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The age of *Orrorin tugenensis*, an early hominid from the Tugen Hills, Kenya

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Abstract – Throughout the history of the East African Rift valley, tectonic depressions and volcanic dams formed within the graben in which Middle Miocene to Recent volcanic rocks and lacustrine to fluvial sediments accumulated. During the Late Miocene, voluminous trachytes erupted in the vicinity of Kabarnet and almost filled the valley to its brim. Continued tectonic activity formed new basins floored by the Kabarnet Trachyte, one of which was located in the region immediately east of the present day Tugen Hills. The Lukeino sediments that accumulated in this basin crop out over an area of 44 km × 13 km. In 2000, *Orrorin tugenensis*, which is important for understanding the earliest stages of human evolution, was found in the Lukeino Formation [12, 13]. It is concluded that the Lukeino formation accumulated between 6.0 and 5.7 Ma. ***To cite this article: Y. Sawada et al., C. R. Palevol 1 (2002) 293–303.*** © 2002 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

early hominid / Late Miocene / K–Ar age / magnetostratigraphy / chrons C3n to C3r / Lukeino Formation / Kenya

Résumé – L'âge d'*Orrorin tugenensis*, un hominidé ancien des collines Tugen au Kenya. Tout au long de l'histoire de la *Rift Valley* est-africaine, se sont formés des dépressions tectoniques et des barrages de coulées volcaniques à l'intérieur du graben dans lequel des roches volcaniques et des sédiments fluvio-lacustres se sont accumulés du Miocène moyen à l'Actuel. Au cours du Miocène supérieur, se sont produites dans la région de Kabarnet d'importantes éruptions de trachytes, qui comblèrent pratiquement la vallée. L'activité tectonique continue engendra la formation de nouveaux bassins, dont le plancher était constitué des trachytes de Kabarnet. Un de ces bassins était situé juste à l'est des collines Tugen actuelles. Les sédiments de Lukeino qui s'y sont déposés affleurent dans une zone de 44 km de long sur 13 km de large. En 2000, était découvert dans cette formation l'hominidé *Orrorin tugenensis*, important pour comprendre les premiers stades de l'évolution humaine [12, 13]. Les résultats montrent que la formation de Lukeino s'est accumulée entre 6,0 et 5,7 Ma. ***Pour citer cet article : Y. Sawada et al., C. R. Palevol 1 (2002) 293–303.*** © 2002 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

hominidé ancien / Miocène supérieur / âge K–Ar / magnétostratigraphie / chrones C3n à C3r / formation de Lukeino / Kenya

Version abrégée

1. Introduction

Tout au long de l'histoire du Rift est-africain, des dépressions tectoniques et des barrages dus aux coulées volcaniques se sont formés dans le graben où se sont accumulés des roches volcaniques et des dépôts fluvio-lacustres entre le Miocène moyen et l'Actuel. À la fin du Miocène moyen, d'importantes éruptions de trachytes dans la région de Kabarnet ont pratiquement comblé le rift. L'activité tectonique se poursuivant, de nouveaux bassins se sont établis

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reposant sur le trachyte de Kabarnet. Un de ceux-ci était situé juste à l'est des collines Tugen actuelles, le bassin de Lukeino, où furent découverts en 2000 les restes d'*Orrorin tugenensis*, très importants pour comprendre les premiers stades de l'évolution humaine [13], tout comme le sont les pièces mises au jour plus récemment en Éthiopie [6, 16] et au Tchad [2].

La cartographie de la formation de Lukeino a été complétée par de nouvelles prospections. Une carte géologique au 1:1000^{e} et des colonnes stratigraphiques ont été mesurées par les auteurs sur tous les sites ayant livré des hominidés (Aragai, Cheboit, Kapcheberek). Les âges radiométriques calculés sur des échantillons récoltés dans un contexte stratigraphique clair et l'étude magnétostratigraphique des dépôts permettent d'affiner l'âge des hominidés que ces derniers renferment.

2. Contexte sédimentologique

Le bassin de Lukeino (Fig. 1) s'étend sur 44 km, du sud vers le nord, et sur au moins 15 km, d'est en ouest ; sa partie orientale s'est effondrée, puis a été recouverte de roches plus jeunes. Le plancher du bassin est constitué de la Phonolite de Tiim et du Trachyte de Kabarnet, sur lesquels repose la formation de Lukeino, elle-même surmontée par les basaltes de Kaparaina. La formation de Lukeino consiste principalement en des dépôts clastiques, avec un faible apport volcanique à sa base, mais qui devient plus fort vers le sommet du membre de Kapcheberek, où l'on rencontre des dépôts relativement purs de cinérites. La formation est pénétrée par des dykes de trachybasalte et par au moins deux sills (les sills de Rormuch). Dans le Sud, un de ces derniers, hautement porphyritique, a atteint la surface et participe à la base de la formation des basaltes de Kaparaina, indiquant que les sills étaient intrusifs, au moment même où l'activité volcanique de Kaparaina débutait. Dans les parties sud de la formation, les sédiments de Lukeino consistent principalement en des dépôts de plaine alluviale, avec des faciès peu développés de bord de lac et clairement lacustres (shales). Vers le nord, la grande majorité des dépôts sont lacustres [11]. À Kapsomin, la formation de Lukeino renferme une coulée de basalte à olivine, qui se biseaute vers le nord. Sa surface a été altérée et érodée avant d'être enfouie au cours de la sédimentation, suggérant qu'elle a été contemporaine des sédiments.

2.1. Membre de Kapgoywa

À Aragai, le fragment d'hominidé a été trouvé dans un dépôt de chenal gréseux, très riche en fossiles, situé à 2 m au-dessus du Trachyte de Kabarnet. C'est le même cas à Cheboit.

2.2. Membre de Kapsomin

Les restes les plus abondants d'*Orrorin* ont été découverts à Kapsomin, dans le membre de Kapsomin, situé stratigraphiquement juste au-dessus du basalte de Kapsomin. Un des fémurs et une dent isolée ont été mis au jour un peu plus haut dans la section. Le Membre de Kapsomin présente des faciès principalement de bord de lac, riches en stromatolites et en gastéropodes. Juste au nord du site, il y avait une source chaude qui a déposé de grandes quantités de travertins, dont certains se retrouvent sur le site à hominidés.

2.3. Membre de Kapcheberek

Une phalange d'hominidé a été récoltée dans les grès fluviatiles à Kapcheberek, dans l'unité clastique intermédiaire. Le milieu de dépôt consistait en une plaine alluviale, au cœur de laquelle des rivières coulaient généralement vers le nord-est.

Ces données sédimentologiques indiquent qu'*Orrorin* vivait dans la plaine alluviale qui limitait le paléo-lac Lukeino ou à sa proximité.

3. Stratigraphie des formations du Miocène supérieur à Kapgoywa, Aragai et Cheboit

À Kapgoywa, Aragai et Cheboit (Figs 2–4), la succession stratigraphique locale prospectée est divisée en trois formations d'âge Miocène supérieur. On trouve, à la base, le trachyte de Kabarnet, recouvert par la formation de Lukeino, elle-même surmontée par la formation des basaltes de Kaparaina. De la base au sommet, la formation de Lukeino est composée du membre de Kapgoywa, recouvert du basalte de Kapsomin, puis du membre de Kapsomin, lui-même surmonté du membre de Kapcheberek ; elle est recoupée par les sills intrusifs de Rormuch. Le membre de Kapcheberek est divisé en trois sous-unités, une unité basale clastique rouge, une unité clastique intermédiaire, et une unité supérieure clastique cinéritique. Les lithofaciès et la puissance de la formation de Lukeino varient fortement de place en place. Les fossiles attribués à *Orrorin tugenensis* (Hominidae, Mammalia) ont été découverts dans les trois membres de la formation de Lukeino et sur quatre localités, Aragai et Cheboit, à la base du membre de Kapgoywa, à Kapsomin, près de la base et au milieu du membre de Kapsomin, et à Kapcheberek, dans la sous-unité clastique intermédiaire du membre de Kapcheberek.

4. Radiométrie

En 1985, Hill et al. [7] estimaient, par la méthode au K–Ar appliquée à des cristaux de feldspaths et à des roches entières, l'âge de la formation à environ 6 Ma. Plus récemment [5], un âge de 5,73 ± 0,05 Ma a été publié à partir d'analyses au ^{40}Ar–^{39}Ar, réalisées sur des cristaux d'anorthoclase provenant des tufs lapillitiques de la partie supérieure de la formation. Toutefois, les lieux de prélèvement n'ont été précisés dans aucun de ces deux articles.

Pour les datations au K–Ar de cette étude, neuf échantillons ont été prélevés, provenant de la phonolite de Tiim, du trachyte de Kabarnet, du tuf ponceux lapillitique à Kapcheberek, des basaltes de Kaparaina, du basalte du premier sill de

Rormuch, du trachybasalte aphyrique du second sill de Rormuch et d'un dyke de trachybasalte aphyrique.

Les analyses ont été réalisées suivant les méthodes publiées par Nagao et al. [10], Itaya et al. [8] et Steiger et Jäger [14]. Les résultats de l'analyse radiométrique au K–Ar (Tableau 1) sont les suivants : l'âge des anorthoclases des deux échantillons de la phonolite de Tiim à Aragai sont 12,57 ± 0,31 et 12,43 ± 0,30 Ma ; pour les phénocristaux d'anorthoclase et les pâtes du trachyte de Kabarnet, les âges sont respectivement de 6,17 ± 0,15 Ma et 6,09 ± 0,14 Ma. L'anorthoclase des tufs lapillitiques ponceux de la partie supérieure de la formation de Lukeino à Kapcheberek donne un âge de 5,66 ± 0,14 Ma. Les âges des pâtes du trachybasalte de Kaparaina, qui recouvrent la formation de Lukeino sont respectivement de 5,68 ± 0,18 Ma et 5,47 ± 0,16 Ma ; ceux des pâtes et feldspaths du sill de Rormuch sont respectivement de 5,80 ± 0,22 Ma et 5,72 ± 0,14 Ma. La pâte des trachybasaltes du dyke intrusif dans la formation de Lukeino donne un âge de 5,61 ± 0,17 Ma. Ces âges K–Ar concordent avec ceux qui avaient été estimés auparavant pour les séries du Miocène supérieur des Tugen Hills [5, 7, 9], bien que la provenance de ces échantillons n'ait pas été précisée.

5. Paléomagnétisme

L'étude de polarité magnétique a montré deux inversions magnétiques : la partie inférieure de la formation de Lukeino présente une polarité normale, alors que le trachyte de Kabarnet et les parties moyenne et supérieure de la formation de Lukeino, le basalte de Kapsomin, le membre de Kapsomin, les sills de Rormuch et les trachybasaltes de Kaparaina ont tous une polarité inverse.

6. Conclusions sur l'âge d'*Orrorin tugenensis*

Sur la base des âges au K–Ar et ^{40}Ar–^{39}Ar et de la magnétostratigraphie, on peut déduire que l'inversion de polarité magnétique (inverse à normale), mise en évidence entre le trachyte de Kabarnet et la partie inférieure de la formation de Lukeino, correspond à la limite entre les chrones C3An.1r et le C3An.1n, dont l'âge est estimé à 6,05 Ma selon Wei [15], à 6,14 Ma selon Baksi [1] et à 6,14 Ma selon Cande et Kent [3]. De la même manière, l'inversion reconnue (normale à inverse) dans la partie inférieure de la formation de Lukeino correspond à la limite entre les chrones C3An.1n et C3r, dont la limite est située à 5,83 Ma selon Wei [15] et Baksi [1] et à 5,89 Ma selon Cande et Kent [3]. Dans leur publication, Deino et al. [5] concluent que la formation est située magnétostratigraphiquement dans le chrone C3r ; mais ils n'ont pas relevé l'inversion de polarité mise en évidence dans la partie inférieure de la formation de Lukeino, bien que cette limite ait déjà été reconnue par Dagley et al. [4]. Nous en concluons que la formation de Lukeino, qui a livré *Orrorin tugenensis*, s'est déposée entre 6,0 et 5,7 Ma. Les spécimens de Kapsomin, les plus nombreux et les plus importants de l'échantillon, seraient situés entre 5,9 et 5,8 Ma.

1. Introduction

The origin of humans is one of the most interesting topics in Earth Sciences. During the past decade, hominoid fossils were found in Kenya, Ethiopia, and Chad, which are important for clarifying human evolution [2, 6, 13, 16]. *Orrorin tugenensis* from Kenya is interpreted as the earliest known hominid [12, 13], *Ardipithecus ramidus kadabba* has been classified in the autralopithecines by Haile Selassie [6] whereas the hominid status of *Sahelanthropus tchadensis* is being debated [2, 17].

Hill et al. [7] reported K–Ar ages for whole rock and feldspar crystals from the Lukeino Formation which later yielded *Orrorin tugenensis*. They also dated the underlying Kabarnet Trachyte, and the overlying Kaparaina Basalt. They concluded that the age of the Lukeino Formation was ca 6 Ma. However, the collecting stations for the date samples were not described. Recently Deino et al., [5] reported that ^{40}Ar–^{39}Ar analyses of anorthoclase crystals from lapilli tuff in the upper part of the Lukeino Formation indicate an age of 5.73 ± 0.05 Ma (weighted mean age), and that the Lukeino Formation is magnetostratigraphically within chron C3r.

Geological route mapping (1:1000) and measuring of columnar sections of the strata were carried out by the authors at Kapcheberek, Aragai and Cheboit. In this paper, K–Ar ages and magnetostratigraphy of the Kabarnet Trachyte, Lukeino and Kaparaina Basalt Formations and the Rormuch Sills are reported, and the age of *Orrorin tugenensis* is refined.

2. Sedimentological background of *Orrorin tugenensis*, Tugen Hills

The Lukeino Basin (Fig. 1) is some 44 km in north–south extent and at least 15 km east–west, the eastern portion of the basin having been downfaulted and covered by younger rocks. The floor of the basin is comprised of the Tiim Phonolite and Kabarnet Trachyte, and the Lukeino Formation is capped by Kaparaina Basalts. The Lukeino Formation consists mainly of clastic deposits with minor primary volcanic input, which increases at the top of the Kapcheberek Member, where relatively pure tuffaceous deposits are

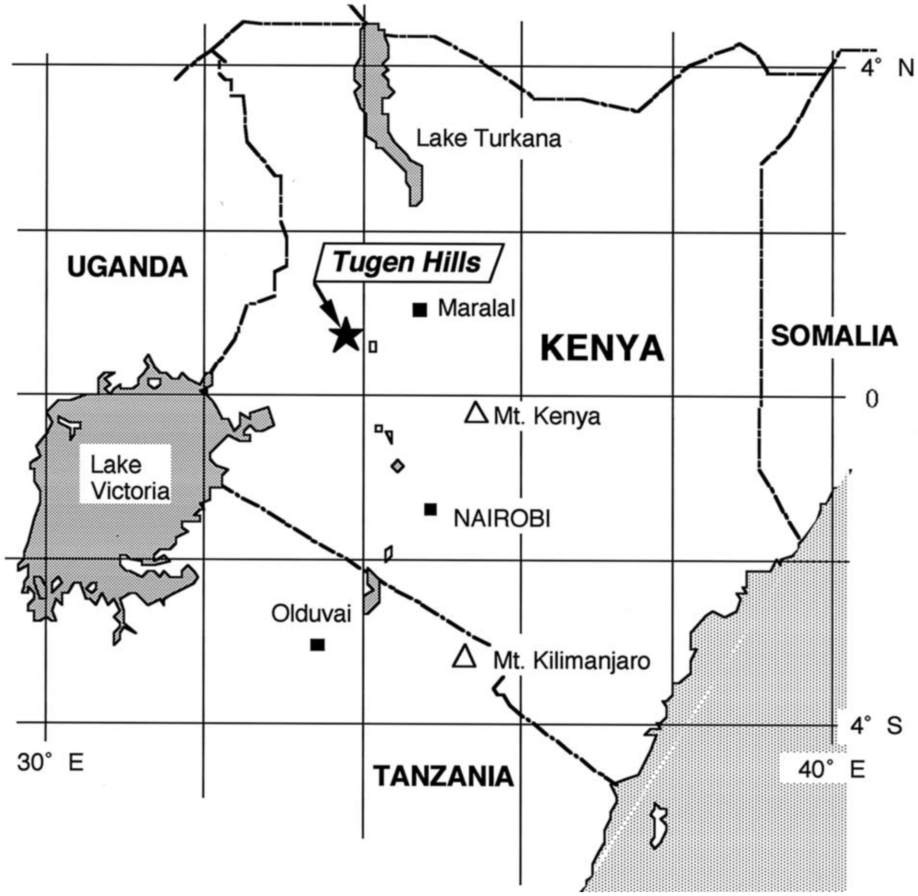

Fig. 1. Map showing the location of the Tugen Hills.

Fig. 1. Localisation des collines Tugen.

encountered. The formation has been intruded by trachybasalt dykes and at least two sills (Rormuch Sills), the latter being basin wide. One of the sills (highly porphyritic) reached the surface in the south, where it contributes to the base of the Kaparaina Basalt Formation, indicating that the sills were intruded at the same time as the onset of the Kaparaina volcanic activity. In the southern parts of the formation, the Lukeino sediments consist predominantly of flood plain (fluvial and overbank) deposits, with minor lake margin and fully lacustrine (shale) facies. Northwards, most of the sediments are lacustrine [11]. At Kapsomin, there is an olivine basalt flow within the Lukeino Formation, which pinches out northwards. Its surface was weathered and eroded prior to burial by continued sedimentation, proving that it is contemporary with the Lukeino sediments.

2.1. Kapgoywa Member

At Aragai, a femur fragment of *Orrorin* was found in a gritty channel deposit rich in vertebrate remains. The deposits are near the base of the Lukeino Formation about 2 m above the weathered upper surface of the Kabarnet Trachyte. Likewise, at Cheboit, a lower molar of *Orrorin* was found in a richly fossiliferous channel deposit just above the Kabarnet Trachyte. Deposition was in rivers that flowed generally northwards across a flood plain.

2.2. Kapsomin Member

The bulk of the *Orrorin* material was found in the Kapsomin Member stratigraphically above the Kapsomin olivine basalt flow. The richest assemblage of specimens occurs in sediments that accumulated at the foot of a cliff of this basalt, blocks of which have been incorporated into the sediments. Higher in the section additional material of *Orrorin* was found, including a well-preserved femur and an isolated lower premolar. The Kapsomin Member is predominantly of lake-margin facies, rich in algal stromatolites and gastropods. Immediately north of the site, there was a hot spring, which deposited large amounts of travertine, some of which occurs at the hominid site. A few of the bones are covered in layers of stromatolite and are well preserved, but others apparently lay on the surface before being buried and are cracked and broken.

2.3. Kapcheberek Member

A manual phalanx of *Orrorin* was recovered from fluvial grits at Kapcheberek, in the intermediate clastic unit of the Kapcheberek Member. The depositional environment was a flood plain across which rivers flowed generally northeastwards.

From the sedimentary evidence, we conclude that *Orrorin* lived in or near the flood plain that bordered Palaeolake Lukeino.

3. Detailed stratigraphy of Late Miocene formations at Kapgoywa, Aragai, and Cheboit

At Kapgoywa, Aragai and Cheboit, Late Miocene strata consist of the Kabarnet Trachyte at the base, Lukeino Formation in the middle and Kaparaina Basalt at the top. Route maps, stratigraphy, lithology and columnar section were compiled for these three areas (Figs. 2– 4).

The Kabarnet Trachyte consists of massive and coarsely porphyritic trachyte–phonolite lava flows. Phenocrysts of anorthoclase and a few of clinopyroxene are set in a trachytic groundmass of anorthoclase, clinopyroxene amphibole, apatite, and opaque minerals.

The Lukeino Formation consists of sedimentary and pyroclastic rocks and a basalt lava flow, and is 95 m in thickness. In ascending order, it is divided into the Kapgoywa, Kapsomin Basalt, Kapsomin and Kapcheberek Members. The Kapgoywa Member consists mainly of sandstone–siltstone, with a basal conglomerate and intercalations of basaltic and trachytic tuff beds. The upper part of the member consists of white shale. The Kapsomin Basalt Member is composed of an olivine phyric basalt lava flow about 6 m in maximum thickness pinching out northwards at Kapsomin. The Kapsomin Member consists mainly of tuffaceous siltstone and sandstone with basaltic and trachytic tuff beds, and calcareous beds and nodules.

The Rormuch Sills are aphyric and highly porphyritic trachytes, which intruded the boundary between the Kapsomin and Kapcheberek Members. Heat from the intrusions has baked the underlying and overlying sediments. Irregular silicified blocks of the lowest part of the Kapcheberek Member are included within the sill. An aphyric trachyte dyke compositionally similar to the aphyric sill also intruded the Kapgoywa Member.

The Kapcheberek Member is subdivided into three units. In ascending order the constituents of each unit are as follows: (1) red basal clastic unit (brick-red weakly laminated fine sandstone with siltstone, tuff and limonite beds, intruded by a thin trachyte dyke); (2) intermediate clastic unit (sandstone and siltstone with conglomerate and limonite); (3) upper tuffaceous to clastic unit (tuffaceous siltstone, sandstone with tuff, pumice tuff and conglomerate). An aphyric trachybasalt lava of the Kaparaina Basalt Formation overlies basaltic sandstone with conglomerate in the uppermost part of the Kapcheberek Member, which it baked red. The lower part of the lava is vesicular. At least three Kaparaina lava flows are recognised in the Kapcheberek area.

4. K–Ar ages

4.1. Samples

Nine samples were collected for K–Ar age determination.

4.1.1. Tiim Phonolite (LK81301)

The Tiim Phonolite from the Aragai area consists of phenocrysts of anorthoclase, nepheline, augite and biotite, with a groundmass of alkali feldspar, augite, aegirine–augite, biotite, apatite and opaque minerals. Anorthoclase phenocrysts are slightly replaced by carbonate.

4.1.2. Kabarnet Trachyte (TG-KB02)

The Kabarnet Trachyte is composed of massive and coarsely porphyritic trachyte–phonolite lava flows. Phenocrysts of anorthoclase and a few clinopyroxene crystals set in a trachytic groundmass of anorthoclase, clinopyroxene, amphibole, apatite and opaque minerals.

4.1.3. Pumiceous lapilli tuff (LK33)

Pumiceous lapilli tuff is characterised by the abundance of pumice (< 2 cm) with trachytic scoria clast in a tuffaceous matrix. Pumices contain large anorthoclase phenocrysts up to 7 mm in diameter and fine-grained biotite pseudomorphs.

4.1.4. Basalts from the Kaparaina Basalt Formation (LK34 and LK10–1)

They are aphyric trachybasalt, which consist of a small amount of plagioclase phenocrysts in a groundmass of plagioclase, olivine (rare), clinopyroxene, ilmenite, magnetite, apatite and very fine-grained brown

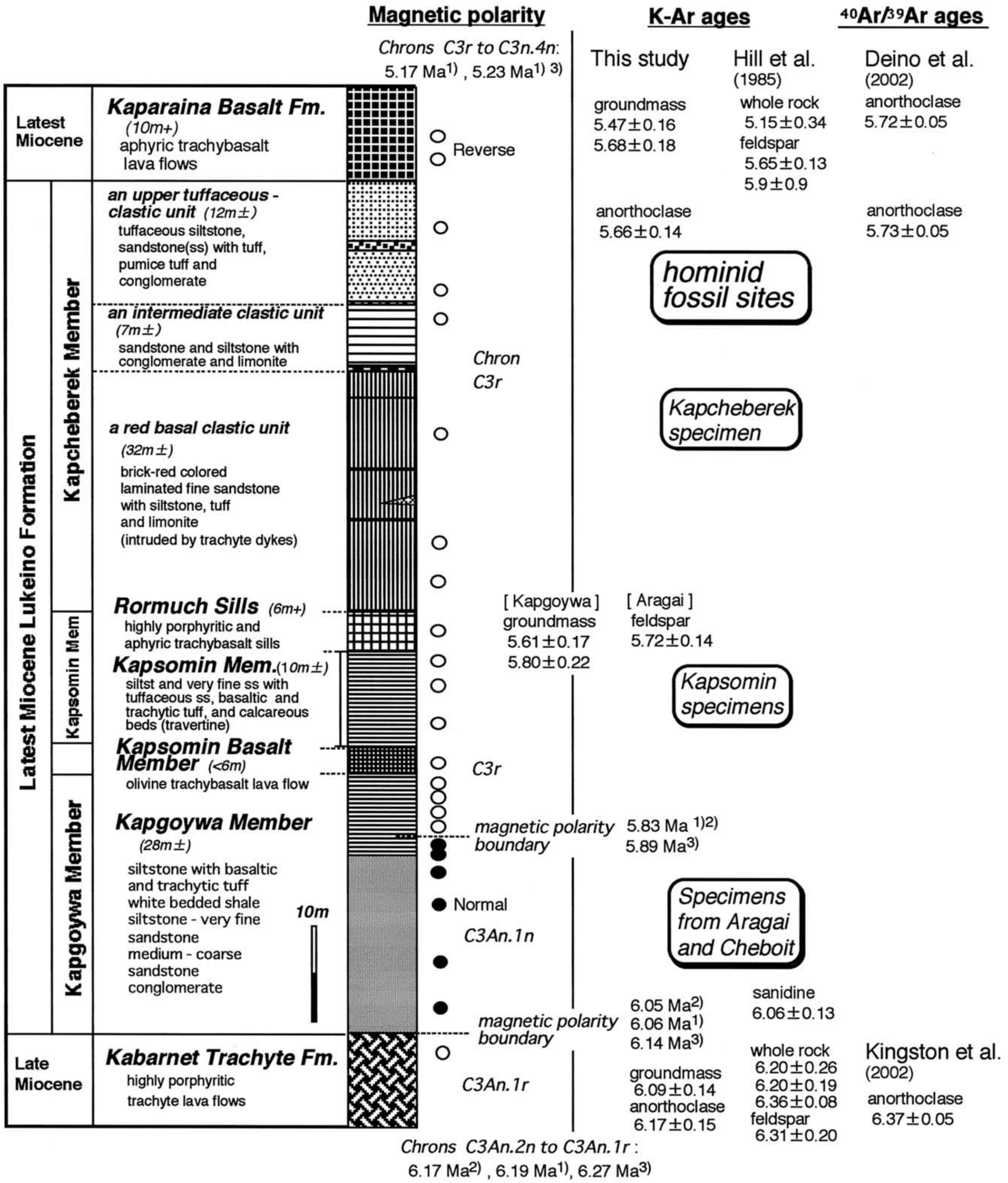

Fig. 2. Columnar section of the Late Miocene series with lithofacies, K–Ar ages, ^{40}Ar–^{39}Ar ages and magnetic polarity. **Fm**: Formation, **Mem**: member. Numbers of K–Ar ages and ^{40}Ar–^{39}Ar ages are in Ma. Solid and open circles are normal and reversed polarity, respectively. The ages of the geomagnetic polarity time scale are after (1) Baksi [1], (2) Wei [15], and (3) Cande and Kent [3].

Fig. 2. Colonne stratigraphique des séries du Miocène supérieur avec les lithofaciès, les âges K–Ar, ^{40}Ar–^{39}Ar et la polarité magnétique. **Fm** : Formation, **Mem** : membre. Les nombres correspondant aux âges radiométriques sont en Ma. Les cercles pleins et ouverts représentent respectivement les polarités normales et inverses. Les âges de l'échelle chronologique de polarité géomagnétique sont tirés de (1) Baksi [1], (2) Wei [15] et de (3) Cande and Kent [3].

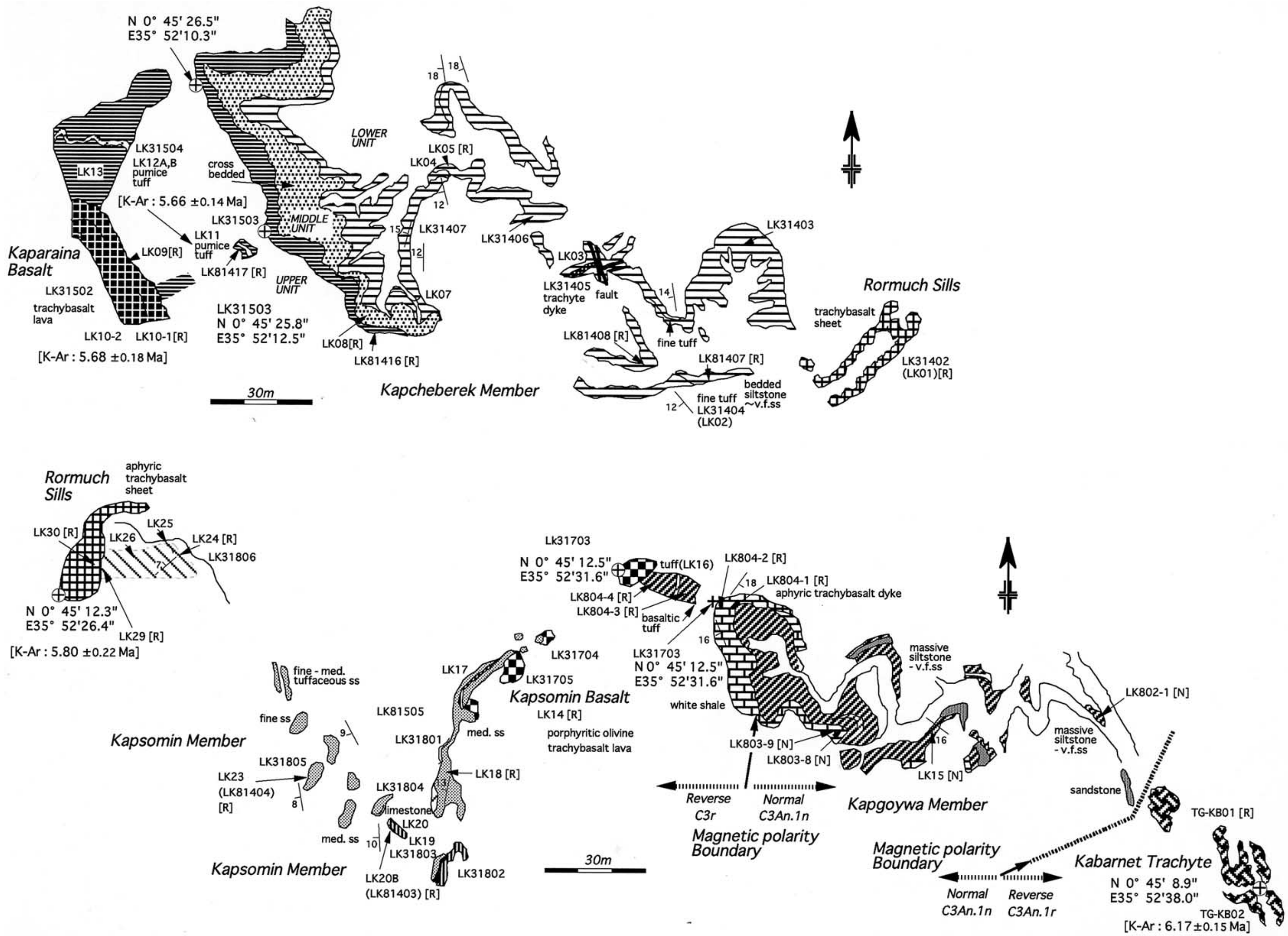

Fig. 3. Route maps with GPS co-ordinates of the Late Miocene series in the Kapgoywa area, showing lithofacies, sample locations, K–Ar ages and magnetic polarity. [N] and [R] indicate magnetic polarity normal and reverse, respectively.

Fig. 3. Pistes avec les coordonnées GPS des séries du Miocène supérieur dans la région de Kapgoywa montrant les lithofaciès, les lieux de prélèvements, les âges au K–Ar et la polarité magnétique (N pour normale et R pour inverse).

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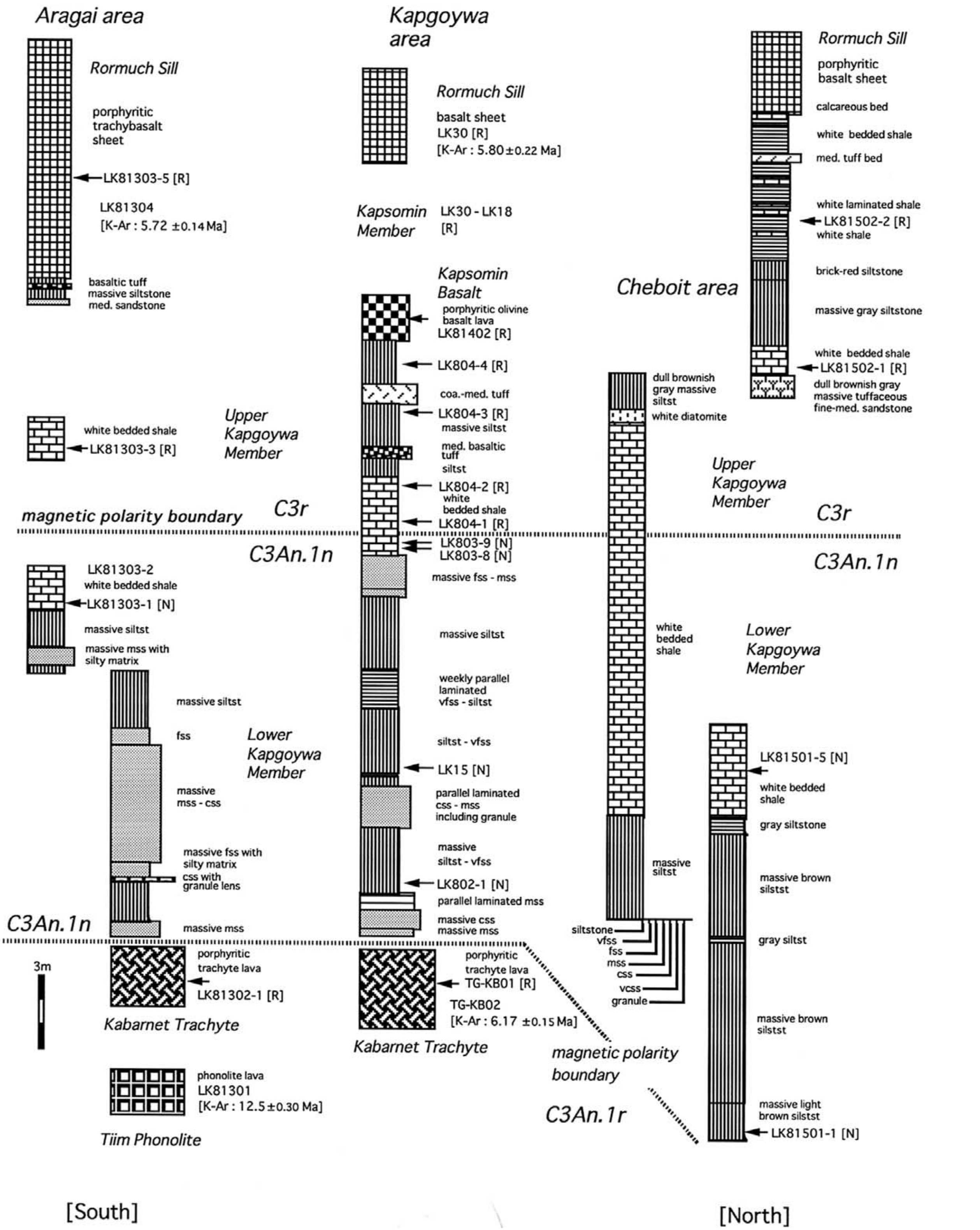

Fig. 4. Columnar sections with lithofacies and magnetic polarity showing correlation of the Kabarnet Trachyte and lower Lukeino Formation at Kapgoywa, Aragai and Cheboit. Magnetic polarity boundary from Chrons C3An.1n to C3r is clearly recognised within the white shale of the lower Lukeino Formation.

Fig. 4. Colonne stratigraphique avec les lithofaciès et la polarité magnétique, montrant la corrélation entre le trachyte de Kabarnet et la partie inférieure de la formation de Lukeino à Kapgoywa, Aragai et Cheboit. La limite de polarité magnétique entre les chrones C3An.1n et C3r est clairement reconnaissable à l'intérieur des argiles feuilletées de la partie inférieure de la formation de Lukeino.

minerals, with small amounts of chlorite and carbonate as secondary minerals.

4.1.5. Basalt of the Rormuch Sill (LK 30)

Basalt of the Rormuch Sill in the Kapgoywa area is composed of small plagioclase phenocrysts (< 4 mm) in a groundmass of plagioclase, olivine and clinopyroxene, opaque minerals and apatite. The rock is slightly altered and includes carbonate, iddingsite and chlorite as secondary minerals.

4.1.6. Aphyric trachybasalt of the Rormuch Sill (LK 81304)

Aphyric trachybasalt of the Rormuch Sill in the Aragai area is petrographically very similar to LK30.

4.1.7. Aphyric trachybasalt dyke (LK32)

Aphyric trachybasalt dyke consists of small plagioclase phenocrysts (< 1.5 mm) in a groundmass of plagioclase, olivine and clinopyroxene, opaque minerals and apatite. It is slightly altered and includes carbonate, iddingsite and chlorite as secondary minerals.

4.2. Sample preparation and analytical procedure

Samples of groundmass and feldspar were prepared by crushing and sieving for K–Ar age determination. Grain sizes of analysed samples are 423–254 µm for groundmass and 127–85 µm for feldspar. For pumiceous lapilli tuff anorthoclase phenocrysts of 423–254 µm were firstly sieved, and then 127–85 µm samples were separated. Samples ground to less than a few micrometers were used for potassium analysis.

Analytical procedure for determining potassium and argon and calculations of ages and errors were carried out using the method described by Nagao et al. [10] and Itaya et al. [8]. Potassium was analysed by flame photometry using a 2000 ppm Cs buffer and has an analytical error of under 2% at 2 σ confidence level. Argon was analysed on a 15 cm radius sector-type mass spectrometer with a single collector system, using an isotopic dilution method and ^{38}Ar spike [8]. Multiple runs of a standard (JG-1 biotite, 91 Ma) indicate that the error of argon analysis is about 1% at 2 σ confidence level. The decay constants for ^{40}Ar and ^{40}Ca, and ^{40}K content in potassium used in the age calculation are from Steiger and Jäger [14] and are 0.581×10^{-10} yr^{-1}, 4.962×10^{-10} yr^{-1} and 0.000 116 7, respectively.

4.3. Results

The results of K–Ar age determinations are shown in Table 1. The anorthoclase ages for two samples of the Tiim Phonolite (LK81301AF, LK81301H) at Aragai are

Table 1. K–Ar ages of the Miocene series at Kapgoywa and Aragai. Abbreviations of analysed materials are as follows; Gm: groundmass; Fd: feldspar; AF: anorthoclase.
Tableau 1. Ages K–Ar des séries miocènes à Kapgoywa et Aragai. Les abréviations pour les matériels analysés sont les suivantes : Gm, pâte; Fd, feldspath, AF, anorthoclase.

Sample number	Location	Formation	Stratigraphic position	Rock type	Occurrence	Material	K (wt%)	Rad. ^{40}Ar (10^{-8} ccSTP g^{-1})	Non-rad. ^{40}Ar (%)	K–Ar age (Ma)
LK10-1Gm	Kapgoywa	Kaparaina Basalt	lowest	trachybasalt	lava	Gm	1.39 ± 0.03	29.5 ± 0.6	44.8	5.47 ± 0.16
LK34Gm	Kapgoywa	Kaparaina Basalt	lowest	trachybasalt	lava	Gm	1.75 ± 0.04	38.7 ± 1.0	52.5	5.68 ± 0.18
LK32Gm	Kapgoywa	Dyke in Lukeino Fm	in lower Lukeino Fm.	trachybasalt	dyke	Gm	1.59 ± 0.03	34.6 ± 0.8	47.7	5.61 ± 0.17
LK30Gm	Kapgoywa	Rormuch Sill	in middle Lukeino Fm.	basalt	sheet	Gm	1.05 ± 0.02	23.6 ± 0.8	61.8	5.80 ± 0.22
LK81304F	Aragai	Rormuch Sill	in middle Lukeino Fm.	trachybasalt	sheet	Fd	1.64 ± 0.03	36.5 ± 0.5	21.4	5.72 ± 0.14
LK33AF	Kapgoywa	Lukeino Fm	Kapcheberek	trachytic	pumice tuff	AF	5.76 ± 0.12	126.8 ± 1.8	26.3	5.66 ± 0.14
TG-KB02M2	Kapgoywa	Kabarnet Trachyte		trachyte	lava	Gm	4.53 ± 0.09	107.2 ± 1.4	20.0	6.09 ± 0.14
TG-KB02AF	Kapgoywa	Kabarnet Trachyte		trachyte	lava	AF	5.32 ± 0.11	127.7 ± 1.6	17.8	6.17 ± 0.15
LK81301AF	Aragai	Tiim Phonolite		phonolite	lava	AF	5.21 ± 0.10	252.1 ± 3.5	25.7	12.43 ± 0.30
LK81301AF	Aragai	Tiim Phonolite		phonolite	lava	AF	5.66 ± 0.14	242.4 ± 3.4	25.4	12.57 ± 0.31

12.57 ± 0.31 and 12.43 ± 0.30 Ma. The ages of anorthoclase (TG-KB02AF) and groundmass (TG-KB02M2) from the Kabarnet Trachyte are 6.17 ± 0.15 Ma and 6.09 ± 0.14 Ma, respectively. Anorthoclase from sample LK33AF, a pumiceous lapilli tuff in the Kapcheberek Member of the Lukeino Formation is dated to 5.66 ± 0.14 Ma. Groundmass ages of the basalts LK34Gm and LK10–1Gm from the Kaparaina Basalt Formation are 5.68 ± 0.18 Ma and 5.47 ± 0.16 Ma, respectively. Groundmass age of LK30Gm and feldspar age of LK81304F from the Rormuch Sill are 5.80 ± 0.22 Ma and 5.72 ± 0.14 Ma, respectively. Groundmass age of the aphyric trachybasalt dyke (LK32Gm) is 5.61 ± 0.17 Ma.

5. Magnetostratigraphy

5.1. Samples

Oriented block samples were collected from siltstone, fine sandstone, and lavas. In the Kapgoywa area, 23 samples were taken from the Kabarnet Trachyte, Lukeino Formation, and Kaparaina Basalt. In the Aragai and Cheboit areas, four samples were collected from each of the Kabarnet Trachyte and Kapgoywa Member. Sample locations and stratigraphic positions are shown in Figs. 2–4.

5.2. Palaeomagnetic measurements

Cylindrical specimens 2.5 cm in diameter and length were taken from the block samples. A spinner magnetometer or a 2G cryogenic magnetometer was used for magnetisation measurements. All the specimens were subjected to progressive demagnetisations (6–17 steps) at temperatures up to 680 °C or in alternating field (AF) up to 200 mT. The thermal technique was the main one used, while AF-demagnetisation technique was applied to fragile specimens.

5.3. Magnetostratigraphy

The virtual geomagnetic pole (VGP) position is calculated from a tilt-corrected ChRM direction. Normal (or reverse) magnetic polarity is defined as the VGP position lying within the northern (or southern) hemisphere. The Kabarnet Trachyte has a reverse polarity magnetisation in both the Kapgoywa and Aragai areas. The reverse polarity lava is overlain by a normal polarity magnetozone in the lower part of the Lukeino Formation at Kapgoywa, Aragai and Cheboit. The upper boundary of the normal polarity magnetozone is located within a white shale bed in the uppermost part of the Kapgoywa Member at Kapgoywa, Aragai and Cheboit (Fig. 4). Above the polarity boundary, a reverse polarity magnetozone continues through the middle and upper parts of the Lukeino Formation and into the Kaparaina Basalt Formation.

6. The age of *Orrorin tugenensis*

Although sample locations were not described, the geochronology of the Late Miocene strata in the Baringo Basin including the Lukeino Formation was reported by Hill et al. [7] and Kingston et al. [9]. According to these authors, whole rock and plagioclase K–Ar ages of the Kabarnet Trachyte range from 6.36 ± 0.08 Ma to 6.20 ± 0.26 Ma, and a sanidine K–Ar age from the base of the Lukeino Formation was 6.06 ± 0.13 Ma, and feldspar K–Ar ages of the Kaparaina Basalt are 5.9 ± 0.9 Ma and 5.65 ± 0.13 Ma. Recently Deino et al. [5] published that $^{40}Ar/^{39}Ar$ ages of anorthoclase phenocrysts from a lapilli tuff in the upper Lukeino Formation and within the Kaparaina Basalts were 5.73 ± 0.05 Ma and 5.72 ± 0.05 Ma, respectively, as mean values. In general, the K–Ar ages of the Kabarnet Trachyte and Kaparaina Basalt determined in this study are consistent with those published by Hill et al. [7] and Deino et al. [5]. The anorthoclase K–Ar age from the pumiceous lapilli tuff of the upper Lukeino Formation was 5.66 ± 0.14 Ma, and is consistent with the age (5.73 ± 0.05 Ma) of the lapilli tuff published by Deino et al. [5], which is stratigraphically correlated with it.

Magnetostratigraphic studies were also done by Deino et al. [5], who concluded that the upper part of the Lukeino Formation at Kapcheberek was deposited during Chron C3r. However, they did not locate normal polarity in the lowest part of the Lukeino Formation, although it was recognised by Dagley et al. [4]. In the magnetostratigraphic study reported here, it is very important that a normal/reverse magnetic polarity boundary was recognised within the Kapgoywa Member, the lower part of the Lukeino Formation.

7. Conclusions

Based on a combination of radiogenic ages and magnetostratigraphy, it is deduced that the magnetic polarity change from reverse to normal from the Kabarnet Trachyte to the lower Lukeino Formation corresponds to the boundary between Chrons C3An.1r and C3An.1n, which is aged 6.05 Ma according to Wei [15], 6.06 Ma according to Baksi [1], and 6.14 Ma according to Cande and Kent [3]. Likewise, the transition from normal to reversed magnetisation within the lower part of the Lukeino Formation corresponds to the boundary between Chrons C3An.1n and C3r, which is 5.83 Ma after Wei [15] and Baksi [1], and 5.89 Ma according to Cande and Kent [3].

It is concluded, on the basis of K–Ar ages and magnetostratigraphy, that the Lukeino Formation, which yielded *Orrorin tugenensis*, was deposited between 6.0 and 5.7 Ma. The Kapsomin hominid specimens that are the most important are between 5.9 and 5.8 Ma.

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