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Promise and pitfalls for characterizing and correlating the zeolitically altered tephra of the Pleistocene Peninj Group, Tanzania

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A B S T R A C T

The Pleistocene Humbu and Moinik formations of the Peninj Group in northern Tanzania preserve an important archaeological and paleontological record, in addition to a record of local volcanism in the form of tephra and lavas. Samples of the major Humbu and Moinik formations' basaltic and trachytic tephra were collected and characterized using phenocryst composition and both primary and authigenic mineral assemblage, since the volcanic glass was completely altered to zeolite. Some tephra are distinguishable solely using phenocrysts, but some are too similar in mineral composition or too poor in phenocrysts to definitively "fingerprint" without glass. Titanomagnetite phenocrysts were mostly altered; characterization was thus limited to feldspar, augite, and hornblende compositions for most tephra. Phenocryst compositions were compared to Olduvai tephra compositions to see if any regional tephra could be identified that could help correlate the sites. Augite or hornblende composition rules out potential correlations of Olduvai Bed I Tuff IF and the Bed II Bird Print Tuff or Tuff IID to otherwise similar Peninj Group tephra. Despite their overlap in age and locations at less than ~80 km from the Ngorongoro Volcanic Highlands, Peninj and Olduvai have different tephra records, which limits the possibilities for establishing a regional tephrostratigraphic framework.

Introduction

The Pleistocene Peninj Group includes the largely deltaic Humbu Formation and predominantly lacustrine Moinik Formation, observed in badlands and escarpment exposures near modern-day Lake Natron in northern Tanzania (Isaac, 1967). The Humbu Formation has produced a hominin fossil (*Australopithecus boisei*) mandible and numerous artifacts of both the Oldowan and Acheulean stone tool industries (e.g., Isaac, 1965; Isaac and Curtis, 1974; Domínguez-Rodrigo et al., 2001) and is located near the other paleoanthropological sites of Olduvai Gorge (to the south) and Olorgesailie (in Kenya, to the north). Both formations contain volcanic ash layers that could be used to correlate sites in the region and exposures within the Natron basin. Tephrochronostratigraphic correlations can be used to establish a regional geochronological framework by linking undated sites or those with problematic age records to those with better age control.

Geochemical fingerprinting of tephra is difficult where isotropic volcanic glass is highly altered. At Peninj, interaction with saline–alkaline lake, stream, and groundwater has converted volcanic glass into zeolites and other authigenic minerals such as montmorillonite. Thus, a different analytical approach involving the compositions of the more resistant phenocrysts is required. This method is similar to one that was successfully applied to Pliocene–Pleistocene Bed I at nearby Olduvai Gorge (McHenry, 2005, submitted for publication). The results of the current study can be compared directly to that study and to ongoing research on the younger Olduvai Beds.

Objectives

The objectives of this research are to (1) document the primary igneous and authigenic compositions of the varied tephra from Peninj, (2) develop geochemical or mineralogical fingerprints for individual altered tephra that can potentially be used for in situ and regional correlations, (3) test proposed tephra correlations between the Peninj Type (Maritanane) Section and the South Escarpment exposures within the Peninj area, and (4) test potential correlations between Peninj and Olduvai Gorge tephra.

Background

Stratigraphic context

Peninj is situated on the western shore of Lake Natron in northern Tanzania. It straddles the western escarpment of the Tanzanian sector

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of the East African Rift System (EARS), with exposures at the top of the escarpment (South and North Escarpment sites, formally named in Luque et al., 2009a,b) and the valley floor (Type Section, or Maritanane: Luque et al., 2009a,b) (Figs. 1 and 2). Note that "Type Section" as used herein is the informal name for this area (introduced by Isaac, 1965 and is used consistently since, see Luque et al., 2009a,b), and not a formal stratigraphic type section. The Pleistocene Peninj Group consists of a series of exposures of Pleistocene lacustrine and deltaic sediments, largely exposed in short sections of badlands type topography. It overlies a series of Pliocene and lower Pleistocene lavas (Mozonik, Hajaro, Sambu), and comprises the Humbu Formation (basaltic tephra and largely deltaic sediments to the north and west) and the overlying Moinik Formation (predominantly lacustrine sediments and trachytic volcanic layers) (Fig. 3; Isaac, 1967; Luque et al., 2009a). These two formations include greater than 100 m of sediments and overlie greater than 300 m of lavas (Isaac and Curtis, 1974). The present topography, with a steep and high escarpment overlooking Lake Natron, was formed after deposition of the Moinik Formation, and in places, sediment deposited at former lake high-stands overlies the Peninj Group sediments (Isaac, 1965; Luque et al., 2009a).

The Humbu Formation is subdivided into (1) the basal sands with clays member (Luque, 1995; Luque et al., 2009b), with coarse-grained alluvial sands and basaltic tephra; (2) the Main Humbu Tuff (Isaac, 1967, "limestone and basaltic tuff member"; Manega, 1993, "Main Basaltic Tuff"; Luque et al., 2009b, "Main Tuff"); and (3) the upper sands with clays member (Luque, 1995; Luque et al., 2009b), which also contains basaltic tephra in discrete layers or as disseminated shards. The Moinik Formation is almost entirely composed of lacustrine sediments, with interlayered clays and trachytic tephra (clays and trachytic tuffs member; Isaac, 1967; Luque et al., 2009b). It is capped by the thick (10–15 m) trachytic Upper Moinik Tuff (Isaac's (1967) and Luque et al.'s (2009b) "Upper Tuff member"). Tephra within each formation are named in stratigraphic order; those within the basal sands with clays member of the Humbu Formation are numbered TBS-1 through TBS-3, tephra within the upper sands with clays member of the Humbu Formation are numbered T-1 through T-5, those within the interlayered clays and trachytic tephra member of the Moinik Formation are numbered TM-1 through TM-4, and the Upper Moinik Tuff is labeled as TM-5 (Fig. 3; Luque et al., 2009a,b).

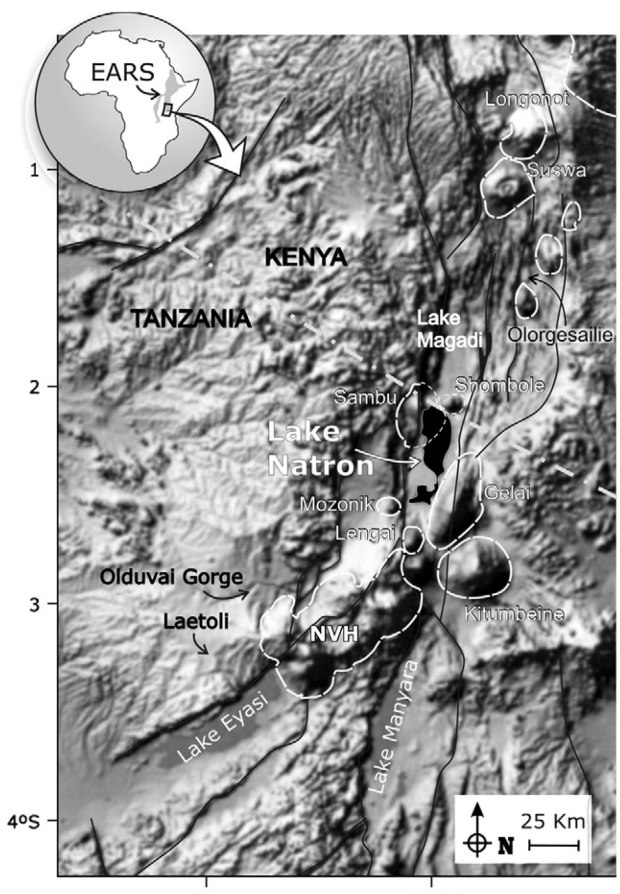

Figure 1. Map of the East African Rift in northern Tanzania and southern Kenya, centered on Lake Natron. Peninj lies on the western shore of this lake. Nearby volcanoes, including the Ngorongoro Volcanic Highlands (NVH), are outlined in white and labeled. Figure after Luque et al., 2009a.

Geochronological context

Age estimates for the Peninj Group have been suggested over the years based on a combination of paleomagnetic stratigraphy (Thouveny and Taieb, 1986), biostratigraphy (e.g., Geraads, 1987), and K–Ar (Isaac, 1967; Isaac and Curtis, 1974) and $^{40}Ar/^{39}Ar$ (Manega, 1993; Deino et al., 2006) dating of volcanics. Dawson (2008) provides an extensive list of published and unpublished (up to 1997) dates for tephra and lavas in the Natron basin. The radiometric dates place the base of the Humbu Formation (TBS-1) at ~1.72 ± 0.03 Ma (Manega, 1993) or ~1.75 Ma (Deino et al., 2006), the Wa Mbugu lava within the Main Humbu Tuff at 1.91 Ma or between 0.96 and 1.21 Ma (Isaac and Curtis, 1974) or 1.19 ± 0.03 Ma (Deino et al., 2006), the base of the Moinik Formation at 1.33 ± 0.05 Ma (Isaac and Curtis, 1974), and the Upper Moinik Tuff at 1.01 ± 0.03 Ma (Deino et al., 2006). Note that the older Wa Mbugu age (Isaac and Curtis, 1974) is stratigraphically inconsistent with the newer ages for the base of the Humbu Formation (Manega, 1993; Deino et al., 2006) and that the younger ages (Isaac and Curtis, 1974) are inconsistent with the age for the base of the Moinik (Isaac and Curtis, 1974); further geochronological research is required to resolve these and other age related questions. The fauna of the Humbu Formation is consistent with that of Olduvai Upper Bed I through Middle Bed III (Gentry and Gentry, 1978; Denys et al., 1986; Denys, 1987; Geraads, 1987; Manega, 1993).

Potential volcanic sources

The EARS in Tanzania and southern Kenya has been a volcanically active area during the Pliocene, Pleistocene, and Holocene, and there are numerous potential eruptive sources for the tephra preserved at Peninj. First, nearby and to the south, there are many small basaltic tuff cones that could have provided a local source for the tephra and lavas of the Humbu Formation (Isaac, 1967). Second, the Pliocene–Holocene Ngorongoro Volcanic Highland (NVH) volcanoes that supplied tephra to the Olduvai and Laetoli paleoanthropological sites (Hay, 1976) are about 80 km to the south. Tephra at Olduvai that were derived from the NVH include abundant trachytes (McHenry et al., 2008; Mollel et al., 2009), suggesting that the trachytic Moinik tephra could be related. Thicknesses, descriptions, and mineral assemblages of the NVH-derived Olduvai tephra are reported in Hay (1976). The ages of the Humbu and Moinik tephra overlap the dates of activity for certain NVH volcanoes, including Olmoti (the source of trachytic/ phonolitic Olduvai Tuff IF: McHenry et al., 2008, dated to ~1.75 Ma: Walter et al., 1992) and Embagai (nephelinitic, active 1.16 ± 0.04 Ma to 0.81 ± 0.02 Ma, Mollel, 2007).

Finally, rift volcanoes to the north in Kenya could also have provided volcanic ash. For example, the thick trachytic tephra at the top of the Moinik Formation (Upper Moinik Tuff) thins dramatically to the south, suggesting a source to the north or northeast (Isaac, 1967). Olorgesailie, a Pleistocene archaeological site about 80 km north in

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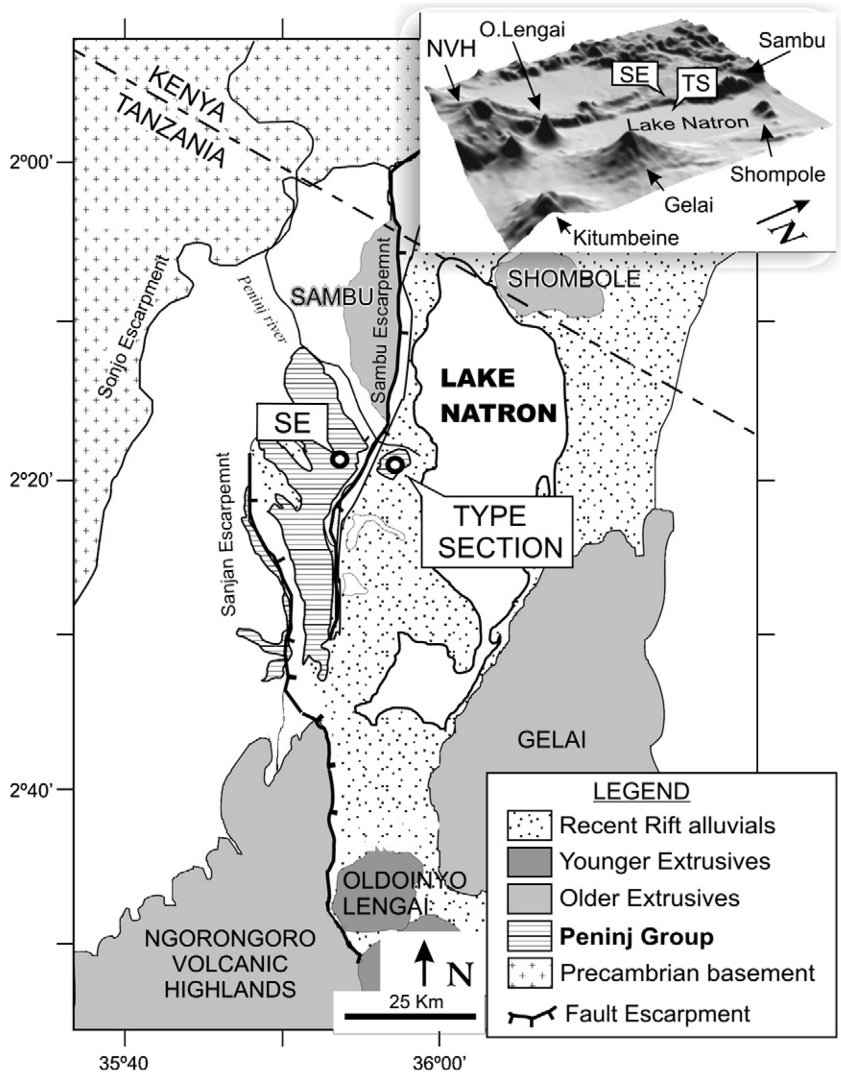

Figure 2. Map of the Lake Natron basin, showing the areal extent of the Peninj Group and the locations of the Type Section and South Escarpment (SE) sites. Nearby volcanoes (Sambu, Shombole, Ngorongoro Volcanic Highlands (NVH), and Gelai) are labeled. Inset shows exaggerated topography. Figure after Luque et al., 2009a.

the EARS in Kenya, also preserves tephra. These likely derived from nearby Ol Doinyo Nyegi (youngest activity 1.05 ± 0.014 Ma: Deino and Potts, 1990), Suswa, or Longonot volcanoes (Isaac, 1978; Behrensmeyer et al., 2002).

Archaeological background

The Humbu Formation includes, in addition to an *A. boisei* jaw (Leakey and Leakey, 1964; Wood and Constantino, 2007), abundant archaeo-paleontological sites that make west Lake Natron one of the most interesting regions for the study of early Pleistocene archaeology in East Africa. Archaeologically fertile sediments in the upper sands with clays member are located in three different ecological areas (Domínguez-Rodrigo et al., 2005). The Type Section (or Maritanane), a deltaic environment located in the proximity of the paleo-lake shore, has provided both stone artifacts (Domínguez-Rodrigo et al., 2002) and a diverse Pleistocene faunal record (e.g., Geraads, 1987; Ndessokia, 1987). Both Oldowan (Torre et al., 2003) and Acheulean (Diez Martín et al., 2009) stone tool assemblages have been described for the Type Section. Furthermore, the distal North and South Escarpment exposures contain Acheulean archaeological sites (Isaac, 1967; Isaac and Curtis, 1974; Domínguez-Rodrigo et al., 2001; Domínguez-Rodrigo et al., 2009a,b).

Methods

Field methods

The Humbu and Moinik tephra of the Type Section were sampled in 2007 and then revisited in 2008 and 2010 for more detailed sampling. Tephra of the South Escarpment were also collected in 2008. (Luque's 1995; Luque et al., 2009a,b) detailed sections were used for stratigraphic placement, and each sample site was documented using GPS. Abundant minor faults in the Type Section made it impossible to define a single sequential tephrostratigraphic section, thus a composite section is used. The tephra sampled and analyzed include, in stratigraphic order: lower Humbu tuffs (TBS-1 to 3), the Main Humbu Tuff, upper Humbu tuffs (T-1 to 5), Moinik tuffs (TM-1 to 4), and the Upper Moinik Tuff (TM-5, after Luque et al., 2009b). GPS coordinates, and brief sample descriptions, are provided in Appendices 1 and 2.

Laboratory methods

Sample preparation and X-ray diffraction (XRD)

Samples were prepared for XRD by hand crushing and powdering samples in an agate mortar and pestle under acetone. Powders were air-dried, mounted as random powder mounts, and analyzed using a Bruker

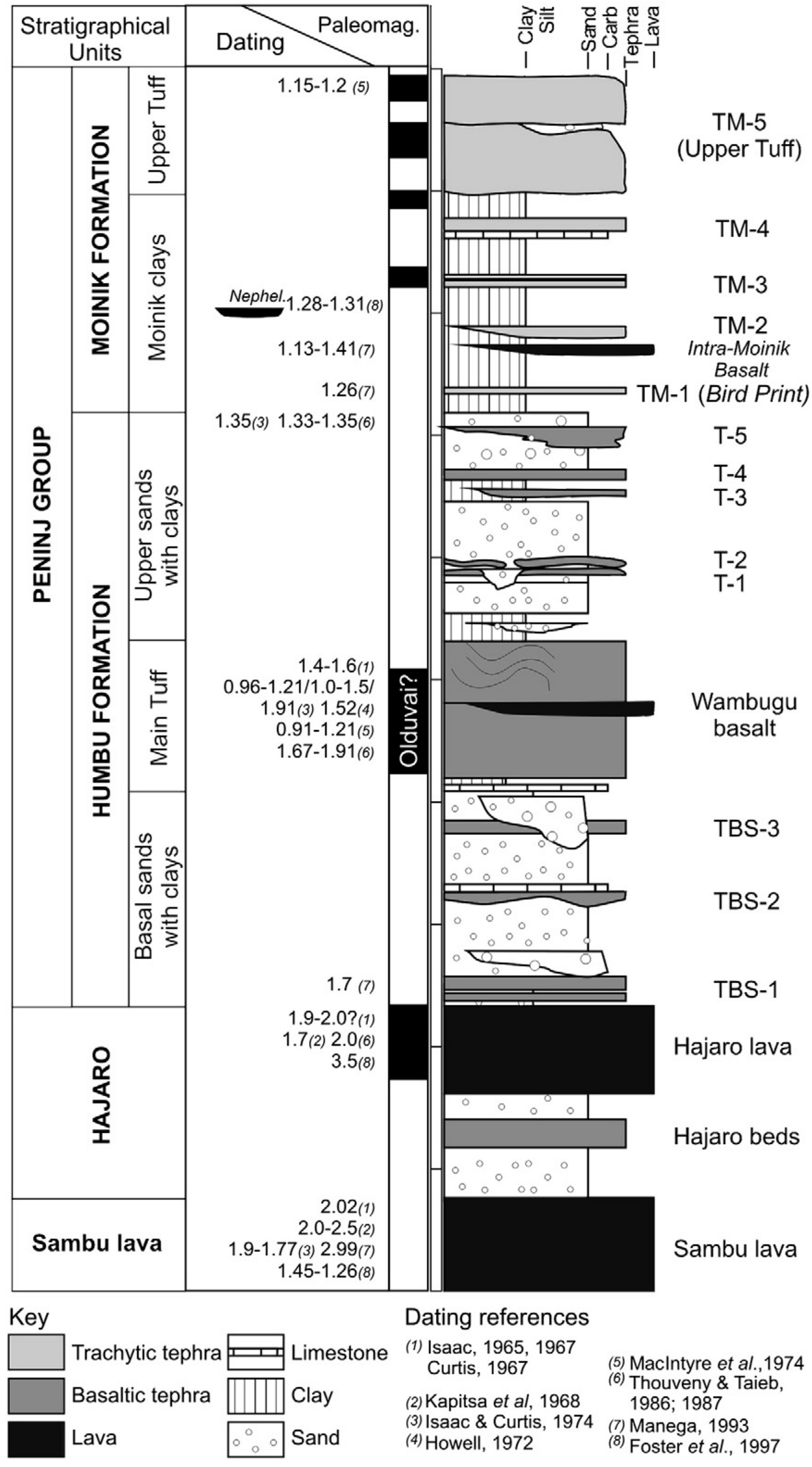

Figure 3. Composite stratigraphic column for the Humbu and Moinik formations, indicating the relative stratigraphic positions of the sampled tuffs and the surrounding lithology. The lower Humbu tuffs have a prefix of "TBS," the upper Humbu tuffs have a prefix of "T," and the Moinik tuffs have a prefix of "TM." Figure after Luque et al., 2009a. Dates from Isaac, 1965; 1967; Curtis, 1967; Kapitsa, 1968; Howell, 1972; Isaac and Curtis, 1974; MacIntyre et al., 1974; Thouveny and Taieb, 1986; 1987; Manega, 1993; and Foster et al., 1997.

D8 Focus XRD (Cu Kα radiation, 1 s per 0.02° 2θ, 2°–60° range, Sol-X energy dispersive detector; methods of McHenry, 2009). Mineral phases were identified by comparison to the International Centre for Diffraction Data Powder Diffraction File (ICDD PDF) database.

Electron microprobe

Thin sections of most tephra samples were prepared and polished for electron probe microanalysis (EPMA). These were supplemented by grain mounts of target minerals (feldspar, augite, hornblende, titanomagnetite) as needed. Grain mounts were prepared following the methods of McHenry (2005). Thin sections and grain mounts were carbon coated and analyzed using a Cameca SX51 electron microprobe at UW Madison following the methods of McHenry et al. (2008). Energy dispersive spectrometry (EDS) was used to identify minerals and determine what elements needed to be measured using wavelength dispersive spectrometry (WDS). Samples were analyzed

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using a 15 kV, 15 nA focused beam, and the calibration was based on appropriate mineral standards (full list of standards in McHenry, submitted for publication). Co-magmatic minerals were distinguished from detrital minerals by identifying remnant volcanic glass textures adjacent to them or avoiding stained or rounded grains. Contaminated samples were easily recognized, as the dominant detrital grains are highly rounded quartz, a mineral not found in the primary tephra.

Data processing and interpretation

Analyses with low totals (<96% for feldspar and pyroxene, <94% for hornblende) were excluded from further consideration. These minerals are not prone to significant hydration, thus low totals indicate a poor analysis, likely the result of overlap with void space or adjacent minerals during analysis of small grains, or incipient alteration. Hornblendes typically have lower totals since they contain unanalyzed OH or F in their structures. A significant contribution from unanalyzed elements (e.g., Cr, Sr) is unlikely since these elements were not observed in the EDS spectra.

Similar mineral grains were grouped together into distinct populations (e.g., high-calcium vs. high-sodium plagioclase) and chemical data points were averaged. Data for each type of phenocryst were plotted on *x*–*y* and ternary diagrams for comparison between samples and to establish compositional trends. Potential correlations were only considered when two samples contained the same general mineral assemblage, and when both the mean and spread of the compositions of each type of phenocryst analyzed were consistent for all elements analyzed.

Results

Authigenic minerals/ diagenesis

XRD results indicate a range of diagenetic minerals at Peninj (Table 1). The zeolite mineral analcime dominates the Humbu tephra, though chabazite and phillipsite are also present in some samples. No tephra sample contained isotropic glass shards, and all contained at least some zeolites, indicating ubiquitous saline–alkaline conditions during diagenesis. Except for phillipsite-rich TM-4, Moinik tephra contained only rare analcime, instead consisting primarily of the zeolite mineral erionite or authigenic potassium feldspar. TM-3 consists almost entirely of authigenic potassium feldspar. An iron or magnesium-rich clay mineral (provisionally identified as palygorskite) is also common, especially in the Humbu tephra.

Primary igneous assemblage

The primary igneous mineral assemblage of the Humbu and Moinik tephra is presented in Table 2. All phenocryst populations represented by two or more data points are reported. Since no fresh glass is preserved, tephra composition is determined using the phenocryst assemblage. The Humbu tephra are predominantly basaltic, with a phenocryst assemblage largely consisting of plagioclase and augite. Quartz and other mineral grains from the surrounding quartz-rich deltaic sands occasionally contaminate these tephra, but are easily distinguished from the phenocrysts based on their rounded shapes, discoloration, and composition.

The Moinik tuffs are predominantly trachytic. Their mineral assemblages are dominated by anorthoclase or sanidine phenocrysts along with hornblende and augite. Titanomagnetite is almost universally absent (because of alteration) in both the Moinik and Humbu tephra and thus cannot be used for geochemical characterization.

Electron microprobe results confirm the petrography of the Humbu and Moinik tephra. Most tephra within each formation are associated with a very narrow range of phenocryst compositions, making identification of some tephra impossible using this methodology alone. The electron microprobe results are reported in Tables 3 (Humbu) and 4 (Moinik).

Characterization of individual Humbu and Moinik tephra

TBS-1 is trachytic with predominantly anorthoclase to sanidine composition feldspar (Fig. 4A), magnesium-rich augite (Fig. 4B), and minor sodic hornblende. TBS-2 and 3 are both basaltic with calcic plagioclase and magnesium-rich augite (Fig. 4A–C), but TBS-2 lacks hornblende.

The Main Humbu Tuff, a thick (~5-m thick) devitrified and altered red bed marking the transition between the basal sands with clays member and upper sands with clays member of the Humbu Formation, is virtually devoid of phenocrysts. Multiple samples from different sites in the vicinity of the Type Section and one closer to its presumed source to the south (Isaac and Curtis, 1974) have thus far only yielded six grains of feldspar of varied composition (see Table 3).

Table 1
Peninj authigenic minerals.

Tuff	Sample	Intensity	Smectite	Analcime	Chabazite	Phillipsite	Erionite	Clinoptilolite	K-spar	Calcite	Plagioclase/ anorthoclase	Quartz	Augite	Dolomite	Fluorite
TBS-1	07-P20	231	XX	XX	XX	–	–	–	–	XXX	XX	–	–	–	–
TBS-2	07-P5	1086	X	XXX	–	X	–	–	–	–	XX	–	–	–	–
TBS-3	07-P6	2005	X	XX	–	–	–	–	–	–	–	XXX	–	–	–
Main Humbu	07-P7	144	XXX	XX	XX	XX	–	–	–	–	–	–	–	–	–
T-1	07-P8	460	XX	XXX	–	–	–	–	–	X	X	–	–	–	–
T-2	07-P9	450	XX	XXX	+	–	–	–	–	X	X	–	–	–	–
T-3	08-P11	634	X	XXX	+	–	–	–	–	–	+	–	–	–	–
T-4	07-P12	836	XX	XXX	–	XX	–	–	–	–	+	–	+	–	–
T-5	07-P13	572	X	XXX	–	–	–	–	+	–	XXX	XX	–	–	–
TM-1	07-P14	637	+	X	–	–	–	–	X	–	XX	–	–	XXX	–
TM-2	07-P16	1481	–	+	+	+	XXX	–	+	–	XXX	XX	–	–	X
TM-3	07-P17	361	–	–	–	–	–	–	XXX	–	–	–	+	–	–
TM-4	07-P18	406	+	XXX	–	XXX	–	+	X	–	–	–	–	–	–
Upper Moinik	07-P19	2131	–	–	–	–	XXX	–	–	–	–	–	–	–	–

XXX = abundant, XX = common, X = between common and rare, + = rare, – = absent.
Intensity: XRD counts per second of highest peak.

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Table 2
Primary ingneous mineral assemblages.

Tuff	Sample	Augite	Hornblende	Fe-rich hb	High-Ca plag	Low-Ca plag	Anorthoclase	Ti-magnetite	Ilmenite
Type Section									
TBS-1	07-P20	XX	–	+	–	–	XX	–	+
TBS-2	07-P5	XX	–	–	XX	–	–	–	–
TBS-3	07-P6	XX	X	–	XX	–	–	–	–
Main Humbu	08-P12	–	–	–	–	+	–	–	–
Wa Mbugu	07-P21	XXX	–	–	–	–	X	–	–
T-1	07-P8	XX	–	–	XX	–	–	–	–
T-2	07-P9	X	–	–	X	–	–	–	–
T-3	08-P11	XX	–	–	X	–	–	–	–
T-4	08-P8	XXX	–	–	XX	–	–	–	–
T-5	07-P13	–	+	X	–	–	XX	–	–
TM-1	07-P14	X	XX	+	–	–	XX	–	–
TM-2	07-P16	+	X	–	–	–	XXX	–	–
TM-3	07-P17	X	XXX	–	–	XXX	X	–	–
TM-4	07-P18	–	–	–	–		XXX	–	–
Upper Moinik	07-P19	X	+	–	–	+	XX	+	–
South Escarpment									
Main Humbu	08-P1	XX	–	–	–	+	X	–	–
T-4	08-P10	XXX	–	–	XX	–	–	–	–
Olduvai Gorge									
Bird Print Tuff	06-T5	XX	X	–	XXX	–	–	–	–

XXX = abundant, XX = common, X = between common and rare. + = rare, – = absent.
hb = hornblende, plag = plagioclase.

T-1 to 4 are all plagioclase and augite-bearing basaltic tephra, while T-5 is trachytic, containing abundant anorthoclase, sodium and iron-rich hornblende, and no augite.

TM-1 contains high-potassium anorthoclase feldspar, hornblende, and magnesium-rich augite (Fig. 4C). TM-2 also contains anorthoclase and more hornblende than augite. TM-3 has a range of feldspar compositions from high-potassium anorthoclase to low-calcium plagioclase. Hornblende is more abundant than augite and is titanium-rich. TM-4 is rich in anorthoclase but has so far yielded no mafic phenocrysts. Overall the Upper Moinik Tuff is phenocryst-poor;

Table 3
Humbu Formation tephra phenocryst compositions from the Type Section and South Escarpment (SE), with Olduvai IF and BPT for comparison.

Tuff	Sample	n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	BaO	SUM
Augite													
TBS-1	07-P20	12	50.29	1.09	3.85	6.96	0.16	15.81	21.13	0.34	n.d.	n.d.	99.66
	StDev		1.08	0.27	0.85	0.48	0.06	0.97	0.74	0.05			0.60
TBS-2	07-P5	29	49.87	1.21	4.59	7.37	0.18	15.05	21.10	0.39	n.d.	n.d.	99.54
	StDev		1.28	0.40	1.14	0.57	0.04	0.73	0.63	0.07			0.53
TBS-3	07-P6	28	50.55	1.06	4.28	7.08	0.19	15.58	20.61	0.35	n.d.	n.d.	99.12
	StDev		1.37	0.37	1.37	0.66	0.06	1.02	0.80	0.06			0.52
T-1	07-P8	8	48.94	1.56	4.13	8.89	0.22	14.03	21.14	0.37	n.d.	n.d.	99.35
	StDev		1.61	0.51	1.11	1.30	0.07	1.31	0.64	0.08			0.84
T-2	07-P9	5	48.93	1.66	4.19	7.90	0.16	13.83	21.61	0.38	n.d.	n.d.	98.70
	StDev		2.17	0.85	1.67	0.82	0.05	1.23	0.54	0.05			0.66
T-3	08-P11 Pop1	8	47.24	2.12	5.67	9.27	0.18	13.05	20.51	0.50	n.d.	n.d.	98.53
	StDev		1.68	0.59	1.58	0.39	0.03	0.95	0.47	0.08			0.59
	08-P11 Pop2	4	50.49	1.18	1.78	11.73	0.46	12.78	20.35	0.47	n.d.	n.d.	99.25
	StDev		0.36	0.42	0.69	1.64	0.19	1.21	0.32	0.05			0.62
T-4, Type	08-P8	20	48.57	1.91	4.98	8.27	0.19	13.55	21.40	0.39	n.d.	n.d.	99.25
	StDev		1.54	0.49	1.44	0.58	0.06	0.76	0.55	0.07			0.59
T-4, SE	08-P10	12	47.65	1.87	4.26	8.75	0.20	13.40	21.85	0.45	n.d.	n.d.	98.42
	StDev		1.77	0.58	1.66	1.06	0.08	0.85	0.98	0.08			0.78
Olduvai BPT	06-T5	23	49.84	1.35	3.42	7.94	0.20	14.68	21.42	0.72	n.d.	n.d.	99.58
	StDev		1.76	0.59	1.32	2.24	0.09	1.89	1.52	0.65			1.47
Olduvai IF surge	02-T101 Pop1	8	50.93	0.50	1.23	14.96	0.91	9.22	20.78	1.15	n.d.	n.d.	99.68
	StDev		0.98	0.05	0.25	1.37	0.10	1.21	0.67	0.48			
	02-T101 Pop 2	2	50.94	0.32	0.69	21.52	1.18	4.55	17.95	2.51			99.65
Olduvai IF LF	02-T101 LF Pop 1	5	50.22	0.97	0.93	25.12	0.78	1.05	9.36	7.40	n.d.	n.d.	95.82
	StDev		1.01	1.03	0.26	1.14	0.25	0.41	2.93	1.91			
	02-T101 LF Pop 2	3	50.76	1.10	2.26	17.63	1.02	5.45	16.44	3.11	n.d.	n.d.	97.77
	StDev		0.96	0.16	0.52	0.36	0.06	1.06	1.52	0.35			
Olduvai IF lapilli	02-T103	21	50.93	0.93	1.45	13.48	0.80	11.20	20.27	0.82	n.d.	n.d.	99.87
	StDev		0.58	0.26	0.39	0.45	0.07	0.39	0.31	0.10			
Hornblende													
TBS-1	07-P20	3	49.54	1.92	0.59	30.36	1.30	1.10	2.25	6.48	1.31	n.d.	94.86
	StDev		2.12	1.06	0.18	3.86	0.31	1.09	0.71	1.08	0.14		1.34
TBS-3	07-P6	6	42.16	0.69	12.64	17.78	0.40	10.17	11.01	1.48	1.11	n.d.	97.70
	StDev		1.91	0.10	0.78	1.96	0.10	1.61	0.84	0.40	0.69		0.52

(continued on next page)

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Table 3 (*continued*)

Tuff	Sample	n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	BaO	SUM
T-5	07-P13 Pop 1	6	47.79	1.86	1.44	30.78	1.15	2.68	5.14	5.44	1.30	n.d.	97.68
	StDev		0.81	0.42	0.82	4.34	0.11	3.08	1.73	0.90	0.14		0.54
	07-P13 Pop 2	2	43.04	0.86	13.39	14.96	0.17	10.78	11.28	1.62	0.45	n.d.	96.48
Olduvai BPT	06-T5	7	48.05	2.59	14.33	11.76	0.23	5.54	10.80	3.66	0.66	n.d.	97.63
	StDev		0.66	0.13	0.17	0.76	0.03	0.43	0.93	0.26	0.08		0.94
Olduvai IF surge	02-T101 Pop 1	12	42.66	3.01	8.36	20.44	0.75	8.76	10.36	3.11	1.02	n.d.	98.47
	StDev		1.44	0.24	0.52	1.60	0.12	0.80	0.37	0.45	0.11		
	02-T101 Pop 2	2	50.16	1.13	2.72	20.86	0.96	9.30	6.60	5.12	1.28	n.d.	98.12
Olduvai IF LF	02-T101 LF	8	48.82	0.97	3.17	18.54	0.90	10.08	7.22	5.06	1.50	n.d.	95.86
	StDev		1.31	0.24	1.18	2.77	0.10	1.68	0.82	0.40	0.11		
Feldspar													
TBS-1	07-P20	14	66.60	n.d.	19.70	0.50	n.d.	n.d.	0.78	6.96	6.02	0.19	100.73
	St Dev		1.18		1.23	0.48			0.94	0.46	1.42	0.17	0.53
TBS-2	07-P5	16	52.31	n.d.	30.22	0.65	n.d.	n.d.	13.17	3.80	0.22	0.07	100.36
	St Dev		0.85		0.46	0.12			0.44	0.61	0.03	0.08	0.98
TBS-3	07-P6	14	51.54	n.d.	30.73	0.59	n.d.	n.d.	13.74	3.60	0.18	0.05	100.37
	StDev		0.64		0.35	0.10			0.33	0.19	0.03	0.08	0.87
Main Humbu, Type	08-P12	2	61.76	n.d.	24.28	0.02	n.d.	n.d.	5.66	8.04	0.17	0.08	99.96
Main Humbu, Type	10-T26 Pop 1	2	66.69	n.d.	19.20	0.48	n.d.	n.d.	0.05	6.99	6.62	0.04	100.08
	10-T26 Pop 2	2	49.48	n.d.	33.14	0.55	n.d.	n.d.	15.18	2.73	0.15	0.00	101.16
Main Humbu, SE	08-P1 Pop 1	9	66.90	n.d.	19.47	0.09	n.d.	n.d.	0.44	6.86	6.43	0.03	100.18
	StDev		0.82		0.66	0.10			0.50	0.24	0.65	0.06	0.43
	08-P1 Pop 2	3	64.06	n.d.	23.22	0.00	n.d.	n.d.	4.13	8.94	0.25	0.02	100.51
	StDev		1.75		1.00	0.01			1.18	0.78	0.06	0.03	0.48
T-1	07-P8	14	52.13	n.d.	29.81	0.59	n.d.	n.d.	12.58	4.06	0.29	0.07	99.49
	StDev		0.78		0.57	0.05			0.65	0.36	0.06	0.07	0.69
T-2	07-P9	9	50.80	n.d.	29.76	0.62	n.d.	n.d.	13.05	3.88	0.24	0.09	98.42
	StDev		0.41		0.38	0.12			0.26	0.22	0.05	0.09	0.40
T-3	08-P11 Pop 1	6	53.52	n.d.	29.04	0.56	n.d.	n.d.	11.50	4.67	0.41	0.15	99.83
	StDev		1.71		1.35	0.09			1.59	0.92	0.12	0.17	0.74
	08-P11 Pop 2	2	67.64	n.d.	18.72	0.52	n.d.	n.d.	0.03	6.46	7.02	0.00	100.37
T-4, Type	08-P8	14	52.95	n.d.	29.56	0.58	n.d.	n.d.	12.26	4.22	0.40	0.08	100.00
	StDev		0.72		0.55	0.07			0.53	0.25	0.11	0.09	0.79
T-4, SE	08-P10	10	53.11	n.d.	28.81	0.53	n.d.	n.d.	11.78	4.59	0.45	0.11	99.27
	StDev		0.94		0.32	0.10			0.47	0.29	0.05	0.15	0.73
T-5	07-P13	15	67.51	n.d.	19.14	0.56	n.d.	n.d.	0.18	7.06	6.41	0.11	100.94
	StDev		0.40		0.47	0.26			0.19	0.56	0.68	0.13	0.46
Oldvai BPT	06-T5	6	52.60	n.d.	30.09	0.54	n.d.	n.d.	13.03	4.11	0.21	0.31	100.76
	StDev		0.72		0.73	0.08			0.67	0.41	0.05	0.17	0.56
Olduvai IF surge	02-T101	10	63.63	n.d.	20.74	0.30	n.d.	n.d.	1.12	8.41	3.70	0.42	98.43
	StDev		1.83		0.85	0.11			0.49	0.46	0.94	0.24	
Olduvai IF LF	02-T101 LF	10	65.12	n.d.	18.52	0.67	n.d.	n.d.	0.34	7.28	6.23	0.07	98.24
	St Dev		0.83		0.34	0.12			0.30	1.07	1.60	0.09	
Olduvai IF lapilli	02-T103 Pop 1	16	2.06	n.d.	19.15	0.46	n.d.	n.d.	0.80	8.23	3.51	0.70	99.32
	StDev		0.56		0.43	0.10			0.17	0.26	0.35	0.37	
	02-T103 Pop 2	3	64.65	n.d.	20.10	0.45	n.d.	n.d.	1.16	7.46	3.26	2.67	100.15
	StDev		0.28		0.58	0.04			0.51	0.36	0.52	0.71	

All concentrations in wt.% oxide.
Pop = population. All populations with at least two analyses per sample are reported.
n.d. = not determined.
Olduvai IF data from McHenry et al., 2008. LF = lava fragment.

it contains a minor amount of anorthoclase feldspar (along with a trace percentage of plagioclase) and very rare hornblende and augite.

Discussion

Authigenic minerals and diagenetic conditions

The presence of abundant analcime, erionite, and authigenic potassium feldspar and the absence of volcanic glass and titanomagnetite in the tephra confirm that the conditions during deposition and/or diagenesis were highly saline–alkaline. Diagenetic conditions for tephra preservation at Peninj were harsher than at Olduvai, where titanomagnetite is preserved at most localities and isotropic volcanic glass is occasionally present. Other phenocrysts, including feldspar, augite, and hornblende, were less affected at Peninj; therefore, these can still be used for tephra characterization. In this study, the authigenic mineral assemblages determined in the altered Peninj Group tephra is consistent with that observed by Icole et al. (1987) in their study of the overall secondary mineralogy of the Humbu and Moinik formations.

"Fingerprinting" Peninj tephra

Unlike Olduvai tephra, only a small number of the Humbu and Moinik tephra can be distinguished solely using phenocryst composition. The distinguishing features for each tephra (sampled in the area of the Type Section) are described below.

The Humbu tuffs

TBS-1 (sample 07-T20) differs from the other Humbu tephra in its more trachytic composition, especially the presence of anorthoclase rather than plagioclase feldspar and abundance of hornblende. Its mineral assemblage (anorthoclase, sodic hornblende, and high-magnesium augite) appears to be distinctive within the Peninj Group. TBS-2 and 3 are indistinguishable from each other using their plagioclase and augite compositions, but can be distinguished

Table 4
Moinik Formation tephra phenocryst compositions, with Olduvai IID and IVA for comparison.

Tuff	Sample	n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	BaO	SUM
Augite													
TM-1	07-P14	3	49.40	1.42	4.09	6.49	0.09	15.11	22.02	0.57	n.d.	n.d.	99.26
	Stdev		1.06	0.73	0.88	0.86	0.06	2.03	1.69	0.34			0.51
TM-2	07-P16	2	48.74	2.13	4.21	7.42	0.18	13.26	23.28	0.57	n.d.	n.d.	99.79
TM-3	07-P17	11	49.82	0.86	2.18	13.97	0.54	9.42	22.24	0.70	n.d.	n.d.	99.17
	StDev		0.71	0.38	0.49	2.23	0.22	1.64	0.29	0.15			0.41
Upper Moinik	07-P19 Pop 1	3	49.43	1.64	3.55	8.11	0.18	14.33	21.17	0.41	n.d.	n.d.	98.87
	StDev		0.33	0.50	0.03	1.77	0.04	1.18	1.08	0.12			0.60
	07-P19 Pop 2	2	50.11	0.53	0.58	20.26	1.15	6.30	19.76	0.51	n.d.	n.d.	99.25
Olduvai IID	06-T15	18	50.00	1.31	2.11	12.52	0.38	10.82	20.82	1.66	n.d.	n.d.	99.68
	StDev		1.75	0.71	1.84	5.20	0.28	3.19	2.83	1.70			0.88
Olduvai IVA	07-T65	3	48.40	1.78	2.87	13.03	0.54	10.39	20.67	1.28	n.d.	n.d.	99.07
	StDev		1.36	1.42	2.58	3.60	0.40	2.44	1.38	0.82			1.05
Hornblende													
TM-1	07-P14 Pop 1	9	42.08	0.93	12.68	17.00	0.33	9.49	11.58	1.52	0.88	n.d.	96.45
	StDev		1.24	0.60	1.25	2.63	0.21	1.40	0.40	0.17	0.56		0.62
	07-P14 Pop 2	2	47.99	1.40	0.66	32.61	1.31	0.95	3.71	6.79	1.36	n.d.	96.85
TM-2	07-P16	7	43.51	0.76	11.86	15.19	0.29	11.22	11.55	1.32	0.76	n.d.	96.51
	StDev		1.96	0.23	1.12	2.58	0.08	1.57	0.74	0.21	0.59		0.70
TM-3	07-P17	25	39.19	4.52	11.57	19.67	0.50	7.51	11.07	2.81	1.21	n.d.	98.18
	StDev		0.43	0.49	0.47	1.76	0.09	1.32	0.20	0.14	0.12		1.60
Upper Moinik	07-P19	4	43.42	1.03	11.76	14.98	0.38	11.20	11.24	1.72	0.73	n.d.	96.58
	StDev		1.34	0.39	1.37	2.44	0.12	1.76	0.10	0.17	0.43		1.05
Olduvai IID	06-T15	10	39.86	4.33	11.40	19.10	0.42	8.79	10.87	2.86	1.05	n.d.	98.77
	StDev		0.75	0.53	1.00	3.69	0.18	2.14	0.34	0.19	0.21		1.25
Olduvai IVA	07-T65	4	39.47	2.90	10.06	23.87	0.74	5.18	9.92	3.04	1.53	n.d.	96.57
	StDev		0.42	0.86	1.44	2.8	0.32	1.31	0.64	0.29	0.1		0.41
Feldspar													
TM-1	07-P14	14	66.80	n.d.	18.88	0.55	n.d.	n.d.	0.21	6.76	6.94	0.07	100.16
	StDev		0.55		0.46	0.32			0.21	0.70	1.02	0.09	0.64
TM-2	07-P16	22	67.24	n.d.	19.05	0.37	n.d.	n.d.	0.20	6.61	6.95	0.08	100.42
	StDev		0.57		0.24	0.19			0.15	0.54	0.81	0.12	0.64
TM-3	07-P17 Pop 1	26	61.85	n.d.	23.93	0.21	n.d.	n.d.	4.83	7.83	1.25	0.34	100.24
	StDev		1.74		1.19	0.08			1.33	0.55	0.45	0.20	0.80
	07-P17 Pop 2	6	64.82	n.d.	19.96	0.20	n.d.	n.d.	1.04	6.21	6.83	0.35	99.41
	StDev		1.13		0.52	0.08			0.71	0.91	1.40	0.15	0.87
TM-4	07-P18	24	67.03		19.29	0.32	n.d.	n.d.	0.37	6.80	6.65	0.07	100.50
	StDev		0.57		0.42	0.10			0.15	0.50	0.72	0.08	0.90
Upper Moinik	07-P19 Pop 1	12	66.59	n.d.	19.20	0.51	n.d.	n.d.	0.42	6.98	6.31	0.16	100.15
	StDev		0.58		0.88	0.38			0.59	0.65	1.33	0.16	0.60
	07-P19 Pop 2	2	61.11	n.d.	24.29	0.29	n.d.	n.d.	5.56	7.74	0.61	0.02	99.48
Olduvai IID	06-T15	17	61.95	n.d.	22.34	0.30	n.d.	n.d.	3.63	7.90	1.96	0.33	98.41
	StDev		3.11		2.04	0.11			2.39	0.74	1.33	0.28	0.74
Olduvai IVA	07-T65	11	66.43		19.79	0.29	n.d.	n.d.	0.41	6.53	7.10	0.25	100.81
	StDev		0.48	n.d.	0.55	0.09			0.39	0.78	1.53	0.18	0.57

All concentrations in wt.% oxide.
Pop = population. All populations with at least two analyses per sample are reported.
n.d. = not determined.

based on the presence (TBS-3) and absence (TBS-2) of hornblende. TBS-1, 2, and 3 all have similar augite compositions.

Until better-preserved microphenocrystic volcanic ash samples can be recovered, correlation of the Main Humbu Tuff between sites or to its eruptive source is only possible via physical mapping. Fortunately, its thickness and distinctive orange color make it easy to recognize.

T-1 and 2 are indistinguishable from each other based on plagioclase and augite data, though they differ from the overlying upper Humbu tuffs in their slightly more calcium-rich plagioclase composition (Fig. 4A). T-3 feldspar is slightly lower in calcium than that of T-1 and 2 (11.50 wt.% CaO, compared to 12.58 and 13.05 wt.%), though it covers a broader compositional range with some overlap (standard deviation 1.59, compared to 0.65 and 0.26). It also contains a few grains of anorthoclase. T-4 has plagioclase that is slightly higher in potassium than T-1 and 2 (0.40 wt.% K_2O, compared to 0.29 and 0.26 wt.%) and less variable than T-3 in sodium (Fig. 5), though significant overlap between T-1 and 4 feldspar make it impossible to uniquely identify either using feldspar composition alone. T-5 is more consistent with the Moinik trachytes.

The Moinik tuffs

The Moinik tuffs have similar trachytic compositions, but subtle differences in mineral assemblage can help distinguish some of them. TM-2 hornblende has slightly lower iron than most other Moinik tuffs. TM-3 is the most distinctive of the Moinik tuffs, with high-titanium hornblende and a range of feldspar compositions from low-potassium anorthoclase to low-calcium plagioclase unlike the other Moinik tuffs. Sparse phenocrysts make TM-4 and the Upper Moinik Tuff difficult to characterize mineralogically, though a lack of mafic phenocrysts appears to be diagnostic for TM-4. The mineral assemblages described above are summarized in Table 2.

Correlating between the Peninj Type Section and the South Escarpment

A short artifact-bearing section of the Humbu Formation is exposed on the South Escarpment (Fig. 6). Two significant tuffs are present in this section, thought to be the Main Humbu Tuff and T-4 based on physical characteristics and relative stratigraphic position. Table 3 documents the phenocryst compositions of samples from these two units.

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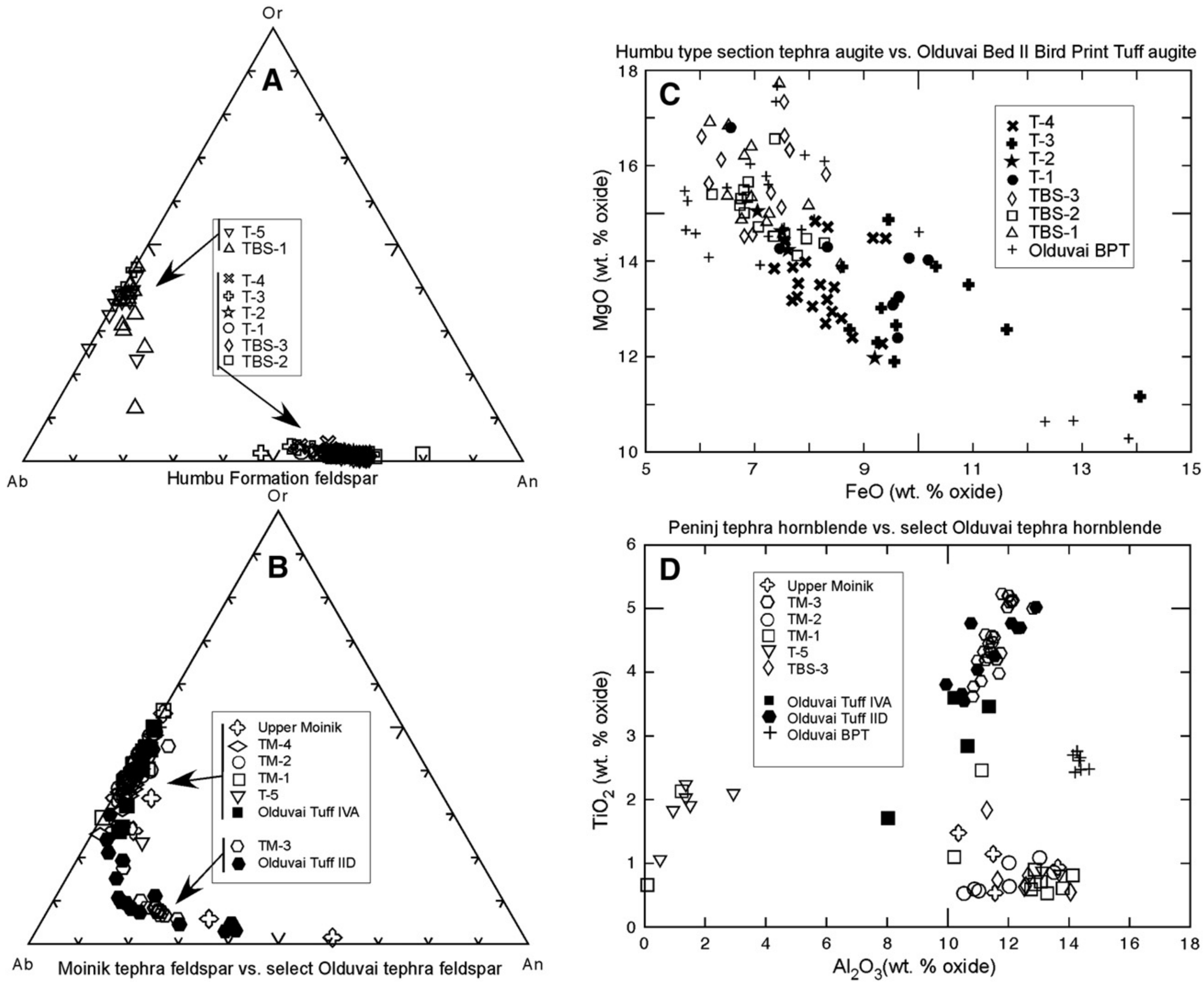

Figure 4. Phenocryst compositions for tuffs in the Humbu and Moinik formations, as determined by electron microprobe. (A) Feldspar ternary diagram for Humbu tephra. Data plotted as formula units of albite (Ab), anorthite (An), and orthoclase (Or). TBS-1 and T-5 contain anorthoclase/sanidine feldspars, the others tuffs are rich in plagioclase feldspars which are so close in composition that they cannot be distinguished using this diagram. (B) Feldspar ternary diagram for Moinik tuffs, compared to two Olduvai tuffs (Tuffs IID and IVA) feldspar. Anorthoclase/sanidine dominates, except for TM-3 and Olduvai Tuff IID, which contain calcium-poor plagioclase. The Upper Moinik Tuff has an anorthoclase population slightly lower in potassium than the bulk of the other Moinik tephra. (C) Humbu tuffs augite composition, MgO vs. FeO (wt.% oxide) compared to the augite compositions of the Bed II Olduvai Bird Print Tuff (BPT). The lower Humbu tephra augites (and augite crystals in the Olduvai BPT) are distinctly higher in MgO and lower in FeO than the upper Humbu tuffs, but are otherwise more difficult to distinguish. (D) Hornblende scatter plot: all Peninj tuffs, Al_2O_3 vs. TiO_2, compared to Olduvai Tuffs IID, IVA, and the Olduvai BPT hornblende. TM-3 hornblende has distinctively high TiO_2, and T-5 and TM-1 are bimodal. TBS-3 and the Olduvai BPT have different hornblende compositions, despite their similarities in feldspar and augite.

The layered appearance of the T-4 strata collected from the South Escarpment resembles the volcaniclastic deposits at the Type Section. T-1 to 4 are difficult to definitively distinguish using phenocryst compositions though. The augite compositions are consistent between T-1 through 4 (Figs. 4B and 5). However, the plagioclase compositions in T-4 (South Escarpment) and T-4 (Type Section) show slight offsets in calcium and potassium concentrations compared to T-1 to 3 (Fig. 5). The similar geochemistry and comparable field characteristics suggest that the tuffs in the two sections are probably correlative. Additional lines of evidence, such as improved stratigraphic context, better preserved or dated tephra, or higher resolution analytical data, would be required to test this further.

The Main Humbu Tuff at the South Escarpment is much more crystal-rich than the presumably equivalent tuff at the Type Section. While multiple samples of the Type Section Main Humbu Tuff yielded only rare mineral grains, augite and feldspar at the South Escarpment are more abundant. This suggests that the two are different units or different phases in eruption of the same unit (since the Main Humbu Tuff represents multiple eruptions). The thickness, similarity in appearance, and position relative to T-4 suggest that this unit correlates to the Main Humbu Tuff of the Type Section or is at least the product of a related event, but presently this correlation cannot be confirmed based on phenocryst compositions.

Comparison to Olduvai tephra and tuffs

At the onset of this project, we expected to find TBS-1 to be equivalent to Olduvai Tuff IF, the major marker tephra at the boundary between Olduvai Beds I and II. Based on previous studies (e.g., Manega, 1993), it is similar in appearance, mineral assemblage, and age (Tuff IF: 1.75 ± 0.01 Ma, Walter et al., 1992; TBS-1: ~1.75 Ma, Deino et al., 2006). While its anorthoclase feldspar composition is consistent with the anorthoclase fingerprint found in Tuff IF rock fragments (see Table 3 and McHenry et al., 2008), its augite is substantially different and follows the trend of the other lower Humbu tephra with its higher aluminum and lower iron content. TBS-1 is substantially different from any anorthoclase-bearing Olduvai Bed I tephra (Fig. 7, McHenry, 2005).

Basaltic tephra are rare at Olduvai, limiting the possibilities for comparing the Humbu Formation to the Olduvai Beds through

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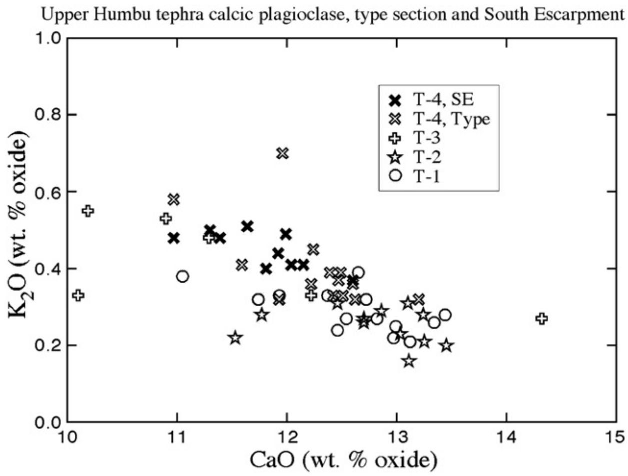

Figure 5. Upper Humbu tephra plagioclase compositions (CaO vs. K_2O, wt.% oxide) from the Type Section compared to T-4 from the South Escarpment (SE). T-4 is slightly less Ca-rich than the other tephra at both localities.

tephrostratigraphy. Within Beds I and II, only the Olduvai Bird Print Tuff (BPT) contains phenocrysts comparable to the basaltic Humbu tephra. Humbu basaltic tephra differ little in phenocryst composition, but based on the presence of plagioclase and subtle differences in the iron and magnesium content of the augite crystals, the BPT is most consistent with Lower Humbu TBS-2 or 3 (Fig. 4B). However, Olduvai BPT does not chemically correlate well with these lower Humbu tephra since it contains sodium and titanium rich hornblende (Fig. 4D). Thus, it is most likely not directly related to any Humbu tephra analyzed in this study.

The trachytes of the Moinik Formation potentially offer more opportunities for regional correlation, as trachytes are abundant at Olduvai. Olduvai Bed I contains the most abundant trachytes, but these are too old (Deino et al., 2006) to correspond to the Moinik tephras (youngest Bed I tuff is ~1.75 Ma, Walter et al., 1992). Trachytes within Beds II, III, or IV would be more likely correlatives. Of these deposits, Tuff IID (near the top of Bed II) has similar hornblende and feldspar composition to TM-3 (Figs. 4 and 8). However, their augite compositions are distinct. The other Moinik tephra are substantially different from Olduvai Bed II tephra,

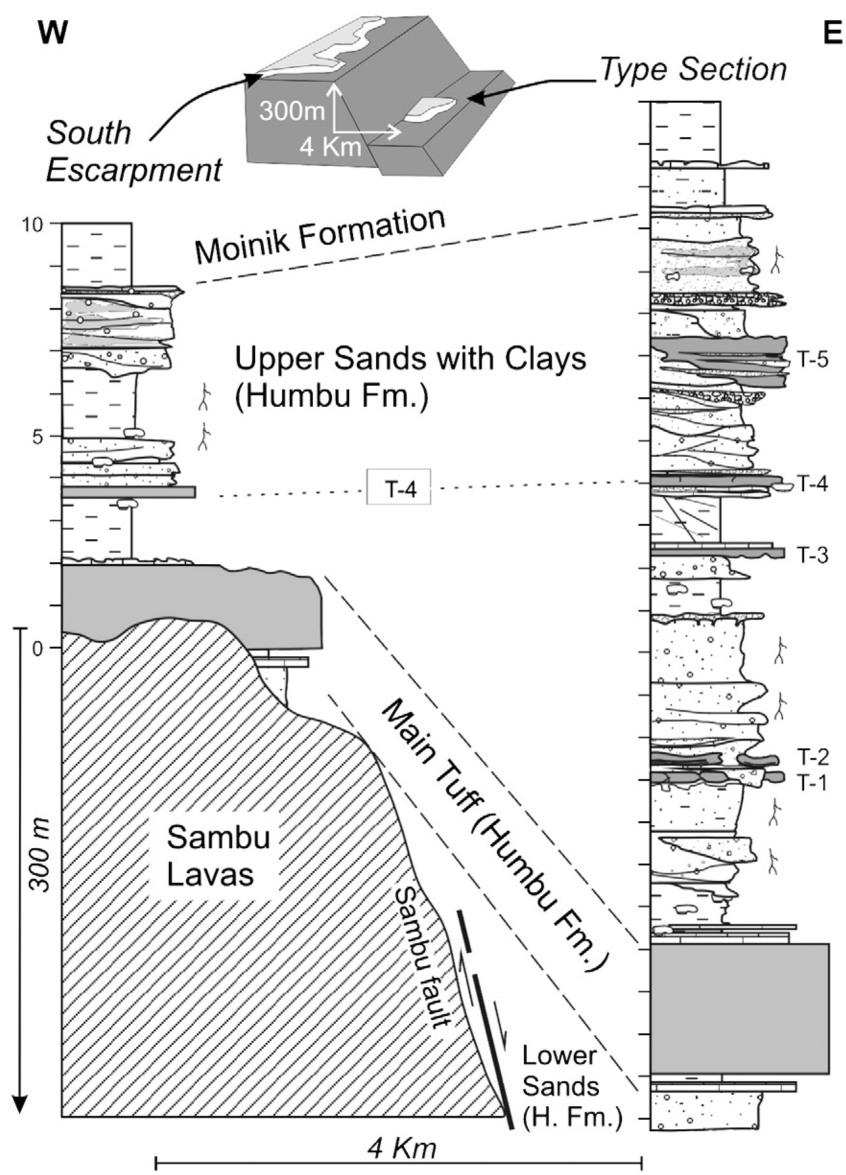

Figure 6. Proposed correlation between the Type Section and South Escarpment strata. T-4 has a similar appearance and phenocryst compositions at both sites. However, the correlation between the Main Humbu Tuff at both sites cannot be confirmed based on phenocryst compositions at the sampled Type Section localities.

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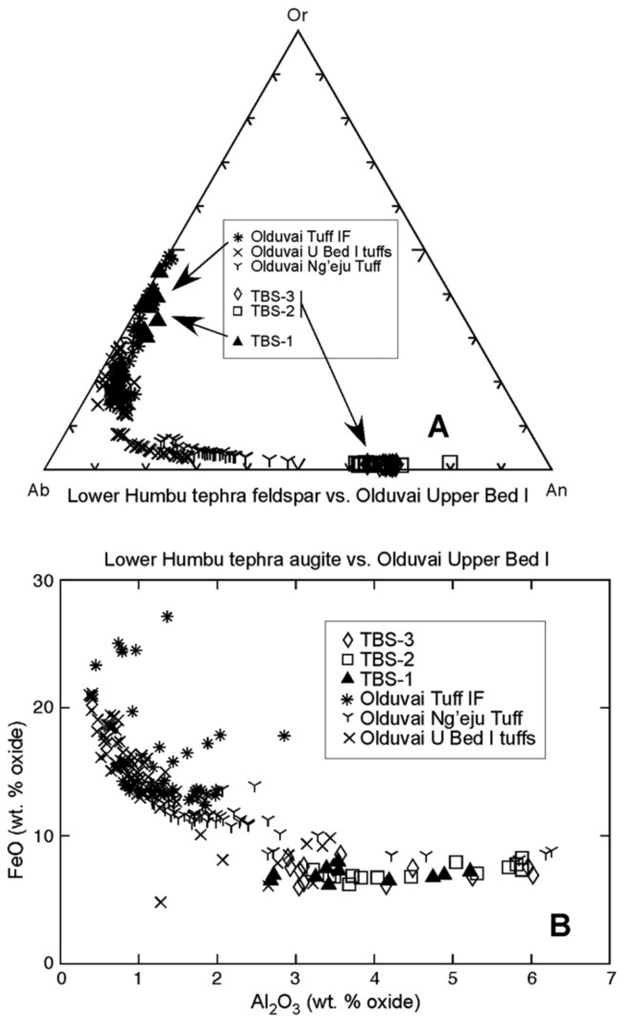

Figure 7. Comparison of feldspar and augite compositions in lower Humbu and Olduvai Bed I tephra. (A) Feldspar ternary diagram (plotted as formula units, Ab = albite, An = anorthite, Or = orthoclase). TBS-1 feldspar is consistent with Bed I tephra feldspar, particularly with Tuff IF. (B) Augite phenocrysts, FeO vs. Al_2O_3. TBS-1 is consistent with other lower Humbu tuffs, but not with Olduvai Bed I, including Tuff IF.

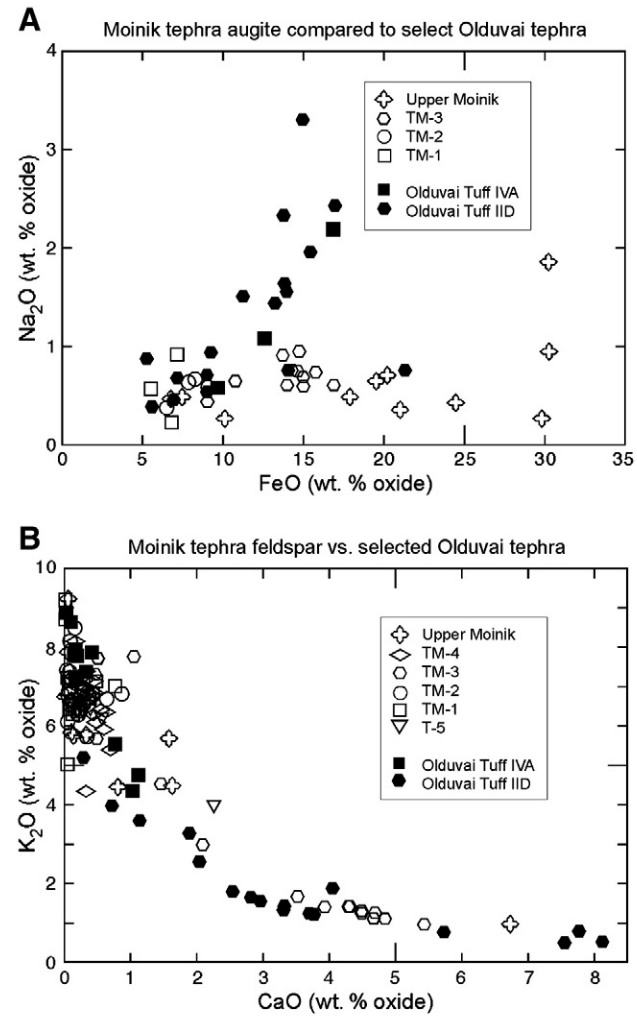

Figure 8. Comparison between Moinik and Olduvai tephra. (A) Augite phenocrysts, Na_2O vs. FeO. Olduvai Tuff IID has more sodium-rich augite, disproving the proposed correlation between TM-3 and Olduvai Tuff IID. (B) Feldspar phenocrysts, K_2O vs. CaO. Note the similarity between TM-3 and Olduvai Tuff IID feldspar, and between the Upper Moinik Tuff and Olduvai Tuff IVA.

particularly due to the elevated potassium concentrations in their anorthoclase/sanidine feldspars.

Compared to previously measured Olduvai tephras (McHenry, 2005, submitted for publication, and unpublished data; McHenry et al., 2008), Tuff IVA (in Bed IV) is the most consistent in feldspar composition with the other Moinik tephra at Peninj, including the massive Upper Moinik Tuff (Fig. 8). Unfortunately both tephra are deficient in augite and hornblende phenocrysts, making it difficult to test this potential correlation. The three to four augite and hornblende phenocrysts analyzed per sample are insufficient for a robust statistical comparison. Moreover, the titanium values for hornblende are slightly too high compared to the Upper Moinik Tuff (Fig. 4D).

The lack of definitive correlations makes it difficult to apply ages derived from one site to another. The Olduvai BPT is found in middle Bed II, about 10.8 m above Tuff IF (1.75 ± 0.01 Ma: Walter et al., 1992). Thus correlating the BPT to TBS-2 or 3 is consistent with the dates for TBS-1 (~1.75 Ma, Deino et al., 2006). However, this correlation is not plausible because of differences in hornblende abundance and composition. If Olduvai Tuff IVA is correlative with the Upper Moinik Tuff, Deino et al.'s (2006) date for this tephra (1.01 ± 0.03 Ma) would imply a slightly older age for Olduvai Bed IV than has previously been accepted (Hay, 1976), perhaps more in line with Tamrat's paleomagnetic stratigraphy for Olduvai (Tamrat et al., 1995) in which the magnetic reversal within Bed IV is attributed to the Jaramillo event (0.99–1.07 Ma) rather than the Brunhes/Matuyama boundary (0.78 Ma, as favored by Hay, 1976).

Source implications and future work

The lack of correlative tephra and tuffs between Olduvai and Peninj suggests that the NVH were not a major source area for the pyroclastic deposits at Peninj. Olduvai is much closer to this source and is also downwind. Paleowind directions in the region are projected to have been similar (dominantly east to west; Hay, 1976), thus a northerly dispersal of ash from a minor eruption towards Peninj would not be expected under normal wind conditions. Local or northerly volcanic sources are therefore more likely for most of the Peninj tephra (Isaac, 1967). This, unfortunately, limits the formation of a regional tephrostratigraphic framework linking Olduvai and Peninj, though correlation between Peninj and Olorgesailie to the north could still be possible. Improved mineralogical and geochemical characterization of the younger and more northerly NVH volcanoes (e.g., Embagai—active 1.16 ± 0.04 Ma to 0.81 ± 0.02 Ma; Kerimasi—active 0.50 to 0.22 Ma, Mollel, 2007) could also help determine if the younger (Moinik and post-Moinik) Peninj tephra could have originated there.

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It should be noted that the presented mineral compositions are not definitive "fingerprints" for the tephra studied, but they can serve to test whether or not compositional differences in co-magmatic crystals can be used to correlate anisotropic tephra or tuffs from different sites. Without isotropic volcanic glass shards it might be impossible to chemically fingerprint the Peninj tephra, though additional work involving melt inclusion composition or the identification of distinctive stratigraphic "packages" of tephra could help to further constrain the tephra record of these paleoanthropologically important strata. More detailed tephrostratigraphic analysis of Beds II-IV at Olduvai, including minor tephra not yet analyzed, could yield additional potential correlative units in the future.

Conclusions

A number of the altered tephra of the Humbu and Moinik Formations of Peninj can be distinguished using phenocryst composition, providing geochemical "fingerprints" that can be used for local correlation across the faulted landscape on the western side of Lake Natron. Compositional similarities between the phenocrysts of many of the Peninj Group tephra make definitive fingerprinting impossible, though compositional trends and "packages" of stratigraphically associated tephra can help determine general stratigraphic position. The similarity between T-4 at the Type Section and the South Escarpment provides another line of evidence supporting the stratigraphic correlation between these two sites.

Despite its proximity (within 80 km) to Olduvai Gorge and its volcanic source area, the NVH, the Peninj tephra record shows little overlap in phenocryst composition with tephra, tuffs, and lava from these areas. Hornblende or augite composition rules out correlations between Olduvai Bed I Tuff IF and Bed II BPT and Tuff IID with otherwise similar tephra in the Humbu and Moinik Formations. Peninj more likely received its volcanic input from local or northerly sources, which limits the possibilities for establishing direct stratigraphic links between Peninj and Olduvai.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.yqres.2010.11.008.

References

Behrensmeyer, A.K., Potts, R., Deino, A., Ditchfield, P., 2002. Olorgesailie, Kenya: a million years in the life of a rift basin. In: Renaut, R.W., Ashley, G.A. (Eds.), Sedimentation in Continental Rifts. : SEPM Special Publication No. 73. SEPM, Tulsa, pp. 97–106.

Curtis, G.H., 1967. Notes on some Miocene to Pleistcene potassium/argon result. In: Bishop, W.W., Miller, J.A. (Eds.), Calibration of Hominoid Evolution. Scottish Academic Press, Edinburgh, p. 367.

Dawson, J.B., 2008. The Gregory Rift Valley and Neogene-Recent Volcanoes in Northern Tanzania. Geological Society, London, Memoirs 33. The Geological Society, London.

Deino, A.L., Domínguez-Rodrigo, M., Luque, L., 2006. $^{40}Ar/^{39}Ar$ dating of the Pleistocene Peninj Group, Lake Natron, Tanzania. Eos, Transactions, American Geophysical Union 87 (52) (Fall Meeting Supplement, Abstract V53C-1771).

Deino, A.L., Potts, R., 1990. Single-crystal $^{40}Ar/^{39}Ar$ dating of the Olorgesailie Formation, southern Kenya rift. Journal of Geophysical Research 95, 8453–8470.

Denys, C., 1987. Micromammals from the west Natron Pleistocene deposits (Tanzania). Biostratigraphy and paleoecology. Sciences Geologiques (Bulletin) Strasbourg 40, 185–201.

Denys, C., Chorowicz, J., Tiercelin, J.J., 1986. Tectonic and environmental control on rodent diversity in the Plio-Pleistocene sediments of the African Rift System. In: Frostick, L.E., et al. (Ed.), Sedimentation in the African Rifts, 25. Geological Society Special Publication, pp. 363–372.

Diez Martín, F., Luque, L., Domínguez-Rodrigo, M., 2009. ST-69: an Acheulean assemblage in the Moinik Formation of Type Section of Peninj (Lake Natron, Tanzania). In: Domínguez-Rodrigo, M., Alcalá, L., Luque, L. (Eds.), Peninj. A research project on the archaeology of human origins (1995-2005). Oxbow, Cambridge, pp. 193–206.

Domínguez-Rodrigo, M., Alcalá, L., Luque, L., Serrallonga, J., 2005. Quelques aperçus sur les significations paléoécologique et comportamentale des sites oldowayens anciens et acheuléens du Peninj (Upper Humbu Formation, Ouest du Lac Natron, Tanzanie). In: Sahnouni, M. (Ed.), Le Paléolithique en Afrique. ArtCom/Errance, Paris, pp. 129–156.

Domínguez-Rodrigo, M., Diez Martín, F., Luque, L., Alcalá, L., Bushozi, P., 2009a. The archaeology of the North Escarpment. In: Domínguez-Rodrigo, M., Alcalá, L., Luque, L. (Eds.), Peninj. A research project on the archaeology of human origins (1995-2005). Oxbow, Cambridge, pp. 229–258.

Dominguez-Rodrigo, M., Serrallonga, J., Juan-Tresserras, J., Alcalá, L., Luque, L., 2001. Woodworking activities by early humans: a plant residue analysis on Acheulian stone tools from Peninj (Tanzania). Journal of Human Evolution 40, 289–299.

Domínguez-Rodrigo, M., Serrallonga, J., Luque, L., Diez-Martín, F., Alcalá, L., Bushozi, P., 2009b. The Acheulean sites from South Escarpment. In: Domínguez-Rodrigo, M., Alcalá, L., Luque, L. (Eds.), Peninj. A research project on the archaeology of human origins (1995-2005). Oxbow, Cambridge, pp. 207–227.

Domínguez-Rodrigo, M., Torre, I., Luque, L., Alcalá, L., Serrallonga, J., Medina, V., 2002. The ST site complex at Peninj, West Lake Natron, Tanzania: implications for early hominid behavioural models. Journal of Archaeological Science 29, 639–665.

Foster, A., Ebinger, C., Mbede, E., Rex, D., 1997. Tectonic development of the northern sector of the East African Rift System. Journal of the Geological Society, London 154, 689–700.

Gentry, A.W., Gentry, A., 1978. Fossil Bovidae of Olduvai Gorge, Tanzania. Bulletin of the British Museum, Natural History 29, 289–446.

Geraads, D., 1987. Le faune des dépôts pléistocènes de l'Ouest du lac Natron (Tanzanie), Interprétation biostratigraphique. Sciences Geologiques (Bulletin) 40, 167–184.

Hay, R.L., 1976. Geology of the Olduvai Gorge: a study of sedimentation in a semiarid basin. University of California Press, Berkeley. 203 pp.

Howell, F.C., 1972. Pliocene/Pleistocene hominidae in eastern Africa: absolute and relative ages. In: Bishop, W.W., Miller, J.A. (Eds.), Calibration of hominoid evolution. Scottish Academic Press, Edinburgh, pp. 331–368.

Icole, M., Taieb, M., Perinet, G., Manega, P., Robert, C., 1987. Minéralogie des sédiments du groupe Peninj (Lac Natron, Tanzanie). Reconstitution des paléoenvironments lacustres. Sciences Geologiques (Bulletin) 40, 71–82.

Isaac, G.L., 1965. The stratigraphy of the Peninj Beds and the provenance of the Natron Australopithecine mandible. Quaternaria 7, 101–130.

Isaac, G.L., 1967. The stratigraphy of the Peninj Group- early Middle Pleistocene Formations west of Lake Natron, Tanzania. In: Bishop, W.W., Clark, J.D. (Eds.), Background to Evolution in Africa. University of Chicago Press, Chicago, pp. 119–257.

Isaac, G.L., 1978. The Olorgesailie Formation: Stratigraphy, tectonics and the palaeogeographic context of the Middle Pleistocene archaeological sites. In: Bishop, W.W. (Ed.), Geologic background to fossil man: recent research in the Gregory Rift Valley. East Africa. Scottish Academic Press Ltd., Edinburgh, pp. 173–206.

Isaac, G.L., Curtis, G.H., 1974. Age of Early Acheulian industries from the Peninj Group, Tanzania. Nature 249, 624–627.

Kapitsa, A.P., 1968. Preliminary report of the Soviet East African expedition of the Academy of Sciences of the USSR in 1967. Moscow. Unpublished. 62 pp.

Leakey, L.S.B., Leakey, M.D., 1964. Recent discoveries of fossil hominids in Tanganyika: at Olduvai and near Lake Natron. Nature 202, 3–9.

Luque, L., 1995. Los yacimientos Plio-Pleistocenos del Grupo Peninj (Oeste del lago Natron, Tanzania). Geogaceta 18, 125–127.

Luque, L., Alcalá, L., Domínguez-Rodrigo, M., 2009a. The Peninj Group: Tectonics, volcanism, and sedimentary paleoenvironments during the lower Pleistocene in the Lake Natron basin. In: Domínguez-Rodrigo, M., Alcalá, L., Luque, L. (Eds.), Peninj. A research project on the archaeology of human origins (1995-2005). Oxbow, Cambridge, pp. 15–48.

Luque, L., Alcalá, L., Domínguez-Rodrigo, M., 2009b. The Peninj Group in Type Section (Maritanane): an analysis of landscape evolution. In: Domínguez-Rodrigo, M., Alcalá, L., Luque, L. (Eds.), Peninj. A research project on the archaeology of human origins (1995-2005). Oxbow, Cambridge, pp. 49–72.

MacIntyre, R.M., Mitchell, J.G., Dawson, J.B., 1974. Age of the fault movements in the Tanzanian sector of the East African rift system. Nature 247, 354–356.

Manega, P., 1993. Geochronology, geochemistry and isotopic study of the Plio-Pleistocene hominid sites and the Ngorongoro volcanic highland in northern Tanzania. Ph.D. Thesis, University of Colorado, Boulder, Colorado. 382 pp.

McHenry, L.J., 2005. Phenocryst composition as a tool for correlating fresh and altered tephra, Bed I, Olduvai Gorge, Tanzania. Stratigraphy 2, 101–115.

McHenry, L.J., 2009. Element mobility during zeolitic and argillic alteration of volcanic ash in a closed-basin lacustrine environment: Case study Olduvai Gorge, Tanzania. Chemical Geology 265, 540–552.

McHenry, L.J., submitted for publication. A revised stratigraphic framework for Olduvai Gorge Bed I based on tuff geochemistry.

McHenry, L.J., Mollel, G.M., Swisher III, C.C., 2008. Compositional and textural correlations between Olduvai Gorge Bed I tephra and volcanic sources in the Ngorongoro Volcanic Highlands, Tanzania. Quaternary International 178, 306–319.
Mollel, G.F., 2007. Petrochemistry and Geochronology of Ngorongoro Volcanic Highland Complex (NVHC) and its relationship to Laetoli and Olduvai Gorge, Tanzania. Ph.D. thesis, Rutgers University, New Jersey, 232 p.
Mollel, G.F., Swisher III, C.C., McHenry, L.J., Feigenson, M.D., Carr, M.J., 2009. Petrogenesis of basalt-trachyte lavas from Olmoti Crater, Tanzania. Journal of African Earth Sciences 54, 127–143.
Ndessokia, P.N.S., 1987. Paleofauna composition and paleoenvironment of Peninj (Marita-Nane site) in West Lake Natron basin, northern Tanzania. Sciences Geologiques (Bulletin) 40, 203–208.
Tamrat, E., Thouveny, N., Taïeb, M., Opdyke, N., 1995. Revised magnetostratigraphy of the Plio-Pleistocene sedimentary sequence of the Olduvai Formation (Tanzania). Palaeogeography, Palaeoclimatology, Palaeoecology 114, 273–283.
Thouveny, N., Taieb, M., 1986. Preliminary magnetostratigraphic record of Pleistocene deposits, Lake Natron Basin, Tanzania. In: Frostick, L.E., et al. (Ed.), Sedimentation in the African Rifts, 25. Geological Society Special Publication, pp. 331–336.
Thouveny, N., Taieb, M., 1987. Etude paleomagnetique des formations du Plio-Pleistocene de la region de Peninj (Ouest du lac Natron, Tanzanie). Sciences Geologiques (Bulletin) 40, 50–62.
Torre, I., Mora, R., Domínguez-Rodrigo, M., Luque, L., Alcalá, L., 2003. The Oldowan industry of Peninj and its bearing on the reconstruction of the technological skills of Lower Pleistocene hominids. Journal of Human Evolution 44, 203–224.
Walter, R.C., Manega, P.C., Hay, R.L., 1992. Tephrochronology of Bed I, Olduvai Gorge: an application of the laser-fusion $^{40}Ar/^{39}Ar$ dating to calibrating biological and climatic change. Quaternary International 13–14, 37–46.
Wood, B., Constantino, P., 2007. Paranthropus boisei: fifty years of evidence and analysis. Yearbook of Physical Anthropology 50, 106–132.