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GEOLOGY, GEOCHEMISTRY, AND STRATIGRAPHY OF THE LEMUDONG'O FORMATION, KENYA RIFT VALLEY

STANLEY H. AMBROSE
Department of Anthropology
University of Illinois, 109 Davenport Hall, 607 S. Mathews Ave.
Urbana, Illinois 61801-3636

CHRISTOPHER M. NYAMAI, ELIUD M. MATHU
Department of Geology
University of Nairobi, P.O. Box 30197-0100
Nairobi, Kenya

AND **MARTIN A. J. WILLIAMS**
Department of Geographical & Environmental Studies
Adelaide University
Adelaide SA 5005, Australia

ABSTRACT

The Lemudong'o Formation is defined here as part of a late Miocene to Late Pleistocene sequence of stratified lavas, air-fall and waterlain tuffs, lacustrine, alluvial, and fluvial sediments, and paleosols, that crop out over an approximately 25 × 50 km area on the western margin of the southern Kenyan Rift Valley, approximately 100 km west of Nairobi. The study area is deeply incised by three major permanent river systems that expose sediments of three late Neogene lake basins. The Lemudong'o Formation comprises deposits of the second paleolake basin, which formed during the late Miocene. Stratigraphic sections in several localities are described and correlated in this report, the Lemudong'o Formation is defined, and a basin sedimentary history and environmental reconstruction is proposed.

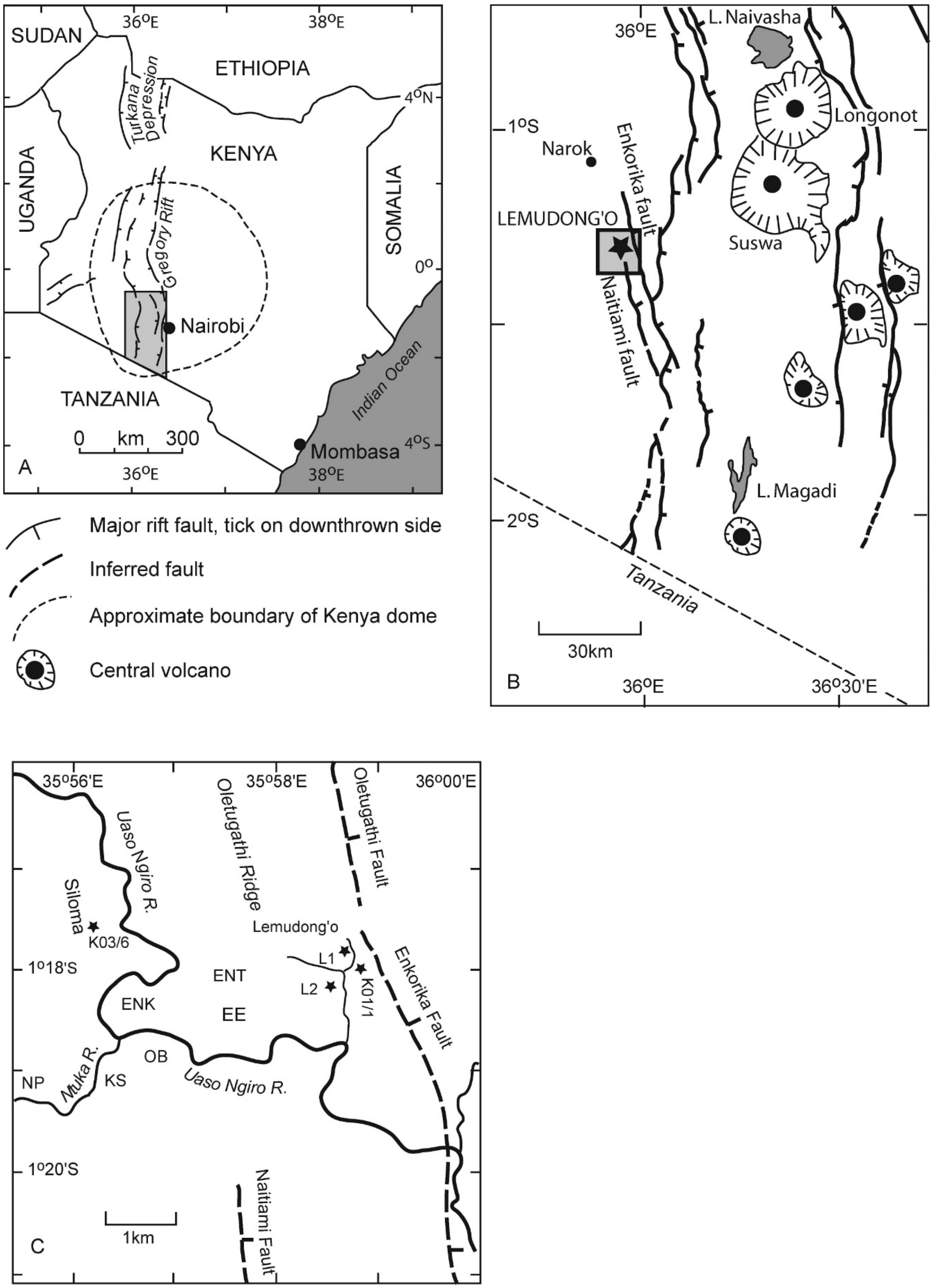
The Lemudong'o Formation has three main phases of sedimentation with a total thickness of 135 m. Phase 1 is represented by predominantly lacustrine and lake-margin siltstones, mudstones, and sandstones. Phase 2 comprises paleosols in the basin center, and fluvial and alluvial sediments on the eastern basin margin. Phase 3 comprises mainly waterlain tuffs and silts, capped by a welded tuff. Phase 2 may reflect a more arid climate, or a lower basin-overflow elevation.

Four tuffs in upper phase-1 mudstones in Lemudong'o Gorge are dated to 6.12–6.08 Ma. The main fossil-bearing horizons at Lemudong'o Gorge Locality 1 lie between, and immediately above, the dated tuffs. Fossils are associated with beach and/or deltaic sands and fine gravels, and silty and sandy claystones representative of an intermittently flooded lake margin.

Introduction

The Lemudong'o Formation is located in the South Narok District of Kenya, approximately 30 km south of Narok town and 100 km west of Nairobi (Figure 1). The regional geological sequence is exposed over an approximately 25 × 50 km area west of the western margin of the southern Kenyan Rift Valley in the confluences and lower reaches of the Uaso Ngiro, Ntuka, and Seyabei river valleys and their seasonal tributaries. The outcrops are characterized by thick sequences of stratified lavas, air-fall and waterlain tuffs, ignimbrites (welded tuffs), and alluvial, fluviolacustrine sediments and paleosols of late Miocene to Late Pleistocene age.

The geology of this region was first described and mapped by J. B.Wright (1967) for the Geological Survey of Kenya. He reconstructed a stratified sequence of three major ancient lake-basins and two smaller isolated lake basins that he thought were formed during the Pliocene and early Pleistocene. The major objective of this report is to describe the stratigraphic sequence of Wright's second paleolake. In this study we refer to deposits of this lake as the Lemudong'o Formation, after Lemudong'o


SUDAN
ETHIOPIA
UGANDA
KENYA
SOMALIA
TANZANIA
Turkana Depression
Gregory Rift
Nairobi
Mombasa
Indian Ocean
36ºE
38ºE
4ºN
0º
4ºS
0 km 300
A
Major rift fault, tick on downthrown side
Inferred fault
Approximate boundary of Kenya dome
Central volcano
L. Naivasha
Longonot
Suswa
Narok
LEMUDONG'O
Enkorika fault
Naitiami fault
L. Magadi
Tanzania
1ºS
2ºS
36ºE
36º30'E
30km
B
35º56'E
35º58'E
36º00'E
1º18'S
1º20'S
Uaso Ngiro R.
Oletugathi Ridge
Oletugathi Fault
Siloma
K03/6
Lemudong'o
L1
L2
K01/1
Enkorika Fault
ENT
ENK
EE
OB
NP
KS
Muka R.
Naitiami Fault
1km
C

Gorge, the location of a major fossil site. Masai place names are used for all localities. We will briefly summarize previous geological research and regional and local geology, describe the key stratigraphic sections, define the Lemudong'o Formation, and present a provisional reconstruction of its sedimentary history.

Wright (1967) conducted detailed geological work in the area covered by latitude 1° 00′ S to 1° 30′ S and longitude 35° 30′ E to 36° 00′ E. Crossley (1979) described the stratigraphy, structure and geochronology of the western margin of the rift from 1° 30′ S to 2° 0′ S. Waibel and McDonough (1977) conducted a brief survey of archaeological and paleontological sites in the Ntuka River valley for the University of Massachusetts archaeological research project in 1976. Archeological surveys and excavations in the study area by the University of Illinois team (Kyule et al., 1997; Ambrose et al., 2000, 2003; Hlusko et al., 2002) have identified over 100 new archeological sites and several paleontological occurrences since 1994. University of Illinois team members made numerous brief visits to Lemudong'o from 1994 to 2006. Leslea Hlusko directed intensive paleontological work at Lemudong'o Locality 1 and other sites from 2001 to 2004 (Ambrose, Kyule, and Hlusko, 2007). Deino and Ambrose collected tuffs for dating at Lemudong'o 1 and 2 in 2001. Williams measured and described stratigraphic section at Ol Doinyo Siloma and Lemudong'o in 2001 and 2003, and Ambrose and Williams described two excavated stratigraphic sections of the lower fossil-bearing horizons at Lemudong'o 1. Ambrose, Mathu and Nyamai measured sections at Lemudong'o Gorge, Enamankeon and Kasiolei, and collected samples for petrographic and geochemical analyses during three brief field seasons in 2004–05.

Geological Setting

Regional geology

The Lemudong'o Formation lies on the western shoulder of the Gregory Rift Valley in southern Kenya. The southern section of the rift is superimposed on an uplifted region known as the Kenya Dome (Figure 1A). Prior to the upwarping of the Dome, the region was a peneplaned surface of Precambrian rocks (Mathu and Davies, 1996, p. 522). During the early Miocene, before 15 to 12 Ma, the margins of the future rift began to warp downwards. Faulting of the western margin of the rift, forming a half-graben, commenced during the late Miocene prior to 6.9 Ma (Crossley, 1979). The focus of faulting gradually shifted east towards the rift axis, and recent faulting has been concentrated within an axial zone less than 10-km wide (King, 1978; Shackleton, 1978; Birt et al., 1997).

Volcanism on the west side of the nascent southern Kenya rift began around 15 to 12 Ma with eruption of extensive melanephelinite lavas (Crossley, 1979). By 6.9 Ma more silicic lavas such as trachytes flooded the rift floor and overflowed onto its flanks. During the past 2 Ma volcanism has largely been confined to the rift floor, including a chain of silicic caldera volcanoes including Suswa and Longonot (Figure 1B) (Baker et al., 1972; Williams, 1972; Baker, 1986; Macdonald et al., 1994).

Local geology

The Lemudong'o Formation lies ~40 km east of the western margin of the rift, and 15–20 km west of the N/S-trending late Precambrian Basement System metamorphic rocks of the Loita Hills. Stratigraphic sections described in this report are located in the middle of the eastern margin of the area studied by Wright (1967) from 1° 15′ S to 1° 20′ S, and 35° 55′ E to 36° 0′ E (Figure 1C, Figure 2). The geology here is dominated by Neogene volcanics and sediments of the rift system, with a few exposures of the underlying metamorphic rocks of the Neoproterozoic Mozambique Belt (Figure 3). Photographs of the type-section areas of Enamankeon and Lemudong'o Locality 1 are shown in Figures 4 and 5.

Basal Neoproterozoic Mozambique Belt metamorphic rocks comprising gneisses, schists and quartzites, are exposed at an isolated inselberg named Ol Doinyo Oborosoit (hill of white rock) on the south side of the Ewaso Ngiro River near Kasiolei; a small quartzite outlier extends north of the Ewaso Ngiro River below Emowuo Enkijape. The overlying beds comprise Neogene volcanics and sediments. Earlier Neogene volcanic rocks include melanephelinite and olivine melanephelinite lavas, phonolites, basalts, alkali basalts, and trachytic ignimbrites and trachytes (Wright, 1967). Later Neogene beds include mudstones, siltstones and sandstones, tuffs, and sediments that are in part lacustrine, welded tuffs, trachyte lavas, paleosols (fossil soils), boulder beds, and Uaso Ngiro pebble beds (Figure 3).

The folded metamorphic rocks of Ol Doinyo Oborosoit are resistant to erosion and would have formed an area of high relief during deposition of the Lemudong'o Formation. The Enkorika and Naitiami faults (Figure 1C) are oriented NNW-SSE and are downthrown to the east. The Oletugathi Ridge parallels these faults on the east side of the Ewaso Ngiro River. The Siyabei River valley defines the east side of this ridge. Faulting controls drainage patterns in this region, particularly the trends of some sections of the Uaso Ngiro and Ntuka rivers and their tributaries. Beds of the Lemudong'o Formation are generally horizontal in the center and west side of their distribution area, with occasional tilting near minor faults. However, the elevation of the top of the Lemudong'o Formation decreases by ~70 m between Kasiolei and Lemudong'o, suggesting downwarping, undetected faults and/or subsidence to the east, toward the modern rift valley. The Enkorika fault forms a pronounced, deep, straight gully exposing the main sedimentary sequence at Lemudong'o Gorge. At

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Figure 1. Location of Lemudong'o in relation to major structural features of the Kenya (Gregory) Rift Valley. A, location of the Kenya Dome and the Gregory Rift Valley, adapted from fig. 7 in Mathu and Davies (1996). The shaded trapezoidal area in map A shows the location of map B. B, major faults and volcanic centers in the southern Gregory Rift Valley, adapted from fig. 5 in Baker (1986). The shaded rectangle in map B indicates the area of the map C, which shows the location of sections in relation to major geological and geographic features. Key to map C: L1, Lemudong'o Locality 1; L2, Lemudong'o Locality 2; K01/1, Lemudong'o 1-S step trench 1; K03/6, Ol Doinyo Siloma section; ENK, Enamankeon; KS, Kasiolei; OB, Ol Doinyo Oborosoit; ENT, Entapot; EE, Emowuo Enkijape.

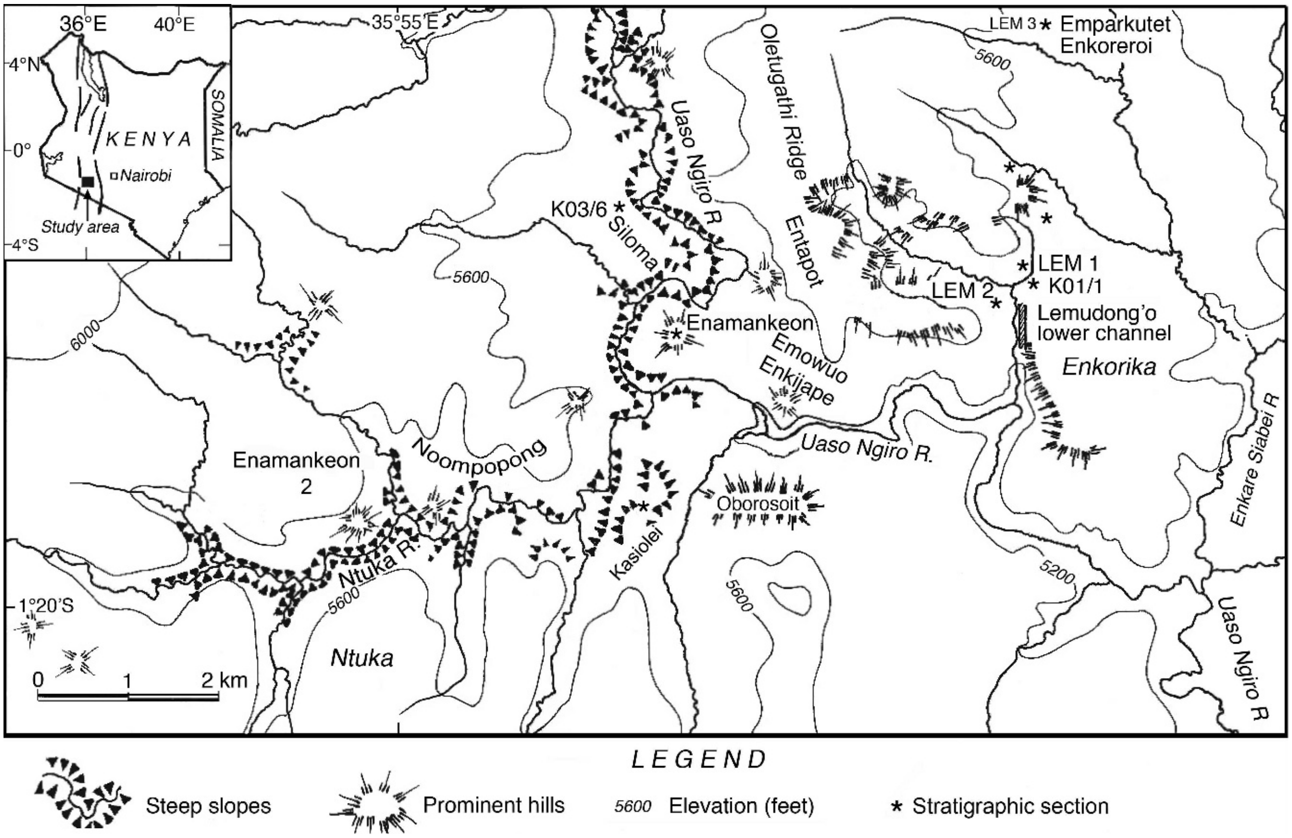

Figure 2. Map of locations of Lemudong'o, Enamankeon, Siloma, Kasiolei and other major localities in relation to the major topographic features of the research area. The inset map of Kenya is adapted from fig. 7 in Mathu and Davies (1996).

Lemudong'o Locality 1, a minor fault oblique to the Enkorika fault separates the north (Lemudong'o 1-N) and south (1-S) sedimentary sections.

Materials and Methods

Figure 2 shows the locations of major sections described in this report. The Uaso Ngiro River separates the Lemudong'o, Enamankeon, Emowuo Enkijape, and Entapot sections to the east from Kasiolei and Ol Doinyo Siloma on the west, respectively; Kasiolei lies on the south side and Siloma on the north side of lower Ntuka River valley near the confluence with the Ewaso Ngiro River (Figure 2). Similar sequences are exposed at several outcrops up to 10 km west and northwest of Lemudong'o at Enamankeon 2, Emowuo Enkijape, Entapot, Kasiolei, and Noompopong.

Sections were measured using a GPS, Jacob's staff, and clinometer. Lithostratigraphic units are formally defined and named using the conventions of the North American Stratigraphic Code (NACSN, 1994) and the *International Stratigraphic Guide* (Salvador, 1994).

A total of 70 samples from three sections were collected for major and trace element analyses by atomic absorption spectrophotometry (AAS) at the Kenya Geological Survey, Nairobi. Petrographic studies of rock sample thin sections with transmitted polarizing microscopy were performed at the University of Nairobi. Correlations of beds between stratigraphic sections are based on stratigraphic relationships, lithology, and field and laboratory petrography and chemical composition. Trace element and petrographic analyses are intended to be reported elsewhere by Nyamai and Mathu.

Stratigraphy

The lowest Neogene lithostratigraphic units that unconformably overlie the Neoproterozoic metamorphic rocks are largely melanephelinite lavas (Table 1). Wright (1967, p. 25–31) considered the overlying pyroclastics to be mainly "ashes and tuffs, in part waterlain" that were subaerially deposited in three Pleistocene lake basins. Radiometric dates of ~6 Ma (Ambrose et al., 2003; Deino and Ambrose, 2007) show that the age of the second lake is late Miocene, so the time range of these three lake basins is likely to be late Miocene to Pliocene. Beds of the oldest lake, mapped by Wright (1967, p. 28) as the "2nd (lower level) Uaso Ngiro lake," lie mainly south of 1°20′ S. Wright's (1967, p. 31) second-oldest lake basin, which he called the "1st Uaso Ngiro lake," lies mainly north of 1°20′ S. We designate the beds of this lake as the Lemudong'o Formation. The youngest lake, mapped by Wright as the "Seyabei lake," lies mainly north of 1°15′ S, but it caps outcrops of the Lemudong'o Formation on the Oletugathi ridge on the east side of the Ewaso Ngiro valley, including sections at Lemudong'o. The highest outcrops of the Seyabei lake reach an elevation of 1794 m at Entapot. Wright (1967) reconstructed the minimum extent of the Lemudong'o Formation lake as 16 km from north to south and 8 km from east to west. The south shore of this lake is partly defined by Ol Doinyo

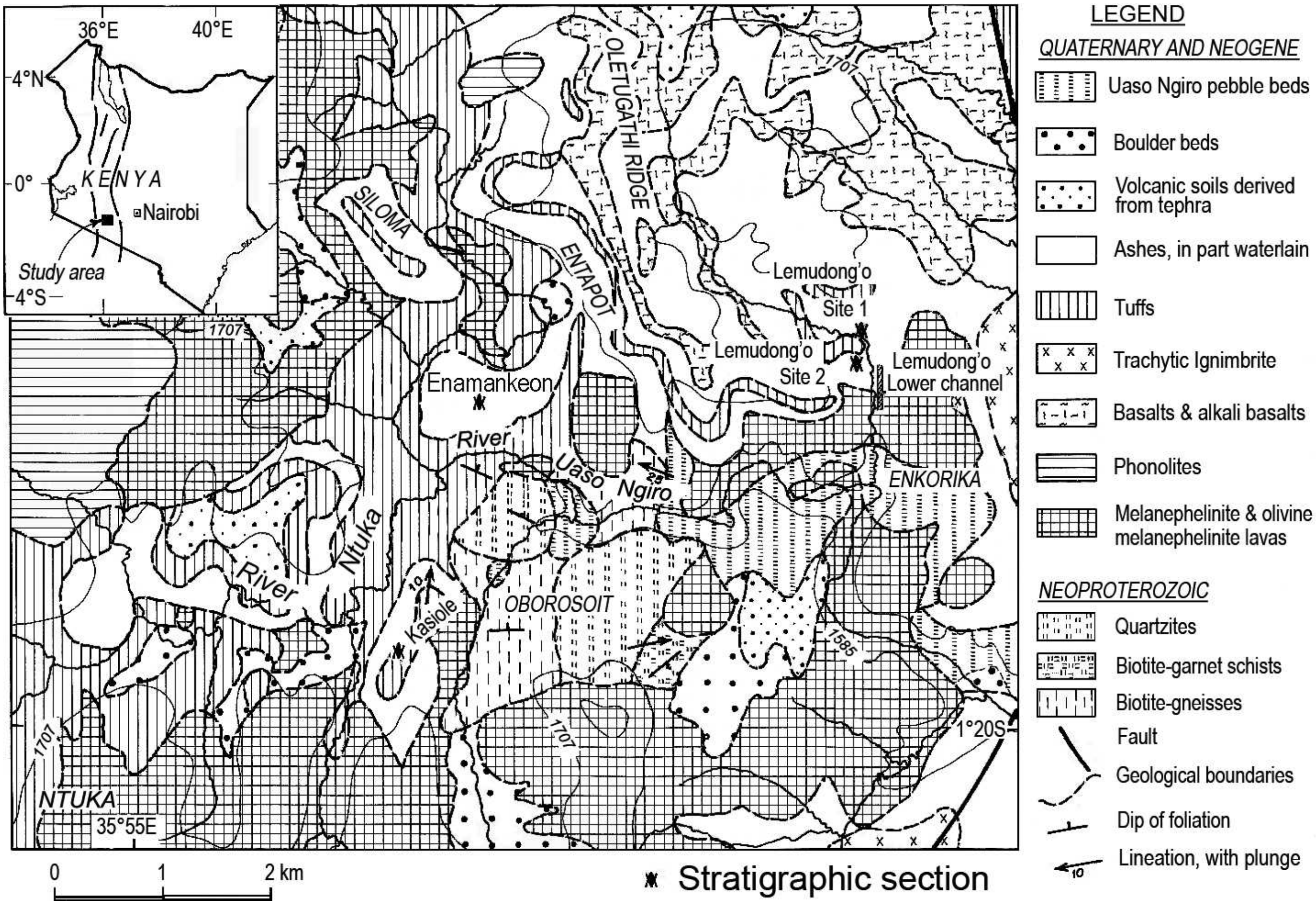

Figure 3. Geological map of Narok area (map modified after Wright, 1967), showing the locations of stratigraphic sections at Lemudong'o, Enamankeon, Kasiolei and Siloma.

Oborosoit and the west shore is bounded by contact with a variety of lavas and sediments. The eastern and northern margins of the basin are poorly exposed and remain poorly defined.

Sections and locations studied in this report will be described from west to east. Bed boundaries are conformable unless noted as unconformable. Elevations are taken from GPS readings. Figure 6 shows the stratigraphic sections of Kasiolei, Enamankeon West, Siloma, Lemudong'o 2, and Lemudong'o 1-S. The view from the top of the section at Kasiolei looking northeast toward Siloma and Enamankeon (Figure 4) shows that upper beds of the Lemudong'o Formation can be visually traced between sections, and are not deformed, tilted or faulted in this part of the paleobasin. The Lemudong'o Gorge sections (Figure 5) are not in direct line of sight of the Enamankeon outcrops, and correlated strata lie at lower elevations, but the major tuffs in the middle and upper part of the Lemudong'o sections are traceable in outcrops throughout the paleobasin (Figures 3 and 6). A fault with substantial displacement occurs between Lemudong'o 1-S and 1-N sections, and distinctive marker beds of the Lemudong'o Formation are absent from Lemudong'o 1-N. Lemudong'o 1-N lies closer to the rift axis and thus may be downfaulted rather than uplifted, and may correlate with the younger beds of Wright's (1967) Seyabei lake.

Representative sections of the central and western side of the paleolake basin at Kasiolei and Enamankeon West are described below (Figure 6). The Siloma sequence closely resembles that in the upper half of the Kasiolei and Enamankeon West sections and does not warrant separate description.

Kasiolei

Kasiolei is located at 1°19′35″ S, 35°55′58″ E; the elevation of the top of the section is 1721 m. The measured section lies south of the Ntuka River west of Ol Doinyo Oborosoit. Metamorphic rocks lie unconformably beneath $>$ 30 m of lavas and tuffs, comprising phonolite, basalt, and gray ignimbrite (welded tuffs) with abundant clasts ($<$ 3 cm) of fiamme (glassy, compacted pumice). Sandy conglomerates unconformably overlie the gray ignimbrite, followed by brown, clayey mudstones with thin bands of interstratified sands, gravels, calcretes, and tuffs (~21 m). Gray, poorly consolidated coarse-grained cindery laminated tuff (~3 m), with red/purple laminations in the middle, lies beneath another series of brown mudstones with calcrete horizons and poorly consolidated gray tuff (~16 m). Yellow-brown laminated and banded silts (~7 m) overlie the mudstones, followed by a pale-yellow tuff with devitrified pumice inclusions to $>$ 1 cm (~8 m). Gray ignimbrite (~11 m) caps the section.

Outcrops at Noompopong, upstream on the Ntuka River, ~2 km west of Kasiolei, have a closely similar sequence, including the basal gray ignimbrite, mudstones, gray cindery laminated tuff with red/purple laminations within the mudstone beds, and the

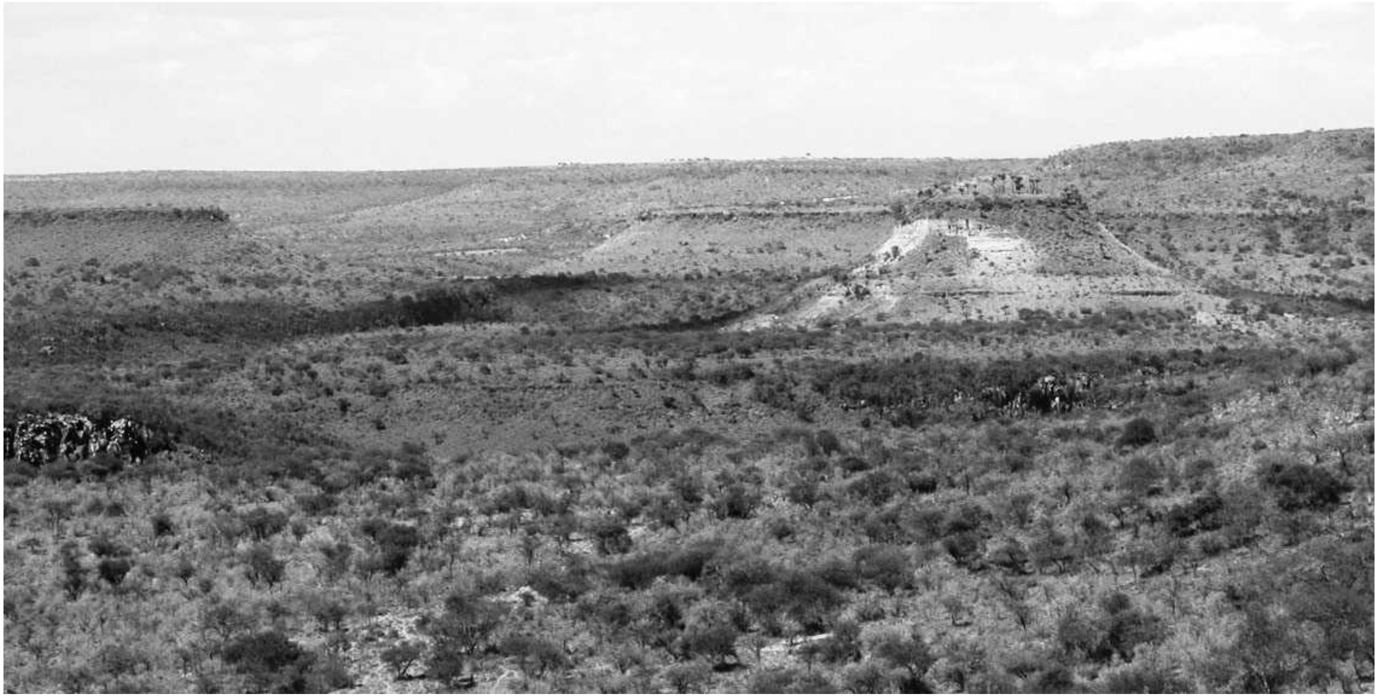

Figure 4. Photograph of the area around Enamankeon hill, a flat-topped erosional remnant exposing sections of stratified waterlain and terrestrial sediments and tuffs. The view is toward the northeast from Kasiolei, with Ol Doinyo Siloma on the left, Entapot on the right, and Oletugathi Ridge in the background. The cliffs in the foreground, which rise above the deeply incised Ntuka River (left) and Ewaso Ngiro River (right), are exposures of the basal gray ignimbrite that unconformably underlie the Lemudong'o Formation in the western half of the paleobasin. Enamankeon and surrounding outcrops are conformably capped by the upper gray ignimbrite, which defines the upper boundary of the Lemudong'o Formation. Sediments of Wright's (1967) Seyabei lake lie above the upper gray ignimbrite below the horizon on Oletugathi Ridge. The horizontal scarp near the base of Enamankeon is the gray cindery tuff. The light yellow-brown rocks exposed on steep slopes near the top of the section are laminated lacustrine-siltstones and the vertical wall above is the yellow tuff.

pale-yellow tuff and gray ignimbrite at the top of the section at ~1712 m.

Enamankeon

Enamankeon is an isolated, flat-topped, conical hill forming an erosional remnant of horizontally bedded sedimentary rocks and tuffs in the center of the Ewaso Ngiro River valley east of Entapot (Figure 4). Fossil-bearing sediments are exposed on the east, north, and west sides of the base of the hill. The longest stratigraphic sequence in the Lemudong'o Formation is exposed on the west side of Enamankeon, so it is designated as the type section (stratotype).

Enamankeon West

Enamankeon West is at 1°18′33″ S, 35°56′40″ E. The elevation at the top of the section is 1714 m. The Enamankeon West sequence begins at the river bank at an elevation of 1589 m with a dark gray ignimbrite with widely spaced joints (> 7 m), overlain by phonolite (~7.5 m), and massive gray ignimbrite (~40 m) whose upper surface is incised into a deep E-W orientated channel, with up to 35 m of vertical relief. Within this channel, micritic white carbonate (0.7 m) capped by 40 cm of arkosic carbonate-cemented coarse sand (0.4 m) unconformably overlies the ignimbrite, followed by brown-gray clayey mudstones with interstratified lenses of cemented sandstones and poorly-sorted subrounded gravel conglomerates and two calcrete beds that may be tufas (total thickness from 1st to 3rd calcrete ~20 m). Similar clayey and sandy mudstones (~32 m) overlie the upper calcrete. Mammal fossils occur from beneath and within the upper calcrete to near the top of the mudstones. A thin layer of yellow to red-brown massive siltstone (~0.25 m) overlies a weakly developed brown paleosol with carbonate rootcasts and spherical carbonate nodules up to 10 cm in diameter (~0.4 m). Poorly consolidated dark brownish-gray massive cindery tuff (~2.2 m), with black pumice clasts up to 1.5 cm and large black, spherical carbonate nodules at the base, overlies this siltstone and paleosol. A thin layer of coarse tuff grit (5–7 cm) within this tuff marks the transition to ~5 m of dark-gray coarsely laminated waterlain cindery tuff. Brown, massive well-sorted silts overlie this tuff, and grade upward to a series of superimposed reddish-brown to yellowish-brown sandy and silty loam paleosols with sub-rounded blocky- to columnar-blocky structure and occasional mammal fossils (~11 m). Carbonate nodules > 5 cm in diameter occur in some paleosol horizons. Massive, grayish siltstone caps the paleosol bed. The siltstone is overlain by poorly consolidated gray tuff (~1.2 m). Light-gray to light-brown massive sandy tuffaceous to blocky clayey rhythmically banded silts (~3.5 m) follow, overlain by gray clayey columnar-laminated silts (2.5 m). Yellow tuff (~7 m), laminated near the base, becoming massive with devitrified green and yellow pumice, overlies the lacustrine silts. The top of the sequence comprises massive, poorly welded gray ignimbrite (~3 m) that grades into more consolidated gray ignimbrite (~5 m).

Figure 5. Photograph of Lemudong'o Gorge Locality 1, showing the positions of the 2001 and 2004 step trenches (T1, T2), yellow, laminated lacustrine siltstones (1), fossil-bearing coarse gravelly sandstone (2) and finer-grained fossil-bearing clayey mudstones (3), the green tuff (4, behind tree), the speckled tuff (5), silty to sandy mudstones (6), undescribed gray sediments (7), brown-gray mudstones (8) and poorly sorted sandstones (9).

Enamankeon East

Enamankeon East, a gully on the east side of Enamankeon, has a pale blue-gray massive ignimbritic tuff > 1.7 m thick at the base of the section (1°18′31.2″ S, 35°56′53.4″ E, elevation 1621 m). This tuff is overlain by mudstones (~30 m) with terrestrial vertebrate fossils. The mudstones are overlain by cindery tuff (~7 m) and the overlying strata described in the west section. The mudstones in the East section span approximately the same elevations as those above the third carbonate bed in the West section (1624–1656 m). The blue-gray tuff does not appear in the West section, but one or more lithologically dissimilar tuffs crop out in an analogous position in most sections at the base of the Oletugathi Ridge at Emowuo Enkijape and other outcrops between Enamankeon East and Lemudong'o 2.

Lemudong'o Gorge

Lemudong'o Gorge is a fault-controlled, deeply incised gully system bounded on the east by the Enkorika Fault (Wright, 1967). The most productive late Miocene fossil site in the gorge is Locality 1-S, which was initially given an archaeological site designation GvJh15 in the Standard African Site Enumeration System. Locality 2 was originally designated GvJh32. The base of the sedimentary sequence in the lower Lemudong'o channel is defined by an unconformable contact with weathered basalt at an elevation of ~1569 m at 1°18′38″ S, 35°48′53″ E. Mudstones, lacustrine silts, fluvial sands and pale blue-gray laminated tuffs are exposed in several outcrops upstream along the narrow, steep-sided channel of the lower Lemudong'o Gorge, where sections are difficult to measure and GPS readings are inaccurate. Lacustrine silts also occur in the west gully of Lemudong'o 2 and 1-S. Lacustrine beds do not occur in the lower mudstones further west at Kasiolei, Siloma and Enamankeon.

Lemudong'o Locality 2

Lemudong'o Locality 2 is at 1°17′59″ S, 35°59′38″ E. The top of the section is at ~1634 m. The Lemudong'o 2 section is exposed in a small channel on the west side of the gorge. The upper third of this section is partially obscured by trees and shrubs, which reduced the accuracy of GPS elevation readings. The sequence begins at 1577 m with clayey to sandy mudstones and sands (> 1 m) overlain by a pale blue-gray tuff, laminated at the base, becoming massive and cindery upward (~1.6 m), overlain by mudstones (~9 m), and a pale blue-gray coarsely laminated tuff (2.2 m) that dips 6° SSW. Poorly sorted gravelly silt, fining upward to cemented sandstone, siltstone, and claystone (~1.8 m), capped by a thin (1–3 cm) platy carbonate, underlies the mottled

Table 1. Summary of the regional volcanic stratigraphy of Narok (modified from Wright, 1967, p. 14).

Lithostratigraphy	Age
7. pyroclastics (tuffs and ashes) 6. olivine melanephelinite plugs 5. Angata Naado trachytes 4. ignimbrites (Plateau trachytes) 3. alkali basalts	Pleistocene & Pliocene
Unconformity	
2. phonolites 1. Kishalduga melanephelinites	Miocene
Unconformity	
Mozambique-belt metamorphic rocks	Neoproterozoic

and cindery third pale-blue-gray tuff (0.6 m). Brown silty claystone fining upward to green waxy claystone (1.6 m) underlies the fourth blue-gray tuff (1.9 m), which is laminated at the base, becoming massive upward. Brown clayey mudstone (~1.6 m) underlies a bright white fine-grained tuff (0.6 m). Radiogenic-argon dates of 6.10 ± 0.03, 6.087 ± 0.013 and 6.12 ± 0.07 Ma were obtained for the third and fourth gray tuffs and the white tuff, respectively (Ambrose et al., 2003; Deino and Ambrose, 2007). Waxy claystone (0.5 m) laminated siltstones (3.3 m), and clayey to sandy to silty mudstones (~9.5 m) overlie the white tuff. Dark-grey unconsolidated fine-grained laminated tuff (0.5 m) overlies the claystones. Pale-yellow to gray to green fine-grained tuff (~7 m) with large pale-yellow and green devitrified pumice clasts (< 2 cm) lies above the gray ash. Gray ignimbrite (~4 m), overlain by blue-gray trachyte lava (10.5 m) forms the top of the outcrop.

Lemudong'o Locality 1 South

Lemudong'o Locality 1 South is located at 1°18′1″ S, 35°58′44″ E, 1648 m (Figure 4). The Lemudong'o 1-S section is exposed in the upper gorge and in a WNW-trending side gully that forms the southern boundary of the outcrops. Figure 5 shows the view to the west across the main gorge toward the lower end of the west gully, and the locations of step trenches T1 and T2, excavated in 2001 and 2004. Numbers in Figure 5 refer to features described below. Thicknesses of some beds vary widely across the exposures, and beds tilt ~7° NNE in the 2004 step trench (Figure 5, T2). Dense bush and trees obscure the highest parts of the exposures. A fault crosses the north end of the main gorge, defining the boundary with Lemudong'o 1-N. Beds upstream from this fault comprise mainly sands, silts, and clayey sands with three pale brown, pale gray and pale green fine-grained tuffs that do not correlate with those in Lemudong'o 1-S. They may be downfaulted beds from Wright's (1967) youngest paleolake, and will not be described in detail in this report.

Brown clayey mudstones (> 1 m) form the base of the 1-S section. Light yellow to gray and pale brown sandy to clayey laminated siltstone (0.4 to > 4 m) lies above the mudstones, and it thickens substantially toward the west gully (Figure 5, 1). Microscopic study of this silt by Frances Williams revealed no diatoms. Gray-to-brown coarse sandy to well-sorted fine gravelly mudstone (~0.8-2 m) with dark green mammal fossils, sometimes rolled (Figure 5, 2), fines upward to brown-gray sandy to clayey siltstone (~3.6 m) with light-brown to pink well-preserved fossils and abundant round iron pisoliths (~5 mm) (Figure 5: 3). A lens of dark-green tuff (0.2 m) fills an indistinct small shallow channel in the lower sandy/gravelly claystones at the base of the outcrop (Figure 5, 4, behind tree). Pale-gray tuffaceous silt/fine sandstone grades laterally to a pale-yellow speckled tuff (0.2 m), dated to 6.08 ± 0.019 Ma (Figure 5, 5). The speckled tuff contains a micromammal breccia and seeds of *Celtis zenkeri*. Brown-gray-green silty to sandy mudstones continue for ~4 m above the speckled tuff (Figure 5, 6). A light gray bed that has not been sampled and described lies within the upper clayey mudstones (Figure 5, 7). The overlying brown-gray mudstones (Figure 5, 8) coarsen upward to gray clayey to silty poorly sorted sandstones (~12 m) (Figure 5, 9). Brown silicified tuff directly above the main fossil-bearing exposures grades laterally to a light-yellow-brown laminated to massive tuff (~4 m) with devitrified pumice clasts < 2 cm. Gray ignimbrite (~4 m) overlies the yellow-brown tuff. Sandstones overlie the ignimbrite, indicating an unconformity beneath the blue-gray trachyte at the top of the section.

Lemudong'o Formation Definition, Distribution and Sedimentary History

The Lemudong'o Formation is named after exposures at Lemudong'o 1-S and 2, where the most productive fossil beds are located, and where the tuffs of the higher levels of the lower mudstone member have been radiometrically dated to 6 Ma (Ambrose et al., 2003; Deino and Ambrose, 2007). The maximum thickness of the volcanics and sediments in these stratigraphic columns is about 135 m at Enamankeon West. We designate this section as the type locality and stratotype for the Lemudong'o Formation because it is located near the center of the paleolake basin. The pale blue-gray tuff beneath the mudstones in the Enamankeon East section provides an uncertain link to the lower levels of sections on the Oletugathi Ridge and Lemudong'o Gorge.

The Lemudong'o Formation is defined as the conformable sequence of lacustrine, fluvial and alluvial sediments and tuffs that lie beneath the gray ignimbrite and yellow tuff in sections between Noompopong on the west, and Lemudong'o 1-S on the east (Figures 2, 3, and 6). The ignimbrite is the highest point on each outcrop in sections on the west side of this Formation, including Noompopong, Kasiolei, Siloma and Enamankeon. A thick bed of trachyte lava overlies this ignimbrite in sections on the east side of the paleobasin along the Oletugathi Ridge at Entapot, Emowuo Enkijape, Lemudong'o 2, and Lemudong'o 1-S. The trachyte lies unconformably above this ignimbrite at Lemudong'o 1-S. This unconformity defines the top of the Formation. The base of the Lemudong'o Formation at Kasiolei, Enamankeon and Siloma is defined by unconformable contact with the top of a sequence of dark gray tuff, phonolite and a dark gray ignimbrite that often contains fiamme. Weathered basalts lie unconformably beneath the basal Lemudong'o Formation

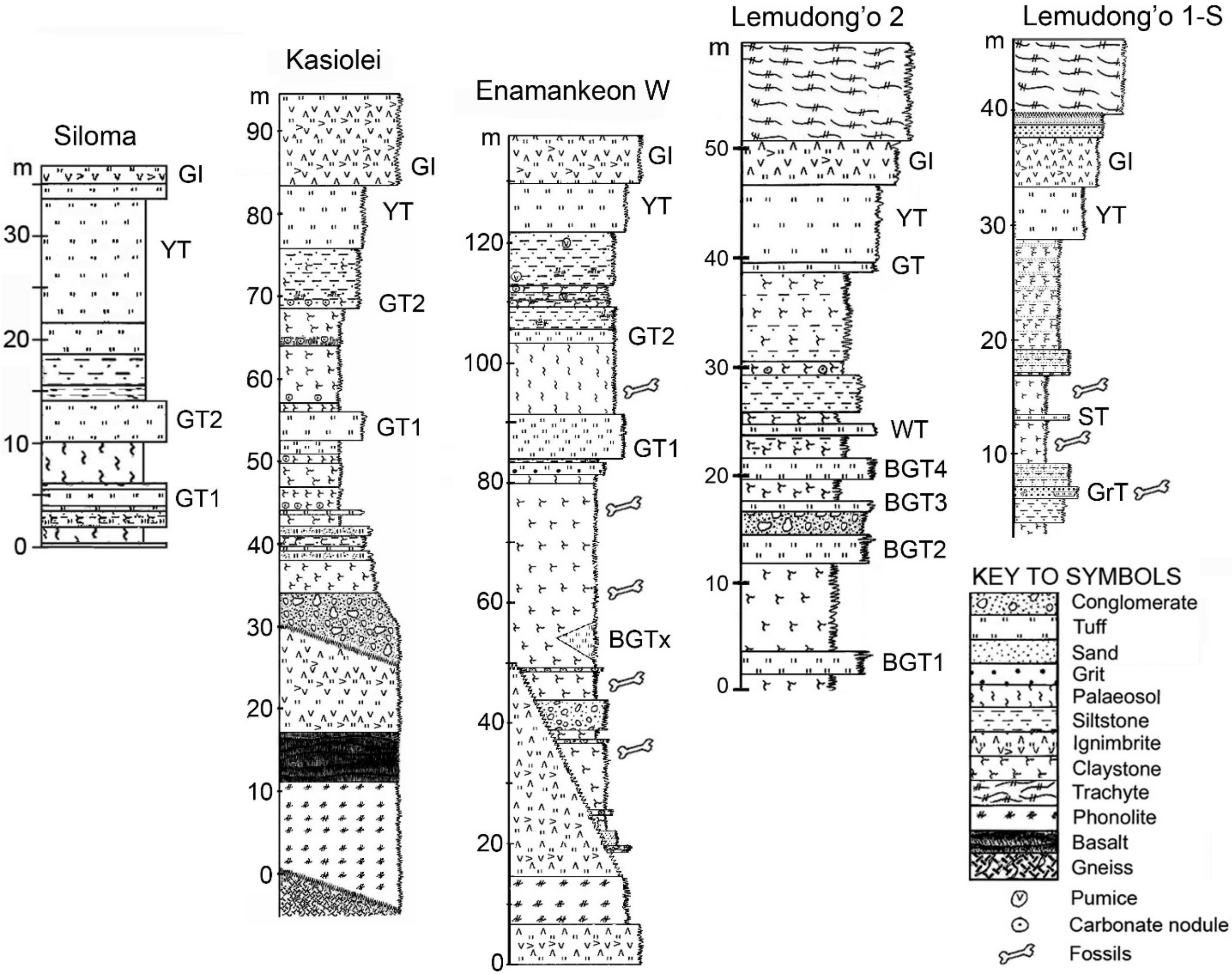

Figure 6. Stratigraphic sections of the sequences exposed at Siloma. Kasiolei, Enamankeon and Lemudong'o 2 and Lemudong'o 1-S, Narok area, southwest Kenya. Stratigraphic correlations between sections are indicated by abbreviations of tuffs: GI, upper gray ignimbrite; YT, yellow tuff; ST, speckled tuff; GrT, green tuff; GT, gray tuff; GT1, gray tuff 1; GT2, gray tuff 2; BGT1–4, pale blue-gray tuffs 1–4; BGTx, pale blue-gray tuff of uncertain correlation.

mudstones in most sections on the east and south side of the Oletugathi ridge, including Entapot and the lower Lemudong'o Gorge.

Three main sedimentary depositional phases are evident within the Lemudong'o Formation. The first phase comprises mudstones, siltstones, sandstones, and fine-grained laminated to massive tuffs, reflecting lake, lake margin, and small stream-channel depositional environments. The second phase of deposition includes predominantly alluvial, fluvial and subaerial sandstones, siltstones and paleosols. The third phase is primarily lacustrine siltstones, mudstones and tuffs, culminating in a thick lacustrine tuff (the yellow tuff) and the subaerial gray ignimbrite. These phases are discussed in more detail below.

The main widespread marker beds and distinctive beds with more restricted distributions within the Lemudong'o Formation are listed in stratigraphic order in Table 2. Within phase-1 deposits at Lemudong'o 1-S, Lemudong'o 2, and the Lower Lemudong'o channel six tuffs are interstratified with lacustrine siltstones and claystones and lake-margin mudstones. The lowest four tuffs are lithologically similar light-blue-gray, fine-grained laminated to massive tuffs. Outcrops on the west side of the Oletugathi Ridge at Entapot and Emowuo Enkijape contain a laminated pale-blue-gray tuff that may correlate with one of the four lithologically similar tuffs at Lemudong'o 2. Correlation with the blue-gray ignimbritic tuff at Enamankeon East remains to be demonstrated. The white tuff occurs only at Lemudong'o 2. Mudstones above the white tuff are overlain by lacustrine siltstones up to 9-m thick in the lower Lemudong'o Gorge and > 4-m thick in the west gully at Lemudong'o 1-S. Lacustrine siltstones do not occur in this stratigraphic position in sections north and west of Lemudong'o Gorge. A dark-green dense tuff lies within a small shallow channel in the coarse sandy to gravelly mudstones of the lowest fossil-bearing deposits above the lacustrine siltstones at Lemudong'o 1-S. The speckled tuff is

Table 2. Presence/absence of major (**bold**) and minor (regular type) marker beds, and their depositional modes in stratigraphic sections of the Lemudong'o Formation at LEM 1, LEM 2, Entapot, Enamankeon East and West, Kasiolei and Ol Doinyo Siloma. These correlations are also shown in Figure 6. Key: A, airfall or subaerial; F, fluvial; L, lava flow; M, lake-margin or shallow-water mudstones; U-, unconformity below; W, waterlain lacustrine; ?, uncertain correlation.

			Enamankeon			
Bed and depositional phase	**LEM 1**	**LEM 2**	**East**	**West**	**Kasiolei**	**Siloma**
trachyte (U-)	x	x				
			phase 3			
gray ignimbrite (A) GI	x	x	x	x	x	x
yellow tuff (A/W) YT	x	x	x	x	x	x
yellow siltstone (W)	?	?	x	x	x	x
gray tuff (W/A) GT2	x	x	x	x	x	x
			phase 2			
alluvium (A)	x	x				
paleosols (A)			x	x	x	x
gray cindery tuff (A/W) GT1			x	x	x	x
paleosol (A)				x		
			phase 1			
mudstones (M)	x	x	x	x	x	x
speckled tuff (A/M) ST	x					
green tuff (F) GrT	x					
fine gravels and sandstones	x					
laminated siltstones (W)	x	x				
white tuff (A/M) WT		x				
blue-gray mottled tuff (A/M) BGT4		x	?			
blue-gray cindery tuff (A/M) BGT3		x	?			
blue-gray laminated tuff (M/W) BGT2	x	?	?			
blue-gray laminated tuff (M/W) BGT1	x	?	?			
mudstones (M, U-)		x		x	x	x
			major unconformity			
gray ignimbritic tuff (A)				x	x	x
basalt (L, U-)					x	
phonolite (L)				x		
gray tuff (A)				x		
			major unconformity			
Proterozoic metamorphic rocks					x	

discontinuously stratified within the upper fossiliferous mudstones at Lemudong'o 1-S. The green and speckled tuffs are restricted to Lemudong'o Locality 1-S.

The transition to the second phase of sedimentation is marked at Enamankeon West by the paleosol with carbonate nodules underlying the gray cindery tuff. Phase-2 beds comprise siltstones, sandstones, and mudstones, and a series of brown paleosols that reach a maximum thickness of ~11 m at Enamankeon West. At Lemudong'o 1-S, sediments above the fossil-bearing mudstones coarsen upward, reflecting a shift to an alluvial-fan depositional environment. Depositional phase 3 marks a return to deeper water, with thick beds of lacustrine siltstones and tuffs at Enamankeon, Kasiolei. and Siloma. The lacustrine yellow tuff and overlying gray ignimbrite occur at the top of the Lemudong'o Formation in all sections studied.

The topography of the floor of the paleobasin included areas of high and low relief. The metamorphic rocks of Ol Doinyo Oborosoit would have formed the highest point on the paleolandscape, > 100 m above the basal gray ignimbrite. The gray ignimbrite beneath the basal mudstones at Enamankeon West and Kasiolei is deeply eroded, with at least 35 m of vertical relief, possibly reflecting an ancient landscape incised by a river channel. The weathered basalts exposed at the bases of outcrops at Entapot and the Lemudong'o lower channel may have formed a low ridge or line of low hills beneath the modern Oletugathi Ridge.

The earliest stages of deposition of the phase-1 mudstones first filled in the lowest points of the landscape. Upper phase-1 mudstone beds have a wider and more continuous distribution. A relatively deep lake occupied the Lemudong'o Gorge area. The presence of a lake in this part of the basin may reflect syndepositional subsidence of the southeast side of the paleobasin, toward the modern rift axis. Fossil-bearing horizons at Lemudong'o and Enamankeon lie above the lacustrine siltstones in mudstones that represent predominantly lake-margin environments. With the exception of crocodile and hippopotamus, aquatic fauna, including fish and shellfish are absent, suggesting lakes were too small and ephemeral to sustain aquatic (fish and shellfish) faunas. The terrestrial fauna at Lemudong'o 1-S suggests locally forested environments in a wider mosaic of humid grassy woodlands and woodlands (Ambrose et al., 2007). The thick paleosol horizons in phase-2 deposits at Enamankeon indicate a long period of soil formation in dry terrestrial environments. Fossils are present but are rare. Whether these paleosols reflect a period of drier climate, down-cutting of the basin outlet, or tectonic controls on lake levels remains uncertain. Lacustrine siltstones and thick beds of waterlain ash, including the yellow tuff, are found in depositional phase 3. Fossils have not been observed in these beds. Climate change, volcanic eruptions, and/or tectonic activity may have all contributed to high lake levels during the last phase of sedimentation in the Lemudong'o Formation.

Summary and Conclusions

The Lemudong'o Formation represents sediments and volcanic tephra deposited in a terminal Miocene (6 Ma) rift-valley-margin lake basin. The topography of the landscape on which the sedimentary sequence was deposited was heavily eroded. The sedimentary sequence includes claystones, siltstones, sandstones, tuffs, and paleosols. Depositional environments include shallow and deep lakes, lake margins, swamps, and subaerially exposed terrestrial landscapes with paleosols, airfall tuffs, and ignimbrites. Thinner beds of predominantly waterlain ash are common in the middle levels of phase 1 of the sedimentary sequence on the east/southeast side of the paleobasin (Enamankeon East to Lemudong'o 1-S), but are absent from the west side of the basin (Enamankeon West to Kasiolei and Noompopong). This is consistent with prevailing wind directions from the east, which would have carried airfall tephra from Rift Valley volcanoes. Three major sedimentation phases have been recognized, representing a sequence of wetter, drier, and wetter environments. Vertebrate fossils are most abundant in the mudstones of the upper half of phase 1.

The stratigraphic study reported here provides an outline of the geology of the Lemudong'o Formation. More fieldwork is needed to properly define the geometry of this paleobasin. A comprehensive program of mapping of outcrops, tephrastratigraphy, magnetostratigraphy, geochemistry, paleopedology, sedimentology and paleolimnology is needed to complement the lithostratigraphy and paleontology. The beds overlying the trachytes at Lemudong'o 1 & 2 and Entapot belong to Wright's (1967) younger Seyabei paleolake, and an older series of waterlain tuffs and ashes of Wright's 2nd Uaso Ngiro lake extends far south of our present study area. The boundaries and morphologies of these paleobasins remain poorly defined. These lakes may reflect long-lasting structural and tectonic control on drainage and sedimentation between the western margin of the southern rift valley and the east side of the Loita Hills. Long-distance inter-basin correlation of tephra beds in East Africa may be possible.

The Lemudong'o Formation dates to the terminal Miocene, which is one of the most poorly known periods of human evolution. Molecular genetics and paleontology indicate that the human lineage originated and expanded to African savanna environments between eight- and four-million-years ago (Kumar and Hedges, 1998; Leakey and Harris, 2003). Hominins are absent from the diverse faunal assemblage at Lemudong'o and from the late Miocene beds at Lothagam, but are relatively abundant in the late Miocene of the Middle Awash Valley, where more closed habitats predominate (Haile-Selassie et al., 2004). Further research in southern Narok may be able to provide a firm geochronological framework for this period and, if a wider range of paleoenvironmental settings is found, evidence for the environmental context of human origins, and perhaps direct evidence for our earliest hominin ancestors.

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