Crevasse-splay and associated depositional environments of the hominin-bearing lower Okote Member, Koobi Fora Formation (Plio-Pleistocene), Kenya

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ABSTRACT

The Okote Member from the northeast Turkana Basin of Kenya represents an exceptionally good archive of Early Pleistocene archaeological and fossil sites. Field study of the lower Okote Member and underlying deposits was conducted in detail at two sets of outcrops (500 to 1000 m long) separated by some 22 km of modern landscape. The examined sections (10 to 15 m thick) preserve two facies: interbedded sandstones, tuffs and mudstones (crevasse splay) and ribbon-like bodies of sandstone/tuff (crevasse channel). Mudstones are overprinted with small carbonate nodules and sparse slickensides that are interpreted as evidence of weak soil development after the cessation of suspension deposition in a floodplain. The immaturity of the ancient soils implies that sediment accumulation was fairly rapid, yet the nodules and slickensides indicate seasonal contrasts in moisture. Episodically rapid sedimentation is suggested by the types of depositional environments and their structures, and indications of soft-sediment deformation. Crevassing may have been influenced by rivers that flooded in response to monsoonal rainfall variations and the voluminous influx of fluviolacustrine reworked volcanioclastics to the basin. A well-developed palaeosol directly underlying the lower Okote Member suggests that the deposits accumulated following a significant depositional hiatus. This basal contact, in addition to the apparent pervasiveness and penecontemporaneity of the sedimentary facies, resembles a crevasse-splay system deposited by a sub-delta lobe or river avulsion. A paucity of lacustrine/deltaic indicators might indicate that the studied deposits correspond better with an avulsion origin. Sedimentation rates calculated from prior radiometric dating of tuffs tend to overestimate the timeframe of accumulation for individual strata of the lower Okote Member. Many appear to have formed on the order of $10^6$ to $10^7$ years, as suggested by facies, palaeosols and observations of modern crevasse splays. This cautions against using sedimentation rates alone to infer how much time a stratum preserving fossil/archaeological information represents.

INTRODUCTION

The Okote Member (ca 1.6 to 1.4 Ma) of the Plio-Pleistocene Koobi Fora Formation crops out in the northeast part of the Turkana Basin, in northwest Kenya (Fig. 1). It is an important sedimentary unit for studying early hominin evolution, preserving a plentiful and diverse record that includes fossils of at least three hominin species and two genera (Wood, 1991), cut-marked fossil bones indicative of hominins butchering mammals for food (Bunn, 1981), stone tools (Rogers et al., 1994), and animal track ways that include hominin footprints (Laporte & Behrensmeyer, 1980). Such a diverse combination of evidence rarely—if ever—has been reported from other Early Pleistocene sites in Africa or elsewhere (Klein, 2009). However, while there have been several geological (Brown & Feibel, 1985; Brown et al., 2006; Gathogo & Brown, 2006; McDougall & Brown, 2006) and
palaeoanthropological (Spoor et al., 2007; Braun et al., 2008; Pobiner et al., 2008; Bennett et al., 2009) studies on the Okote Member, few studies have attempted to explain why this unit’s hominin record appears to be so different from other localities. For example, some sites preserve footprints or cut-marked bones, and others have hominin fossils and stone tools (Leakey, 1971; Leakey & Harris, 1987), yet the Okote Member has all of these. As a step towards addressing the comprehensive nature of this record, the paper presented here reports new geological data from Okote Member strata cropping out along the Karari Escarpment and near the town of Ilseret (Fig. 2). New stratigraphic correlations between the two Okote Member localities are established (Fig. 3), in addition to interpretations for the depositional environments. Both sets of observations aid in understanding the context in which the hominin record was formed and preserved.

The stratigraphy and sedimentology of the Koobi Fora Formation have been studied for decades, which have led to revisions and in some cases contrasting interpretations of the depositional environments for the members. Prior work has tended to emphasize either a site-specific approach (Kaufulu, 1987; Isaac & Behrensmeyer, 1997; Bennett et al., 2009), which provides contextual details for a certain fossil/archaeological site, or a basin-wide approach (Brown & Feibel, 1991; Rogers et al., 1994; Feibel, 2013), which synthesizes a variety of outcrop data in order to generate idealized palaeoecographic models for large temporal/spatial scales. This study attempts to find a middle ground between these two scales by examining Okote Member outcrops of roughly the same dimensions (500 to 1000 km long by 10 to 15 m thick) and of a comparable chronostratigraphic interval, but separated by 20 to 25 km across the modern landscape.

A need to compare the different localities with Okote Member outcrops has been underscored by Behrensmeyer et al.’s (2015) recent review of the several different, and seemingly incompatible in some instances, palaeoecographic reconstructions of the member. Behrensmeyer et al.’s (2015) observations come at a time when the Okote Member’s footprints are being interpreted as indicative of ‘intensive use of lake-margin habitats by Homo erectus groups’ (Roach et al., 2016). This is a fairly novel supposition, as definitive evidence of hominin group behaviour in a lake-margin setting is rare. However, other studies have argued that the Okote Member deposits were accumulated by fluvial environments (Rogers et al., 1994). Similarly, Quinn et al. (2007) intimated that many outcrops of this member preserve evidence of fluvial floodplain aggradation. Additional work has suggested that the outcrops show indications of both fluvial and lacustrine conditions (Isaac & Behrensmeyer, 1997; Gathogo & Brown, 2006). What is not clear with these reconstructions is whether they represent mutually exclusive interpretations, or if the palaeolandsapes of the Okote Member had high temporal and spatial variability (Feibel et al., 1991). Refining these interpretations is not only key for addressing this possibility but also for further understanding the depositional environments in which the Okote Member’s hominin record was formed and preserved. Further sedimentological and stratigraphic study of the member will help to provide additional palaeoenvironmental constraints on the evolutionary data being gleaned from the H. erectus footprints (Bennett et al., 2016a; Hatala et al., 2016; Roach et al., 2016) and comparisons with hominin footprints from elsewhere in eastern Africa (Bennett et al., 2016b; Liutkus-Pierce et al., 2016; Masao et al., 2016). The new data presented here argue that a number of the Okote Member’s hominin-bearing strata are best interpreted as the products of crevasse-splay and crevasse-channel sedimentation (Table 1).

Hitherto, there have only been cursory reports of such depositional environments within this member. These new data not only argue for fluvial floodplains being an important palaeoenvironmental component of the Okote Member, but also bring attention to how the processes of crevasse splays and channels may have contributed to the preservation of the member’s exceptional archaeological and fossil record. Crevasse-splay deposition, in particular, appears to have the potential for unusually good preservation of vertebrate fossil assemblages (Coram et al., 2017).

Firstly, discussed in this article are new stratigraphic interpretations of the two Okote Member localities (Fig. 3). These interpretations are based on palaeoenvironmental and lithological field observations, supplemented with chronostratigraphic data reported by other researchers. Secondly, two depositional environments are interpreted from the description of facies and associated palaeosols. Thirdly, these new data are used to discuss the amount of time represented by the deposits, a palaeolandscape depositional model, and the possible controls on sediment accumulation. These new lines of evidence refine the palaeoenvironmental context of the Okote Member’s hominins remains.

**Geological background**

The Turkana Basin of northwest Kenya is a series of half-graben sedimentary basins that are part of the eastern branch of the East African Rift System (Ebinger et al., 2000). The basin has been rifting and filling with sediment episodically since the Oligocene (Brown & McDougall, 2011). Sedimentary outcrops at Ilseret and the Karari Escarpment are prominent features of the landscape in the northeast part of the basin, east of the shoreline of modern Lake Turkana (Figs 1 and 2). The northeast basin is
Fig. 1. Map of the study area showing outcrop extent of the Koobi Fora Formation within the northeast Turkana Basin of northwest Kenya (see location map at lower left). Map is after Vondra & Bowen (1978); White et al. (1981); Brown & Feibel (1986); Gathogo & Brown (2006). Red square at upper right and red triangle at top, respectively, indicate the study areas along the Karari Escarpment (Fig. 2A) and near the town of Ileret (Fig. 2B).
Fig. 2. (A) Map of studied outcrops along the Karari Escarpment modified from Frank (1976). (B) Map of studied outcrops near Ileret. Base map from Google Earth Pro. Symbols as for Fig. 2A.
Fig. 3. Correlation of idealized stratigraphic sections for the studied Early Pleistocene sediments of the Karari Escarpment and Ileret. Lithostratigraphy and placement of archaeological and fossils sites after Frank (1976); Brown et al. (2006); Pobiner et al. (2008); Bennett et al. (2009); this study. Dates of tuffaceous marker horizons from McDougall & Brown (2006) and Mana et al. (2016). Woody cover interpretations are based on the stable isotopic composition of palaeosol carbonates interpreted by Quinn et al. (2007), and applying the method of Cerling et al. (2011) to the Quinn et al. (2007) data. Quinn et al. (2007) collected carbonates from immature palaeosols (see ‘dite’ palaeosol of Wynn, 2000); thus, the stratigraphic distribution of data points approximates the distribution of immature palaeosols in the examined strata of the lower Okote Member.
Table 1. Aspects of the sedimentary facies and their inferred depositional environment

| Facies                  | Description                                                                 | Interpretation                                                                 |
|-------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Crevasse splay          | Multiple, vertically successive, fining-upward sequences comprising decimetre thick, sheet-like to lens-like units that laterally pinch-out, terminate at wedge-shaped margins, or diffusely grade into adjacent strata. Sandstone and tuff units are commonly massive but may preserve cross beds, wavy to parallel laminations and ripples. Mudstones locally show soft-sediment deformation structures, small carbonate nodules and few slickensided fractures. | Simple lobes with wedge-shaped cross-sections that form solitary stage 1 crevasse splay; sandy levee deposits; sheet floods; weak soil formation after secession of flooding and fine-grained suspension sedimentation (Smith et al., 1988; Willis & Behrensmeier, 1994; Bristow et al., 1999; Kraus & Wells, 1999; Perez-Arlucea & Smith, 1999; Farrell, 2001; van Toorenenburg et al., 2016; Burns et al., 2017; Gulliford et al., 2017). |
| Interbedded sandstone,  | Concave-up, lenticular units surrounded by crevasse-splay sandstones, tuffs and mudstones. Maximum thickness ca 3 m. Erosive lower and lateral contacts. Fining upward into mudstone, with upper contact being sharp, diffuse or showing ‘wings’ that extend laterally. Thinly to thickly bedded. Commonly massive or cross-bedded. Calcic root traces occur near upper margins. | Floodplain channels in close proximity to main fluvial channel; flood breach of the fluvial channel; scour-and-fill deposition by short-lived, turbulent and confined flows (Miall, 1996; Bristow et al., 1999; Kraus & Wells, 1999; Perez-Arlucea & Smith, 1999; Farrell, 2001; van Toorenenburg et al., 2016; Burns et al., 2017) |
| tuff and mudstones      |                                                                             |                                                                                 |
| Crevasse channel        |                                                                             |                                                                                 |
| Ribbon-like bodies of   |                                                                             |                                                                                 |
| sandstone or tuff       |                                                                             |                                                                                 |

rimmed at its eastern margin by rift-related volcanic rocks (basalts) probably uplifted sometime after ca 1 Ma. To the north, the modern Lake Turkana Basin spays out into the broadly defined zone of rifting that connects the Main Ethiopian Rift to the Kenyan Rift ( Ebinger et al., 2000).

For most of the Plio-Pleistocene, the basin alternated between being dominated by a fluvial or a lacustrine depositional system (Brown & Feibel, 1991). Volcano-tec tonic events led to the formation of a deep lake at about 2.14 Ma that occupied most of the basin’s axis for approximately the next half million years (Lepre, 2014). By ca 1.87 Ma, the lake shallowed and underwent a series of oscillations in water level, culminating at ca 1.78 Ma with restricted circulation and the development of a limited biotic community centred on algal biolithites (Brown & Feibel, 1991; Lepre et al., 2007; Lepre & Kent, 2010). Fluvial conditions resumed dominance in the basin by ca 1.4 Ma (Brown & Feibel, 1991; McDougall & Brown, 2006; Gathogo & Brown, 2006).

The type section of the Okote Member is exposed at the Karari Escarpment and has a thickness of 20 to 25 m (Brown & Feibel, 1986). However, correlating other Okote Member sections to the type locality has proved difficult because of high lithological variability in this member, rapid lateral facies changes, the dissected nature of the northeast Turkana Basin’s outcrops, and few pervasive chronostratigraphic markers (see Lepre & Kent, 2015 for a review of the issues with interpreting the chronostratigraphy and the physical definition of the Okote Member). Regarding this last difficulty, the tuff that defines the base of the member (i.e., the Okote Tuff) seldom crops out in the basin, making it complicated to identify basal Okote Member strata in some study areas (see discussion by Brown et al., 2006). Furthermore, the Okote Tuff itself has not been directly dated, but is inferred to have been deposited at 1.56 ± 0.05 Ma (McDougall & Brown, 2006). The top of the Okote Member is defined formally by the Chari Tuff, which is more commonly found throughout outcrops of the Turkana Basin (Brown et al., 2006). The Chari Tuff is securely dated by direct radiometric analyses to 1.38 ± 0.03 Ma (McDougall & Brown, 2006). Thus, the Okote Member represents nearly 170 kyr of sediment accumulation.

What is now defined as the Okote Member (Brown & Feibel, 1986) has been referred to by several informal names, such as the Okote tuffaceous siltstone complex or Okote tuff complex (Cerling & Brown, 1982; Brown & Feibel, 1985), which denote the many stratigraphic levels preserving fluvially reworked, rhyolitic ash beds. Systematic facies analyses formally introduced the term interbedded sandstone and tuffaceous siltstone facies to describe strata that eventually were folded into the Okote Member (Burggraf et al., 1981). However, most of this facies definition was derived from observations taken from outcrops along the Karari Escarpment. Other workers reported many similarities between the Okote Member strata from Ilaret and the Karari Escarpment (Findlater, 1978; Vondra & Bowen, 1978). An exception to this was that some research suggested the presence of lacustrine and deltaic environments at Ilaret during Okote Member times (Isaac & Behrensmeier, 1997; Gathogo & Brown, 2006). Such environments have yet to be observed from Okote outcrops within the Karari Escarpment. Poor stratigraphic control complicates correlations between the facies of the two localities; but the age control has now been much improved (Brown et al., 2006; McDougall & Brown, 2006) and allows for more
direct comparisons between the Karari and Ileret outcrops (Fig. 3). This has revealed that the Okote Member is almost twice as thick at Ileret, with the lower ca 20 m resembling the facies of the Karari section, yet the upper part almost entirely lacks tuffaceous strata (Gathogo & Brown, 2006). The lower Okote Member of Ileret has yielded an abundance of mammalian fossils, including hominins (Spoor et al., 2007), whereas the upper part has more fossil fish nests and bivalve moulds in life positions—both of which have conventionally been interpreted as lake-margin indicators (Gathogo & Brown, 2006).

Ribbons and sheet sandstones, tuffs and mudstone strata are common aspects of the Okote Member from the Karari Escarpment and the lower Okote Member from Ileret (Burggraf et al., 1981; Isaac & Behrensmeyer, 1997; Gathogo & Brown, 2006). Gravelly strata and large channel sandstone complexes comprise a smaller portion of the overall stratigraphy. At the Karari Escarpment, mudstones have been observed to preserve slickensides, carbonate nodules and granular ped structures indicative of palaeosols (Wynn, 1998; Quinn et al., 2007). Sub-aerial indications are also noted from Ileret, but these tend to be animal footprints (Bennett et al., 2009) and pedogenic carbonate nodules (Quinn et al., 2007). Ribbon sandstones and tuffs from the Karari Escarpment commonly show wings along their upper margins (Vondra & Burggraf, 1978; Kafulu, 1987). These wings extend laterally into adjacent mudstone strata where they form thin sandstone sheets. Such features have been interpreted as the deposits of fluvial floodplains, overbank levees and crevasse splays (Burggraf et al., 1981).

METHODS

The sedimentology and stratigraphy of the lower part of the Okote Member were analysed in detail along outcrops exposed at the Karari Escarpment and Ileret (Figs 1 to 5). At both localities, the examined exposures are formed by small cliffs and badland-like hills developed along the reaches of seasonally dry streambeds (Fig. 6). This study used a Jacob Staff and Brunton Compass to measure stratigraphic sections of the outcrops and record a cumulative thickness of 10 to 15 m for the lower Okote Member from each of the two localities (Figs 3, 4 and 5). A particular focus was to examine beds that had thicknesses on the order of 10 to 100 cm and to record from these lithology, grain size, sorting, upper and lower contacts, primary sedimentary structures, post-depositional features and fossil content (Miall, 1996; Retallack, 2001; Bridge, 2003). Additional information noted was the outcrops’ strike/dip and GPS location, and photographs were taken of important features. Many were followed along strike to appreciate their lateral geometry (Jones et al., 2001), which was done by correlating adjacent sections through the use of conspicuous markers—such as greyish blue tuffaceous strata or Bk horizons of palaeosols—that contrasted prominently with the quartzofeldspathic sandstones and reddish/brownish mudstones. At outcrops that appeared to be amenable for close inspection of the sedimentary features, the two-dimensional (2D) architecture of the strata was documented. Data collected by the use of stratigraphic sections were combined with the 2D observations to help interpret the overall lateral and vertical variability of outcrop across distances on the order of 10 to 100 m. In order to facilitate comparisons between the two lower Okote Member study areas, which are some 22 km apart (Figs 1 and 2), sections from the Karari Escarpment and Ileret were correlated using inferences from palaeosols, facies similarities and chronostratigraphic data reported elsewhere (Fig. 3).

Stratigraphic correlations

Description

The two study localities are spaced ca 22 km apart (Fig. 1), yet both have outcrops that strike along a NE-SW axis (Fig. 2). Examined strata near Ileret reach a cumulative thickness of ca 15 m and are exposed along the N/NW facing slopes of a hillock for a length of ca 500 m (Figs 2B and 4). An approximate 12 m thick stratigraphic interval of the lower Okote Member of the Karari Escarpment was inspected across some 1200 m of lateral exposure (Figs 2A and 5). At both Ileret and the Karari Escarpment, the top of the section is truncated and the upper formal boundary of the Okote Member was not recognized. Also common to each is a well-developed palaeosol (Fig. 7) that provides an informal stratigraphic boundary to the base of the lower Okote Member. This is termed the ‘basal palaeosol-bearing mudstone’ in Figs 3, 4 and 5.

At Ileret, this basal mudstone has a thickness of 50 to 100 cm. The fabric of the mudstone varies from being massive with small carbonate nodules, to having vertically elongated prismatic structures (Fig. 7A and B). These vertical, prismatic structures have smoothed surfaces, which resemble a slickensided polish, and sometimes are separated by sub-vertically orientated cracks that extend downward from the upper contact of the mudstone. Such cracks are in varying degrees of openness and tend to be more open towards the upper contact, yet are not filled with sediment like a clastic dyke. Above this basal mudstone is an interbedded series of sandstones, tuffs and mudstones (Figs 4 and 7A). The contact between these interbedded strata and the basal mudstone is very sharp, often with a sandstone or tuff directly overlying the mudstone. Locally, the contact surface appears to be nearly
flat lying, yet can exhibit centimetres of scoured relief. Within the interbedded series of sandstones, tuffs and mudstones, no indications of any other laterally pervasive mudstone like the basal one were identified.

Northeastward along the examined Ileret outcrops (Fig. 2B), prismatic structures of the basal mudstone are less apparent, and the mudstone is more massive and has less carbonate nodules (section A in Fig. 4). Farther to
the northeast, this basal mudstone stratum pinches out and the interbedded sandstones, tuffs and mudstones directly overlie sandstones. These sandstones bear carbonate nodules that probably formed in situ (i.e., the nodules do not appear to be an intraformational gravel lag accumulated by a channel). The carbonate nodules are preserved in the uppermost level of the sandstones, which comprised coarse quartzfeldspathic grains and have an exposed thickness of ca 2 m (Fig. 4).

For the Karari Escarpment, the examined outcrops preserve sediments that are broadly similar to Ileret in terms of stratigraphic arrangement and lithology (Fig. 6). The studied interval begins at a basal mudstone that is between 50 and 300 cm thick (Fig. 7C and D). The mudstone directly underlies interbedded sandstones, tuffs and mudstones that attain a cumulative thickness of at least ca 12 m (Figs 3 and 5). The contact between the basal mudstone and these overlying strata is at a nearly flat-

Fig. 5. Sedimentary logs I, II, III, IV and V for the Karari outcrops, correlated over a lateral distance of ca 1250 m. See Fig. 2A for general locations of where logs were taken. Stratigraphic position and date of Orange Tuff after Frank (1976); Brown et al. (2006); McDougall & Brown (2006); and this study. Date of FxJj 18 tuff after Mana et al. (2016).
lying erosive surface, with some minor undulatory relief locally evident (Figs 6A and 7C).

The Karari Escarpment’s basal mudstone comprises clays and silts, but is typically poorly sorted and varies along strike to include fractions of sand. Most prominently, however, well-developed carbonate is preserved through this basal mudstone (Fig. 7C). The carbonate consists of numerous interlocking nodules (and to a lesser extent tubules) that vary in diameter from a few centimetres up to 10 to 15 cm (Fig. 7D). The interbedded sandstones, tuffs and mudstones overlying this basal mudstone have few apparent differences from their counterparts at Ileret. A distinction for the Karari Escarpment, however, is the presence of a large (ca 5 m thick by ca 1000 m long) sandstone complex almost completely isolated within these interbedded sandstones, tuffs and mudstones (Fig. 5). The lower margin of this sandstone complex has an erosive contact along its ca 1000 m lateral extent, and incises through the interbedded sandstones, tuffs and mudstones as well as the upper part of the basal mudstone (Fig. 5). These observations suggest that the accumulation of the sandstone complex post-dates the basal mudstone and was more contemporaneous with the deposition of the interbedded sandstones, tuffs and mudstones.

**Interpretation**

Documented for the Okote Member is a broadly correlative set of tuff complexes that have been dated to 1-6 to 1.5 Ma (Brown & Feibel, 1985; Brown et al., 2006; McDougall & Brown, 2006). On the Karari Escarpment, the predominant one is the Okote Tuff complex, whereas at Ileret, it is referred to as the Ileret Tuff complex. Their
constituent tuffs provide chronostratigraphic control for the lower part of the member (Fig. 3).

At the Ileret section, Bennett et al. (2009) have recognized the Ileret Tuff complex within an ca 8 m interval directly overlying the basal mudstone (Fig. 3). A prominent tuff within this interval, which stands out because of its bluish colour, can be followed across the outcrop for a few hundred metres (Figs 2B and 4). Bennett et al. (2009) correlated this tuff to the Northern Ileret Tuff, which is inferred to have been deposited at >1.51 Ma (Brown et al., 2006). Bennett et al. (2009) also reported that occurring in the examined stratigraphic interval from Ileret (Fig. 3) are tuffs correlated with the Ileret Tuff (ca 1.5 Ma; Brown et al., 2006) and the Lower Ileret Tuff, which is radiometrically dated to 1.53 ± 0.01 Ma (McDougall et al., 2012).

In their study of Ileret, Gathogo & Brown (2006) have placed the base of the Okote Member at a caliche-bearing sandstone overlain by a carbonaceous palaeosol that has desiccation cracks, and named this level as the ‘main Ileret caliche’ (cf., sections PGN-12-2, PGN-08A, and PGN-06A of Gathogo & Brown, 2006). These authors suggest that this stratigraphic level closely approximates the base of the Okote Member, which has an estimated date of 1.56 ± 0.05 Ma (McDougall & Brown, 2006). This study’s basal mudstone and underlying carbonate sandstone at Ileret (Figs 3, 4 and 7A) resembles Gathogo & Brown’s (2006) informal definition for the base of the Okote Member. Furthermore, this basal mudstone is overlain by the Ileret tuffs, dated between 1.53 and 1.51 Ma (Fig. 3). Based on these observations, it seems reasonable to infer that the base of the Okote Member in

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**Fig. 7.** Contact of the lower Okote Member with the basal palaeosol-bearing mudstone. (A) Contact at Ileret showing interbedded sandstone, tuff and mudstone overlying basal palaeosol. P = palaeosol; tS = tuffaceous sand; M = mudstone; szT = sandy/silty tuff. Knife is ca 25 cm long. (B) Close-up of prismatic structure of the basal palaeosol. Note white specs in the claystone, which are small carbonate nodules. (C) Contact at the Karari Escarpment showing whitish tuffaceous deposits overlying the well-developed basal palaeosol. Contact is at the level of arrow. Red pocketknife for scale. Note green-grey colour mottles and thick accumulations of carbonate overprinted on the brownish mudstone. (D) Close-up of carbonate in (C).
the studied deposits at Ileret can be approximated by the contact between the basal mudstone and the overlying series of interbedded sandstones, tuffs and mudstones (Fig. 3). The spatial occurrence of measured sections reported by Gathogo & Brown (2006) intimates that the Ileret palaeosol extends laterally for a distance between 5 and 10 km.

Within the examined outcrops of the Karari Escarpment, the upper age control is provided by a tuff that crops out at archaeological site FxJj 18 (Figs 2A, 3 and 5). Using the single-crystal Ar\(^{40}/\text{Ar}\(^{39}\) technique, Mana et al. (2016) dated sanidine in pumices from the FxJj 18 tuff and reported an age of ca 1.54 Ma. The stratigraphic level of the FxJj 18 tuff is approximately 4 m above the contact between the basal mudstone and the overlying interbedded sandstone, tuffs and mudstones (Figs 3 and 5). Lower age control on the Karari section is provided by the stratigraphic position of the Orange Tuff (Brown et al., 2006), which is radiometrically dated to ca 1.76 Ma (McDougall et al., 2012). The Orange Tuff is located at almost 3.5 m below the contact between the basal mudstone and the interbedded sandstones, tuffs and mudstones (Figs 3 and 5).

Each of the basal mudstones from Ileret and the Karari Escarpment is interpreted as having characteristics that indicate the presence of a well-developed palaeosol (Fig. 7). The basal mudstone at Ileret is interpreted to have small pedogenic carbonate nodules (Quinn et al., 2007) as well as primary peds that are prismatic (compare figs 3.11 and 3.12 in Retallack, 2001 to Figs 7A and B this study). For the Karari basal mudstone, Wynn (1998) interpreted one outcrop of this palaeosol as being ca 2 m thick, with a 20 cm thick A horizon, 140 cm thick Bsk horizon, and a 40 cm thick IIc horizon. It may be a composite or compound palaeosol (Kraus, 1999) because its thickness can exceed 2 m at some outcrops (section V in Fig. 5). At the Karari Escarpment and Ileret, the contact between the basal palaeosol-bearing mudstone and the overlying interbedded sandstones, tuffs and mudstones is used to informally mark the lower boundary of the Okote Member (Fig. 3).

Chronostratigraphic, lithological and palaeosol observations suggest that the studied deposits from Ileret and the Karari Escarpment are nearly contemporaneous. These observations also raise the possibility that the well-developed palaeosol at each locality (Fig. 7) is the same correlative horizon, indicative of a palaeolandscape across a distance of ca 22 km that sustained a pronounced episode of low/no sediment accumulation. Pedogenesis was probably not uniformly active or of the same intensity simultaneously across the palaeolandscape, and an offset in the timing of the resumption of sediment accumulation may explain some of the chronostratigraphic age differences between the two sections from the study areas (Fig. 3).

**Sedimentary facies descriptions and interpretations**

The sedimentary outcrops of both localities show similar primary structures, post-depositional features and arrangement of beds. The outcrops are dominated by sandstones, tuffs and mudstones. Invariably the tuffs are...
not airfall deposits. In fact, there have been very few observations of airfall tuffs within the entire Koobi Fora Formation. Most of the tuffs from the Okote Member were brought into the Turkana Basin by fluvial transportation and reworked by aqueous processes prior to deposition (see discussion in Brown et al., 2006).

Based on field examinations, two sedimentary facies have been described and interpreted (Table 1). These are as follows: (i) interbedded sandstones, tuffs and mudstones and (ii) ribbon-like bodies of sandstone or tuff. The former is interpreted as crevasse-splay deposits, which are most often recognized from sheets of sandstone and tuff that have erosive and fining-upward contacts with the mudstones (see Fig. 8). ‘Ribbon-like bodies’ (p. 174 in Miall, 1996) are analogous to the sandstone ribbons with width/height ratios less than 15 that have been described by Friend et al. (1979). The ribbon-like bodies of sandstone and tuff from the Okote Member are interpreted as crevasse channel fills (Miall, 1996) representing the more channelized areas of the floodplain adjacent to the main fluvial channel (Fig. 8).

**Interbedded sandstones, tuffs and mudstones**

**Description**

This facies (Table 1) consists of fining-upward, sheet-like to lens-like units of interbedded sandstones, tuffs and mudstones (Figs 6, 9 and 10B, C). Individual units of this facies range in thickness from a few decimetres to almost 2 m, and most have a length between 10 and 100 m, although in several cases the units extend farther than the view provided by an outcrop. Each unit generally has sub-parallel upper and lower contacts that are recognizable because of changes in grain size, lithology and/or colour that occur across the contact (Figs 6, 9 and 10B, C, F, G). The lateral margins of these units are variable; they...
pinch-out, terminate at wedge-shaped contacts and inter-finger with adjacent units (Figs 6B, 9 and 10C).

Units of this facies are arranged into 1 to 3 m thick, fining-upward sequences that are successively stacked upon each other within an individual outcrop (Fig. 9). The beginning of a fining-upward sequence is at an erosion surface, usually developed through a subjacent mudstone that is the top unit of an underlying sequence. Basal erosion surfaces are nearly flat lying with some centimetre-scale erosive relief (Fig. 10F). Some lower contacts are locally punctuated with concave-up, scour-shaped features that are <1 m wide and have up to 25 cm of erosive relief (Fig. 10A and G). These scour contain crude cross-stratifications or an infill with no apparent structure.

The fining-upward sequences normally consist of a coarse unit overlain by a mudstone. Coarse units are composed of rhyolitic ash shards and/or quartzofeldspathic sands, which vary in size from fine to medium. These coarse basal units may incorporate a mud fraction, and some examples are poorly sorted admixtures of mud, tuff and sand. There is a noticeable rarity of gravel—

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*Fig. 10.* Ileret depositional and post-depositional features of the Okote Member. (A) Tuffaceous layer indicated by ‘T’ incised through mudstone indicated by ‘M’. Note concave-up scouring at the tuff’s base. (B) Mudstone (‘M’) stratified between tuffaceous silt (‘tZ’) and silty tuff (‘zT’). Litre water bottle for scale in centre of photograph. (C) Lateral termination of a tuff that is embedded within mudstones. Note wedge-shaped margin indicated by arrow. (D) Small, white pedogenic carbonate nodules in mudstone. Scale at right. (E) Exhumed slickensided surface within mudstone. Scale at left. (F) Basal contact of tuff sheet showing centimetre-scale erosive relief. (G) Tuff deposit showing basal incision through mudstone with small carbonate nodules.
except for granules and small pebbles of pumice and occasionally mud rip-up clasts. Many of the coarse units have a massive fabric, parallel laminations or wavy laminations. Convolute bedding and mammal footprints, including those of hominins, are preserved locally by the mudstones (Vondra & Bowen, 1978; Bennett et al., 2009; Roach et al., 2016). Medium- to fine-grained sandstones and tuffs preserve cross-stratifications and planar laminations interstratified with small-scale cross strata (Vondra & Burggraf, 1978; Bennett et al., 2009).

Mudstones fine upward from basal coarse units, and the transition between the two is either diffuse or across a sharp (non-erosive) contact (Figs 6B, 7A, 9 and 10C). At their tops, the mudstones are often scoured by an overlying coarse unit (Figs 6B, 9 and 10A, B, C, F, G). The mudstones generally are dominated by silt and lack primary sedimentary structures, but some units preserve faint horizontal laminations. Mudstones preserve small carbonate nodules, which are not concentrated into distinctive horizons but are found disseminated throughout mudstones as small clasts, usually no larger than granules (Fig. 10D). These are sub-spherical to elongate micritic nodules made from microcrystalline and sparry calcite (Quinn et al., 2007). Some mudstones locally have slickened fracture surfaces (Fig. 10E).

Interpretation

Okote Member strata from Ileret and the Karari Escarpment have sedimentological features that have been documented for crevasse splays deposited by rivers and deltas (Table 1). These features include sheet-like to lens-like geometry (Figs 6, 9 and 10C), erosive lower contacts (Figs 6B, 9 and 10A, B, F, G), interbedded sandstones and mudrocks (Figs 6, 9 and 10B), weakly developed soils (Fig. 10D and E), and metre-scale fining-upward sequences (Figs 4, 5, 7A, 9, and 10C) that suggest a progressive decrease in the flow regime associated with flood and slack-water sedimentation. Crevasse-splay strata are characterized by sand bodies that have variable dimensions, extending through floodplain areas for multiple kilometres or being of much more limited aerial extent and only a few centimetres thick (O’Brien & Wells, 1986; Mjøs et al., 1993). Crevasse splays (e.g., Fig. 8) vary from simple lobes with wedge-shaped cross-sections to more complex splays that comprised both sand sheets and channels of varying geometry (Smith et al., 1989).

Crevasse-splay deposition is often associated with frequent inundation of the floodplain and short hiatuses between floods, which limits the amount of time for subaerial exposure of the landscape and thus inhibits maturation of floodplain soils (Kraus & Aslan, 1993; Kraus, 1997; Kraus & Wells, 1999). Okote Member mudstones preserve evidence of immature palaeosols (Fig. 10D and E). None of the mudstones interbedded with the sandstones or tuffs preserve features of a mature palaeosol or a palaeosol with multiple strongly developed horizons. Some Karari mudstones of the lower Okote Member have weakly developed palaeosols characterized by thin A and C master horizons (Wynn, 1998). These have been interpreted as Calcic Cambisols or Mollic Ustorthents and include crumb-like peds that suggest a mollic epipedon of past herbaceous vegetation (see Wynn, 2000 and references within).

Sharp and erosive basal contacts for the sandstones and tuff are interpreted as indicative of a high-energy flow generated directly after crevasse formation, when sediment-laden water entered the floodplain under a waning flow regime (van Toorenenburg et al., 2016). These coarse sediments may have been deposited within small, anastomosed reaches or by density current induced sheet floods (Elliott, 1974; Mjøs et al., 1993). The fining-upward character of the Okote Member sandstones/tuffs into mudstones suggests a transition to suspension deposition, occurring when the floodplain was inundated and suspended-load sediment started to form conformable drapes of floodplain fines (van Toorenenburg et al., 2016). The suspended sediments accumulate as a result of a trunk channel flooding into the floodplain or at all stages of flow with crevasse-splay sands that break through channel walls (Kraus & Wells, 1999).

Frequent, yet short-lived floods and rapid accumulation of detritus are processes often associated with the sedimentary structures and lithologies of crevasse splays (Smith et al., 1989; Bristow et al., 1999; Farrell, 2001; Bridge, 2003). Massive sandstones/tuff units of the Okote Member may indicate the depositional environment frequently experienced rapid fallout of sediment from short-lived flows that were laden with detritus (e.g., hyper-concentrated density currents of Hjellbakk, 1997). The planar laminated strata from the sandstone/tuff parts of fining-upward sequences of the Okote Member may be indicative of high-energy flood sedimentation related to unconfined sheet flows in floodplain areas (Tunbridge, 1981; Bridge, 2003). Although these sandstone/tuff units have nearly flat-lying (erosive) bases, they are locally punctuated with concave-up scour features (Fig. 10A and G) that suggest the sheet flows locally had basal channelized portions. These scours also may represent a channel developed under waning flow conditions following a sheet-flood event (Fisher et al., 2007).

Ribbon-like bodies of sandstone or tuff

Description

Ribbon-like bodies are found isolated within the interbedded sandstones, tuffs and mudstones facies (Figs 11 and
12). These bodies range in thickness from 0·2 to 3·1 m and have sharp erosive bases. They are composed of medium-grained or coarse-grained sandstone/tuff that is moderately to poorly sorted. The sandstones and tuffs fine upward and are commonly massive. Some Okote Member ribbons have cross-stratified cosets up to ca 1·0 m thick (Fig. 11) and contain mudstone rip-up clasts in the basal parts of sandstones/tuffs (Burggraf et al., 1981). Other ribbon-like bodies comprise multiple layers of sandstone/tuff separated by erosive reactivation surfaces (sections C and D in Fig. 4). There is no evidence for fine-grained deposition between surfaces.

Ribbon-like bodies that crop out near archaeological site FxJj 17 (Fig. 12) are lone semi-symmetrical, concave-up bodies that have wings extending from their uppermost margins. The wings fine laterally (Friend et al., 1979; fig. 5A in Hirst, 1991). In the case of the FxJj 17 ribbon (Fig. 12), one of the wings fines laterally into a friable mudstone that is overprinted with a weakly developed palaeosol (Kaufulu, 1987; Wynn, 1998).

At some Karari outcrops, ribbons are part of a laterally pervasive sheet-like body that often extends farther than outcrop dimensions and connects multiple ribbons situated at nearly the same stratigraphic level (Fig. 13). Each connected ribbon is a small, single-story body that fines upward yet lacks sedimentary structures. These connected ribbons resemble what have been termed ‘ribbon tiers’ (Kraus & Wells, 1999), which are stratigraphically equivalent ribbon sandstones connected by laterally extensive and thin (0·3 to 1·0 m thick) sandstone or siltstone sheets. In sections of the upper Willwood Formation (Lower Eocene Bighorn Basin, Wyoming), the tiers extend for >500 m and the ribbons are less than a metre thick in most cases (Kraus & Wells, 1999; see their fig. 10). The lateral extent in the Okote Member is not comparable because of outcrop limitations, but the ribbons and sheets are of similar thickness (Fig. 13).

**Interpretation**

These ribbon-like bodies are interpreted as channel deposits incised through crevasse-splay and floodplain strata. Their size, geometry, lithology and encasement within the interbedded sandstones, tuffs and mudstones suggest that the ribbons are similar to crevasse channels and small floodplain channels (Table 1). These crevasse channels are different to the Okote Member’s major channel sandstone complexes (Figs 5 and 12), which attain thicknesses of nearly 5 m, extend laterally for ca
1 km, and consist of polymictic gravels and sandstones (Burggraf et al., 1981).

The concave-up shape and erosive margins of these ribbons suggest scour-and-fill deposition generated by turbulent, confined flows (Fisher et al., 2007; Nichols & Fisher, 2007). A decrease in flow velocity and eventual secession of flow is suggested by the ribbon’s overall fining-upward progression and the presence of calcareous root traces at the top (Fig. 11). Ribbons comprising a single fining-upward trend are interpreted to indicate deposition from a decelerating flow, perhaps produced by an episodic flood event that caused the channel to rapidly infill and abandon. Miall (1996) has suggested that one cause of this may be a meagre difference in the elevation between the point of origin for the channel and adjacent floodplain. As a result, the small gradient contributes to a low flow competency and the channel rapidly becomes plugged with sediment before any lateral migration (Hirst, 1991). Ribbons

Fig. 12. Karari outcrops near archaeological sites FxJj 17. (Top) Panel cartoon is redrawn from Kaufulu (1987) and Isaac & Behrensmeyer (1997). Note the margin of the major channel sandstone complex that is also depicted in Fig. 5. For description of ‘ friable palaeosol ’ see ‘ dite palaeosol ’ of Wynn (2000). (Middle) Photo-mosaic of outcrops depicted in (Top) except the view (looking into the west) is nearly perpendicular to the SE-NW perspective of the panel cartoon in (Top). (Bottom) Interpretative overlay of photo-mosaic showing the location of the ribbon body depicted in (Top) as well as the contact of the lower Okote Member with the basal palaeosol-bearing mudstone. However, at this locality, the basal palaeosol diffusely pinches out and the interbedded sandstones, tuffs and mudstones of the lower Okote Member directly overly gravels/sands of the upper KBS Member.
characterized by the stacking of sandstone/tuff layers, which are separated by erosive surfaces, may indicate that the channel remained fixed in its palaeogeographic position for successive flood events (Friend et al., 1979). Sheet-like wings extending from a ribbon’s top are interpreted as crevasse-splay deposit emanated from the crevasse channel (Friend et al., 1979; Hirst, 1991).

Ribbon tiers have been interpreted as indicative of crevasse-splay channels that prograde into a floodplain area and establish the initial basis to an avulsing channel belt (Kraus & Wells, 1999). The sheets connecting the ribbons in these tiers are thought to be sheet-flood deposits derived from the crevasse channels. Multiple ribbon-like bodies cropping out along the same stratigraphic horizon within a relatively small area is consistent with having multiple active channels coexisting on a particular area of the floodplain (Smith et al., 1989; Kraus & Wells, 1999; Roberts, 2007). The Karari succession coarsens upward in the example documented for this study (Fig. 13), with the upper tier-shaped strata in the examined outcrop being coarser than the lower one. Coarsening-upwards sequences are expected to be produced by levees or crevasse splays prograding into floodplain areas (Bridge, 1984).

**DISCUSSION**

The examined sediments of the lower Okote Member share many features in common with those deposited in other tropical or semi-arid, half-graben rift basins. In the Plio-Pleistocene Rio Grande rift (USA), major sandstone complexes—like that from the Karari Escarpment—attain thicknesses of 5 to 10 m and are between 1 and 3.5 km in length (Perez-Arlucea et al., 2000). These channel complexes are associated with crevasse-splay beds of comparable thicknesses (5 cm to 3.5 m) and lateral extents (10s to 100s of m) (Perez-Arlucea et al., 2000) to the ones observed at Ileret and the Karari Escarpment. Volcaniclastic strata of the lower Okote Member are analogous to the 30 cm thick, tabular units of pumice-bearing tuffs that were deposited by crevasse splays in Plio-Pleistocene floodplains of the Rio Grande (Mack et al., 1996). Interbedded mudstones of the Rio Grande rift are overprinted with numerous calcic palaeosols (Mack & Madoff, 2005). Similar palaeosol-bearing mudstones have been reported from the Newark Supergroup (Mesozoic rifts of eastern North America) (Smoot & Olsen, 1988). These mudstones are associated with crevasse-splay sandstones of the Stockton and Sanford formations, and they have slickenside planes and spherical carbonate nodules ranging from sand-sized to several millimetres in diameter (Smoot, 1991). Such case studies and others are used to discuss (i) time represented by the deposits, (ii) depositional model, (iii) potential influence of volcaniclastic input on deposition, and (iv) the possibility that the lower Okote Member strata are a fluvial avulsion complex.

**Time represented by the deposits**

The stratigraphic record for a depositional environment represents only a fraction of the gross amount of sediment the environment accumulated through a given time interval. In most depositional environments, sediment accumulation occurs episodically with a recurrence frequency that is cyclic or random (Sadler, 1981). Between episodes of deposition, the accumulated sediment typically experiences erosion or, especially in floodplain settings, pedogenic modification (Kraus & Bown, 1986). Episodic sedimentation, erosion and pedogenesis generate gaps in the temporal continuity of a fluvial stratigraphic record (Behrensmeier, 1982). To assess this incompleteness, numerical dates, palaeosol maturity and inferences from depositional process are used to calculate
sedimentation rates and estimate the amount of time represented by the gaps and preserved strata (Sadler, 1981; Badgley & Tauxe, 1990; Behrensmeier et al., 1995; Kraus, 1999).

A nominal (un-compacted) rate of accumulation for the Okote Member has been estimated at about 19 cm kyr⁻¹ based on linear interpolation between dated tuff horizons (Brown & Feibel, 1985; McDougall & Brown, 2006; McDougall et al., 2012). These data suggest that about 1 m of thickness in the Okote Member equals ca 5 kyr. Individual Okote Member crevasse splays, therefore, represent a similar amount of time, considering each has a thickness of no more than a metre or so. However, 5 kyr is a substantially longer accumulation time than would be expected for an individual crevasse-splay deposit that is on the order of a metre thick (Bridge, 2003). Okote Member crevasse splays have thicknesses and lateral extents that suggest they are singular, small-scale crevasse splays (Smith et al., 1989; Mjøs et al., 1993), which normally have life spans of days to years (Kraus & Wells, 1999). Therefore, ca 1 m of sediment from the lower Okote Member probably accumulated over a period of time that was much less than 5 kyr. The timeframe of accumulation for these sediments is significantly influenced by the highly localized and episodic nature of crevasse-splay and crevasse-channel deposition (van Toorenenburg et al., 2016). Because of this, the number of observed crevasse splays and the thickness of the stratigraphic record preserving these sediments probably do not archive the entirety of the floodplain depositional events that occurred (Kraus & Wells, 1999). Furthermore, the Okote Member mudstones having features of weakly developed paleosols suggest instances when the rate of sediment accumulation was unsteady. These observations suggest that only a portion of the actual Early Pleistocene sediment accumulation has been preserved in the examined stratigraphic record of the Okote Member.

Floodplain pedogenesis has been linked to the amount of time between episodes of deposition and the rates of sediment and water input to a floodplain (Kraus, 1999). Weakly developed paleosols are thought to be indicative of less time between depositional events and a faster sediment accumulation rate (Kraus, 2002). Ancient pedogenic modification of the Okote Member mudstones appears to be limited; the stratigraphic levels that are overprinted with paleosol features tend to be thin (<0.5 m) and are not well differentiated into multiple horizons. The small carbonate nodules and few slickensides suggest weak pedogenic modification of these fine-grained strata. Modern carbonate nodules in East African soils form over relatively short (historic) timescales (Cerling, 1984), whereas the slickensides are vertic structures that begin to form over tens to hundreds of years in modern soils (Ahmad, 1983). Sparse slickensides, few and small carbonate nodules, and limited horizonation suggest a formation time on the order of 10⁶ to 10⁷ years for floodplain paleosols formed in Early Pleistocene half-graben rifts with semi-arid climates (Mack & Madoff, 2005) like the Turkana Basin.

A short timeframe between depositional events is suggested by the footprint-bearing sediments and overlying deposits (Bennett et al., 2009). Footprint-marked levels suggest secession of deposition and landscape stability; however, if the pauses in sedimentation were long, then sub-aerial processes (e.g., soil formation, wind abrasion) would have obliterated the footprints, which is not the case. The multiple, well-defined impressions (Bennett et al., 2009) indicate that sedimentation resumed and the footprints were buried not too long after they were made (Roach et al., 2016).

The repetitiveness of fining-upward sequences in the Okote Member might be indicative that deposition was strongly influenced by the seasonality of African monsoonal rainfall. In Kenya, river flooding is strongly related to the monsoonal cycle, which typically has two rainy seasons. The occurrence of soil carbonate nodules, albeit small in diameter, disseminated through individual Okote Member mudstones may indicate a net deficit in ambient moisture during the dry phases of the monsoon. The slickensides within the Okote Member mudstones also suggest a seasonal contrast in moisture.

**Depositional model**

Smith et al. (1989) described small, singular crevasse-splay sands from alluvial plain settings as having a lobate shape in plan view (e.g., Figs 8 and 14 this study). These sands are lenticular along width and sheet-like along length, yet distal thinning and limited outcrop perspectives can complicate these simple relationships (Mjøs et al., 1993). Crevasse-splay deposition typically takes place within a low-lying, proximal area that slopes away from a main trunk channel (Bristow et al., 1999; Perez-Aslucea & Smith, 1999; Farrell, 2001). Prior to the accumulation of thick crevasse-splay sequences, there may be prolonged periods of depositional inactivity and sub-aerial exposure, allowing for extensive pedogenesis and resulting in mature paleosol formation (e.g., flood basin paleosols of Aslan & Blum, 1999; cumulative paleosol of Kraus & Wells, 1999; basal paleosol of van Toorenenburg et al., 2016).

The well-developed paleosol at the base of the examined sections from Ileret and the Karari Escarpment indicates a palaeolandcape that rarely received sediment and water input. This implies that the depositional site initially was at a location that was far away from an active channel. At some point, the paleosol development was arrested when crevasse-splay and associated deposits began to accumulate. Channel avulsion is one process
that can inhibit soil formation and increase the influx of clastic deposition to particular areas of a floodplain (Davies-Vollum & Kraus, 2001). If an active channel avulsed farther away from the study area, the palaeosol would have continued to mature, but the maturation of the palaeosol that had been developing was halted. Because the mature palaeosol suggests that this distal area did not aggrade over time, it may have gradually become one of the topographically lower areas on the palaeoland-scape, which is a favourable location for a channel to avulse closer to. Crevasse-splay deposition is a process that often heralds channel avulsion into a location (Smith et al., 1989; Kraus & Wells, 1999; Jones & Hajek, 2007). The soil development was arrested when crevasse splays prograded into the floodplain.

During floods, feeder channels leaving a trunk channel’s levee probably scoured the tops of pre-existing floodplain substrate and accumulated coarse detritus as small, lobate crevasse splays (Smith et al., 1989). A network of narrow, shallow and unstable distributary channels directing flow to the splay margins locally incise these splays (Davies-Vollum & Kraus, 2001; Farrell, 2001). These channels fed the crevasse splays as they prograded out onto the floodplain and were erosive, incising through associated fine-grained strata (e.g., Fig. 14). At Ileret, the flow emplaced scour topography as it incised through floodplain mudstones and immature palaeosols (Fig. 10A, F and G). Other times, however, it appears that the flow was not sufficiently energized to generate enough scour to remove footprint-bearing sediment. Footprint-marked levels at archaeological site FwJj 14E may suggest that lower flow velocities were common along the edges of shallower parts of the splay, and at the splay’s peripheral margins (Fig. 14). Lower flow velocities would have promoted slack water to form, leading to the deposition of soft muddy substrates conducive for recording the imprints of foot track ways (see fig. 9 in Bristow et al., 1999 for an analogous depositional setting and foot-prints). As flooding waned, decreased flow velocity would promote the accumulation of fine-grained detritus over the splay’s sand and tuff sediments. Small calcium carbonate nodules and slickensides found with the muddier strata suggest that drainage conditions improved, and perhaps that splay deposition infilled the pre-existing topography, causing soils to form on a now elevated part of the floodplain (Davies-Vollum & Kraus, 2001). The palaeosols also suggest that the rate of sediment accumulation slowed in selective parts of the floodplain.

### Potential influence of volcanioclastic input on deposition

The Okote Member is well-known for its numerous tuffaceous marker horizons that have been radiometrically

| Not to any scale |
|-----------------|
| **Fig. 14.** Schematic block model showing crevasse splay and crevasse-splay channels. Diagram generalizes the depositional setting of select archaeological sites. |

Note: FxJj 11, 16, 17, and 18 are from the Karari and FwJj 14A, 14B and 14E are from Ileret. Sites are combined into one diagram for heuristic purposes.
dated (Brown et al., 2006; McDougall & Brown, 2006). One estimate suggests that the Okote Member’s tuff horizons are almost twice those found in other members of the Koobi Fora Formation (Feibel, 1999). The greatest frequency of tuffs appears to be dated at ca 1.5 Ma (McDougall et al., 2012). Numerous fluvially reworked tuffs preserved in the studied sections indicate episodic increases in the sediment supply to the Turkana Basin caused by extra-basin volcanism. Increased volcanlastic input probably caused channel beds to aggrade more rapidly, leading to a greater increase in the frequency of crevassing. Episodic explosive volcanism, associated with crevasse-splay deposition, has been documented as an important agent for increasing fluvial sediment supplies in half-graben settings (Mack et al., 1996). Numerous models and outcrop data (Wright & Marriott, 1993; Mackey & Bridge, 1995; Heller & Paola, 1996; Kraus, 2002; Mack & Madoff, 2005; and references within) have suggested that elevated rates of sediment supply can increase rates of avulsion frequency within a basin. Increased rates of sediment supply caused by periodic explosive volcanism may increase topographic relief of channels above the floodplain, leading to a greater increase in avulsion frequency (Allen & Fielding, 2007).

Fluvial avulsion complex?

Crevasse-splay deposits are common to three types of depositional settings: alluvial plain, sub-delta lobes that fill bays and lagoons, and fluvial avulsion complexes. Classification of deposits into these types has been based on stratigraphic thickness, geometry, stacking patterns, interconnectivity, lateral pervasiveness and palaeosols (Mjøs et al., 1993; Kraus & Wells, 1999; Davies-Vollum & Kraus, 2001). The Okote Member preserves deposits of small, alluvial crevasse-splay lobes (e.g., Figs 8 and 14).

Composite crevasse-splay deposits form sub-delta lobes and fluvial avulsion complexes (Mjøs et al., 1993; Kraus & Wells, 1999; Davies-Vollum & Kraus, 2001). These consist of thick successions of stacked crevasse-splay sandstones and related fine-grained strata that result from sustained growth of a splay system covering an area ≥500 km² (Davies-Vollum & Kraus, 2001). Several aspects of the Karari and Ileret sections suggest that the identified crevasse-splay and associated depositional environments of the Okote Member covered an extensive area. The Karari and Ileret sections are situated about 22 km apart on the modern landscape (Fig. 1), and tephrachronology suggests the penecontemporaneousness of the deposits at ≥1.5 Ma (Fig. 3). The total stratigraphic package of the Ileret section does not appear to thin along the ca 500 m strike exposure. In addition, it has been demonstrated extensively that the Okote Member along the Karari Escarpment shows no signs of thinning for several kilometres of lateral exposure (Isaac & Behrensmeier, 1997). Moreover, the crevasse-splay and associated deposits dominate the stratigraphic thickness of the measured Karari and Ileret sections (each 10 to 15 m thick). At its type section within the Karari Escarpment, the member is at most 25 m thick (Brown & Feibel, 1986). Crevasse splay and associated deposits also are prominent components of the Okote Member at several localities of the Karari Escarpment where the member is exposed (Burggraf et al., 1981). The stratigraphic abundance of the crevasse splay and associated deposits perhaps also suggest that the depositional system was aerially widespread (Davies-Vollum & Kraus, 2001).

Within the examined Ileret and Karari sections, there are few if any indicators of the Turkana Basin’s well-documented lacustrine, deltaic and lake-margin deposits. The Karari and Ileret sections neither preserve nor are interbedded with inclined strata-sets and shell hashes like those of the Turkana Basin’s Holocene beach deposits (Owen & Renaut, 1986). Gilbert-style delta geometry and primary sedimentary structures, as well as pro-deltaic laminated mudstones, have not been observed (Burggraf et al., 1981; Gathogo & Brown, 2006). There are few, if any, invertebrate aquatic fossils (e.g., gastropods, bivalves, stainediatolites) that are well-known from the lacustrine/deltaic deposits of the Koobi Fora Formation (Williamson, 1981; Abell et al., 1982). However, a vertical stratigraphic changeover from a mature palaeosol to crevasse-splay and associated deposits, which bear weakly developed palaeosols, has been noted by other studies as potential indicators of fluvial channel avulsion (Aslan & Blum, 1999; Kraus & Wells, 1999; van Toorenburg et al., 2016). This stratigraphy is common to both the Ileret and Karari sections.

Avulsion results in a channel moving and occupying a new depositional site on the landscape (Mohrig et al., 2000; Slingerland & Smith, 2004; Jones & Hajek, 2007). In the Karari section (Figs 5 and 12), the large sandstone complex surrounded by interbedded sandstones, tuffs and mudstones may, in fact, be representative of an avulsed fluvial channel incised through an avulsion belt. The presence of such a large channel sandstone complex embedded within crevasse-splay strata is a characteristic of avulsion deposits accumulated by modern and ancient fluvial systems (Davies-Vollum & Kraus, 2001). This stratigraphy from the Karari Escarpment resembles what has been described as a ‘stratigraphically transitional’ avulsion stratigraphy, defined by an obvious phase of crevasse splay and associated deposits accumulated prior to the deposition of the avulsed channel’s sediments (Jones & Hajek, 2007).

However, unlike the Karari section, major channel sandstone complexes were not identified within the Ileret
section. A lack of these channel deposits in the Ileret section does not preclude Ileret's crevasse splay and associated deposits from being indicative of fluvial avulsion. Such major channels may be difficult to locate within the outcrops of the Okote Member since they can represent only a small fraction of the total stratigraphy in comparison to the floodplain strata. The channel belt occupies only a small part of the avulsion deposits because it is narrow compared to the width of the avulsion belt (Smith et al., 1989; Davies-Vollum & Kraus, 2001). The absence of a major channel sandstone body in the Ileret section may be due to the lateral scale of the depositional system relative to the small scale of the outcrops, and thus the examined strata do not preserve the part of the avulsion belt incised by the newly established palaeo-channel (Aslan & Blum, 1999; Kraus & Wells, 1999; Davies-Vollum & Kraus, 2001).

**CONCLUSIONS**

Detailed comparisons of the lower Okote Member strata cropping out near the town of Ileret and along the Karari Escarpment were accomplished through lithostratigraphic and sedimentological analyses. This provided an improved understanding of the palaeoenvironmental context, depositional history, and controls on the accumulation of strata containing fossil and archaeological sites. The conclusions of the research can be summarized as follows:

- An abundance of crevasse splays, crevasse channels and weakly developed palaeosols—in addition to soft-sediment deformation features and the types of primary sedimentary structures—suggest seasonal flooding and rapid, yet unsteady aggradation in a floodplain setting.
- A majority of the examined Ileret and Karari deposits of the lower Okote Member probably accumulated within a low-relief floodplain proximal to a main fluvial channel. The exception to this is the major channel sandstone complex observed in the Karari section, and the well-developed palaeosol that is common to both the Ileret and Karari sections.
- The top of the well-developed palaeosol at Ileret and the Karari Escarpment is a local approximation for the boundary between the upper KBS Member and the lower Okote Member (c.f., ‘main Ileret caliche’ of Gathogo & Brown, 2006). It represents a temporally and spatially extensive hiatus in sedimentation before the accumulation of the crevasse-splay and crevasse-channel deposits.
- Lower Okote Member strata from Ileret and the Karari Escarpment resemble composite crevasse-splay deposits, which accumulate as a result of sub-delta lobe deposition or river avulsion. However, the lack of lacustrine or deltaic indicators interbedded with these lower Okote Member strata may align them better with river avulsion. The vertical stratigraphic changeover from a well-developed palaeosol to a heterolithic interval characterized by crevasse splays, crevasse channels and weakly developed palaeosols is also consistent with a transitional river avulsion stratigraphy (cf., Jones & Hajek, 2007).
- Numerous fluvially reworked tuffs preserved in the studied sections indicate episodic increases in the sediment supply caused by extra-basin volcanism. Increased volcaniclastic input probably caused channel beds to aggrade more rapidly, leading to a higher frequency of crevassing.

Lastly, the Okote Member’s high sediment accumulation rate of ca 19 cm kyr$^{-1}$ calculated from radiometrically dated tuff horizons (McDougall & Brown, 2006; McDougall et al., 2012) is consistent with rapid aggradation indicated by the crevasse-splay depositional environments, immature floodplain palaeosols and overall stratigraphy. However, using the calculated sedimentation rate alone tends to overestimate the amount of time represented by a stratum that is on the order of 10 to 100 cm thick. Information from palaeosols, sedimentary facies and depositional process suggests that the archaeological-bearing and fossil-bearing layers formed within a timeframe of $10^0$ to $10^2$ years. These sediment accumulation conditions and modes of crevasse-splay deposition probably contributed to the exceptionally good record of hominin evolution preserved by the lower Okote Member.

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