Christian A. Tryon
University of Connecticut,
Department of Anthropology,
Box U-2176, Storrs,
Connecticut 06269, U.S.A.
E-mail:
christian.tryon@uconn.edu

Sally McBrearty
University of Connecticut,
Department of Anthropology,
Box U-2176, Storrs,
Connecticut 06269, U.S.A.
E-mail: mcbrearty@uconn.edu

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Tephrostratigraphy and the Acheulian to Middle Stone Age transition in the Kapthurin Formation, Kenya

Sites containing Acheulian, Sangoan, Fauresmith, and Middle Stone Age artefacts occur within and below the Bedded Tuff, a widespread volcaniclastic member of the Kapthurin Formation, Kenya. The Bedded Tuff eruptive complex consists of up to twelve tephra beds, intercalated sediments, and paleosols. Two pumiceous units, high in the Bedded Tuff sequence, have been dated by $^{40}Ar/^{39}Ar$, one to 235 ± 2 ka (Deino & McBrearty, 2002, *Journal of Human Evolution*, **42,** 185–210, cf. Tallon, 1978, *Geological Background to Fossil Man*, pp. 361–373, Scottish Academic Press), the other to 284 ± 12 ka (Deino & McBrearty, 2001), the latter now providing a minimum age estimate for all underlying archaeological sites. Bedded Tuff outcrops are correlated through field stratigraphic and electron microprobe geochemical analyses of individual beds. Bedded Tuff units show increasingly evolved composition through the stratigraphic succession, indicating that the beds are the product of intermittent eruption of a single differentiating magma system, and the chemical signatures of these beds permit the chronological ordering of archaeological sites. Our results indicate that the transition to Middle Stone Age technology occurred prior to 285 ka in this region of East Africa. The interstratification of sites containing Acheulian, Sangoan, Fauresmith, and Middle Stone Age artefacts suggests that these technologies were contemporary in a single depositional basin over the duration of the transition.

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What is the Acheulian to Middle Stone Age Transition?

During the late Middle Pleistocene, hominids in Africa abandoned the manufacture of handaxes and cleavers, and began making points. For archaeologists, this signals the end of the Acheulian and the commencement of the Middle Stone Age (MSA). It is a conspicuous event, due to the long duration of the Acheulian, and perhaps a significant one, because it may coincide with the appearance of *Homo sapiens*.

Terminology

The system inaugurated by Goodwin & Van Riet Lowe (1929) dividing the prehistory of Africa in to Earlier, Middle, and Later Stone Ages continues in use, although its shortcomings are almost universally acknowledged. Originally defined on the basis of surface material from South Africa, the system relies upon diagnostic artefacts (*fossiles directeurs*), such as the handaxe and point, for the diagnosis of industries to period. Contrary to common belief, the African Acheulian is not synonymous with "mode 2" of Clark (1977). For example, assemblages from the Kapthurin Formation usually attributed to the terminal Acheulian are known to contain handaxes (mode 2), Levallois debitage (mode 3), and blades (mode 4). African MSA assemblages may contain all of these elements plus "mode 5"

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(microlithic) items (e.g., geometrics in the Howiesons Poort). All Middle Pleistocene industries share a simple flake and core component (mode 1) with its roots in the Oldowan (Kleindienst, 1961; Clark, 1994; Clark *et al.*, 1994), and many assemblages lack diagnostic artefacts, either as a result of sampling bias or functional variability among sites. In the absence of *fossiles directeurs* it is therefore quite difficult, and no doubt inappropriate, to assign such assemblages to either the Acheulian or the MSA.

Nature of the transition

Although the Acheulian is usually characterized as uniform and exhibiting little directional change over its ~1·4 Ma lifespan, several syntheses recognize the appearance of distinct features in the latest Acheulian, including a trend towards fewer cleavers, smaller, more extensively flaked handaxes (Chavaillon *et al.*, 1979; Clark, 1982*a*; Klein, 1999), and the introduction of novel flaking methods, including blade production and the Levallois technique. The latter may at times be used in the production of large bifaces (Leakey *et al.*, 1969; Clark, 1982*a*; McBrearty *et al.*, 1996; Deacon & Deacon, 1999:83). Regional variants are apparent in the MSA (Clark, 1988; McBrearty & Brooks, 2000), and chronological change within the MSA is detectable at stratified sequences (e.g., Wendorf & Schild, 1974; Volman, 1984; Brooks *et al.*, 1999).

In part due to a recognition that many industries could not be comfortably accommodated within the tripartite ESA–MSA–LSA scheme, transitional periods or "Intermediates" were adopted at the 1955 Panafrican Congress (Clark, 1957*a*:xxxiii). The "First Intermediate", encompassing the period between the Acheulian and the MSA, was to include the Sangoan and Fauresmith industries. The Sangoan, characterized by heavy duty tools such as picks and core axes, as well as light duty flake tools, has been considered a forest or woodland adaptation, largely due to its geographic distribution, and Sangoan tools are presumed to have functioned as wood working implements (Clark, 1964, 1970, 1972, 1982*a*, 1988, 1999). Sampson (1974), however, has questioned the assumption that Sangoan implements functioned as woodworking tools, and McBrearty (1987, 1991, 1993) has pointed out that while many Sangoan sites are found in areas that are wooded today, conditions may well have been more open in the past. The Sangoan site of Simbi, Kenya, for example, appears to have been occupied during isotopic stage 6, a period during which the forests of Africa were much reduced (McBrearty, 1991, 1993).

The Fauresmith, characterized primarily by small handaxes and Levallois flake production, has been thought to be confined to savanna zones (Clark, 1970). The term was originally defined on the basis of material from surface context at localities near Kimberley, South Africa. Humphreys (1970) equated features of Fauresmith handaxes with the quality of the raw material available in the Kimberley region, but occurrences with similar artefact suites have been encountered in East Africa and the Horn, where they have been described as Fauresmith (e.g., Clark, 1945; Cole, 1954; Hours, 1976). The "Intermediate" concept was formally abandoned (Bishop & Clark, 1967:987), when a mixture of different occupation levels was found to have occurred during excavation at the "Second Intermediate" type site of Magosi (Wayland & Burkitt, 1932; Clark, 1957*b*; Hole, 1959; Cole, 1967*a*). Sampson (1974) urges substitution of the term Final Acheulian for Fauresmith, but the status of both the Sangoan and the Fauresmith remains unresolved.

Few locations preserve a continuous well-dated sedimentary or occupational record across the Acheulian–MSA transition. At the few sites in northern and southern Africa containing both Acheulian and MSA material, the MSA deposits are separated from the underlying Acheulian levels by major erosional unconformities suggesting a significant temporal gap (Clark, 1982*a*; Wendorf *et al.*, 1994). Local Acheulian–MSA sequences in Ethiopia, such as at Melka Kunturé (Hours, 1976; Chavaillon *et al.*, 1979), Gademotta (Wendorf & Schild, 1974; Wendorf *et al.*, 1975, 1994) and in the Middle Awash (Brooks, 1998; Brooks *et al.*, 1999) are as yet only cursorily described. Better comparative data exist for the Acheulian and Sangoan at Kalambo Falls, Zambia (Clark, 1969, 1974; Sheppard & Kleindienst, 1996), at Nsongezi, Uganda (Cole, 1967*b*), at Isimila, Tanzania (Howell *et al.*, 1962; Cole & Kleindienst, 1974) and for the Sangoan and MSA at Muguruk, Kenya (McBrearty, 1988), but chronologic resolution at these sites is poor.

Timing

The few radiometric dates obtained for late Acheulian and early MSA occurrences cluster between about 200 ka and 300 ka. U-series dates for late Acheulian material were reported in the 1970s from Isimila, Tanzania, and Rooidam, South Africa, of ~260 ka and 174 ka, respectively (Howell *et al.*, 1972; Szabo & Butzer, 1979). Rooidam is usually attributed to the Fauresmith or Final Acheulian (Fock, 1968; Clark, 1970; Butzer, 1974, 1984; Sampson, 1974; Deacon & Deacon, 1999). Dates obtained by a variety of techniques led McHugh *et al.* (1988) to estimate the age of the Acheulian in the western desert of Egypt at ~200 ka, whereas Wendorf & Schild (1992) give an estimate of perhaps 350 ka.

The Sangoan consistently overlies the Acheulian and underlies the MSA when it has been found in stratigraphic context (McBrearty, 1987). Artefacts of the Njarasa industry, a local manifestation of the Sangoan, in the Eyasi Beds, northern Tanzania, are estimated by Mehlman (1987) to date to ~370–170 ka, based upon sedimentation rates inferred from radiocarbon and U-series dates on the overlying Mumba Beds. Artefacts typologically and technologically similar to those from Eyasi are reported from the Ndutu Beds at Olduvai and the upper Ngaloba Beds at Laetoli (Leakey *et al.*, 1972; Leakey, 1979; Mehlman, 1987; Braüer & Mabulla, 1996; Mabulla, 1996). Improved chronology for these deposits provided by new ^{40}Ar/^{39}Ar and provisional paleomagnetic determinations allows their age to be estimated at 300–200 ka (Walter *et al.*, 1991, 1992; Manega, 1993; Tamrat *et al.*, 1995). Age estimates of 100 ka and 190 ka for the Sangoan at Kalambo Falls, Zambia, have been reported by Clark (1982*b*, 1988), based on amino acid racemization dates on wooden objects from the underlying Acheulian levels, though these are probably minimum estimates (Lee *et al.*, 1976; Clark, 1999). At Simbi, Kenya, ^{40}Ar/^{39}Ar dates (Deino, personal communication) indicate that the Sangoan is present at ~200 ka, but that it may persist as late as 60 ka (McBrearty, 1991, 1993). Binneman & Beaumont (1992) report an age of ~200–350 ka for assemblages ascribed to the Fauresmith at Wonderwerk Cave, South Africa, based on U-series and amino acid racemization on ostrich eggshell (cf. Butzer, 1984; Beaumont, 1990).

The oldest date for the MSA in South Africa is derived from the sequence at Florisbad, where a direct assay ESR determination of ~260 ka on a hominid tooth from the spring vent (Grün *et al.*, 1996) allows Kuman *et al.* (1999) to extrapolate an age of ~280 ka for the undiagnostic MSA assemblage from the basal deposits (units N, O, and P). In Egypt, OSL, AAR, ESR, TL, and U-series dates indicate that the MSA at Bir Tarfawi and Bir Sahara East begins ~230 ka (Miller *et al.*, 1991; Wendorf & Schild, 1992; Bluszcz, 1993; Miller, 1993;

Schwarcz & Grün, 1993). In East Africa, K/Ar estimates suggest that MSA assemblages at Gademotta, Ethiopia, date to 235 ± 5 ka, rather than to the previously reported 181 ± 6 ka (Wendorf *et al.*, 1975, 1994). U-series dates on speleothem support a similar antiquity for the early MSA at Twin Rivers, Zambia, of ∼230 ka (Barham & Smart, 1996; Clark & Brown, 2001). Previously reported K/Ar dates for the Kapthurin Formation, Kenya (Leakey *et al.*, 1969; Tallon, 1976, 1978; McBrearty *et al.*, 1996), indicated an age of >240 ka for the late Acheulian. This date is now revised by ^{40}Ar/^{39}Ar to >285 ka (Deino & McBrearty, 2002), and evidence discussed here indicates that the MSA in the Kapthurin Formation also predates 285 ka.

Evolutionary and behavioral implications

Acheulian technology has traditionally been discussed in connection with *H. erectus,* broadly defined. Both early African *H. erectus* (*H. ergaster* of Wood, 1992) and the Acheulian industry appeared between 1·7 Ma and 1·8 Ma, (Feibel *et al.*, 1989; Roche & Kibunjia, 1994), though direct associations of Acheulian artefacts with hominid fossils is extremely rare in the Pliocene and Early Pleistocene record. In the Middle Pleistocene, however, Acheulian artefacts have been recovered in association with *H. rhodesiensis* (attributed by others to late *H. erectus* or *H. heidelbergensis*) at sites such as Bodo, Ethiopia, and in the Ndutu Beds, Tanzania (Mturi, 1976; Conroy *et al.*, 1978; Asfaw, 1983). MSA artefacts are associated with fossils of *H. helmei* at sites including Florisbad, South Africa, and in the Ngaloba Beds, Tanzania (Leakey & Hay, 1982; Magori & Day, 1983; Kuman & Clarke, 1986; Kuman *et al.*, 1999), but with *H. sapiens* at sites that include Klasies River, South Africa (Singer & Wymer, 1982). Behavioral similarities suggest a close phylogenetic relationship between the latter two species (McBrearty & Brooks, 2000), and Lahr (1996) and Stringer (1996, 1998) have suggested including some or all *H. helmei* fossils in *H. sapiens*. Should it emerge that there are grounds for sinking the taxon *H. helmei* into *H. sapiens,* it would seem that our species appears simultaneously in the record with MSA technology between 250 ka and 300 ka.

It has been suggested that the emergence of the MSA or perhaps of Mode 3 technology is coincident with a major behavioral shift and possible speciation event (Foley & Lahr, 1997; McBrearty & Brooks, 2000). Clark (1988) has emphasized that the Acheulian to MSA transition is a switch in emphasis from hand-held to hafted implements. Tangs on Aterian artefacts from the Sahara and basal thinning on many MSA points support the idea that they were indeed hafted. Other design features, such as equal distribution of weight around the midline, indicates that many MSA points were used as projectiles (McBrearty & Brooks, 2000). Other behavioral advances seen in the MSA in addition to composite tool manufacture include blade and microlithic technology, formal bone tools, increased geographic range, specialized hunting, use of aquatic resources, long distance trade or transport of raw materials, systematic processing and use of pigment, art and decoration, and habitation of previously unoccupied water-poor environments (Deacon & Deacon, 1999; Klein, 1999; McBrearty & Brooks, 2000).

The Kapthurin Formation

The Kapthurin Formation forms part of the sedimentary sequence in the Tugen Hills, a complex tilted fault block about 75 km long, lying on a roughly N–S axis in the floor of the Kenya Rift west of Lake Baringo (Figures 1 & 2). The formation is exposed over an area of about 150 km^2, and has a thickness of 120–150 m. It represents the Middle Pleistocene portion of the

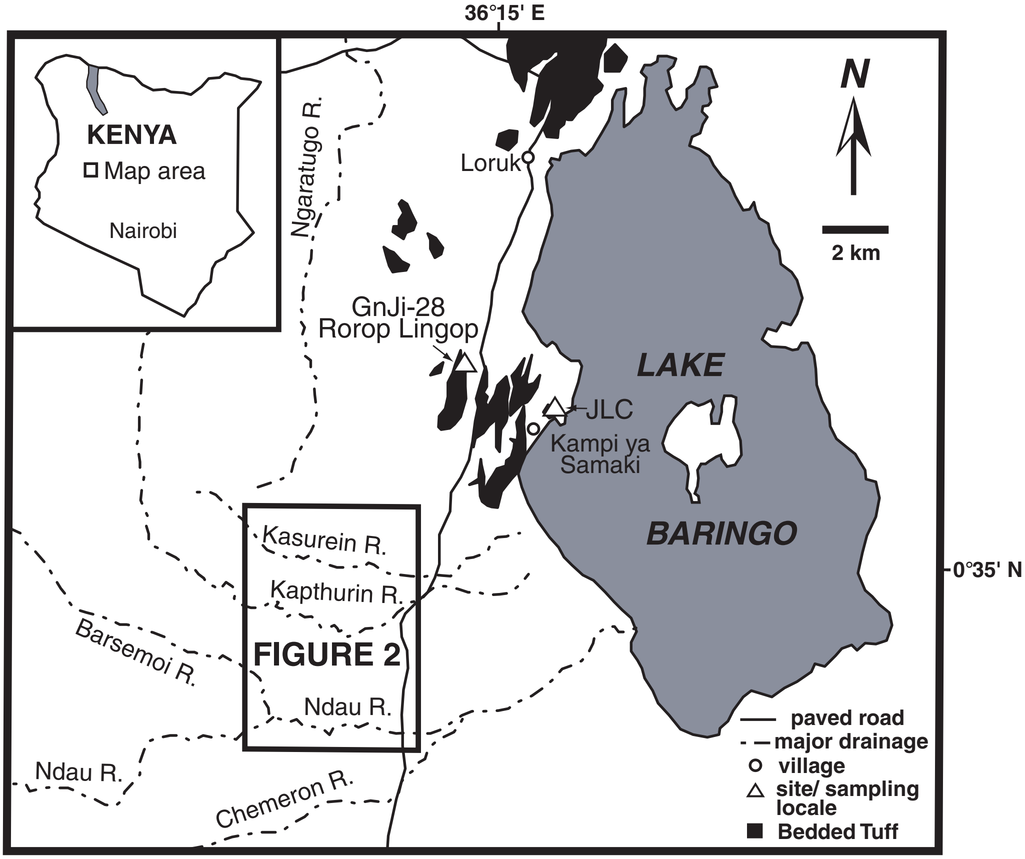

Figure 1. The Lake Baringo region. After Martyn (1969).

well-calibrated Tugen Hills sequence that documents a nearly continuous record of the past 16 Ma of African earth history (Hill *et al.*, 1986; Hill, 1999). The area has long been known to be fossiliferous (Fuchs, 1950; Bishop *et al.*, 1971; Bishop, 1978), and sediments now referred to the Kapthurin Formation were part of the type section for the "Kamasian pluvial" of Leakey (1955).

The Middle Pleistocene age of the Kapthurin Formation was established on the basis of its vertebrate fossils (McCall *et al.*, 1967; Leakey *et al.*, 1969). The formation is comprised of fluvial, lacustrine, and volcanic sediments; paleosols imply a series of intermittently stable landsurfaces. It was divided by Martyn (1969) into five members (K1 through K5; Figure 3), and the stratigraphy was further refined by Tallon (1976, 1978). Predominantly fluvial sediments are termed the Lower, Middle, and Upper Silts and Gravels Members (K1, K3, and K5). The Pumice Tuff Member (K2) and the Bedded Tuff Member (K4) are primarily volcanic in origin. An additional unnumbered volcanic unit, the Grey Tuff, occurs in the Middle Stilts and Gravels Member (K3). Lacustrine sediments are for the most part confined to facies of the Lower and Middle Silts and Gravels Members (K1′ and K3′).

The Kapthurin Formation lies unconfomably upon the Chemeron Formation. The Ndau trachymugearite, dated at 1·57 Ma

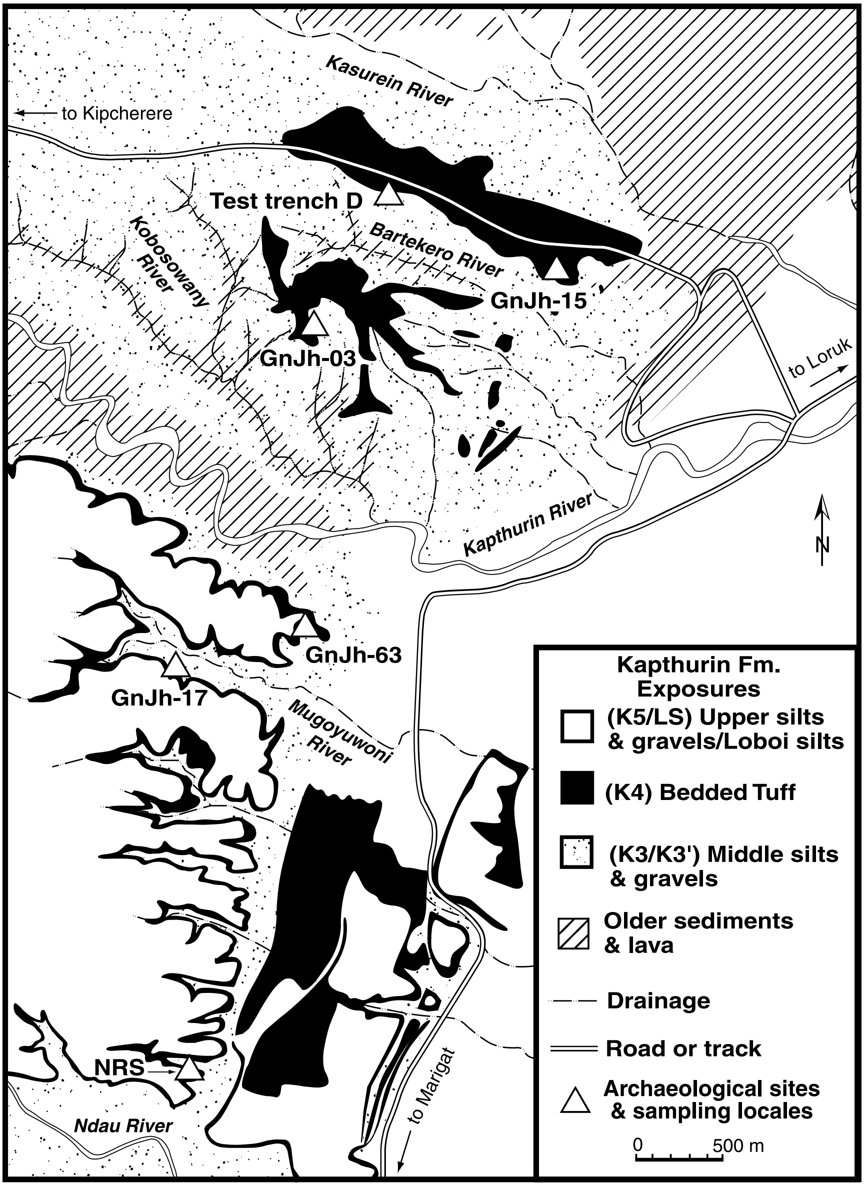

Figure 2. Detail of Kapthurin Formation exposures and archaeological sites and Bedded Tuff sampling locales. After Tallon (1976) and McBrearty *et al.* (1996).

(Hill *et al.*, 1986), near the top of the Chemeron Formation provides a maximum age for Kapthurin rocks. The entire formation is normally magnetized (Dagley *et al.*, 1978; Cornelissen *et al.*, 1990), indicating that its accumulation postdates 780 ka (Baksi *et al.*, 1992; Cande & Kent, 1992). Previously reported K/Ar results (Cornelissen *et al.*, 1990) indicated an age of ~600–900 ka for the lower part of the Kapthurin Formation. A recent program of ^{40}Ar/^{39}Ar dating has obtained age estimates

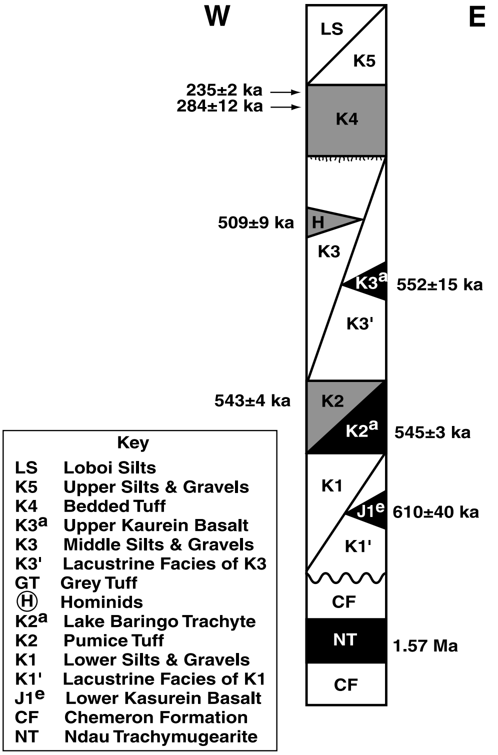

Figure 3. Idealized stratigraphic column of the Kapthurin Formation (after Tallon, 1976). Not to scale. ^{40}Ar/^{39}Ar dates from Hill *et al.*, 1986; Deino & McBrearty, 2002.

for the Kapthurin Formation tephra units [the Pumice Tuff (K2), the Grey Tuff and the Bedded Tuff (K4)], and dates on intercalated lavas, the Lake Baringo Trachyte and the Upper and Lower Kasurein Basalts, provide additional chronologic control. The lower part of the formation appears to have accumulated rapidly between ~600 ka and ~550 ka, and dates on the Grey Tuff in the Middle Silts and Gravels Member (K3) indicate an age of 509 ± 9 ka providing a lower age limit for all the archaeological occurrences discussed here (Deino & McBrearty, 2002).

Stone artefacts and fossil fauna and flora are found throughout the sequence. Earlier workers have reported archaeological occurrences and hominid fossils from various parts of the section (e.g., Leakey *et al.*, 1969; Van Noten, 1982; Wood & Van Noten, 1986; Cornelissen *et al.*, 1990). The present project, directed by McBrearty and active since the early 1990s, has reported discovery of about 30 new archaeological and paleontological sites, and the excavation of selected localities. Reports (e.g., McBrearty *et al.*, 1996; McBrearty, 1999) have stressed the variability in Kapthurin Formation archaeology due to the presence of handaxes, cleavers, picks, points, blades, and at least three distinct types of Levallois debitage at penecontemporaneous sites (Figure 4). The material discussed in this paper lies within and immediately beneath the Bedded Tuff (K4), near the top of the Formation. Conventional K/Ar dates for K4 were reported by Tallon (1978) of 250 ± 120 ka and 240 ± 8 ka, corrected for new constants using formulae provided by Ness *et al.* (1980). This estimate, frequently cited as the age of the African terminal Acheulian, is confirmed by a recent program of ^{40}Ar/^{39}Ar dating, but the Kapthurin Formation Acheulian is now known to underlie a second unit in K4 now dated to ~285 ka (Deino & McBrearty, 2002). The material found in this part of the Kapthurin Formation clearly has a critical bearing on our understanding of the Acheulian to MSA transition.

Archaeological sites and tuff sampling localities

This paper discusses material from five archaeological sites as well as from a number of geologic sampling localities within the upper portion of the Kapthurin Formation (Figures 1 and 2). All the artefacts discussed here are made of lava, usually trachytic basalt. Site GnJh-03 is a site complex about 2 ha in area near a drainage head of the Kobosowany tributary of the Kapthurin River. It was discovered by Edward Kandindi and first reported by Leakey *et al.* (1969). It contains a number of collecting localities, and one of the most productive,

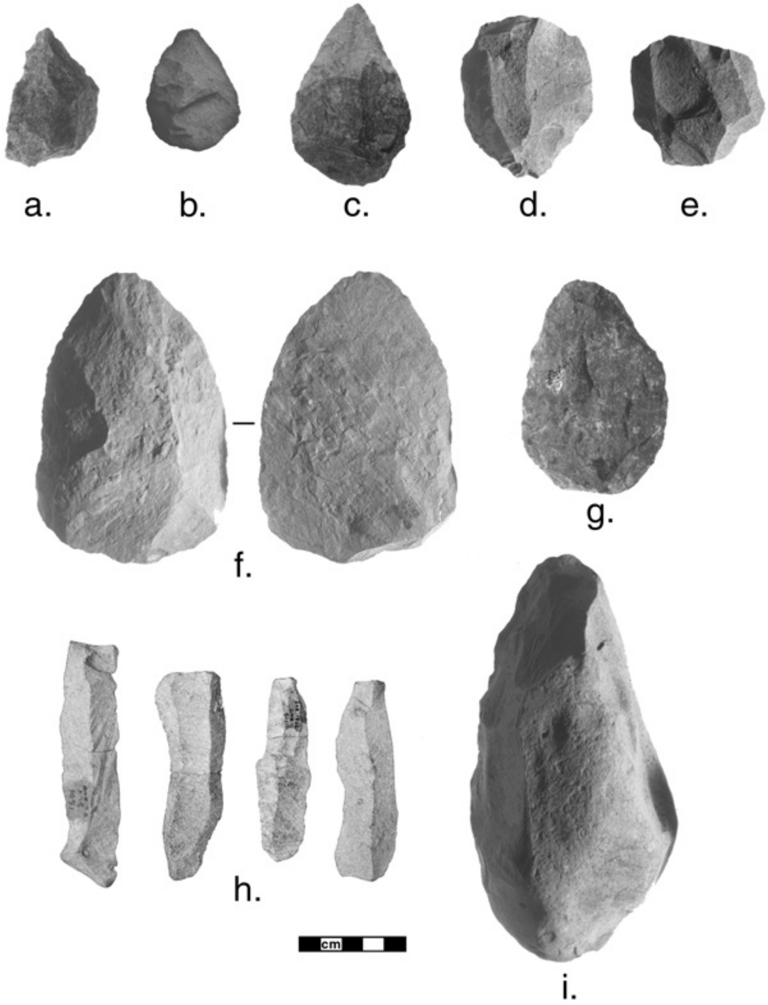

Figure 4. Artefacts from the Kapthurin Formation. (a) point rough-out, GnJh-63; (b) informal unifacial point, GnJi-28 (Rorop Lingop); (c) point, GnJh-17; (d), (e) Levallois cores, GnJi-28 (Rorop Lingop); (f) ovate unifacial handaxe made on Levallois flake, GnJh-03; (g) handaxe, GnJh-63; (h) blades, GnJh-03; (i) pick, GnJh-51.

the Leakey Handaxe Area (LHA) or the "Living Site", was systematically collected and partially excavated by Leakey and her colleagues. Further material was collected at GnJh-03 by McBrearty in 1993 (McBrearty *et al.*, 1996). The bulk of the material from the site is derived from sediments of the Middle Silts and Gravels Member (K3) of the Kapthurin Formation, from a depth of about 3 m beneath the local base of the Bedded Tuff (K4). More than 10% of Leakey's sample (n=1377) is reported to refit by Cornelissen (1992), and artefacts recovered by McBrearty have been found to refit with Leakey's material. The combined assemblage includes the highly distinctive "unifaces", handaxes made on large Levallois flakes with minimal ventral trimming [Figure 4(f)], in addition to well executed blades [Figure 4(h)] and both Levallois and non-Levallois debitage (Leakey *et al.*, 1969; Cornelissen, 1992, 1995; McBrearty *et al.*, 1996; Texier, 1996; McBrearty, 1999).

Site GnJh-15 lies adjacent to the Kipcherere track on a bluff on the northern edge of the valley of the Bartekero tributary of the Kapthurin River. It was discovered by John Kimengich and summarily reported by Van Noten (1982, Van Noten *et al.*, 1983; 1987*a*,*b*), whose team excavated nearly 500 m^2 at the site in successive seasons in the early 1980s. The archaeological remains are found on a paleosol lying immediately below the local base of K4. Work at the site was abandoned by Van Noten's team in the mid-1980s, and the material from the site was temporarily lost. A team led by McBrearty excavated another ~100 m^2 in 1997, and she and her colleagues, notably Cornelissen, have undertaken analysis of the recovered material, which is not yet published. Artefacts at the site (n>5000) consist of products of an informal flake-production technique that includes many refitted sets, as well as rare small bifaces and biface fragments made on cobbles. Also notable at GnJh-15 is a large quantity of what appears to be red ochre, and a small number of grindstones.

Site GnJh-17, located on the south bank of the Mugoyuwoni River, was discovered by members of Van Noten's team, and was excavated by Cornelissen in the 1980s. Over 160 m^2 have been excavated as a series of trenches into K3 sediments at varying depths beneath the local base of K4. These revealed assemblages containing 9025 artefacts, including handaxes, picks, and points [Figure 4(c)], associated with a series of paleosols and alluvial sediments (Cornelissen *et al.*, 1990; Cornelissen, 1992, 1995).

Site GnJh-63 is found on a bluff immediately south of the main Kapthurin River channel. It was discovered by Kiptalam Cheboi in 1997, and McBrearty's team carried out excavation of ~30 m^2 in 1997 and 1999. Artefactual and faunal material has been excavated from a paleosol lying within K4 itself. Artefacts thus far found *in situ* are few in number (n<100), but include a handaxe [Figure 4(g)], cores, and, from a slightly higher stratigraphic level, an apparent point rough-out [Figure 4(a)]. Fauna include *Equus, Crocuta, Damaliscus, Phacochoerus,* and *Hystrix.*

Site GnJi-28, known as Rorop Lingop, was discovered by John Kimengich in the early 1980s and test excavations were carried out by John Okongo of the University of Nairobi for an uncompleted master's thesis soon thereafter. McBrearty performed a controlled surface collection at the site in 1993 (McBrearty *et al.*, 1996; McBrearty, 1999). The site is located about 6 km north of the main area of Kapthurin Formation exposures (Figure 1). Here tuffaceous sediments lie directly upon an upfaulted graben of Lake Baringo Trachyte. Unpublished preliminary X-ray fluorescence analysis carried out by McBrearty and Kingston suggested, but did not irrefutably establish, that this tuff was identical with the Kapthurin Formation Bedded Tuff. The area has been cultivated in the recent past, and many of the artefacts lie on and in disturbed superficial soil. However, McBrearty has observed artefacts *in situ* in the tuff, where ripple marks and the footprints of wading birds suggest a nearshore lacustrine depositional environment. The small surface sample obtained by McBrearty at GnJi-28 (n=770) includes small handaxes, Levallois flakes and cores, and a small number of informally-made points [Figure 4(b), (d), (e)].

Stratigraphy and geochemistry of the Bedded Tuff

A detailed analysis of the Bedded Tuff was undertaken to demonstrate the stratigraphic relationship of the $^{40}Ar/^{39}Ar$ dated units to the archaeological occurrences, and to provide a more finely resolved chronology for those sites found within and beneath K4 exposures. The Bedded Tuff has a maximum thickness of >15 m (Tallon, 1976, personal observation), and consists of up to 12 0·1–4·0 m thick horizontal layers of buff-green to grey consolidated ash. Individual layers may be massive or composed of finer beds 1–4 cm in thickness. Average grain size increases northwards, probably indicating the direction of its volcanic source (Tallon, 1978: 365). Although this source is not yet positively identified, it is likely to be the Pleistocene volcano Karosi at the northern end of Lake Baringo. Deposition of this air-fall tuff was episodic, and produced a succession of buried landsurfaces. The duration of these intereruption periods (Smith, 1991; see also Orton, 1996) is unknown, but they were sufficient for channel incision, alluviation, and the formation of weakly expressed paleosols at some locations. Variably calcified or iron-stained root casts and rare plant fossils occur within the tuff itself (Tallon, 1976: 188ff, 1978; Spooner *et al.*, n.d.; Van Noten *et al.*, 1983; Cornelissen *et al.*, 1990; McBrearty *et al.*, 1996; personal observation). Artefacts and vertebrate fossils occur between and occasionally within beds of tuff, suggesting continuous hominid occupation of the area.

Volcaniclastic deposits are useful chronostratigraphic markers because of their rapid deposition, wide distribution, and unique chemical compositions (Thorarinsson, 1974; Fisher & Schmincke, 1984; Steen-McIntyre, 1985; Sarna-Wojcicki & Davis, 1991; Knox, 1993; Brown, 1994; Feibel, 1999). They are invaluable for identifying synchronic variation in paleoenvironments, as well as among contemporary fossil and artefact assemblages, and have been used in investigations of landscape archaeology at Koobi Fora (Isaac, 1981; Isaac *et al.*, 1981; Stern, 1993; Rogers *et al.*, 1994; Rogers, 1997), Olduvai Gorge (Blumenschine & Masao, 1991; Peters & Blumenschine, 1995; Blumenschine & Peters, 1998) and Olorgesailie (Potts, 1994; Potts *et al.*, 1999; Sikes *et al.*, 1999).

In the Kapthurin Formation, establishing the stratigraphic equivalency of layers of the Bedded Tuff is possible in the field using distinct marker tuffs where outcrop is continuous, but variable paleotopography, facies changes, and local unconformities often prevent lateral tracing of individual beds. Subsequent erosion and faulting have created complex patterns of exposure and preservation. As a consequence, not all outcrops contain the complete Bedded Tuff sequence or even similar portions of the sequence, but petrographic and geochemical analyses provide a basis for tephrostratigraphic correlation among dispersed outcrops. Mineralogical and textural properties are visible in thin section, and electron microprobe analyses of volcanic glass provides a geochemical signature for each unit in the eruptive complex. Although subject to secondary alteration (Cerling *et al.*, 1985), the composition of the glass reflects that of the parental magma at eruption; glass chemistry is highly variable among eruptions due to the complex nature of the magmatic processes involved (e.g., Fisher & Schmincke, 1984; Sarna-Wojcicki & Davis, 1991; Brown, 2000).

Petrography

The Bedded Tuff consists of two distinct lithologies: (1) widespread beds of fine-grained mafic ash, overlain by (2) sparse deposits of coarse, locally pumiceous material (Martyn, 1969; Leakey *et al.*, 1969; Tallon, 1976, 1978; Spooner *et al.*, n.d.). The majority of Bedded Tuff exposures studied consist of the lower fine-grained material, which is a vitric–lithic tuff of alkali olivine basaltic composition. Within it, pale brown glass shards (~0·3 mm) are fresh, angular, and contain few vesicles. These occur with forsteritic (Mg-rich) olivine (~Fo_{78-84}), plagioclase, rare spinel and microcrystalline basalt and trachyte clasts in a fine-grained, glassy groundmass. A small localized outcrop of the upper unit at Johnnie Leakey's Compound (JLC) (Figure 1), immediately north of the village of Kampi-ya-Samaki, was dated to ~240–250 ka (Tallon, 1978), and this approximate age has been confirmed through redating by $^{40}Ar/^{39}Ar$ (Deino & McBrearty, 2002). The upper unit is particularly well exposed at Ndau River Section (NRS) (Figure 2). Here it consists of trachytic glass shards and pumices (~4 mm), feldspars and pyroxenes (aegerine and titaniferous augite) in a clay-like groundmass. Sample McB97-02, from a 10–25 cm-thick trachytic bed at NRS, contains ~10 mm pumice fragments, and has been radiometrically dated by $^{40}Ar/^{39}Ar$ to 284 ± 12 ka (Deino & McBrearty, 2002). All archaeological sites associated with the Bedded Tuff occur within or beneath beds of basaltic ash, which has been found by intense scrutiny in the field and laboratory to lack suitable material for precise dating by radiometric means.

Geochemistry: methods

Use of the wavelength-dispersive electron microprobe (EMP) allows multiple grain-specific analyses to assess sample homogeneity and is a quick and reliable means of determining major-element abundance (Froggatt, 1992; Reed, 1996). For most major element concentrations under standard analytical conditions, accuracy and precision generally are estimated at ~1%. Work in the Kapthurin Formation focused on reference sections at NRS and site GnJh-15, located near the boundaries of the study area (Figure 2). Both are judged to preserve relatively complete portions of the Bedded Tuff sequence. At NRS, intercalated conglomerates and sands, current bedding and silty admixture within the tuff indicate that deposits were laid down within a fluvial regime. At GnJh-15, beds of tuff rest unconformably upon each other, suggesting a subaerial environment that was not accumulating sediment between eruptions. Twenty-five samples from seven measured sections at geological and archaeological sites were included in this study (Figures 1 and 2, Table 1). From each bed, one or more resin-impregnated polished thin sections were prepared. Approximately five shards per bed were analyzed directly from thin section as a preliminary assessment of glass homogeneity. Quantitative chemical analyses were acquired using a JEOL-8600A EMP housed at the Kline Geology Laboratory, Yale University. Secondary electron and back-scattered electron imaging capabilities facilitated the detection of compositional heterogeneity within glass shards, as well as the selection of unaltered glass surfaces for analysis (Reed, 1996). Analyses of the basaltic glass used 15 kv accelerating voltage, 20 nA current and a 10 μm beam. Samples of trachytic tuff were analyzed at 15 kv, 7·5 nA, with a 15 μm beam size to minimize Na loss, following the recommendations of Froggatt (1992). All analyses employed 10 s count times using off-peak backgrounds with TAP, PET and LIF crystals. Raw data were converted to concentrations using standard calculations with a PhiRhoZ matrix correction. Standards used for calibration include well characterized silicate and oxide minerals.

Tephrostratigraphic results

As seen in Figure 5, elemental oxide abundance within the Bedded Tuff basaltic samples follows a single trend. Comparison of sample chemistry with stratigraphic position (Figure 6) shows that samples from higher in the sequence have more evolved compositions (lower MgO and CaO) (cf. Yoder, 1979; McBirney, 1984; Wilson, 1993) (see also Table 1). This is particularly visible at GnJh-15. There are four factors that may explain the slight variation within this overall trend seen at NRS. These are (1) subsequent reworking, (2) fluctuations in the rate of eruption and magma replenishment at

Table 1 Summary of electron microprobe analyses

Sample	*n*	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO
Basaltic glass								
NRS								
CAT97-70	(1)	50·766	2·972	14·44	11·471	0·214	3·469	7·117
CAT97-74	(4)	48·24 ± 0·73	2·97 ± 0·37	13·50 ± 0·56	12·52 ± 1·05	0·20 ± 0·06	4·38 ± 0·63	9·10 ± 0·73
CAT97-67	(4)	49·26 ± 0·18	2·60 ± 0·03	15·10 ± 0·22	11·57 ± 0·14	0·22 ± 0·02	4·73 ± 0·04	9·75 ± 0·23
CAT97-66	(4)	50·73 ± 0·35	2·45 ± 0·05	15·38 ± 0·08	11·40 ± 0·05	0·18 ± 0·00	4·48 ± 0·08	8·99 ± 0·13
CAT97-65	(4)	48·91 ± 0·34	2·04 ± 0·14	16·22 ± 0·24	10·23 ± 0·36	0·18 ± 0·05	6·07 ± 0·14	10·09 ± 0·34
CAT97-64	(6)	47·97 ± 0·52	2·12 ± 0·09	15·68 ± 0·32	10·58 ± 0·33	0·19 ± 0·03	6·41 ± 0·24	10·96 ± 0·08
CAT97-63	(4)	48·43 ± 0·37	2·18 ± 0·08	16·21 ± 0·34	10·96 ± 0·16	0·22 ± 0·04	6·19 ± 0·23	11·05 ± 0·10
CAT97-62	(4)	47·56 ± 0·17	2·17 ± 0·13	16·11 ± 0·26	10·95 ± 0·34	0·16 ± 0·04	6·18 ± 0·21	11·02 ± 0·11
GnJh-63								
CAT97-75	(4)	49·99 ± 1·91	2·10 ± 0·51	15·99 ± 0·70	10·38 ± 0·33	0·21 ± 0·03	5·41 ± 1·70	9·97 ± 2·56
CAT97-77	(4)	49·60 ± 0·75	2·17 ± 0·28	16·27 ± 0·67	11·07 ± 0·38	0·20 ± 0·05	5·54 ± 0·51	10·05 ± 0·66
LHA								
CAT97-60	(5)	48·01 ± 0·44	2·69 ± 0·34	14·88 ± 0·39	11·00 ± 0·58	0·20 ± 0·04	5·23 ± 0·64	9·85 ± 0·40
GnJh-15								
CAT97-15	(4)	48·66 ± 0·43	2·64 ± 0·07	16·02 ± 0·19	11·44 ± 0·17	0·19 ± 0·02	5·25 ± 0·16	9·57 ± 0·26
CAT97-14	(4)	47·73 ± 0·27	2·71 ± 0·13	15·48 ± 0·43	11·48 ± 0·49	0·23 ± 0·04	5·18 ± 0·12	8·97 ± 0·49
CAT97-09	(6)	48·17 ± 0·60	2·70 ± 0·15	15·64 ± 0·40	11·12 ± 0·18	0·18 ± 0·06	5·15 ± 0·39	9·55 ± 0·18
CAT97-09T‡	(5)	48·08 ± 0·13	2·54 ± 0·08	15·75 ± 0·12	10·71 ± 0·09	0·19 ± 0·08	5·41 ± 0·08	9·65 ± 0·10
CAT97-08	(5)	48·16 ± 0·38	2·56 ± 0·24	15·80 ± 0·31	10·94 ± 0·39	0·19 ± 0·03	5·43 ± 0·51	9·99 ± 0·59
CAT97-06	(4)	48·42 ± 0·14	2·14 ± 0·12	16·24 ± 0·36	10·91 ± 0·34	0·22 ± 0·02	6·26 ± 0·28	11·09 ± 0·19
CAT97-05	(4)	47·84 ± 0·20	2·10 ± 0·12	16·19 ± 0·45	10·96 ± 0·33	0·19 ± 0·05	6·41 ± 0·25	11·18 ± 0·12
CAT97-04	(5)	47·38 ± 0·25	1·90 ± 0·02	14·59 ± 0·29	10·38 ± 0·10	0·21 ± 0·06	6·57 ± 0·07	11·85 ± 0·14
Test trench D								
CAT97-38	(5)	47·66 ± 0·36	2·86 ± 0·16	15·28 ± 0·30	11·40 ± 0·30	0·21 ± 0·05	4·84 ± 0·42	8·92 ± 0·45
CAT97-39	(5)	47·41 ± 0·31	2·78 ± 0·20	15·41 ± 0·22	11·07 ± 0·45	0·21 ± 0·03	5·17 ± 0·25	9·62 ± 0·08
JLC								
McB97-01	(3)	47·96 ± 0·52	3·29 ± 0·39	14·37 ± 0·41	12·79 ± 0·33	0·23 ± 0·04	4·52 ± 0·63	8·87 ± 0·57
Rorop Lingop								
CAT99-05	(5)	49·05 ± 0·24	1·88 ± 0·03	16·24 ± 0·12	10·28 ± 0·18	0·19 ± 0·04	6·18 ± 0·08	9·68 ± 0·08
CAT99-04	(4)	49·87 ± 0·37	1·89 ± 0·08	16·31 ± 0·44	10·56 ± 0·21	0·16 ± 0·02	5·90 ± 0·30	9·12 ± 0·28
CAT99-03	(5)	49·71 ± 0·21	1·94 ± 0·06	16·36 ± 0·25	10·62 ± 0·18	0·18 ± 0·05	6·03 ± 0·11	9·28 ± 0·10
Trachytic glass								
JLC								
McB97-01	(3)	63·85 ± 0·82	0·17 ± 0·05	18·23 ± 0·92	1·48 ± 0·61	0·05 ± 0·09	0·05 ± 0·04	1·02 ± 0·12
NRS								
CAT97-70	(3)	62·58 ± 2·29	0·54 ± 0·28	15·55 ± 0·89	5·68 ± 1·64	0·23 ± 0·11	0·41 ± 0·29	1·88 ± 0·94
McB97-02	(6)	61·74 ± 0·43	0·41 ± 0·12	14·36 ± 0·26	4·20 ± 0·17	0·16 ± 0·04	0·12 ± 0·02	1·10 ± ·04
CAT97-74	(4)	60·38 ± 1·28	0·69 ± 0·18	15·12 ± 0·31	6·09 ± 0·83	0·16 ± 0·04	0·42 ± 0·29	1·88 ± 0·51

Samples within each in sampling locale listed in stratigraphic order. All analyses as wt. %. *n*=number of glass shards analyzed per sample. Results are listed as mean and one standard deviation. NA=not analyzed, ND=not detected. Also analyzed but below detection limits were Cr, Ni and F.

*Total Fe as FeO.

‡Single grain traverse; analyses 20 μm apart.

the source, (3) inter-sample compositional similarity beyond the resolution of the EMP, and (4) a small sample size that does not adequately account for within-sample variability. Additional analyses for a broader suite of elements using techniques such as X-ray fluorescence may refine this sequence (Westgate & Gorton, 1980; Feibel, 1999). We interpret the general trend in compositional variation among these basaltic layers

Table 1 ***Continued***

Sample	*n*	Na_2O	K_2O	P_2O_5	SO_3	Cl	BaO	SUM
Basaltic glass								
NRS								
CAT97-70	(1)	3·319	1·92	1·143	0·069	NA	NA	96·932
CAT97-74	(4)	3·19 ± 0·34	1·62 ± 0·31	0·56 ± 0·13	0·12 ± 0·08	NA	NA	96·45 ± 0·72
CAT97-67	(4)	3·67 ± 0·28	1·56 ± 0·03	0·56 ± 0·03	0·10 ± 0·03	NA	NA	99·16 ± 0·14
CAT97-66	(4)	4·05 ± 0·03	1·43 ± 0·02	0·50 ± 0·04	0·06 ± 0·02	NA	NA	99·69 ± 0·35
CAT97-65	(4)	3·79 ± 0·14	1·04 ± 0·11	0·37 ± 0·07	0·06 ± 0·03	NA	NA	99·06 ± 0·24
CAT97-64	(6)	3·50 ± 0·10	0·86 ± 0·01	0·30 ± 0·04	0·05 ± 0·02	NA	NA	98·62 ± 1·03
CAT97-63	(4)	3·50 ± 0·07	0·91 ± 0·10	0·28 ± 0·03	0·08 ± 0·05	NA	NA	100·07 ± 0·36
CAT97-62	(4)	3·59 ± 0·11	0·94 ± 0·04	0·34 ± 0·03	0·07 ± 0·02	NA	NA	99·16 ± 0·29
GnJh-63								
CAT97-75	(4)	3·71 ± 0·65	1·26 ± 0·79	0·38 ± 0·16	0·08 ± 0·02	NA	NA	99·50 ± 0·28
CAT97-77	(4)	3·85 ± 0·11	1·12 ± 0·21	0·40 ± 0·10	0·07 ± 0·01	NA	NA	100·36 ± 0·24
LHA								
CAT97-60	(5)	3·69 ± 0·25	1·29 ± 0·46	0·46 ± 0·09	0·08 ± 0·04	NA	NA	97·41 ± 0·67
GnJh-15								
CAT97-15	(4)	3·98 ± 0·07	1·32 ± 0·06	0·49 ± 0·05	0·10 ± 0·03	NA	NA	99·72 ± 0·55
CAT97-14	(4)	4·00 ± 0·21	1·39 ± 0·05	0·57 ± 0·08	0·10 ± 0·01	NA	NA	97·83 ± 0·20
CAT97-09	(6)	3·86 ± 0·14	1·32 ± 0·13	0·49 ± 0·06	0·08 ± 0·02	NA	NA	98·26 ± 0·39
CAT97-09T‡	(5)	4·10 ± 0·07	1·24 ± 0·04	0·45 ± 0·04	0·08 ± 0·03	NA	NA	98·22 ± 0·28
CAT97-08	(5)	3·83 ± 0·23	1·21 ± 0·25	0·44 ± 0·05	0·10 ± 0·03	NA	NA	98·66 ± 0·42
CAT97-06	(4)	3·54 ± 0·12	0·90 ± 0·12	0·30 ± 0·03	0·07 ± 0·03	NA	NA	100·12 ± ·0·39
CAT97-05	(4)	3·44 ± 0·09	0·86 ± 0·09	0·29 ± 0·02	0·08 ± 0·02	NA	NA	99·60 ± 0·32
CAT97-04	(5)	3·10 ± 0·08	0·60 ± 0·03	0·28 ± 0·02	0·08 ± 0·02	NA	NA	96·97 ± 0·22
Test trench D								
CAT97-38	(5)	3·85 ± 0·23	1·43 ± 0·12	0·57 ± 0·08	0·09 ± 0·03	NA	NA	97·11 ± 0·35
CAT97-39	(5)	4·02 ± 0·20	1·32 ± 0·12	0·46 ± 0·04	0·07 ± 0·04	NA	NA	97·54 ± 0·21
JLC								
McB97-01	(3)	3·63 ± 0·28	1·35 ± 0·30	0·63 ± 0·16	0·06 ± 0·05	NA	NA	97·71 ± 0·94
Rorop Lingop								
CAT99-05	(5)	3·83 ± 0·06	1·02 ± 0·03	0·35 ± 0·05	0·07 ± 0·01	NA	NA	98·81 ± 0·34
CAT99-04	(4)	3·98 ± 0·08	1·07 ± 0·07	0·43 ± 0·03	0·07 ± 0·01	NA	NA	99·38 ± 0·60
CAT99-03	(5)	3·84 ± ·010	1·09 ± 0·03	0·39 ± 0·04	0·06 ± 0·02	NA	NA	99·55 ± 0·47
Trachytic glass								
JLC								
McB97-01	(3)	6·89 ± 0·99	4·92 ± 0·49	0·02 ± 0·03	0·07 ± 0·06	ND	0·32 ± 0·20	97·19 ± 1·72
NRS								
CAT97-70	(3)	4·75 ± 0·58	4·01 ± 0·82	0·11 ± 0·09	ND	0·15 ± 0·03	0·35 ± 0·27	96·47 ± 2·78
McB97-02	(6)	3·93 ± 0·31	4·58 ± 0·07	0·03 ± 0·03	ND	0·15 ± 0·01	0·14 ± 0·13	91·04 ± 1·01
CAT97-74	(4)	4·27 ± 0·60	3·88 ± 0·47	0·10 ± 0·05	ND	0·14 ± 0·03	0·37 ± 0·20	93·55 ± 1·87

as being stratigraphically consistent with the chemical evolution of a magma chamber over time. Temporal changes in composition are recorded in the successive deposits resulting from periodic eruptions.

The basaltic samples are divided into two chemical subgroups defined by a compositional gap between ~5·5–6 wt. % MgO (Figure 5). Associated with this gap are jumps in wt. % CaO and TiO_2 (and usually but not entirely in FeO) that are not accompanied by a major change in SiO_2, which remains at ~48–49 wt. % (Table 1). This subdivision is appropriate for the sequences from NRS and GnJh-15. These subgroups are termed "lower" and "upper" based on their relative stratigraphic positions at these locations (Figures 5 and 6).

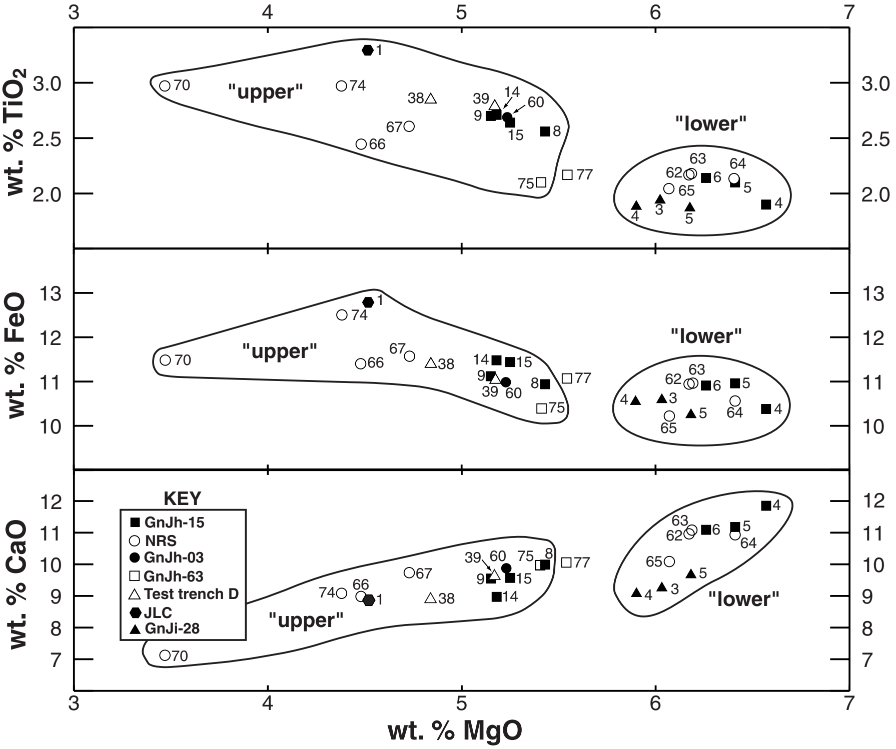

Figure 5. Oxide variation diagrams of sample means for all Bedded Tuff basaltic ash deposits. Sample numbers are abbreviated; see Table 1 for details. "Lower" and "upper" subdivisions refer to stratigraphic position in Figure 6. Sample 77 is heterogenous, probably due to mechanical mixture of deposits. See text for discussion.

The geochemical results readily distinguish between the basaltic and trachytic beds, consistent with petrographic observations. The trachytic beds show a continuation of the chemical trend seen in the basaltic layers (Figure 7); this, combined with petrographic evidence, suggests eruption from the same magma system. Sample McB97-01 is a single ~2·5 cm pumice from JLC (Figure 2) that contains separate but adjacent portions of both trachytic and Mg-poor basaltic glass (Table 1), apparently fused together as later eruptions sampled remnant older deposits during magma ascent. The overall compositional trend of basalts with increasingly evolved compositions, followed by mixed basalt/trachyte eruptions, seen in both NRS in the south of the study area (Figures 4 and 5) and to the north at JLC (Martyn, 1969; Tallon, 1976; Spooner *et al.*, n.d.) (Figure 1) parallels observations of volcano evolution and magma differentiation in the Rift and elsewhere (cf. Baker *et al.*, 1972; Wilson, 1989). Similar bimodal suites of alkali basalt–trachyte lava characterize all Kenyan Pleistocene central Rift Valley volcanoes north of Lake Baringo (Weaver *et al.*, 1972; Baker, 1987; MacDonald, 1987).

Implications for the age and extent of the Bedded Tuff

We conclude that the upper and lower basaltic units recognized here provide a correlation tool that is useful within the

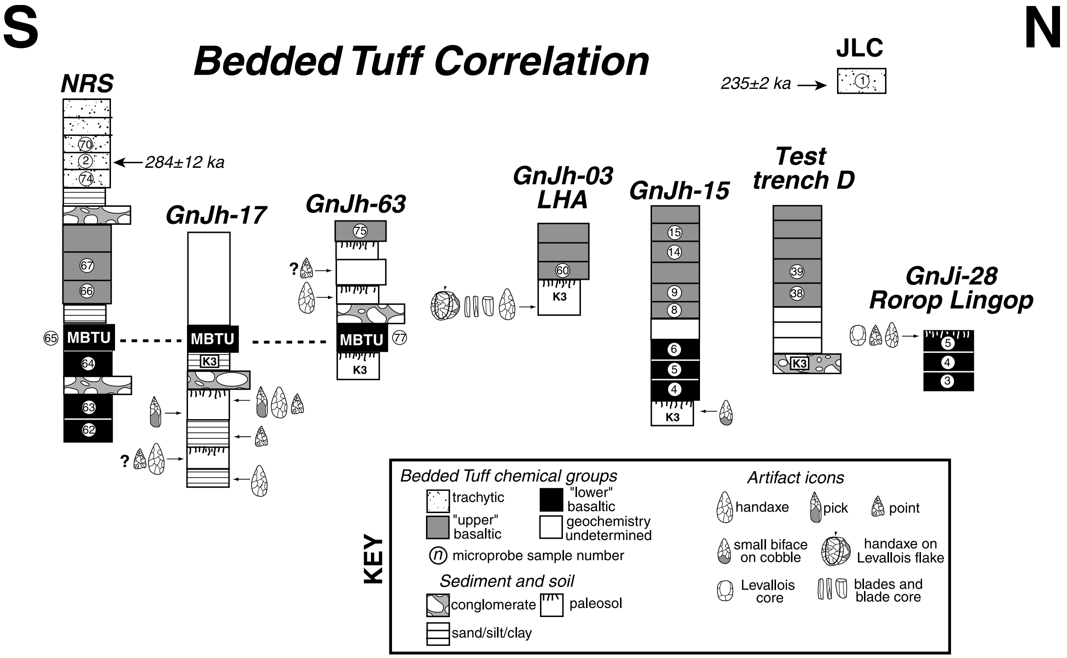

Figure 6. Schematic geologic sections of Bedded Tuff (K4) exposures and underlying sediment (K3). Stratigraphic columns are aligned roughly south to north; vertical axis is relative, showing approximate location within tephra sequence. "MBTU" is a field marker bed; dashed lines indicate lateral tracing in the field. Circled numbers refer to tuff samples. Sample numbers are abbreviated; see Table 1 for details. Artefact icons after Clark & Kleindienst, 1974; Gowlett, 1984; Clark, 1982*a*,*b* and McBrearty & Brooks, 2000.

Kapthurin Formation. These groups are based on a uniform basaltic stratigraphy observed at a number of sites in the study area, and determined by geochemistry and by tracing of beds in the field. The EMP analyses clearly show that different portions of the Bedded Tuff eruptive sequence are preserved at different outcrops. For example, the lowermost unit at GnJh-03 is an "upper" basaltic bed; earlier deposits have either been removed by erosion or were never present. Tephrostratigraphy thus provides an important means of inter-site correlation, and assists in the chronological ordering of sites (Figure 6).

The stratigraphic succession observed in the Ndau River, with pumiceous trachyte overlying basaltic units of the Bedded Tuff, can therefore be used to apply age limits to the entire Bedded Tuff eruptive complex. Sample McB97-02 from the pumiceous trachyte at NRS has been dated by $^{40}Ar/^{39}Ar$ to 284 ± 12 ka (Deino and McBrearty, 2002). This date and the geochemical data are consistent with an additional $^{40}Ar/^{39}Ar$ date of 235 ± 2 ka from sample CYS97-01 (=McB97-01) from sampling locality JLC (see Figure 6) (Deino & McBrearty, 2002). The more evolved composition of McB97-01 (Figure 7) reflects its origin at a later stage of eruption. The total amount of time over which the Bedded Tuff accumulated remains unknown, and rates of magma evolution and eruption in the Rift Valley and elsewhere are highly variable (cf. Fisher & Schmincke, 1984; Orton, 1996; Simkin & Siebert, 2000). Paleosols, if present between beds of tuff, are weakly expressed, and suggest intereruption periods on the order of 10–10 000 years (e.g., Bown & Kraus, 1993;

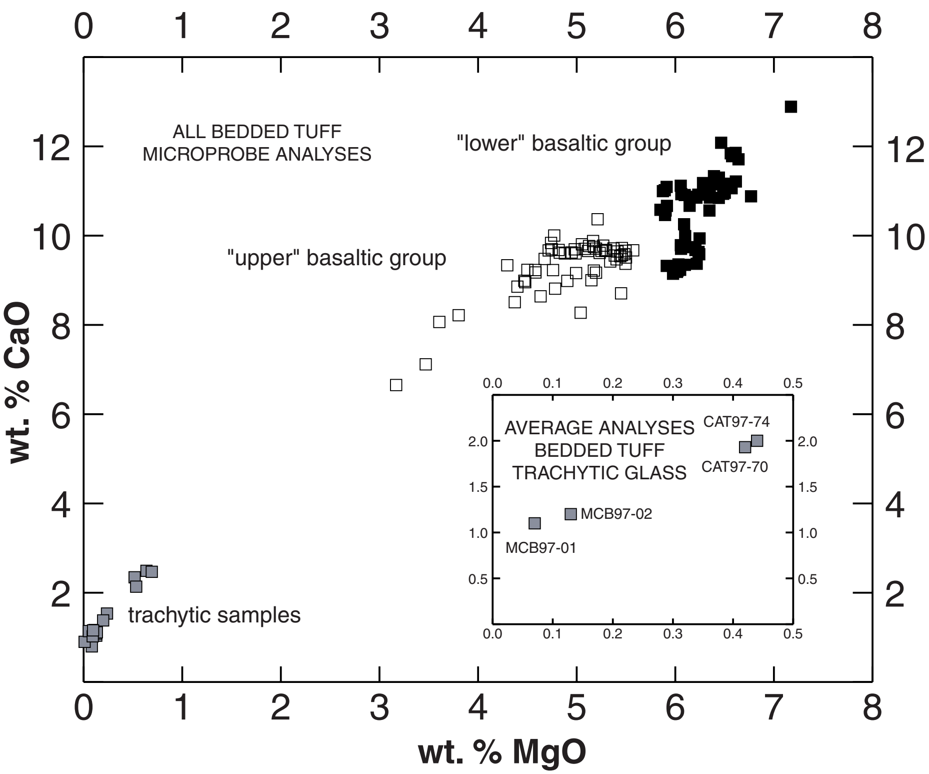

Figure 7. Oxide variation diagram of all microprobe analyses, showing linear relationship between basaltic and trachytic samples of Bedded Tuff. The "gap" between the "upper" and "lower" basaltic groups is clearly visible. Inset: sample averages for trachytic beds.

Birkeland, 1999), although substantiation of this estimate requires more detailed study.

Rorop Lingop (GnJi-28) and JLC contain tephra deposits previously mapped as the Kampi-ya-Samaki beds (Martyn, 1969; Tallon, 1978; Spooner *et al.*, n.d.). The Kampi-ya-Samaki beds appear to be lithologically identical to the main Bedded Tuff exposures, and consist of a similar stratigraphic sequence of basaltic ash overlain by trachytic pumices. While earlier workers hypothesized that these downfaulted lacustrine sediments were indeed equivalent to the Bedded Tuff, the correlation between them could not be traced laterally in the field. The geochemical results reported here confirm the equivalence of these deposits to the main Bedded Tuff exposures, and tie the dates from locality JLC into the main Bedded Tuff sequence.

Temporal placement of archaeological sites

Using the "lower" and "upper" subdivision of basaltic tephra established at the NRS and GnJh-15 reference sections, archaeological occurrences may be chronologically ordered (Figures 5, 6 and 7). Our best approximation of the temporal spans of the sites discussed here is set out in Figure 8. The main archaeological occurrence at site GnJh-15 underlies "lower" basaltic units. Rorop Lingop samples plot within the "lower" basaltic group, whereas those from GnJh-03 and Test trench D are chemically similar to "upper" basaltic tephra. Site GnJh-17 is physically correlated to the NRS

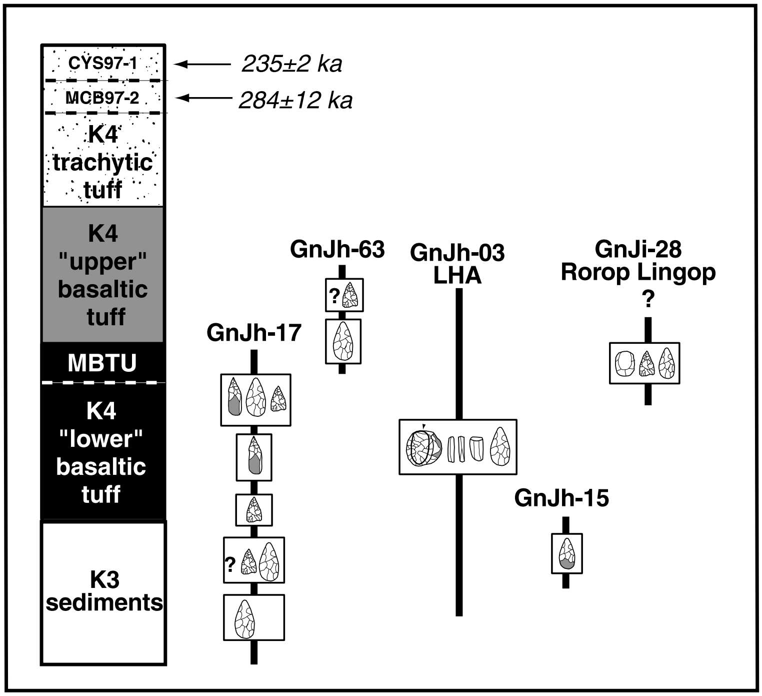

Figure 8. Summary stratigraphic relationships between units of the Bedded Tuff, radiometric dates, and archaeological assemblages. Icons as in Figure 6.

reference section by the physical tracing of a massive ~3 m-thick bioturbated field marker unit, informally named the "Massive Buff Tuff Unit" (MBTU), equivalent to Cornelissen's (1992:18) "Bedded Tuff catwalk" at GnJh-17. The MBTU is the uppermost unit of the "lower" basaltic group at NRS (sample CAT97-65). This same field marker can be traced to GnJh-63, where the "upper" and "lower" subdivision of the basaltic ash is less apparent. All Bedded Tuff samples from GnJh-63 appear weathered in thin section, with scarce shards of fresh glass suitable for EMP analysis. This is the probable partial explanation for the wide range of values within each sample from this site (Table 1), as subaerial weathering of basaltic tephra results in variable glass composition due to hydration, oxidation and element depletion (Hay & Jones, 1972; Singer & Banin, 1990). Although its mean value lies within the range of "upper" basaltic units (Figure 5), we place sample CAT97-77 (MBTU) in the "lower" basaltic group on the basis of physical tracing in the field. Sample heterogeneity suggests a mixed population of "upper" and "lower" basaltic glass shards. In addition to alteration, this may reflect compositional grading within the ~3 m thick bed, with formerly discrete beds obscured by postdepositional processes, including bioturbation. This may be resolved in future by additional vertical sampling within the MBTU. Sample CAT97-75 is tentatively placed in the "upper" basaltic group on the basis of average chemical composition, subject to revision with additional analyses at this locale. All the sites discussed here underlie the pumiceous unit sampled at NRS and dated by ^{40}Ar/^{39}Ar to 284 ± 12 ka by Deino & McBrearty (2002).

Discussion

There are three important general implications of these results. First, the archaeological occurrences discussed here all antedate ~285 ka, indicating that the Acheulian–MSA transition in this part of East Africa had begun at least by this date. Second, the points present at GnJh-17, GnJh-63, and GnJi-28 are the oldest yet known from Africa. Third, chronological ordering of sites shows no clear unidirectional succession from the Acheulian to the MSA in the Kapthurin Formation, as defined by the presence of *fossiles directeurs* (Figure 8). Rather, the Acheulian is interstratified with Sangoan, MSA, and perhaps Fauresmith components. Unlike sequences elsewhere, such as at Kalambo Falls, Cave of Hearths, Isimila, or Muguruk (Howell *et al.*, 1962; Mason, 1962, 1993; Howell & Clark, 1963; Clark, 1969; Cole & Kleindienst, 1974; McBrearty, 1988), strata of the Kapthurin Formation containing Acheulian artefacts (handaxes) overlie those containing artefacts diagnostic of the Sangoan (picks) and the MSA (points). Artefacts diagnostic of the Acheulian, Sangoan, Fauresmith, and MSA are found at contemporary sites, and in some cases, from the same level at the same site. These results demonstrate the variability present in late Acheulian and post-Acheulian assemblages. Two of these industries, the Sangoan and Fauresmith, were formerly attributed to geographically distinct ecological zones. It remains unclear whether the technological diversity seen within the Kapthurin Formation is a result of complex hominid adaptations, diverse paleoenvironments within a single basin, or even the presence of multiple hominid species.

There remains the question of the reliability of *fossiles directeurs* for industrial attribution, particularly when they comprise a small proportion of the total assemblage. There is clearly a danger in assigning a sample to industry based upon the presence of a few diagnostic tools drawn from an assemblage of many thousands of flakes and cores. Both the Sangoan and the Fauresmith industries were originally defined on the basis of surface collections that may well represent objects from disparate time periods. Thus, while generally considered diagnostic of the MSA, points are included in the original definition of the Fauresmith (e.g., Goodwin, 1928). Picks, the hallmark of the Sangoan, are also found in undoubted Achuelian and MSA assemblages. How are we to interpret the presence of a handaxe, a pick and a point from a single level at GnJh-17 (Cornelissen, 1992, 1995), for example? Similar occurrences are known from Level 7, Garba III at Melka Kunturé, where handaxes and foliate points were recovered from beneath an iron-cemented paleosol (Hours, 1976). Such occurrences emphasize the arbitrariness of the ESA/MSA division, and recall the warnings of Kleindienst (1967) and Mehlman (1991), among others, on the misuse of typology as chronology. Several interpretations can be suggested. First, the combination of artefacts at sites such as GnJh-17 may represent variation within the late Acheulian or early MSA, reflecting habitat or activity specific adaptations. Second, they may be evidence of the persistence of older stone working methods during the process of accumulation of novel technology, within a single tradition. Third, the different artefact classes may denote separate occupations by different contemporary hominid groups employing different technologies. Or fourth, they may be a palimpsest of deposits accumulated over time.

Conclusions

The Acheulian to Middle Stone Age transition, like most major technological transitions in prehistory, remains incompletely understood. Most discussions of archaeological change at this time depth contain assumptions of gradual and unidirectional change, although these are rarely explicitly expressed. At a regional scale and using a broad chronological framework, a simple succession of tool-making traditions may seem apparent at the Acheulian–MSA boundary, but the actual events can be quite complex when examined at the local level with improved temporal resolution. Our work in the Kapthurin Formation shows that the processes leading to MSA technological adaptations were under way before 285 ka, and that assemblages that can be attributed to different industrial traditions are interstratified. Chronological overlap among industries within a single depositional basin shows that the transition to the MSA was not unidirectional, but was time-transgressive in this part of the Rift Valley.

These data reveal a picture not unlike that for the late MSA and early LSA. The *fossile directeur* of the LSA is the backed geometric microlith. Backed geometrics first appear in the MSA, however. They occur in the Howiesons Poort industry of South Africa and in the Mumba Industry of northern Tanzania at ~70 ka (McBrearty & Brooks, 2000). They vanish from the record ~60 ka only to reappear in LSA assemblages after ~40 ka. The Lazarus-like return of the microlith may indicate reinvention or rediscovery of this form of composite tool technology. Alternatively, it may simply illustrate the incompleteness of the archaeological record for the intervening time interval, combined with the ebb and flow of Late Pleistocene hominid populations across the landscape (cf. Jablonski, 1986; Brooks & Robertshaw, 1990).

Later technological transitions in prehistory are of course better constrained temporally. While we lack the chronologic resolution in the Middle Pleistocene to justify use of most ethnographically based interpretive models (cf. Stern, 1993), it is worthwhile to note that they frequently feature episodic change and the presence of multiple contemporaneous traditions. During the transition from the Later Stone Age to the Iron Age in eastern and south-central Africa, for example, microlithic industries persisted for centuries after the introduction of iron. Phillipson (1977, 1980) has noted the "technological disparity" among contemporary assemblages from this time period, a product of the spatial overlap of groups employing fundamentally different technologies. New technology was not universally beneficial, its utility and desirability mediated by a range of ecological and social factors (e.g., Musonda 1997; Gifford-Gonzalez, 1998; Smith, 1998), and contemporary foragers and food producers appear to have maintained complex exchange relationships (e.g., Blackburn, 1982; Brooks *et al.*, 1984). The outcome is a highly varied archaeological record. The Kapthurin Formation presents a similarly complex pattern of variability during the transition from the Acheulian to the MSA.

There is no *a priori* reason to link major technological changes with the appearance of new hominid species (Bar-Yosef, 1998), but in Africa hominids that appear to represent our lineage (*H. helmei*), MSA technology, and evidence for a range of modern behaviors all appear in the record shortly after 300 ka. These behaviors include range expansion, use of formal bone tools, specialized hunting, the use of aquatic resources, long-distance trade or transport of raw materials, and the use of pigment (Deacon & Deacon, 1999; Klein, 1999; McBrearty & Brooks, 2000). From this perspective, the transition from the Acheulian to the early MSA is not simply a change in artefact types. Rather it records adaptive changes that may signal the appearance of a morphologically and behaviorally distinct hominid species employing novel technology.

The African Acheulian–MSA transition is as yet poorly documented. The transition from the late Acheulian to the early MSA certainly marks a period of technological change, but we need to understand more fully the nature of these changes, the prevailing conditions, and the adaptive responses to these conditions that led to the evolution of modern human behavior. The Kapthurin Formation provides one of the few instances where this transition can be dated and the stratigraphic succession of assemblages within a single depositional basin observed. We cannot develop higher-order theories of process until we have established the basic chronological sequence of change. Further archaeological research in the highly resolved record of the Kapthurin Formation's Bedded Tuff, enhanced by a larger sample size, may help to explain this patterning.

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