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# New Olduvai Basin stratigraphy and stratigraphic concepts revealed by OGCP cores into the Palaeolake Olduvai depocentre, Tanzania

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ABSTRACT

The Olduvai Gorge Coring Project (OGCP) drilled four boreholes 1A, 2A, 3A, 3B at three sites into the central palaeolake of the Olduvai Basin depocentre. Previously known Beds I, II, III, IV, Masek Beds and Ndutu are identifiable in the upper part of the cores, and from these formations predominantly lacustrine facies associations are recognised. These are described and then interpreted in terms of their palaeoenvironmental significance. However, stratigraphy known from natural outcrop exposures is more than doubled by strata intersected below. For example, an extra 135 m of pre-Bed I stratigraphy in Core 2A records the entire volcanic history of a fan-delta sourced from Ngorongoro Volcano. Beneath that fan sequence is an interval of fluvio-lacustrine non-volcaniclastic sediments. For the latter the new stratigraphic term Naibor Soit Formation is introduced, because these strata were discovered for the first time in Boreholes 2A and 3A, to either side of Naibor Soit Inselberg, where they thus lap onto its basement topography. The volcanically sourced unit above is named Ngorongoro Formation, including Marker Tuffs CFCT (Coarse Feldspar Crystal Tuff) and the Naabi Ignimbrite within its topmost portion. Only the dominantly lacustrine sediments above the main Ngorongoro sourced fan body are now attributed to Lower Bed I. The Ngorongoro Formation defined here contains primary Tuff Markers NgA to NgQ, and volcaniclastic fan-delta deposits that interfinger with and overlie claystones and interbedded sandstones of the fluvio-lacustrine Naibor Soit Formation. Boreholes 1A and 2A intersect the Bed I Basalt, but not Borehole 3A, where the position of the lava is marked by three separated volcaniclastic sandstone layers, containing pebble-sized basalt scoriae, likely correlating to three complex basalt flows at Locality 9A and Orkeri and allowing assessment of syn-basalt sedimentation. Disconformities bounding Beds I, II, III, IV, Masek Beds and Ndutu Beds provide important stratigraphic markers for the novel application of sequence stratigraphic concepts, as they mark lowstands of Palaeolake Olduvai, guiding outcrop to core correlations. Major disconformities are identified in: (1) Core 1A, where the Lower Bed II Crocodile Valley Incision Surface cuts out Tuff IF; (2) Core 1A, where disconformities and facies within Beds II, III, IV, and Masek Beds are identified; (3) Cores 2A and 3A, where Tuff IF is identified below the Lower to Middle Bed II disconformity; and (4) Lower Bed I claystones and Tuff IA in Core 3A that correlate to similar sedimentary units from Locality 66e in the Western Gorge, but which are absent from Core 2A because of a newly identified major disconformity, which causes the Bed I lava to sit directly on top of the CFCT marker.

## 1. Introduction

During August 2014 four boreholes 1A, 2A, 3A, 3B were drilled into the Olduvai Basin (Fig. 1) at three sites. All were drilled as vertical boreholes, apart from 3B, which was inclined 23.5° from the vertical, to facilitate palaeomagnetic reversal analysis. The principal targets were selected to probe the purported deepest lake areas through time (Hay, 1976), to derive a cumulative maximally lacustrine and maximally

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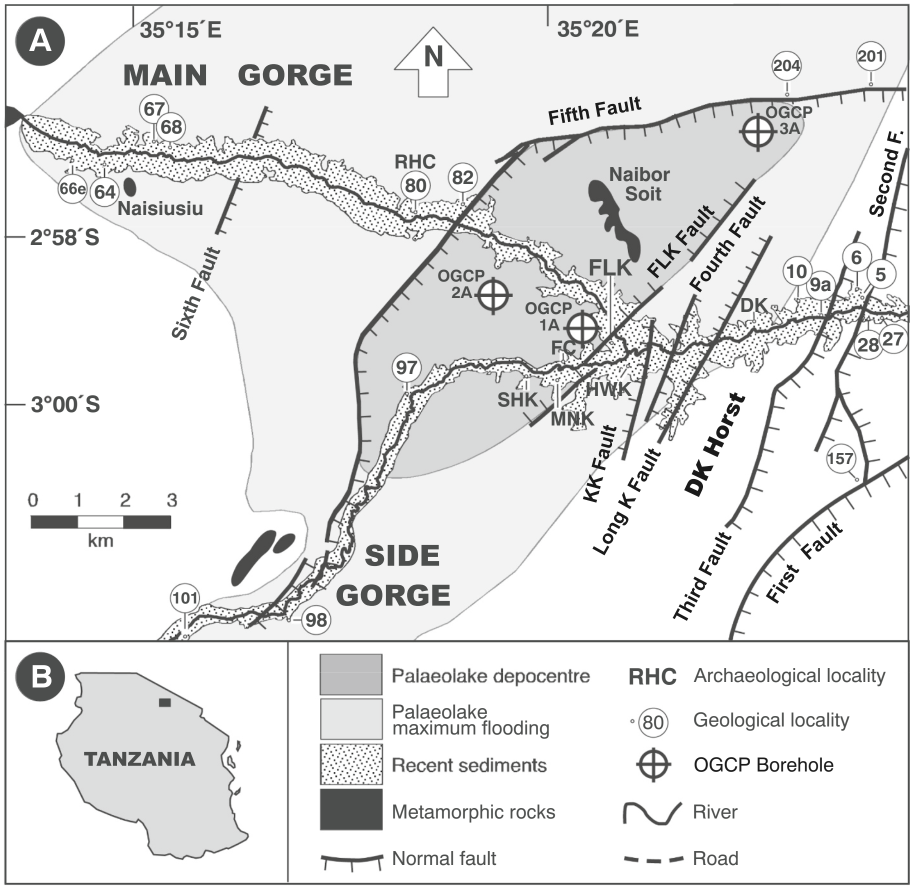


**Fig. 1.** The Olduvai Basin borehole locations placed within a new reconstruction of its palaeogeography during Upper Bed I. The deep lake is restricted by Fifth and FLK Faults. Outcrop sites marked include encircled numbers, indicating Localities of Hay, 1976 and Habermann et al., 2016a, and capital letters, indicating archaeological sites of Leakey (1971). The "Junction Area" is that area defined by Leakey (1971) as the meeting place of Main and Side Gorges. Loc. 1 and the Orkeri Locality are situated adjacent to First Fault 8 km east-southeast of Loc. 201 and 6 km southwest of Loc. 157 respectively. Black rectangle in Fig. 1B shows the position of the detailed map, given in Fig. 1A

continuous record for palaeoclimatic proxy sampling and analysis from the Late Pleistocene Ndutu Beds down to the Early Pleistocene Bed I strata (Fig. 2). The philosophy was also to relate this to the wide-ranging record of hominin evolution recognised in the Olduvai Basin (e.g. Leakey, 1971, Leakey and Roe, 1994), contained within the known outcrop stratigraphy formulated by Hay (1976) and updated by others (e.g. McHenry, 2005; Stanistreet et al., 2018b). Another aim was to drill beyond the depth recorded by that ~100 m of known outcrop stratigraphy and to attempt to intersect bedrock beneath the Olduvai Beds.

Hay, 1976 identified the Ngorongoro Volcanics, capped by the Naabi Ignimbrite, as the oldest stratigraphic unit of the Olduvai Basin, unconformably overlying Archaean basement of the Tanzania Craton and Neoproterozoic basement of the Mozambique metamorphic belt (Fig. 3). According to Hay (1976), Olduvai Bed I extends from the top of the Naabi Ignimbrite up to the top of Tuff IF, whereas McHenry et al. (2008) included the Naabi Ignimbrite in the Bed I succession. A complicating factor in this regard, that needed to be resolved, is that the Naabi Ignimbrite to Tuff IA succession is only exposed in the western part of the Main Gorge, while natural exposures of the Bed I lavas are confined to its eastern part (Habermann et al., 2016a).

Fig. 3 shows correlation of Beds I, II, III, IV, Masek and Ndutu in outcrops along the Main Olduvai Gorge and illustrates the control of syn-sedimentary faulting on sediment thicknesses. While based on Hay (1976), this diagram includes updates from more recent work, correcting Hay's miscorrelation of Tuff IB as Tuff IF in the two westernmost sections indicated. There Tuffs IB, IC and ID have been subsequently traced after Tuff IB (previously miscorrelated as Tuff IF) and Tuff IC had been recognised and located by Blumenschine et al. (2003) following the discovery of the *Homo habilis* maxilla OH 65 at Loc. 64. These tuffs establish Upper Bed I and the continuation of Tuff IB in the westernmost sections, but Tuff IF is absent there due to incision of the sub-Augitic Sandstones (Lower, Middle and Upper Augitic Sandstones) incision surface (c.f., Stanistreet et al., 2018b, McHenry and Stanistreet, 2018), above which only Middle and Upper Bed II were deposited in that region.

Archaeological sites related to valleys (K = korongos, e.g. FLK = Frida Leakey Korongo, HWK = Henrietta Wilfrida Korongo in Fig. 1) and cliffs (e.g. RHC = Richard Hay Cliff) were named by Leakey (1971) and Leakey and Roe (1994), whereas geological locality numbers (e.g. Loc. 66e, Loc. 80) refer to section localities measured by Hay (1976). From outcrop data collection, Fifth Fault was suggested by Stollhofen and Stanistreet (2012) to represent the major extensional detachment, on which the entire Olduvai Basin rode and developed, subsiding down-to-the-southeast, in concert with synthetic faults, including Second, Third, and Fourth Faults (Fig. 4). They further recognised the FLK Fault as one of a series of antithetic faults that had opposite senses of throw to the major detachment, and these faults, and the DK Horst (DK = Douglas Korongo) they define, also rode on top of the main fault detachment. Based on this structural configuration the lake depocentre was expected to be between Fifth Fault and FLK Fault. However, prior to the OGCP (Olduvai Gorge Coring Project) drilling campaign, the older parts of the basin stratigraphy (including the whole of Bed I) were inaccessible in that area, due to downfaulting and overburden of younger strata. OGCP drillsite locations were consequently chosen to test the envisaged structural model, as all three boreholes would intersect the proposed deepest palaeolake in an area of

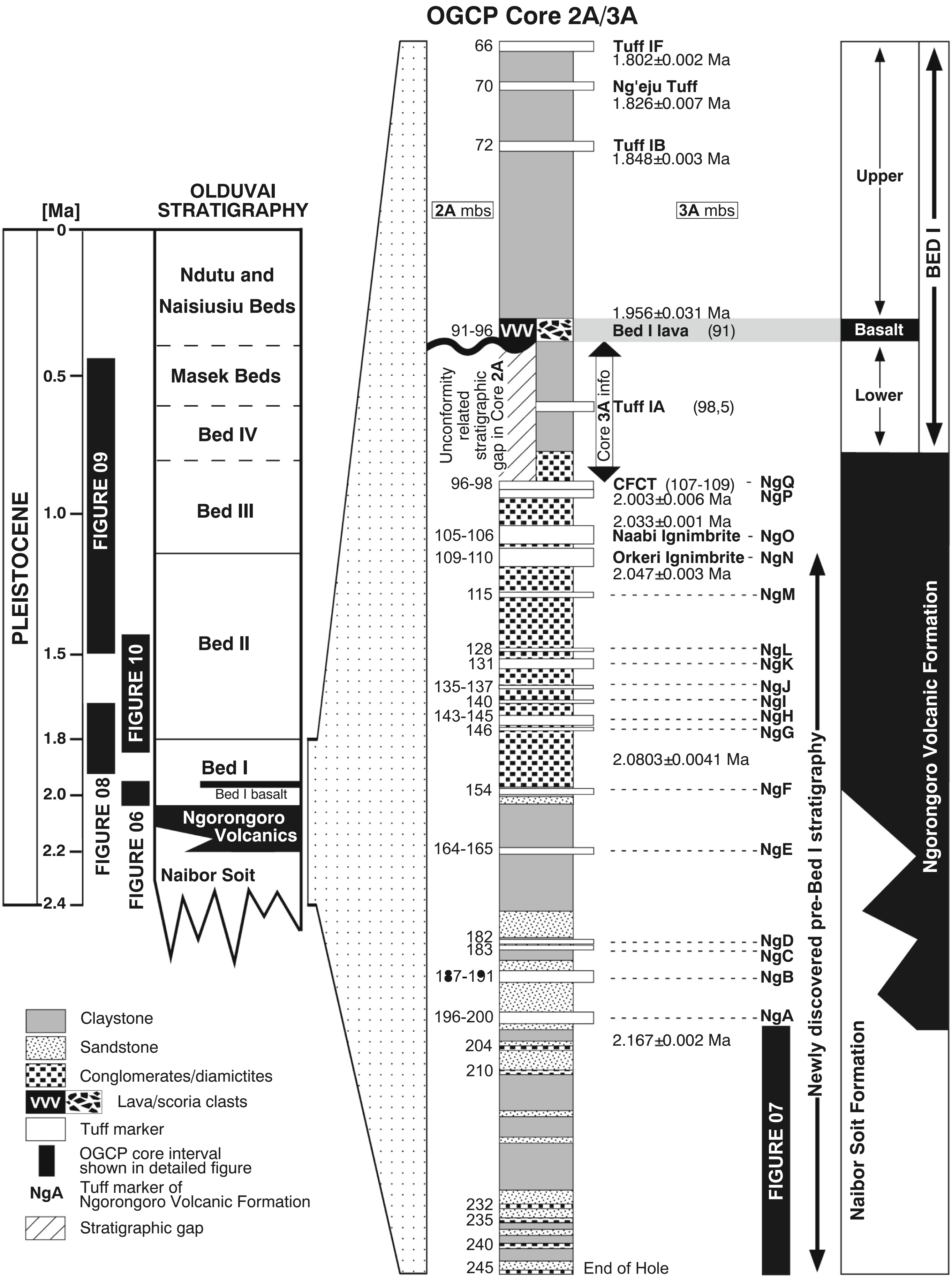


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**Fig. 2.** Generalized Olduvai Basin stratigraphy (left column), based on Hay (1976). Middle stratigraphic column provides a combination of OGCP Core 2A and Core 3A stratigraphy with Ar/Ar dates of tuffs derived from Deino et al. (this volume). mbs = metres below surface. Most of the information is derived from Core 2A with numbers to the left of the stratigraphic column indicating mbs positions of marker beds. Only the CFCT to Bed I lava interval (marked by an arrow) is added from Core 3A (with mbs labels to the right of the column), because this interval is missing in Core 2A due to an unconformity. Newly discovered are sub-Bed I strata (Naibor Soit and Ngorongoro Volcanic Formations), with NgA to NgQ labels indicating positions of marker tuffs in the Ngorongoro Formation (middle and right column). Tuff IF, Tuff IB, NgP = Naabi Ignimbrite, and NgQ = Coarse Feldspar Crystal Tuff (CFCT) ignimbrite have been geochemically fingerprinted by McHenry et al. (2020, this volume). Black vertical bars mark stratigraphic positions of figures that follow.

assumed maximum basin subsidence and most continuous lacustrine deposition. The drilling results aimed to achieve high-resolution records of changing palaeoclimatic and palaeoenvironmental conditions at particular sites of the Olduvai Basin through time, whereas complementary 2D seismic lines would test the proposed basin model in a NW-SE cross-section running between the Olduvai Main and Side Gorge (Lu et al., 2019).

## 2. Methods

### 2.1. Drilling and core handling

Three vertical OGCP (Olduvai Gorge Coring Project) boreholes were sited in the sub-basinal depocentre (Figs. 1, 3 and 4) towards the southeastern, southwestern and northern edges of the deepest paleolakes, as reconstructed by Hay (1976) (Fig. 1). The boreholes were intended to maximize core retrieval from maximum thicknesses of lake sediments, retrieve sedimentary cores from all major Olduvai sequence geological formations, aiming to obtain a palaeoenvironmental and palaeoclimatic dataset as complete and continuous as possible. An extra Borehole 3B at Site 3, inclined 23.5° from the vertical, was drilled to facilitate palaeomagnetic reversal analysis, necessary particularly for more finely resolved chronostratigraphy in the upper formations.

Coring was accomplished with an Atlas Copco CS 14 Diamond Core Drill Rig, using HQ3 surface set core bits (3.782″ × 2.400″). Drilling employed the HQ3 triple tube method whereby cores were collected in carefully sealed polycarbonate liners, ~6 cm diameter. The core was removed in 3 m intervals and the short extra core in the core-catcher was removed separately. The 3 m core was halved to approximately 1.5 m core segments, which were numbered for a single drilling interval. For example, in Core 2A, drilling interval 15 was subdivided into: 2A-15Y-1 (1.53 m long); 2A-15Y-2 (1.54 m long); 2A-15Y-3 (0.14 m long from corecatcher). These separate intervals are identifiable against the whole core stratigraphy that resulted (Fig. 5). A total of 575.48 m of core was retrieved from the 4 boreholes, with a total depth of 611.72 m achieved and 94.1% core recovery overall (Table 1). All drill sites record an almost zero stratal dip.

The sealed cores were then flown to the LacCore storage and handling facility at the University of Minnesota, Twin Cities, where the cores were split into mirroring "archive" (A), and "working" (W), intervals. The working W-split was systematically sampled for a variety of purposes, including palaeoclimatic proxy analysis, radiometric dating, tuff fingerprinting, and palaeomagnetic reversal analysis. The A-split was documented at LacCore using high-resolution linescan GEOTEK system core imaging, and by manual logging to < cm resolution, using LacCore Psicat and Corelyzer software, supported by stereo microscope and smear slide sample inspection. This was followed later by XRF scanning at the University of Minnesota, Duluth at high (1 cm step) resolution, to acquire geochemical proxy data for testing palaeosalinity and palaeoclimatic variation with orbital cyclicity (Stanistreet et al., 2020a) and to apply to other studies.

### 2.2. Core logging and intra-basinal correlation

Many of the "classic" Bed I and Bed II sections measured by Hay, 1976 are exposed in natural outcrops of both the eastern and western Olduvai Gorge and about 200 archaeological trenches excavated by the OLAPP (Olduvai Landscape Palaeoanthropology Project) and OGAP (Olduvai Geochronology Archaeology Project) teams. Those trenches had been previously logged to > cm accuracy to derive grain size, structural, textural and petrographic data for process-related sedimentological (e.g., Stollhofen et al., 2008; Stanistreet et al., 2018a), sequence stratigraphic (e.g., Stanistreet, 2012; Stanistreet et al., 2018b) and palaeoecological interpretations (e.g., Bamford et al., 2008; Albert et al., 2015, 2018). Wherever possible, these outcrop-related data were integrated with the core logging results as the latter provide high resolution and continuous records, but only at one particular locality, while facies architecture, palaeotransport indicators and spatial coverage of additional outcrop analogue data enable interpretations on a basinal scale.

Disconformities bounding Beds I, II, III, IV, Masek and Ndutu Beds, were determined within the cores and were used to apply sequence stratigraphic concepts. The latter are recognised as a method for the definition of time slices at multi-millennial scale, using lake-level related disconformities, paraconformities, maximum flooding surfaces and the facies architecture of enclosed sedimentary sequences for the identification of stratigraphic gaps and for intra-basinal correlation (Stanistreet, 2012; Stanistreet et al., 2018a, 2018b).

The established tephrostratigraphy initiated by Hay (1976) and Leakey (1971), and modified and extended subsequently (McHenry, 2005, 2012; McHenry et al., 2008, 2013, 2016, 2020; Habermann et al., 2016a) facilitated core to outcrop correlations (Figs. 2 and 3). Tephrostratigraphic correlation at Olduvai has been refined by tuff fingerprinting techniques, involving microprobe analyses of characteristic single mineral grain separates and glass particles (McHenry, 2005, 2012), and the definition of geochemical zones, based on the statistical analyses of geochemical data (McHenry et al., 2013; Habermann et al., 2016a). In addition, many of the Bed I and older tuffs have been precisely $^{39}Ar/^{40}Ar$ dated (Deino, 2012; Deino et al., in preparation, this volume).

## 3. Results

### 3.1. Results of the drilling

The first borehole, 1A, was drilled into the lake sump about 300 m southwest of the Leakey Research Camp, 600 m west of the FLK Fault on its downthrown (hangingwall) side (Figs. 1, 3 and 4). The hole was collared on the plateau of the Serengeti Plain, 400 m away from the south side of the Main Gorge, to avoid down-cutting effects into the gorge, associated particularly with the base of the capping Ndutu Beds. The topmost Ndutu Beds provided the boreholes with a substantial well lithified collar, although Borehole 2A also intersected unlithified, recent sediments even above the Ndutu. After problems with accessing water, by End-of-Hole 85 m of core had been retrieved (Figs. 3 and 5), with the drill only just penetrating below the basalt lava, 2.5 m into Lower Bed I (sensu McHenry, 2012). Useful, continuous lacustrine Bed II core was retrieved, with least fluvio-deltaic or fan-deltaic processes affecting the sequence.

The rig was moved on its caterpillar tracks another 2 km to the west, just to the south of Bos Korongo of Leakey (1971). The Borehole 2A location was again in a hangingwall position, c. 1.5 km SE from the Fifth Fault, which bounds the west side of the lake depocentre. This time the drilling easily penetrated the Bed I Basalt (Fig. 3) and

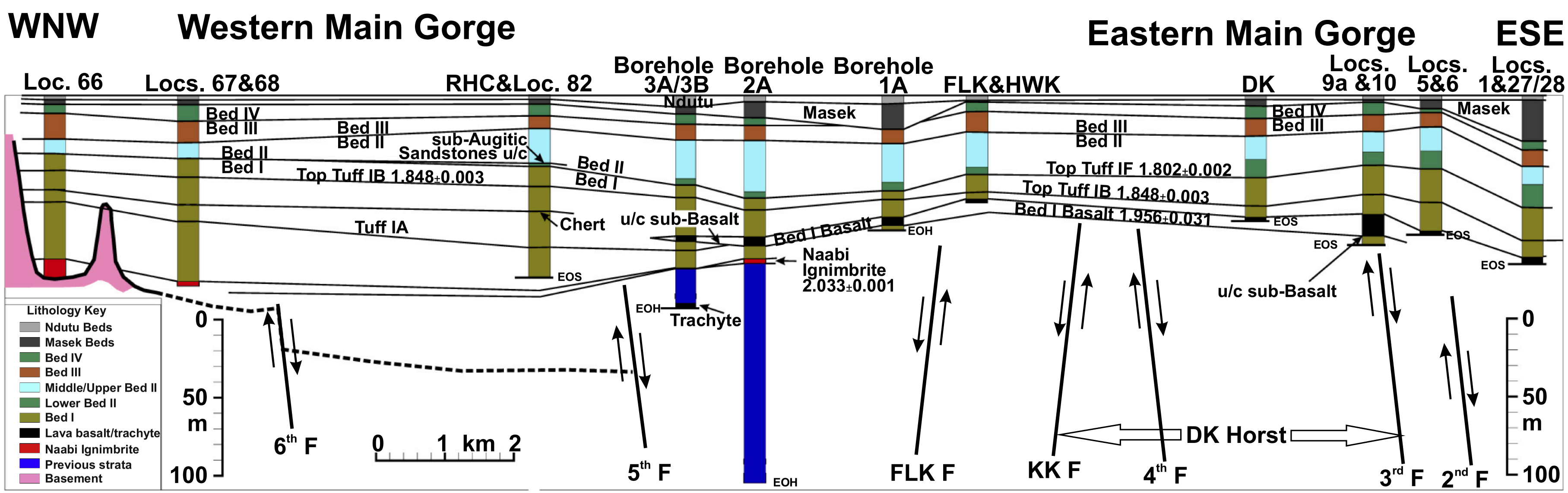


**Fig. 3.** The outcrop stratigraphy of Hay (1976) correlated to the borehole logs, modified by section measurements of HS & IGS, particularly in the far westernmost Main Gorge, where the top of Bed I has been truncated by the sub-Augitic Sandstones unconformity (c.f. Stanistreet et al., 2018b, McHenry and Stanistreet, 2018). Dates of Tuffs and Basalts are those measured by Deino et al. (in preparation, this volume) from Borehole 2A. Faults are shown for positional and polarity information only. This paper includes Hay's (1976) lowermost Bed I as the top of the newly defined Ngorongoro Formation in subsequent diagrams. Cores 1A, 2A, 3A are arranged perpendicularly across tectonic strike (i.e., orthogonal distance from the Fifth Fault). This has the additional advantage that proximal/distal facies variation in the newly defined Ngorongoro Formation of Fig. 5 is best ordered and displayed.

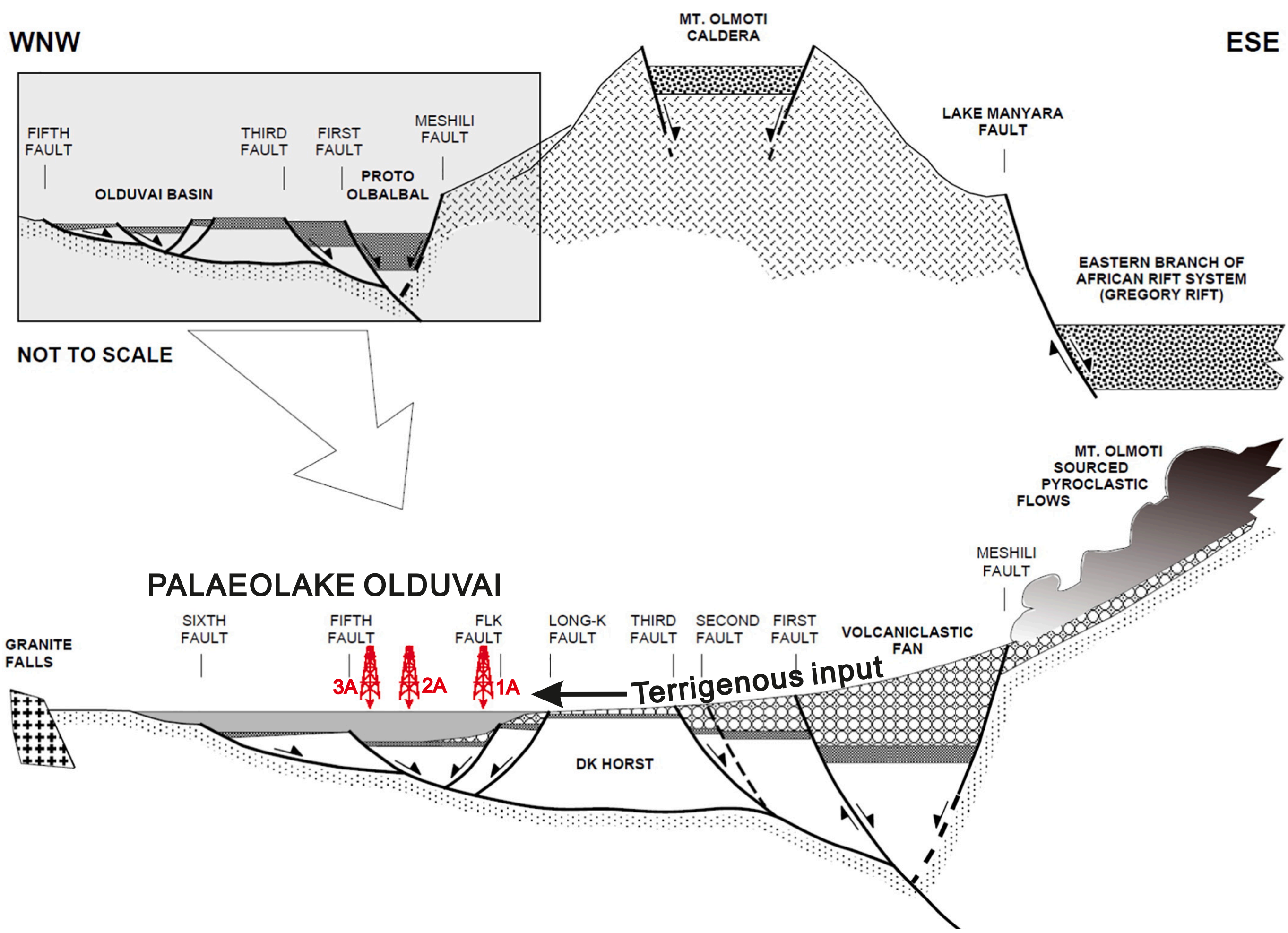


**Fig. 4.** Structural elements of the Olduvai Basin and the structural positions of the drill sites, with Boreholes 1A, 2A and 3A detailed with respect to Fifth and FLK Faults (see Fig. 1 for spatial distribution). The palaeogeographic reconstruction is shown for the time of Tuff IE at ~1.81 Ma, when Olmoti was the active volcano. Modified from Stollhofen and Stanistreet (2012).

continued down beneath. However, drilling continued even further below the level of the Naabi Ignimbrite, which had previously defined the base of the Olduvai Beds in the far western gorge (see Locs. 66, 67 and 68, Fig. 3), where it sits upon Archaean gneissic and Neoproterozoic schist and metaquartzitic basement. Subsequently, the drill penetrated a further ~137 m of primary volcanics, tuffs, volcaniclastic sandstones, claystone and sandstone beds. Significantly the hole bottomed out at 245 m in a purely fluvio-lacustrine sedimentary sequence, dominated by basement rather than volcanically derived detritus.

Boreholes 3A and 3B were drilled in a most northerly position within the lake depocentre only about 400 m to the south of Fifth Fault, again on its downthrown side. The site was chosen with the intention of penetrating the majority of lacustrine sequences of Beds III, IV and Masek, as portrayed by Hay (1976, his Fig. 63), where he speculated that such lakes were in small localised depocentres that migrated to the northeast. This proved a surprisingly fortuitous site. Not only were Beds III and IV lacustrine there, but Beds I and II were also. The two cores constitute the stratigraphically most complete, as well as the most continuous lacustrine record that has been documented within the basin for the stratigraphy defined by Hay, (1976).

Correlation of cardinal stratigraphic units (Hay, 1976; McHenry, 2005; Stanistreet et al., 2018b) to those of the borehole relied upon comparison to the measured sections of Hay (1976), as close to the individual boreholes as possible. In this regard, Hay, 1976 relied heavily on major disconformities to provide boundaries to almost all his major units (Beds II, III, IV, Masek, Ndutu, Naisiusiu), only the Bed I/Bed II boundary was marked by a time plane defined by the top of Tuff IF. In his use of disconformities, Hay (1976) anticipated (Stanistreet, 2012; de la Torre et al., 2018; Stanistreet et al., 2018b) the development of Sequence Stratigraphic usage (Van Wagoner et al., 1988) of disconformities for worldwide correlation of orbitally forced boundaries of Sequences and Parasequences.

All Beds encountered in the cores will now be designated together with their contained lithofacies associations in the borehole cores according to increasing age, in the order encountered during the drilling. Previously known stratigraphy is dealt with first and then newly intersected stratigraphy is dealt with later in the section.

### 3.2. The Ndutu Beds in Cores 1A, 2A, 3A

The facies association of the Ndutu Beds is fairly constant in all three boreholes (Fig. 5) and is similar to facies described from the same unit by Hay (1976). It comprises thick (20 cm to 100 cm) units of brown rather well sorted medium to coarse sandstone (yellow ornament on Fig. 5) comprising quartz, feldspar, augite, clay and volcanic grains. The sandstones are interleaved with relatively thin (5 cm to 20 cm) units of conglomerate (orange ornament) with clasts (< 5 cm) of calcrete, quartzite, claystone and rare granite. Shell material was identified in some of the sandstones, likely gastropod, as Hay, 1976 reports the presence of remains of the land snail, *Limicolaria*, from the same levels. The sandstones are overprinted by calcareous nodular horizons 20 cm to 40 cm thick, some of which show laminated flowstone

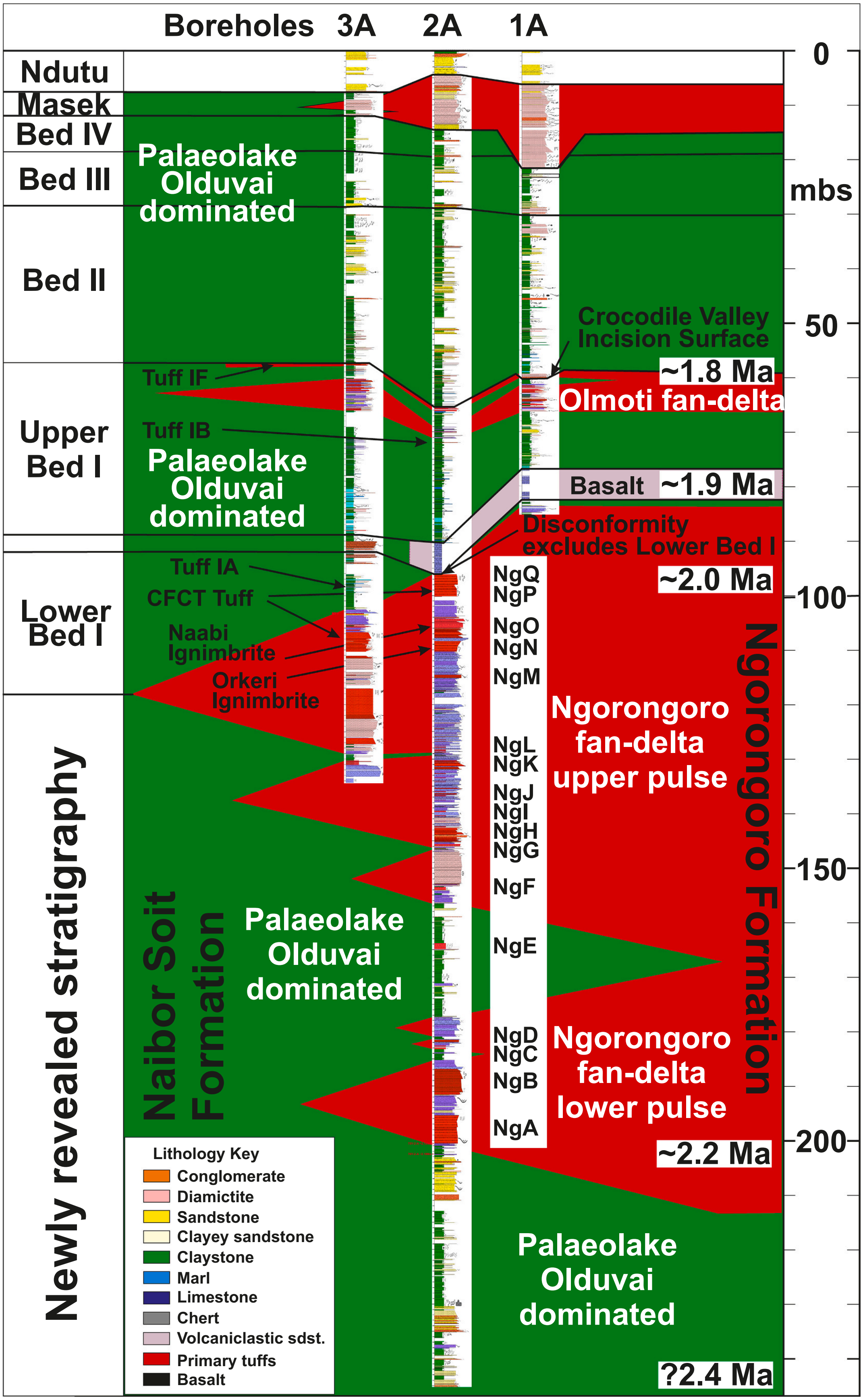


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**Fig. 5.** Correlation of the cores from Boreholes 1A, 2A and 3A, applying the known outcrop stratigraphic terminology of Hay (1976) to the borehole stratigraphy of Boreholes 2A and 3A. Borehole positions are located in Fig. 1. Note that they are placed in the "lake sump" here in their NW-SE structural positions within the depocentre, related to distance from Fifth Fault, not in an east-west line. Core 3A was sited adjacent (~0.4 km) to, but on the downthrow side of Fifth Fault, the master detachment. Cores 2A and 1A are respectively ~1.5 km and ~3.6 km to the east of Fifth Fault. Legend as for Fig. 6. NgA, NgB,……. represent newly defined Tuff Markers. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

structure. Bioturbation is common at some horizons with burrows often showing characteristics of insects, particularly the vertical burrows (5 mm to 12 mm diameter) and horizontal galleries of termitaria. Carbonate overprints often preferentially form within termitarian burrows, picking out their geometry.

### *3.3. The Masek Beds in Cores 1A, 2A, 3A*

Diamictites (pink motif in Fig. 5) dominate the facies association of the Masek Beds, particularly so in Cores 1A and 2A, with clasts < 10 cm diameter, more usually < 2 cm. Two varieties are present, clay diamictite, in which clasts are supported in a very clay-rich matrix, and sandy diamictite, in which sand forms up to half the matrix material. Clasts comprise transported carbonate nodules, highly altered mafic volcanics, claystone, clay and rare pink feldspar. Those facies are associated with coarse to very coarse sandstone (yellow in Fig. 5) and clayey sandstone (light yellow in Fig. 5), and conglomerate (orange in Fig. 5) interbeds from 5 cm to as much as 55 cm thick. In Core 3A that facies association is interbedded with another facies association comprising claystone and sandy claystone units (20 cm to 50 cm thick green colour in Fig. 5), commonly containing nodular limestone horizons (~6 cm thick). The claystone facies interfinger with the diamictite dominated facies to such an extent that thin claystone layers as thin as a few centimetres can be found interleaved with diamictite units as far east as Borehole 1A.

### *3.4. Bed IV facies associations in Cores 2A and 3A*

Bed IV was not intersected in Borehole 1, where it is removed by the sub-Masek unconformity, as first recognised by Hay, 1976, as part of a feature that he termed the "main drainageway". In Core 3A the facies association resembles closely that described by Hay from Loc. 204, which is not surprising, because Borehole 3A is only 500 m away from that locality, but 3A is sited on the hangingwall (downthrow) of Fifth Fault, and so doubles its thickness. The Bed IV facies association in Core 3A comprises claystone and sandy claystone units 4 cm to 140 cm thick (green in Fig. 5). Ostracods are relatively common. Interlayered with the claystones are sandstone (yellow in Fig. 5) and clayey sandstone (light yellow) layers 2 cm to 30 cm thick, which can fill desiccation cracks and burrows, developed in the top surface of the underlying claystones, which also contain nodules. Rare meniscate burrows are present.

The facies association of Bed IV in Core 2A is similar to that just described from 3A, but differs in certain details. The claystone and sandy claystone units are 20 cm to 100 cm thick, but much more dominated by sandy claystone facies, which might contain scattered authigenic calcite crystals (< 0.2 mm). No ostracods were recognised. Coarse sandstone and clayey sandstone facies units are 5 cm to 20 cm thick, with quartz, calcite crystal, carbonate and rare feldspar and augite grains. They are joined by erosionally based granule and pebble clast-supported conglomerate units (orange in Fig. 5) 10 cm to 20 cm thick. Clasts include common quartz, carbonate nodule, and claystone with less common quartzite, feldspar and volcanic lava clasts. Horizons ~15 cm thick exhibit inclined or vertical burrows (4 mm diameter).

### *3.5. Bed III facies associations in Cores 1A, 2A and 3A*

Bed III was intersected in all the boreholes, but its top was truncated by the sub-Masek unconformity in Borehole 1A. Its main facies association again comprises claystone and sandy claystone facies (green in Fig. 5), with claystone most abundant in Core 3A, intermediate in Core 1A and least abundant in Core 2A, where sandy claystones dominated. Interbedded are layers of medium to coarse sandstone, some fining upward with typically erosional bases, comprising common quartz, augite, feldspar and clay grains.

Another facies association is developed at the base and top of Bed II in Cores 1A and 2A, sandwiching the previous facies association. This includes diamictites (clay and sandy clasts, < 8 mm), granule conglomerate (clay pellet, carbonate nodule, quartz, pink feldspar clasts < 4 mm), and fine to very coarse sandstone and clayey sandstone units (20 cm to 50 cm), including phonolite grains (and clasts), quartz, augite, and uncommon pink and clear feldspar grains. Interlayered are subordinate sandy claystone (dominant) and claystone layers 2 cm to 30 cm thick.

### *3.6. Bed II facies associations in Cores 1A, 2A and 3A*

The claystone and sandy claystone facies association, described previously, dominates Bed II, where it is associated with thin layers of sandstone, calcarenite or siltstone which can be normally graded and occasionally exhibit ripple cross-lamination, loaded bases or internal convolute lamination. Ostracods and bivalves are found rarely. Straddling the Lower Bed II and Middle Bed II boundary are two horizons bearing chert nodules. Primary thin tuffs are also laid down within the claystone facies association as thin (2 cm to 6 cm) layers, usually normally graded, but sometimes not graded, depending upon grain sorting. Bed II tuffs are discussed in more detail later.

The claystone facies association intertongues with the conglomerate, sandstone, clayey sandstone and claystone facies association at various levels, especially well developed in Middle Bed II in Core 2A and the upper half of Middle Bed II in Core 3A. Those sandstones are coarse to very coarse, usually augitic to very augitic, comprising also quartz, calcite crystal and less common lava lithic grains, with varying amounts of clay grains. Thin (< 15 cm) erosively based granule and pebble conglomerates are interlayered, containing quartz, carbonate nodule and clay clasts in a sand matrix of quartz with some augite grains.

Within Upper Bed II of Core 1A, the diamictite facies association

**Table 1**
Positions, depths and recoveries of OGCP 2014 boreholes.

| Borehole | Drilled (m) | Recovery (m) | Recovery (%) | Position (latitude longitude) |
|---|---|---|---|---|
| 1A | 85.05 | 77.16 | 90.7 | S2 59′ 08.2″ E35 20′ 34.1″ |
| 2A | 245.40 | 236.55 | 96.4 | S2 57′ 13.9″ E35 15′ 33.2″ |
| 3A | 134.37 | 121.19 | 90.2 | S2 56′ 41.6″ E35 22′ 51.5″ |
| 3B (incl. 23.5°) | 146.90 | 140.58 | 95.7 | S2 56′ 41.6″ E35 22′ 51.5″ |
| TOTAL | 611.72 | 575.48 | 94.1 | |

described previously, containing diamictite and sandy diamictite units 30 to 60 cm thick (clast diameter < 10 mm), intertongues with the claystone and sandy claystone facies association, more typical of the Bed II depocentre as a whole.

### 3.7. Bed I facies associations in Cores 1A, 2A and 3A

The claystone and sandy claystone facies association dominates Bed I, however in this formation it is joined by two facies not yet encountered in the cores, those of primary micritic carbonate layers and marlstone in units 10 cm to 50 cm thick. Also included in the facies association are thin layers of fine sandstone, calcarenite or siltstone, sometimes normally graded. Occasionally such layers contained ripple cross-lamination and showed load casting of their bases or convolute lamination within.

In the upper half of Upper Bed I a contrasting facies association intertongues with the claystone association. Particularly well developed in Cores 1A and 3A, this facies association is dominated by erosionally based fine to very coarse volcaniclastic sandstones in beds 5 cm to 20 cm thick and primary tuff deposits (layers 2 cm to 25 cm thick) comprising fine and coarse ash tuff, lapilli ash tuff and ash lapilli tuff. Pumice is a common constituent, together with euhedral crystals and crystal fragments, including augite and rarely hornblende. Tuff layers are usually massive or laminated, with normal grain-size grading common and some reverse grading. The latter facies association also includes some diamictite and sandy diamictite units < 10 cm thick.

### 3.8. The Ngorongoro Volcanic Formation in Cores 2A and 3A

Of the new sub-Bed I stratigraphy discovered by OGCP, the first major unit intersected by Boreholes 2A, 3A and 3B is a thick 105 m pile of volcanic and volcano-sedimentary deposits (Fig. 5), topped by the Coarse Feldspar Crystal Tuff (CFCT) and its subsequent or occasionally laterally equivalent mass flow and fluvial deposits. These units have been identified in outcrop and have previously been designated the Ngorongoro Volcanics (Hay, 1976; McHenry, 2005; Mollel and Swisher, 2012; McHenry, 2012). From a conservative stratigraphic standpoint (see also Stanistreet et al., 2018a) we name this unit more formally the Ngorongoro Volcanic Formation or Ngorongoro Formation, with Core 2A as its Type Section. However, from the perspective of the cores we now formally designate its topmost boundary with Bed I as the interface between the reworked units of the CFCT (Habermann et al., 2016a) and the overlying thick lacustrine claystone interval (Figs. 5 and 6). Then all the underlying volcanic and volcaniclastic products of Ngorongoro Volcano, including the CFCT and Naabi Ignimbrite are contained within a single formation all associated with the lava and pyroclastic deposits generated by Ngorongoro Volcano itself. Validating the geographical use of the name Ngorongoro, some correlatory units are found in the lavas and tuffs recorded by Grommé et al., 1970 and Mollel et al. (2008) exposed in the wall of Ngorongoro Caldera.

Where appearing in diagrams in the literature, the contact between the Ngorongoro Formation and overlying Bed I is always represented correctly as a pronouncedly diachronous boundary (Hay, 1976; Mollel and Swisher, 2012). This is represented in the borehole correlations (Fig. 5). Indeed, formational boundaries in the deeper parts of Boreholes 2A and 3A are visibly diachronous (Fig. 5), as is generally the case sedimentologically (Stanistreet et al., 2018b). Timelines such as those represented by primary Marker Tuffs should cross the lithostratigraphic boundaries from one formation into the adjacent one. A good case in point is Tuff NgE (Figs. 2 and 5), which crosses from the Ngorongoro Formation into the adjacent sedimentary unit, the Naibor Soit Formation, defined below.

In terms of facies associations, the Ngorongoro Formation comprises volcaniclastic sandstones, in units typically 20 cm to 100 cm thick of coarse to very coarse sandstones, containing grains and scattered granule to pebble clasts of lava, tuff, pumice, feldspar, some obsidian, scoriae, clay grains and euhedral feldspar fragments. The sandstones are interbedded with volcanic conglomerates 20 to 70 cm thick, normally, reverse, or non-graded, containing clasts of lava, some vesicular, tuff (some bedded), pumice, with occasional obsidian, clay and feldspar. Also present are 5 cm to 250 cm thick sandy and lesser clay diamictite units, also normally, reverse or non-graded, with a clast composition similar to that of the associated conglomerates. The facies association is completed with primary volcanic fine ash, coarse ash, lapilli ash, ash lapilli tuffs, in units 5 cm to 200 cm thick. Included are pumice-rich and crystal-rich varieties, also comprising lithic fragments in variable mixes.

Many major volcanic events or closely spaced sets of events can be identified within the Ngorongoro Formation, most of which can be attributed to the more major eruptions of Ngorongoro Volcano. Logical letter coding of these events provides a tephrostratigraphic framework for the newly discovered unit. To create this logical coding, we conformed as closely as possible with the method previously applied by Hay (1976) to the Tuff Markers of the Olduvai Beds, whereby “tuff” refers to individual ash fallout, ash flow or surge deposits, and the capitalized “Tuff” refers to a marker unit that might contain multiple eruptive events, together with reworked sedimentary layers. For example, Bed I contains Tuffs IA, IB, IC, ID, IE, IF. Note however that not all these derived from the same volcano: Tuff IA derived from Ngorongoro, while the others came from Mount Olmoti (McHenry et al., 2008). It is the stratigraphic unit in which they are contained that provides the nomenclatural prefix, not the source. Therefore the 17 Marker Tuffs within the Ngorongoro Formation are named NgA, NgB, NgC………, but this nomenclature does not require that all of the Marker Tuffs derive from Ngorongoro Volcano. However, there is little doubt that most of them should prove to have derived from this source, as the only known nearby active eruptive centre at the time (Mollel et al., 2008).

### 3.9. The Naibor Soit Formation in Cores 2A and 3A

Facies that were deposited to form the Naibor Soit Formation in Palaeolake Olduvai were intersected mostly in Borehole 2A in a major unit that intertongues with, and underlies the Ngorongoro Formation (Fig. 5) described above. We name it the Naibor Soit Formation because the unit was deposited to either side of and would have lapped up against the Naibor Soit metaquartzite inselberg (Fig. 1). We designate Borehole 2A as the Type Section of the new formation. Within the intertongue, the sequence is dominated by claystone facies and sandy claystone facies, an association well represented and previously described from Beds I, II, III, IV and Masek. Interbedded are thin 2 cm to 5 cm sandstone beds, with erosive bases that have picked up clay clasts during their emplacement. Also interbedded are three short intervals, erosively based, where are deposited volcaniclastic and clayey sandstones, thin diamictites and a series of primary fine ash layers 2 cm to 10 cm thick, normally graded with lapilli concentrations at the base, termed Marker Tuff, NgE.

In the unit below the Ngorongoro Formation, the facies association is somewhat different (Fig. 7). There is an interplay between two facies associations. One is the claystone and sandy claystone facies association once again. The other is contained in interleaved units 2 m to 6 m thick comprising mostly medium to coarse siliciclastic (grains mainly quartz) sandstone and clayey sandstone facies layers, 5 cm to 100 cm thick, interbedded with conglomerate units with mainly metaquartzite clasts and some feldspar clasts varying from 4 mm to 16 mm diameter. Thus, there is a pronounced compositional contrast with the overlying Ngorongoro Formation, which is dominated by volcaniclastic material. The facies association is arranged in overall upward and downward thinning and coarsening cycles (Fig. 7). Fining and thinning upward cycles are erosionally based, typically with a gravel unit or units at the base, fining into sandstone and clayey sandstone. Coarsening and thickening upward cycles typically comprise sandstones and clayey

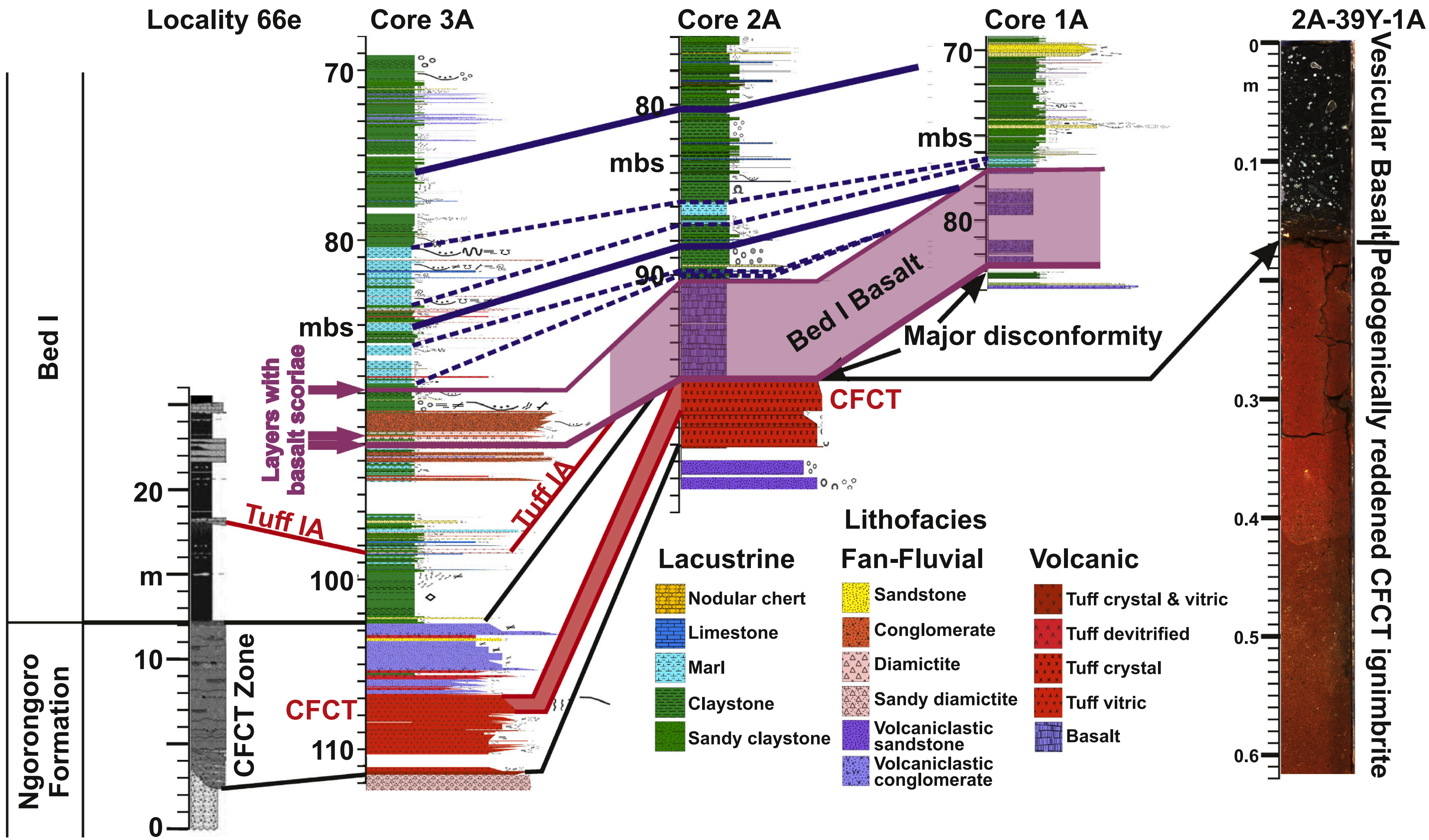


**Fig. 6.** The top boundary contact of the Ngorongoro Volcanic Formation with the overlying Bed I Formation as it is expressed in Cores 1A, 2A, 3A and at Loc. 66e in the western Olduvai Gorge. Lower Bed I in Core 3A correlates with that in the westernmost Gorge (Locality 66e, Habermann et al., 2016a, 2016b) almost unit by unit, whereas at Borehole Site 2A the topmost Ngorongoro Formation and Lower Bed I are eliminated along a major disconformity. Coarse Feldspar Crystal Tuff (CFCT) ignimbrite correlation is proved geochemically (McHenry et al., 2020, this volume). The image of Core interval 2A-39Y-1A shows the disconformity surface in detail as it is intersected in Core 2A. There the Bed I Basalt sits disconformably on the deeply pedogenically affected and reddened CFCT ignimbrite. CFCT Zone is that defined by Habermann et al., 2016a. Blue lines and dashed lines are correlatory tie lines for Upper Bed I carbonates (see Stanistreet et al., 2020b for more detailed descriptions and interpretations). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

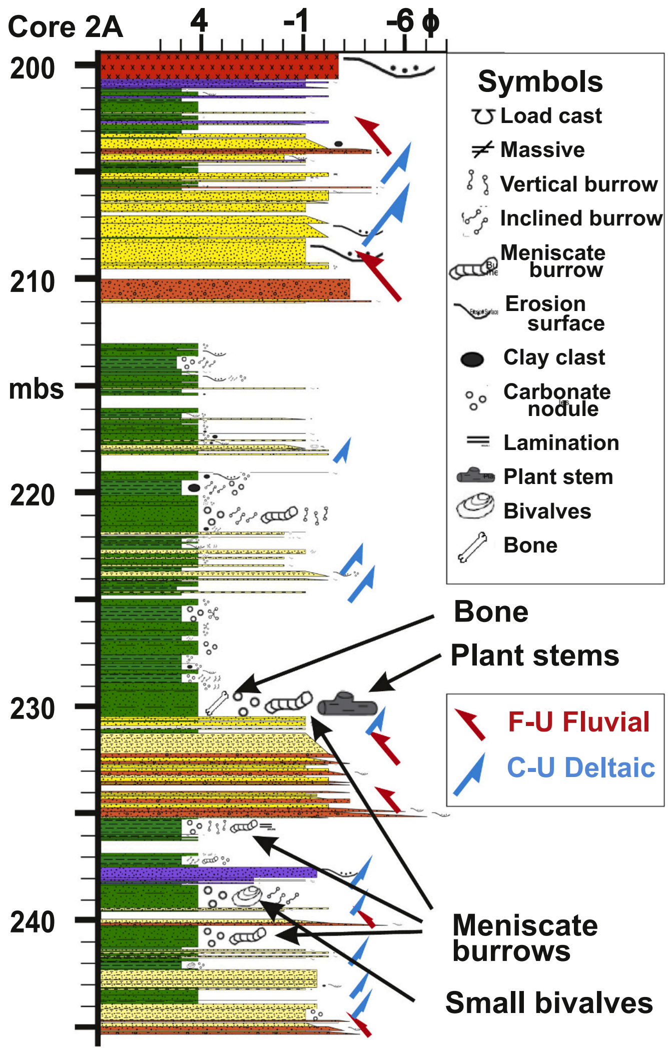


**Fig. 7.** Sedimentary characteristics of the Naibor Soit Formation where it is preserved below the earliest Ngorongoro Formation. Lithofacies as for Fig. 6. Upward fining and thinning trends = fluvial channel bodies; Upward coarsening and thickening trends = delta progradations. Meniscate burrows and preservation of small bivalves, bone fragments and plant stems point towards lake waters slightly fresher than those of the later Palaeolake Olduvai.

sandstones (10 cm to 50 cm thick) interbedded with claystones.

## 4. Correlation of volcanic and tephrostratigraphic markers

Following sedimentological logging and fingerprinting of tuffs within the four borehole cores (McHenry et al., 2020, this volume) preliminary correlation of the core logs was made (Fig. 3) and with the known stratigraphy (Hay, 1976; Blumenschine et al., 2003; Habermann et al., 2016a, 2016b; Stanistreet et al., 2018b) (Figs. 3 and 5). In this regard prominent volcanic markers needed to be correlated.

### *4.1. The Bed I Basalt*

The Bed I Basalt intersected in Boreholes 1A and 2A is 5.7 m thick. Best preserved in Borehole 2A, the same flow facies are preserved in both cores, up to ~2.5 km farther west from previously known FLK outcrop localities. The unit can be subdivided into a porphyric vesicular and amygdaloidal basal lava unit 55 cm thick, containing large lath-shaped feldspar phenocrysts ~2.5 cm long, aligned sub-parallel to the base. Above is a non-vesicular unit 98 cm thick, containing chlorite altered pseudomorphs, possibly after pyroxene, possible olivine crystals, and feldspar laths randomly distributed and oriented. This is succeeded by a 40 cm unit of fine grained basalt with feldspar laths almost absent and then 75 cm of compact lava flow with randomly oriented and distributed feldspar laths < 2 cm long. At the top is a 245 cm thick flow top unit containing plentiful vesicles and randomly oriented feldspar crystal laths. Thus, a single complex subaerial lava flow is preserved almost in its entirety, with no evidence of any magma-water interaction.

No basalt unit was intersected at Borehole site 3. Instead, in Core 3A the stratigraphic position of the basalt was marked by three basaltic scoria-rich pebble layers at 88.9 mbs, 91.5 mbs and 92.0 mbs. These potentially represent separate times when basalt flows were emplaced elsewhere in the basin. Although only a single flow reached the sites of Boreholes 1A and 2A, Habermann et al., 2016a record a pile of at least three complex flows, with no sedimentary interbeds, further east at Locs. 9A and 28 of Hay (1976) and at the Orkeri locality described by Habermann et al., 2016a.

### *4.2. Tuff IF, subaqueous tuffs and the correlation of Upper Bed I*

The crucial Marker Tuff IF did not initially require geochemical fingerprinting, because its volcano-sedimentary facies characteristics were almost identical to those described from outcrop at Richard Hay Cliff (RHC) or Loc. 80 (Stollhofen et al., 2008), although its identity has since been confirmed using phenocryst composition (McHenry et al., 2020, this volume). The subaerial characteristic airfall and vesiculated surge tuff facies (Stollhofen et al., 2008) are also present in Cores 2A, 3A and 3B. Tuff IF was not preserved in Borehole 1A, where it was cut out by a prominent incision surface, as detailed later.

Other Tuffs IB, ID, IE and Ng'eju are thin and deposited subaqueously (similar to those at RHC interpreted by McHenry, 2005). Because the vesiculated tuff facies of Tuff IF indicates subaerial deposition, the interesting preliminary conclusion could be drawn, that even the deepest lake between Fifth and FLK Faults (Fig. 4) was dried and/or emptied at that time of Tuff IF due to megadrought (c.f., Stollhofen et al., 2008; Bamford et al., 2008; Stanistreet et al., 2020a, 2020b). The Ng'eju Tuff was identified at logging stage by its hornblende content (Hay, 1976; McHenry, 2005; McHenry et al., 2020, this vol), but Tuffs IB and CFCT (Coarse Feldspar Crystal Tuff) and the Naabi Ignimbrite required geochemical fingerprinting to identify them unequivocally (McHenry et al., 2020, this volume). It should be emphasised that the cores provided a much more complete tephrostratigraphic record for Bed I than known from any surface outcrop equivalent (Fig. 5).

A stratigraphic marker that benefits the first stage subdivision and correlation of the boreholes is the volcaniclastic sandstone and primary tuff facies association of Upper Bed I (Fig. 5) that comprises the Olmoti fan-delta deposits, with their associated sequence of marker Tuffs IB, IC, ID, IE, Ng'eju and IF. Those Tuffs are all present in the four borehole cores, but not necessarily all of them in each of the cores (McHenry et al., 2020, this volume). The Olmoti fan-delta body is well documented by Hay (1976) in the eastern outcrop area of Olduvai Gorge. There he traced the stratigraphy westwards throughout the Junction Area (Fig. 1), where the fan sediments and tuffs interleave with lake sediments, deposited during lacustrine transgressive phases. Lake clays and sandy clays become more dominant in that subaqueous fan area, until at the most distal position (Borehole 2A), lake clays totally predominate (Fig. 5). Thus, Borehole 2A correlates most closely to the tephrostratigraphic sequence at RHC (Fig. 1), which is even more distal with respect to the fan-delta body, and where Tuffs IB, ID, IE and Ng'eju settled directly into Palaeolake Olduvai (McHenry, 2005) as water-lain deposits in a low energy environment with high preservation potential. The Olmoti Fan extended westwards from Olmoti Volcano, incrementally filling the precursor of the present-day Olbalbal Depression as it developed, overtopping the DK Horst (Stollhofen and Stanistreet, 2012) (Figs. 1 and 4) to prograde into localities further west. It is for that reason that Boreholes 1A, 3A and 3B, which are situated only hundreds of metres west of the DK Horst, are the more proximal Olmoti Fan-delta locations and Borehole 2A is the most distal fan-delta intersection at its extreme subaqueous toe (Fig. 5).

## 5. Discussion: Bed I and post-Bed I palaeoenvironments encountered in the cores

### 5.1. Palaeoenvironments of the Ndutu Beds

Because of the similarity to the facies association described by Hay (1976) across the entire depocentre, palaeoenvironments recognised by him also accord. The well-sorted nature of the Ndutu sandstones suggests a dominantly aeolian source, however no primary aeolian structures are obvious, such as large scale cross-bedding, reverse graded avalanche layers, or pin-stripe cross beds. The massive nature of the sandstones is more similar to that developed by hyperconcentrated flow reworking of aeolian sands described by Svendsen et al. (2003). Interlayer surfaces must have been stabilised by vegetation to support the activities of termites that formed the common termitaria evident in this unit. The surfaces were also pedogenically affected to develop calcrete horizons down from the top of sandstone layers. Intermittent fluvial phases are indicated by the erosively based conglomerate interlayers developed.

### 5.2. Depocentre palaeoenvironments of the Masek Beds

The diamictite dominated facies association characteristic of the Masek Beds, with conglomerate and sandstone interbeds, is the classic facies assemblage developed in alluvial fan systems. The volcanic provenance of lava clasts in the diamictites and conglomerates ties in with the identification of Kerimasi Volcano as the likely source for these units (Hay, 1976). Mudflows would have entered the Olduvai Basin from the eastern side of the basin, and the fan facies register most obviously in Boreholes 1A and 2A. In Borehole 3A the toe of the fan system progrades into the still extant Palaeolake Olduvai, but at that time it was restricted to a far smaller area on the northern side of the depocentre.

### 5.3. Bed IV depocentre palaeoenvironments

Bed IV is the youngest formation within the depocentre to be dominated throughout by claystone and sandy claystone facies. However Core 2A comprises a lake facies association dominated by sandy claystone, and interbedded with erosionally based conglomerates that indicate at least three phases of very low lake level and emergence of the lake bed, when rivers incised shallowly into the subaerially exposed lake bed and then deposited gravel material, prior to the recovery of the lake and its transgression over the fluvial deposits. The dominance of sandy claystone facies at Borehole 2A indicates that this was relatively close to shore, a shallow lake, as proposed by Stanistreet (2012), Stanistreet et al. (2018a) and de la Torre et al., 2018a, 2018b. Deeper lake conditions were maintained at the site of Borehole 3A, where the offshore pure claystones facies is much more common and the sequence yields ostracods.

### 5.4. Bed III depocentre palaeoenvironments

During deposition of Bed III, Palaeolake Olduvai still filled much of the depocentre, although fluctuations in lake level are recorded in the claystone facies association by alternations between sandy claystones and claystones, between lake nearshore and offshore respectively. However, such conditions are best represented at the Borehole 3A site. Further to the east a fan system entered the depocentre to deposit the diamictite, conglomerate and sandstone facies association, representing mass flow and braided stream deposition, particularly at the base of Bed III, and a second fan pulse is evident entering the depocentre towards the top of Bed III. Hay (1976) referred to these two fan pulses as the "Eastern Fluvial Facies", as opposed to the so-called "Western Fluvial Facies" (see also later).

### 5.5. Bed II depocentre palaeoenvironments

Bed II represents a time when Palaeolake Olduvai dominated the entire depocentre, flooding frequently across the Fifth and FLK Faults, which constrained its deepest development, at times of high lake water levels. The lake was deeper, causing low density turbidity currents or tempestites to transport small amounts of coarser siliciclastic or carbonate material into the lake depths. Ostracods and bivalves are only rarely found in the claystones. The chert layers probably represent phases of high alkalinity in the lake, when much silica was taken into solution, to be precipitated below the sediment water interface when water influx became slightly fresher (Eugster and Hardie, 1978; Jones and Deocampo, 2003). They are important for stratigraphic purposes, correlating with two chert nodule horizons described by Hay (1976) from the Olduvai side gorge, particularly in the area of MNK, that straddle the Lower/Middle Bed II boundary.

The lower half of Middle Bed II received quantities of augitic sandstones that mark the levels of the Middle and Upper Augitic Sandstones within the borehole sequence. The material entered the depocentre from the northeast, from which direction a fluvially dominated fan system toed out into the palaeolake. During upper Middle to lower Upper Bed II, more quartzose sands were fluvially carried into the depository from the southwest, in what appears to represent a fluvio-deltaic system. By contrast, during Upper Bed II on the eastern side of the depocentre, mudflows entered the lake to deposit diamictites, where a fan system from the Ngorongoro Volcanic Highlands once more toed into the deepest lake. More proximal stratigraphic equivalents of these mudflows can be found at the EF-HR site (de la Torre et al., 2018; Stanistreet et al., 2018b) and localities east of Second Fault, as described by Hay, 1976.

### 5.6. Bed I depocentre palaeoenvironments

During the deposition of Bed I, the lake was developed more deeply than at any other time. During the lower part of Upper Bed I, between the extrusion of the Bed I Basalt and Tuff IB, the lake in the depocentre became meromictic (Stanistreet et al., 2020a, 2020b). The sediments at that time are carbon-rich, preserving fine laminae, possibly annual (Colcord, et al., 2018, 2019; Shilling et al., 2019, this volume). Anoxic conditions on the lake bottom ensured that there was no bioturbation of the bottom sediment. This phase is related to enhanced basinal extension and subsidence, allowing extrusion of basalt, associated with further extrusion of basaltic tuff units (Stanistreet et al., 2020a).

Primary carbonate and marl layers, deposited in the basinal depocentre, represent the setting up of hemipelagic and pelagic environments during maximum lake transgression, when clay sources were restricted farthest away from the deep lake (Stanistreet et al., 2020a). A complete cycle of lake facies at this time proceeds from interbedded sandstone and/or clayey sandstone facies → sandy claystone facies → claystone facies → marl facies → micrite or dolmicrite facies. The reader is directed to Stanistreet et al., 2020b, where the relationships are figured and dealt with in greater detail.

During later Upper Bed I, as described earlier, the Olmoti Fan-delta system sourced from the active Olmoti Volcano to the east of the basin prograded into the palaeolake. Fan facies filled the Olbalbal Depression and prograded over the DK Horst to toe into the deep palaeolake's east side at Borehole sites 1A and 3A. Only much more distal units extended to Borehole site 2A and not at all to Loc. 80.

## 6. Nature and palaeoenvironments of newly discovered stratigraphy below Bed I

In the deepest parts of Borehole 2A, cored strata below the Naabi Ignimbrite (verified by tuff fingerprinting, McHenry et al., 2020, this volume) amounted to ~135 m, without intersecting basement. Seismic investigations show that sedimentary fill extends to as much as ~320 m below the Naabi Ignimbrite (Lu et al., 2019). However, a good proportion of that deeper stratigraphy likely comprises also the Laetolil Beds (Lu et al., 2019), a unit previously identified beneath the Olduvai Beds at outcrop Locality 101 by Hay (1976). About 15 m of previously unidentified strata were also intersected at the base of Boreholes 3A and 3B, the most intriguing of which are flow units of trachyte/trachybasaltic lavas at the bases of both holes. These are Ngorongoro effusive lavas that sit near the middle of the acidic suite of pyrolastic and volcaniclastic deposits. Thus, they most likely result from magma mixing of basic and acidic melts associated with the emplacement of the bimodal Ngorongoro volcanic suite (McHenry, 2012; Habermann et al., 2016a). Potential equivalents are trachybasaltic lavas at the top of the volcanic sequence exposed in a roadcut of the ascent road out of Ngorongoro Caldera (Grommé et al., 1970; Mollel et al., 2008).

### 6.1. The Ngorongoro Volcanic Formation

The facies association of volcaniclastic sandstones, conglomerates, diamictites and primary tuffs indicates the development of a volcanically sourced fan system, combining debris flow and fluvial processes (Stanistreet and McCarthy, 1993). The Ngorongoro source volcano in this case was a giant stratovolcano that collapsed after major magma ascent and explosive eruptions to form the Ngorongoro Caldera, that persists morphologically to the present. The Ngorongoro Fan debouched directly into Palaeolake Olduvai during two major pulses (Fig. 5), with a major phase of lake transgression in between, and is therefore more correctly termed a fan-delta. At the height of the larger, upper progradational pulse the fan entirely filled the deepest depository, and any lake remaining at that time would only have survived further to the northwest outside the depocentre.

The newly defined contact between Bed I and the Ngorongoro Formation, at the interface between the CFCT and related mass flow units and overlying lake strata (Fig. 6), differs critically between Boreholes 2A and 3A. Borehole 3A offers the most continuous sequence across the boundary, with mass flow deposits following CFCT emplacement giving way to deposition of lake clays, and the interval correlates very well with outcrop localities of the western Gorge (Fig. 6) such as Loc. 66e (Habermann et al., 2016b). By contrast, at Borehole 2A the contact is a pronounced disconformity, with pedogenically modified and reddened CFCT ignimbrite below the contact and vesicular porphyritic Bed I Basalt above, which flowed over the unconformity surface. A similar scenario is seen at Geological Locality 9A (Hay, 1976), at the footwall of Third Fault, where a 1.5 m sedimentary interval of lacustrine claystones and earthy claystones intervenes; Locality 157 (Hay, 1976, see his Fig. 10, reinterpreted by Stollhofen and Stanistreet, 2012); and Orkeri (Habermann et al., 2016a), the latter two exposed on the footwall of First Fault, where the Bed I Basalt lava overlies the red CFCT ignimbrite directly. The red ignimbrite was previously discussed as a potential Tuff IA equivalent by McHenry (2012), but has more recently been re-interpreted as a CFCT equivalent by McHenry et al. (2020, this volume). All the lava facies in Boreholes 1A and 2A are subaerial in nature, with no pillow basalts or other features evident that would suggest any lava-water interaction. The interval including Lower Bed I and the uppermost Ngorongoro Formation are missing at this unconformity, representing a major time gap. The Ngorongoro Fan-delta would have been topographically high and broad at the end of Ngorongoro volcanic activity, occupying the majority of the Olduvai Basin. Remnants of Palaeolake Olduvai would have been restricted far to the northwest by protracted fan progradation. Borehole Core 2A likely represents a position high on the Ngorongoro Fan-delta. There, cessation of volcanic and pyroclastic output has led to long term erosional degradation associated with deep weathering and pedogenesis. The subaerial Bed I Basalt (1.956 ± 0.031 Ma; Deino et al. in preparation, this volume) flowed over that surface (CFCT 2.003 ± 0.006 Ma, Deino et al. in preparation, this volume) ~77 ka later, prior to the initial lake transgressions there of lowermost Upper Bed I (Hay, 1976; Stanistreet et al., 2018a, 2018b). Thus, part of the missing sequence was probably due to the required onlap of lacustrine claystones onto the steeply inclined subaerial part of the fan surface sloping down from Ngorongoro Volcano.

### 6.2. The Naibor Soit Formation: lake deposits and fluvio-lacustrine input

The upper Naibor Soit Formation intertongue (Fig. 5) is dominated by offshore lacustrine (claystone) and nearshore (sandy claystone) facies, in an association well known from higher in the Olduvai Beds in Beds I, II, III, IV and Masek. The interleaved thin sandstones represent small, dilute turbidity current deposits, whereas the thicker erosionally based sandstone, diamictite and tuff units represent phases of lake withdrawal, when fluvial, mass flow and volcanic activity transported material onto the fluvially eroded lake-bed. These essentially represent short-lived progradations of the Ngorongoro fan system into the depocentre.

The lower Naibor Soit unit beneath the Ngorongoro Formation (< 45 m) differs considerably. The claystone and sandy claystone facies association is still well represented, showing that the lake was occupying the depocentre, forming the deepest part of the lake system. The fining and thinning upward gravel to sandstone cycles and coarsening and thickening up sandstone and claystone cycles are well defined (inclined half-arrows Fig. 7). The latter represent increments of fluvio-deltaic to pro-delta systems prograding into the lake, most probably from the southwest, from where exposed metaquartzite inselbergs could provide quartz-rich sediments at various times throughout the history of Palaeolake Olduvai. The coarsening and thinning upward conglomerate facies to sandstone facies represent classic fluvial increments, deposited by rivers that fed the deltaic system and transported material across the previous delta top.

The overall coarsening and fining variations are of a scale recognised elsewhere in the Olduvai Beds as Sequences (in terms of lacustrine sequence stratigraphy Stanistreet, 2012; Stanistreet et al., 2020a), which contain nested Lake-parasequences on a multimillennial scale. The Sequences help to identify overall phases of lake withdrawal and flooding which can be used as timelines for correlation and are associated with Milankovitch climatic changes (Stanistreet, 2012; Stanistreet et al., 2020a).

That the previously defined Ngorongoro Formation comprises deposits of a fan-delta system is shown by five successive lake transgressive interludes, during which the lacustrine sandy claystone and claystone facies association and other facies associations were deposited (Fig. 5). The sedimentary deposits preceded and were then contemporaneous with the early history of the volcaniclastic Ngorongoro Fan-delta.

A basement quartzitic sand and gravel source to the southwest of the Olduvai Basin appears several times during Olduvai Basin history. The quartzose nature of sand grains and quartzite clasts in conglomerates suggests and corroborates that Ngorongoro volcanism had not started at the time of deposition of the lowermost Naibor Soit Formation. Much later, a similar source was actively providing quartz-rich sand into the basin from the south and west. Thus, the same quartzose source becomes apparent again during Bed II, after the deposition of the Augitic Sandstones, and continued providing sand to the Bed III "Western Fluvial Facies", as mentioned earlier (and see also Hay, 1976). It was because of this source that Borehole 1A was placed where it was, to catch the "sweet spot" between that quartzose source and Ngorongoro Volcanic Highlands volcaniclastic sediment provision during later Bed II and Bed III deposition, to provide maximal lake facies for analysis. For this provenance of sediment to show dominance at three times during basin history implies that the source terrain was a persistent entity. Metaquartzite clasts of the lowermost Naibor Soit Formation gravels show that it was the Neoproterozoic metaquartzite of the Mozambique Belt that mainly provided that provenance. Such a source persists today as inselberg outliers such as Naisiusiu (Fig. 1). Additionally, erosional windows to the west of the Laetoli area show that quartzitic sources are also available in that region, preserved beneath the Ndutu Formation cover.

Logging of the core revealed a greater number of small molluscan fossils in the pre-Ngorongoro sequence (Fig. 7) than elsewhere, that suggests fresher water conditions only rarely replicated in the younger lacustrine sequences of the Olduvai Beds. Small bivalves, plant stems, and small fragments of animal bone were recorded, that would not have survived more caustic conditions of highly alkaline lake waters. More intricate burrow systems were logged, some involving spreiten or meniscate structure, indicating more sophisticated burrowing organisms typical of less extreme lake water conditions (e.g., Buatois and Mángano, 2007). It is not surprising therefore that nodules forming at this early stage in the evolution of Palaeolake Olduvai show the lightest δC and δO values of any in the entire sequence (Stanistreet et al., 2020b). This would imply that heavier isotopic values caused by mixing with lacustrine saline-alkaline groundwaters (Liutkus and Ashley, 2003; Bennett et al., 2012; Rushworth, 2012) were less prevalent at that time. Considering seismic data (Lu et al., 2019), the 45 m of Naibor Soit Formation below the Ngorongoro Formation should be considered as a minimum thickness.

The very different nature of Palaeolake Olduvai during deposition of the Naibor Soit Formation is also reflected in the lowest of the transgressive tongues (Fig. 5) that interleave with the Ngorongoro Formation. This is the one part of the core where lake facies preserve diatoms and phytoliths in recoverable quantities, with phytolith results indicating a surrounding savannah environment dominated by grasses and diatoms, sponge spicules and chrysophyte cysts providing fresh water markers (Rodríguez-Cintas et al., 2020, this volume). Less alkaline lake conditions are indicated, possibly supported by enhanced precipitation and/or diagenetic fresh porewater flux derived through aquifers within the adjacent Ngorongoro Fan-delta sequence.

## 7. Particular stratigraphic problems resolved from the cores

During our analysis, various specific stratigraphic problems were encountered, both in correlating between boreholes and between boreholes and nearby surface outcrops. Some of these difficulties and how they were overcome are dealt with below and in Figs. 8, 9 and 10. The stratigraphy, facies architecture and hominin relationships of the uppermost Ngorongoro Formation will be dealt with in other papers that detail the progradation of the Ngorongoro Fan-delta into the basin (e.g., Stollhofen et al., in press).

### 7.1. Tuff IF and the Crocodile Valley Incision Surface

Tuff geochemical fingerprinting revealed that Tuff IF is not present in Borehole 1A (McHenry et al., 2020, this volume). Review of the borehole logging (Fig. 8) then revealed that a major phase of incision, previously termed the Crocodile Valley Incision Surface (CVIS) from surface outcrop analogues, had removed topmost Bed I and lowermost Bed II (see also Stanistreet, 2012; Blumenschine et al., 2012). The CVIS, first defined by Stanistreet (2012) and traced further by Stanistreet et al. (2018a, 2018b) and McHenry and Stanistreet (2018), is known to have eroded into the top of Tuff IF, shallowly at HWK and deeply at Site FC (=Fuch's Cliff) (Fig. 1). Further west, the CVIS at Borehole Site 1A is incised to a level above the Ng'eju Tuff (McHenry et al., 2020, this volume). Crocodile Valley itself (Blumenschine et al., 2009; Stanistreet, 2012) is interpreted as a lacustrine analogue of incised valleys,

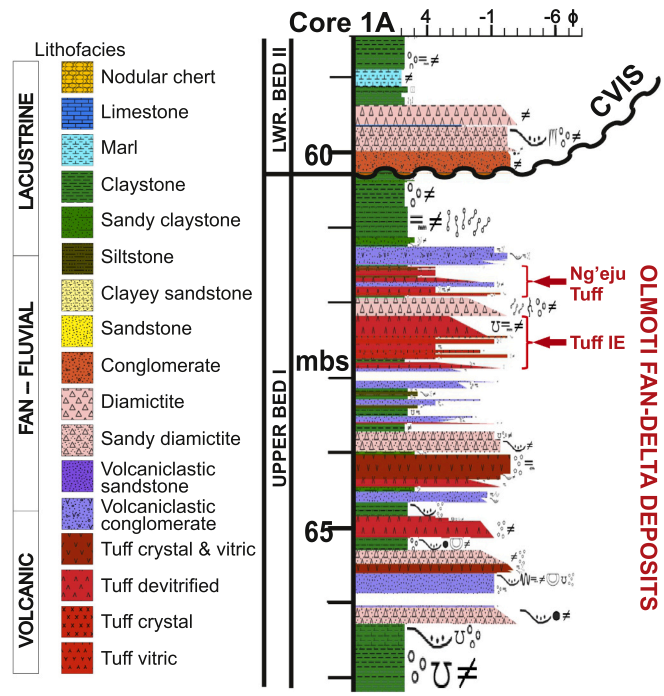


**Fig. 8.** The 59 to 67 mbs depth interval of Core 1A. Lowermost Bed II, Tuff IF, and uppermost Bed I are eroded away by the Crocodile Valley Incision Surface (CVIS) (Stanistreet, 2012; Stanistreet et al., 2018a, 2018b; McHenry and Stanistreet, 2018) down to a level above the Ng'eju Tuff. Symbols as for Fig. 7. Grain size scale is the Krumbein φ scale, whereby 4 = silt/sand; −1 = sand/gravel; and −6 = pebble/cobble grain size boundaries.

originally documented from marine shelf sequences (e.g. Van Wagoner et al., 1988), but also now recognised in fluvio-lacustrine settings (Lemons and Chan, 1999; Keighley et al., 2003; Ilgar and Nemec, 2005). Stollhofen et al. (2008) have documented, on the basis of sedimentary facies analysis, how the lake had almost dried out at the time of Tuff IF, and it must have been a similar major lake-level fall and retreat into the lake depocentre that forced fluvial systems sourced from Olmoti volcano to incise and excavate the Crocodile Valley due to maximal base-level drop. The latter is suggested by Stanistreet (2012) and Stanistreet et al., 2020a) to be associated with aridity related to the MIS 62 glacial. In boreholes 2A, 3A and 3B by contrast, Tuff IF is preserved as an obvious unit.

### 7.2. Bed II and Bed III correlation

Unfortunately, no specific Marker Tuffs recorded by Hay (1976) and McHenry et al. (2016) in outcrops have been identified directly in cores of Beds II, III, or IV. Definition of geochemical zones, applying the techniques of McHenry et al. (2013) and Habermann et al., 2016a will be needed to apply tephrostratigraphy to Upper Bed II. More immediately, chronostratigraphy of all the younger stratigraphic units requires palaeomagnetic reversal determinations. The age model under development by Deino et al. (In preparation, this volume) places the base of the Jaramillo subchron at 26 mbs (within Bed III) in Core 2A, and the base of the Brunhes at 12 mbs (within the Masek Beds). A correlation of the stratigraphy above Tuff IF has however been achieved by recognising the major disconformities that Hay (1976) and Stanistreet et al. (2018b) chose for their stratigraphic subdivisions (Figs. 5 and 9). In this regard, certain sedimentary facies and their compositional characteristics, such as the Upper Bed II mudflows (Hay, 1976; Stanistreet et al., 2018b; McHenry and Stanistreet, 2018; de la Torre et al., 2018a, 2018b) (mudflow diamictite units coloured pink in Figs. 5 and 9) and the Bed III Eastern Fluvial and “Western Fluvial”

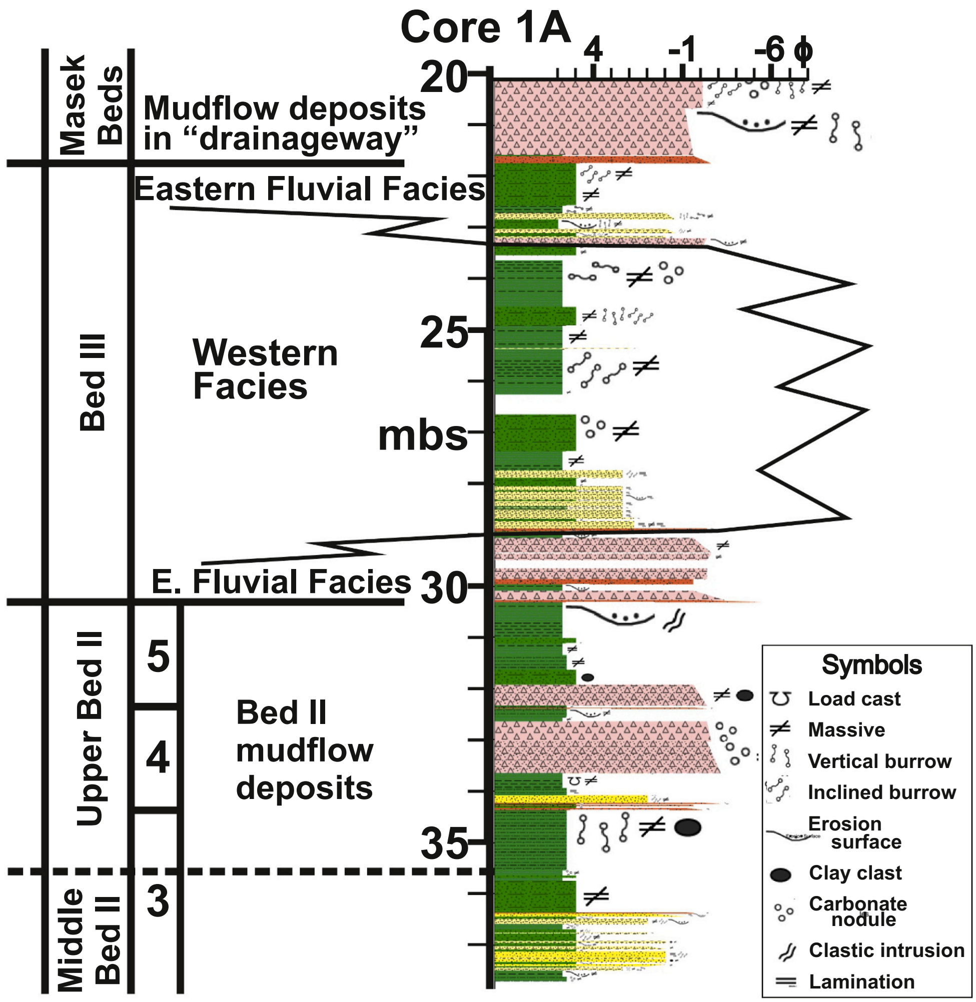


**Fig. 9.** Bed II mudflows and Bed III Eastern Fluvial and Western Facies in Borehole 1A establish a correlation between this borehole and sequences measured by Hay, 1976 in the eastern Main Gorge. Numbers 3, 4, 5 refer to Sequences defined by Stanistreet et al. (2018b) in Bed II. In this borehole, the unconformity underlying the Masek Beds cuts out Bed IV and topmost Bed III (see Fig. 5) and the Masek diamictites (mudflow deposits) sit in the resulting erosional "drainageway" identified and mapped by Hay (1976). Lithofacies legend as for Fig. 8. Grain size scale is the Krumbein φ scale, whereby 4 = silt/sand; −1 = sand/gravel; and −6 = pebble/cobble grain size boundaries.

Facies defined by Hay (1976) intersected in Borehole 1A were most useful in helping to define those formations and constrain their bounding unconformities. The latter could then be correlated across the basin through the other two boreholes as shown in Fig. 5. In this regard Borehole 1A sits at the boundary where the "Eastern Fluvial" and "Western Fluvial" facies meet. This abutting of the two "facies" was mapped by Hay, 1976 at JK (=Juma's Korongo), FLK, and along the Side Gorge, where it passes between Localities 98 and 97 and Borehole 1A sits exactly on this line.

Hay, 1976 characterised his Eastern Fluvial Facies as an interbedding of fluvial and mudflow deposits, with the sand and gravel fraction dominated by volcanic grains and clasts. It is essentially the deposits of the Embagai sourced volcaniclastic fan/fan-delta systems, that continued during deposition of Bed III (Greenwood, 2014), westward off the Ngorongoro Volcanic Highlands into the Olduvai Basin. By contrast, Hay (1976) characterises his "Western Fluvial Facies" as dominated by claystones with fluvial sandstones and some gravels. There the sandstone fraction is dominantly composed of quartz-rich metamorphic debris, as discussed above, mostly derived from the Neoproterozoic quartzite basement. Transport is axial along the tectonic grain of the Olduvai Basin with some input from the west.

### 7.3. Bed II tuffs in the OGCP cores

The only primary (non-reworked) tuffs identified above Bed I were encountered in uppermost Lower Bed II and the lower part of Middle Bed II (sensu stratigraphy of Stanistreet et al., 2018a, 2018b; McHenry and Stanistreet, 2018), comprising thin (3 cm–6 cm thick), well sorted augite-rich basaltic ash tuff layers (red ornament in Fig. 10 log), often normally grain-size graded, a characteristic of airfall and water-settling of ash. Palaeolake Olduvai was relatively deep during Beds I and II (Hay, 1976; Stanistreet et al., 2020a, 2020b), so grains would have sunk below wave-base and settled with size and density grading to preserve the ash layers in the lake depths in a relatively low energy setting. This mode of deposition gives those tuffs characteristics very different from their equivalents in lake marginal and alluvial fan settings to either side of the deep lake. They preserve much more their settling textures and primary volcanic compositions, because the hosting non-volcanic sediment supply is low compared to the classic sections from where they were first described Hay, 1976. Thus, they are relatively little reworked by comparison to Lower and Middle Bed II tuffs to the east at, for example, FLK and HWK (Fig. 1; Stanistreet et al., 2018b). These tuffs are illustrated in Fig. 10, where the base of Bed II is defined by the top of the obvious Tuff IF marker, and the tuffs are associated with two chert nodule horizons. Apart from a chert horizon at the middle of Bed I at

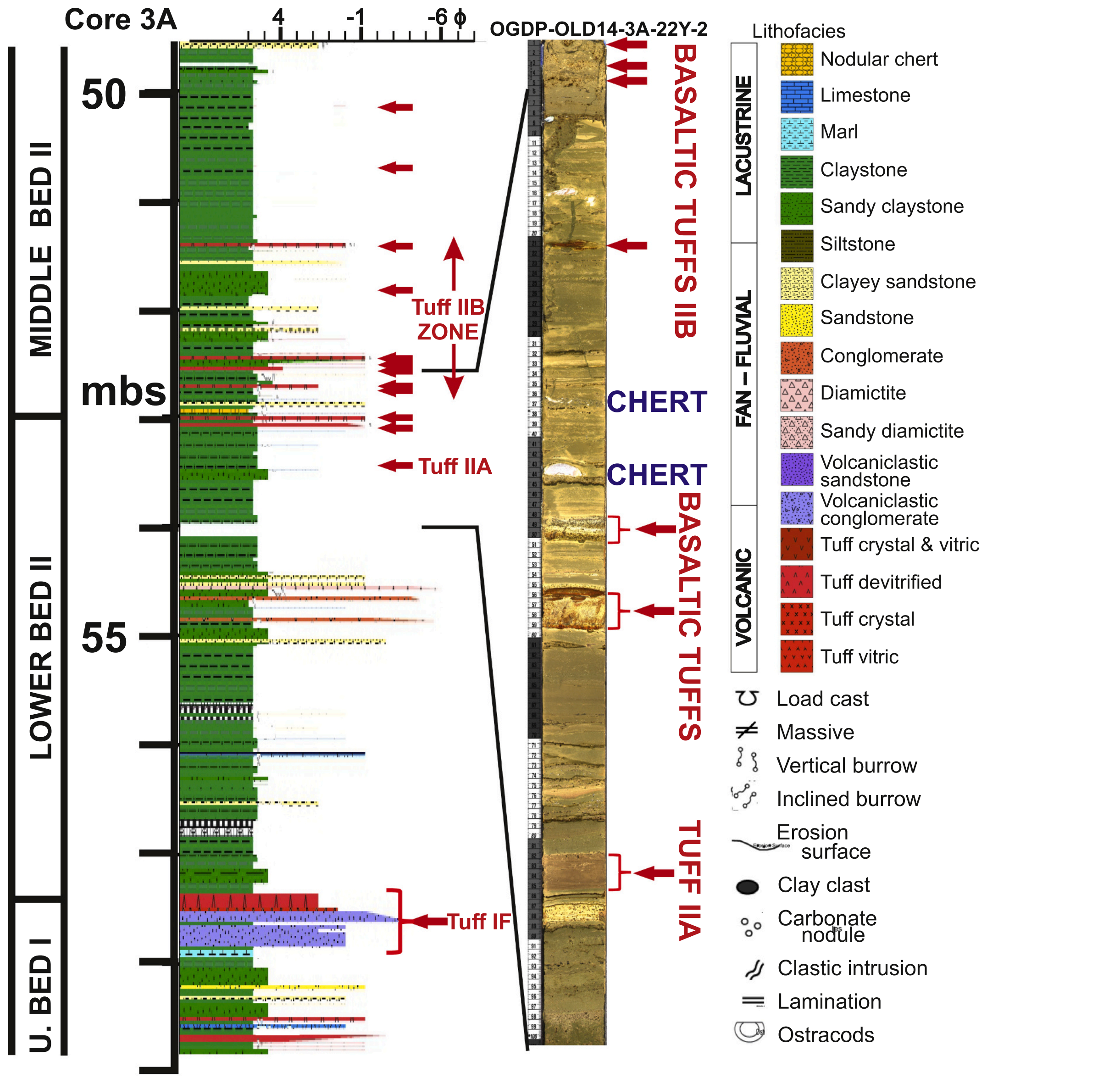


**Fig. 10.** Lower and Middle Bed II tuffs, intersected in Borehole 3A, preserve a more primary airfall texture than their aeolian and alluvially reworked equivalents from nearby outcrop type sections. Chert nodule horizons correlate with those documented by Hay, 1976 straddling the Lower/Middle Bed II boundary in the MNK to SHK area, where they are associated with Tuff IIA. The tuff identified as Tuff IIA in this chert nodule-bearing section of Core 3A has the augite fingerprint characteristics of Tuff IIA in outcrop (McHenry et al., 2020, this volume). The majority of tuffs of Middle Bed II appear to correspond stratigraphically to the overall reworked tuffaceous material of the Tuff IIB zone. Grain size scale is the Krumbein φ scale, whereby 4 = silt/sand; −1 = sand/gravel; and −6 = pebble/cobble grain size boundaries.

RHC and nearby, cherts such as those intersected in Boreholes 2A and 3A are described by Hay (1976) only from above and below the Lower to Middle Bed II boundary at Loc. 201 (along Fifth Fault) and within the MNK (=Mary Nichol Korongo) to SHK (=Sam Howard Korongo) section, at a stratigraphic position equivalent to that in the borehole. The layers, which lie above Tuff IIA, provided the source for the so-called "chert factory" for tool manufacture in the MNK area (Stiles et al., 1974; Stiles, 1991). McHenry et al. (2020, this vol) have recognised Tuff IIA composition augite in a tuff at 3A-22Y-2 (85–89 cm), which, given its stratigraphic placement relative to the chert horizons, we correlate with Tuff IIA. We perceive the Lemuta tuffaceous sandstones of the lake marginal zone to the east as aeolian and fluvially reworked equivalents (Hay, 1976; Stanistreet et al., 2018a, 2018b) of the more primary tuffs preserved in the lake environment.

The thin basaltic tuff layers above the chert horizons occupy a position in the stratigraphy equivalent to the Tuff IIB zone of Hay, 1976, which he characterises in the eastern lake marginal area as heavily reworked and admixed with older detritus. There they are fingerprinted as similar in character to the Lemuta tuffs (McHenry and Stanistreet, 2018). de la Torre et al., 2018 and Stanistreet et al. (2018b) additionally identify mass flow diamictite deposits as reworking this tuffaceous sediment at HWK EE and as a result McHenry and Stanistreet (2018) report that they rarely have a significant juvenile volcanic component. The sedimentary setting in the deepest lake provided an area where disturbance of the primary volcanic ash fallout was minor and ash grains could settle subaqueously and be preserved with their original fine lamination and/or grain size grading. By contrast, in the lake marginal zone, tephra was reworked so that primary textures are no longer apparent there.

## 8. Conclusions

The OGCP drilled at three sites to extract four borehole cores, 1A, 2A, 3A, and 3B, from the depocentre of the Olduvai Basin. The cores from the upper beds (Beds III, IV, Masek Beds and Ndutu) contain no primary Tuff Markers, but can be correlated to outcropping sequences using major disconformities. The latter correlate with those disconformities previously identified as forming the tops and bottoms of the units, supplemented by the identification of the bases of the Brunhes and Jaramillo paleomagnetic normals. Starting at the top of the section, as throughout the basin, the Ndutu Beds constitute aeolian derived sands, punctuated by phases of calcrete formation. The Masek Beds are dominated in the east by a mudflow-dominated fan-delta (Cores 1A and 2A) that toed into the remaining Palaeolake Olduvai in the area of Site 3. Bed IV is predominantly lacustrine, with occasional lake retreats promoting fluvial incision followed by deposition of fluvial gravels and sands. Ostracods are fairly common at the site of Core 3A, whereas in Core 1A, Bed IV is cut out entirely by the sub-Masek disconformity. Bed III is also predominantly lacustrine, but a mixed debris flow/fluvial fan-delta sequence progrades from the east into Site 1 (Core 1A), which is the equivalent of a previously recognised “Eastern Fluvial Facies”, most likely sourced from Embagai Volcano.

Lake sedimentation is the major component of Bed II, joined by coarse sediment input of sands and gravels from external sources. In Middle to Upper Bed II a debris flow dominated fan system entered the depository from the east, evident at Borehole Site 1, toeing into the lake between there and Sites 2 and 3. In lower Middle Bed II, augitic sands entered the basin from the northeast, and following this, quartz-rich sands entered the basin via fluvio-deltaic input from the southwest.

Palaeolake Olduvai was most deeply developed during Bed I due to enhanced extensional faulting, which was also associated with the eruption and deposition of basaltic lavas and tuffs and enhanced basin subsidence. Upper Bed I claystones, with higher TOC values and lacking bioturbation, preserve fine lamination, formed under meromictic conditions. During lake flooding phases, dolmicrites and micrites were deposited in pelagic and hemipelagic settings. During later Upper Bed I, the Olmoti fan-delta, sourced from the adjacent Olmoti Volcano, toed out into the deepest lake, overtopping the topographic barrier underpinned by the DK Horst, into Borehole Sites 1 and 3, with only the most distal subaqueous toe of the fan reaching Site 2 to the west. The Bed I Basalt, in the middle of Bed I, comprises only a single complex lava flow at Sites 1 and 2, but in Cores 3A and 3B, a sequence is marked by three separate layers containing basaltic scoriae. These likely equate to three complex flows entering the deepest lake, probably correlating to those exposed in the eastern gorge. Lower Bed I was only intersected at Site 3, where it correlates well with outcrop exposures of the western gorge, whereas at Sites 1 and 2 it is represented by a major hiatal disconformity surface, with the basalt lying on top of the CFCT ignimbrite.

Two newly revealed formations are defined below Bed I in Boreholes 2A and 3A. The top of the Ngorongoro Volcanic Formation was previously defined, but now includes the CFCT Zone, Naabi Ignimbrite, and all the other acidic and intermediate primary volcanic and volcanically sourced sediments associated with Ngorongoro Fan-delta progradation, including newly identified Tuff Markers NgA to NgQ. Lacustrine claystone sequences containing thin sandstone and conglomerate beds underlie, are adjacent to, and interfinger with the lower part of the Ngorongoro Fan-delta. These claystone-dominated strata are named the Naibor Soit Formation. Pore fluids fresher than that of the saline-alkaline lake, passing through the Ngorongoro Formation, likely promoted preservation of phytolith, diatom and sponge skeletal material within the first major tongue of lake clays into the Ngorongoro Formation. Sedimentary, biological and geochemical indicators suggest that the earliest pre-Ngorongoro Formation Palaeolake Olduvai contained slightly fresher waters than later saline-alkaline lake phases, which are also expressed in outcrop.

## Declaration of competing interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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