tuff at its type locality in area 112.

Results of measurement of 2 of the feldspars by the $^{40}Ar/^{39}Ar$ age spectrum technique are listed in Table B and shown in Figures 7 and 8. One sample (79-17) is from a pumice at the type locality of the Malbe Tuff with a K-Ar age of 1.87 ± 0.01 Ma (McDougall and others, 1980), and the other (81-196) is from the locality in the eastern part of area 105. Both show essentially flat age spectra. Results from individual steps for sample 79-17 are somewhat scattered about the mean age, whereas sample 81-196 has a near-perfect flat age spectrum. The ages derived from analysis of these age spectra (Table 3) are all similar and in the range 1.84 to 1.86 Ma, emphasizing the homogeneity of the data. Note, however, that the $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ regression of data from sample 79-17 shows scatter beyond that expected from experimental error, as the MSWD is significantly greater than 2.5. The estimated age nevertheless is consistent with the other data, and the indicated composition of the nonradiogenic Ar is essentially that of atmospheric Ar. Regression of data from sample 81-196 yields a line that fits to within experimental error and gives an age of 1.86 ± 0.01 Ma. The estimated $^{40}Ar/^{36}Ar$ value for the nonradiogenic Ar component is just statistically different from the atmospheric Ar value of 295.5. Possibly this is fortuitous, as it can be seen from Figure 8 that the data points are mainly rather remote from the $^{36}Ar/^{40}Ar$ axis, attesting to the high proportion of radiogenic Ar in each gas fraction released from the sample.

The $^{40}Ar/^{39}Ar$ data provide strong evidence that the K-Ar system of the feldspars has not been disturbed significantly since their crystallization and cooling. The $^{40}Ar/^{39}Ar$ and conventional K-Ar age data are in satisfactory agreement with one another. The best estimate for the age of the Malbe Tuff pumices is taken to be the average of the conventional K-Ar ages measured in this laboratory, 1.86 ± 0.02 Ma, based upon results on feldspars from 13 separate pumices. This age remains indistinguishable from that obtained from feldspars in pumices in the underlying KBS Tuff.

The mean K content of the 13 feldspars analyzed from Malbe Tuff pumices is 5.11 (± 0.06)%, indistinguishable from the average of 5.16 (± 0.03)% for 13 feldspars measured from pumices in the KBS Tuff. This similarity is perhaps unexpected, as it has been shown (Cerling and others, 1979; Cerling and Brown, 1982) that the glasses in the two tuffs are chemically distinctly different from one another.

Okote Tuff Complex

Between the KBS and Chari Tuffs there occur numerous tuffaceous beds (Fig. 3). These beds have been given different names in different areas in the Koobi Fora region and include the following formal or informal

TABLE 6. POTASSIUM-ARGON AGE DATA ON ANORTHOCLASE SEPARATED FROM PUMICE CLASTS FROM THE TYPE LOCALITY OF THE MALBE TUFF AND FROM A CORRELATIVE OF THE MALBE TUFF IN AREA 105, KOOBI FORA REGION, NORTHERN KENYA

Lab. no.	K (wt %)	Radiogenic ^{40}Ar (10^{-11} mol g^{-1})	$\frac{100 \text{ Rad. } ^{40}Ar}{\text{Total } ^{40}Ar}$	Calculated age (Ma) ± 1 s.d.	Average age (Ma) ± 1 s.d.
Area 112, HBH792482, photo 1656/040-102†*					
81-162	5.168, 5.162	1.672 1.654	75.7 75.7	1.866 ± 0.020 1.845 ± 0.021	1.86 ± 0.02
81-163	5.062, 5.082	1.662 1.660	78.1 76.5	1.888 ± 0.020 1.886 ± 0.020	1.89 ± 0.02
81-164	5.180, 5.181	1.658 1.656	77.1 76.8	1.844 ± 0.019 1.842 ± 0.020	1.84 ± 0.02
Area 105, HBH759482, photo 1656/184-103					
81-196	5.124, 5.109	1.624 1.631	84.8 80.9	1.829 ± 0.019 1.837 ± 0.020	1.83 ± 0.02
81-197	5.186, 5.171	1.670 1.677	78.5 76.9	1.859 ± 0.020 1.866 ± 0.020	1.86 ± 0.01
81-198	5.130, 5.079	1.629 1.620 1.656	84.9 74.5 84.7	1.839 ± 0.019 1.829 ± 0.020 1.869 ± 0.024	1.85 ± 0.02

$\lambda_e + \lambda'_e = 0.581 \times 10^{-10} a^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10} a^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol mol^{-1}.

Concentrates have crushed grain size of 150 to 350 μm, except 81-162 and 81-163, which have grain size 170 to 350 μm.

For Ar extractions, 1.50g used.

Mean age, area 112 = 1.86 ± 0.02 Ma; mean age: area 105 = 1.85 ± 0.02 Ma.

Mean age, all samples = 1.85 ± 0.02 Ma.

*†See footnote to Table 1 for explanation.

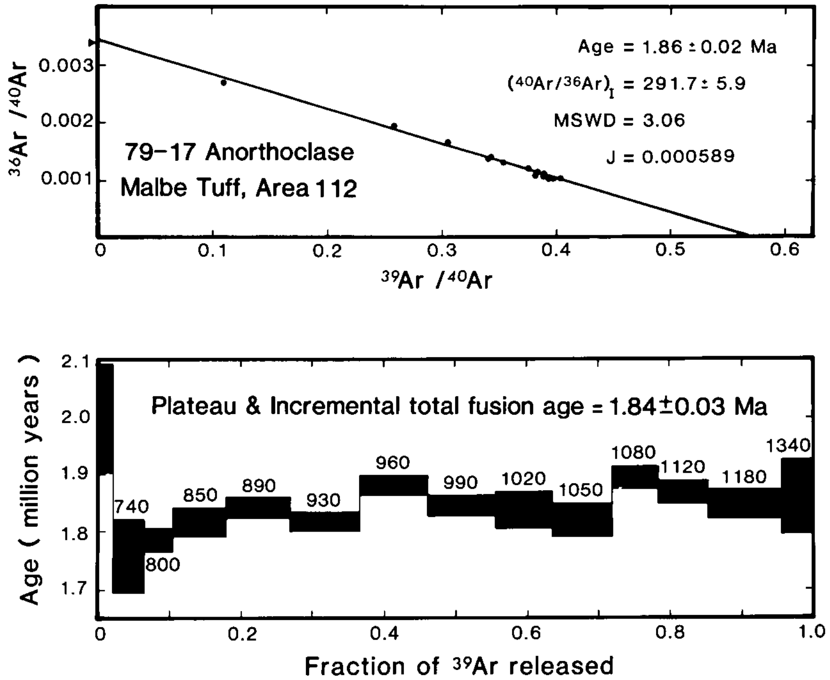

Figure 7. Age spectrum and correlation diagram for anorthoclase from pumice clast 79-17, Malbe Tuff.

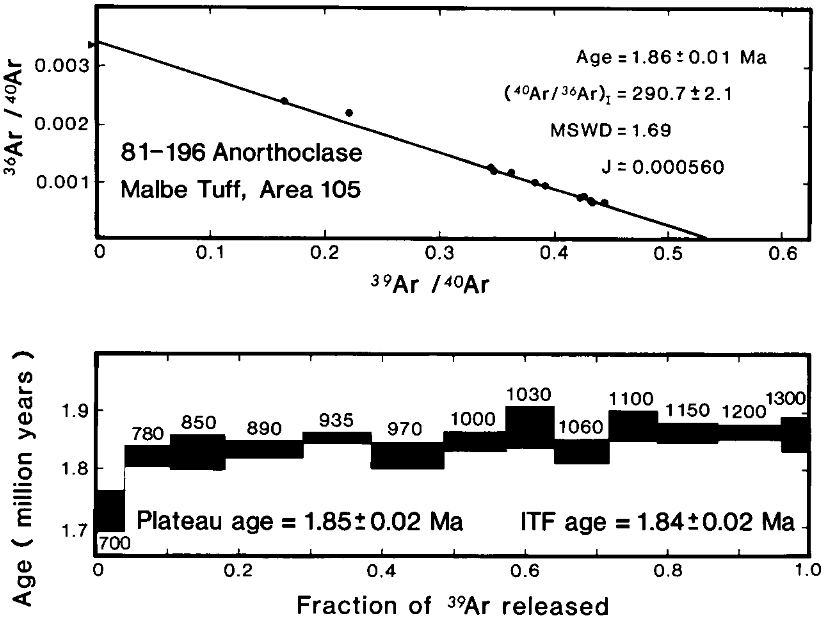

Figure 8. Age spectrum and correlation diagram for anorthoclase from pumice clast 81-196, Malbe Tuff.

names: "Okote," "BBS," "Ileret," "Lower/Middle," and "Koobi Fora Tuff Complexes."

For the present study, a number of pumice clasts were collected from the type area of the Okote Tuff Complex (HBH ~793592), ~100 m north of the archeological site FxJj20 (Cerling and Brown, 1982; Findlater, 1978b). These pumices, which appeared to be weathering out of the tuff, were somewhat calcified. Although they contained little feldspar, sufficient anorthoclase was obtained from two samples to enable conventional K-Ar age measurements to be made. The K contents were concordant at 4.75%, but the 2 feldspars yielded quite different apparent ages, with one giving 1.65 ± 0.07 Ma (sample 81-133) and the other giving 1.94 ± 0.02 Ma (81-134). Owing to the lack of consistency, the analytical data are not tabulated here. Perhaps the older apparent age can be accounted for by the presence of unrecognized contamination by a small proportion of detrital feldspar in the separate. The younger apparent age might be regarded as a maximum age for the Okote Tuff Complex, because complete absence of detrital contamination cannot be ruled out. With no confirmatory data, however, this result must be treated cautiously, even though it fits well between the limiting values provided by the age of 1.39 Ma for the Chari Tuff at a higher stratigraphic level and the 1.88-Ma age for the underlying KBS Tuff.

Fitch and Miller (1976) reported a large number of ages on feldspars separated from pumices in these tuffs. The Koobi Fora Tuff in areas 102 and 103 yielded ^{40}Ar/^{39}Ar total fusion ages on 10 feldspars ranging from 0.53 to 4.4 Ma, and age spectra on 2 of the feldspars were stated to be disturbed. A preferred age of 1.57 ± 0.00 Ma (1.61 Ma) was quoted for this tuff, despite "severe overprinting." Similarly, they recorded $^{40}Ar/^{39}Ar$ total fusion ages on 6 feldspars from pumices in the BBS Tuff Complex in the range 0.87 to 1.66 Ma. An $^{40}Ar/^{39}Ar$ age spectrum on one of these feldspars was thought to indicate the presence of 2 age components at 1.56 ± 0.02 Ma (1.60 Ma) and 1.70 ± 0.04 Ma (1.75 Ma). A single $^{40}Ar/^{39}Ar$ total fusion age on feldspar from pumice in the Lower/Middle Tuff at Ileret was listed as 1.48 ± 0.17 Ma (1.51 Ma). For the majority of these age measurements, the proportion of radiogenic Ar in the gas extracted from the samples was <20%. Fitch and Miller (1976) gave preferred ages in the range 1.5 to 1.7 Ma for these beds. Such ages fit within the geochronological control provided in this paper, but it is considered that these ages must be disregarded because of lack of authentication and lack of justification for choosing a particular age out of a very large range of results. The numerical ages of tuff beds that lie between the KBS and Chari Tuffs thus must be left open at the present time.

Chari Tuff

The Chari Tuff of Bowen and Vondra (1973) and the Karari Tuff of Findlater (1976) were shown by Cerling and others (1979) to be the same tuff on the basis of geochemical data, confirming a view expressed previously by various workers. The recommendation by Cerling and others (1979) that Chari Tuff is the appropriate name to use for this bed is followed here. The Chari Tuff was designated by Bowen and Vondra (1973) as marking the top of the Koobi Fora Formation. It is especially well exposed in erosional escarpments in the Ileret area and along the Karari Ridge in the northern part of the Koobi Fora region. The tuff commonly is 1 to 2 m thick and locally contains an abundance of well-rounded pumice clasts ranging as large as 30 cm in diameter. Pumices were collected for dating purposes from the Chari Tuff in area 1, Ileret, and area 131, Karari Ridge (Fig. 2).

Results of conventional K-Ar dating of anorthoclase from 12 separate pumice clasts are listed in Table 7. The feldspar concentrates have a characteristic K content of 4.2 (± 0.1)%. The average measured ages range from 1.37 to 1.49 Ma, with only 2 outside the range 1.37 to 1.41 Ma. The over-all mean age is 1.40 ± 0.04 Ma. Sample 79-8 gives a rather poorly reproducible age (1.45 ± 0.05 Ma), possibly reflecting minor and variable contamination by detrital feldspar. Sample 78-1061 yields an age of 1.49 ± 0.02 Ma that is significantly older than the other 11 samples, probably because of detrital contamination. Excluding this last result, the mean age changes to 1.39 ± 0.02 Ma. Clearly, the measured ages from the two collecting sites at Ileret and Karari are indistinguishable, providing further confirmation that the tuff is the same bed in both areas. The concordance of these results, if the result from 78-1061 is excluded, gives great confidence that the age of 1.39 ± 0.02 Ma is recording the time of crystallization and cooling of the feldspar.

Of the anorthoclase separates, four were measured by the $^{40}Ar/^{39}Ar$ age spectrum technique; the results are listed in Table C and shown in

TABLE 7. POTASSIUM-ARGON ANALYTICAL DATA ON ANORTHOCLASE PHENOCRYSTS SEPARATED FROM PUMICE CLASTS FOUND WITHIN THE CHARI TUFF, KOOBI FORA, EAST OF LAKE TURKANA, NORTHERN KENYA

Lab. no.	K (wt %)	Radiogenic ^{40}Ar (10^{-11} mol g^{-1})	$\frac{100\ \text{Rad.}\ ^{40}Ar}{\text{Total}\ ^{40}Ar}$	Calculated age (Ma) ± 1 s.d.	Average age (Ma) ± 1 s.d.
Area 131, Karari Ridge, HBH797587, photo 1750/067-150†*					
78-1053	4.255, 4.245	1.024 1.019	66.5 75.1	1.388 ± 0.016 1.382 ± 0.016	1.38 ± 0.02
78-1056	4.213, 4.237	1.009 1.016	75.7 83.5	1.377 ± 0.016 1.386 ± 0.016	1.38 ± 0.02
81-144	4.181, 4.158	1.005 0.980 1.014	77.2 75.0 72.9	1.388 ± 0.015 1.354 ± 0.014 1.402 ± 0.018	1.38 ± 0.03
81-146	4.140, 4.137	0.974 0.992 0.982	83.2 82.5 82.3	1.356 ± 0.013 1.381 ± 0.015 1.368 ± 0.015	1.37 ± 0.01
81-147	4.163, 4.173	0.987 1.028 1.033	80.8 79.4 76.1	1.365 ± 0.013 1.421 ± 0.015 1.429 ± 0.016	1.41 ± 0.03
81-148	4.152, 4.149	0.987 1.015 0.996	81.5 79.7 81.8	1.370 ± 0.012 1.409 ± 0.015 1.383 ± 0.015	1.39 ± 0.02
79-8	4.311, 4.296	1.042 1.116 1.083	64.0 74.6 76.6	1.402 ± 0.018 1.502 ± 0.019 1.450 ± 0.015	1.45 ± 0.05
Area 1, Ileret, HBH638753, photo 1467/067-122					
78-1060	4.173, 4.208	0.999 1.009	75.8 66.5	1.374 ± 0.019 1.388 ± 0.019	1.38 ± 0.02
78-1061	4.081, 4.083	1.055 1.058	75.4 71.1	1.490 ± 0.015 1.494 ± 0.015	1.49 ± 0.02
78-1063	4.236, 4.229	1.034 1.044	79.6 72.2	1.408 ± 0.017 1.422 ± 0.015	1.41 ± 0.02
78-1064	4.213, 4.208	1.027 1.019	65.9 71.5	1.405 ± 0.014 1.395 ± 0.015	1.40 ± 0.01
78-1066	4.096, 4.051	0.982	72.8	1.389 ± 0.017	1.39 ± 0.02

$\lambda_e + \lambda'_e = 0.581 \times 10^{-10} a^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10} a^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol mol^{-1}.
Mean ages: Karari Ridge = 1.394 ± 0.027 Ma; Ileret (excluding 78-1061) = 1.396 ± 0.015 Ma.
All Chari Tuff ages = 1.403 ± 0.035 Ma; all Chari Tuff ages (excluding 78-1061) = 1.395 ± 0.023 Ma.
Mass used in Ar extractions normally 2.0g, but ranging from 1.5 to 2.5g.
Final crushed feldspar fraction in size range 150–350 μm.
*†See footnote to Table 1 for explanation.

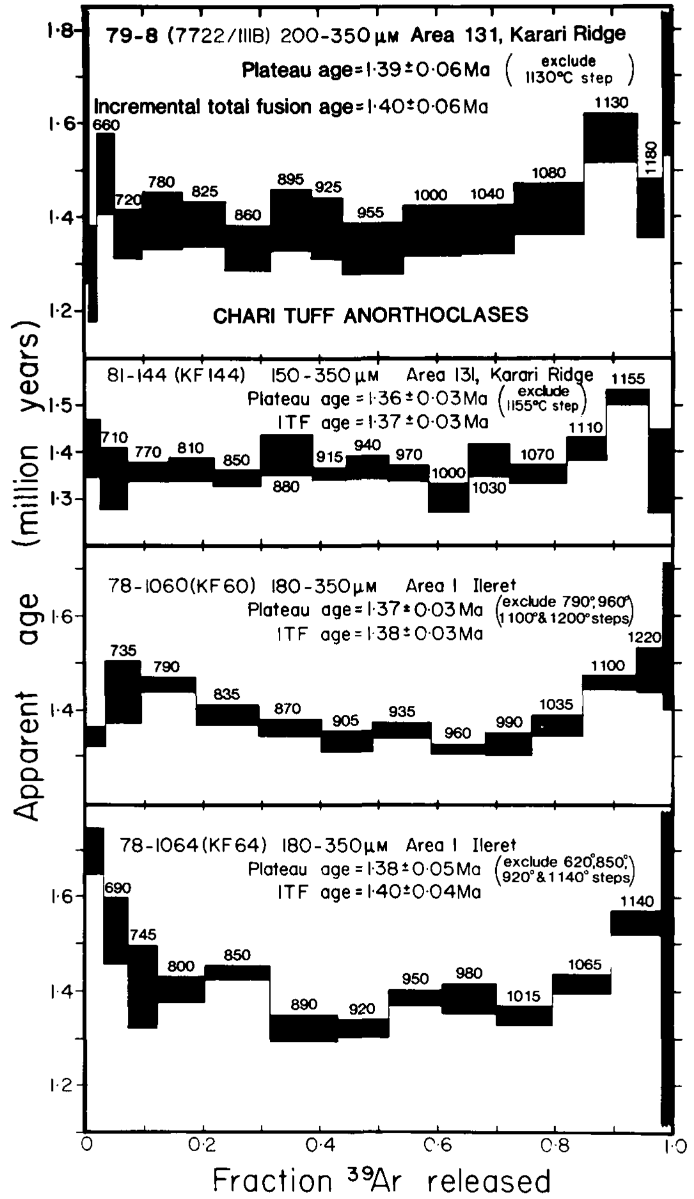

Figure 9. Age spectra for four samples of anorthoclase from pumice clasts in the Chari Tuff.

Figures 9 and 10. Two of the spectra (samples 79-8, 81-144) are essentially perfectly flat and provide good evidence that the feldspars have remained undisturbed since crystallization. The plateau and incremental total fusion ages, as well as the directly measured ^{40}Ar/^{39}Ar total fusion ages, all agree to within error with the K-Ar ages (Table 3).

The two feldspars from the Ileret area (78-1060, 78-1064) show some structure in their age spectra, with both exhibiting slightly high apparent ages at the beginning and end of the step heating experiments. Nevertheless, with >60% of the gas released yielding nearly concordant ages in both cases and giving calculated plateau ages similar to the other two age spectra, and with the incremental total fusion ages only slightly greater, it can be seen that the over-all discordance of the age spectra is small. The tendency toward saddle-shaped spectra, characteristic of excess radiogenic Ar in some feldspars, may indicate that a minor component of excess Ar is present.

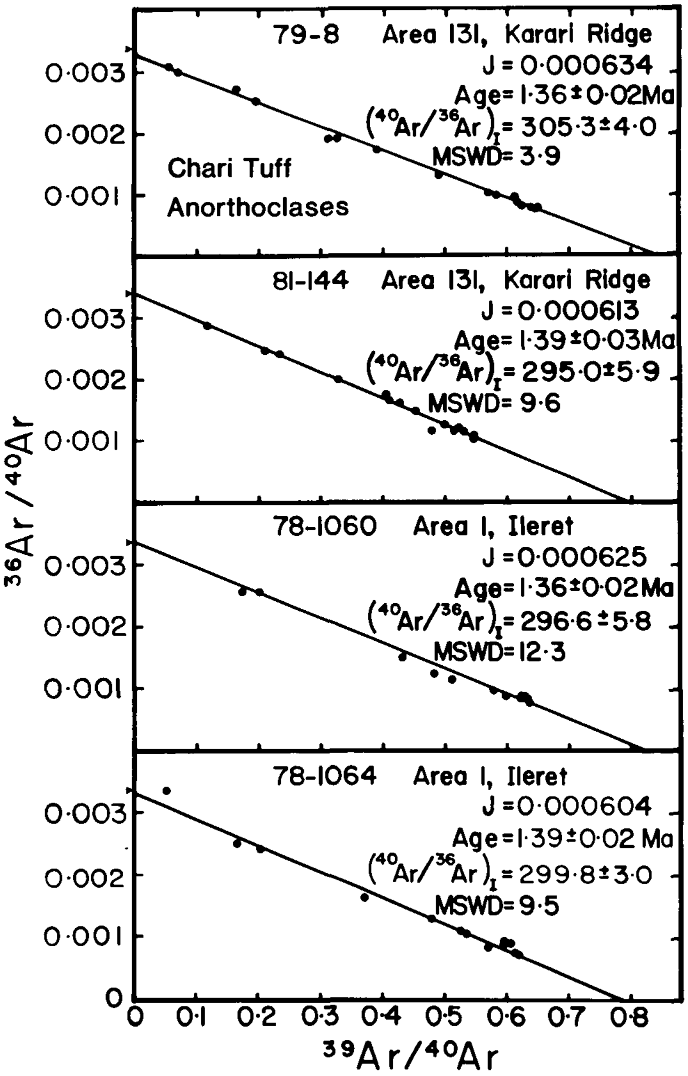

Figure 10. Correlation diagrams showing data from step heating experiments on samples of anorthoclase from pumice clasts in the Chari Tuff.

Correlation plots for the four ^{40}Ar/^{39}Ar step heating experiments are shown in Figure 10. For feldspars 79-8 and 81-144, the regression lines fit to within experimental error when one datum from each experiment is excluded (Table 3). The derived ages are in good agreement with the incremental total fusion ages and the conventional K-Ar ages. In the case of feldspars 78-1060 and 78-1064, there is considerable scatter, beyond that expected from experimental error, as shown by the high MSWD values (Table 3), reflecting the somewhat discordant nature of the age spectra. After excluding the most discordant ages found in the experiments, the regressions fit to within error, but the derived ages change little (Table 3). Although two of the feldspars show discordant age spectra, possibly indicating the presence of small amounts of excess Ar, the ^{40}Ar/^{39}Ar age data from all four feldspars amply confirm that crystallization and cooling occurred sometime in the interval 1.35 to 1.40 m.y. ago, in excellent agreement with the mean conventional K-Ar age of 1.39 ± 0.02 Ma. This latter age is accepted as the best estimate for closure of the K-Ar system in the feldspars and probably closely approximates the time of deposition of the Chari Tuff soon after the explosive volcanic episode that produced the tuffaceous material.

Fitch and Miller (1976) gave preferred ages for the Chari Tuff in the range 1.2 to 1.3 Ma, based upon $^{40}Ar/^{39}Ar$ age spectrum measurements, but as the analytical data have not been published, it is not possible to fully assess these estimates. Drake and others (1980) reported K-Ar ages on feldspars from 6 pumices in the Chari Tuff ranging from 1.29 to 1.52 Ma, with a mean of 1.41 ± 0.08 Ma. Our new data thus agree well with those of Drake and others (1980) but are more precise.

Silbo Tuff

The Silbo Tuff is one of the youngest tuffs in the Koobi Fora region. The type locality for the tuff is northwest of Shin near the eastern margin of the basin, some 30 km east of Koobi Fora spit (Cerling and Brown, 1982). Here, the tuff is as much as 2 m thick and locally contains abundant rounded pumice clasts, some of which attain a diameter of 60 cm. Pumices were collected for dating from the type area of the Silbo Tuff and also from a correlative on the western flanks of the Kokoi.

The Silbo Tuff lies within the Guomde Formation, a sequence of sands and silts as much as 40 m thick, the type locality of which is on the Chari Ridge in the Ileret area (Bowen and Vondra, 1973; Vondra and Bowen, 1978).

Results of conventional K-Ar dating on alkali feldspars separated from pumices of the Silbo Tuff are given in Table 8. Samples 81-151, 81-152, and 81-153 are from pumices at the type locality, and samples 81-158 and 81-160 are from pumices collected from the same tuff ~2 km east of the type locality. The 5 ages are concordant at 0.75 ± 0.01 Ma. Of the 3 K-Ar ages on samples from west of Kokoi, 2 agree at 0.73 ± 0.01 Ma, not significantly different from the age measured at the type locality, whereas the third sample (81-117) gives an older apparent age (0.79 ± 0.01 Ma), probably to be explained by the presence of some detrital contamination. The similarity of the measured K-Ar ages and also the characteristic high K content of the alkali feldspar (5.6 ± 0.1%) provide confirmation of the equivalence of the tuff at the 2 localities, which are ~40 km apart.

TABLE 8. POTASSIUM-ARGON ANALYTICAL DATA ON ANORTHOCLASE PHENOCRYSTS SEPARATED FROM PUMICE CLASTS FOUND WITHIN THE SILBO TUFF, KOOBI FORA REGION, EAST OF LAKE TURKANA, NORTHERN KENYA

Lab. no.	K (wt %)	Radiogenic ^{40}Ar (10^{-12} mol g^{-1})	$\frac{100 \text{ Rad. } ^{40}Ar}{\text{Total } ^{40}Ar}$	Calculated age (Ma) ± 1 s.d.
South of Kolom Silbo, northwest of Shin. 81-151, -152, -153: HBH819409, photo 1741/140-067†*				
81-151	5.605, 5.631	7.346	39.8	0.754 ± 0.009
81-152	5.750, 5.741	7.360	68.9	0.738 ± 0.009
81-153	5.624, 5.649	7.412	35.4	0.758 ± 0.010
81-158	5.580, 5.609	7.236	67.7	0.746 ± 0.008
81-160	5.670, 5.676	7.371	63.7	0.749 ± 0.009
Northwest flanks of the Kokoi, south of Ileret, HBH622596, photo 1404/084-099				
81-116	5.475, 5.440	6.936	65.3	0.733 ± 0.008
81-117	5.657, 5.626	7.861 7.631	74.2 64.3	0.803 ± 0.010 0.780 ± 0.010
81-118	5.771, 5.776	7.290	74.7	0.728 ± 0.008

$\lambda_e + \lambda'_e = 0.581 \times 10^{-10} a^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10} a^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol mol^{-1}.
Size fraction for all crystal concentrates is 150–350 μm.
Samples 81-151 and 81-153 not washed in HF. For each Ar extraction, 2.0g of sample used.
Mean ages: northwest of Shin = 0.75 ± 0.01 Ma;
northwest flanks of Kokoi (excluding 81-117) = 0.73 ± 0.01 Ma.
Over-all mean age (excluding 81-117) = 0.74 ± 0.01 Ma.
*†See footnote to Table 1 for explanation.

One feldspar (81-152) was measured by the $^{40}Ar/^{39}Ar$ age spectrum technique; results are listed in Table B and illustrated in Figure 11. The Ar was released from the sample in 15 steps; the ages measured yielded a nearly ideal flat spectrum with a plateau and incremental total fusion age of 0.72 ± 0.02 Ma, in reasonable agreement with its K-Ar age of 0.74 ± 0.01 Ma. Regression of the results on the correlation plot gives a slightly younger age of 0.71 ± 0.01 Ma; the indicated composition of the nonradiogenic Ar is indistinguishable from that of atmospheric Ar (Table 3 and Fig. 11). The age spectrum shows that this feldspar has remained thermally undisturbed since crystallization and cooling.

The best estimate for the age of the pumice in the Silbo Tuff is given as 0.74 ± 0.01 Ma, which is the mean of 7 conventional K-Ar ages, excluding the older apparent age found for sample 81-117. The measured age for the Silbo Tuff is very close to that for the boundary between the Matuyama and the Brunhes chrons, which is often taken as the boundary between the early and middle Pleistocene.

SYNTHESIS AND CONCLUSIONS

Koobi Fora Sequence

A summary of the age data obtained in this study is shown in Figure 12. Conventional K-Ar ages measured on basalts of the local basement are interpreted as indicating that Koobi Fora Formation sedimentation began subsequent to 4.3 Ma ago. Anorthoclase feldspars separated from pumice clasts contained within tuffaceous beds in the basin have proved to be ideal for dating by the K-Ar and $^{40}Ar/^{39}Ar$ techniques. Consistent results commonly have been obtained on feldspars separated from several different pumices from the same tuff. In such cases, the measured age is regarded as providing a good measure of the time since cooling of the feldspars, immediately following the explosive eruption that produced the tuff and pumices. Geological arguments favor the view that deposition of the tuffs in the Koobi Fora region occurred very soon after the explosive volcanism, so that the ages are effectively recording the time of deposition. Overall, the results are consistent with the stratigraphic order, providing additional confidence that the ages are geologically meaningful.

The conventional K-Ar and the $^{40}Ar/^{39}Ar$ age measurements agree to within experimental error in virtually all cases. Most of the $^{40}Ar/^{39}Ar$ age spectra exhibit nearly ideal flat patterns, accepted as good evidence that the feldspars have not suffered any significant thermal disturbance since they cooled below the temperature at which Ar is retained quantitatively. This closure temperature is probably ~250 °C, judging from the moderately high activation energy for Ar diffusion from anorthoclase (Harrison and McDougall, 1982). In contrast, Fitch and Miller (1976) postulated that thermal overprinting of the feldspars from pumices in the tuffs of the Koobi Fora region was nearly universal, causing partial and variable disturbance and resetting of the K-Ar system. No evidence for such behavior has been found in the present study, and this is in accord with the geologic information. The sediments are poorly consolidated and have not been buried by more than several hundred metres, so that significant elevation of temperature subsequent to their deposition is most unlikely.

The Moiti Tuff is the stratigraphically lowest tuff in the Koobi Fora Formation, ~30 m above its base. Feldspars from 3 pumice clasts yielded a mean conventional K-Ar age of 4.10 ± 0.07 Ma, early Pliocene. As the results spread over >3%, some contamination by old detrital feldspar was suspected, so that the measured age is regarded as a maximum. The age is consistent with control provided by the preferred age of 4.3 Ma for the

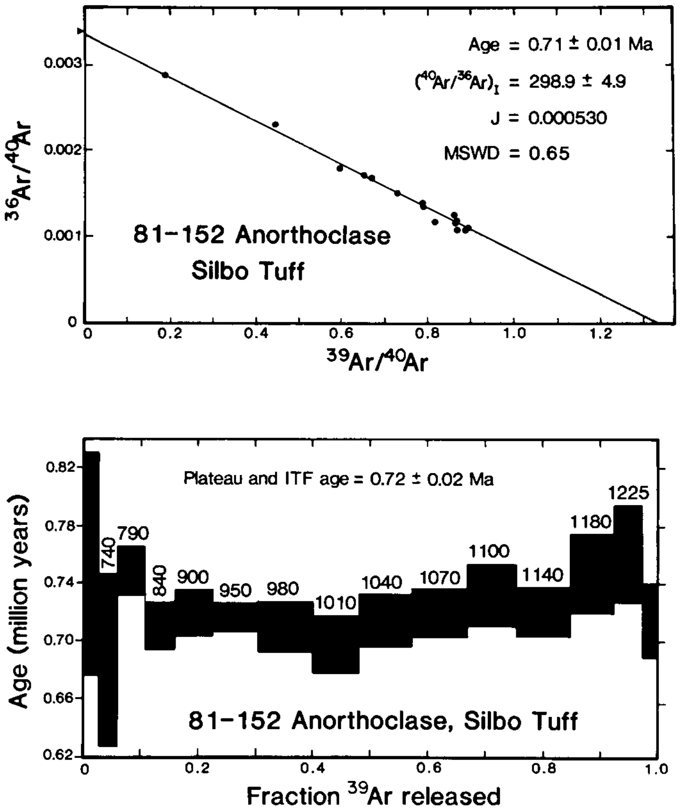

Figure 11. Age spectrum and correlation diagram for anorthoclase from a pumice clast in the Silbo Tuff.

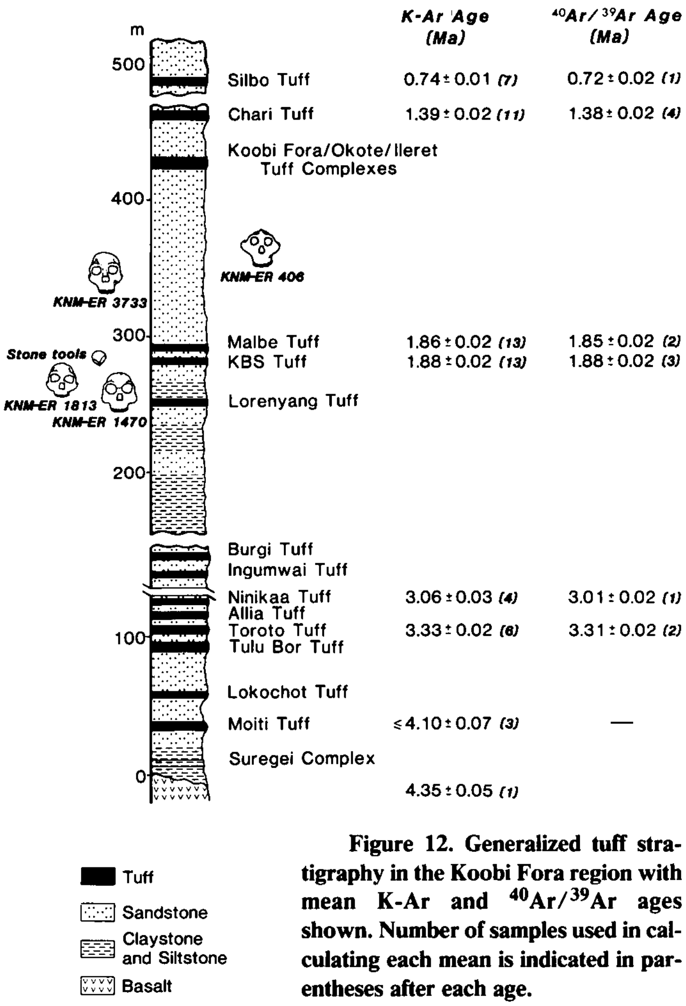

Figure 12. Generalized tuff stratigraphy in the Koobi Fora region with mean K-Ar and $^{40}Ar/^{39}Ar$ ages shown. Number of samples used in calculating each mean is indicated in parentheses after each age.

younger basalt at Karsa Waterhole but inconsistent with previously reported K-Ar ages of about 3.6 to 3.8 (± 0.4) Ma for some other basalts in the region (Fitch and Miller, 1976). As the basalt ages are likely to be minimum values, because of possible loss of radiogenic ^{40}Ar from glass, there is no serious conflict with these earlier results, however.

The Toroto Tuff is ~100 m above the base of the Koobi Fora Formation. Both K-Ar and $^{40}Ar/^{39}Ar$ age results on feldspars from pumice clasts within this tuff yield concordant ages with a mean of 3.32 ± 0.02 Ma, mid-Pliocene. This age is regarded as extremely secure.

The difference in apparent age between the Moiti Tuff and the Toroto Tuff of ~0.8 Ma is unexpectedly large, as no stratigraphic breaks have been reported from this part of the sequence (Cerling and Brown, 1982; Brown and Cerling, 1982). Some explanations include: a slow sedimentation rate, the presence of one or more unrecognized hiatuses in the sequence between the tuffs, and the possibility that all three K-Ar ages on feldspars from the pumices in the Moiti Tuff are too old owing to contamination by detritral feldspar. At the present time, it does not seem possible to distinguish between these alternatives.

If no stratigraphic hiatus occurs between the Toroto Tuff and the underlying Tulu Bor Tuff, then the latter probably is only slightly older than 3.32 Ma. As the Tulu Bor Tuff has normal magnetic polarity at its type locality in area 129, it may lie within the Gauss chron and thus be younger than ~3.41 Ma, the estimated age for the boundary between the Gauss and Gilbert chrons (McDougall, 1979; Mankinen and Dalrymple, 1979). In view of the old apparent age for the Moiti Tuff, however, care must be exercised in using this type of argument.

Feldspars from pumices in the Ninikaa Tuff yielded a relatively large spread of K-Ar ages, possibly owing to contamination by small amounts of detrital feldspar, but a case was argued for a preferred age of 3.06 ± 0.03 Ma for this bed. It is inferred, therefore, that the Ninikaa Tuff must be higher in the sequence than the Toroto Tuff, a view also put forward by Brown and Cerling (1982) on different grounds. From other evidence, it seems likely that the Ingumwai and Burgi Tuffs are higher in the sequence than the Ninikaa Tuff (Cerling and Brown, 1982; Brown and Cerling, 1982).

From these considerations, the Allia Tuff, which is stratigraphically < 10 m above the Toroto Tuff and is inferred to be below the Ninikaa Tuff, has an age lying within the interval 3.32 to 3.06 Ma.

The KBS Tuff and the Malbe Tuff have indistinguishable ages of 1.88 ± 0.02 Ma and 1.86 ± 0.02 Ma, respectively. Both tuffs can now be regarded as very securely dated. The normal magnetic polarity of sediments at the level of the KBS Tuff and extending to at least 20 m below the tuff (Brock and Isaac, 1974, 1976; Hillhouse and others, 1977), together with the age data, indicates that this part of the sequence was deposited during the Olduvai normal polarity subchron in the Matuyama chron, in the latest Pliocene. Recent estimates for the age limits of the Olduvai subchron are 1.76 to 1.91 Ma (McDougall, 1979) and 1.67 to 1.87 Ma (Mankinen and Dalrymple, 1979). Taken at face value, the data from Koobi Fora might indicate that the older boundary of the Olduvai subchron needs revision to a somewhat older age.

The age data show that there is ~1.2 Ma between the KBS Tuff and the next oldest directly dated bed, the Ninikaa Tuff, in the Koobi Fora sequence. Faunal evidence, especially that from the Suidae (Maglio, 1972; Cooke and Maglio, 1972; White and Harris, 1977; Harris and White, 1979), indicates that there is a significant hiatus in the sequence at a level somewhere below that of the KBS Tuff and above that of the Tulu Bor Tuff. This hiatus probably occurs higher in the sequence than the Burgi Tuff (Fig. 12) and may represent an interval of ~0.5-Ma duration.

The Chari Tuff, at present defined as the top of the Koobi Fora Formation, is now very well dated at 1.39 ± 0.02 Ma, early Pleistocene. The interval between the KBS and Chari Tuffs thus covers ~0.5 Ma. It is unfortunate that additional reliable age control is not available from this part of the sequence, as many fossils, including hominids, have been found in the sediments between these two tuffs. The lack of consistency of the results obtained in this study and by Fitch and Miller (1976) on feldspars from tuffs at about the Okote Tuff Complex level means that an age cannot be assigned with any confidence to this stratigraphic level, apart from the constraints provided by the age measurements on the KBS and the Chari Tuffs.

It is of some importance to know whether there are significant breaks in the sequence between the KBS and the Chari Tuffs. Much of the sequence above the KBS Tuff, at least in the Ileret area, has reverse magnetic polarity (Hillhouse and others, 1977), consistent with deposition during the Matuyama chron subsequent to the Olduvai normal polarity subchron. The lack of significant section with normal geomagnetic polarity above the KBS Tuff, representing the younger part of the Olduvai normal polarity subchron, may indicate a hiatus in the order of 0.1-Ma duration, possibly correlating in part with the post-KBS Tuff erosion surface of Findlater (1978a). Whether other significant intervals of nondeposition or erosion occur requires further detailed work.

The Silbo Tuff, regarded as part of the Guomde Formation, overlying the Koobi Fora Formation, has a well-constrained age of 0.74 ± 0.01 Ma, essentially at the middle-late Pleistocene boundary. This result demonstrates that a hiatus of ~0.7 Ma is represented by the disconformity between the Koobi Fora and the Guomde Formations. Similarly, a hiatus of about the same duration is inferred between the Guomde Formation and the Holocene Galana Boi beds, a sequence as much as ~30 m thick that occurs in the region (Bowen and Vondra, 1973; Owen and others, 1982).

In summary, initiation of deposition of the Koobi Fora Formation occurred earlier than 3.3 Ma ago and later than 4.3 Ma ago, possibly commencing as early as 4.1 Ma ago, in the early Pliocene. The stratigraphic sequence accessible for study in the Koobi Fora region does not represent a continuous record of sedimentation since the basin was formed, as at least 3 significant hiatuses are recognized, each probably of ~0.5- to 0.7-Ma duration, and thus less than one-half of the total time since the basin came into existence is represented by sediments. Whether these intervals represent periods of nondeposition or deposition followed by stripping is not yet clear; further work in the Turkana Depression no doubt will provide answers to such questions in the future.

Hominid Fossils

About 200 fossil hominid individuals, comprising both cranial and postcranial specimens, have been recovered since 1968 from the sediments of the Koobi Fora region (Leakey, 1980). Together with other fossils from East Africa and elsewhere, these finds are providing important information concerning hominid evolution. The present work yields an improved numerical age framework for these studies.

Almost all of the hominid fossils from the Koobi Fora region were found in the upper part of the Koobi Fora Formation, that is, above the major hiatus recognized to occur at about the middle of the sequence. Fossils from sediments lying between the KBS Tuff and the Chari Tuff clearly must have an age in the interval 1.88 to 1.39 Ma, latest Pliocene to early Pleistocene. Some important fossils, including cranium KNM-ER 1470 (Day and others, 1974; Leakey, 1976, 1980; Findlater, 1978a), were recovered from sediments below the KBS Tuff and must therefore be older than 1.88 Ma. These hominid fossils, mainly from areas 130, 131, and 105, lie within faunally defined collection unit 3 (Harris, 1978; Leakey and others, 1978), which equates with the "*Mesochoerus limnetes* suid zone" of Maglio (1972), more properly named the "*Kolpochoerus limnetes* zone" (Cooke, 1978). The upper limit for both faunal units is the KBS Tuff. If we assume continuous sedimentation at a more or less uniform rate above and below the level of the KBS Tuff, then an age for the sediments that contained KNM-ER 1470, ~36 m below the KBS Tuff, of ~2.0 Ma is derived.

The majority of the hominid fossils recovered from the Koobi Fora region thus are found in sediments that were deposited during the interval 2.0 to 1.4 Ma ago. It is of particular interest that from this part of the sequence a diversity of hominid types is represented in the finds. Leakey (1976) and Leakey and Walker (1976) established unequivocally that at least two hominid species existed contemporaneously, thus negating the single species hypothesis of hominid evolution. A lineage identified as belonging to the genus *Homo* has been well documented from this stratigraphic interval. The cranium KNM-ER 1470, usually assigned to *Homo habilis*, was found below the KBS Tuff, and forms regarded as *Homo erectus* (for example, KNM-ER 3733) have been recovered from sediments above the KBS Tuff. At essentially the same stratigraphic level as KNM-ER 3733, the cranium KNM-ER 406 was found, and this is accepted as a robust form of the genus *Australopithecus.* This represents the other lineage, evidence for which is much more extensive, as many other fossils assigned to the robust *Australopithecus* species have been recovered from the same general stratigraphic interval. In addition, Leakey (1974, 1980) suggested that gracile cranium KNM-ER 1813, probably from a level about that of the KBS Tuff, has affinities with *Australopithecus africanus,* although other workers have advanced the view that this belongs to the *Homo* lineage.

The evidence from Koobi Fora probably is the most definitive regarding the contemporaneity of at least two hominid lineages in the late Pliocene to early Pleistocene in East Africa, although additional strong support derives from the important collections from Olduvai Gorge, Tanzania, and from the Shungura Formation in Ethiopia. The geochronological data given here help to place this parallel development in a numerical time context and to provide a time calibration for the evolution of the many other vertebrates and invertebrates preserved as fossils in the sequences of the Turkana Depression.

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