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Sequence of tuffs between the KBS Tuff and the Chari Tuff in the Turkana Basin, Kenya and Ethiopia

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Abstract: This paper describes a sequence of tuffs between the KBS and the Chari Tuff of Omo Group formations in Kenya and Ethiopia. These tuffs have recently been shown to be 1.87 ± 0.02 Ma and 1.38 ± 0.03 Ma in age, respectively. The sequence of tuffs that is derived is consistent with $^{40}Ar/^{39}Ar$ ages reported separately, and provides the stratigraphic framework for interpreting those ages. Further, new correlations are established to the Konso Formation in southern Ethiopia. As drainage from the Ethiopian Rift to the Omo–Turkana Basin developed after deposition of the Konso Formation, pumice clasts in tuffs of the Omo–Turkana Basin probably were transported there by the Omo River. The tuffs are divided into five groups on the basis of their stratigraphic position in relation to extensive ash layers. The sequence of tuffs has import for the placement and age of archaeological sites in the Koobi Fora Formation, and for ages of mammalian faunas (including hominids). Many tuffs were deposited during a 90 ka interval during which Mediterranean sapropels are lacking, suggesting that Nile flow was reduced, and that the level of a lake that occupied the Omo–Turkana Basin at the time was low. Thus the record of climatic influence on deposition in the Omo–Turkana Basin, previously shown for the Kibish Formation ($\leqslant$200 ka), extends at least to early Pleistocene time.

Pliocene and Early Pleistocene strata of the Omo Group (de Heinzelin 1983) exposed in the Omo–Turkana Basin in northern Kenya and southern Ethiopia have yielded a vast number of vertebrate fossils since modern work began there nearly four decades ago (e.g. Harris 1991). Amongst these are hominid fossils, for which the region is well known (e.g. Wood 1991). In addition to the fossils, archaeological sites in the Omo Group have yielded important information about the technological development of early man (e.g. Isaac & Isaac 1997). Further, the Omo Group, exposed over an area measuring some $100\ \text{km} \times 400\ \text{km}$, has provided much information about the geological development of the basin, and its stratigraphy and sedimentology are the basis for palaeogeographical reconstructions at various times (e.g. Feibel *et al.* 1991).

The principal constituent formations of the Omo Group are the Shungura Formation in the lower Omo valley, the Koobi Fora Formation east of Lake Turkana, and the Nachukui Formation west of Lake Turkana (Fig. 1). These formations have been stratigraphically linked through correlation of volcanic ash layers on the basis of the chemical composition of their glass fractions. In this way, it has been possible to interpret the geological history of the basin as an integrated system (Feibel *et al.* 1991).

Brown (1994) recounted development of the chronology of these formations. More recent papers, including those by Leakey *et al.* (1995, 1998, 2001), and McDougall & Feibel (1999) have provided still more chronological information. An accompanying paper provides new ages on a number of tuffs discussed here.

Despite the success in correlating tephra between many local stratigraphic sections and between formations, relations between volcanic ash layers in the stratigraphic interval between the KBS Tuff (1.88 ± 0.02 Ma; McDougall 1985) and the Chari Tuff (1.39 ± 0.02 Ma; McDougall 1985) have been difficult to decipher. Cerling & Brown (1982) correlated the KBS and Chari Tuffs with Tuffs H-2 and L of the Shungura Formation, respectively. These correlations are borne out by the composition of their glass fractions, by their general stratigraphic position in the two formations, by their associated faunas, and by their isotopic ages. Tuffs in the stratigraphic interval discussed here belong to Members H, J, and K of the Shungura Formation (de Heinzelin 1983), to the KBS and Okote Members of the Koobi Fora Formation (Bowen & Vondra 1973; Brown & Feibel 1985, 1986), and to the Kaitio and Natoo Members of the Nachukui Formation (Harris *et al.* 1988*a*, *b*). In the Koobi Fora Formation the tuffaceous interval between the KBS and Chari Tuffs exposed along the Karari Ridge has been termed the Okote Tuff Complex. At Ileret, Findlater (1976) called a similar interval the Ileret Tuff Complex, or the Lower–Middle Tuffs, and at the west end of Koobi Fora Ridge, a tuffaceous interval in similar stratigraphic position is called the Koobi Fora Tuff Complex.

During the course of the work, several correlations with the Konso Formation (Katoh *et al.* 2000) were noted. The Konso Formation is exposed on the western margin of the southern part of the main Ethiopian Rift (inset, Fig. 1). These correlations are important for two reasons: (1) because several tephra layers in the Konso Formation have been dated, so that ages on correlative units, or on units stratigraphically related to them, can be used in further developing the chronology of the Omo Group; (2) because the Konso Formation is located along a route through which water and sediment is proposed to have entered the basin via the Bakate Gap (e.g. Isaac & Behrensmeyer 1997). Isaac & Behrensmeyer (1997) argued that water-deposited tuffs may have been transported to the Koobi Fora Region via the Abyata–Chew Bahir–Bakate drainage. The character of correlated tuffs at Konso, and the development of the present drainage between Konso and Lake Turkana, bears strongly on these ideas.

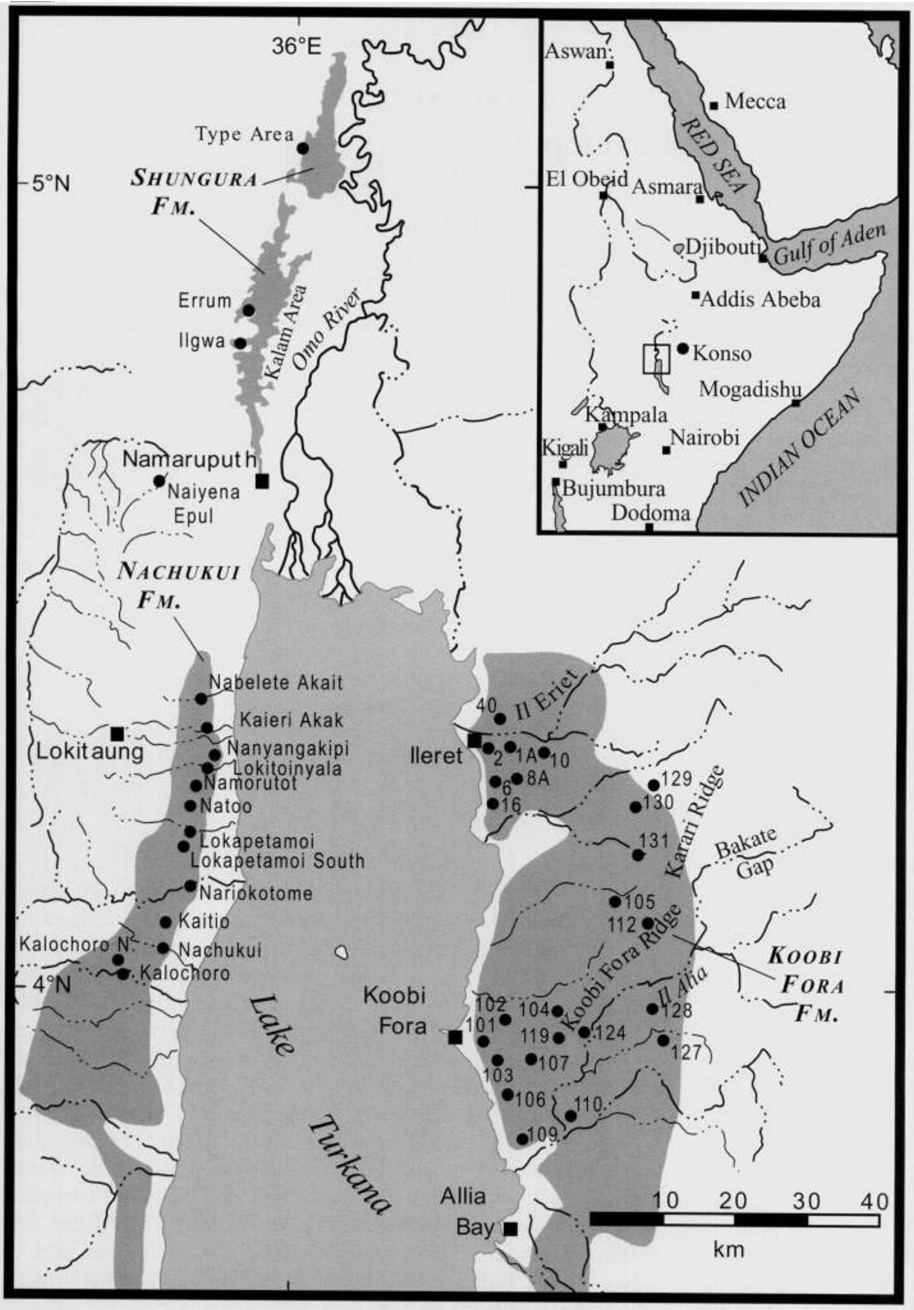

Fig. 1. Map of the lower Omo Valley of Ethiopia and the northern part of Lake Turkana in Kenya showing the Koobi Fora, Nachukui, and Shungura Formations as light stipple. Numbered points east of the lake refer to palaeontological collection areas. Section names are given for the Shungura and Nachukui Formations. The location of Konso is shown in the inset.

The paper proceeds in three sections. First we describe the stratigraphic order of volcanic ash layers. Then we discuss correlations between Omo Group Formations and the Konso Formation. Finally, we discuss some geological, stratigraphic, and palaeoclimatic implications that result from the new age information and understanding of stratigraphic relations in this interval. Short descriptions of named, correlated, and dated tuffs are given, along with a chemical analysis of each, and type locations are given for named tuffs. Analytical techniques, sample locations, additional analyses, and analyses of tuffs correlated in this paper as well as those believed to have been miscorrelated in previous publications are available online at http://www.geolsoc.org.uk/SUP18232. A hard copy can be obtained from the Society Library.

Methods

In the field, samples were collected from sections measured at the time or previously. The glass fraction of tuffs was separated and analysed for trace elements using methods described by Cerling & Brown (1982). Selected samples were analysed for major elements by electron microprobe using methods described by Nash (1992). Analytical conditions, standards used, and standard values are given in the Supplementary Publication. Elemental concentrations were converted to oxide concentrations, computing all Fe as Fe_2O_3, and then converting excess O to H_2O, following adjustment of the oxygen concentration for F and Cl by the procedure described by Nash (1992). As needed, the analyses were divided into modes principally on the basis of iron and aluminium content. Averages of constituent modes of many tuffs are presented in Tables 1–6, and analyses of other samples used in figures or mentioned in the text are given in the Supplementary Publication.

Table 1. *Analyses of volcanic glass from tuffs in the interval from the KBS Tuff (= H-2) to the Morutot Tuff (= J-4)*

		Average analyses of glass shards by electron microprobe (wt%)															XRF analyses of bulk separates (ppm)								
	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	F	Cl	Sum	Less Cl, F for O	H_2O†	Total	Ba	Mn	Nb	Rb	Sr	Ti	Y	Zn	Zr
Kimire Tuff (~J-3)																									
K83-1634	12	70.00	0.29	9.27	5.01	0.19	0.02	0.23	2.05	3.20	0.21	0.08	90.53	0.10	8.85	99.27	45	1540	135	110	<5	1960	100	215	1100
1σ	12	1.46	0.03	0.16	0.18	0.02	0.02	0.01	0.66	0.40	0.06	0.01		0.03	1.56										
K83-1629 (~J-3)																									
K83-1629	11	67.83	0.35	12.25	4.67	0.23	0.10	0.53	3.46	4.27	0.00	0.14	93.83	0.03	6.18	99.97	690	1750	105	95	5	2220	75	180	845
1σ	11	0.62	0.07	0.19	0.11	0.03	0.01	0.02	0.58	0.13	0.00	0.02		0.00	0.51										
ETH45 (~J-3)																									
ETH85-045	11	71.79	0.21	10.24	4.13	0.16	0.07	0.17	1.75	2.89	0.25	0.17	91.83	0.14	7.82	99.50	<25	1280	230	163	5	1470	130	230	1745
1σ	11	0.85	0.02	0.14	0.06	0.02	0.01	0.02	0.73	0.61	0.08	0.01		0.03	1.36										
ETH314 (~J-3)																									
ETH86-314 M1	12	72.04	0.25	9.94	4.15	0.15	0.05	0.16	1.38	3.19	0.51	0.18	92.00	0.26	8.38	100.13									
1σ	12	1.44	0.04	0.18	0.20	0.03	0.02	0.01	0.59	0.43	0.07	0.02		0.03	1.41										
ETH86-314 M2	3	74.60	0.06	11.23	1.99	0.03	0.00	0.17	2.96	4.33	0.43	0.19	95.98	0.23	5.35	101.10									
1σ	3	0.42	0.03	0.08	0.06	0.01	0.00	0.02	0.08	0.17	0.06	0.02		0.03	0.16										
ETH86-314 M3	3	71.41	0.10	11.72	2.09	0.05	0.01	0.33	3.01	4.47	0.35	0.23	93.79	0.20	6.39	99.98									
1σ	3	0.24	0.01	0.14	0.07	0.03	0.01	0.01	0.06	0.22	0.04	0.02		0.02	0.32										
White Tuff (~J-3)																									
K80-169	21	74.58	0.08	11.20	1.81	0.04	0.01	0.18	3.65	2.59	0.29	0.20	94.63	0.17	5.34	99.80	<25	240	115	175	<5	500	95	120	525
1σ	21	0.49	0.03	0.07	0.05	0.03	0.01	0.01	0.20	0.32	0.03	0.01		0.01	0.77										
K83-1626	21	73.90	0.07	11.07	1.81	0.04	0.01	0.18	3.22	4.62	0.29	0.20	95.41	0.17	5.08	100.33									
1σ	21	0.30	0.03	0.09	0.06	0.02	0.01	0.02	0.17	0.06	0.03	0.01		0.02	0.44										
Orange Tuff (~J-2)																									
K80-236 M1	15	73.06	0.09	11.66	2.00	0.06	0.01	0.33	3.53	4.51	0.16	0.22	95.62	0.12	4.13	99.63	30	450	75	145	<5	835	65	80	525
1σ		0.24	0.03	0.08	0.06	0.02	0.01	0.01	0.21	0.51	0.08	0.01		0.02	0.96										
K80-236 M2	3	73.89	0.28	9.51	5.07	0.23	0.06	0.25	2.00	1.93	0.18	0.15	93.55	0.11	9.40	102.84									
1σ		0.12	0.15	1.28	2.35	0.13	0.04	0.06	0.99	1.58	0.09	0.07		0.02	3.29										
K80- 236 M3	2	65.72	0.40	14.80	3.61	0.15	0.27	1.10	3.65	5.29	0.15	0.11	95.25	0.09	5.03	100.20									
1σ		0.83	0.05	0.01	0.08	0.03	0.06	0.05	0.53	0.54	0.00	0.00		0.01	2.13										
Chibele Tuff (KIB03-265), and pumices (KIB03-264a,b)																									
KIB03-264a		67.51	0.51	14.75	4.48	0.22	0.49	0.70	3.84	5.49	0.22	0.04	98.27	0.10	3.22	101.39									
1σ		0.38	0.05	0.11	0.14	0.03	0.02	0.02	0.10	0.04	0.02	0.01		0.01	0.38										
KIB03-264b		73.09	0.33	10.77	5.41	0.22	0.20	0.27	2.30	4.85	0.26	0.10	97.81	0.13	3.25	100.92									
1σ		0.52	0.04	0.11	0.11	0.03	0.03	0.02	0.45	0.17	0.03	0.01		0.01	0.46										
KIB03-265	14	70.21	0.35	9.37	5.03	0.23	0.11	0.17	3.34	3.80	0.37	0.15	93.13	0.19	6.92	99.86									
1σ		0.94	0.06	0.16	0.08	0.02	0.02	0.02	0.88	0.57	0.09	0.01		0.04	1.23										
Tuff J																									
780-5J (Pumice)	16	68.30	0.43	10.97	4.83	0.23	0.21	0.25	1.82	2.67	0.23	0.11	90.05	0.12	10.20	100.13	<25	2000	185	131	<5	2700	105	225	1275
1σ	16	0.90	0.05	0.13	0.06	0.02	0.01	0.02	0.26	0.11	0.04	0.01		0.02	0.99										
ETH86-293	6	65.89	0.51	13.49	5.36	0.25	0.36	1.09	2.20	2.68	0.00	0.09	91.90	0.02	7.94	99.82	615	2060	110	102	30	2060	80	170	800
1σ	6	1.32	0.15	0.47	0.18	0.02	0.16	0.43	0.72	0.30	0.00	0.02		0.00	1.13										
Steel-grey Tuff (~H-6)																									
K80-217	19	70.14	0.37	10.34	5.85	0.15	0.00	0.41	2.33	3.96	0.23	0.13	93.91	0.13	5.51	99.30	240	1200	115	105	5	2390	100	245	945
1σ		0.38	0.04	0.12	0.08	0.03	0.00	0.02	0.92	0.50	0.03	0.01		0.01	1.16										
IL02-069	21	72.10	0.37	10.83	5.70	0.16	0.00	0.42	1.36	1.33	0.32	0.14	92.73	0.17	8.04	100.60									
1σ	5	0.35	0.04	0.10	0.11	0.03	0.01	0.02	0.30	0.28	0.07	0.01		0.03	0.58										
Malbe Tuff (= H-4)																									
K80-225 M1	7	68.91	0.60	13.89	4.30	0.23	0.41	0.48	1.95	2.56	0.27	0.07	93.67	0.13	7.83	101.37	60	1900	140	105	<5	3350	80	195	995
1σ		1.06	0.04	0.57	0.13	0.03	0.05	0.07	0.37	0.59	0.03	0.01		0.02	1.14										
K80-225 M2	6	71.56	0.46	11.71	5.08	0.23	0.27	0.29	2.13	2.75	0.35	0.12	94.95	0.17	6.50	101.28									
1σ		0.86	0.08	0.48	0.15	0.02	0.03	0.05	0.85	1.05	0.04	0.01		0.02	1.88										
Ain Bura Tuff (= H-3B)																									
K80-231	13	69.54	0.37	8.68	6.43	0.30	0.09	0.22	1.31	0.93	0.16	0.11	88.13	0.09	11.32	99.35	25	2510	135	85	10	2570	90	250	965
1σ		1.03	0.04	0.13	0.10	0.02	0.01	0.01	0.40	0.27	0.06	0.02		0.01	1.10										
Tuff H-3A																									
ETH85-038	13	72.37	0.20	10.32	3.78	0.15	0.04	0.18	2.22	3.08	0.34	0.19	92.86	0.19	7.83	100.50	<25	1330	240	175	<5	1480	140	235	1830
1σ		0.94	0.03	0.12	0.05	0.03	0.01	0.01	0.63	0.41	0.06	0.01		0.02	1.79										
Brown Tuff (~H-2)																									
K83-1515	14	69.83	0.25	13.42	3.64	0.14	0.08	0.81	3.70	3.85	0.14	0.15	96.01	0.09	5.20	101.12	675	1150	80	80	60	1685	75	145	855
1σ		0.80	0.03	0.11	0.08	0.03	0.01	0.02	0.70	0.21	0.05	0.01		0.02	1.59										
KBS Tuff (= H-2)																									
77-17	3	70.37	0.16	10.80	3.09	0.12	0.03	0.16	3.23	3.27	0.13	0.19	91.56	0.10	6.53	98.00	30	870	195	170	5	1240	130	250	1265
1σ		2.46	0.02	0.10	0.04	0.01	0.01	0.02	2.17	0.50	0.03	0.01		0.03	0.54										

Modes are designated M1, M2 and M3.
*All iron expressed as Fe_2O_3.
†Water calculated as explained in text.

Table 2. *Analyses of volcanic glass from tuffs in the interval from the Morutot Tuff (= J-4) to the Black Pumice Tuff (= J-7)*

	Average analyses of glass shards by electron microprobe (wt%)																XRF analyses of bulk separates (ppm)								
	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	F	Cl	Sum	Less Cl, F for O	H_2O†	Total	Ba	Mn	Nb	Rb	Sr	Ti	Y	Zn	Zr
Elomaling'a Tuff																									
K93-6005	7	72.28	0.30	9.74	4.84	0.23	0.04	0.18	1.78	1.62	0.12	0.15	91.26	0.08	8.66	99.84									
1σ	7	2.01	0.08	0.69	0.27	0.06	0.05	0.04	0.37	0.22	0.11	0.07		0.06	1.65										
IL02-030	11	74.57	0.27	9.80	4.73	0.16	0.01	0.25	3.31	2.93	0.38	0.08	96.48	0.18	5.69	101.99									
1σ	11	0.50	0.03	0.12	0.12	0.03	0.01	0.02	0.56	0.74	0.04	0.02		0.02	1.12										
K88-3258	8	68.37	0.30	9.73	4.82	0.18	0.01	0.26	2.12	3.38	0.19	0.07	89.44	0.10	9.33	98.67	85	1520	120	95	<5	1910	85	175	940
1σ	8	1.26	0.03	0.12	0.06	0.02	0.00	0.02	0.66	0.62	0.04	0.01		0.02	1.54										
K93-6007																									
K93-6007	9	71.87	0.34	9.29	5.13	0.22	0.03	0.19	1.81	1.65	0.16	0.12	90.82	0.09	8.84	99.56									
1σ	9	0.93	0.04	0.18	0.11	0.05	0.07	0.05	0.23	0.11	0.07	0.08		0.03	0.61										
K83-1641	12	71.16	0.30	8.98	5.31	0.19	0.01	0.23	2.31	3.75	0.39	0.09	92.70	0.18	5.76	98.28	35	1460	145	120	10	2210	105	225	1160
1σ	12	1.58	0.03	0.15	0.12	0.02	0.01	0.01	0.72	0.51	0.17	0.01		0.07	1.26										
K93-6004																									
K93-6004	7	72.21	0.27	9.78	4.80	0.19	0.04	0.18	2.87	2.23	0.22	0.16	92.94	0.13	7.53	100.34	50	1300	130	95	15	2220	90	200	1090
1σ	7	1.22	0.08	0.14	0.14	0.06	0.05	0.03	1.19	0.93	0.07	0.06		0.04	2.57										
Okote Tuff, Area 131																									
K83-1636	11	70.45	0.29	9.66	4.85	0.22	0.10	0.17	2.42	3.71	0.30	0.18	92.36	0.17	5.57	97.76	<25	1760	240	145	<5	1900	120	265	1540
1σ	11	1.28	0.04	0.13	0.14	0.03	0.01	0.02	0.98	0.71	0.07	0.01		0.03	1.71										
Tuff J-6C																									
ETH86-305	12	73.41	0.15	10.15	3.94	0.11	0.00	0.21	2.04	3.14	0.19	0.09	93.43	0.10	7.26	100.60	40	830	135	115	5	1615	105	185	1360
1σ	12	0.97	0.02	0.17	0.08	0.02	0.00	0.01	0.59	0.35	0.06	0.01		0.03	1.38										
Tuff J-6B																									
ETH86-304	27	73.73	0.19	10.06	3.83	0.11	0.00	0.21	2.42	3.32	0.10	0.09	94.07	0.06	5.76	99.77	25	770	150	130	<5	1465	115	195	1430
1σ	27	1.01	0.06	0.26	0.14	0.04	0.01	0.03	0.58	0.45	0.12	0.01		0.05	1.33										
Tuff J-6A																									
ETH86-319	16	69.49	0.36	9.34	5.82	0.28	0.16	0.22	1.55	2.59	0.23	0.20	90.23	0.14	9.18	99.27	<25	2140	230	140	<5	2560	120	275	1535
1σ	16	1.16	0.02	0.14	0.09	0.01	0.01	0.01	0.44	0.34	0.11	0.01		0.05	1.31										
Tuff J-5																									
ETH86-318 M1	17	67.90	0.39	13.99	2.95	0.13	0.52	1.35	3.93	3.75	0.11	0.09	95.11	0.07	6.55	101.59	515	875	95	90	115	3045	70	110	705
1σ	17	1.54	0.20	0.22	0.10	0.02	0.02	0.04	0.49	0.09	0.05	0.01		0.02	0.84										
ETH86-318 M2	14	74.09	0.10	11.22	2.40	0.06	0.02	0.25	3.31	3.84	0.20	0.09	95.58	0.10	7.32	102.80									
	14	1.46	0.04	0.20	0.07	0.02	0.01	0.04	0.44	0.27	0.06	0.01		0.02	1.32										
Channel tuff, Area 8A																									
IL02-043	6	73.99	0.13	11.73	2.31	0.04	0.01	0.21	2.33	2.00	n.a.	0.17	92.92												
1σ	6	1.61	0.03	0.06	0.03	0.02	0.01	0.00	0.16	0.13		0.06													
Lower Okote Tuff																									
K83-1635	16	72.73	0.18	9.32	4.63	0.15	0.02	0.14	2.87	3.91	0.00	0.21	94.16	0.05	5.61	99.72	25	1105	165	170	<5	1190	125	260	1540
1σ	16	0.64	0.05	0.15	0.13	0.04	0.01	0.02	0.79	0.51	0.00	0.03		0.01	1.18										
Morutot Tuff																									
K81-511	20	72.02	0.17	11.94	2.99	0.09	0.01	0.33	4.09	4.83	0.13	0.14	96.74	0.09	3.60	100.25	220	710	155	95	<5	1110	115	245	1045
1σ	20	0.42	0.04	0.12	0.05	0.03	0.01	0.02	0.35	0.18	0.09	0.01		0.04	1.01										

Modes are designated M1 and M2; n.a., not analysed.
*All iron expressed as Fe_2O_3.
†Water calculated as explained in text.

Table 3. *Analyses of volcanic glass from tuffs in the interval from the Black Pumice Tuff (= J-7) to the Koobi Fora Tuff (= K-1)*

		Average analyses of glass shards by electron microprobe (wt%)															XRF analyses of bulk separates (ppm)								
	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	F	Cl	Sum	Less Cl, F for O	H_2O†	Total	Ba	Mn	Nb	Rb	Sr	Ti	Y	Zn	Zr
Koobi Fora Tuff (= K-1)																									
K80-113	9	73.42	0.33	9.45	5.37	0.24	0.08	0.19	1.10	1.70	0.38	0.20	92.45	0.21	4.55	96.79	<25	1860	250	120	5	2180	130	305	1660
1σ	9	0.61	0.03	0.11	0.08	0.02	0.02	0.02	0.40	0.54	0.13	0.03		0.06	1.17										
ETH85-057	10	72.00	0.30	9.26	5.15	0.24	0.05	0.19	1.72	2.86	0.00	0.14	91.92	0.03	7.20	99.09	<25	1940	245	155	<5	2010	130	275	1630
1σ	10	1.66	0.04	0.23	0.21	0.03	0.04	0.04	0.98	0.58	0.00	0.06		0.01	1.87										
Lower Koobi Fora Tuff																									
K93-6012	14	72.72	0.30	9.42	5.39	0.22	0.04	0.21	2.15	2.33	0.43	0.13	93.34	0.21	7.76	100.89	35	1580	150	95	10	2320	90	195	1100
1σ	14	0.70	0.04	0.11	0.11	0.03	0.05	0.04	0.97	0.75	0.11	0.06		0.06	1.41										
K80-112																									
1σ	18	0.76	0.04	0.16	0.16	0.03	0.04	0.03	0.86	0.80	0.05	0.03		0.05	1.64										
IL02-060	6	74.23	0.30	9.42	5.46	0.21	0.01	0.24	2.28	3.12	0.41	0.08	95.76	0.19	3.68	99.25									
1σ	6	0.53	0.05	0.09	0.06	0.01	0.01	0.01	0.32	0.59	0.08	0.01		0.03	0.40										
Tuff K-β																									
ETH86-324	19	71.64	0.29	9.94	4.84	0.23	0.10	0.19	1.56	2.90	0.40	0.18	92.27	0.21	8.65	100.71	<25	1590	130	100	5	1980	100	215	1050
1σ	19	0.99	0.04	0.54	0.43	0.03	0.03	0.02	0.68	0.57	0.09	0.02			1.49										
Tuff K-α																									
ETH86-322	17	71.05	0.29	9.62	4.88	0.21	0.09	0.19	1.80	3.00	0.37	0.19	91.69	0.20	9.06	100.55	45	1620	230	150	20	1810	120	235	1465
1σ	17	1.09	0.02	0.17	0.09	0.02	0.02	0.01	0.65	0.46	0.10	0.04			1.30										
Upper Okote Tuff																									
K86-2375	16	71.16	0.30	9.21	5.78	0.24	0.08	0.17	2.14	3.91	0.51	0.22	93.74	0.27	6.60	100.07	<25	1870	235	160	10	1890	130	250	1560
1σ	16	1.00	0.02	0.09	0.11	0.02	0.01	0.01	1.19	0.73	0.08	0.01		0.03	2.11										
K93-6010, -6011, -6014																									
K93-6010	11	72.51	0.31	9.47	5.02	0.20	0.02	0.20	2.22	1.93	0.15	0.09	92.12	0.09	7.69	99.73									
1σ	11	1.00	0.06	0.27	0.29	0.04	0.04	0.03	0.81	0.57	0.05	0.04		0.03	1.46										
K93-6011 M1	5	73.54	0.30	9.65	5.17	0.21	0.04	0.21	3.64	3.10	0.13	0.10	96.09	0.08	5.37	101.39	40	1460	110	75	10	2240	85	185	880
1σ	5	1.65	0.04	0.27	0.12	0.02	0.07	0.01	1.15	0.92	0.08	0.04		0.04	2.07										
K93-6011 M2	3	72.67	0.26	9.73	4.68	0.17	0.02	0.20	2.44	2.06	0.14	0.10	92.46	0.08	7.51	99.88									
1σ	3	1.46	0.04	0.25	0.45	0.05	0.04	0.03	0.99	0.66	0.06	0.04		0.03	1.93										
K93-6014	3	72.03	0.33	9.21	5.15	0.24	0.04	0.18	1.56	1.45	0.15	0.15	90.49	0.10	9.39	99.78									
1σ	3	0.36	0.06	0.22	0.05	0.06	0.06	0.05	0.21	0.16	0.05	0.12		0.05	0.10										
K93-6014	3	72.43	0.26	10.13	4.70	0.21	0.08	0.21	2.65	2.32	0.21	0.15	93.33	0.12	7.91	101.12									
1σ	3	1.50	0.02	0.17	0.11	0.04	0.06	0.01	1.42	0.79	0.06	0.05		0.04	2.20										
IL02-057	9	74.17	0.28	9.47	5.16	0.18	0.01	0.23	2.79	3.46	0.30	0.07	96.13	0.14	5.44	101.43									
1σ	9	0.48	0.03	0.15	0.11	0.03	0.01	0.02	0.20	0.67	0.03	0.01		0.01	0.89										
Morte Tuff																									
K84-1805	12	72.80	0.30	10.25	4.91	0.21	0.11	0.20	1.43	2.03	0.44	0.18	92.85	0.22	5.20	97.82	30	1810	230	135	<5	2120	120	245	1485
1σ	12	1.65	0.04	0.24	0.12	0.02	0.04	0.02	0.66	0.94	0.09	0.04			2.09										
K80-108	47	71.06	0.32	10.15	4.67	0.23	0.12	0.19	2.06	1.84	0.23	0.18	91.05	0.14	7.76	98.67	<25	1610	215	120	<5	2490	115	240	1395
1σ	47	1.03	0.04	0.15	0.15	0.03	0.02	0.01	0.98	0.63	0.13	0.02		0.06	1.78										
K02-08	8	72.90	0.32	10.10	4.96	0.22	0.10	0.19	2.86	1.79	0.52	0.17	94.14	0.26	6.22	100.10									
1σ	8	1.07	0.02	0.12	0.06	0.03	0.01	0.01	0.77	0.77	0.04	0.01		0.01	0.82										
Northern Ileret Tuff																									
K83-1663	10	69.03	0.37	12.90	5.02	0.24	0.11	0.56	2.14	2.39	0.28	0.14	93.18	0.15	5.38	98.41	850	1970	85	80	10	2390	65	200	695
1σ	10	0.63	0.02	0.16	0.09	0.02	0.02	0.03	0.56	0.38	0.03	0.01		0.01	1.16										
ETH85-055 M1	13	70.50	0.35	12.37	5.62	0.26	0.03	0.52	2.50	3.47	0.40	0.18	96.18	0.21	3.56	99.53	755	1840	90	85	25	2610	70	170	720
1σ	13	0.96	0.04	0.10	0.11	0.03	0.01	0.03	0.85	0.26	0.09	0.02		0.04	1.26										
ETH85-055 M2	3	73.46	0.14	12.25	3.07	0.11	0.00	0.33	3.89	4.94	0.27	0.15	98.61	0.15	2.52	100.98									
1σ	3	2.18	0.03	0.09	0.11	0.02	0.00	0.03	0.50	0.09	0.10	0.01		0.04	3.62										
Ileret Tuff																									
K83-1664	14	72.69	0.25	9.18	5.37	0.22	0.05	0.15	1.45	1.64	0.65	0.24	91.92	0.33	5.61	97.20	<25	2050	310	180	<5	1670	165	350	2150
1σ	14	1.02	0.02	0.09	0.13	0.03	0.01	0.01	0.41	0.26	0.08	0.02		0.03	0.95										
IL02-054	13	73.30	0.26	9.27	5.31	0.22	0.04	0.18	2.30	2.57	0.44	0.16	94.06	0.22	7.01	100.85									
1σ	13	0.71	0.03	0.29	0.42	0.03	0.02	0.03	0.39	1.01	0.10	0.07		0.06	0.97										
K93-6009																									
K93-6009	7	71.57	0.25	9.69	4.79	0.20	0.05	0.17	2.36	1.79	0.23	0.16	91.48	0.13	8.30	99.43									
1σ	7	1.27	0.06	0.43	0.13	0.04	0.05	0.03	0.71	0.34	0.09	0.06		0.05	0.90										
IL02-052	10	73.96	0.30	9.67	4.85	0.21	0.02	0.21	2.83	3.63	0.32	0.10	96.10	0.16	6.06	102.00									

(*Continued*)

Table 3. *Continued*

	Average analyses of glass shards by electron microprobe (wt%)																XRF analyses of bulk separates (ppm)								
	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	F	Cl	Sum	Less Cl, F for O	H_2O†	Total	Ba	Mn	Nb	Rb	Sr	Ti	Y	Zn	Zr
1σ	10	0.38	0.08	0.21	0.17	0.04	0.04	0.05	0.27	0.85	0.05	0.05		0.03	0.96										
Lower Ileret Tuff																									
K00-6156	14	73.64	0.22	9.13	5.95	0.26	0.03	0.15	1.47	1.50	0.43	0.28	93.07	0.25	7.46	100.29									
1σ	14	0.32	0.04	0.08	0.08	0.03	0.01	0.01	0.32	0.17	0.06	0.01		0.03	0.30										
77-20	9	71.04	0.22	8.87	5.82	0.26	0.04	0.14	1.71	1.60	0.37	0.26	90.33	0.22	7.93	98.05	<25	2020	355	180	<5	1490	190	405	2540
1σ	9	0.53	0.03	0.05	0.09	0.02	0.01	0.01	0.27	0.12	0.09	0.01		0.04	0.80										
Black Pumice Tuff																									
K83-1643	18	69.47	0.47	13.37	2.40	0.14	0.27	0.82	3.86	4.12	0.20	0.08	95.36	0.10	4.62	99.87	760	1020	85	80	110	2470	65	100	730
1σ	18	0.63	0.05	0.11	0.05	0.02	0.02	0.03	0.52	0.27	0.05	0.01	1.34	0.02	1.09	0.61									
K80-195	14	70.31	0.41	13.52	2.36	0.12	0.29	0.88	2.93	2.96	0.16	0.09	94.02	0.09	8.24	102.18	785	980	85	85	120	2720	60	100	680
1σ	14	0.61	0.06	0.15	0.06	0.02	0.03	0.06	1.10	0.71	0.08	0.01		0.03	1.18										
K93-6008 M1	24	68.53	0.45	13.34	2.57	0.14	0.34	1.02	3.36	3.28	0.20	0.07	93.30	0.10	8.27	101.47	675	1065	85	75	100	2590	65	105	730
1σ	24	1.67	0.05	0.39	0.10	0.02	0.04	0.07	0.65	0.40	0.04	0.01		0.02	1.94										
228-11	20	68.66	0.47	13.59	2.37	0.13	0.31	0.91	3.96	3.78	0.11	0.08	94.37	0.07	6.64	100.94	720	870	80	80	60	2540	60	110	660
1σ	20	0.89	0.06	0.14	0.19	0.02	0.04	0.08	0.82	0.21	0.03	0.01		0.01	0.88										

Modes are designated M1 and M2.
*All iron expressed as Fe_2O_3.
†Water calculated as explained in text.

Table 4. *Analyses of volcanic glass from tuffs in the interval from the Koobi Fora Tuff (= K-1) to the Lokapetamoi Tuff (~K3)*

	Average analyses of glass shards by electron microprobe (wt%)																XRF analyses of bulk separates (ppm)								
	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	F	Cl	Sum	Less Cl, F for O	H_2O†	Total	Ba	Mn	Nb	Rb	Sr	Ti	Y	Zn	Zr
Lokapetamoi Tuff																									
K84-2972	16	74.81	0.15	11.28	1.27	0.07	0.05	0.24	3.34	4.14	0.00	0.14	95.49	0.03	4.84	100.30	1060	490	80	125	205	1440	70	95	300
1σ	16	0.39	0.04	0.11	0.05	0.02	0.01	0.02	0.13	0.29	0.00	0.02		0.00	0.39										
Karari Grey Tuff																									
BT-10	15	72.38	0.31	9.00	5.73	0.21	0.01	0.21	1.67	3.43	0.12	0.10	93.14	0.07	5.94	99.01									
1σ	15	0.91	0.04	0.20	0.29	0.02	0.01	0.01	1.30	0.97	0.05	0.01		0.02	2.37										
K88-3265	11	72.23	0.28	9.22	5.71	0.19	0.01	0.20	2.42	3.44	0.21	0.10	94.01	0.11	7.01	100.91									
1σ	11	0.72	0.03	0.05	0.06	0.02	0.01	0.01	0.84	0.58	0.03	0.01		0.01	1.18										
Akait Tuff																									
K88-3263	27	73.54	0.17	10.68	3.10	0.09	0.02	0.20	3.11	4.00	0.18	0.14	95.22	0.11	4.80	99.92	30	675	110	120	20	1470	80	160	1000
1σ	27	1.49	0.03	0.27	0.16	0.02	0.01	0.02	0.48	0.40	0.05	0.01		0.02	1.12										
K93-6013	9	74.23	0.15	10.93	3.11	0.08	0.02	0.21	3.65	2.55	0.21	0.14	95.27	0.12	6.39	101.54									
1σ	9	0.67	0.03	0.21	0.14	0.02	0.01	0.05	0.27	0.19	0.05	0.02		0.02	0.57										
Etirr Tuff																									
K88-3019	20	72.15	0.36	8.47	6.45	0.34	0.08	0.18	1.84	2.29	n.a.	0.28	92.44	0.06	7.01	99.39	<25	2560	315	155	<5	2290	150	300	1935
1σ		0.48	0.06	0.08	0.16	0.04	0.01	0.01	1.09	0.93	n.a.	0.02		0.01	1.45										
BT-8	13	71.02	0.33	8.52	6.41	0.31	0.06	0.17	1.84	3.50	0.26	0.27	92.69	0.17	6.74	99.26									
1σ		0.75	0.04	0.09	0.10	0.02	0.01	0.01	1.12	0.96	0.11	0.01		0.04	1.76										
Ebei Tuff																									
K86-3016	13	71.12	0.51	8.49	5.94	0.37	0.08	0.08	0.594	1.35	0.24	0.37	89.15	0.19	7.85	96.71	<25	2960	275	50	10	3750	115	290	1345
1σ	13	0.70	0.06	0.11	0.11	0.03	0.01	0.01	0.085	0.23	0.05	0.02		0.02	0.73										
Karari Blue Tuff																									
BT-1	8	71.66	0.44	8.81	5.59	0.31	0.07	0.12	1.41	3.31	0.22	0.24	92.18	0.15	6.69	98.72									
1σ	8	0.78	0.09	0.31	0.19	0.06	0.04	0.06	1.19	0.98	0.09	0.10		0.05	2.01										
K88-3262	19	73.28	0.51	8.97	5.37	0.31	0.09	0.14	0.84	2.25	0.40	0.28	92.43	0.23	6.91	99.11	<25	2300	215	140	5	2940	95	215	1095
1σ	19	0.76	0.08	0.19	0.08	0.04	0.02	0.04	0.31	0.38	0.06	0.05		0.03	0.67										
K88-3261																									
K88-3261	17	73.98	0.17	10.14	3.42	0.10	0.02	0.20	3.33	4.46	0.00	0.15	95.97	0.03	4.91	100.84	65	950	140	139	<5	1180	100	190	1175
1σ	17	0.51	0.06	0.11	0.30	0.04	0.01	0.11	0.30	0.31	0.00	0.01		0.00	0.67										
K02-06	9	74.45	0.15	10.16	3.26	0.08	0.01	0.18	3.61	2.09	0.45	0.15	94.58	0.22	5.98	100.34									
1σ	9	1.39	0.03	0.19	0.23	0.02	0.01	0.02	0.86	0.26	0.03	0.02		0.02	1.11										

n.a., not analysed.
*All iron expressed as Fe_2O_3.
†Water calculated as explained in text.

Table 5. *Analyses of volcanic glass from tuffs in the interval from the Lokapetamoi Tuff (= Kyyy1) to the Chari Tuff (= L)*

	Average analyses of glass shards by electron microprobe (wt%)																XRF analyses of bulk separates (ppm)								
	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	F	Cl	Sum	Less Cl, F for O	H_2O†	Total	Ba	Mn	Nb	Rb	Sr	Ti	Y	Zn	Zr
Tuff of FxJj 63																									
K81-607	20	72.48	0.20	11.87	2.78	0.11	0.04	0.33	3.52	3.30	0.22	0.15	95.00	0.13	4.79	99.67	235	950	129	99	5	1244	87	153	929
1σ		0.38	0.04	0.11	0.05	0.03	0.01	0.01	0.43	0.32	0.04	0.01		0.02	0.82										
K83-1647																									
K83-1647	19	67.96	0.41	11.78	4.90	0.30	0.12	0.48	2.15	3.79	0.00	0.17	92.04	0.04	7.24	99.24	145	2150	150	115	<5	2640	85	190	995
1σ		0.63	0.08	0.14	0.14	0.03	0.01	0.03	0.83	0.49	0.00	0.02		0.00	1.22										
K88-3247																									
K88-3247	15	74.80	0.25	10.06	4.27	0.13	0.01	0.21	2.13	3.36	0.34	0.11	95.67	0.17	5.57	101.07	400	1060	120	95	<5	1480	105	245	1055
1σ		0.46	0.03	0.11	0.09	0.02	0.01	0.01	0.67	0.56	0.04	0.02		0.02	1.17										
K86-2880																									
K86-2880	17	60.75	0.45	16.18	6.19	0.27	0.23	1.06	2.29	2.98	0.00	0.24	90.62	0.05	8.97	99.53	<25	2090	195	95	<5	2570	55	150	635
1σ		0.52	0.09	0.15	0.18	0.04	0.05	0.08	0.83	0.78	0.00	0.05		0.01	1.29										
K86-2878																									
K86-2878	21	61.01	0.40	16.85	6.29	0.25	0.20	1.01	1.30	2.42	0.48	0.27	90.48	0.27	10.03	100.24									
1σ		0.39	0.06	0.14	0.25	0.03	0.05	0.13	0.19	0.41	0.09	0.06		0.05	0.60										
K88-3284																									
K88-3284 M1	10	68.58	0.27	8.77	6.40	0.25	0.01	0.25	2.98	3.37	0.26	0.17	91.31	0.15	8.07	99.22	355	1710	130	90	15	2330	85	185	860
1σ		0.74	0.07	0.08	0.18	0.02	0.01	0.02	0.91	0.40	0.07	0.03		0.03	0.97										
K88-3284 M2	6	69.16	0.18	10.48	3.22	0.10	0.01	0.20	3.39	3.97	0.17	0.13	91.00	0.10	7.73	98.84									
1σ		0.91	0.03	0.25	0.31	0.02	0.01	0.02	0.48	0.42	0.02	0.01		0.01	0.89										
Nabelete Tuff																									
K86-2877	17	74.66	0.17	10.69	3.08	0.09	0.01	0.19	3.44	3.40	0.19	0.13	96.05	0.11	4.89	100.83	195	800	115	105	<5	1170	105	200	1130
1σ	17	0.49	0.03	0.07	0.06	0.01	0.01	0.01	1.09	0.81	0.03	0.01		0.01	1.39										
Tuff K-3																									
ETH85-058	16	72.04	0.25	8.59	5.90	0.17	0.04	0.18	1.10	2.35	0.00	0.18	90.80	0.04	7.65	98.41	175	1490	195	135	25	1800	150	295	1725
1σ	16	0.73	0.05	0.11	0.14	0.04	0.01	0.02	0.19	0.17	0.00	0.01		0.00	0.63										

Modes are designated M1 and M2.
*All iron expressed as Fe_2O_3.
†Water calculated as explained in text.

Table 6. *Comparative analyses of tuffs from the Turkana Basin and the Konso Formation*

	Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	Sum
Bright White Tuff (BWT)	9412-42	71.97	0.16	10.64	2.78	0.06	0.00	0.17	2.76	4.09	92.63
Chari Tuff	K77-23	73.65	0.17	10.77	2.80	0.08	0.01	0.18	3.92	3.79	95.74
Bench Tuff (BNT)	9312-35	71.42	0.20	11.77	2.76	0.11	0.02	0.32	3.60	4.03	93.97
Tuff of FxJj 63	K81-607	72.45	0.20	11.90	2.79	0.11	0.04	0.34	3.48	3.28	95.11
Ivory Tuff (IVT)	938-17	72.65	0.15	11.21	1.32	0.07	0.04	0.22	2.81	4.75	93.22
Lokapetamoi	K84-2972	74.81	0.15	11.28	1.27	0.07	0.05	0.24	3.34	4.14	95.54
Hope Tuff (HPT)	9413-101	70.56	0.15	10.38	2.99	0.07	0.00	0.19	3.15	5.00	92.49
Nabelete	86-2877	71.56	0.17	10.38	2.92	0.09	0.01	0.18	4.20	3.51	92.82
Akait	88-3263	73.54	0.17	10.68	3.10	0.09	0.02	0.20	3.11	4.00	95.36
Trail Bottom Tuff	9311-43	68.33	0.37	8.34	6.40	0.27	0.05	0.16	3.34	3.78	90.43
Etirr Tuff	K86-3019	72.15	0.36	8.47	6.45	0.34	0.08	0.18	1.84	2.29	99.64
Hand Axe Tuff (HAT)	954-1	71.57	0.33	9.48	5.09	0.19	0.08	0.18	3.07	2.61	92.60
Koobi Fora Tuff Complex	K93-6014	72.23	0.30	9.67	4.92	0.22	0.06	0.19	2.10	1.88	92.09
Turoha Tuff (av. of 155 analyses)	944-57, 58, 59; 964-21, 27	70.95	0.18	10.31	2.90	0.10	0.03	0.18	3.62	4.18	92.20
KBS Tuff	77-17	70.37	0.16	10.80	3.09	0.12	0.03	0.16	3.23	3.27	91.24

*Total iron expressed as Fe_2O_3.

Correlations reported previously (Cerling & Brown 1982; Brown & Feibel 1985; Feibel & Brown 1993) were based on a relatively small amount of data, derived from relatively few tuffs. Information is now available on a much larger number of tuffs, and through correlation, it is possible to suggest the sequence of many of them, which suggests strongly that some correlations proposed previously are not valid.

By correlation we mean that two or more ash layers are the products of a single volcanic eruption, or a series of volcanic eruptions closely spaced in time, that were deposited soon after eruption. The ultimate aim is to establish time-equivalence between widely separated sections. In correlating volcanic ash layers, many features are important: chemical composition of juvenile phases within the tephra, gross stratigraphic position of the layers, homotaxial sequences of layers for which compositions have been determined, their palaeomagnetic polarity, the relation of the layers to biostratigraphically significant faunas, and their isotopic ages. All correlations are permissive, and no single test can determine whether a proposed correlation is correct, but many tests can determine whether a proposed correlation is incorrect. For example, two volcanic ash layers at similar positions in two different sections may be so different in composition that correlation is very unlikely. Or, two compositionally similar layers may be present in a single section, separated by a layer of different composition. In this case, it is unlikely that the upper layer correlates with the lower layer, although in Area 110 at Koobi Fora the airfall KBS Tuff is separated from the fluvially deposited KBS Tuff by the airfall Brown Tuff. Some examples of such difficulties have been discussed by Feibel *et al.* (1989). Similarly, two compositionally different pumices from a single tephra layer may yield indistinguishable isotopic ages, and actually be products of the same eruption, but at different stages of the eruption. In this case, they correlate temporally, but not compositionally.

A further problem is that the volcanic glass separated from a tuff is not compositionally the same as it was when it erupted. In many cases the glass has been hydrated, perhaps to a different extent in different depositional settings, and it may have variably lost or gained alkalis. It follows that not all elements are equally reliable for correlation. In the proposed correlations that follow, we use the following rules. Where homotaxial stratigraphic sequences of tuffs occur, we correlate compositionally indistinguishable tuffs in those sequences, relying especially on the concentrations of aluminium, iron, calcium, titanium, manganese, chlorine, magnesium, zirconium, niobium, yttrium, and barium. Accompanying tables of analyses give the standard deviation for each major element in each analysis. In almost all instances, tuffs that we regard as correlates have concentrations within one standard deviation of each other for all of the elements listed above (i.e. ignoring alkalis, fluorine, silica, and water). In some cases we suggest a tentative correlation between tuffs when the stratigraphic position allows such a correlation, and the composition is very similar but still distinguishable on the basis of the concentration of one or more elements in the two analyses. Analyses of correlated tuffs, and of tuffs believed to have been miscorrelated previously are available as a Supplementary Publication (see p. 186).

Stratigraphic sequence of tuffs

The following text discusses the sequence, and age of many volcanic ash layers in this interval, and tables of chemical analyses of glass from the tuffs are provided. Location information on all samples is available as a Supplementary Publication (see p. 186) along with other details, where type locations of named tuffs are also noted.

De Heinzelin (1983) provided the most complete description of the Shungura Formation, which is divided into 12 members (Basal Member, Members A to H followed by Members J to L) with a prominent tuff at the base of each member except for the Basal Member. Each member is divided into submembers numbered sequentially from the base to the top. Here, tuffs in the Shungura Formation are designated by the submember in which they occur, except for the defining tuffs, following the practice of de Heinzelin (1983). Thus Tuff F-1 lies in submember 1 of Member F of the Shungura Formation. Where more than one tuff occurs within a submember, the different tuffs are distinguished by adding a letter to the submember designation. Thus Tuff H-1A lies below Tuff H-1B in submember H-1 of the Shungura Formation. This system provides a ready method of keeping track of the order of volcanic ash layers in the Omo Group formations. In the tuffs described here we append a parenthetic designation that shows the submember (or approximate submember if preceded by a tilde ($\sim$)) to which each named tuff of the Nachukui and Koobi Fora Formations belongs the first time a named tuff is mentioned in a paragraph. As the KBS Tuff has been correlated with Tuff H-2 of the Shungura Formation, it is referred to throughout as the KBS Tuff (= H-2).

In presenting the sequence of ash layers in this complicated interval, we divide the interval into five parts (Fig. 2). The first begins at the KBS Tuff (= H-2) and ends at the Morutot Tuff (= J-4). It is relatively simple to describe, as volcanic ash layers are not too abundant, and only the Shungura and Koobi Fora Formations need be considered. Apart from the lower bounding tuff, only one volcanic ash layer has been noted in this interval in the Nachukui Formation. The second interval, from the

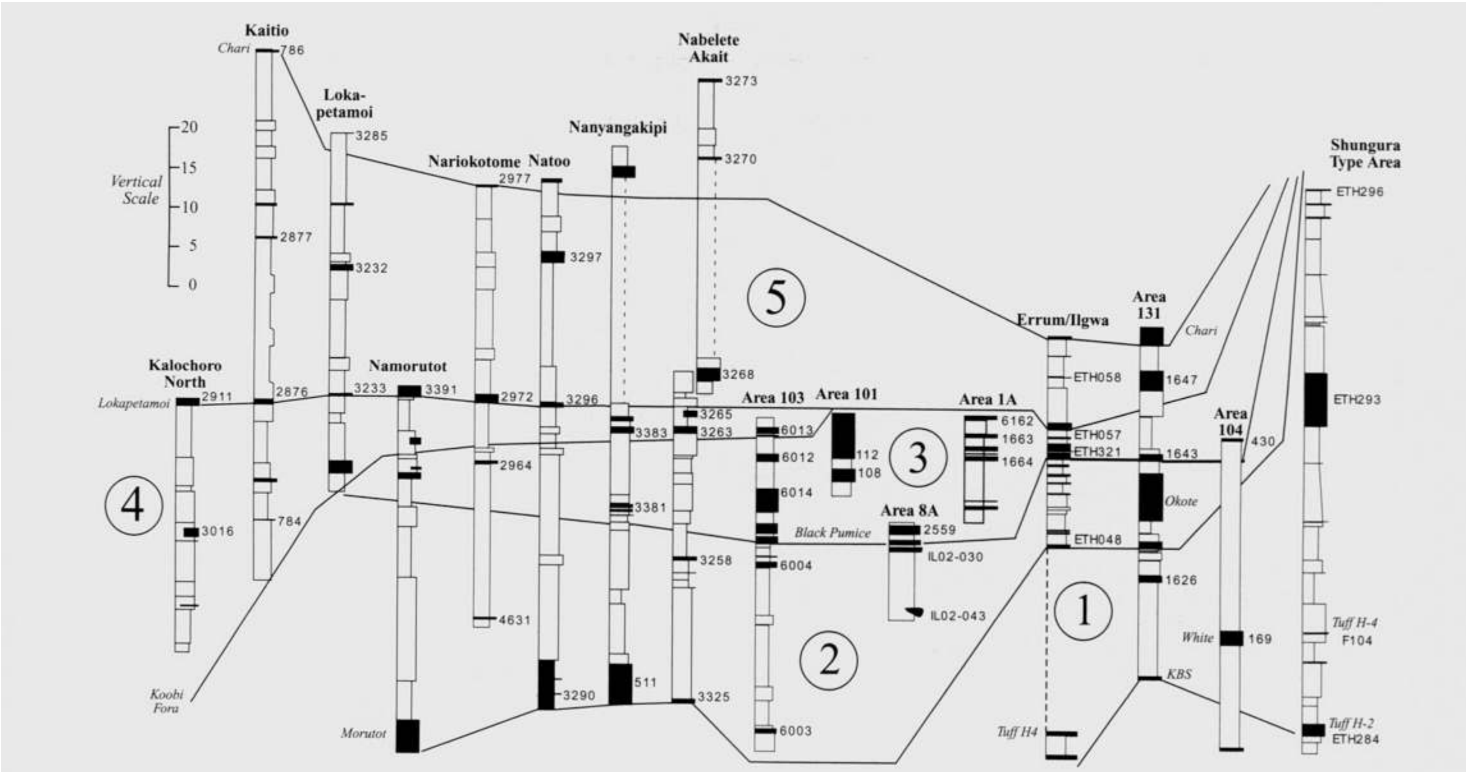

Fig. 2. Stratigraphic relations between numbered groups of tuffs that are shown in more detail in ensuing figures. On this and subsequent figures, only the final four digits of samples labelled in the format KYY-xxxx are given; full sample numbers are given in the tables. Additionally, sample numbers for tuffs from the Shungura Formation have been shortened by deleting the year of collection, thus ETH86-317 becomes ETH 317 in the figures.

Morutot Tuff to the Black Pumice Tuff (= J-7A), is represented in all three formations, as is the third interval, which extends from the Black Pumice Tuff to the Koobi Fora Tuff (= K-1). The fourth interval comprises a set of tuffs that lie above the top of the Koobi Fora Tuff and below the top of the Lokapetamoi Tuff (~K-3). Tuffs of this interval are known principally from the Nachukui Formation. The fifth interval includes tuffs that lie between the Lokapetamoi Tuff and the Chari Tuff (= L).

On the basis of ages presented by McDougall & Brown (2006), the interval between the KBS Tuff (= H-2) and the Chari Tuff (= L) spans about 0.49 Ma, and contains at least 65 compositionally or stratigraphically distinct tuffs. Fewer than 20 of these correlate from one formation to another, but many are useful for correlations over tens of kilometres, and several have been dated. Some are similar in composition, even though separated by tephra layers of different composition. At least 35 of these lie in the temporal interval from *c.* 1.43 to 1.53 Ma, so eruptions occurred on average every 3 ka.

In the interval under consideration, different areas of the Turkana Basin have different depositional histories and stratigraphic thicknesses. For example, along the western end of Koobi Fora Ridge the section in this interval is *c.* 180 m thick, at Ileret it is *c.* 120 m thick, but on the Karari Ridge it occupies <45 m of section. In the Shungura Formation the stratigraphic thickness is *c.* 115 m. Where sediment accumulation rates are roughly the same, and some correlations have been established between two or more sections, other tuffs that lie at similar positions in those sections probably also correlate. That is, the stratigraphic distance by which they are separated is a guide to possible correlations. Other information (e.g. glass composition) is still needed to show whether a particular correlation is reasonable. Where sediment accumulation rates differ markedly from one section to another, the distance by which tuffs are separated stratigraphically provides little help in assessing probable correlation. An example of this is the Steel-grey Tuff (~H-6) in Koobi Fora Areas 10 and 130 (Fig. 3), where the stratigraphic separations are very different, but the compositions are indistinguishable.

Group 1

Fifteen different tuffs have been analysed from the interval between the KBS Tuff (= H-2) and the Morutot Tuff (= J-4), which represents *c.* 300 ka. These are discussed in order from the base to the top. Although the Morutot Tuff and the KBS Tuff are known in the Nachukui Formation, only one tuff has been noted there in strata between them: the Orange Tuff (~J-2). Stratigraphic relations between these ash layers are shown in Figure 3, and representative analyses for named, dated, and correlated tuffs are given in Table 1, arranged with the youngest at the top and the oldest at the bottom. Additional analyses are available as a Supplementary Publication (see p. 186).

KBS Tuff (= H-2). Vondra *et al.* (1971) established the type locality of this tuff at archaeological site FxJj 1 in Area 105 of the Koobi Fora region (sample 77-17). In the Shungura Formation, its correlate is known only from the Type Area (see Fig. 1), where it is a thin unit (0.4 m) with pumice clasts up to 40 cm in diameter. In the Nachukui Formation it is an airfall ash within lacustrine claystones exposed for *c.* 10 km southward from Kaitio. In the Koobi Fora region, the KBS Tuff lies within a fluvial sequence at the type locality, and in most other outcrops

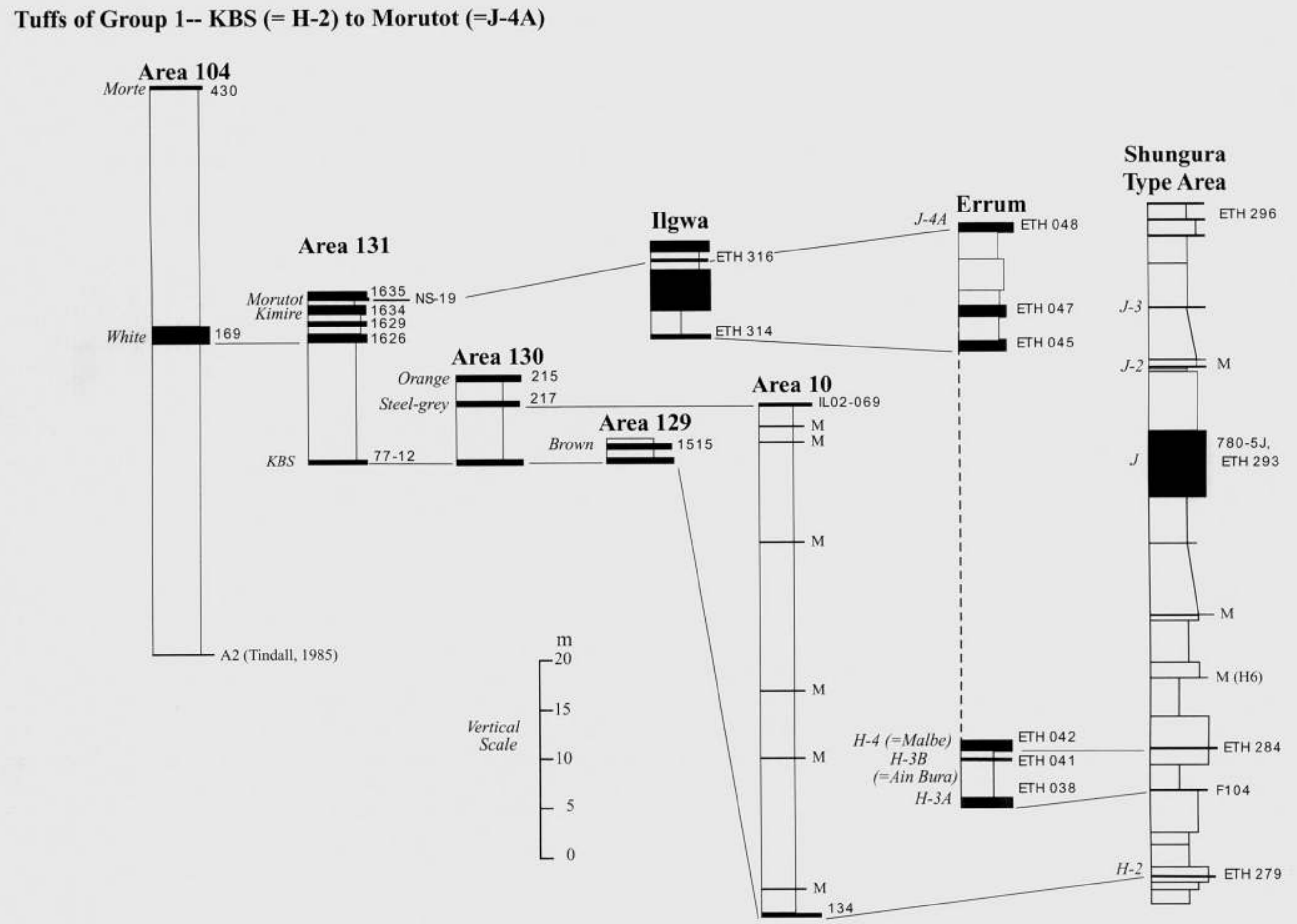

Fig. 3. Stratigraphic relations between tuffs of Group 1 that lie between the KBS Tuff and the Morutot Tuff. M, mollusc-rich layer. The schematic stratigraphic sections are left unornamented, but the width of the column is a rough guide to grain size; the wider the column, the coarser the material. The section for Area 104 is after Section 104-13 of Tindall (1985); for Area 131, after Brown & Feibel (1985); for Area 10, after Section PNG-10.1 of Gathogo (2003; with additions), for Ilgwa and Errum, after Haileab (1995); and for the Shungura Type Area, after figures 45 and 46 of de Heinzelin (1983). Others are from field notes of F.H.B.

along the Karari Ridge, but it is an airfall ash in lacustrine strata in Area 110. Not all pumice clasts from this tuff correspond to the composition of the tuff itself (Curtis *et al.* 1975; Cerling *et al.* 1979). In the Koobi Fora Formation the KBS Tuff contains pale grey and dark brown shards, which are compositionally identical. The colour is caused by minute crystals of magnetite that give the dark shards extremely high magnetic susceptibility (Schlinger & Smith 1986). Dark shards are not present in Tuff H-2 of the Shungura Formation, implying that a different part of the eruption was sampled in the two areas.

Brown Tuff (~H-2). This tuff probably lies next in sequence. In Area 129 it is separated from the KBS Tuff (= H-2) by 1.8 m of medium brown mudstone with carbonate nodules at the top. In Area 110 it is a coarse airfall ash layer in a claystone *c.* 2 m above the KBS Tuff. Informally it has been called the 'brown tuff' because of its appearance in outcrop. Here we formalize this name, with the type locality designated in Area 129 (K83-1515).

Tuff H-3A. Two tuffs are known from submember H-3 in the Type Area of the Shungura Formation. Tuff H-3A lies in a siltstone about 5 m above the base of the submember, but at Errum (Fig. 1) it rests almost directly on Tuff H-1B. Thus it is likely that submember H-2 is absent or very thin at Errum, where a second tuff, Tuff H-3B, lies *c.* 6 m higher in the section.

Ain Bura Tuff (= H-3B). In the eastern part of the main gully at Errum, Tuff H-3B (ETH 41) is separated from the Malbe Tuff (= H-4) by a 10 cm sandstone rich in fossil gastropods. It is a lenticular dark grey tuff, and correlates with a tuff exposed in Koobi Fora Area 128 west of a hill known as Gum Ain Bura. Here this tuff is named the Ain Bura Tuff, with the type locality designated in Area 128 (K80-231).

Malbe Tuff (= H-4). Cerling & Brown (1982) defined the Malbe Tuff, with its type locality in Koobi Fora Area 112 (K80-225). It is also known from Areas 102, 105, 106, and 127 at Koobi Fora, from the Type and Kalam areas of the Shungura Formation, and from the Nachukui Formation. In many localities at Koobi Fora this tuff is lenticular, and it contains pumice of several related compositions. The position of the Malbe Tuff in Area 102 is known from chemical analysis of feldspar phenocrysts enclosed within altered pumice clasts (Feibel 1983).

Steel-grey Tuff (~H-6). This tuff lies above the KBS Tuff, but below the Orange Tuff (~J-2; defined below). It was first identified in Area 130 (K80-217), and later in Area 10 (IL02-069) where it fills a channel situated *c.* 52 m above the KBS Tuff. Here this tuff is named the Steel-grey Tuff, with its type locality designated in Area 130 (K80-217).

Tuff J. Tuff J is known only from the Type Area of the Shungura Formation, where it was defined by de Heinzelin (1983) as the basal unit of Member J. It is a unit 6 m thick that contains lenses of pumice pebble gravels. The composition of glass separated from a composite pumice sample (780-5J) does not correspond to that of the tuff itself (ETH 293). Its approximate age is 1.76 Ma.

Chibele Tuff (~J-2). This tuff, named here, is a vitric tuff 1 m thick that overlies an indurated brown sandstone. It is disconformably overlain by the Kibish Formation at Chibele, its type (and only known) locality (KIB03-265), and presumably is a part of the Nkalabong Formation (Butzer & Thurber 1969). Neither its relation to Tuff J nor to the tuffs of submember J-4 in the Type Area of the Shungura Formation is known from direct stratigraphic observations. It is placed here in the sequence solely on the basis of its measured age, 1.72 Ma (McDougall & Brown 2005). One pumice is similar to, although different from the composition of the tuff, and the other is compositionally very different from any other analysed material in this interval.

Orange Tuff (~J-2). The Orange Tuff was first referred to by Bowen (1974) in Area 130 at Koobi Fora, where it lies about 8 m below the locally defined Okote Tuff Complex. It was defined by Harris *et al.* (1988*a*), who incorrectly gave the type locality as Area 131 rather than Area 130 (Fig. 1); coordinates of the type locality are those for sample K80-215. In Area 109 at Koobi Fora the tuff (K80-236) includes an intercalated shellbed, and lies below a bioclastic sandstone.

White Tuff (~J-3). The White Tuff, defined by Brown & Feibel (1985), is known only from Areas 104 and 131 at Koobi Fora. Its type locality is in Area 131 (K83-1626). In Area 104 it occupies a channel, situated 36 m above an algal biolithite labelled A2 (Tindall 1985). Stratigraphically it is the lowest tuff known to have been mapped as part of the Okote Tuff Complex in Area 131, where it lies within the KBS Member of the Koobi Fora Formation 11.5 m above the KBS Tuff. It is apparently about 250 ka younger than the KBS Tuff, and a hiatus of this duration appears to be present in many sections above the KBS Tuff in Areas 130, 131, and 105 (Isaac & Behrensmeyer 1997).

ETH 45 (J-3). De Heinzelin (1983) correlated a fine white tuff (sample ETH 45) at Errum with Tuff J of the Type Area on the basis of stratigraphic similarities in the sections. Yet it is compositionally distinct from Tuff J (see Table 1), and it is likely that it lies above Tuff J in the sequence because it correlates with a tuff (ETH 314) that de Heinzelin (1983) described as Tuff J-3 at Ilgwa. The principal mode of ETH 314 matches the single mode of ETH 45, and we correlate them on this basis. The other two modes of ETH 314 are probably reworked shards, and compositionally match the Orange Tuff and the White Tuff (see Table 1), hence ETH 45 and ETH 314 are placed above these two tuffs.

Kimire Tuff (~J-3). The Kimire Tuff (K83-1634) was named by Brown & Feibel (1985) in their discussion of the Okote Tuff Complex in Area 131 of the Koobi Fora region. They noted that it is stratigraphically distinct, but cannot be confidently distinguished chemically from some other tuffs collected higher in the same section. It is underlain by a thin tuff (K83-1629) in Area 131 (Brown & Feibel 1985). Its type locality is in Area 131 (K83-1634).

Group 2

This group comprises tuffs that lie between the Morutot Tuff (= J-4) and the Black Pumice Tuff (= J-7A). Tuffs of this interval comprise parts of the Okote, Ileret and Koobi Fora Tuff Complexes at Koobi Fora. Analyses of glass from tuffs in this group are given in Table 2. Figure 4 shows the disposition of ash layers in the interval under discussion.

Morutot Tuff (= J-4A). The Morutot Tuff, defined by Harris *et al.* (1988*a*), is known from the Kalam Area, from the northern part of the Nachukui Formation, and from Koobi Fora Area 131. In the Shungura Formation, Tuff J-4 is an impure ash layer 45 cm thick with root-casts and carbonate concretions in its upper part. In the Nachukui Formation it is 5 m thick at Nanyangakipi (its type locality) with occasional pumice clasts, but at Natoo it forms a series of thin (0.1–0.5 m), discrete layers in a siltstone over a 3.2 m interval. In Area 131 at Koobi Fora, it is a calcified pale orange tuff normally <0.5 m thick. Stern (1993) demonstrated that it lies below the Lower Okote Tuff.

Lower Okote Tuff (~J-4). Brown & Feibel (1985) defined the Lower Okote Tuff in Area 131 at Koobi Fora (K83-1635). It contains pumice clasts of the same composition as the Morutot Tuff, and is the source of the dated materials from the Koobi Fora Formation attributed to the Morutot Tuff (McDougall *et al.* 1985).

Tuff J-5. This tuff (ETH 318) was sampled at Ilgwa from submember J-5, although de Heinzelin (1983) did not record a tuff from this submember. Electron microprobe analysis demonstrates that this tuff is at least bimodal, and possibly trimodal; the two dominant modes are given in Table 2. One mode is very similar to the composition of a tuff that fills a channel in Area 8A (IL02-043), and these two units may correlate.

Tuffs of Shungura submember J-6. Tuffs ascribed to submember J-6 at Ilgwa and Errum in the Kalam Area of the Shungura Formation do not correlate, but are placed together here in the sequence. Tuff J-6A (ETH 319; also 228-7) was collected from unit J-6 in the section below Tuff K at Ilgwa (de Heinzelin 1983). It contains large calcified rootlike concretions, but is not laterally extensive. Compositionally it is similar to the Lower Koobi Fora Tuff (~K-1), discussed below. Another sample of this tuff (228-7) was given as a reference sample of the Koobi Fora Tuff (Feibel & Brown 1993), a matter discussed below.

Three other tuffs from the type section of submember J-6 at Errum are compositionally very distinct from Tuff J6-A. Two of the samples (ETH 304, ETH 305) are similar in composition, although they were collected from different levels (Fig. 4). The third tuff (sample ETH 307) correlates with no other tuff analysed thus far. These tuffs are labelled J-6B to J-6D in Figure

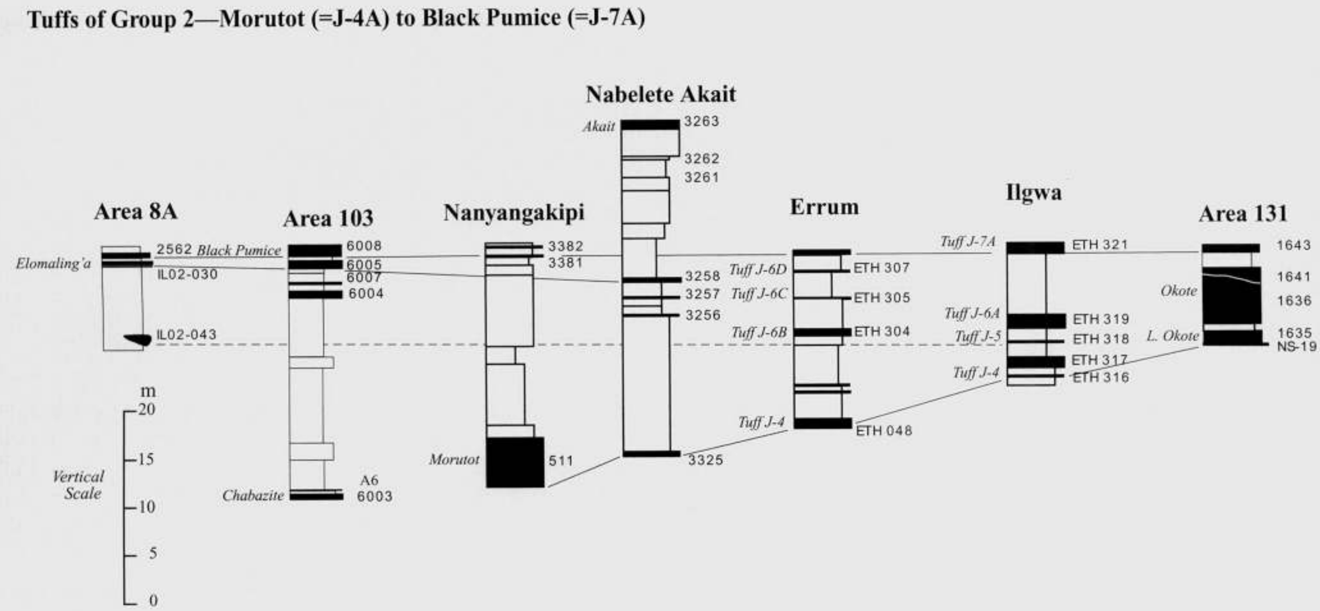

Fig. 4. Stratigraphic relations of tuffs of Group 2 that lie between the Morutot Tuff and the Black Pumice Tuff. The section for Area 8A is after Section PNG-8A of Gathogo (2003; with additions); for Ilgwa and Errum, after Haileab (1995); for Area 131, from Brown & Feibel (1985). Others are from field notes of F.H.B.

4. Although this treatment is not satisfactory, we can say little more without additional field investigation.

Okote Tuff (~J-6). Brown & Feibel (1985) gave the type locality of the Okote Tuff as Area 131 at Koobi Fora (K83-1636). Its iron content (*c.* 4.8% as Fe_2O_3) allows ready distinction from the Upper Okote Tuff (*c.* 5.8% Fe_2O_3). It is placed at this position in the sequence of tuffs because it is most closely associated with the Lower Okote Tuff and the Morutot Tuff on the Karari Ridge (Stern *et al.* 2002).

K83-1641. This unnamed tuff lies above the Okote Tuff but below the Black Pumice Tuff in Area 131. Compositionally it is similar to sample K93-6007, a layer of pumice granules that lies below the Black Pumice Tuff in Area 103. Brown & Feibel (1985) had correlated it with the Lower Koobi Fora Tuff, which lies above the Black Pumice Tuff, thus it is considered to be a tuff of similar composition (Table 2).

Elomaling'a Tuff (~J-6). In Area 103 at Koobi Fora a 30 cm siltstone separates the mollusc-bearing sandstone that contains K93-6007 from a tuff with pumices up to 10 cm in diameter (K93-6005). This latter sample correlates with a tuff (IL02-030) that lies stratigraphically within 10 cm of a prominent caliche layer used as the local boundary between the KBS Member and the Okote Member of the Koobi Fora Formation at Ileret (Gathogo 2003). Here this tuff is named the Elomaling'a Tuff, with the type locality designated as Area 8A (IL02-030). This tuff correlates with sample K88-3258 from the Nachukui Formation (Fig. 4).

Group 3

This group comprises tuffs between the Black Pumice Tuff (= J-7A) and the Koobi Fora Tuff (= K-1). It is represented in the Kalam Area of the Shungura Formation, in the Nachukui Formation north of Kaitio, in Areas 101 and 103 at Koobi Fora, and in the Ileret Area. Relations between tuffs of this group are shown in Figure 5, and analyses are given in Table 3.

Before proceeding with discussion of the sequence of tuffs in other areas, a few words are necessary about two previously named tuffs: the Upper Okote Tuff and the Middle Ileret Tuff. Feibel & Brown (1993) defined the Upper Okote Tuff in Area 131 at Koobi Fora (see coordinates for sample K86-2375, in the Supplementary Publication, for type locality). They correlated it with Tuff K-α of the Shungura Formation, and gave K89-3384 as a reference sample in the Nachukui Formation. However, the Upper Okote Tuff differs compositionally from Tuff K-α in several respects (Fe_2O_3, Al_2O_3, and Zr). The reference sample, K89-3384, is bimodal, and likewise differs in these elements from the Upper Okote Tuff in addition to TiO_2. Stratigraphically it lies above the Black Pumice Tuff and below the Chari Tuff, but cannot be more closely constrained, although it lies immediately above sample K83-1645, which is trimodal. The major element composition of the Upper Okote Tuff most closely corresponds to sample K88-3304, which lies below the Etirr Tuff (defined below) in a small southern tributary of Nachukui (Fig. 6), and its trace element contents are also reasonably similar to those of sample K88-3304. If this correlation can be proven, then the Upper Okote Tuff will lie in the sequence near the base of Group 4. In any case, the name is not available to apply to any other tuff that is compositionally distinct from the Upper Okote Tuff.

The Middle Ileret Tuff in Area 6 is a poorly sorted, poorly bedded unit with a wide range in grain sizes, which may have been deposited as a debris flow. It lies between the Ileret Tuff and the Chari Tuff (Fig. 3), but cannot be more closely placed at present. Compositionally it is a multimodal unit.

Black Pumice Tuff (= J-7A). In Koobi Fora Area 131, a channel above K83-1641 is filled with a very distinctive tuff with black pumice clasts, which Brown & Feibel (1985) named the Black Pumice Tuff (see Supplementary Publication for coordinates of the type locality). The correlative unit in the Shungura Forma-

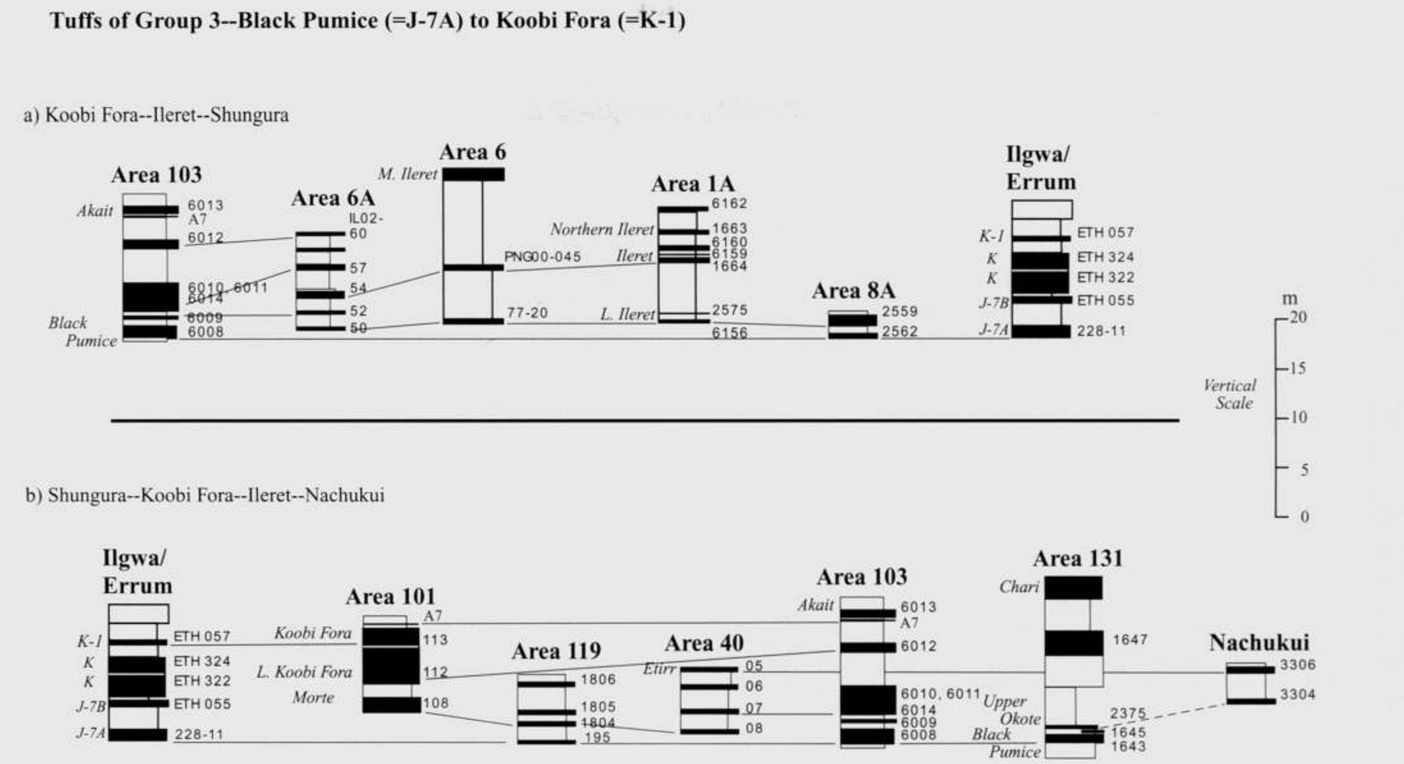

Fig. 5. Stratigraphic relations of tuffs of Group 3, between the Black Pumice Tuff and the Koobi Fora Tuff. The section for Area 6A is after Section PNG-06A of Gathogo (2003); for Ilgwa and Errum, after Haileab (1995); for Area 131, after Brown & Feibel (1985). Others are from field notes of F.H.B.

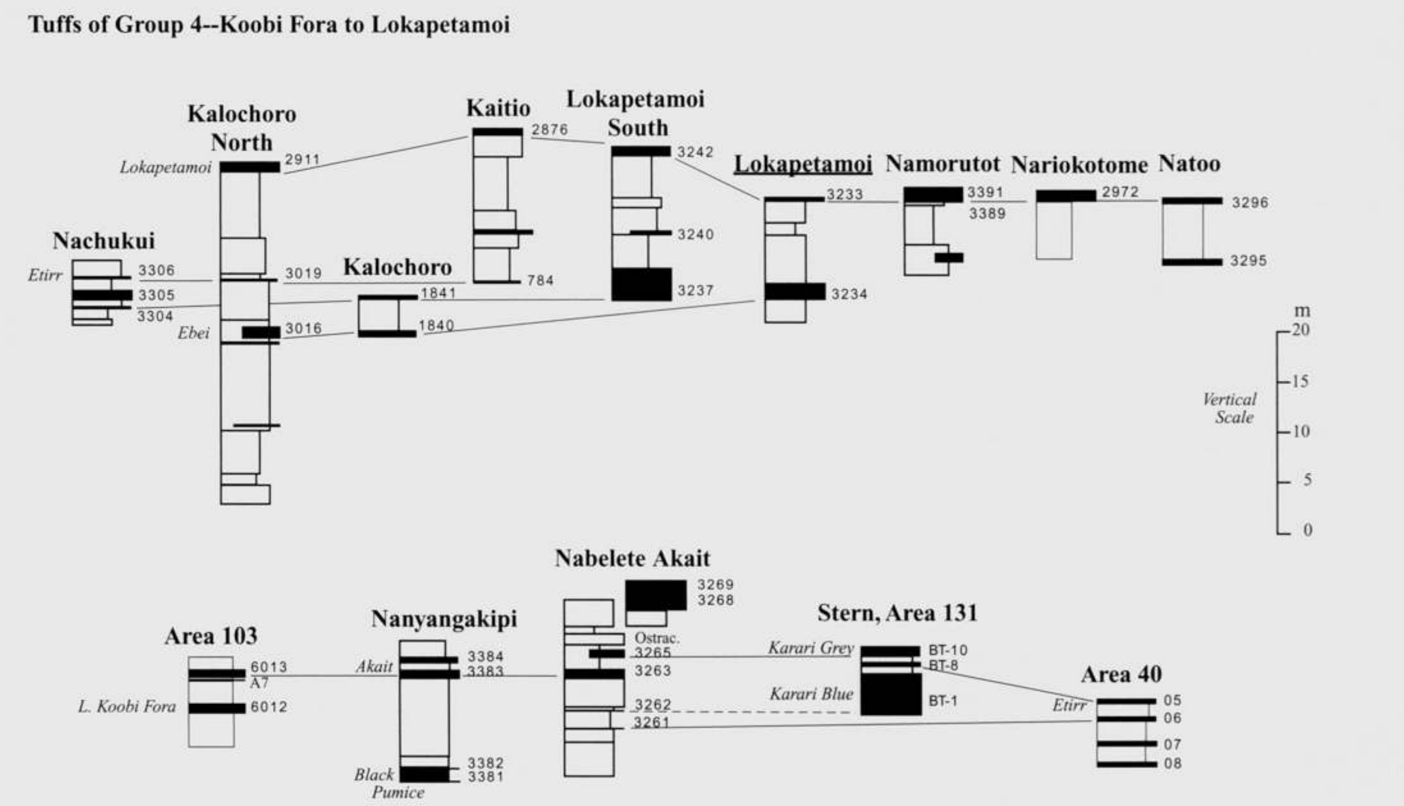

Fig. 6. Stratigraphic relations of tuffs of Group 4, from the Koobi Fora Tuff up to and including the Lokapetamoi Tuff. The section labelled Stern, Area 131 is from Stern (1993). Others are from field notes of F.H.B.

tion, Tuff J-7A lies 1–2 m below Tuff K-α at Ilgwa. Although ≤1 cm thick, it is a useful unit for correlation from Ilgwa to Namaruputh. It has been identified in Areas 8A, 103, 119, and 124 at Koobi Fora, and also in the Nachukui Formation.

Lower Ileret Tuff (~J-7). The lowest tuff in the Ileret Tuff Complex in Area 6 was named the Lower Ileret Tuff by Cerling & Brown (1982). This is its type locality (77-20). In many localities near Ileret (Areas 1A, 4, 5, 6, 6A, and 8A) it is a medium grey vitric tuff that locally contains small pumice clasts. Compositionally it has amongst the highest concentrations of trace elements in the entire dataset (e.g. Zr >2000 ppm, Nb>300 ppm, etc.).

K93-6009 (~J-7). This tuff lies above the Black Pumice Tuff (= J-7A) in Koobi Fora Area 103 immediately above a mollusc-packed sandstone, and correlates with sample IL02-052 in Area 6A at Ileret. At the latter locality it is bracketed by the Lower Ileret Tuff (~J-7) and the Ileret Tuff (discussed next), neither of which have been identified in Area 103.

Ileret Tuff (~J-7). The Ileret Tuff, named here, is similar to the Lower Ileret Tuff in its high residual element content, but its iron content is distinctly lower (5.4% v. 5.8% Fe_2O_3). The type locality is in Area 1A (K83-1664), where the tuff is dark grey and forms a prominent ledge at the edge of a small plateau where small-scale ripple marks are exposed on the surface of the unit. It is also present in Area 6A (sample IL02-054; Fig. 5).

Northern Ileret Tuff (~J-7). At Ileret a vitric tuff with undulating laminae in its upper part is a useful unit for correlation between local sections in Areas 1, 1A, 3, 5, and 11. We define this tuff as the Northern Ileret Tuff, with its type locality in Area 1A (K83-1566). In that area it lies *c.* 5 m above the Ileret Tuff.

Morte Tuff (~J-7). In Area 119 at Koobi Fora, the Black Pumice Tuff (= J-7A) lies <2 m below a tuff that we name the Morte Tuff (K84-1804, 1805), after a large tributary of Il Alia. The tuff has a pumice cobble and pebble gravel at the base that fines upward to a vitric ash. We correlate it here with K80-108, which lies 1 m below the Lower Koobi Fora Tuff in Area 101. Further, we correlate it with a tuff in Area 40 (K02-08), which lies 8 m below the Etirr Tuff (defined below; Fig. 5). It has been dated at 1.51 Ma (McDougall & Brown 2005).

Brown & Feibel (1985) correlated the lowest tuff in the sequence in Area 101 (K80-108) with the Okote Tuff in Area 131, and indeed the two are compositionally similar. However, in Area 131 the Okote Tuff lies below the Black Pumice Tuff, whereas K80-108 in Area 101 lies only a small distance below the Lower Koobi Fora Tuff, which itself lies above the Black Pumice Tuff. Thus it is more probable that K80-108 correlates instead with the Morte Tuff, an arrangement shown in Figure 5.

K93-6010, and -6011, -6014 (~K-1). These samples from Area 103 are treated together, although they lie at different stratigraphic levels in the Koobi Fora Tuff Complex (Fig. 5). Sample K93-6014 lies about 3 m above K93-6009, and the intervening sandy section has a layer rich in *Corbicula*. K93-6010 and -6011 lie 1.9 and 3 m above this sandstone. These samples are all bimodal (Table 3). These tuffs probably correlate with a tuff or tuffs in Area 6A at Ileret (e.g. IL02-057, Fig. 5). Below we suggest that this group of tuffs may correlate with the Hand Axe Tuff at Konso.

Tuff K-α. Tuff K-α of the Shungura Formation is a fine ash layer (0.5 m) with small-scale ripple marks that forms a long cuesta at Errum. At Ilgwa the tuff contains pumice clasts at its upper contact.

Tuff K-β. Tuff K-β (ETH 324; Table 3) is separated from Tuff K-α by a siltstone layer 1.2 m thick in the type section, but by only 0.5 m at Ilgwa. It grades upward into a tuffaceous siltstone. Feibel & Brown (1993) correlated it with a lenticular tuff at Nabelete Akait (K88-3265; Table 4) in a pale orange sandy siltstone situated 2 m above the Akait Tuff. Major element analyses show that the two units are very different in Al_2O_3, Fe_2O_3, and MgO content, and thus cannot be correlated.

Lower Koobi Fora Tuff (~K-1). Brown & Feibel (1985) designated the lower 4.1 m of the thick tuff exposed in Area 101 as the type locality of the Lower Koobi Fora Tuff (K80-112); the upper 3.3 m of this tuff was designated the type locality of the Koobi Fora Tuff (K80-113). It correlates with a tuff in the upper part of the Koobi Fora Tuff Complex in Area 103 (K93-6012).

Koobi Fora Tuff (= K-1). Brown & Feibel (1985) defined the Koobi Fora Tuff, designating the type locality as being in Area 101 (see previous paragraph). Later Haileab (1988) correlated it with Tuff K-1 of the Shungura Formation at Errum. In Area 101 it immediately overlies, and appears to be in stratigraphic continuity with the Lower Koobi Fora Tuff, and contains pumice of the same composition as the enclosing ash. The Koobi Fora Tuff is not present in the section through the Okote Tuff Complex in Area 131 published by Brown & Feibel (1985). Feibel & Brown (1993) gave 228-7 as a reference sample for the Koobi Fora Tuff, but this sample is from submember J-6 of the Shungura Formation, not submember K-1. That is, it underlies the Black Pumice Tuff whereas the Koobi Fora Tuff lies above it. In addition, 228-7 differs from the Koobi Fora Tuff in its TiO_2, Fe_2O_3, MgO, and Zr content. Thus we do not believe their suggested correlation, instead reaffirming the original correlation of Haileab (1988).

Group 4

This group of tuffs is exposed principally in the Nachukui Formation between Lokitoinyala and Kalochoro (Fig. 1), but some are also present in the Koobi Fora Formation. Relations between them are shown in Figure 6; analyses are given in Table 4.

K88-3261(~K2). At Nabelete Akait, this tuff is 0.1–0.2 m thick, and is deposited with slight disconformity on the underlying sandstone. It correlates with a tuff (K02-06) about 50 cm thick that is exposed in Area 40 at Ileret, which itself lies 1.5 m below the Etirr Tuff described below.

Karari Blue Tuff (~K-2). Stern (1993) informally described a tuff in Area 131 as the 'blue tuff'. As this is a dated unit, we formalize the name here, designating it the Karari Blue Tuff to distinguish it from 'blue' tuffs elsewhere (e.g. at Konso). The type locality is as defined by Stern (1993) in Area 131 on the Karari Ridge (see Supplementary Publication for coordinates). It correlates with sample K88-3262, a 0.4 m dark grey, cross-laminated tuff at Nabelete Akait. Stern *et al.* (2002) placed it about 1 m below a tuffaceous sand. Glass from this tuffaceous sand contains several compositional modes, some of which are of the same composition as K88-3261, but the dominant mode is of the same composition as the Etirr Tuff. Thus the Karari Blue Tuff lies below a reworked unit that lies above the Etirr Tuff and K88-3261.

Ebei Tuff (~K-2). This tuff is one of three that underlies the Etirr Tuff in the Nachukui Formation (Fig. 6). It is named here because it has been dated at 1.48 ± 0.03 Ma (McDougall & Brown 2005). Its type locality is in the northern branch of Kalochoro (K86-3016), where it fills a channel, the top of which is 4 m below the Etirr Tuff, and it contains pumices up to *c.* 5 cm across. As noted in the introduction to Group 3, the Upper Okote Tuff possibly lies between this tuff and the Etirr Tuff, described next.

Etirr Tuff (~K-2). At Kaitio the Etirr Tuff is the first tuff exposed above a 10 m sandstone marking the end of a thick sequence of olive grey siltstones and claystones. It is a striking unit <10 cm thick composed of sparkling dark grey shards. Here we name this tuff the Etirr Tuff, with the type locality designated in the north branch of Kalochoro (K86-3019). In Area 40 (Ileret) the Etirr Tuff (K02-05) lies above K02-07, which corresponds compositionally to the tuffs labelled K93-6010, 6011, and 6014.

Akait Tuff (~K-3). Feibel & Brown (1993) defined the Akait Tuff, and named Nabelete Akait as the type locality (K88-3263). It occurs in many exposures in the northern part of the Nachukui Formation (see Fig. 6), and contains small pumices at Namorutot. A correlative unit in Koobi Fora Area 103 (K93-6013) lies *c.* 0.5 m above algal stromatolite A7 of Feibel (1983).

Karari Grey Tuff (~K-3). Stern *et al.* (2002) reported a 1 m ash that lies 1.7 m above the Karari Blue Tuff (~K-2) in Area 131 on the Karari Ridge. They referred to it informally as the 'grey tuff', a name that we formalize here as the Karari Grey Tuff, for which Stern *et al.* (2002) gave the type locality (BT-10). This tuff lies above the tuffaceous sand discussed along with the Karari Blue Tuff, hence it must lie above the Etirr Tuff. At Nabelete Akait (K88-3265), it overlies the Akait Tuff.

Lokapetamoi Tuff (~K-3). Feibel & Brown (1993) named a reworked tuff of very low Fe_2O_3 content the Lokapetamoi Tuff, and designated the type locality at Lokapetamoi (K88-32432), with a reference locality on the south bank of Nariokotome (K84-2972), near the site of the *Homo erectus* skeleton KNM-WT-15,000. In many localities this tuff contains sparse, poorly preserved gastropod shells near the base.

Group 5

Constitutents of this group are known from all three formations under discussion. Figure 7 includes the Lower Nariokotome Tuff, which lies above the Chari Tuff (= L), as an additional unit for correlation between sections because the Chari Tuff west of Lake Turkana is known only at Kaitio and Nariokotome. Tuffs from this interval are easily sequenced in the Nachukui Formation, but placement of them relative to tuffs in the Koobi Fora and Shungura Formations is less secure. Analyses are given in Table 5.

Tuff K-3. ETH 058 is from a 20 cm vitric tuff situated near the middle of submember K-3 at Errum (de Heinzelin 1983). It is placed here in the sequence because of its apparent age interpolated from its position between Tuff K and Tuff L of the Shungura Formation.

Nabelete Tuff (~K-4). In the Nachukui Formation a widespread

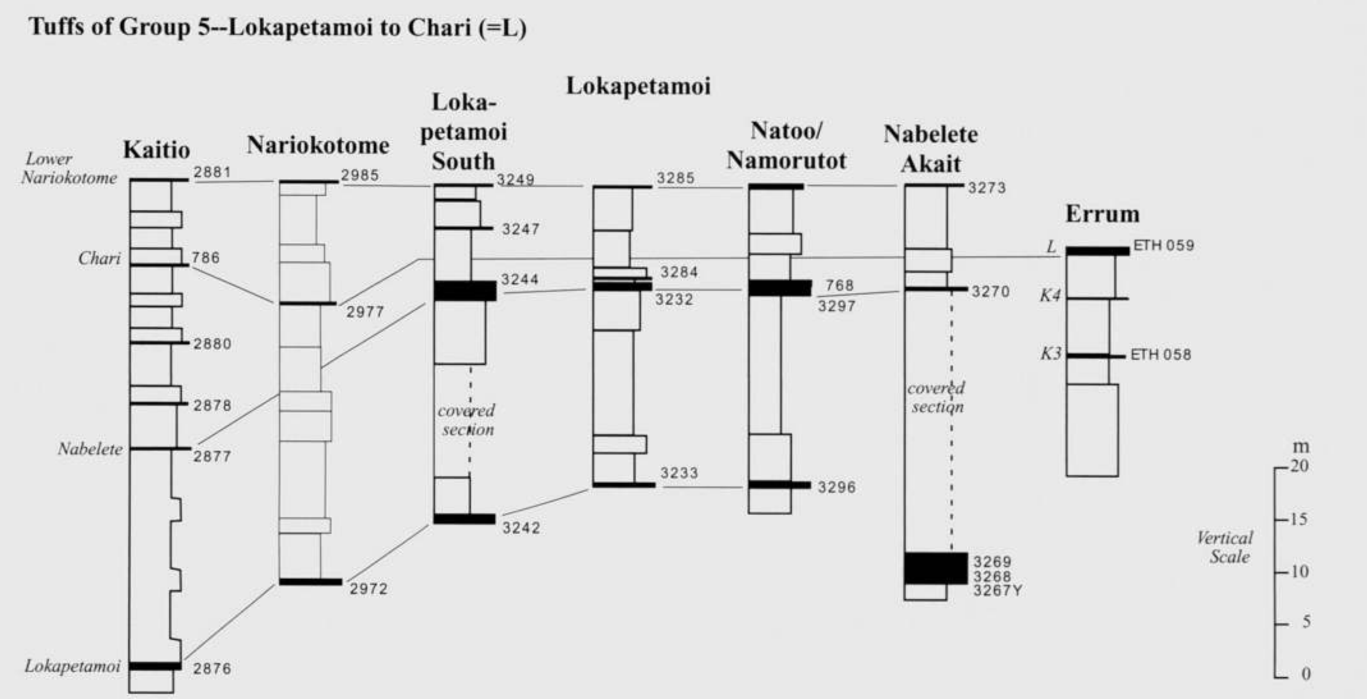

Fig. 7. Stratigraphic relations of tuffs of Group 5 that lie above the Lokapetamoi Tuff but below the Chari Tuff (= Tuff L). The Lower Nariokotome Tuff is shown on some columns where the Chari Tuff is absent. The section at Errum is after description by de Heinzelin (1983). Others are from field notes of F.H.B.

airfall tuff near the top of the Natoo Member is present in almost every section from Nabelete Akait to Kaitio. It probably lies at about the level of Shungura submember K-4, for which no sample is available. It was named the Nabelete Tuff by Haileab (1995) with the type locality designated as its occurrence in the type section of the Natoo Member along Kaitio (K86-2877).

Bench Tuff. Archaeological site FxJj 63, on the back slopes of the Karari Escarpment in Area 112, contains a tuff lens (K81-607) compositionally similar to, yet distinct from, the Chari Tuff (= L). It is placed here in the sequence on the basis of correlation with the Bench Tuff (sample 9312-35) at Konso reported by Katoh *et al.* (2000).

In the preceding text, the various tuffs were described in terms of their position in local sections. A summary is provided by distributing them chronologically in Figure 8. Only those ash layers that have been named, or that correlate between formations, are given in this diagram, but further relations are easily obtained from the preceding diagrams and discussion.

Stratigraphic implications

The sequence of tuffs described above, and their correlations between sections, have implications for the stratigraphic nomenclature of the Shungura, Nachukui, and Koobi Fora Formations. This results from using key beds as boundary units between members of the formations. Two problems that arise from this new evaluation of the tuffs in this interval are discussed below.

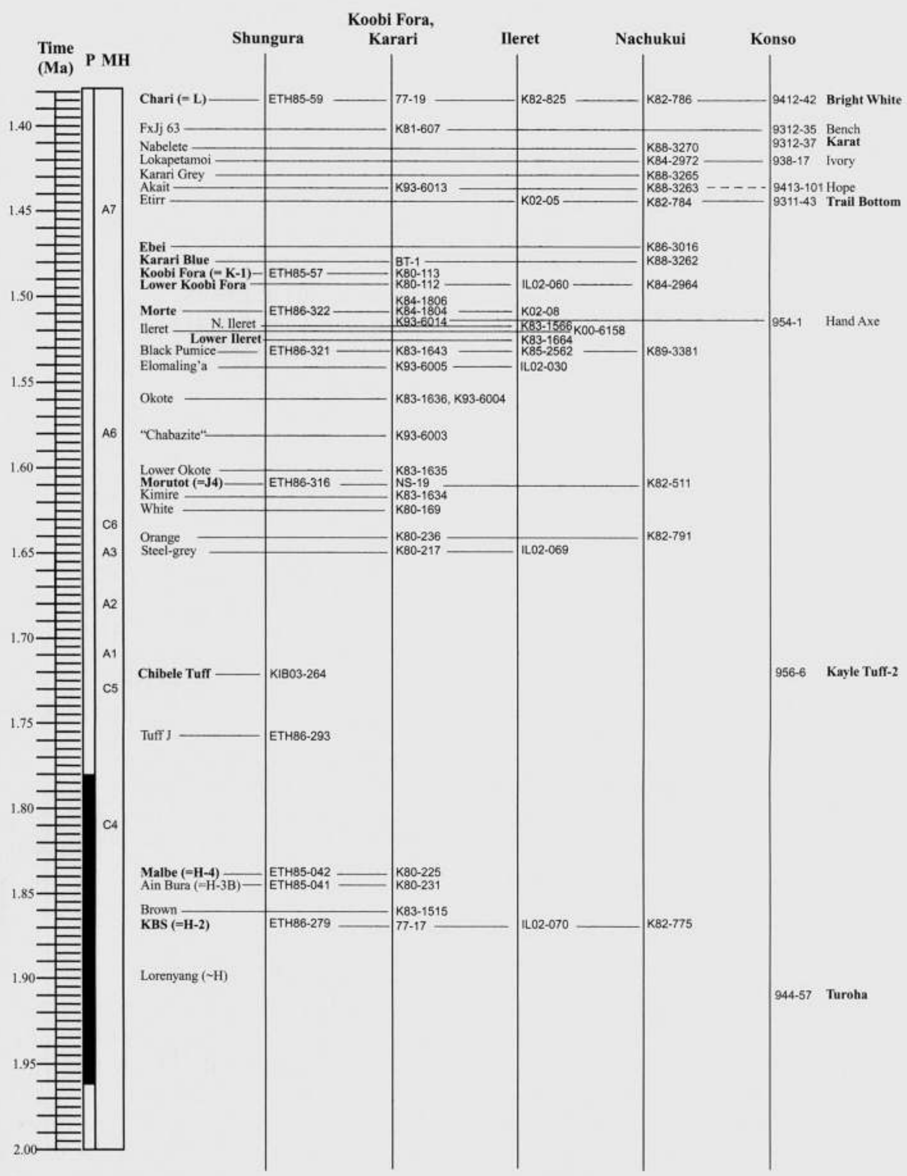

Fig. 8. Chronological distribution of named and correlated tuffs in the five groups. Correlations and probable correlations with tuffs of the Konso Formation are also shown. Ages given by Katoh *et al.* (2000) are increased by 0.93% to account for the different ages used for the monitor (Fish Canyon Sanidine) by the two laboratories. Units that have been dated are shown in bold. The column labelled P shows palaeomagnetic polarity (black is normal); the column labelled MH shows marker horizons used along western Koobi Fora ridge.

Shungura Formation, Member J

De Heinzelin (1983) designated the type section of Member J in two parts, one in Sector 19 of the Type Area of the Shungura Formation up to Unit J-3 (= 16.80 m) and a second at Errum from Unit J-4 to J-7 (= 24.40 m). We have only one sample of a tuff from submember J-4 in the Type Area, but it is compositionally different from any tuff of submember J-4 in the Kalam Area.

De Heinzelin (1983) showed that Tuff H-2 lies 82.4 m below a tuff believed to be Tuff K in the Type Area of the Shungura Formation. Similarly, he gave 78 m for the stratigraphic separation between Tuff K and what he believed to be Tuff H at Errum in the Kalam Area. The tuff thought to be Tuff H at Errum is actually Tuff H-3 (Haileab 1995), but it is not known if the tuff believed to be Tuff K in the Type Area is actually Tuff K, as no sample is available. The stratigraphic repositioning of the section at Errum brings into question whether the uppermost tuff in the Type Area is actually Tuff K. There is no doubt that de Heinzelin's correlation is approximately correct, and the difficulty can be accommodated if it is assumed that strata assigned to submember J-3 at Errum actually lie within the interval assigned to J-4 in the Type Area, or perhaps even higher. The change has little effect on the overall thickness of the Shungura Formation, which remains at about 766 m.

Three volcanic ash layers lie between Tuff J-4B and Tuff K at Ilgwa, and five in the same interval at Errum (Fig. 4). None of these ashes correlates, even though the sections are separated by less than 3 km. This feature is typical of strata in this part of the section, and implies that the area over which a particular tuff was deposited may have been rather restricted.

The boundary between the KBS and Okote Members of the Koobi Fora Formation

Volcanic ash layers in Omo Group formations are used as marker beds to divide local stratigraphic sequences. This is convenient for field mapping, and useful for defining palaeontological collection units, because each member is essentially a chronostratigraphic unit when its boundaries are set at identifiable volcanic ash layers. The strategy works reasonably well in the Shungura Formation, although field characters alone are insufficient to correlate the ashes.

Similarly, members of the Koobi Fora Formation are bounded by specified tuffs (Brown & Feibel 1986). The Okote Tuff (~J-6) defines the base of the Okote Member, and its age, suggested to be 1.56 ± 0.05 Ma (McDougall & Brown 2005), provides the best current estimate of the age of the base of the Okote Member. However, choice of the Okote Tuff was unfortunate because it appears not to be widespread, being identifiable with certainty only in the type section on the Karari Ridge. Correlation of the Okote Tuff with K80-108 in Area 101 is not proven, and we believe that it is more likely that K80-108 correlates with the Morte Tuff (~J-7; 1.51 Ma). If lithostratigraphic units in the Koobi Fora Formation continue to be defined so that they correspond closely to chronostratigraphic units, the only solution is to choose a different tuff for the basal boundary of the Okote Member. Possible candidates for such a function are the Morutot Tuff (= J-4) or the Black Pumice Tuff (= J-7A), but only the latter has been identified at Ileret or near Koobi Fora. Were the Black Pumice Tuff used as the basal unit, it would unite the Koobi Fora, Shungura, and Nachukui Formations at a common boundary, but has the drawback that the type Okote Tuff would lie within the upper part of the KBS Member. The problem will be more fully treated elsewhere.

Correlations to the Konso Formation

Katoh *et al.* (2000) described tuffs from the Konso Formation located near the southern end of the Ethiopian Rift Valley, and correlated two of them with tuffs in the Turkana Basin: the Turoha Tuff with the KBS Tuff and the Bright White Tuff with the Chari Tuff. The composition and age of the Bright White and Chari Tuffs agree fairly well. On the other hand, the iron and aluminium contents of the Turoha Tuff are distinctly lower than those of the KBS Tuff (Table 6), even though the ages agree well (1.91 ± 0.03 Ma, Turoha; 1.87 ± 0.02 Ma, KBS).

Here we establish four other correlations between tuffs in the Konso Formation and tuffs in the Turkana Basin, and discuss one other possible correlation. The data on which these correlations are based are assembled in Table 6 (see also Fig. 8). The oldest correlated unit is the Hand Axe Tuff at Konso, which correlates with a tuff of the Koobi Fora Tuff Complex in Area 103 (K93-6014), and with a similar tuff in Area 16 at Ileret (K83-1681).

The Ivory Tuff at Konso is correlated here with the Lokapetamoi Tuff of the Nachukui Formation. At Konso this tuff lies above the Trail Bottom Tuff dated at 1.43 ± 0.02 Ma, but below the Karat Tuff dated at 1.41 ± 0.02 Ma (Katoh *et al.* 2000), and must have an age very near 1.42 Ma. This is consistent with ages on the Chari Tuff (1.38 ± 0.03 Ma) and the Ebei Tuff (1.48 ± 0.03 Ma, McDougall & Brown 2005), which lie above and below the Lokapetamoi Tuff (Fig. 8), respectively.

Harris & Isaac (1997) reported a tuff at archaeological site FxJj 63 in the Koobi Fora region, which was believed to lie near the level of the Chari Tuff, but which was chemically distinct from it. Here, this tuff (K81-607) is correlated with the Bench Tuff in the Konso Formation, which lies between the Karat Tuff (1.41 ± 0.02 Ma) and the Bright White Tuff (1.40 ± 0.02 Ma; Katoh *et al.* 2000). This tuff interfingers with the clays on which the artefacts lie, thus providing a maximum age for this site of 1.41 Ma.

Finally, we correlate the Trail Bottom Tuff at Konso with the Etirr Tuff in the Turkana Basin. At Konso, the Trail Bottom Tuff is dated at 1.43 ± 0.02 Ma, which agrees with the stratigraphic placement of the units in each basin, and it also agrees (within error) with measured ages on overlying and underlying units (Fig. 8).

One other correlation seems likely, and demonstrates very well the difficulties involved. Analyses of the Nabelete Tuff and the Akait Tuff of the Nachukui Formation compare favourably with an analysis of the Hope Tuff (HPT) of the Konso Formation (Table 6). The Hope Tuff matches the composition of the Nabelete Tuff better than the Akait Tuff. Yet at Konso, the Hope Tuff lies below the Ivory Tuff, and in the Turkana Basin, the Nabelete Tuff lies above the Lokapetamoi Tuff. Hence, if correlation of the Lokapetamoi Tuff with the Ivory Tuff is accepted, the only stratigraphically allowable correlation of the Hope Tuff is with the Akait Tuff of Turkana. This possibility is shown as a dashed line in Figure 8. Both SiO_2 and Al_2O_3 contents measured for this study are slightly higher on the Akait Tuff than those measured by Katoh *et al.* (2000) on the Hope Tuff.

With these new correlations, five (possibly six) tuffs between the Turoha Tuff and the Bright White Tuff at Konso now correlate with tuffs in the Turkana Basin. In combination, age information from the Omo–Turkana Basin and from Konso shows that tuffs of Groups 5 are confined to the interval 1.38-1.43 Ma. Above we noted that eruptions must have occurred about once each 3 ka between *c.* 1.48 and 1.53 Ma ago. In the Turkana sections, there are at least 12 tuffs in the interval between 1.48 and 1.43 Ma. At Konso, at least 10 tuffs lie between 1.43 and 1.38 Ma, and more than five additional tuffs lie in the same interval in the Turkana Basin, showing that the high eruptive rates must have continued until at least 1.38 Ma ago.

Large pumice clasts (up to *c*. 90 cm diameter) in tuffs of the Omo Group reflect transportation to the basin by water (Brown 1972). No Pliocene or Early Pleistocene rhyolitic volcanoes are near enough to the Omo–Turkana Basin for these clasts to be airfall tephra. The only known volcanoes of similar composition and age are in the Ethiopian highlands (WoldeGabriel & Aronson 1987), and the most likely agent of dispersal is the Omo River. Findlater (1976), and later Isaac & Behrensmeyer (1997), argued that pumice clasts may have entered the basin through the Bakate Gap in the northeastern part of the Koobi Fora region. This latter scenario is unlikely, because tuffs of the Konso Formation lack pumice clasts, yet the Konso region lies along the proposed path of dispersal. Further, the Konso Formation was deposited in a basin bounded on the west by a topographic high (Katoh *et al.* 2000). The present course of the Weyto River, which flows into Chew Bahir (and perhaps into the Omo–Turkana Basin in the Late Pleistocene), was not established until deposition of the Konso Formation ceased <1.4 Ma ago (Katoh *et al.* 2000). Thus, the distribution of pumice clasts in tuffs of the Turkana Basin records, in some sense, the extent of the Omo River southward in the basin, which is of importance to the next topic.

Climatic influence on deposition in the Turkana depression

Recently McDougall *et al.* (2005) showed that deposition of the Kibish Formation during the Pleistocene Epoch occurred simultaneously with the formation of sapropels in the Mediterranean Sea. Deltaic and lacustrine strata of the Kibish Formation were deposited *c*. 100 km north of the present shoreline of Lake Turkana when it was at a higher level. The causative relation is that during periods of high rainfall, sapropels form, and also lake levels in the Omo–Turkana Basin are high because the principal source of water for Lake Turkana is the Omo River, which shares a drainage divide with the Nile. The Okote Tuff Complex provides a clear counter-example to that afforded by the Kibish Formation. At the time of deposition of the complex, no sapropels are recorded in the Mediterranean Sea, and Lake Turkana or its predecessor was at a lower level. This is shown by the nature and location of the Okote Tuff Complex, where fluvial deposits extend far south of the present northern shoreline of the lake.

Cores from the Mediterranean Sea, the Gulf of Aden, and the Arabian Sea contain a detailed record of climatic changes in northeastern Africa. Sapropels are the most prominent feature of the Mediterranean record (Rossignol-Strick *et al.* 1982; Rossignol-Strick 1985; Rohling 1994; Emeis & Sakamoto 1998), whereas in the Gulf of Aden and Arabian Sea climatic changes are reflected by changes in the amount of terrestrial sediment (dust) in the cores (deMenocal 2004). Both features reflect the intensity and latitudinal position of the African monsoon. Sapropels form during precessional minima, coincident with stronger insolation in northern hemisphere summer and weaker insolation in northern hemisphere winter (Rohling 1994). The increased seasonal contrast intensifies monsoonal circulation in summer, leading to increased precipitation over eastern equatorial Africa. Consequently, the Nile discharges more water into the Mediterranean, resulting in increased organic productivity and development of anoxic conditions in the deep water so that organic carbon is preserved. In the Gulf of Aden and Arabian Sea, increase in monsoonal intensity decreases the amount of dust available for transport from land to sea, because lake levels rise, and also because the land is more completely covered with vegetation (Melieres *et al.* 1998). When lake levels fall, previously deposited fine sediment is available for wind transport, but during highstands the sediment is protected from wind erosion.

DeMenocal (2004, and references therein) has provided a cyclostratigraphically tuned dust record for cores at Deep Sea Drilling Project Sites 231 and 232 in the Gulf of Aden, and at Ocean Drilling Program Sites 721 and 722 in the Arabian Sea including the time period under consideration here. Sarna-Wojcicki *et al.* (1985; also Brown *et al.* 1992; deMenocal & Brown 1999) linked records in the Gulf of Aden and the Arabian Sea to the sedimentary record in the Omo–Turkana Basin through correlated tuffs. Although most of their correlations are to volcanic ash layers of Pliocene age, the Silbo Tuff (0.75 Ma), of Pleistocene age, has also been identified.

Although the precessional orbital cycle controls monsoonal intensity, the effect is modulated by eccentricity and obliquity cycles, so sapropels do not form at each precessional minimum. Rather sapropels are absent for extended periods despite precessional minima.

Besides the Kibish Formation, a strong case for a connection between sapropels (or lack thereof), dust peaks, and deposition in the Omo–Turkana Basin exists between 1.56 Ma and 1.47 Ma ago, when there are no well-developed sapropels in the Mediterranean (e.g. Emeis & Sakamoto 1998), and when dust levels in the Arabian Sea are elevated (deMenocal & Brown 1999). This is the time of deposition of most tuffs of the Okote Tuff Complex, ages of which range from 1.48 ± 0.01 to 1.53 ± 0.01 Ma (McDougall & Brown 2005). The sedimentology of sequences at Ileret and Koobi Fora (Feibel *et al.* 1991) demonstrates that this is a time of lowered lake level in the Omo–Turkana Basin. As shown, the Ileret Tuff Complex correlates with the Koobi Fora Tuff Complex in Area 103. At Ileret, the tuffaceous section contains no mollusc-bearing marginal lacustrine layers, whereas at Koobi Fora, such layers are frequent. Clearly, the northern margin of the lake lay near Koobi Fora, well south of Ileret, which is consistent with the lack of sapropels in the Mediterranean.

The foregoing example is the most obvious correlation between the marine record and the terrestrial record in the Turkana depression. A more detailed examination of the entire record is under way, but is beyond the scope of this paper.

Conclusions

The present approximation to the tephrostratigraphy between the KBS and Chari Tuffs shows that at any particular time, deposition took place over restricted areas of the Turkana Basin. Thus from 1.54 to 1.45 Ma, different localities record slightly different time intervals, and no ash layers of Group 4 are known from the Shungura Formation. Localization of deposition is apparent because the number of tuffs is large, and although correlations to nearby sections are straightforward, only a few tuffs correlate over larger areas. Also, new ages on many units in this interval reported in an accompanying paper (McDougall & Brown 2005) will allow better estimates for many fossils from it. Despite progress in deciphering this interval, much remains to be done to determine the order and age of archaeological sites on the Karari Ridge. Further progress will require analysis of many more shards from each tuff, to determine the number of modes and to determine a precise average analysis of each mode. In this way, the first appearance of each mode within each stratigraphic section can be determined.

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