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Stratigraphy, correlation, and age estimates for fossils from Area 123, Koobi Fora

Craig S. Feibel[a,b,*], Christopher J. Lepre[b], Rhonda L. Quinn[a]

[a] Department of Earth and Planetary Sciences, Rutgers University, Busch Campus, 610 Taylor Road, Piscataway, NJ 08854-8066, USA
[b] Department of Anthropology, Rutgers University, Douglass Campus, 131 George Street, New Brunswick, NJ 08901-1414, USA

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ABSTRACT

Geological data from the Bura Hasuma region at Koobi Fora provide important constraints for estimating the ages of hominin fossils recovered there, including the cranium KNM-ER 1813. Strata of the upper Burgi, KBS, and Okote members in this part of Koobi Fora reflect three depositional regimes driven by changing paleogeography through time. The upper Burgi and lowermost KBS sequence in the southern Bura Hasuma region accumulated in a lacustrine to delta front setting, with highly localized depositional patterns, limiting the lateral extent of lithostratigraphic markers. Farther north, uppermost upper Burgi through KBS member strata document a fluctuating lake margin, with complex facies patterns. This interval is marked by laterally extensive lithostratigraphic markers, including molluscan packstones, beach sandstones, and stromatolite beds. The uppermost KBS and Okote members show a transition to dominantly fluvial character, with localized and discontinuous accumulation.

An age model for the richly fossiliferous Area 123 sequence demonstrates the complexity of terrestrial accumulation patterns. Early lacustrine and delta front accumulation is marked by fairly continuous sedimentation, and high accumulation rates (up to ca. 91 cm/k.yr.). The fluctuating lake margin interval reflects lower sedimentation rates coupled with intervals of exposure, decreasing accumulation significantly (to ca. 13 cm/k.yr.). The capping fluvial interval is marked by significant erosion surfaces, breaks which may drop the overall accumulation rate even lower (ca. 0.3 cm/k.yr.).

The data provided here establish a geological framework at odds with a recent proposal of ages considerably younger (by ca. 250 k.yr.) for many of the fossils from Area 123 and elsewhere. Tests of age models demonstrate that the younger ages are not possible. While minor refinements to age estimates for fossils are indicated by improved chronostratigraphic control, in the case of KNM-ER 1813, an age of younger than 1.78 Ma is precluded on magnetostratigraphic grounds.

Introduction

The establishment of an accurate and precise framework for the fossil and archaeological record has long been a preoccupation of geologists interested in evolutionary and environmental problems (e.g., Bishop and Miller, 1972; Bishop, 1978). In East Africa, the context of hominin fossils and sites has been a particular focus, in part due to the excellent opportunities afforded by the stratigraphic record, and the intercalation of significant chronostratigraphic markers. In the four decades since the first application of numerical dating techniques to the hominin record of Olduvai Gorge (Evernden and Curtis, 1965), a detailed and robust framework of numerical age markers has been established for the Neogene of East Africa (e.g., Walter et al., 1991; Brown, 1994; Deino et al., 2006). Throughout this interval of development, scientific testing of numerical age estimates has confronted inconsistencies and apparent conflicts (e.g., Lewin, 1987). This has ultimately resulted in a high-resolution dataset, often allowing the control of fossil and archaeological localities to very limited numerical age spans. Of central importance to this process has been the interplay between geological field techniques and laboratory approaches. Critical field tools include mapping, analysis of stratigraphic sections, and correlation, while laboratory techniques such as geochemistry and isotopic age estimation provide more quantitative approaches to correlation and age.

Here we present stratigraphic data that falsify suggested revisions to age estimates for hominin and other fossils from Area 123 of the Koobi Fora region (Gathogo and Brown, 2006). Detailed mapping and stratigraphic analysis provided here obviate revisions in correlations made in that publication, while magnetostratigraphic data demonstrate that the younger ages are not possible.

* Corresponding author.
E-mail address: feibel@rci.rutgers.edu (C.S. Feibel).

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The Bura Hasuma region and its fossils

The discovery of the hominin fossil KNM-ER 1813 during the 1973 field season in Koobi Fora Area 123 focused geological interest on a complicated set of strata in the southern part of the Bura Hasuma region at Koobi Fora (Fig. 1). Exposures there include a prominent landmark, Bura Hasuma Hill (in southern Area 110), which is separated by nearly 2 km of poor exposure from a highly faulted belt of badlands exposures in Area 123 where KNM-ER 1813 and a number of associated fossils were recovered. The KBS Tuff was identified at the base of Bura Hasuma Hill, but no tephra were encountered in Area 123. Strata of comparable antiquity were recognized based on faunal assemblages and lithologic similarity, but crucially, the KBS Tuff itself is not present in Area 123.

Early reports concerning KNM-ER 1813 (Leakey, 1974; Leakey et al., 1978; Walker and Leakey, 1978) listed the specimen's stratigraphic derivation as either "Lower Member" or "Upper Member" within the Koobi Fora Formation, reflecting the uncertainty of the fossil's stratigraphic position relative to the KBS Tuff. With revisions to the stratigraphic nomenclature of the Koobi Fora region (Brown and Feibel, 1986), the interval of concern became the upper Burgi Member and the overlying KBS Member. The problem of stratigraphic attribution remained unchanged, however, as the delimiting KBS Tuff was not found in Area 123, and the position of the member boundary continued to be estimated. Lithologic correlations placed the level from which KNM-ER 1813 derived close to that of the tuff. While the actual chronostratigraphic significance of a precise attribution might be minimal, the relative placement of the Area 123 fossils with respect to other specimens, such as KNM-ER 1470, is significant. Subsequent detailed analysis of Koobi Fora stratigraphy (Brown and Feibel, 1986) and of the context of fossil hominins throughout the Turkana Basin (Feibel et al., 1989) placed KNM-ER 1813 beneath the level of the KBS Tuff, and assigned it an age between 1.88 Ma and 1.90 Ma (essentially 1.89 ± 0.05 Ma). Since that time, the framework within which the Koobi Fora hominins are constrained has been refined, but no major revisions have been proposed.

Geological context of the Bura Hasuma region

Over more than four decades of geological investigations at Koobi Fora, geologists have amassed a large database, and considerable understanding of its stratigraphic framework (e.g., Brown and Feibel, 1991). Recent difficulties in assessing the stratigraphy of Area 123 (Gathogo and Brown, 2006) result from neglecting crucial spatial context, integrating Area 123 with geographic and geologic mapping, and from misinterpreting lithological correlation and its chronostratigraphic calibration. We will treat first the spatial context surrounding the important fossils of Area 123, and then develop the stratigraphic framework within which the fossils can be placed. We will also demonstrate with stratigraphic data that the proposed age revisions of Gathogo and Brown (2006) can be falsified. We will then discuss the implications for the chronostratigraphic context of the Area 123 fossils as well as related examples. We hope to provide sufficient data here to demonstrate what is, and is not, possible with respect to the ages of these fossils.

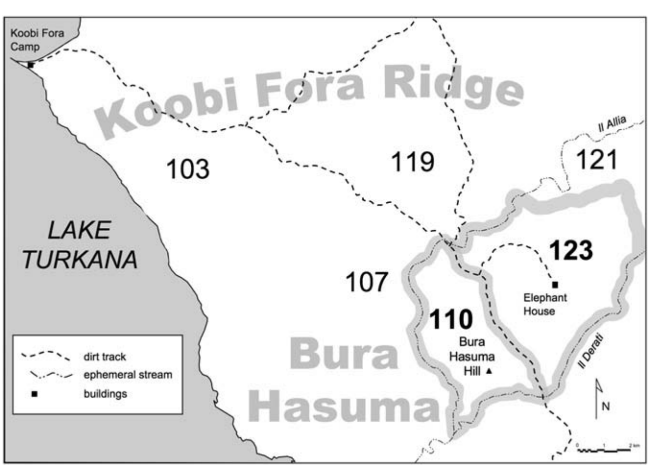

Figure 1. Location map of the Koobi Fora Ridge and Bura Hasuma regions showing major drainages, established dirt tracks (roads), and geographic landmarks discussed in the text. Boundaries of Areas 123 and 110 are outlined (for a detailed map of Koobi Fora collecting areas see Brown and Feibel [1986]).

Spatial context

There are two aspects of spatial context that are central to understanding the problems in Area 123: geographic localization and geologic mapping. The geographic component of spatial context is generally not a problem these days, especially in this age of GPS navigation and Google Earth. The location map provided by Gathogo and Brown (2006), however, is inaccurate, with implications for interpretation of the associated geology. Several landmarks are misplaced, such as the dirt track that forms the boundary between Area 110 and Area 123 (compare Fig. 1). This is significant in that it provides the only easily mappable landmark in the exposures most confounding to lithologic correlation. More problematic is the location of the marked stratigraphic sections. One of the sections used by Gathogo and Brown (2006) as a basis for their proposed correlations passes next to a local landmark, the Elephant House. This feature (and even the outhouse next to it) is easily seen on Google Earth imagery (near location point 162, Table 1). It is clear that the location given by Gathogo and Brown (2006) for their "Elephant Site" section is misplaced by some 2.5 km. Such problems in geographic placement call into question the location of other features and sections as documented by Gathogo and Brown (2006). For example, the placement of section PNG-123.2 as located by Gathogo and Brown (2006: Fig. 1b) crosses a mapped fault (Fig. 2). If the location provided for the section is accurate, then the tephra used to constrain the upper age of the sequence by Gathogo and Brown (2006) is not in continuity with the underlying strata (the mapped fault would have brought it down from higher in the section). We suspect, however, that the location provided is inaccurate, and does not necessarily bear on the continuity of that particular section.

No geological mapping was provided by Gathogo and Brown (2006). Existing mapping (e.g., Findlater, 1978) and more detailed subsequent work (Feibel, unpublished: Fig. 2) were available at the time of the investigation reported in Gathogo and Brown (2006). Unpublished maps were provided to the Koobi Fora Research

Table 1
GPS Coordinates of significant localities discussed in the text (WGS84 datum).

Point #	Lat/Long	Feature
155	N3.83461 E36.34686	Fault at Bura Hasuma Hill
162	N3.86712 E36.36102	ridge above Elephant House top Section 123-2/3
174	N3.88167 E36.37600	Northern Area 123 fault
MGL 1	N3.88797 E36.35024	Tuff MGL04-1
183	N3.87960 E36.32765	base Section CSF 123-1

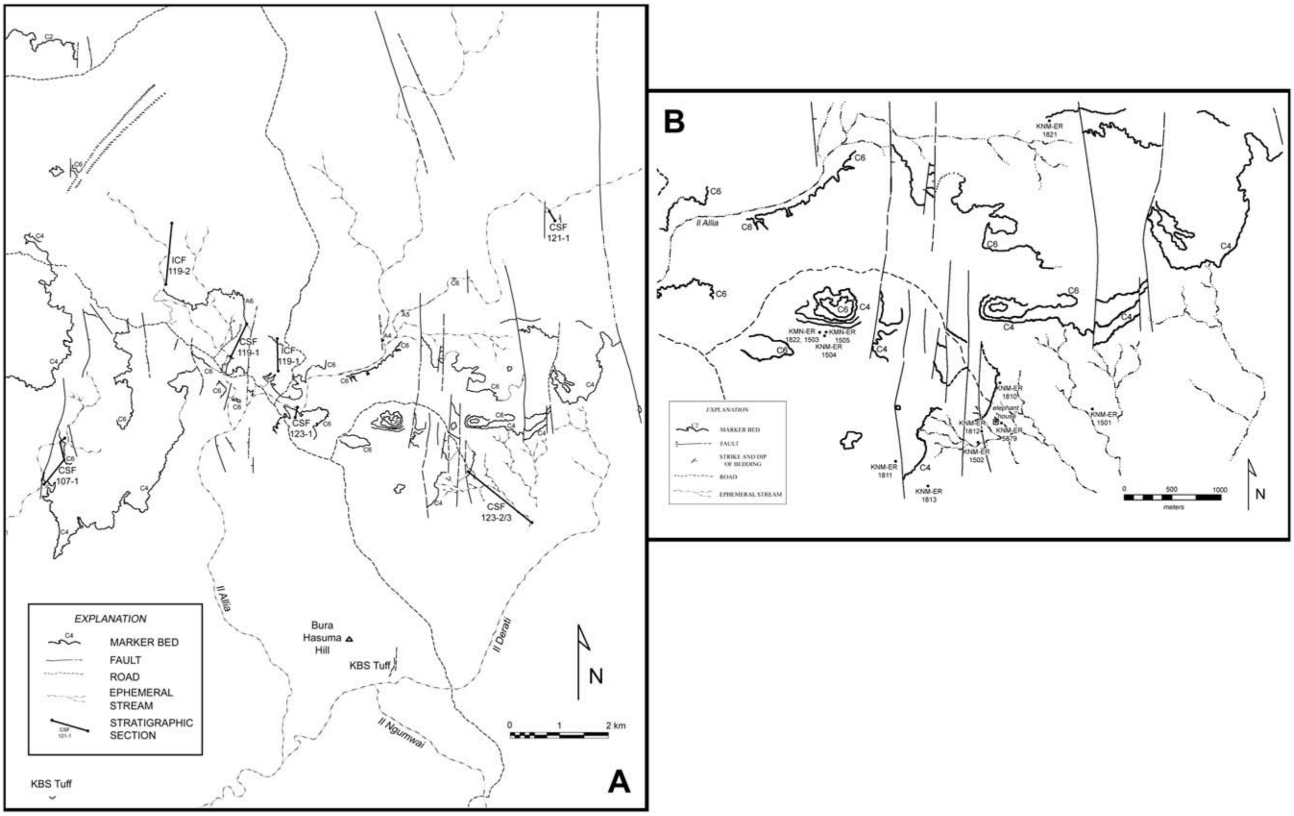

Figure 2. A: Geologic map of the southern Koobi Fora Ridge and Bura Hasuma regions (eastern half of Fig. 1) showing major faults, tracing of stratigraphic marker horizons, and locations of stratigraphic sections discussed here. B: Geologic map detail of Area 123, with locations of significant hominin finds related to marker beds identified there.

Project at the start of the 2003 field season in Area 123. Two aspects of these geologic maps bear on the arguments made by Gathogo and Brown [2006]: 1) the faulting within the areas under discussion, and 2) the established extent of the marker beds used to constrain the placement of fossils.

Geological mapping of the Bura Hasuma region (Fig. 2) shows a series of roughly N-S trending faults. Though the displacement on these faults is generally minimal (meters to tens of meters), they break the continuity of marker beds *and preclude continuous tracing of stratigraphic levels* through much of the region. Gathogo and Brown (2006: 473) claimed to have ''physically traced'' a sandstone body through at least six of these faults. Of equal significance, the prevalence of faulting throughout the region makes correlation across areas of poor exposure a problematic practice. In the Bura Hasuma region, the gap between the base of Bura Hasuma Hill and the badlands of Area 123 has presented an insurmountable obstacle to physically connecting the two sequences for decades. Faulting can be seen at the base of Bura Hasuma Hill (location point 155, Table 1), adjacent to this broad area of poor exposure. Additional faults are mapped throughout Area 123. It is unclear whether or not Gathogo and Brown (2006) were aware of this faulting, but they do not acknowledge its existence in their work. Consideration of the problems presented by faulting in this area is clearly of significance, and a key element in a full understanding of the possibilities and limitations of correlation.

A second aspect of geological mapping, the extensive marker beds within documented stratigraphic sequences, provides the basis of evidence for original lateral continuity and identification of key geologic markers. Mapping of stratigraphic markers was initiated along the Karari Ridge by the Iowa State University stratigraphic research group under Carl Vondra in the 1970s (Bainbridge, 1976; Burggraf, 1976; Frank, 1976; White, 1976; Burggraf et al., 1981; White et al., 1981), and extended to the Koobi Fora Ridge in the 1980s (Feibel, 1983; Tindall, 1985). The mapping of the western Koobi Fora Ridge (Feibel, 1983) was based on a series of highly distinctive and laterally extensive lithologic markers. These became the basis for major subdivision of the upper Burgi and KBS members in the type sections (Brown and Feibel, 1986, 1991). While the western Koobi Fora Ridge is heavily faulted, characteristic sequences of marker beds could be recognized throughout an area of roughly 80 km^2. More than two decades of testing these relationships has not unearthed any significant problems with that mapping. Through the 1980s and 1990s, the mapping done along the western Koobi Fora Ridge (Feibel, 1983) was extended to the north, east, and south as far as those lithologic markers persisted (Fig. 2). This encompasses an area of over 200 km^2. This mapping allowed the tracing of prominent marker beds, and extension of mapping across gaps (correlation) *based on characteristic lithologic sequences*. Again, extensive testing of the correlations proposed in this mapping over more than two decades has produced no significant conflicts.

It must be emphasized that geologic mapping is among the most basic elements of documentation. In the examples under discussion here, lithologic markers are literally walked out, and their basal contacts are mapped directly on air photos. The lines thus mapped represent real surfaces within the geologic framework (see Fig. 2). The only question arises when gaps in exposure or the existence of faults breaks the continuity of the marker. Recognition of the identity of marker beds across faults or breaks in exposure requires the process of correlation. Marker beds with relatively unique characteristics, such as geochemical composition in tephra markers, can often be unambiguously correlated over wide discontinuities. Lithostratigraphic markers are typically less unique, and their correlation is based on a combination of internal characters, associated sequence, understanding of regional context, and additionally an understanding of process.

Stratigraphic framework

The stratigraphic sequence in the Bura Hasuma region is closely comparable to that seen in the type sections of the upper Burgi, KBS, and lowermost Okote member strata to the northwest (Brown and Feibel, 1986). However, there are two significant differences seen in the Bura Hasuma region: 1) the upper Burgi Member strata preserve complex depositional dips associated with delta front deposition, particularly in the south, and 2) the KBS Member becomes thinner to the south and east. A key observation at this point is that stratigraphic sequences are much better understood in a broader context, where regional trends, lateral continuity, and facies transitions can be put into perspective. In the case of Area 123, it is in fact difficult to reconstruct the composite sequence based on local exposures only, but this process is relatively straightforward when data from the surrounding areas are taken into account. The following discussion is based on lithologic characteristics, sequences, and correlations illustrated in Fig. 3. The sections from Area 123 are shown in relation to prominent sections from the surrounding region (Areas 107, 110, 119, 121) and linked to the type sections (Areas 102 and 103).

The Bura Hasuma stratigraphic sequence can be considered in terms of three sedimentary packages. Upper Burgi Member strata are dominated by claystones, siltstones, and fine sandstones. These sediments commonly include a significant biogenic component, including fossil molluscs, ostracods, and fish. The upper Burgi Member here reflects lacustrine deposition and the progradation of several delta lobes. The KBS Tuff as exposed in Area 110 accumulated across a depositional surface related to one of these delta lobes, with a thin vitric facies showing up to 14 m of depositional relief on the subaqueous delta front, and a coarser, impure channel facies marking a distributary on the delta top. The second sedimentary package in the Bura Hasuma region, comprising most of the KBS Member strata there, is characterized by cyclical repetition of a facies complex. Each cycle typically includes a bioclastic carbonate or sandstone (usually well-cemented and utilized as markers in mapping), overlain by clays or laminated siltstones. This finer grained interval grades upwards into mudstones with common pedogenic overprinting, in association with channel-form

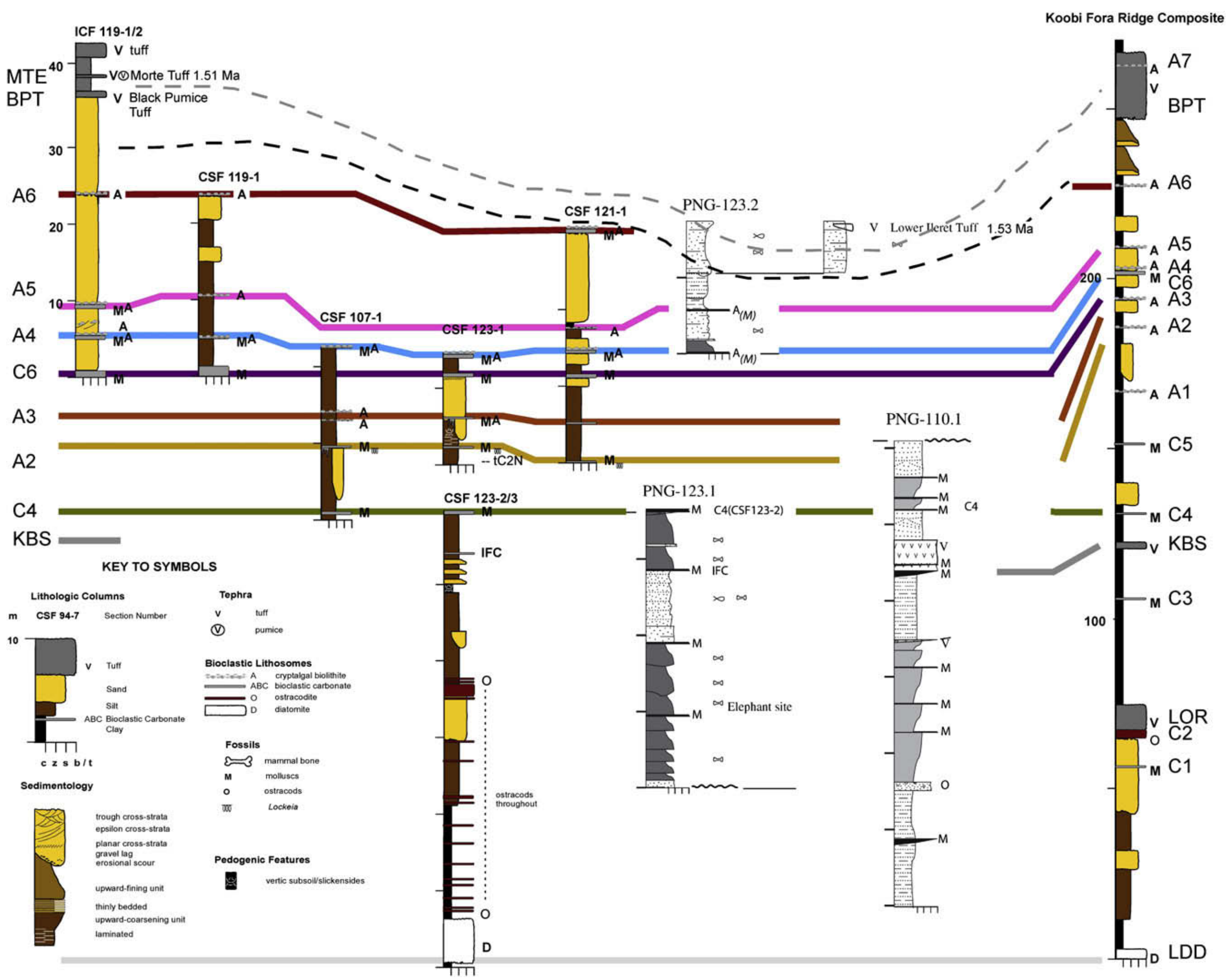

Figure 3. Stratigraphic sections from the Bura Hasuma region correlated by lithostratigraphic and tephrostratigraphic markers, compared to composite type section for this portion of the Koobi Fora Formation along the Koobi Fora Ridge (redrawn after Brown and Feibel [1986]). Sections presented in Gathogo and Brown (2006: PNG and unlabeled sections) are shown in revised context based on data in this paper. Section ICF 119-1/2 redrawn from Findlater (1976). Individual sections are shown to a common scale, but note scale change for composite type section. Dashed lines in upper part of diagram indicate possible erosion surfaces discussed in text.

sandstones. This sequence represents a transgressing lake margin with its bioclastic and beach components, followed by a lacustrine suite of clays and laminated silts. Subsequent emergence with fluvial channel components and adjacent floodplain soils reflects the regressive trend in the cycle. Along the Koobi Fora Ridge to the northwest, this cyclical pattern is well expressed from just below the KBS Tuff (marker C3) to near the Koobi Fora Tuff Complex (marker A6), over a stratigraphic interval of some 130 m. In the Bura Hasuma region, this interval is condensed, spanning only 40–50 m of section. The Koobi Fora Ridge sequence has 10 prominent sedimentary cycles, while in the Bura Hasuma region only seven of these are well represented. The third sedimentary package that makes up the Bura Hasuma sequence is not well expressed locally, primarily due to weakly indurated lithologies. It is a complex sequence of channel-form sandstones, upward-fining cycles, and tuffaceous silts. This sequence is well documented to the northwest in Area 103, where two prominent fluvial cycles overlie marker A6 and are succeeded by the Koobi Fora Tuff Complex. In Area 119 of the Bura Hasuma region, this package attains some 20 m in thickness, with a thick sand body and a complex of tuffs and tuffaceous silts. This third sedimentary package reflects another shift in sedimentary pattern, to a more fluvially dominated system.

Stratigraphic markers are variably expressed in each of the three sedimentary packages. Tephra markers occur sparsely in the lower and upper sedimentary packages, but have not been recognized within the middle package in the Bura Hasuma region. Extensive lithologic markers are well developed in the middle package, but are poorly developed above and below.

Within the lower package, complex paleotopography associated with delta lobe deposition limits both lateral continuity and original horizontality. Facies transitions are rapid, and few markers can be traced over significant distances. The geographic restriction of the two tephrostratigraphic markers in this interval, the KBS and Brown tuffs, demonstrates this problem. Several prominent bioclastic units do occur, such as molluscan coquinas in southern Area 123. These units can be traced over distances of 100s of meters and display prominent depositional dips, which we interpret to reflect accumulation upon an abandoned delta front surface. These beds within the lower package are only of local utility as stratigraphic markers.

A more prominent and laterally continuous lithologic unit is known from eastern Area 123, marking the transition to the second sedimentary package. This is an intraformational conglomerate (IFC), with small orange pebble- to granule-sized clasts of reworked carbonate nodules. The IFC here is very similar to two prominent markers along the Karari Ridge, the Gold Pebble Conglomerate and the Limonite Chunk Conglomerate (Isaac and Behrensmeyer, 1997), both of which lie just below the KBS Tuff in Area 105. This marker, and the bioclastic carbonate above it (interpreted to be the marker C4), can be demonstrated to lie stratigraphically above the level from which KNM-ER 1813 was collected. Lithologic markers in the second sedimentary package are prominent and extensive, and these are the units that figure importantly in the discussion at hand. These markers are typically carbonate-cemented sandstones and bioclastic carbonates, including shellbeds, beach sandstones, and stromatolite beds. The sequence of these markers, and the associated terminology, was first established along the western Koobi Fora Ridge (Feibel, 1983) where unusually high accumulation rates have resulted in an exceptionally complete stratigraphic record (Feibel, 1988; Lepre et al., 2007). These markers and the associated sequences were mapped and correlated from the western Koobi Fora Ridge through the study area. It is the continuity of this sedimentary package and the progressive shift in character (e.g., overall thinning) witnessed along this transect which allows a high degree of confidence in identifying the individual stratigraphic markers within the Bura Hasuma region.

A total of seven lithologic markers are recognized within the second sedimentary package in the Bura Hasuma region. These are the markers C4, A2, A3, C6, A4, A5, and A6 (Feibel, 1983, 1988; Brown and Feibel, 1986, 1991). Although each tends to have distinctive characteristics by which it can be recognized (e.g., the abundance of the trace fossil *Lockeia* on the base of A2), *no correlations are based on individual bed recognition*, but rather *sequences* of markers and associated strata are recognized and correlated. As can be seen in Fig. 3, the sequence A2-A3-C6-A4 is commonly repeated in exposures of the Bura Hasuma region, and perhaps the most characteristic stratigraphic progression of this interval. This sequence can be tied unambiguously to the underlying marker C4 in southern Area 107, adjacent to Area 123. Within Area 123, exposures linking C4 to A2 are poorly preserved or exposed, and this is likely one factor contributing to the difficulties encountered by Gathogo and Brown (2006). Likewise, the upper part of the sequence of markers, A5-A6, is only locally preserved in Area 123. The regional perspective, incorporating evidence from all of the available sections, makes clear and unambiguous recognition of the overall sequence possible.

The upper sedimentary package is significant in preserving several additional tephrostratigraphic markers, but it is poorly preserved. The section in Area 119 is key to interpreting the relationships within this interval. Brown et al. (2006) reported both the undated Black Pumice Tuff and the dated Morte Tuff (1.51 Ma) in the tuffaceous capping strata of the Area 119 section. They also placed the Lower Ileret Tuff between these two markers within the overall tephrosequence, based on a combination of stratigraphic and chronometric criteria. The identification of the Lower Ileret Tuff in Area 123, based on a sample collected by M. G. Leakey (Gathogo and Brown, 2006) allows us to correlate the uppermost portions of the upper interval strata. The position of the Lower Ileret Tuff in Area 123 relative to the bracketing tephra in Area 119 suggests that the fluvial sequence in Area 123 may include significant local downcutting (Fig. 3). This has implications for stratigraphic scaling as discussed below.

Utilizing a regional perspective on sedimentary packages, markers, and lateral variation allows the Area 123 sedimentary sequence to be incorporated within a detailed stratigraphic framework and to be understood within a coherent pattern of depositional processes. The sections reported by Gathogo and Brown (2006) can be accommodated within this framework without difficulty (Fig. 3), but in a different configuration than reported by those authors. The validity of the relationships proposed here, versus those given by Gathogo and Brown (2006), can be established with a few simple tests.

Testing hypotheses

The argument put forth by Gathogo and Brown (2006) for a revised stratigraphic framework and a basis for new age estimates on fossils can be reduced to three component points. First, the correlation of the KBS Tuff into the Area 123 sequence must be demonstrated to provide a base for numerical scaling. Second, a revised lithostratigraphic correlation is postulated, which modifies the stratigraphic sequence and establishes an internal framework for scaling. And third, a newly discovered tephra is placed at the top of the sequence to constrain the minimum age and complete the linear age model. The argument for revised ages depends upon demonstration of each of these component points. Failure at any step negates the model for age estimation. In fact, all of the points can be demonstrated to lack supporting data or can be falsified through specifically formulated tests.

For the initial point, we have only a convoluted argument that a sandstone in Area 123 lies over a mollusc-packed sandstone that is linked by unspecified means to a comparable sandstone above the KBS Tuff on Bura Hasuma Hill. It is impossible to devise a test for this particular argument. Without supporting geological mapping, there is nothing to favor it, and the map presented here (Fig. 2) documents some seven faults through this area of exposure. Gathogo and Brown (2006) did not mention the existence of faults in Area 123, and this is the best explanation for the discrepancy in their correlation. There is thus no new evidence to place the KBS Tuff with respect to the sequence in Area 123, and the anchor point for Gathogo and Brown's (2006) age model is removed.

The second argument is fortunately much easier to test. Gathogo and Brown (2006: 473) related their "observations" on the marker bed referred to as C4 in Area 123: "…this bed changes radically in character laterally. Mollusc-rich units prominent in southern exposures are replaced by algal stromatolites farther north." This is the basis for their revised correlation, in which the marker bed associated with the hominin fossils (C4) is reattributed to a marker higher in the section, the stromatolitic unit A4, which provides a modified section for their stratigraphic scaling. Most importantly, the revised correlation places the specimen KNM-ER 1813 some 50 m *above* the level of the KBS Tuff, as opposed to previous interpretations that placed the specimen just below the level of the tuff. The "observation" is easily tested, as there is only one location in Area 123 where lithologic markers C4 and A4 come into close geographic proximity, and a south to north transition might be observed (location point 174, Table 1). If the lithologic transition occurs, this can be verified by walking out the marker bed and observing the change in character. This test was undertaken, and the assertions of Gathogo and Brown (2006) were falsified by simple observation. Following the marker bed C4 northwards from the Elephant House does reach a point where stromatolites characteristic of the marker A4 can be found littering the surface of the unit, *but not* in situ. A fault juxtaposes the two markers, and a shallow stratigraphic dip across an eroded plain places the stratigraphically superior marker A4 at a comparable *elevation* to C4 (Fig. 4). The observations of Gathogo and Brown (2006) can only be replicated by: a) moving up section through the dipping strata to the level stratigraphically higher though at a comparable elevation, or b) crossing the fault where the marker strata are brought into juxtaposition. Nowhere these two beds have been examined in Area 123 does the character of either marker change in the way described by Gathogo and Brown (2006). The second component of Gathogo and Brown's (2006) argument is clearly based on an error of observation in the field, and there is no basis for their revised correlation of markers in Area 123.

A second, and even more persuasive, argument can be found in an additional test of the Gathogo and Brown (2006) correlation (Fig. 5). This test is based on an independent data source, magnetic polarity characteristics. Gathogo and Brown (2006) argued that the stratum mapped as unit C4 in Area 123, and which crucially lies 11 m above KNM-ER 1813 and many of the other hominins (Feibel et al., 1989), is in fact the marker A4. In the type section of the Koobi Fora Formation, work by Hillhouse et al. (1986) and subsequent more detailed examination (Feibel, unpublished) places the magnetostratigraphic transition from normal polarity to reversed polarity, attributed to the top of the Olduvai Subchron (1.78 Ma) shortly above the marker C4. Thus, C4 and subjacent strata are of normal polarity, while strata higher in the sequence, including marker A4, reflect a reversed magnetic polarity. The assertion of Gathogo and Brown (2006) would require that the levels in question, and the strata producing the hominin fossils (e.g., KNM-ER 1813 placed by them at 1.65 Ma) must be of reversed polarity. We collected samples throughout the sequence in Area 123 (Fig. 5 and Appendix 1) and they unequivocally demonstrate that the stratigraphic interval including the unit mapped as C4 in Area 123, along

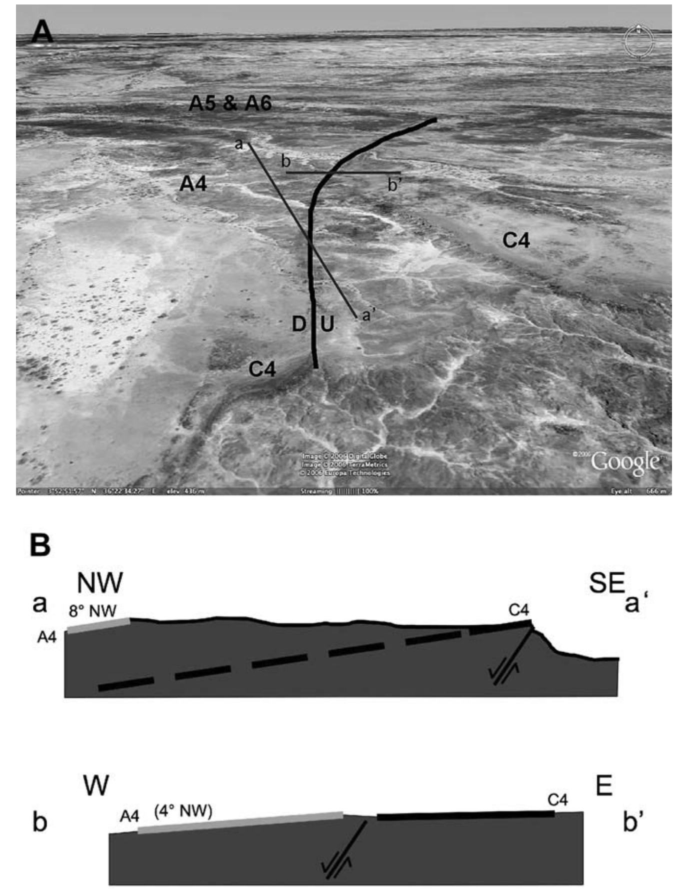

Figure 4. A: Oblique aerial view of fault offsetting the marker C4, and B: diagrammatic representation of stratigraphic relationships between the marker C4 and the marker A4 in north-central Area 123 (approximate location point 176, Table 1). Aerial view captured from Google Earth.

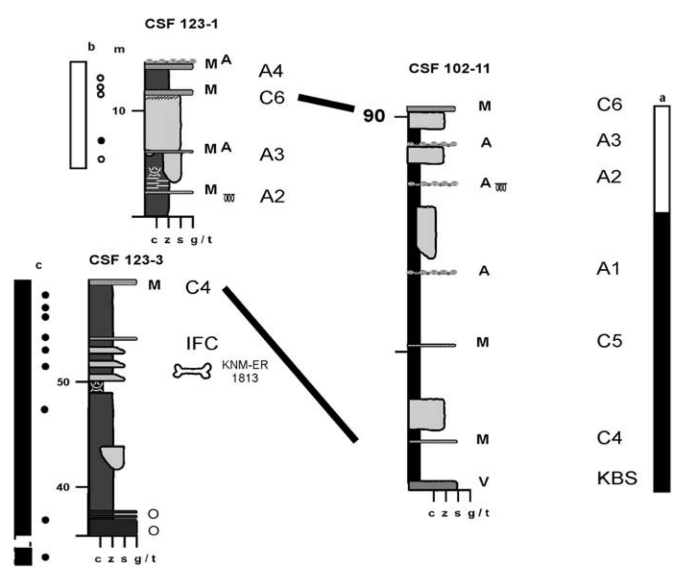

Figure 5. Interpreted magnetic polarity stratigraphic results from samples collected in Area 123, correlated with established magnetic polarity stratigraphy of the type section (lithologies simplified). For key to stratigraphic symbols see Fig. 3. Magnetic polarity symbols for individual samples and columns: black = normal, open = reversed. a: magnetic polarity stratigraphy of type section (Area 102) from Hillhouse et al. (1986); b: sampling and interpretation of Il Allia Cliff Section (CSF 123-1); c: sampling and interpretation of Elephant House Section (CSF 123-2/3).

with KNM-ER 1813 and related fossils, are all within the normal polarity magnetozone attributed to the Olduvai Subchron. The interval surrounding unit A4 and strata higher in the section are of reversed polarity as expected. The Gathogo and Brown (2006) assertion fails this test as well.

The final aspect of the Gathogo and Brown (2006) argument, the placement of the Lower Ileret Tuff at the top of the Area 123 sequence, is something of a moot point at this stage, but it also turns out to be untestable. No locality information was given for the tuff, the section within which it occurs (Gathogo and Brown, 2006: Fig. 2, the unnumbered section) is not marked on the location map, and the section which ties it to the subjacent strata (PNG 123.2) is drawn across a mapped fault (but see concerns above). The tephra sampled by M. G. Leakey (sample MGL04-1) does appear to be similar in composition to the Lower Ileret Tuff. This can be confirmed by an independent laboratory, now that location data has been provided by M. G. Leakey (pers. comm.; location point MGL 1, Table 1). If confirmed, it will provide some constraints on the Area 123 sequence, but there is one further problem with its association. Occurring as it does at the very top of the local section, and as indicated within a channel (on an erosional surface), it is unclear whether this tuff is *in* or *on* the sequence. Were it a much younger tephra, such as the Chari Tuff (1.38 Ma) or the Silbo Tuff (0.75 Ma), either of which could plausibly occur on the top of this section, stratigraphic scaling to this capping age would not yield meaningful information (beyond a minimum possible age). The regional stratigraphic composite (Fig. 3) illustrates that the tephra in nearby Area 119, which bracket the Lower Ileret Tuff in the tephrosequence (Brown et al., 2006), occur at a stratigraphically higher position. This suggests that there may be significant downcutting (on the order of 15 m) associated with the channel tephra identified as the Lower Ileret Tuff in Area 123. In this case, the tephra would not necessarily provide an appropriate tie point for the age model. A capping age establishes a minimum limit for subjacent strata, but to be useful in scaling (establishing an age model) it must be in continuity with the sequence beneath.

Age modeling and age estimates for the hominin fossils

Linear stratigraphic scaling (age modeling) is a useful exercise when the geological context of a sequence is well understood. However, breaks in the sequence (e.g., disconformities) or inflections in accumulation rates may render such approaches problematic. In general, scaling over long, relatively continuous intervals yields fairly consistent results, while scaling through shorter and more frequently interrupted sequences compromises the method. The methodology works quite well in many marine sequences, for example, while terrestrial sequences are commonly more difficult to approach. In the case of the sequence in the Bura Hasuma region, a central geologic observation is that the stratigraphy is composed of three lithologic intervals: 1) a basal lacustrine sequence with little or no evidence for emergence (inundated; no paleosols), 2) a middle interval characterized by facies indicative of a fluctuating lake margin (alternating inundation and exposure including

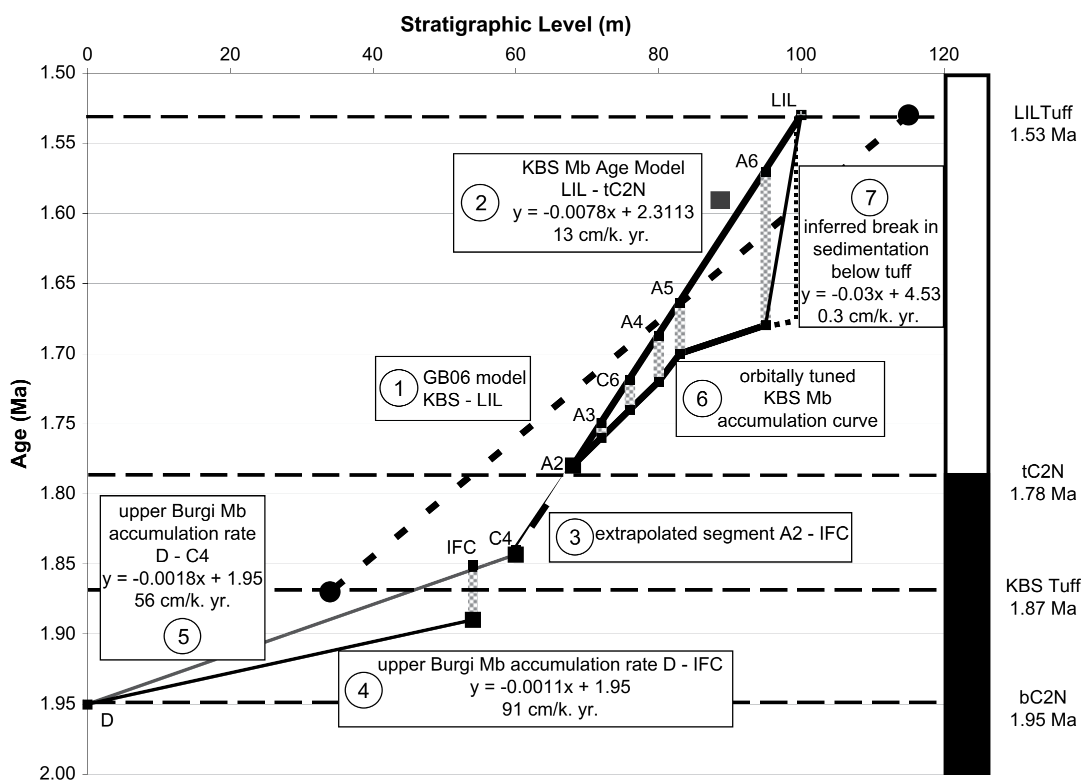

Figure 6. Age models for strata in Area 123. 1: invalid linear model from KBS Tuff to Lower Ileret Tuff of Gathogo and Brown (2006) (see text for inadequacies of this interpretation). 2: simple linear model based on two control points, the Lower Ileret Tuff (LIL, 1.53 Ma) and the top of the Olduvai Subchron (tC2N, 1.78 Ma). 3: extrapolated interval to project possible ages for C4 and IFC in Area 123. 4: inferred accumulation pattern for lacustrine strata of the upper Burgi Member, based on extrapolated age for marker IFC and base of sequence coinciding with base of Olduvai Subchron. 5: variant of segment 4 based on assumption of linear accumulation rate from base of section to C4. Note that the difference in placement of the inflection point affects relationships of fossils below IFC relative to the age of the KBS Tuff. Hachured vertical line at stratigraphic position of IFC indicates range of possible ages for this marker between these models. 6: orbitally-tuned KBS Member accumulation curve, based on data in Lepre et al. (2007). This curve is probably more realistic, and diverges significantly from the linear model in successively younger levels (hachured bars indicate possible ages for key stratigraphic markers). 7: possible resolution to the divergence of linear and orbitally-tuned models, based on observed stratigraphic patterns, which invokes one or more significant breaks in sedimentation (vertical dotted lines) to account for the temporal/stratigraphic offset. These breaks would reflect potential erosion surfaces indicated by dashed lined in Fig. 3.

paleosols), and 3) an interval of capping strata that are predominantly fluvial in nature (largely subaerial, with significant erosional surfaces). Basic geological understanding posits that scaling should be reasonably reliable in the lower interval. An inflection point might be expected in the transition to the second interval, where scaling would be less precise. The upper part of the sequence might well be problematic, with a combination of low accumulation rates, hiatuses, and erosional clipping of the sequence. We will employ a geological understanding of the Bura Hasuma region to construct age models for the strata there (Fig. 6), and take the example of the fossil KNM-ER 1813 to relate these geological hypotheses to the fossil record. For other individual hominin specimens (Fig. 7), their stratigraphic context relative to marker beds (Feibel et al., 1989) can be related to the model accumulation curves, and relevant age estimates derived from there. Given the uncertainties in the possible age models for Area 123 we do not provide a table of scaled ages for these fossils.

We can construct an age model for the Area 123 sequence, beginning with two control points: the magnetic polarity transition at the top of the Olduvai Subchron (1.78 Ma) and the newly recognized Lower Ileret Tuff (1.53 Ma). The top of the Olduvai Subchron has been identified between markers C4 and A2 in Area 102 (Hillhouse et al., 1986), and our recent sampling in Area 123 is consistent with this placement. The precise stratigraphic relation of the Lower Ileret Tuff is slightly problematic at this point, but we can take the Gathogo and Brown (2006) section as a starting point. We can also tie the base of the Area 123 sequence to the base of the Olduvai Subchron (1.95 Ma) for purposes of argument. It can be shown that precision of this point does not materially affect the results here. The resulting age model for Area 123 (Fig. 6) provides some limits on the possible and probable ages of strata and associated fossils.

The two known age points (Lower Ileret Tuff [LIL], 1.53 Ma; top of the Olduvai Subchron [tC2N], 1.78 Ma) establish a model for age relationships within the upper KBS/lower Okote members in Area 123. That model line can be extrapolated back to the stratigraphic position of marker C4. The extrapolated age, 1.84 Ma, matches interpolated ages based on the type section in Area 102, and further supports the identification of this marker bed in Area 123.

Handling the sequence below the marker C4 illustrates some of the potentials and pitfalls of stratigraphic scaling. The base of the section is given a maximum age of 1.95 Ma, using the earliest estimate for the onset of upper Burgi Member deposition following the magnetic polarity studies of Hillhouse et al. (1986). The change of slope between the base of the section and the trends of the KBS Member demonstrates that a significant shift in accumulation rates occurred close to the upper Burgi/KBS member boundary. The exact

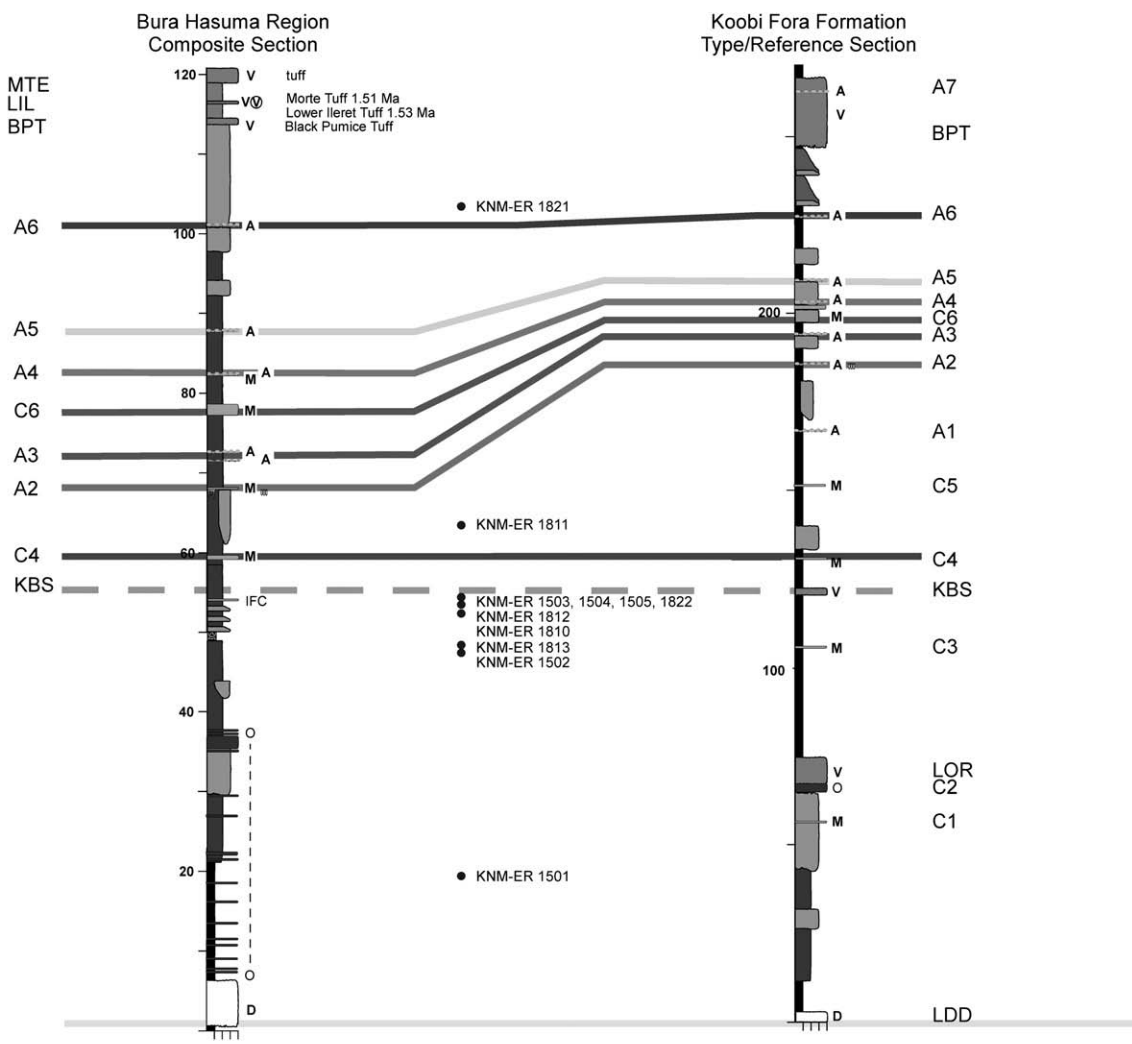

Figure 7. Composite stratigraphic column for the Bura Hasuma region (based on sections from Areas 123, 107, and 119), correlations to the type/reference sections of the upper Burgi, KBS, and lower Okote members along the Koobi Fora Ridge, and stratigraphic placement of the Area 123 hominin specimens.

Table 2
Sampling data for magnetic polarity study.

Sample	Stratigraphic position	Location	Results
0237	0.7 m below A4	Area 123, Cliff along Il Allia	reversed
0235	1.7 m below A4	Area 123, Cliff along Il Allia	reversed
0236	1.7 m below A4	Area 123, Cliff along Il Allia	reversed
0242	1.2 m above A3	Area 123, Cliff along Il Allia	normal
0240	0.6 m below A3	Area 123, Cliff along Il Allia	reversed
123-USX	2.5 m below C4	Area 123, Elephant House	normal
123-3A	4 m below C4	Area 123, Elephant House	normal
123-3B	4.5 m below C4	Area 123, Elephant House	normal
123-IFC	5 m below C4	Area 123, Elephant House	normal
0252	1 m below IFC	Area 123, Elephant House	normal
123-7A	8 m below C4	Area 123, Elephant House	normal
0255	12 m below IFC	Area 123, Elephant House	normal
0244	25 m below C4	Area 123, Elephant House	normal
0200	50 m below C4	Area 123, Elephant House	normal

placement of this inflection point has significant ramifications for the results of age modeling. In the region of Area 123 from which KNM-ER 1813 and many associated fossils were recovered, this stratigraphic interval is transitional in some ways, but has its closest affinities with the lake margin depositional package. If the linear model established by the Lower Ileret Tuff and the top of the Olduvai Subchron is extrapolated below C4, it projects an age of 1.89 Ma for the IFC, and thus forces KNM-ER 1813 well below the KBS Tuff level. If we break the KBS Member linear trend at C4, a linear model from C4 to the base of the section (Fig. 6D, indicating the basal diatomite) places the IFC at 1.85 Ma, which allows the possibility of KNM-ER 1813 to fall stratigraphically above the KBS Tuff. Lithologic considerations presented below support the older age assignment, but the younger option cannot be excluded.

The character of the sedimentary sequence associated with the IFC has its closest similarities with the sequence beneath the KBS Tuff along the Karari Escarpment. In particular, the distinctive orange carbonate nodules find their closest counterparts in two markers there, the Gold Pebble Conglomerate (GPC) and the Limonite Chunk Conglomerate (LCC) (Isaac and Behrensmeyer, 1997). These are a characteristic lithologic feature of the sub-KBS interval on the Karari, and are nowhere else so prominently expressed. However, these lithologies are a facies record of a particular depositional/post-depositional phenomenon, and are not necessarily unique to this level. Accepting the sedimentologic argument for the sequence associated with the IFC in Area 123, details of that marker itself suggest that this interval most likely falls below the KBS Tuff, and would then imply an age of >1.87 Ma for subjacent fossils such as KNM-ER 1813. If the extrapolated age model estimate for the IFC is utilized, the implication would be an age of >1.89 Ma.

In sum, the *possible* age range for KNM-ER 1813 is best constrained by the Olduvai Subchron, that is, within the interval 1.95–1.78 Ma. On this basis, an age estimate of 1.86 ± 0.08 Ma is the most precise estimate possible based on age constraints within Area 123. Lithostratigraphic arguments combined with cyclostratigraphy (Lepre et al., 2007) and age models presented here all support identification of the prominent bioclastic marker overlying the hominin level with marker C4, for which an age of 1.84 Ma has been derived. KNM-ER 1813 was recovered from some 11 m below this marker, and thus the fossil would predate 1.84 Ma on these grounds. Further lithostratigraphic arguments and age modeling suggest an age of 1.89 Ma may be appropriate for the IFC, which overlies KNM-ER 1813 and many associated fossils. The suggestion of ages greater than 1.84 Ma, or slightly greater than 1.89 Ma, are compatible with all available geological observations, but should only be considered as working hypotheses. Testing these hypotheses will require the application on new techniques to help quantify and bolster the data on hand.

Conclusions

The stratigraphic sequence preserved in Area 123 at Koobi Fora is well constrained by large-scale depositional patterning, and a detailed framework has been established utilizing a variety of stratigraphic tools. As with much of the Bura Hasuma region, the most useful stratigraphic markers in Area 123 are the highly resistant and mappable bioclastic carbonates and sandstones. Magnetic polarity stratigraphy provides important constraints on possible (or impossible) correlations, and the top of the Olduvai Subchron (tC2N) provides a significant time line at 1.78 Ma in the sequence. A single tephra, the Lower Ileret Tuff (1.53 Ma), has been identified in the area, and establishes some control on minimum age of the Plio-Pleistocene sequence there. The overall pattern of depositional character, shaped by paleogeographic evolution through time, can only be understood in the context of the geology of the surrounding region. Indeed, the clearest support for the established stratigraphic framework applicable to Area 123 is expressed in exposures of the surrounding areas.

Given the foregoing demonstration, the ages proposed by Gathogo and Brown (2006) for the Area 123 hominins, as well as the other specimens included in their canvas, are too young. Previously proposed age estimates (Feibel et al., 1989) do require relatively minor refinements based on published chronostratigraphic advances. Improved isotopic age determinations (McDougall and Brown, 2006) have refined the KBS Tuff age estimate from 1.88 Ma to 1.87 Ma. The estimate for the age of the base of the Olduvai Subchron is now 1.95 Ma (e.g., Horng et al., 2002), rather than the 1.91 Ma estimate used by Feibel et al. (1989). Similarly, the top of the Olduvai Subchron is now placed at 1.78 Ma, rather than the 1.76 Ma estimate employed in 1989. The impact of these refinements is typically on the order of 10^4 y, well within the standard error estimate of ±0.05 Ma employed in the original synthesis (Feibel et al., 1989). Given the normal polarity of the magnetozone from which KNM-ER 1813 and associated fossils were recovered (identified as the Olduvai Subchron), the best defensible age estimate for these fossils would be 1.86 ± 0.08 Ma. Stratigraphic analysis of the Area 123 sequence suggests that an age of 1.89 Ma may be possible, but this awaits confirmation.

By investigating the stratigraphic framework of Area 123 *within* the context of detailed geological mapping, lithostratigraphic sections, correlations, depositional history, and by using multiple stratigraphic tools, all on the regional scale, we hope to establish a sound and testable basis for estimating ages of fossils from this important part of the Koobi Fora record. The stratigraphic documentation presented here, in conjunction with an understanding of the possibilities and limitations of the sedimentary record, allow reasonable constraints to be placed on the ages of significant fossils, such as KNM-ER 1813, for which the region is so famous.

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Appendix 1. Magnetic polarity methods and results

Sampling procedures

In 2006, we sampled sections in Area 123 for paleomagnetic study. Sampled localities included outcrops adjacent to the elephant house (section CSF 123-2/3) and exposures at the Il Allia cliff section (section CSF 123-1). These localities are separated by approximately 4 km. The sample intervals encompassed ~10 m of section below the C4 marker bed at the elephant house, and ~5 m of section through the A2, A3, C6, and A4 marker beds at the Il Allia cliff section. Additionally, three levels from the elephant house at about 20 m, 25 m, and 50 m below the C4 bed were also sampled (Table 2).

We collected from well-consolidated siltstones and claystone, and avoided sandy and friable beds, as it has been demonstrated that the latter do not provide reliable paleomagnetic results (e.g., Brock and Isaac, 1974; Hillhouse et al., 1977). Sampling sites were preferentially selected at freshly eroded and steeply sided slopes. When such exposure was not available, about 1 m of outcrop was removed to obtain un-weathered material. At each site, samples were cut using stainless-steel tools. *In-situ* coordinates were recorded with a compass and clinometer prior to extraction of the samples. A total of 16 sites, yielding one sample each, were obtained. The samples were wrapped in aluminum foil and plastic, and shipped to Rutgers University (U.S.A.) where they were stored in the shielded room of the Geology Department for about six weeks. The samples were then cut into standard ~11 cm^3 specimens with an electric bandsaw fixed with a non-magnetic blade. Obtained from each sample were two to five specimens.

Laboratory methods

We conducted analyses in the shielded room at the Paleomagnetic Laboratory of Lamont-Doherty Earth Observatory (Columbia University, U.S.A.). Remanent magnetization measurements were done with the lab's 2G Enterprises three-axes cryogenic (SQUID) magnetometer, with noise levels well below the magnetic intensity of the specimens. Four approaches were used to demagnetize the specimens. The first approach was with the alternating field (AF) method, consisting of eight AF steps to a terminal step of 40 mT. The second included 16 AF steps to a terminal step of 80 mT. Increments of 5 mT were used in both instances. The third approach was a hybrid AF and thermal demagnetization (TD) approach, using two AF steps at 5 mT and 10 mT, followed by eight TD steps at 50 °C (150°–500 °C), and three steps at 25 °C (525°–575 °C). For the fourth approach, one specimen from each sample was treated to only TD. This involved an initial step of 100 °C, eight TD steps at 50 °C (150°–500 °C), and three steps at 25 °C (525°–575 °C), for a total of 12 TD steps up to a terminal step of 575 °C.

Orthogonal plots were used to compare the magnetic direction and intensity results from the AF and TD experiments (e.g., Zijderveld, 1967). Stable vectors and component end points on these plots were chosen by eye. A mean characteristic remanent magnetization direction was determined with principal components analysis (PCA). This involved fitting vector data with a least-square line tied to the orthogonal plot origin (Kirschvink, 1980). Calculations of means directions also involved standard Fisher statistics (e.g., Fisher, 1953). Quality of results was examined with the reversal test (McFadden and Lowes, 1981). Thermal unblocking characteristics were used to suggest ferromagnetic composition and to interpret the mineral phases that carried the magnetic components of the specimens. We also conducted isothermal remanent magnetizations (IRM) experiments in direct fields, up to 1000 mT, to infer the magnetic mineral content of the specimens.

Results

The natural remanent magnetization (NRM) directions were mostly dominated by a component of magnetization along the present-day field (normal, 10 samples), while four samples displayed polarities with as strong reversed component (Fig. S1). Most of the analyzed specimens display orthogonal projection plots of typical normal behaviors upon demagnetization. For samples with indications of reversed polarity, such as 0237a and 0237b, declinations are south and inclinations are shallow but either down or up. Specimen 0237a, after AF treatments to 80 mT, had a reversed magnetization. Although the decay behavior is not linear, we suggest the specimen is dominated by magnetic components with reversed directions. This is confirmed by TD treatments to the sister specimen 0237b, which revealed a reversed component from NRM to 200 °C, and another reversed component that shows a linear decay to the plot origin from 250 °C to the terminal TD step of 575 °C. The results of AF demagnetization for specimen 0240a suggested a normal component from NRM to 20 mT and a reversed component from 25 mT to 40 mT. A hybrid AF-TD approach for its sister specimen 0240b yielded three components: a normal component was removed by AF steps 5 mT and 10 mT; a reversed component was unblocked by TD steps 150 °C and 200 °C; and a reversed component with a linear decay to the plot origin was unblocked by TD steps in the range of 250°–575 °C. Separate AF and TD applications to the four specimens from samples 123-USX and 123-3B revealed very similar results. These samples exclusively have components of magnetism with northern declinations and shallow inclinations.

We interpret that the blocking temperature for the modern-field component was generally 100 °C, and the TD temperatures above 100°–250 °C isolated the characteristic magnetizations, as suggested by the orthogonal plots and demagnetization curves. The blocking temperature of the characteristic component is above 500 °C. The observations of (1) a low coercivity at temperatures >500 °C, and (2) maximum blocking temperatures at ~575 °C suggest that the characteristic component is carried by magnetite and is therefore likely to be a primary remanent component. The IRM results also indicate magnetite as the primary carrier of the characteristic magnetism, as the curves all show sharp increases in IRM intensity at applied field below the range of 100–200 mT, a common characteristic of Koobi Fora Formation sediments bearing minerals in the ulvospinel-magnetite solution series (Hillhouse et al., 1986).

The Fisher mean direction of the normal specimens (declination of 3.9°, inclination of −2.6°, α_{95} of 7.6°, k of 41.05, and n of 10) is antipodal to the Fisher mean of the reversed specimens (declination of 183.2°, inclination of −2.7°, α_{95} of 12.3°, k of 30.84, and n of 6). These means also pass the reversal test (McFadden and Lowes, 1981) at a grade of Rb (McFadden and McElhinny, 1990), with an observed gamma of 5.35 less than a critical gamma of 12.81. Based on the difference between these mean remanent directions and the orientation of the modern field, in addition to this positive result of the reversal test, it is considered that the interpreted polarity of specimens listed in Table 2 are indeed indicative of the earth's magnetic field at or near the time of deposition for the sediments.

Appendix. Supplementary data

Supplementary data associated with this article can be found in online version at doi:10.1016/j.jhevol.2009.05.007.

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