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Abstract: Archaeological excavations at EF-HR and HWK EE allow a reassessment of Bed II stratigraphy within the all-important Junction Area and eastern Olduvai Gorge. The application of Sequence Stratigraphic methods provides a time-stratigraphic framework that enables reliable correlation of sedimentary units across facies boundaries, applicable even in those areas where conventional time-lines, such as tephrostratigraphic markers, are absent, eroded, or reworked into tephrostratigraphic "zones". In terms of Sequence Stratigraphy, Bed II subdivides into five major Sequences 1 to 5, all floored by major disconformities that incise deeply into the underlying succession, making the application of oversimplified "layer cake" stratigraphic principles inappropriate. The previous establishment of the Lemuta Member has invalidated the use of Tuff IIA as the boundary between Lower and Middle Bed II. We redefine the latter at the disconformable contact between Sequences 2 and 3, a lithostratigraphic contact that underlies the succession containing the Lower, Middle and Upper Augitic Sandstones. The HWK EE site records Oldowan technology in the Lower Augitic Sandstone at the base of Sequence 3 at this locality, within Middle Bed II. We suggest placement of recently reported Acheulean levels at FLK W within the Middle Augitic Sandstone, thus emphasizing that handaxes are yet to be found in earlier stratigraphic units of the Olduvai sequence. This would place a boundary between the Oldowan and Acheulean technologies at Olduvai in the Tuff IIB zone or earliest Middle Augitic Sandstone. A major disconformity between Sequences 3 and 4 at and near EF-HR cuts through the level of Tuff IIC, placing the main Acheulean EF-HR assemblage at the base of Sequence 4, within Upper rather than Middle Bed II.

Sequence stratigraphic methods yield a more highly resolved Bed II stratigraphic framework. Backwall and sidewall surveying of archaeological trenches at EF-HR and HWK EE to the centimetre scale permits the definition of "Lake-parasequences" nested within the major Sequences, that record: downcutting of disconformities associated with lake regression; then sedimentation associated with lake transgression;

capped finally by an erosional disconformity or hiatal paraconformity caused by the next lake withdrawal. When considered on a relative time scale rather than a vertical metre scale, the resulting time-stratigraphic framework (in the form of a Wheeler diagram) provides a basis for the recognition of time-equivalent depositional episodes and the position of time gaps, which developed at various scales. The relative timing of archaeological assemblage levels can then be related or further differentiated at a millennial scale within this framework.

Bed II Sequence Stratigraphic context of EF-HR and HWK EE archaeological sites, and the Oldowan/ Acheulean succession at Olduvai Gorge, Tanzania.

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1. Introduction

Bed II covers a most interesting interval at Olduvai Gorge, with the disappearance of the Oldowan and appearance of the Acheulean lithic technologies, and the disappearance of *H. habilis* and emergence of *H. erectus* (e.g., Leakey, 1971; de la Torre and Mora, 2014). The stratigraphic framework for Bed II is thus critical for establishing the relative timing and palaeoenvironmental context for these major transitions. However, the lack of broadly mappable marker tuffs and the presence of significant disconformities in the fluvio-lacustrine rock record complicate this framework. Recent stratigraphic and sedimentological studies of Bed II in the Junction Area and eastern areas of the gorge, along with finer detailed study at OGAP (Olduvai Geochronology and Archaeology Project) excavations at HWK EE and EF-HR (Fig. 1) and a new emphasis on erosional disconformities, require a reassessment of the stratigraphic framework of Olduvai Bed II.

This paper presents our initial findings for the Sequence Stratigraphy of Bed II in the context of the stratigraphic framework established by Leakey (1971) and Hay (1976) and in the light of recent archaeological work on the Oldowan/Acheulean transition at Olduvai (de la Torre and Mora, 2014; de la Torre et al., this volume, a, b; Diez-Martín et al., 2015, Uribelarrea et al., 2017). Where possible, we retain (but refine) the stratigraphic units defined by Leakey (1971) and Hay (1976), with which palaeoanthropologists and archaeologists are familiar, while modernizing the terminology to meet current requirements of stratigraphic nomenclature.

2. The classic stratigraphic framework of Olduvai and the Parasequence concept

Olduvai stratigraphy was initially subdivided into Beds I, II, III, IV and V by the pioneering geologist, Reck (1914). This framework stratigraphy was refined by Hay (1963, 1967) and in Leakey (1971), and further improved by Hay (1976) as summarized in Fig. 2. These analyses were at a time before the codification of Stratigraphic Nomenclature, when distinctions between chronostratigraphy (stratigraphy in units of time), biostratigraphy (stratigraphy constrained by the fossil record), and lithostratigraphy (stratigraphy based on lithology, or rock units) had not yet been fully incorporated into everyday geological practice. There was a tendency in the classic Olduvai stratigraphy to combine lithostratigraphic units into a chronostratigraphic unitary nomenclature, despite the fact that most lithostratigraphic boundaries are by their very nature diachronous. For example, a layer developed from a beach sand facies will migrate laterally over time as lake-level rises and the position of the shoreline will move inland. In outcrop, the resulting sandstone could be traced laterally as a single lithostratigraphic unit, although it was not deposited at the same time throughout its lateral extent. Therefore, the use of chronostratigraphic markers such as tuffs (e.g., Tuff IF, Tuff IIA) to define lithostratigraphic boundaries causes problems in the furtherance of lithostratigraphic correlations.

In this regard, Hay (1976) shows an important determination to respect the pre-existing stratigraphy of Reck (1914) as much as possible by classifying Beds I to IV as lithostratigraphic formations, although in some cases chronostratigraphic time-line surfaces provided by Tuff markers are used as their boundaries. Such a conservative approach is necessary, particularly where a stratigraphy is in day-to-day usage across scientific disciplines as diverse as geochronology, geology, palaeontology, archaeology, and palaeoanthropology. In this paper, we attempt to follow in the same spirit of conservatism when practicable. Nevertheless, some issues have arisen that require revision.

Hay (1976) added the Masek, Ndutu, and Naisiusiu Beds as lithostratigraphic formations (Fig. 2), and often in the higher parts of the stratigraphy used regional erosional surfaces (disconformities) to define fundamental stratigraphic boundaries (e.g., boundaries between Bed II/Bed III; Bed III/Bed IV; Bed IV/Masek). In this, Hay was ahead of his time and presaged the use of incision surfaces (disconformities representing periods of erosion) in a fully terrestrial setting, more widely used in marine sequences, as stratigraphic and correlative tools. Vail et al. (1977a,b) and Van Wagoner et al. (1988) pioneered the widespread development of cyclicity and incision surfaces in shallow marine settings as a basis to define sequences bracketed by time-correlatory surfaces, eventually codified in the new stratigraphic concept of Sequence Stratigraphy. In this context, climatically forced falls of sea level were seen to generate Type I (pronounced) and Type II (less pronounced) disconformities and paraconformities (hiatal surfaces). Complementary sea-level rises and subsidence provided accommodation space in which sedimentary increments could be deposited and preserved. The framework of resulting units is defined by time-slices between regional incision surfaces, each bracketing a “Parasequence” as the smallest element. By this means, a Parasequence may incorporate considerable lateral facies change, and the same time-slices could be traced from deepest ocean through ocean shelf to onshore alluvial fan settings. A set of Parasequences makes up a Sequence bracketed by regionally significant (Type 1) disconformities. Sequence Stratigraphy was later also applied to lake basins, notably by Keighley et al. (2003), who identified Parasequences and disconformity-types controlled by changes in lake-level in the Eocene Green River Formation of the Uinta Basin in Utah, U.S.A.

3. Application of Sequence Stratigraphic techniques to the Olduvai Basin

Stanistreet (2012) introduced a general sequence stratigraphic approach to the Olduvai record. Correlation of incised surfaces in the Olduvai Basin refines the original stratigraphy established by Hay (1976), down to a sub-metre to metres scale, by the identification of "Lake-parasequences", based on their bounding (Type II) disconformities and paraconformities. The latter are well recorded by lacustrine claystones bearing widespread nodular to spherulitic calcite nodular horizons, interpreted to represent subsurface pedogenic and/or groundwater carbonate precipitation, and formed when land surfaces developed at times of lake withdrawal (Bennett et al., 2012, Rushworth, 2012). Thus, carbonate nodular horizons, together with rooted and burrowed surfaces, can valuably mark hiatal interludes (or paraconformities) of lake withdrawal within an, at first sight, continuous lake clay succession. Stanistreet (2012) initially applied this approach to Lower Bed II OLAPP (Olduvai Landscape Palaeoanthropology Project) archaeological excavations and natural cliff exposures, such as RHC (Richard Hay Cliff) or Loc. 80 of Hay (1976). Each Lake-parasequence was recognized as a fundamental stratigraphic unit generated by: (1) a fall in the lake-level of Palaeolake Olduvai, generating an incision or hiatal surface; (2) a lake-level rise together with subsidence providing accommodation space to allow deposition of a transgressive, upward deepening sequence; (3) a subsequent lake-level fall, generating the next incisional (disconformity) or hiatal surface (paraconformity). Without the application of Sequence Stratigraphic principles, the long-range correlation of high-resolution stratigraphy through such different, yet contemporaneous, facies as fan, fluvial and lake marginal settings, would have proved impossible for intervals with insufficient marker tuffs.

As with marine Parasequences, Lake-parasequences can be transformed from a measured section at metres depth scale to a relative time scale by transferring their spatial spread onto a Wheeler Diagram (Wheeler, 1958), which emphasizes gaps of missing sedimentary intervals within a succession on a variety of scales. Stanistreet (2012) demonstrated the value of these diagrams by placing archaeological levels onto a Wheeler Diagram for Lower Bed II and uppermost Bed I, to evaluate their temporal as well as spatial relationships.

The frequency of marine Parasequences is on the scale of tens of thousands of years, forced by Milankovich cycles (~21,000, 41,000, 100,000 years). Trauth et al. (2007), Berger et al. (2006), and Maslin et al. (2014) have proposed that modulation of precessional forcing by eccentricity forcing exerted a major control on the hydrological cycle in tropical East-Africa during the Plio-Pleistocene. Comparison of orbitally modulated insolation patterns (c.f., Ashley, 2007; Deino, 2012) to the Olduvai sedimentary record provides evidence that the Bed II fluvio-lacustrine successions might record orbital forcing, specifically precessional forced variations, known from upper Bed I (e.g., Ashley, 2007, 2014; Magill et al., 2014).

Olduvai Lake-parasequences are of much higher frequency (on the order of multimillennia averaging 4,000-5,000 years), than Milankovitch-forced variations, but are nevertheless nested (Stanistreet, 2012) within the Milankovitch cyclicity. Stanistreet (2012) suggested that they are climatically forced by stadially/interstadially controlled changes to the monsoonal effect. Stadial/interstadial colder/warmer oscillations have been shown to control sedimentary variation in basins as far south as the Caribbean (Deplazes et al., 2013), the Arabian Sea (Schulz and von Rad, U., 1998; Deplazes et al., 2013), and Lake Malawi (Scholz et al., 2007, 2011). Such a range therefore would extend those effects from the Arctic (Dansgaard et al., 1993) well into the southern Hemisphere. Also required would be the development of stadials and interstadials within earlier phases of the Pleistocene. Ultimately, however, the style of control on Lake-parasequences is immaterial; they define chronostratigraphic time-slices whatever the nature of their forcing.

4. **Methods**

Sections throughout Bed II were measured at natural outcrop exposures at 18 sites from FC in the Side Gorge, through the Junction Area, as far as MK W in the eastern Main Gorge (Fig. 1), with an emphasis on sections near target excavated sites HWK EE and EF-HR. Measurements were made using a Jacob's Staff, level, and measuring tape where appropriate, recording facies and marker unit lithologies and mineral composition (identified using a hand lens). Key lithologies were studied in closer detail, recording all structural, textural and compositional characteristics (including thin-section analysis) to provide process-related facies interpretations (de la Torre et al., a, b this volume). Feldspar, hornblende, augite, titanomagnetite, and glass (where available) single grain separates of select tuffaceous marker samples were geochemically fingerprinted by microprobe analysis, using techniques described in McHenry et al. (2016) and McHenry and Stanistreet (this volume).

Ultimately, stratigraphic sections were arranged laterally and "hung" on the top of the Lemuta sandstones to correlate them (Fig. 3). The top of Tuff IF was rejected for this purpose, because the overlying Crocodile Valley Incision Surface (cf. Stanistreet, 2012) would have produced an irregular correlation of the units above. The best surfaces on which to hang stratigraphies are normally high in the succession concerned, when sedimentation has mostly filled topographic irregularities by that time. For this reason, Hay (1976) hung his Bed II stratigraphy on the top of Tuff IID. This was impossible in Figure 3, because almost half the sections do not preserve Tuff IID, but we were encouraged in our use of the top of the Lemuta sandstones by the fact that then Tuff IID lines up at a fairly level position where it is preserved.

Main and satellite archaeological trench backwalls and/or sidewalls shown in Figure 1 were mapped in greater detail, whereby all lithostratigraphic boundaries, obvious erosional and hiatal surfaces and archaeological levels were logged to cm resolution (precision limited only by prism placement) using a Leica Total Station (TCR 1100 series), and processed in ArqueoUAB (Mora et al., 2010) and ArcGIS software. Erosional surfaces were recognized because they are sharp and incised downwards into the underlying layers, often forming an irregular, unconformable surface. Material was reworked/recycled from the underlying stratigraphy onto the surface and might be incorporated into the succeeding sedimentary layer. In some instances, the concentration of gravels in the topographic lows of the incision surface aided their identification. Hiatal surfaces were recognized by the lateral correlation of nodular carbonate layers which commonly show features indicating post-depositional pedogenic or groundwater processes, or an alternation of the two, as outlined in Bennett et al. (2012) and Rushworth (2012). Sharply defined surfaces above the nodular carbonate layers, some of them slightly erosional, could then be identified as the hiatal position itself (Bennett et al., 2012). Data were then transferred to a graphics package, and units were coded with a logical ornamentation to complete the backwall and sidewall maps.

5. Results

5.1. A redefinition of the base of Middle Bed II

Figure 2 specifies the development of Olduvai stratigraphy after 1970, through the work of Leakey (1971) and Hay (1976). The stratigraphy used in this paper is founded upon both previous sources, but incorporates the reintroduction of Lower Bed I in the sense of Hay (1967), as proposed by McHenry et al. (2008), and justified in McHenry (2012). Whereas Leakey (1971) designated a Lower, Middle and Upper Bed I above the Basalt Member, Hay (1967), McHenry et al. (2008), and McHenry (2012) defined Upper Bed I as that part of Bed I above the Basalt Member, and Lower Bed I as that part below. This is the present status of the stratigraphy of the Olduvai Basin, and is brought into focus and further validated by the new stratigraphy revealed by recent coring of OGCP (Olduvai Gorge Coring Project).

Use of the terms Lower, Middle and Upper Bed II were accommodated in the Leakey (1971) publication, but not in Hay (1976), who restricted only Upper and Lower Bed I units to Member status. Although terms such as Lower, Middle, and Upper have no geographic name specification (as would be required to define them as formal stratigraphic units), they have traditionally been useful in both Olduvai geology and archaeology, so we assign them an informal subformational status in Figure 2.

An important stratigraphic revision indicated in Figure 2 is the redefinition of the base of Middle Bed II. This was originally defined by Leakey (1971) as the top of Tuff IIA. However, the subsequent introduction of the Lemuta Member by Hay (1976) precludes this stratigraphic positioning, because Tuff IIA is located within the middle of the Lemuta Member, and can therefore no longer be used as a lithostratigraphic boundary. The Lemuta Member comprises Hay's (1976) "eolian tuff facies" in the eastern gorge, where it consists of up to 90% aeolian reworked tephra (with minor limestone and claystone components), together with the sediments that interfinger with these deposits further west into the Junction Area and Side Gorge. Hay (1976) identified three "tongues" of aeolian and aeolian-sourced Lemuta sandstone in the Junction Area, interfingering with lacustrine claystones and other lake margin sediments, and designated the middle tongue as Tuff IIA. Hay's (1976) introduction of the Lemuta as a formal Member within Bed II allows it to incorporate the interfingering non-aeolian sediments, expanding its reach beyond the range of the "eolian tuff facies" of the eastern gorge themselves. McHenry et al. (2016) reintroduced the term Middle Bed II, using the top of the Lemuta Member as its base in place of Tuff IIA. Here we provide a more detailed justification for this change, which is illustrated in Figure 2. In the sections mapped here the boundary is then effectively the disconformity developed prior to the deposition of the Lower Augitic Sandstone, as recorded by Hay (1976). The terms Lower, Middle and Upper "Augitic Sandstone" address three, <4 m thick tongues of augite-rich (including some hornblende, plagioclase and volcanic lithic grains) medium to conglomeratic sandstones, which Hay (1976) identified and used as stratigraphic markers.

This repositioning of the base of Middle Bed II helps clarify and improve Bed II stratigraphy for the following reasons:

1) The boundary is now defined by a major change in lithofacies, rather than attempting to apply a purely chronostratigraphic criterion.
2) Hay (1976) selected the middle tongue of the three “eolian tuff” layers within the Lemuta Member as Tuff IIA, but the three can be practically indistinguishable at many localities.
3) The previous boundary of Tuff IIA cannot be traced within the FLK area, where it has been removed by subsequent erosion surfaces due to the uplift of the FLK Fault footwall (Hay, 1976; Stollhofen and Stanistreet, 2012; Stanistreet, 2012).
4) Tuff IIA cannot be traced satisfactorily to the east of 3rd Fault nor at all to the east of 2nd Fault.
5) Tuff IIA cannot be traced anywhere in the western part of the Main Gorge, including RHC (Loc. 80) and beyond.
6) The major disconformity below the Lower Augitic Sandstone is an easily traceable surface throughout the entire Olduvai Basin.
7) The use of a chronostratigraphically significant disconformity, also distinct lithostratigraphically, as the boundary, applies the same criteria that define all of Hay’s (1976) boundaries in the younger stratigraphy at Olduvai (e.g., boundaries between Bed II/Bed III; Bed III/Bed IV; Bed IV/Masek).

5.2. ***Breaking out Sequences within Bed II between EF-HR and HWK EE***

Sections through Bed II were re-measured during the OGAP excavations at EF-HR and HWK EE and nearby localities (Fig. 3), and these refine previous stratigraphic compilations and benefit from recent geochemical fingerprinting of Bed II tuffs (McHenry et al., 2016). Apart from the basal Bed I/Bed II boundary, which is conformable and a time line on top of Tuff IF, all the through-going tie lines, including the Bed II/Bed III boundary, are major Type I disconformity surfaces, incising deeply into the underlying succession and causing considerable gaps in the sedimentary record. This explains the lateral discontinuities of many of the classic marker beds of Hay (1976), including Tuff IIA at FLK, the horizon of Tuff IIC and Tuff IID (Fig. 3), and emphasizes the need for an alternative stratigraphic approach.

Five major sequence stratigraphic units or Sequences are defined in Figure 3:

1) Sequence 1 represents the uppermost Bed I/lowermost Bed II sequence. It includes the entire sedimentary succession in Bed II below the Crocodile Valley Incision

Surface (CVIS), defined by Stanistreet (2012), and stratigraphically referred to informally in OLAPP publications (e.g., Blumenschine et al., 2012) as “lowermost Bed II”. Because the Bed I/Bed II boundary is the conformable top of Tuff IF, uppermost Bed I units should also be included in Sequence 1.

2) Sequence 2 sits on the heavily incised Crocodile Valley Incision Surface (CVIS), which cuts down deeply into underlying units, particularly well shown at MK W in Figure 3, where a palaeogully (Stanistreet, 2012) cuts down close to the top of Tuff IF. Such a deep downcut is developed again at the west end of Figure 3 (FC W), where lowermost Bed II is eliminated by the CVIS, cutting down into Tuff IF. Sequence 2 incorporates the CVIS incision-fill sediments and the conformably overlying Lemuta Member. Hay (1976) records the Lemuta Member as including three tongues of tuffaceous sandstone that he refers to as “eolian tuffs”. The middle one of these he labelled as Tuff IIA, although all three tongues display very similar lithofacies and compositional characteristics. Sequence 2 is characterized by the sudden introduction of substantial amounts (~15-50%; Hay, 1976) of augite grains into the basin, which when mixed with even proportions of feldspar grains results in the typical “salt and pepper” appearance of Lemuta sandstones.
3) Sequence 3 sits upon the incision surface that developed prior to the deposition of a succession including the Lower, Middle and Upper Augitic Sandstones of Hay (1976), all of which display similar lithofacies and compositional characteristics. Marker units such as Tuff IIB, the Bird Print Tuff (BPT), and the Brown Tuffaceous Siltstone (BTS), are also contained within Sequence 3. Although the BPT is rather continuous between VEK and HWK Tembo, and the BTS between KK and MK W, Tuff IIB is usually hard to pinpoint, as it comprises an interval of devitrified tuffs, volcaniclastic sandy claystones, sandstones and conglomerates between FC W and HWK EE (Fig. 3). As their names would suggest, Sequence 3 sandstones, as well as associated Tuff IIB, are dominated by the input of overwhelming proportions of augite (c. 50-75%; Hay, 1976), including euhedral grains, with far less proportion of feldspar and volcanic lithic grains, distinguishing them from the sandstones of Sequence 2 (Hay, 1976). Lenses of Tuff IIC are included within this sequence, in the few sections where that horizon is not cut out by the incision underlying Sequence 4.
4) Sequence 4 sits on the incision surface that developed a shallow incised valley at EF-HR (see also de la Torre et al., this volume). The downcutting shape of this valley is evident in the easternmost four measured sections of Figure 3 (DK EE, EF-HR W, EF-HR, MK W). The incision cuts out the horizon of Tuff IIC, which only outcrops in the MCK section and in a trench at DK EE (Fig. 3). The Sequence is topped by marker Tuff IID, preserved *in situ* at VEK and localities between HWK W and JK, but found only as eroded blocks in gravel units of the basal Sequence 5 further to the east.
5) The uppermost Sequence 5 fills an incision surface cut down into the previous sequence, which partially or totally erodes Tuff IID. In some places, Tuff IID proved resistant enough to erosion to restrict accommodation space for the deposition of Sequence 5. Between DK and MK and at western localities of Figure 3, however, Tuff IID is totally eroded out. This is demonstrated at EF-HR locations, where large blocks of the tuff are found incorporated into gravels which sit up to 5 metres below the

level of the *in situ* tuff at neighbouring localities (e.g., above EF-HR T2- Main Trench). This indicates that once an incised valley had been excavated at EF-HR near the top of Middle Bed II, this subsequently became a preferred locus for renewed valley incision, probably because of less resistance to erosion of the previous, less consolidated valley-fill sediments.

5.3. The problem of using Tuff IIC to define the Middle to Upper Bed II boundary

Figure 3 also shows the problem involved in the previous subdivision by Leakey (1971) of Bed II such as Middle and Upper Bed II, designated subformations here. Leakey (1971) used Tuff IIC as the demarcation, but Tuff IIC is only obviously present in one Junction Area site, MCK (Fig. 1). This led to the misplacement (Leakey, 1971; Hay, 1976) of EF-HR as a Middle Bed II assemblage, whereas in this paper and de la Torre (201X this volume) it is shown to sit in Upper Bed II, at the base of Sequence 4. Tuff IIC is not easily traceable in either the Western or eastern Main Gorge and was misidentified even by Hay (1976) in parts of the Side Gorge (McHenry et al., 2016), severely hindering stratigraphic boundary delineation basin-wide. This is expressed in Figure 2 by the dashed line that marks that boundary in the stratigraphic subdivisions at the side of the figure. Nevertheless, for conservative reasons the boundary is maintained at Tuff IIC in this paper. To extend the Tuff IIC stratigraphic position laterally would require a combination of Geochemical Zone analysis, pioneered by McHenry et al. (2013) to improve Bed I stratigraphy at the FLK *Zinjanthropus* location and by Habermann,et al. (2016), together with more detailed Sequence Stratigraphic analysis. Such a revision is beyond the scope of this paper.

5.4. Lake-parasequential breakdown at EF-HR

Figures 1 and 3 show spatially and temporally the places where detailed stratigraphies were constructed, based upon the archaeological excavations at EF-HR, HWK EE, and nearby localities. Because of the centimetre-level resolution that trench backwalls and sidewalls afford, the Sequence Stratigraphy can be resolved in those areas down to the level of Lake-parasequences, providing a millennial-scale time-stratigraphic archive. Such units are defined by Stanistreet (2012) as the fundamental time-units, recording a single climatic dry/wet cycle incorporating: a Type I incision or a Type II hiatus, produced by retreat of the palaeolake, followed by in-fill and deposition during its subsequent flooding. The Lake-parasequence is then completed by the next lake retreat to finally produce the next Type I incision or Type II hiatal surface at the time of lake level lowstand. However, erosional downcutting defining such parasequences has also the side-effect that rarely is an entire sequence (recording the complete transgressive/regressive lake cycle) fully preserved.

Figure 4 shows the mapped backwalls at trenches dug between DK and MK (Fig. 1), including the main trench at EF-HR (T2) in the centre. The cross-section has also been rotated slightly westward to correct for the tilting towards the east that was caused by post-depositional fault block rotation associated with the down-faulting of 3rd, 2nd and 1st Faults (Stollhofen and Stanistreet, 2012). Equivalent Lake-parasequence numbers are indicated at each trench.

Once the hiatal and disconformity surfaces between Lake-parasequences have been allocated, the units can be transformed from the spatially designated vertical axis at metre-scale to a time-framework (Figure 5) by means of Wheeler Diagram transformation (Wheeler, 1958). This procedure bears the advantage that increments of time represented by each Parasequence can be displayed along a vertical relative time axis, emphasising the time gap between each. This process was introduced to the Olduvai Basin by Stanistreet (2012) for Lower Bed II and Upper Bed I, but now the pattern of lake withdrawal and flooding can be traced through Middle and into Upper Bed II. As pointed out by Stanistreet (2012), this can be of considerable value to archaeological consideration of a single site or several sites, because archaeological levels can then be viewed in a temporal context, taking account of the time gaps, rather than trying to visually accommodate the complexities of multiple phases of erosion and incision-fill. The main archaeological unit identified at EF-HR (denominated Interval 1 materials by de la Torre et al., this volume), is placed at the base of Lake-parasequence 1 (orange) (Fig. 5). In the positions where the diamictite unit was eliminated by the next phase of incision, stone tools and fossils from the original level were eroded and redeposited with the gravels of Lake-parasequence 2 (orange). This redeposition of material is indicated by appropriate annotations “Original Archaeological Level” and “Displaced fossils and artefacts” on Figure 5.

The EF-HR Wheeler Diagram emphasizes the incised valley that was cut there, just prior to the accumulation of the EF-HR assemblage (de la Torre et al., this volume) on that deeply (>2.5 m according to Fig. 3) eroded surface. At least five underlying Lake-parasequences were cut out by the incision surface in the EF-HR region. Only at Trenches T10 and T11 (excavated at DK EE and MK W respectively) were such units preserved. At T2-Main Trench, deeper and trial trench excavations revealed four underlying Lake-parasequences (1-4 blue), dominated by lake clay deposition. Each of those Lake-parasequences 1-4 is capped by lacustrine claystones bearing laterally extensive calcite nodule horizons which record pedogenic overprinting of a stable land surface during lake withdrawal. The amount of relative time represented by such a hiatal surface (paraconformity) is highlighted in a Wheeler Diagram.

Following the major lake withdrawal that caused the major Type I incision resulting in the large time gap in Figure 5, basin subsidence and subsequent lake rise provided accommodation space for the accumulation of new sediments. These were initially fluvially dominated (Lake-parasequences 1 to 5 (orange)), nesting within the incised valley as a multi-storeyed set. Lake-parasequences 6 to 8 (orange) start to lap over the shoulders of the incised valley and incorporate fluvial, mudflow (diamictite facies) and the first of several thin lake clay facies units, indicating the initial return of Palaeolake Olduvai to the EF-HR area. Lake-parasequences 9 and 10 then record the full return of the lake, with subaerial phases only recorded by diamictites, representing mudflow deposits.

The archaeological assemblage at EF-HR is now revealed to occur in Upper Bed II (see also McHenry and Stanistreet, 201X, this volume and de la Torre et al., 201X, this volume), rather than in the Middle Bed II position to which it was originally attributed by Leakey (1971) and Hay (1976). The Wheeler Diagram (Fig. 5) illustrates how this misdesignation came to be made. Whereas the assemblage sits below the position of Tuff IIC spatially in terms of metres, this is merely because it forms part of the incised valley-fill. Placing the assemblage within the sequence timeframe of Figure 5 shows it to be younger than Tuff IIC. This warns against the use of surveyed height as the sole arbiter of stratigraphic correlation and relative timing of an archaeological assemblage.

5.5. Lake-parasequential breakdown at HWK EE

A similar procedure of Lake-parasequence identification was undertaken at HWK EE (Fig. 1). Figure 6 shows the correlation of the trench backwall and sidewall maps (de la Torre et al., this volume), with 12 Lake-parasequences contained within Sequences 2 and 3 (Fig.3). The most pronounced incision surface (indicated in red in Figure 6) has been identified throughout the basin to be a major disconformity (Hay, 1976) or Type I incision surface (Stanistreet, 2012), on to which on-lap the Lower, Middle and Upper Augitic Sandstone units at various sites throughout the Junction Area. According to the new stratigraphic definitions proposed in this paper (Fig. 2), this is the disconformity that marks the Lower to Middle Bed II boundary.

The resulting Wheeler Diagram (Fig. 7) emphasizes this Type I incision and the pronounced time gap it represents. Below it, there are four Lake-parasequences 1 to 4 (green) belonging to the Lemuta Member. Lemuta sandstones are aeolian sand sourced fluvial deposits, interspersed by lake transgressive phases during which the olive waxy claystone facies were deposited. A rooted and nodular horizon tops the lowermost of the parasequences and marks where lake withdrawal exposed a lake flat. During a subsequent hiatus the surface was subject to rooting, burrowing (see Trench 27 between Lake-parasequences 1 and 2 green in Fig. 6) and sparse nodule formation (see Trench T1 trial trench at base in Fig. 6), all characteristics of a paraconformity.

Above the Type I (incisional) disconformity at the start of Middle Bed II, eight Lake-parasequences (numbered red in Fig.7) can be demarcated. Initially, fluvial gravels and sandstones characterise the facies architecture, but during the development of the Tuff IIB “zone” diamictites become dominant (Lake-parasequences 4 to 6), representing mudflows, and the lake made initial encroachments on the Junction Area to deposit thin clay facies layers. They were then followed by further fluvial augitic sands and gravels. The black numbered arrowed circles superimposed on Fig. 7 correspond to the numbers of archaeological levels defined at the site (de la Torre et al, this volume). Now the archaeological levels can be viewed with respect to recognised time gaps within the sequence, which at this resolution allows further identification of which levels are contemporary or not.

6. Discussion: Towards a stratigraphic specification of the Oldowan/Acheulean boundary at Olduvai

In Mary Leakey's (1971) classic sequence of cultural and biological evolution at Olduvai, the Oldowan prevailed until Tuff IIB times, after which Middle Bed II strata exposed at EF-HR would bear the first evidence of the Acheulean in the area. The stratigraphic analysis outlined in this paper provides a framework within which the Oldowan/Acheulean boundary can be ascertained, including a re-evaluation of the stratigraphic position of EF-HR, now proposed to sit in Upper Bed II (see also McHenry and Stanistreet, this volume). Achievement of a better stratigraphic resolution for the emergence of the Acheulean at Olduvai is one of the primary targets of OGAP (e.g., McHenry et al., 2016), and the stratigraphy and archaeological analyses will be further refined using other sites excavated in the Junction Area and the Side Gorge.

In the meanwhile, Diez-Martín et al. (2015) and Uribelarrea et al. (2017) have reported Acheulean technology from a Bed II archaeological level at site FLK W, which can be contextualised within the new stratigraphic framework of this paper. As Hay (1976: see his Figure 23) and Stanistreet (2012: see his Figure 3) recorded, FLK is an unusual site in which the disconformity below the Lower, Middle and Upper Augitic Sandstones (corresponding to Sequence 3 in this paper) cuts down deeply into Lower Bed II. Figure 3 shows that Bed II Sequences 1 and 2 are largely eliminated below the disconformity that constitutes the Lower/Middle Bed II boundary in the vicinity of FLK. Stanistreet (2012) identified only the two lowermost Lake-parasequences of Lower Bed II below the level of this major disconformity at FLK N. However, this downcut is not related solely to lake level fluctuations; of equal importance is the position of the FLK locality at the edge of an uplifted footwall block to the east of the FLK Fault (Hay, 1976; Stollhofen and Stanistreet, 2012 see their Figures 10 and 13). The latter would enhance the stratigraphic depth of any incision surface due to footwall uplift. As a result, Tuff IF, as well as Lower Bed II strata, form a distinctly condensed sequence in these sections (Stollhofen and Stanistreet, 2012).

The newly reported Acheulean assemblage at FLK W is placed at the base of Hay's (1976) sequence of Augitic Sandstones (our Sequence 3 in Figure 3), and a channelform surface (Diez-Martín et al. 2015) is reported, representing a lateral continuation of the underlying disconformity. However, as Hay (1976) demonstrates, almost the entire succession below the Upper Augitic Sandstone laps up against this disconformity surface at various sites in and near the Junction Area, dependent upon the latter's topography. At locality 20 (i.e., immediately across the Main Gorge from the FLK site), it is the Middle Augitic Sandstone that sits directly upon the disconformity. Diez-Martín et al. (2015) report a "clay tuff" (named by them Tuff FLKWb) overlying the archaeological levels conformably. About ~25 cm above that "clay tuff" in the same general area, Uribelarrea et al. (2017) report the Bird Print Tuff, confirmed as such by geochemical fingerprinting (McHenry and Stanistreet, this volume) using the methods and comparative compositional database of McHenry et al. (2016). Throughout the Junction Area, Hay (1976) places the Bird Print Tuff above the position of the Middle Augitic Sandstone, although the latter unit is not indicated in the sections portrayed by Uribelarrea et al. (2017). We suggest that the most likely relationship is that it is the Middle Augitic Sandstone that sits directly on the disconformity at FLK W, in a fashion similar to the sequence at Locality 20 (Hay, 1976). This would imply that the entire interval between the Lower Augitic Sandstone and the base of the Middle Augitic Sandstone *sensu* Hay (1976), including the Tuff IIB zone, has been eroded off at FLK and FLK W. In view of the missing sequence, the date of the overlying "clay tuff" (1.664±0.019 Ma Diez-Martín et al. 2015) will more closely reflect the age of the Acheulean assemblage at FLK W than the date below the disconformity (1.698±0.015 Ma). We therefore suggest that the date of the assemblage should be stated to be ~1.65 Ma, rather than ~1.70 Ma.

It is crucial to recognize that the FLK W Acheulean site described in Diez-Martín et al. (2015) and Uribelarrea et al. (2017) is situated within the augitic sandstones that post-date the Lemuta, and not within lowermost Bed II. The term lowermost Bed II was designated by Stanistreet (2012) to comprise sediments below the Crocodile Valley Incision Surface and Lemuta Member (Fig. 3), classified as Sequence 1 there. The Acheulean site is instead hosted in an augitic sandstone which is part of Middle Bed II and Sequence 3.

HWK EE assemblages from the Lower Augitic Sandstone have been described as Oldowan in character (de la Torre et al., this volume). Therefore, the arguments laid out above would suggest that Acheulean technologies at Olduvai Gorge first appeared somewhere after the deposition of the Lower Augitic Sandstone in Middle Bed II, i.e., the interval that includes Tuff IIB up to the earliest Middle Augitic Sandstone. This result remains to be further tested, however, by the analysis of assemblages and their contexts from other excavations that have been completed by OGAP.

7. Conclusions

The application of Sequence Stratigraphic concepts combined with modern tephrostratigraphic analysis can overcome problems associated with the time-stratigraphic analysis of Bed II and its archaeological sites. Bed II subdivides into Sequences 1 to 5, each separated by a major Type 1 disconformity. The previous definition of the Lemuta Member has required repositioning the Lower/Middle Bed II boundary from Tuff IIA (a unit within the Lemuta) to the disconformity between Sequences 2 and 3, which underlies the succession containing the Lower, Middle and Upper Augitic Sandstones and the Bird Print Tuff. Although the definition of the Middle/Upper Bed II boundary at the top of Tuff IIC is inadequate, because of its lack of lateral traceability, we conservatively retain the boundary at that level. The main Oldowan archaeological levels of HWK EE are at the base of Sequence 3 (within the Lower Augitic Sandstone, at the base of Middle Bed II), although archaeological levels were also excavated by OGAP in Lower Bed II both within and above Tuff IIA (de la Torre et al., 201Xb, and described in other papers within this Special Volume). The main accumulation of Acheulean materials at EF-HR is at the base of Sequence 4, within Upper Bed II. Our sequence stratigraphic framework also confirms that the transition to earliest Acheulean handaxes at Olduvai, would occur within lower Sequence 3 within the Tuff IIB zone or earliest Middle Augitic Sandstone Further analysis of other OGAP excavations is required to refine this placement.

At EF-HR and HWK EE, mapping of backwalls and sidewalls to centimetre scale allowed the definition of Lake-parasequences to multi-millennial resolution within the larger Sequences, each recording withdrawal followed by a flooding of Palaeolake Olduvai until the next withdrawal. The Lake-parasequences identified at HWK EE include deposits that are assigned to Sequences 2 and 3, whereas the Lake-parasequences defined at EF-HR comprise deposits in both Sequences 3 and 4. By emphasizing the sedimentary time-gaps in the fluvio-lacustrine strata, as well as the intervening depositional episodes, resulting Wheeler Diagrams are very useful for the positioning and understanding the contemporaneity of the contained archaeological assemblages, even in cases where tephrostratigraphic markers are missing.

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Figure Captions

Figure 1. Overview map of the archaeological sites and trenches referred to in the text with detailed maps of trenches (A) at EF-HR, (B) the FLK HWK "Junction Area" around the confluence of the Main and Side Gorges, and (C) the trenches at HWK EE. Squares indicating trench locations are not to scale.

Figure 2. Revised stratigraphic subdivision of Olduvai Bed I (proposed in McHenry et al., 2008 and McHenry, 2012) and Bed II (proposed in this paper) in the right column, compared to previous stratigraphic approaches of Leakey (1971) and Hay (1976).

Figure 3: Measured Bed II sections in the Olduvai eastern Main Gorge, the "Junction Area" and the Side Gorge. Bold orange lines refer to major disconformities. Correlation of tuff markers is indicated by bold grey lines. Encircled numbers distinguish Sequences 1-5, each bounded by unconformity surfaces and containing nested Lake-parasequences illustrated in Figs. 4 and 6. See Fig. 1 for location of sections. CVIS = Crocodile Valley Incision Surface.

Figure 4. Measured backwall and/or sidewall lithofacies maps from EF-HR main and satellite trenches. Blue-circled numbers represent Lake-parasequences contained in Sequence 3 and orange-circled Lake-parasequences are developed within Sequence 4 (c.f., Fig 3). The entire sequence has been rotated to the west by 8 degrees to counteract the effect of post-depositional eastward tilting, associated with downfaulting of 3rd, 2nd and 1st Faults. See Fig. 1 for location of trenches. Versions of this figure without Lake-parasequence flags can be found in this Special Volume in de la Torre et al., (201Xa)

Figure 5. EF-HR (DK EE to MK W) Wheeler Diagram of the Lake-parasequences outlined in Figure 4. Trench T10 is at DK EE and Trench 11 at MK W, others are close to EF-HR (For EF-HR Main Trench 1: T1SW=Sidewall; T1BE=Backwall East; T1BW=Backwall West). The outline of the Incised Valley, cut into Sequence 3 (Lake-parasequences 1-5 in blue and younger unnumbered above) is revealed, with Sequence 4 Lake-parasequences 1 to 5 (orange) constituting an Incised Valley-fill and Lake-parasequences 6 to 10 overtopping the valley flanks. See Fig. 1 for detailed location map of trenches. Please note that the Type I unconformity is shown at both the top and bottom of the time gap that it defines.

Figure 6. Measured backwall and/or sidewall lithofacies maps from HWK EE Main Trench (T1) and satellite trenches (T27-T29). Green-circled numbers represent Lake-parasequences contained in Sequence 2 and red-circled Lake-parasequences are developed within Sequence 3 (c.f., Fig 3). Note the disconformity surface (highlighted in red), separating Sequence 2 from Sequence 3. Augitic sandstones are coloured grey, with increasing abundance of augite grains indicated by enhanced darkness of the grey. See Fig. 1C for location of trenches. The Lemuta sandstone exposed in the backwall of Trench 27 contains a large boulder of the olive waxy claystone that has been eroded from the adjacent cutwall and deposited upon the incision surface underlying the sandstone.

Figure 7. HWK EE Wheeler Diagram of the Lake-parasequences outlined in Figure 6. BW=Backwall, SWn=Sidewall North; SWs=Sidewall South. Sequence 2 Lake-parasequences 1 to 4 are labelled green and Sequence 3 Lake-parasequences 1 to 8 are labelled red. See Fig.

1C for a detailed location map of trenches. Archaeological level numbers are black and circled in black: 10 = L10; 51 = L51, etc. of de la Torre et al. (this volume), except for 6 = L6-LCHA and 1 = L1-L1A.

Figure 1

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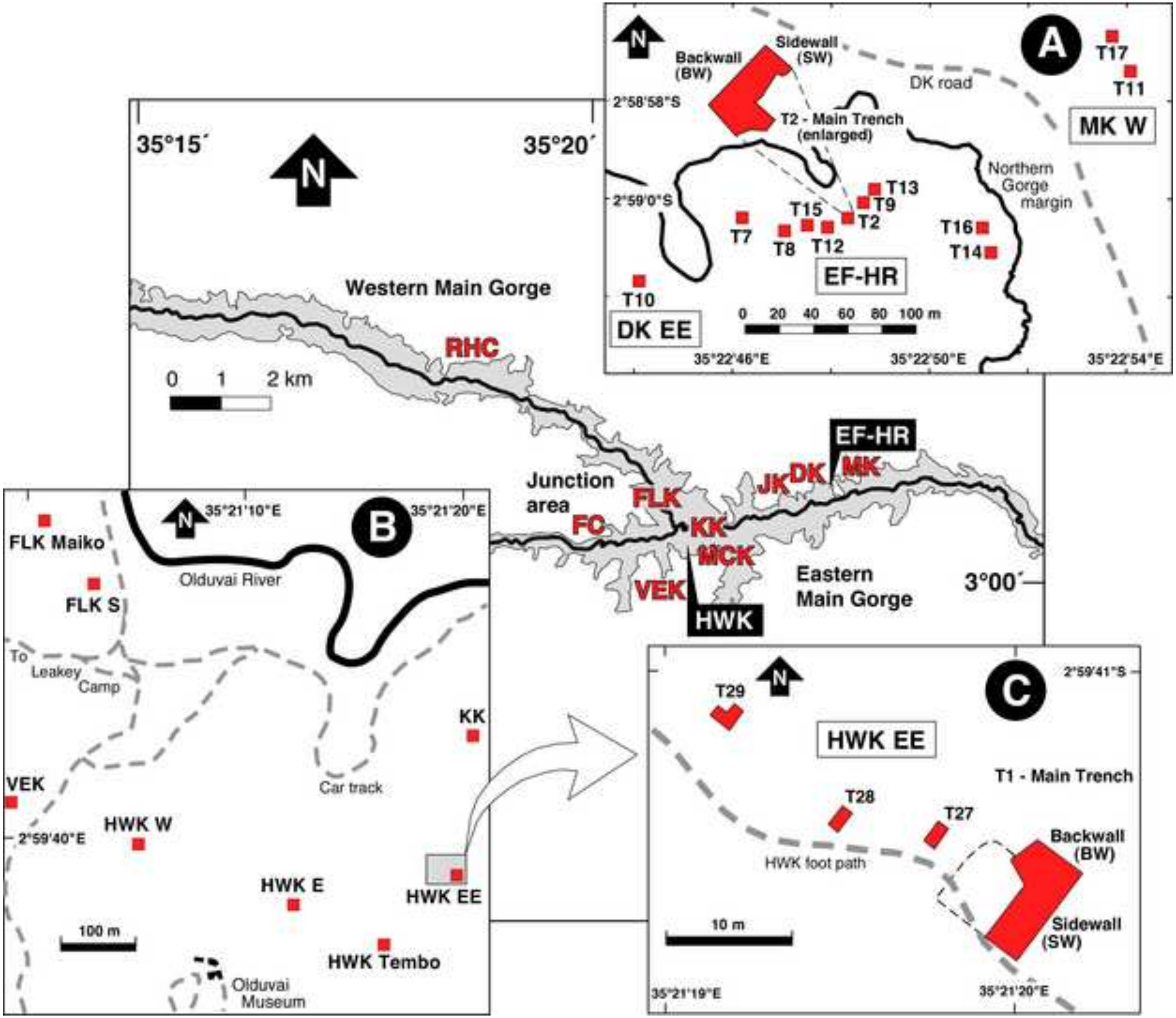

Figure 2

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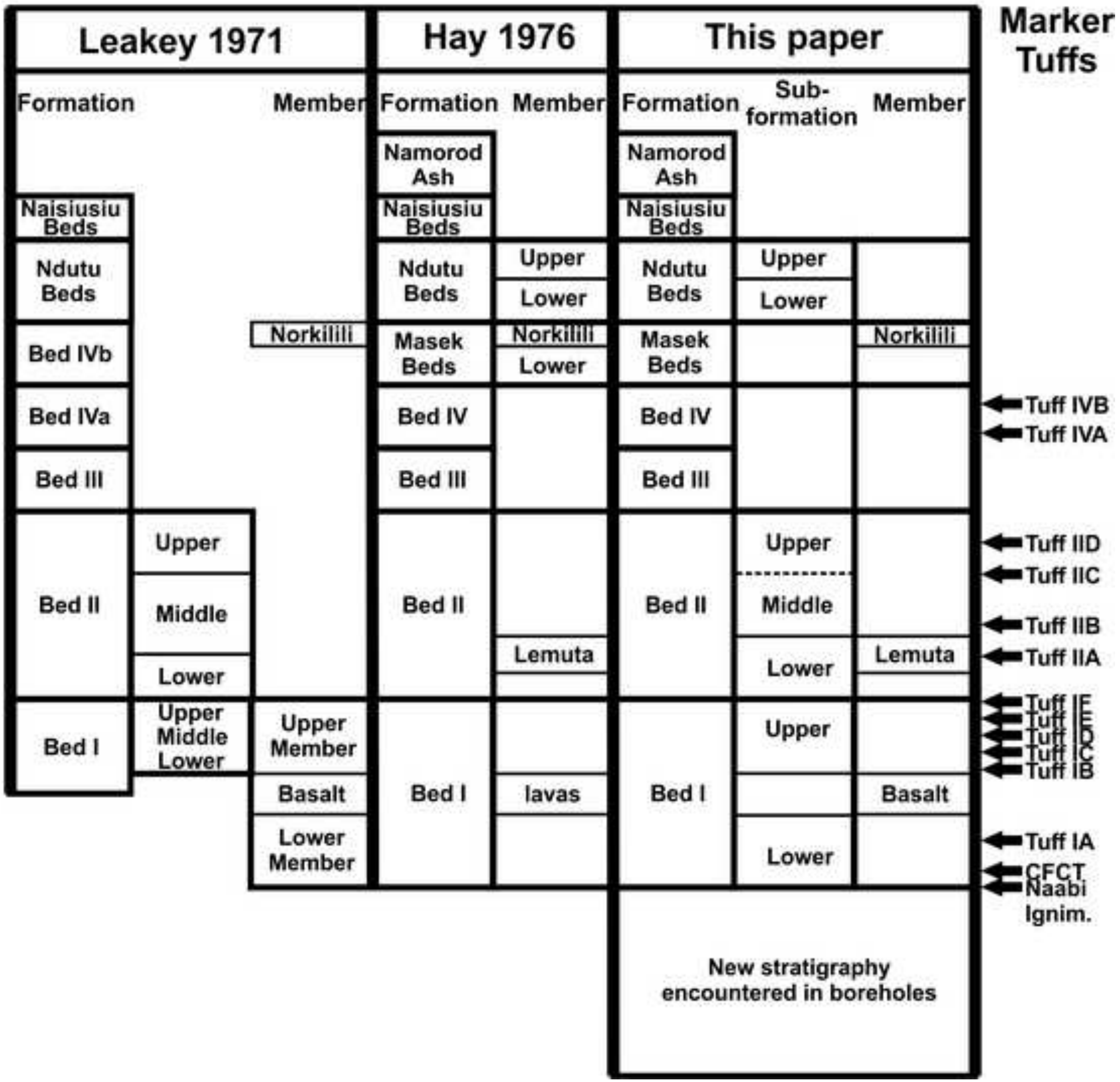
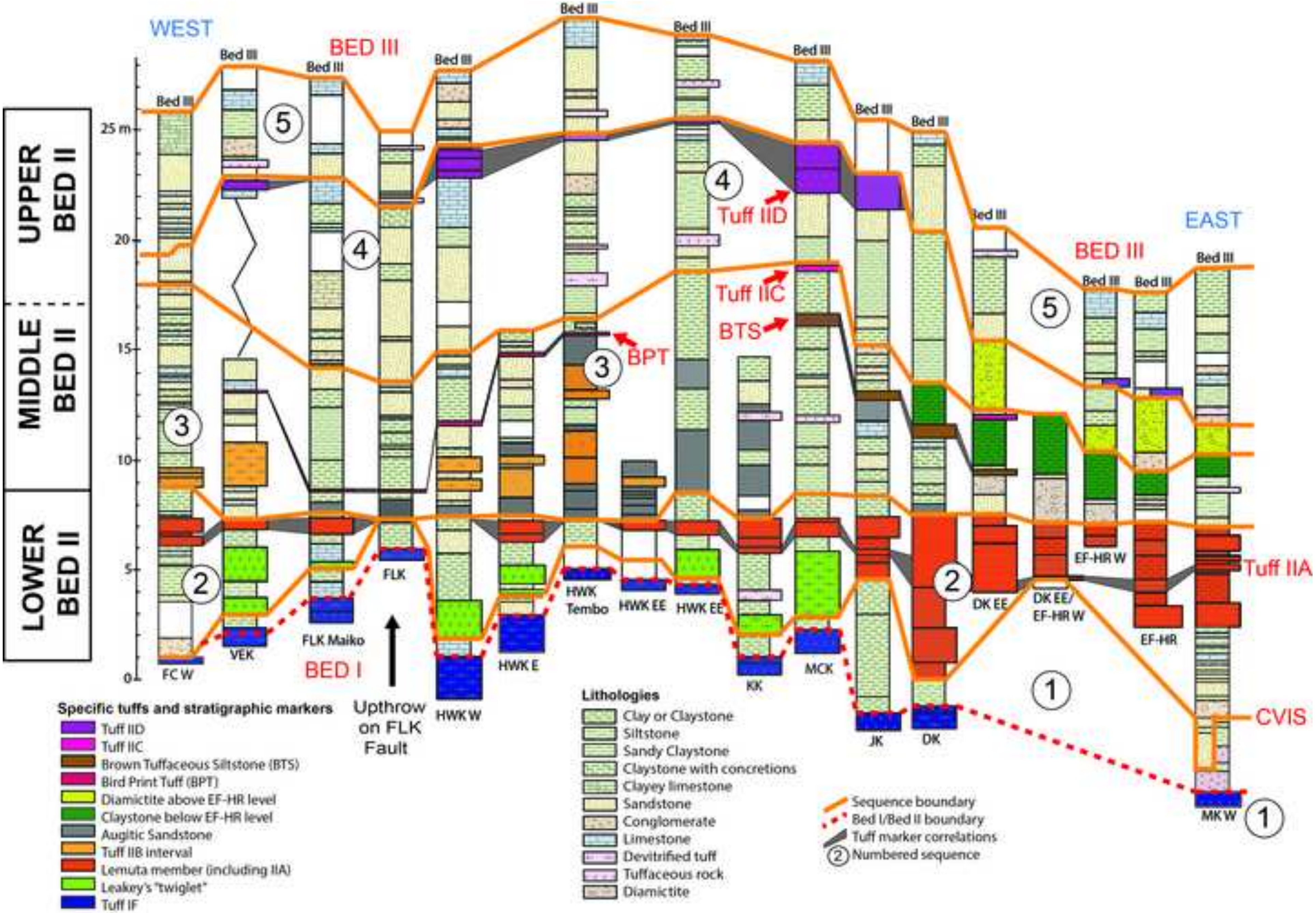


Figure 3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Upthrow on FLK Fault
Tuff IID
Tuff IIC
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5
Specific tuffs and stratigraphic markers
Tuff IID
Tuff IIC
Brown Tuffaceous Siltstone (BTS)
Bird Print Tuff (BPT)
Diamictite above EF-HR level
Claystone below EF-HR level
Augitic Sandstone
Tuff IIB interval
Lemuta member (including IIA)
Leakey's "twiglet"
Tuff IF
Lithologies
Clay or Claystone
Siltstone
Sandy Claystone
Claystone with concretions
Clayey limestone
Sandstone
Conglomerate
Limestone
Devitrified tuff
Tuffaceous rock
Diamictite
Sequence boundary
Bed I/Bed II boundary
Tuff marker correlations
② Numbered sequence

Figure 4

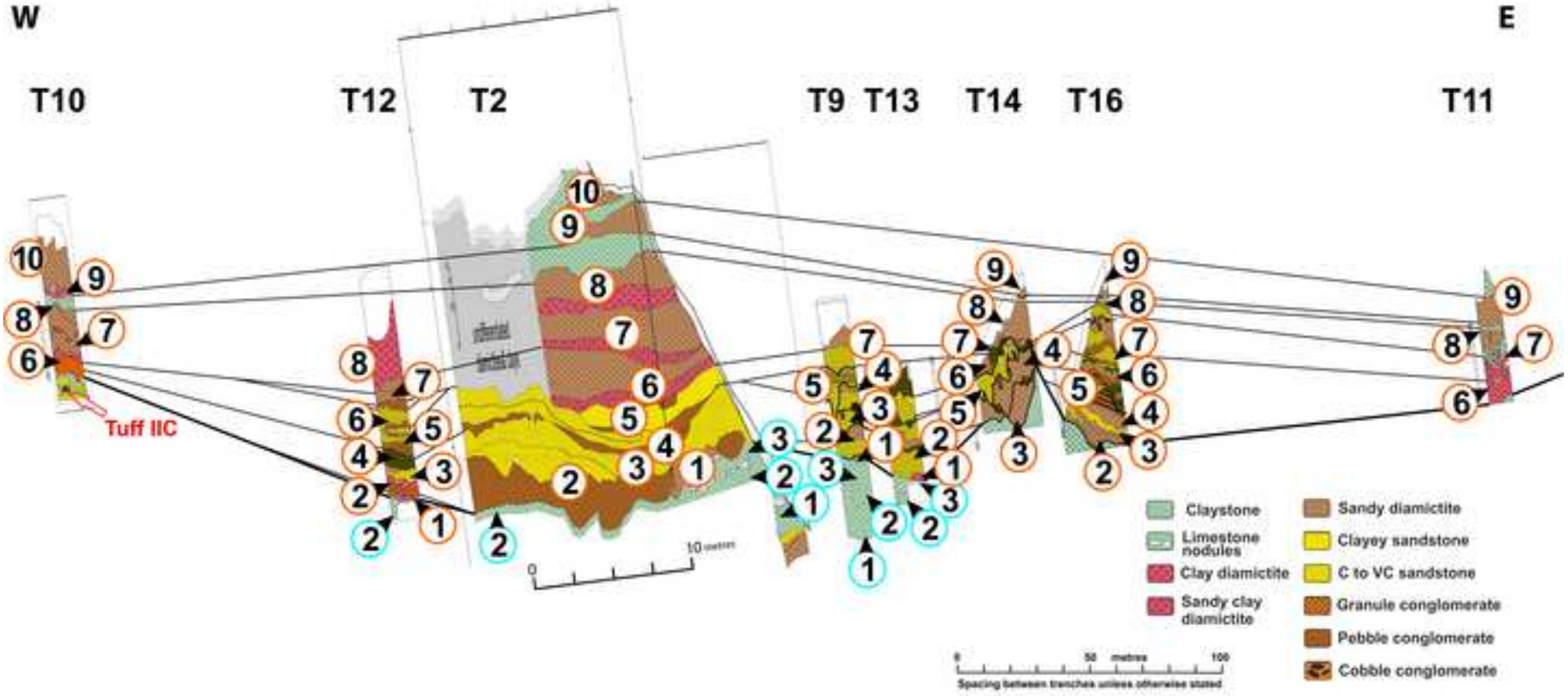
W
E
T10
T12
T2
T9
T13
T14
T16
T11
Tuff IIC
10 metres
0
Claystone
Limestone nodules
Clay diamictite
Sandy clay diamictite
Sandy diamictite
Clayey sandstone
C to VC sandstone
Granule conglomerate
Pebble conglomerate
Cobble conglomerate
0
50
metres
100
Spacing between trenches unless otherwise stated

Figure 5

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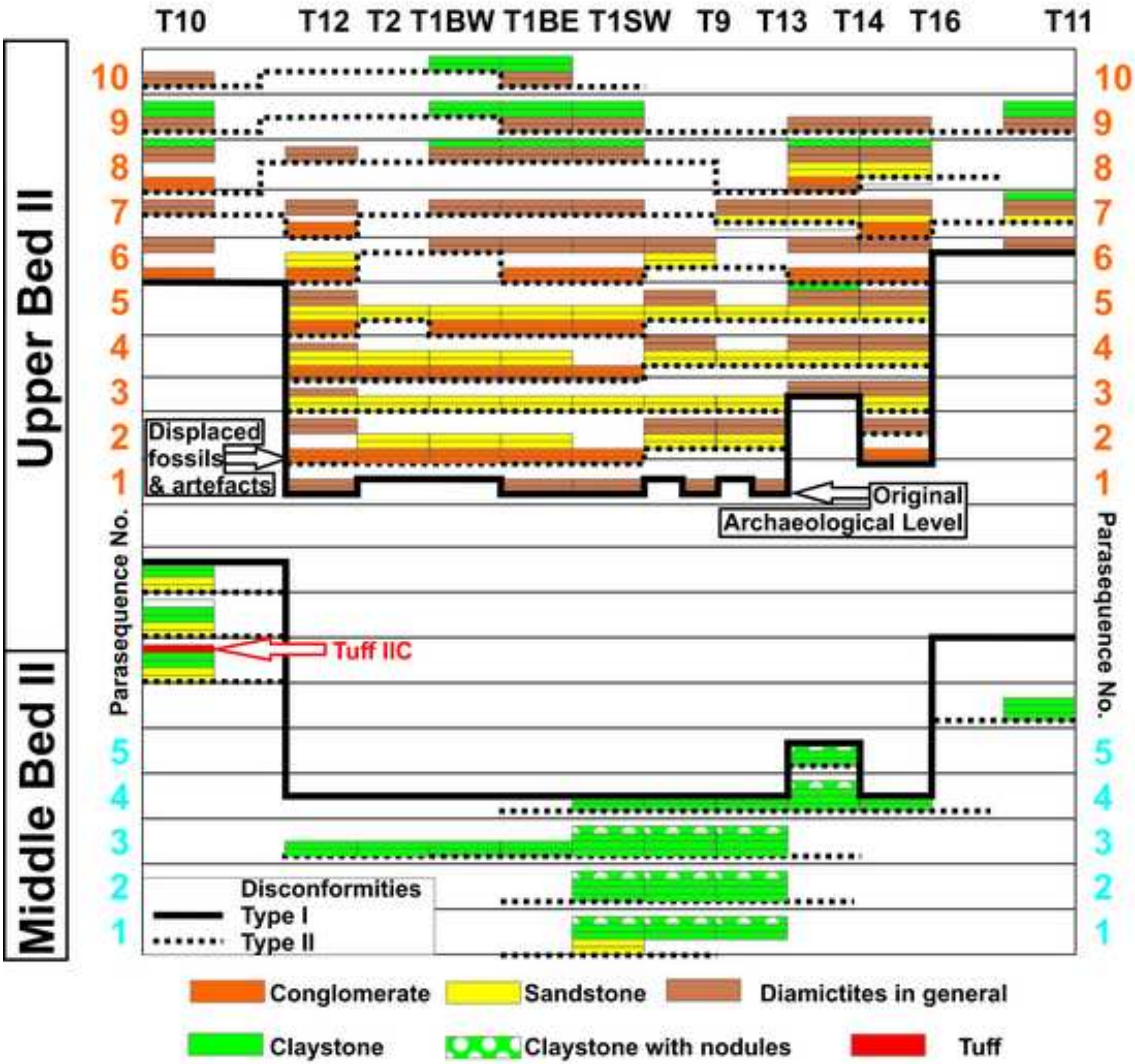


Figure 6

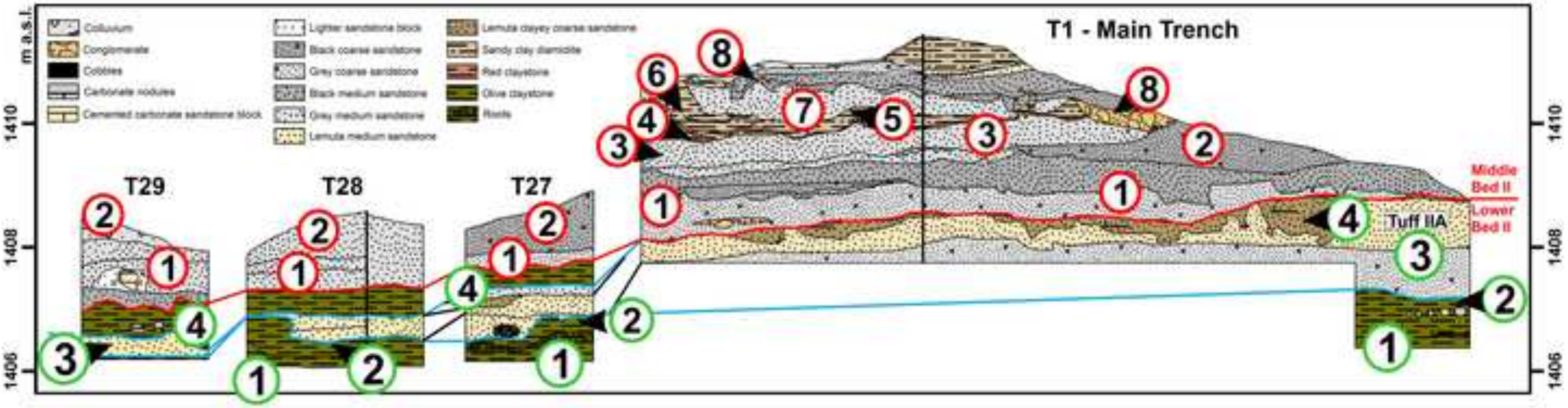
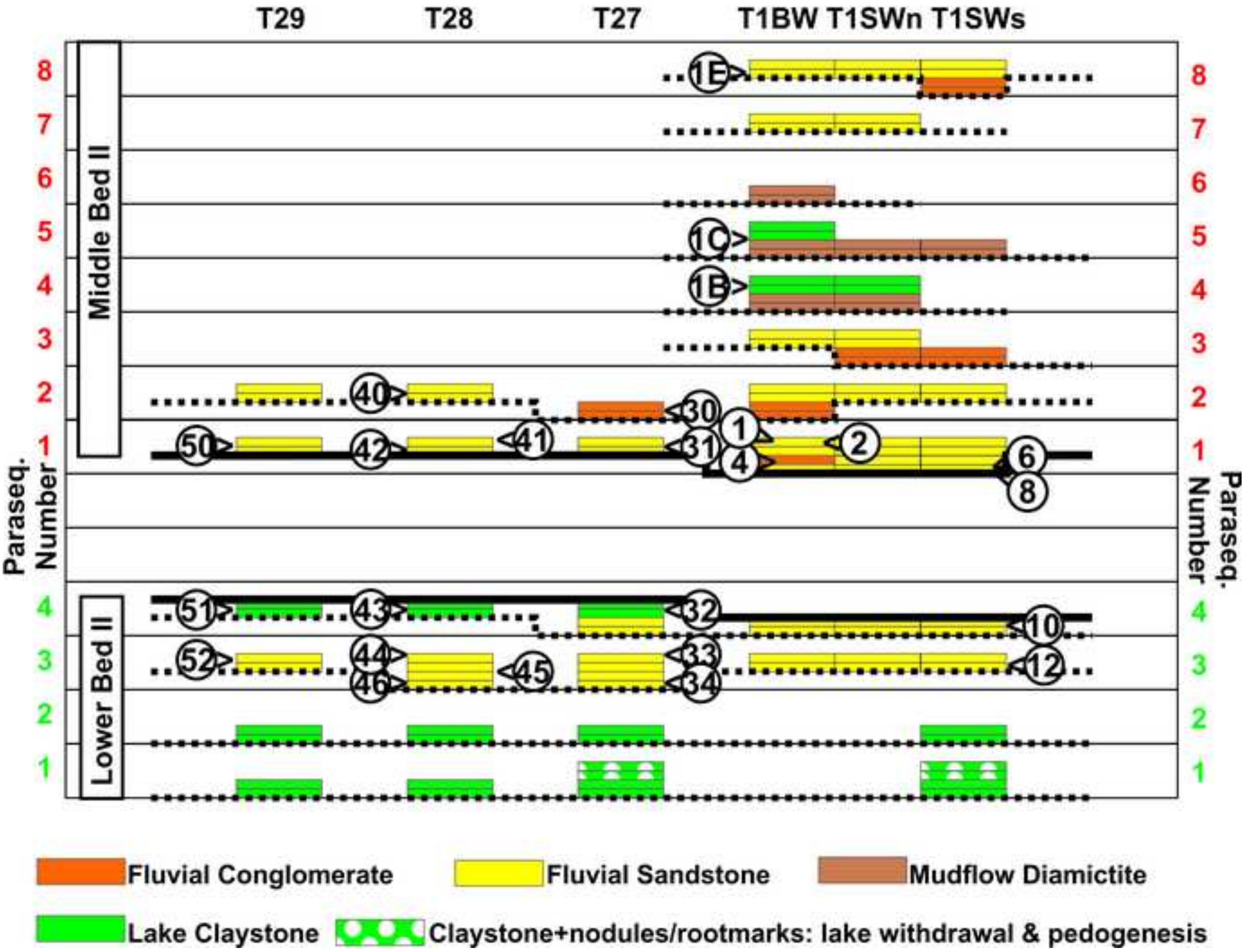

m a.s.l.
1410
1408
1406
Colluvium
Conglomerate
Cobbles
Carbonate nodules
Cemented carbonate sandstone block
Lighter sandstone block
Black coarse sandstone
Grey coarse sandstone
Black medium sandstone
Grey medium sandstone
Lemuta medium sandstone
Lemuta clayey coarse sandstone
Sandy clay diamictite
Red claystone
Olive claystone
Roots
T29
T28
T27
T1 - Main Trench
Middle Bed II
Lower Bed II
Tuff IIA
1
2
3
4
5
6
7
8

Figure 7


T29
T28
T27
T1BW T1SWn T1SWs
Middle Bed II
Lower Bed II
Paraseq. Number
Paraseq. Number
8
7
6
5
4
3
2
1
4
3
2
1
1E
1C
1B
40
30
1
50
42
41
31
2
4
6
8
51
43
32
10
52
44
46
45
33
34
12
Fluvial Conglomerate
Fluvial Sandstone
Mudflow Diamictite
Lake Claystone
Claystone+nodules/rootmarks: lake withdrawal & pedogenesis