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An integrative geochronological framework for the Pleistocene So’a basin (Flores, Indonesia), and its implications for faunal turnover and hominin arrival

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Flores represents a unique insular environment with an extensive record of Pleistocene fossil remains and stone artefacts. In the So’a Basin of central Flores these include endemic Stegodon, Komodo dragons, giant tortoises, rats, birds and hominins, and lithic artefacts that can be traced back to at least one million years ago (1 Ma). This comprehensive review presents important new data regarding the dating and faunal sequence of the So’a Basin, including the site of Mata Menge where Homo floresiensis-like fossils dating to approximately 0.7 Ma were discovered in 2014. By chemical fingerprinting key silicic tephra originating from local and distal eruptive sources we have now established basin-wide tephrostratigraphic correlations, and, together with new numerical ages, present an update of the chronostratigraphy of the So’a Basin, with major implications for the faunal sequence. These results show that a giant...
1. Introduction

Following nearly two decades of research since the initial discovery of Homo floresiensis in Liang Bua, the evolutionary history and immediate ancestry of this now-extinct hominin species continues to be debated (e.g., Argue et al., 2017; Argue et al., 2009; Baab et al., 2016; Brown et al., 2004; Jungers et al., 2009; Kishino et al., 2011; Morwood et al., 2005; Young, 2020). The age and stratigraphic contexts of the H. floresiensis fossils from Liang Bua have recently been revised to 100–50 ka ago (Sutikna et al., 2016), which, while considerably older than the first published estimate of ~12 ka, is still substantially younger than the assemblage of fossils of a small-toothed and small-jawed hominin excavated from the open site of Mata Menge in the So’a Basin. The Mata Menge hominins, dated to ~700 ka (Brumm et al., 2016), are interpreted on the basis of morphological characters to be the most likely ancestors of the Liang Bua hominins (van den Bergh et al., 2016). To date, comparative analyses of the Liang Bua H. floresiensis cranial, dental and skeletal morphological features have been inconclusive regarding ancestry, and two competing hypotheses continue to dominate the debate. One hypothesis proposes that H. floresiensis represents a dwarfed insular descendant of H. erectus (Brown et al., 2004; Kishino et al., 2011; Lyras et al., 2009; van den Bergh et al., 2016; Zanolli et al., 2022), while the other proposes a more archaic, small-bodied ancestor, such as Homo habilis or an Austra-lopothecine (Argue et al., 2017; Brown and Maeda, 2009; Jungers et al., 2009; Tocheri et al., 2007). Given the absence of additional, and more substantive, H. floresiensis fossil assemblages, and the lack of any recoverable aDNA, establishing the timing of the initial hominin colonization of Flores is important for resolving ancestral identity. This paper presents a detailed stratigraphy of the artefact- and fossil-bearing sequences within the So’a Basin, as well as descriptions of key associated tephra marker beds with inferences regarding their eruptive provenance. Together, this evidence provides the geological and palaeontological context bracketing the period of hominin first arrival on Flores, and the role that Pleistocene volcanic activity, climatic fluctuations, and/or the introduction of hominins to this isolated ecosystem may have played on the observed faunal changes during this time.

2. Setting and stratigraphic subdivision

The So’a Basin is a ~400 km² intra-arc basin located in central Flores (Fig. 1). This geological depression comprises a dissected grassland savannah plain with numerous small rounded hillocks and occasional deep valleys cut by the Ae Sesa River and its tribu-
taries, which drain to the northeast through a deeply incised gorge cutting through basement rocks (Brumm et al., 2016; Maringer and Verhoeven, 1970a; Suminto et al., 2009). The basin is almost entirely surrounded by active and inactive stratovolcanoes, remnant caldera structures and associated flanking volcaniclastic fans. The northwestern portion of the So’a Basin encroaches into a large (~15 km (E-W) by 8 km (N–S)) remnant caldera (the Welas Caldera), which has a deeply dissected crater wall breached to the southeast. Little is known about the eruptive age of this caldera structure, but two K–Ar dates from a ‘caldera-forming’ pumiceous tuff provide disparate ages of 1.66 ± 0.11 Ma (980723–06) and 2.52 ± 0.30 Ma (980723–06), with the older age considered the more reliable (Muraoka et al., 2002). Within the Welas Caldera are two mound-shaped topographic high points encircled, and on-
lapped, by lacustrine sediments: a ~1 km diameter lava dome located to the west (Wolo Mowa), and a ~2 km diameter basaltic cinder cone complex situated in the east (Wolo Muo). Other possible remnant caldera structures are located to the east of the So’a Basin: the Keli Lambo Volcanic Complex and a caldera structure near Raja, which lies in between the active Ebu Lobo Volcano to the southwest and the inactive Keli Lambo Volcanic Complex to the northeast (Fig. 1). The southwestern margin of the So’a Basin is occupied by the Bajawa Cinder Cone Complex (BCCC), a clustered field of 60+ craters of basaltic andesite to andesite composition (54–61 wt% SiO₂) that have been active since 0.73 Ma (Sucipta et al., 2006), and which includes the active Inelika Volcano (Fig. 1). Palaeontological and archaeological research began in the So’a Basin during the late 1950s, when Theodorus Theo Verhoeven (1907–1990) commenced excavations at Ola Bula and recovered an assemblage of Stegodon remains (Verhoeven, 1958). In 1960, the Geological Survey of Indonesia embarked on a regional survey of the basin to clarify its fossil-bearing stratigraphy (Hartono, 1961), while Verhoeven continued to perform test excavations at other sites, establishing that Stegodon fossils were associated with stone artefacts at Mata Menge and the nearby site of Boa Leza (Maringer and Verhoeven, 1970a). Follow-up research in the basin identified three main stratigraphic units. From oldest to youngest these are the Ola Kile Formation, the Ola Bula Formation, and younger volcanic rocks that lap on to the basin sequence along the western and southern basin margins, and are associated with still-active vol-
canoes (O’Sullivan et al., 2001; Sondaar et al., 1994; Suminto et al., 2009; van den Bergh, 1999). Overall, this stratigraphic subdivision has continued to provide a reliable basis for the palaeontological and archaeological research undertaken within the So’a Basin — including this current study. A more detailed basin stratigraphy is required, however, to place all the key fossil and archaeological sites and excavations in a chronological and environmental context.

3. Methodology

This section constitutes a brief summary of the methods applied. Further details regarding the analytical procedures, standards,
constants, and so forth, are provided in the Appendices. Excavation methods are detailed in Brumm et al. (2016).

3.1. Geodesy

From 2010 until 2019 we have undertaken multiple field campaigns in the So’a Basin. Initially, stratigraphic sections were exposed at a number of key sites by excavating 1-m wide slot trenches covering the entire basin-fill sequence. Simultaneously, we conducted archaeological and palaeontological excavations at key sites. Stratigraphic sections were recorded and systematically sampled for geochemical analyses, and for palaeomagnetic and numerical dating purposes. The spatial coordinates of concrete pillars erected as reference points for further surveying at key sites and sections were determined using a Trimble Differential GPS. The reference points were calibrated against the Triangulation point at Rakalaba east of Bajawa (Bakosurtanal). All coordinates were recorded in the WGS 84 UTM system (Zone 51S), with all elevations in this paper given as ellipsoidal heights. Total stations (Topcon OS100 and Leica TS11) were used to measure dense grids of surface coordinates and construct detailed topographic maps with 1-m contour intervals of the areas surrounding key excavation sites (see Appendix-A), as well as to record the 3D-coordinates of all excavated finds.

3.2. Chemical fingerprinting of tephra

Glass shard major and trace element determinations were conducted on primary rhyolitic airfall and mass-flow tephra layers to allow the identification and correlation of key stratigraphic markers throughout the basin. In addition, potential correlatives from adjacent field sites were included in the geochemical analyses. Major element data were acquired using a JEOL Superprobe housed at Victoria University of Wellington. Trace elements analyses on glass shards were performed by laser ablation (LA) ICP-MS at the Research School of Earth Sciences, Australian National University (Canberra). Selected trace elements of mafic agglutinated scoria and diabase samples were analysed using nebulation inductively coupled plasma mass spectrometry (SN-ICP-MS) at the Department of Geography and Earth Sciences, Aberystwyth University. See Appendix B for details.

3.3. Dating techniques

Age determinations of key tephra marker beds and fossil occurrences were conducted using various methods. The single crystal 40Ar/39Ar technique was applied on potassium-rich minerals (hornblende and feldspar) from three samples of rhyolitic tephra at the Quaternary Dating Laboratory of Roskilde University (see Appendix C for details). Another method applied on apatite grains from one rhyolitic tephra sample was the (U-Th-Sm)/He dating technique, carried out at the School of Earth Sciences, University of Melbourne (see Appendix D for details).

In addition, two late Pleistocene Stegodon tooth samples were subjected to U-series dating at the Wollongong Isotope Geochronology Laboratory, University of Wollongong, using laser ablation.
multicollector ICP-MS (see Appendix E for details). Two charcoal samples (Wk-48668 and Wk-48669) from the same Late Pleistocene lake deposit from which two Stegodon tooth samples originated, were sent to the University of Waikato Radiocarbon Dating Laboratory for Accelerator Mass Spectroscopy (AMS) radiocarbon (\(^{14}C\)) dating. Samples were pre-treated with hot HCl, rinsed and treated with multiple hot NaOH washes, filtered, rinsed and dried. Both conventional AMS \(^{14}C\) ages are provided in the text, as well as the calibrated \(^{14}C\) ages, using OxCal v4.3.2.

Other age estimates obtained by additional techniques and reported in previous published sources are fission-track dating on zircon crystals from tephra pumice clasts and tuffaceous layers; isothermal plateau fission-track (ITPFT) dating of glass shards; combined U-series and electron spin resonance (ESR) dating on Stegodon molar fragments. In three stratigraphic sections the obtained numerical ages were combined with magnetic polarity measurements.

### 3.4. Stable isotope analysis on fossil tooth enamel

In order to reconstruct the feeding ecology of vertebrates and changes in this ecology over time, stable isotope analysis (\(\delta^{13}C\) and \(\delta^{18}O\)) was performed on fossil tooth enamel of adult individuals of Stegodon and Hooijeromyx from various localities, covering the entire temporal range of the vertebrate-bearing sequence. Stable isotope values are reported in ‰ relative to VPDB (\(\delta^{13}C\)) and VSMOW (\(\delta^{18}O\)). The carbon isotope ratio (\(\delta^{13}C\)) in body tissues of herbivores, including the relatively stable tooth enamel, reflects the types of vegetation consumed. This allows for the detection of trends in relative proportions in diets of plants with different photosynthetic pathways for CO₂ assimilation, namely C₃ plants (most trees shrubs and high-altitude or high-latitude grasses) and C₄ plants (tropical grasses and sedges). As feeding behavior in opportunistic herbivores such as elephants is heavily influenced by available resources, changes in the proportion of C₃ versus C₄ plants in paleo-diets over time is thought to be strongly correlated with changes in vegetation cover and climate (Cerling et al., 1999; DeNiro and Epstein, 1978; Puspaningrum et al., 2020). The \(\delta^{18}O\) incorporated in animal tissues depends on the \(\delta^{18}O\) fractionation in drinking water and food, which is in turn the result of a complex function of geographical, climatic, and ecological conditions, and hence more difficult to interpret. However, on a tropical island such as Flores it can be expected that the \(\delta^{18}O\) values become more positive when the contribution of precipitation to surface drinking water decreases and/or evapo-transpiration increases (see Puspaningrum et al., 2020, and references therein).

### 4. Stratigraphy

Field research and dating between 2010 and 2019 on a number of stratigraphic sections has produced a working model of the stratigraphy across the Sola Basin (Fig. 2). Here we describe the major stratigraphic divisions from earliest to latest.

#### 4.1. Ola Kile Formation

The Ola Kile Formation (hereafter OKF) is a southward tilted (−5°) basement of indurated fluvo-volcaniclastic deposits of at least 100 m thick, that comprise pyroclastic flows, andesitic breccias, lava flows, laharc diamicts and subordinate tuffaceous sandstones and siltstones with intervening lithified palaeosols. One of the most prominent units so far recognised within this formation is a 26-m thick weathered ignimbrite with basal coarse-grained surge (~1.3-m thick) and fall (~2.8-m thick) subunits in the eastern part of the basin (Setiawan, 2018); see Fig. 2; Lowo Mali Ignimbrite). The source of this ignimbrite deposit is unknown, but based on its flow-surge-fall facies architecture and very coarse-grained pumice (P) and lithic (L) clast componentry (i.e., \(P_{\text{max}} 8 \times 7 \text{ cm}; L_{\text{max}} 5 \times 4 \text{ cm}\), it is likely that this deposit is source-proximal and relates to a voluminous late stage eruptive event sourced from either the Keli Labomo or Raja Caldera (Fig. 1). A single Zircon Fission Track (ZFT) age for the ‘upper part’ of the OKF in the eastern part of the basin has provided an age of \(1.86 \pm 0.12 \text{ Ma}\) (O’Sullivan et al., 2001). The dating sample is reported to have been taken below the angular unconformity with the overlying Ola Bula Formation (see below), but it is not clear whether this sample originates from the uppermost part of the OKF sequence (Lowo Mali Ignimbrite) or from an older interval, though it does provide a maximum age for the onset of deposition of the overlying Ola Bula Formation.

#### 4.2. Ola Bula Formation

The Ola Bula Formation (hereafter OBF) overlies the OKF with an angular unconformity and comprises as much as 70 m of largely undeformed and flat-lying volcano-sedimentary deposits. The OBF has been subdivided into three lithological members named (from base to top): Tuff, Sandstone and Limestone Members (Sumitomo et al., 2009; van den Bergh, 1999). The basal Tuff Member consists of dominantly metre-to decimetre-thick pyroclastic (primary) and fluvo-volcaniclastic (secondary) deposits interbedded with subordinate well-developed palaeosols and pedogenically-altered fluviatile silts, sands and conglomerate lenses. Locally a 3 m thick sequence of thin-bedded lacustrine silts and clays is incorporated in the Tuff Member (Fig. 2; Dena Biko Section 272.8 - 276 m). The Tuff Member is only 8 m thick along the NE margin of the basin (at Kobatuwa I) but increases to 33 m thickness in the central basin area (near Tangi Talo) and decreases in thickness again further east.

The basal tuffaceous deposits grade upwards into a middle 20–30 m thick Sandstone Member dominated by well-developed palaeosols overprinted on variably textured conglomerate lenses, sandstones and siltstones, which were deposited by braided rivers. Along the northwestern basin margin, the Sandstone Member encompasses fluvial gravels and sands alternating with clay-textured mudflow deposits (cohesive mass flows; see Appendix F for field criteria) containing diatoms with intervening palaeosols and infrequent basaltic-andesite tephra inter-beds. The latter perceptibly coarsen and thicken northwards towards the Welas Caldera. This mudflow-sandstone-gravel facies association is of limited lateral extent and is deposited in a north-south oriented paleovalley eroded into the basal deposits of the Tuff Member. Further east and along the southern basin margin the Sandstone Member is characterized by an alternation of conglomerates and siltstones, both heavily overprinted by sub-aerial weathering and palaeosol formation.

The middle Sandstone Member is overlain by an 8.5 m thick sequence of thin-bedded lacustrine sediments (Gero Limestone Member, GLM) that caps the basin infill and registers the presence of a basin-wide lake, which formerly extended into the Welas Caldera (Fig. 2). This interval consists predominantly of laminated micritic freshwater limestones, clays and silts, and is interbedded by abundant coarse-grained basaltic and sporadic fine-textured silicic tephra. Palaeosols and infilled polygonal shrinkage cracks
are not uncommon within the lacustrine sequence, indicating fluctuating lake levels and occasional sub-aerial exposure along the lake margins. Along the northeastern basin margin the GLM directly overlies the OKF unconformably (Fig. 2 Alorawe Section). In the southern Solo Roa section the thin-bedded lacustrine GLM sequence is conformably overlain by a 7 m thick clastic sequence that includes 2.5 m high northward dipping clinoforms interpreted as a Gilbert-type delta prograding into the lake.

Stone artefacts and abundant vertebrate fossils are found at numerous localities within the Sandstone Member, commonly in direct association within the same layers. Vertebrate fossils are much less common in the Tuff Member and have so far only been encountered in the central part of the basin near Tangi Talo, where the Tuff Member reaches its maximum thickness. Stone artefacts in the Tuff Member appear to be restricted to the uppermost part, and have not been found associated with vertebrate fossils in this sub-unit. Freshwater algae (oogonia), plant, diatom, fish, ostracod and gastropod fossils have been identified within the GLM, as well as pollen assemblages. Previously the age of the OBF has been reported as ranging from over 1.01 Ma to 0.51 ± 0.03 Ma (Brumm et al., 2010a; Brumm et al., 2016; Morwood et al., 1998; O'Sullivan et al., 2001). Here we show that the basal age of the OBF and the oldest fossil assemblage dates to at least 1.4 Ma.

4.3. Younger volcanics

Along the western, southern and eastern basin margins, younger volcaniclastic sequences mantle the OBF. These include
basaltic to basaltic-andesite lava flow deposits, interbedded with coarse-grained fluvo-volcanic detritus, originating from the surrounding upland volcanoes such as the Bajawa Cinder Cone Complex (BCCC) and the Ebu Lobo Volcano. At a site called Ulu Mala Kata, near the confluence of two major rivers, the Abe Sesa and the Lowo Lele (Fig. 2), a massive laharc sequence of at least 6 m thick forms a recent fill terrace.

5. Key stratigraphic units

5.1. Silicic tephra deposits

Silicic tephra (>60 wt % SiO₂) deposits have played a pivotal role in refining the fossil- and artefact-bearing stratigraphy within the So’a Basin, enabling improved basin-wide correlations as well as more specific targeting of prospective sites for excavation at relevant time-intervals (Brumm et al., 2010a, 2016). Silicic tephra are prevalent within two stratigraphic intervals that correspond with the upper GLM (Figs. 2, 3A-D) and the lower Tuff Member (Figs. 2 and 3E, F). To date, no silicic tephra have been identified within the middle Sandstone Member.

Silicic tephra are typically represented as fine-grained vitric-rich tephra-falls, pumice-rich ignimbrites (gas-supported mass-flow deposits) and ashy-pumiceous debris-hyperconcentrated-flood flow (water-supported mass flow deposits), with each category of deposit able to be distinguished in the field by their sedimentary characteristics (see Appendix-F; Fig. 2). Because silicic tephra deposits are minimally affected by intense tropical surficial weathering (cf. basaltic to basaltic andesite deposits), it is a relatively straightforward exercise to geochemically characterise glass shard and mineral constituents utilising the techniques of electron microprobe (EMP) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) (Figs. 4 and 5; Table 1; Table B1). Similarly, a number of different radiometric dating methods (i.e., ⁴⁰Ar/³⁹Ar, and fission track) have been applied to tephra mineral and glass constituents (Table 2). Radiometric ages have also been corroborated with palaeomagnetic polarity data retrieved from tephra-bearing sequences (i.e., Fig. 2).

5.1.1. Silicic mass-flow deposits

Three prominent silicic mass-flow deposits (Wolo Sege, Turakeo and Pu Maso) are widely recognised throughout the So’a Basin as occurring in close stratigraphic succession, but are separated by well-developed palaeosols (Fig. 6A–C). Of the three mass-flow deposits, Wolo Sege Tephra is the most extensive and stratigraphically significant. Turakeo and Pu Maso mass-flow deposits have a similar field expression, but can be distinguished by a fine-grained silicic ash bed (T3) of distinct mineralogy and glass geochemistry occurring within an intervening palaeosol, as well as by the ubiquity of exceptionally large accretionary lapilli within the texturally finer Pu Maso deposits (see Fig. 6D). It is important to emphasize that field correlation of individual mass-flow deposits can be problematic, particularly in medial to distal areas from an eruptive source area, because they sometimes display transitional sedimentary characteristics indicative of rapid lateral transformation from hot, gas-supported pyroclastic flow/surge into water-supported debris-hyperconcentrated-flood flow deposits (Alloway et al., 2004; Pillans et al., 2005; Smith and Lowe, 1991). Similarly, many outcropping mass-flow deposits may initially display features indicative of primary emplacement but can upwardly transition to reworked deposits. Since the depositional character of silicic mass-flow deposits can vary both laterally and vertically across the So’a Basin, the identity of key tephra units is here verified and correlated on the combined basis of unique depositional architecture and stratigraphic association, which is further verified by glass-shard major- and trace-element chemistry and numerical dating chronology.

5.1.2. Wolo Sege tephra

The Wolo Sege Tephra (WST; previously referred to as Wolo Sege Ignimbrite: Brumm et al., 2010a; Brumm et al., 2016) is the most extensive and stratigraphically significant metre-thick silicic mass-flow deposit within the So’a Basin fossil-bearing sequences. It was first recognised in the west-central part of the basin at the Wolo Sege archaeological site (Brumm et al., 2010a). Within the Wolo Sege type section (Figs. 2, 7A–B), the WST immediately overlies a well-stratified palaeosol containing in situ stone artefacts developed into artefact-bearing fluvialite conglomerate and siltsilt sediments ~2 m above the unconformable contact with the underlying breccias of the OKF. Hornblende crystals extracted from WST at this site yielded a ⁴⁰Ar/³⁹Ar age of 1.02 ± 0.02 Ma (Brumm et al., 2010a, 2016), which also provides a minimum age for the stone artefacts directly underlying WST.

Throughout the So’a Basin, WST has a unique depositional architecture that can be subdivided into three distinctive sub-units enabling an unambiguous field correlation (i.e., Fig. 7A–B); a lower planar-to cross-stratified unit containing accretionary lapilli (dominantly pyrolastic surge with fall component), a middle massive to weakly stratified pumiceous unit (pyroclastic flow) and an upper redeposited unit comprising regular, massive to planar bedded (dm to mm-laminae), well sorted, light grey to pale yellow, coarse to fine sandy vitric ash and conspicuous accretionary lapilli. The middle pumice unit is further characterised by the presence of both white and grey pumice (<10%) and the occurrence of large hornblende crystals. WST is now widely recognised at numerous sites, including Mata Go (Figs. 2, 7D–E), where an in situ stone artefact (Fig. 7E–F) protrudes into basal WST from the surface of an underlying palaeosol, and at Kobatuwa IV (Figs. 2 and 7C), where stone artefacts also occur in situ in a conglomerate lens directly underlying WST.

Based on sedimentary architecture and glass shard major element composition, WST is correlated to the upper part of the Tangi Talo fossil site located in the central part of the So’a Basin (Fig. 7G–H). At Tangi Talo WST was directly dated using the same radiometric technique applied to WST at Wolo Sege. An indistinguishable hornblende ⁴⁰Ar/³⁹Ar isochron age of 0.98 ± 0.02 Ma (SF-FLO12-TT1) was determined (see Appendix-C, Figs. C2, C4). These results are further supported by a hornblende ⁴⁰Ar/³⁹Ar isochron age of 1.01 ± 0.05 Ma for WST in the Mata Menge section (Brumm et al., 2016), and an apatite (U–Th-Sm)/He age of 0.98 ± 0.05 Ma (±2 se) for WST at its type section (see Appendix D). In addition, these WST ages are further supported by palaeomagnetic polarity data from both the Tangi Talo and Mata Menge sections, which indicate a clear polarity change from normal to reverse just below WST, consistent with the base of the Jaramillo normal subchron, dated at 1.07 Ma (see Fig. 2; Yurnaldi et al., 2018).

5.1.3. Other silicic tephra with unique correlation potential

While many airfall tephra beds of silicic composition have been identified throughout the OBF sedimentary succession, there are two white fine-grained vitric-rich ash beds of distinct glass chemistry that standout with unique, regional correlation potential (Figs. 4 and 5; Table 1; Table B1). One is a silicic ash bed (T6) that is exposed at Mata Menge (Trench MM-35: see Fig. 2) within the uppermost part of the lacustrine GLM (Fig. 8 Set A). Here T6 tephra occurs as a discrete cm-thick normal bedded, fine sandy-silt
textured vitric ash and is stratigraphically associated with numerous dark grey ash and lapilli inter-beds of maﬁc composition (collectively referred to as Piga Tephra). A single feldspar crystal 40Ar/39Ar age of 0.51 ± 0.03 Ma was determined for T6 (Brumm et al., 2016).

Another distinctive silicic ash bed (T3) occurs at several So’a Basin localities (i.e. Mata Menge, Kopowatu, Lowo Mali; see Fig. 2) within a prominent palaeosol intervening between Turakeo (lower) and Pu Maso (upper) tephras. In this context the T3 tephra occurs as a cm-thick, massive to normal bedded, biotite bearing, silt-textured vitric ash (i.e., Fig. 8 Set B). The very fine texture of T3 remains the same irrespective of its depositional context, which, together with T3’s location throughout So’a Basin, indicates a likely distal source. A glass shard isothermal plateau ﬁssion-track (ITPFT) mean age of 0.90 ± 0.07 Ma was determined for T3 at Mata Menge (Brumm et al., 2016). This age is also consistent with a hornblende 40Ar/39Ar age of 0.81 ± 0.04 Ma derived from Pu Maso Tephra closely overlying T3, and within the same slot trench section (Brumm et al., 2016).

5.2. Mafic airfall tephra

Tephra inter-beds of mafic (i.e. basaltic andesite to andesite; 54–61 wt% SiO2) composition are concentrated in the middle to upper portions of the OBF sedimentary succession (Figs. 2 and 9), but are of limited correlative value as they are numerous and difﬁcult to differentiate and geochemically analyse. The oldest occur as two dark grey, cm-thick normal bedded scoriaceous coarse ash inter-beds (named upper Mata Menge Tephra [T-UMM] and Lower Mata Menge Tephra [T-LMM]) within the uppermost Sandstone Member in the vicinity of Mata Menge. No direct radiometric
Ages have been determined for tephra from this lower stratigraphic interval.

In closely overlying lacustrine sediments of the GLM, the occurrence of mafic tephra becomes significantly more numerous \( (n > 58) \) (Setiawan, 2018); typically comprising mm-to cm-thick, massive to graded inter-beds of moderate-to well-sorted dark grey scoriaceous ash and lapilli, as well as grey to brown poorly-sorted muddy ash. These tephra exhibit depositional features indicative of explosive magma-water interactions that resulted in magmatic-phreatomagmatic eruptive products. Informally named Piga tephra (PGt), these tephra inter-beds are sequentially numbered upward from the basal contact of the Limestone Member. At Mata Menge

Fig. 4. Selected major element compositions (weight percent SiO\textsubscript{2} vs. K\textsubscript{2}O and FeO vs. CaO and K\textsubscript{2}O) of glass shards from key silicic tephra within the upper Ola Bula Formation (Gero Limestone Member; A, C, D) and lower Ola Bula Formation (Tuff Member; B, E, F).

While major element glass compositions of most tephra within TM are geochemically indistinguishable (except T3 tephra marker), a number of key tephra within this compositional grouping can be distinguished since they consistently occupy subtly different overlapping fields. The overall compositional grouping likely indicates derivation from the same eruptive centre and over a sustained period of time. Discrete compositional groupings of tephra are more discernible within GLM and appear to suggest intermittent eruptions from different centres. The identity of tephra with indistinct glass chemistry can often be readily distinguished in the field by a combination of stratigraphic position and association, as well as by morphological expression.
(slot Trench MM-12 and Excavation MM-32), T-Pg-02 positioned just above the base of the Limestone Member has a single crystal hornblende $^{40}$Ar/$^{39}$Ar age of 0.65 ± 0.02 Ma (Brumm et al., 2016).

Piga tephra can be traced within the Welas Caldera to roadside sections (i.e., Wulubara, Poma; see Fig. 2A) where fine-grained tuffaceous lacustrine sediments are interbedded by abundant mafic lapilli and ash beds that are perceptibly thicker and coarser grained than the mafic inter-beds of the Limestone Member at Mata Menge. Within the Welas Caldera these tephra beds are frequently associated with scoria-bearing debris flow deposits and metre-thick sequences of coarse fragmented scoria and bombs. Bulk solution nebulization ICP-MS (SN-ICP-MS) analyses (see Table B) conducted on selected magmatic-phreatomagmatic tephra from Mata Menge are geochemically indistinguishable from analyses of agglutinated scoria and diabase samples retrieved from a basaltic cinder cone (Wolo Muo; east, Fig. 1) and lava dome (Wolo Mowa, west, Fig. 1) within the Welas Caldera (Fig. 9G and H). At present, it is not known if the two intra-caldera mafic domes are temporally related, but the emergence of the eastern cone complex certainly occurred during an interval when the Welas Caldera contained an extensive lake, and explosive water-magma interactions generated a succession of phreatomagmatic-magmatic fall units and sub-aqueous scoria-bearing debris flow deposits, as well as clay-rich, cohesive mass-flow (mudflow) deposits that extended down ancestral tributaries directly adjacent to the Welas intra-caldera lake.

6. Key fossil- and artefact-bearing sections

In the following section key sites within the So'a Basin are described according to their arrangement from west to east as indicated in Fig. 2, and not in chronological order.

6.1. Kobatuwa

6.1.1. Kobatuwa site stratigraphy

In 2005–2006 three excavations were undertaken at the site Kobatuwa-I in western part of the So’a Basin (Fig. 2). The
<table>
<thead>
<tr>
<th>Tephra</th>
<th>Section</th>
<th>Sample</th>
<th>Probe Run</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>TiO₂</th>
<th>FeO</th>
<th>MgO</th>
<th>MnO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>Cl</th>
<th>H₂O</th>
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<td>12_19_08</td>
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<td>12.61</td>
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<td>0.13</td>
<td>1.85</td>
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<td>WSI-G</td>
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excavations are numbered KBT-I-T1 to KBT-I-T3 (see Appendix A). At KBT-I-T2 an assemblage of comparatively large in situ stone artefacts (cores and flakes) was recovered from a fluvial boulder conglomerate with an erosive base (Jatmiko et al., 2009), but the exact stratigraphic level of the younger tuff layers reportedly from below and above, respectively, the main fossil-bearing layers at Kobatuwa (Jatmiko et al., 2009; O’Sullivan et al., 2001). The lower sample was originally obtained from the reworked Turakeo Tephra lens in the channel-fill (Layer W2) (see in Jatmiko et al., 2009), but the exact stratigraphic level of the younger sample was not documented.
WST is not recorded at KBT-I but can be observed along the opposite, eastern side of the valley bottom at KBT-I, and at KBT-IV, which is further west, and where it directly overlies a conglomeratic fluvial cut-and-fill deposit with in situ stone artefacts (Figs. 2 and 7C).

6.1.2. Kobatuwa fauna and archaeology

The fossil taxa that were excavated from Layers I, G and H are predominantly *S. floresis*, with a Minimum Number of Individuals (hereinafter MNI) of 39, based on dental remains. Only two rolled *Stegodon* molars have been recovered from the older conglomerate layer (Layer K; fauna assemblage KBT-LOW). These molar fragments are above the maximum size range for *Stegodon sondaari*, and allow attribution to *Stegodon cf. floresis* (see Jatmiko et al., 2009: p. 114). The fragments predate the emplacement of the Turakeo Tephras, which in turn underlies the T3 tephras, and which has been dated at 0.90 ± 0.07 Ma in the Mata Menge section (Brumm et al., 2016). With a minimum age of 0.9 Ma, these fossils represent the oldest documented *S. floresis* remains to date. At present it is unknown if the Kobatuwa fossils from Layer K are younger or older than the emplacement of the WST around 1 Ma, because the latter is not developed at the excavation site.

In addition to *Stegodon* remains, Layers G and H contain the remains of crocodiles, represented by a dextral mandible fragment, a left half of a skull and a dextral maxilla fragment, together with some isolated teeth and postcranial elements. The skull and mandible show similarities with *Crocodylus siamensis* from Java (Setiyabudi, 2017). Fossils of microvertebrates are very rare at Kobatuwa, which may be partly due to the fact that the fossil-bearing layers G, H and I are extremely hard and the excavated rock could not be wet-sieved. However, the recovery of a tibia fragment of an unidentified giant rat and a single molar fragment indicate that murine rodents were present at this stage.

Enamel samples of seven excavated adult *Stegodon* molar fossils from Layers F/G/H were extracted for stable isotope analysis (δ¹³C and δ¹⁸O) (for the analytical methods see Appendix G and Brumm et al., 2016). The fragments predate the emplacement of the Turakeo Tephras, which in turn underlies the T3 tephras, and which has been dated at 0.90 ± 0.07 Ma in the Mata Menge section (Brumm et al., 2016). With a minimum age of 0.9 Ma, these fossils represent the oldest documented *S. floresis* remains to date. At present it is unknown if the Kobatuwa fossils from Layer K are younger or older than the emplacement of the WST around 1 Ma, because the latter is not developed at the excavation site.

In addition to *Stegodon* remains, Layers G and H contain the remains of crocodiles, represented by a dextral mandible fragment, a left half of a skull and a dextral maxilla fragment, together with some isolated teeth and postcranial elements. The skull and mandible show similarities with *Crocodylus siamensis* from Java (Setiyabudi, 2017). Fossils of microvertebrates are very rare at Kobatuwa, which may be partly due to the fact that the fossil-bearing layers G, H and I are extremely hard and the excavated rock could not be wet-sieved. However, the recovery of a tibia fragment of an unidentified giant rat and a single molar fragment indicate that murine rodents were present at this stage.

Enamel samples of seven excavated adult *Stegodon* molar fossils from Layers F/G/H were extracted for stable isotope analysis (δ¹³C and δ¹⁸O) (for the analytical methods see Appendix G and Brumm et al., 2016). The fragments predate the emplacement of the Turakeo Tephras, which in turn underlies the T3 tephras, and which has been dated at 0.90 ± 0.07 Ma in the Mata Menge section (Brumm et al., 2016). With a minimum age of 0.9 Ma, these fossils represent the oldest documented *S. floresis* remains to date. At present it is unknown if the Kobatuwa fossils from Layer K are younger or older than the emplacement of the WST around 1 Ma, because the latter is not developed at the excavation site.

In addition to *Stegodon* remains, Layers G and H contain the remains of crocodiles, represented by a dextral mandible fragment, a left half of a skull and a dextral maxilla fragment, together with some isolated teeth and postcranial elements. The skull and mandible show similarities with *Crocodylus siamensis* from Java (Setiyabudi, 2017). Fossils of microvertebrates are very rare at Kobatuwa, which may be partly due to the fact that the fossil-bearing layers G, H and I are extremely hard and the excavated rock could not be wet-sieved. However, the recovery of a tibia fragment of an unidentified giant rat and a single molar fragment indicate that murine rodents were present at this stage.

Enamel samples of seven excavated adult *Stegodon* molar fossils from Layers F/G/H were extracted for stable isotope analysis (δ¹³C and δ¹⁸O) (for the analytical methods see Appendix G and Brumm et al., 2016).
Fig. 6. A, Three prominent silicic mass-flow deposits (bottom to top: Wolo Sege, Turakeo and Pu Maso) occurring in close stratigraphic succession at Lowo Mali (08° 41’ 30.9” S; 121° 10’56.9” E); B, Pu Maso Tephra at Lowo Mali separated from T3 marker tephra, below by an intervening 0.3 m thick palaeosol; C, Low-angle cross-bedded pyroclastic (surge) beds of Pu Maso Tephra well expressed at Lowo Mali and indicate a northward-directed paleo-flow direction; D, Large (~35 mm diameter) accretionary lapilli within the lower pyroclastic flow sub-unit of Pu Maso Tephra at Lowo Mali. The ubiquity and large size of accretionary lapilli within Pu Maso Tephra enables this tephra to be distinguished from the underlying Turakeo Tephra.
et al. (2016)). In the tropics C₃ plants are represented by most tree species and high-altitude grasses, whereas C₄ plants comprise most tropical and subtropical grasses. The δ¹³C values of fossil herbivore teeth have been widely used in reconstructing paleo-diets of herbivores, and indirectly the vegetation cover and changes thereof through time (e.g., Cerling et al., 2015; Lister, 2013). For the Kobotuwa sample the δ¹³C values vary between −6.2‰ and −0.26‰ (Fig. 11; Table G.1). Three individuals have δ¹³C values below −5‰.
and four individuals have $\delta^{13}$C values above $-2\%_o$. For large herbivore tooth enamel $\delta^{13}$C values of between $-8\%_o$ and $-2\%_o$ are generally considered as indicative of mixed feeders that have a diet of both C$_3$ and C$_4$ plants, while values above $-2\%_o$ indicate grass feeders or grazers (Cerling et al., 1999; Puspaningrum et al., 2020). The four Stegodon individuals with values above $-2\%_o$ thus had a diet dominated by C$_3$ grasses.

The Kobatuwa stone artefact assemblage is composed of flakes and cores from reducing locally-available water-rolled cobbles, and reflects the same pattern seen across all of the So'a Basin sites (Appendix H, Table H.1). Kobatuwa, however, is unusual in the high proportion of cores reduced bifacially and centripetally, resulting in ‘radial’ cores ($n = 27$). Three ‘perforators’ were also recovered, consisting of small versions of the picks documented at Wolo Sege; at Kobatuwa, however, these forms were made on flakes rather than cobbles. Perforators also occur in small numbers at Mata Menge and Liang Bua.

The Kobatuwa artefacts have undergone various degrees of taphonomic rounding, with some in fresh ‘as struck’ condition. A conjoin set was recovered from Layer G/H, and to date is the earliest in situ conjoin set recovered in Southeast Asia. The set consists of a flake which conjoins onto a scar on a bifacial radial core, indicating that the reduction of the artefact occurred close to or at this location. This may also indicate that core reduction occurred where the
Fig. 9. Volcaniclastic inter-beds of mafic composition are concentrated in the upper portions of OBF, and are particularly conspicuous within GLM lacustrine sediments within Welas Caldera. A, At Poma Section (08° 36′ 52.6″ S; 121° 04′ 31.4″ E) multiple cm-thick phreatomagmatic and magmatic tephra beds are clearly visible within laminated lacustrine sediments of GLM; B, Nearby at Wulubara (08° 39′ 02.2″ S; 121° 03′ 38.8″ E) subordinate laminated lacustrine sediments are interbedded by numerous scoriaceous coarse ash and lapilli layers with intervening m-thick subaqueous scoriaceous debris-flow deposits; C, At Wolo Meze (08° 38′ 20.8″ S; 121° 03′ 41.0″ E), located mid-way between two intra-caldera basaltic
stones were sourced, with flakes carried back to a (presently un-
identified) living or task site.

6.2. Mata Menge

6.2.1. Mata Menge site stratigraphy

At Mata Menge, the total preserved thickness of OB uncon-
formably overlying OKF is 52 m, including an uppermost 13-m thick
interval of GLM recorded in two step trenches that stratigraphically
partially overlap, one adjacent to Excavation 32 (slot Trench 12) and
one on a hill 600 m further southwest (slot Trench 35, see Appendix
A).

Mata Menge is a highly significant fossil-bearing site located
towards the north-west margin of the So’a Basin, and has long been
of archaeo logical interest (Fig. 2). Mata Menge, and the nearby site
Boa Leza (Appendix A), were discovered and first excavated be-
tween 1963 and 1965 by Theo Verhoeven. At this same locality in
1968, Verhoeven undertook a further excavation with Johannes
Maringer (Maringer and Verhoeven, 1970a), and described stone
artefacts associated with Stegodon, crocodile and rodent fossils. In
1991–92, an Indonesian-Dutch team identified Verhoeven’s former
excavation site at Mata Menge and the Stegodon layer was re-
excavated, confirming the association of fossil remains with stone
artefacts (Sondaar et al., 1994). A series of zircon fission track dates
provided the first numerical age for the layer, estimated to be be-
tween 8.8 ± 0.7 Ma and 8.0 ± 0.7 Ma (Morwood et al., 1997, 1998).
Following the discovery of H. floresiensis at Liang Bua in 2003
(Brown et al., 2004), between 2004 and 2009 small-scale excavations
at Mata Menge were resumed by an Australian-Indonesian-
Dutch team led by the late Mike Morwood (Brumm et al., 2006;
Brumm et al., 2010b; van den Bergh et al., 2009a), with these
covering an area of 82 m² and directly adjacent to Verhoeven’s
original Mata Menge excavations. The principal aim of these exca-
vations was to recover fossil remains of the Mata Menge tool-
maker and putative ancestor of H. floresiensis. Between 2010 and
2014 the scale of the Mata Menge excavation was increased, but
because working near the original Verhoeven site would imply
removing increasingly large quantities of predominantly sterile
overburden, the same fossil-bearing interval was excavated in a
gently sloping surface area 30–80 m to the northwest of Ver-
hoeven’s original site (see Brumm et al., 2016: Fig. 1). Systematic high-
volume excavations (560 m²; see Fig. 12) resulted in the recovery of
more than 11,500 fossil specimens and over 1680 stone artefacts
(this figure only includes stone artefacts from trenches T1-T8, T23
and T27; Appendix H). The vast majority of the fossils originate
from a ~3 m thick multi-layered interval, consisting of up to 0.8 m
thick lenses of tuffaceous fluvial silts and sands showing frequent
cut-and-fill sequences, with intercalations of minor gravels and
clay-rich, cohesive mass-flow (mudflow) deposits (Fig. 12B, E).
Fourteen separate lens-shaped layers were recognised, with vari-
cable concentrations of fossils and artefacts, and are collectively
referred to here as the Lower Fossil-Bearing Interval at Mata Menge
(MM-LOW; Fig. 12D). It should be noted that the ‘Unit B’ described
in earlier papers (Brumm et al., 2006; Brumm et al., 2010b; van den
Bergh et al., 2009a) is a multilayered tuffaceous sandstone unit
exposed in Excavations T1-T8 (Appendix A) adjacent to Verh-
evven’s original excavation site, and correlates laterally with the
basal part of MM-LOW as defined here.

Within the MM-LOW, the majority of the fossil remains are
concentrated in the lower 2 m (Fig. 12F). Most of the fossil speci-
mens comprise indeterminable small bone fragments, many of
which are rounded and worn by fluvial transport. There is addi-
tional evidence that fluvial currents and other taphonomic agents
have acted on the bone assemblage prior to burial. Stegodon bones
have been affected by fluvial sorting (van den Bergh et al., 2009a),
and there is an absence of articulated skeletal elements. However,
in the eastern part of Trench 25 there are also bone clusters
comprising what appear to be single Stegodon carcasses, such as a
concentration of ribs, vertebra, teeth and limb bones. These occur
in the tuffaceous silty layer 8b (Fig. 12B, E, G).

Of further notice is a steep-walled, 2.5 m wide and 2.3 m deep
channel-fill developed in the MM-LOW. This unit could be traced in
the excavations over a horizontal distance of 35 m along the
channel axis (Unit 2, see Fig. 12E, G). The palaeochannel has a high
sinuosity and a predominantly N–S orientation in the excavation
area. The channel-fill consists of massive coarse clasts. It is sug-
gested that the channel was abandoned and subsequently filled with sus-
pended sediments. Only a few reworked fossil fragments are pre-
sent at the base of this channel fill. No palaeo-current measurements
were able to be taken in the channel-fill unit, but the steep lateral sides of the erosive channel walls indicate that the
underlying tuffaceous sediments were well consolidated during
early diagenetic stages, and that reworking of fossil remains from
older deposits likely occurred during periods of low sediment
supply.

In 2013, excavations were initiated in a younger interval strati-
ographically located 10 m above the top of the MM-LOW (Fig. 12D)
and ~150 m further west. Excavations of this 90 cm thick interval,
referred to here as the Mata Menge Upper Fossil-Bearing Interval
(MM-UP) are ongoing. Within this interval (cut by step-Trench-12
and the various sectors of the larger Excavation 32) a well-
developed palaeosol (Layer III) is unconformably overlain by a
<30-cm thick bed of fluvial sands (Layer II), which in turn is overlain
by a ~6.5-m thick sequence of multiple metre-thick clay-rich
mudflow deposits (Layer I). The basal contact of Layer II is sharp but
highly irregular and erosional, whereas the upper contact of Layer II
with the base of mudflow Layer I is almost straight (Brumm et al.,
2016). Towards the west Layer II pinches out against the irregular
erosional surface of Layer III. Most of the fossil vertebrate speci-
mens occur in the fluvial sandstone layer (Layer II), but fossils are
also present within basal portions of the mudflow unit, and very
few in the palaeosol underlying Layer II. In 2014, the excavation
yielded the first hominin remains, belonging to at least three small-
jawed and small-toothed individuals all recovered from the upper

centres that are encrusted and on-lapped by lacustrine sediments, dm-thick mudflow deposits are recognised with numerous rip-up clasts of bedded lacustrine sediments (indicated by arrows). One clast (indicated) appears to have been actively disaggregating into the mudflow matrix as it was rotated in an anticlockwise direction during flowage; D, Compact, brownish-grey, shower-bedded fine-medium basaltic (phreatomagmatic) ash (~22 cm-thick) from the upper Mata Menge tephra sequence located above Trench 32 at Mata Menge (08° 41’ 29.7” S; 121° 05’ 37.9” E; see also Appendix A). This tephra bed has obvious open interstitial pore spaces indicative of syn-depositional rain flushing and is heavily penetrated by bioturbation traces; E, Highly irregular (erosional) basal contact of redeposited cross-bedded basaltic ash (hyperconcentrated-flow flood) exposed in step Trench 36 at Mata Menge (08° 41’ 32.3” S; 121° 05’ 38.5” E; for location see Appendix A). This mass-flow deposit is laterally equivalent to Upper Mata Menge tephra located in nearby exposures; F, A prominent (~1.4 m thick) mudflow deposit (Layer I) overlying fluvial pebbly sands (Layer II) exposed in Trench 32C at Mata Menge (08° 41’ 30.3” S; 121° 05’ 36.7” E). Homo floresiensis-like fossils originate from the top of sandy Layer II (van den Bergh et al., 2016). The upper contact of Layer I is described by a discontinuous and highly irregular fine-
grained basaltic ash bed (red dashed line) that, while partially saturated, was plastically deformed during rapid deposition of an overlying mudflow deposit. G, H, Selected bulk solution nebulization ICP-MS (SN-ICP-MS) trace-element compositions (Th vs. Zr and Nd) from phreatomagmatic tephra from Mata Menge and agglutinated scoria and diabase samples retrieved from a basaltic cinder cone complex (east, Wolo Mua) and lava dome (west, Wolo Mowa) within Welas Caldera (see Fig. 1 for location; Table B3). Analyses are indistinguishable and confirm an intra-Welas Caldera eruption source. Note that phreatomagmatic tephra contain slightly higher values of Th and Nd (cf. magmatic tephra counterparts) and this elemental variation may reflect the incorporation of (and contamination by) lake sediment as the tephra was being violently erupted. Concentrations are expressed in ppm. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
part of Layer II (Brumm et al., 2016; van den Bergh et al., 2016). In September 2019, the excavations in the MM-UP had covered a horizontal area of ~204 m² (where the main fossil-bearing Layer II has been excavated to base; plus 34 m² in sectors where only Layer I and/or a part of Layer II has been excavated).

Palaeomagnetic samples initially taken from the MM-LOW sequence at Mata Menge suggested that the age of the tufaceous layer with stone tools and fossils could be close to the Matuyama–Brunhes boundary (Sondaar et al., 1994). At that time this boundary was thought to be 0.73 Ma, but is now considered to be 0.773 Ma (Cohen and Gibbard, 2019; Mark et al., 2017). These palaeomagnetic results have been confirmed in a more recent study (Yurnaldi et al., 2018), indicating that the base of MM-LOW is younger than 0.773 Ma (Fig. 2). This age is within the error range of the previously obtained 40Ar/39Ar age of 0.80 ± 0.07 Ma for a sample taken from a normal polarized layer (Morwood et al., 1998: sample MM2 from Unit B1, described as a white tuff and laterally equivalent with the MM-LOW). However, another 40Ar/39Ar age of 0.88 ± 0.07 Ma, obtained 1.1 m lower in the stratigraphy (Morwood et al., 1998: sample MM1 from Unit C, described as a ‘pink tuff’) appears to be too old, since this same unit has normal magnetic polarity and should be included in the Brunhes Normal Epoch (Yurnaldi et al., 2018). It is likely that the zircon crystals used for the age track dating were reworked from older deposits, since the layer referred to as ‘pink tuff’ in the publication (Morwood et al., 1998) is now (this study), not considered as a tuff (or tephra) layer but rather represents a zone of intensely altered silty clay with prominent discoloration. This pedogenically-altered silty clay contains rare, poorly preserved bone fragments and stone artefacts (van den Bergh et al., 2009a, p. 66; note that here the fine-grained pink layer is referred to as ‘Unit A’). Therefore, we favour the younger interpretation and conclude that the entire MM-LOW is included in the Brunhes Epoch, with an age younger than 0.773 Ma (Mark et al., 2017).

The WST is prominently represented – 4 m below MM-LOW in step Trench 9, with a white cm-thick silicic ash inter-bed (Wolawu Tephra) occurring ~ 3.6 m below WST (Fig. 12D). At many sections within the So’a Basin, WST is frequently associated with wawu Tephra) occurring ~ 3.6 m below WST (Fig. 12D). The subspecies name florensis was added to distinguish the Stegodon florensis insularis descendant from Liang Bua, S. florensis insularis. The vast majority of the murine rodent molars from both fossil-
bearing levels can be attributed to the endemic extinct species *Hooijeromys nusatenggara*, a medium-sized rat that was excavated by Verhoeven at Ola Bula and first described by Musser (1981). Only a single molar of another large-bodied rat, provisionally attributed to *Spelaeomys florensis*, was identified in the MM-LOW (Excavation T-17). This species has not previously been documented from the OBF, but is well known, though relatively uncommon, from the Late Pleistocene and Holocene records of Liang Bua (Locatelli et al., 2012; Veatch et al., 2019).

*Hooijeromys*, on the other hand, appears to be very rare in the Late Pleistocene Liang Bua sequence (Veatch et al., 2019), suggesting that these differences in rodent species abundances reflect contrasting environmental conditions rather than temporal differences.

The eight hominin fossils from the MM-UP comprise a small mandible fragment, six isolated teeth and a cranial fragment, and belonged to at least three small-jawed and small-toothed individuals, including one or two juveniles as represented by two deciduous canines (van den Bergh et al., 2016).

Various bird taxa have been identified among the fossil remains from Mata Menge (Meijer et al., 2015). From the MM-LOW seven taxa have been identified, including Anatidae (*Cygnus* sp., *Anas cf. gibberifrons* and *cf. Tadorna*), Rallidae (*cf. Gallinula/Fulica*), Accipitridae (*cf. Hieraaetus*), Charadriidae (*Vanellus* sp.), and Passeriformes indet. From the MM-UP a duck has been identified (*cf. Tadorna*) (Meijer et al., 2019), but many bird fossils excavated after 2014 await a detailed identification.

There are 23 varanid fossils from the MM-LOW that can all be attributed to *Varanus komodoensis*, based on the comparatively large size and/or morphology of skeletal elements, and isolated teeth. This material includes a right maxilla and mandible and an isolated parietal (Setiyabudi, 2017) found close together and presumably of a single individual, as well as vertebrae and a humerus. From the MM-UP in total 100 isolated *V. komodoensis* teeth (and tooth fragments) have been recovered, but only five identifiable skeletal fragments.

Crocodilian remains from both Mata Menge levels predominantly consist of isolated teeth, but a small number of skull and postcranial specimens have been recovered from MM-LOW. The anteroposterior diameter and height of the largest recovered tooth measures 13.44 mm and 29.0 mm, respectively, indicating that the Mata Menge crocodiles could reach a considerable size.

Fossils of Anura (frogs) were retrieved from both levels at Mata Menge and are quite rare, but this could be a taphonomic bias. The presence of permanent flowing water during deposition of the MM-LOW is indicated by poorly preserved (casts and moulds) fresh water gastropods, *Brotia testudinaria* and *Tarebia granifera*, indicative of running to episodically stagnant freshwater (van den Bergh et al., 2009a), whereas the MM-UP has yielded numerous moulds of *Cerithidea*, reflecting permanent freshwater conditions (Brumm et al., 2016).

Carbon and oxygen isotope analyses were conducted on tooth enamel samples collected from several *S. florensis* and murine rodent fossils from both fossil-bearing levels at Mata Menge (Brumm et al., 2016; Puspaningrum, 2016). The results indicate a diet dominated by C4 grasses suggesting both species were grazers and imply that open grassland vegetation was predominant within the So’a Basin at that time. The Mata Menge values of δ13C and δ18O of *Stegodon* tooth enamel from both the MM-UP and MM-LOW are compared with the values of *Stegodon* samples from other So’a Basin localities (Fig. 11; Appendix G). Despite the larger number of samples analysed from both Mata Menge levels as compared to only seven samples from the older site Kobatuwa, the spread of δ13C values in both Mata Menge levels is lower and except for one sample from the MM-UP generally above −2‰, indicating a grass-
Fig. 12. Site stratigraphy and fossil and cultural finds at Mata Menge. A, view to the north of the excavations in the MM-LOW towards the end of the 2011 field season. Numbers refer to trenches. The dip slope visible on the horizon is the slope of the east rim of the Welas Caldera, which acted as source of the volcanogenic clay-rich mudflows deposited within the paleo-creek valley at Mata Menge; B, west profile of Trench 23 (MM-LOW) as exposed in 2012 (location indicated with yellow line in Fig. 12G) showing vertically-stacked, multiple horizons of hyperconcentrated stream flow, clay-rich lahar, and fluvially reworked volcaniclastic sand deposits. Numbers refer to layers. Note soft-sediment deformational structures in Layer 8a/b, suggesting very rapid deposition and loading. Layers 8 and 9 are both rich in fossil remains as well as stone artefacts. Poles at top profile are 1-m spaced; C, Concentration of *S. floresensis* bones exposed in Trench 29, Layer 8b (tuffaceous silt); view is towards the west. Scale is 30 cm; D, Schematic stratigraphic section at Mata Menge as recorded in slot trenches MM9þ10 and 12 (see Appendix A for locations), with the lower (MM-LOW) and upper (MM-UP) fossil-bearing intervals indicated. Sections are drawn to the same scale as the stratigraphic profiles covering the MM-LOW shown in Fig. 12E (for a more complete stratigraphy of the upper part of the sequence see Brumm et al. (2016); E, Profile drawings of selected excavation trenches shown in relative elevation. Orientation of the profiles is indicated by green lines in Fig. 12G. Numbers refer to layered units. Note the narrow channel fill (Unit 2) that cuts down into the rapidly deposited fluviomagmatic mass-flow sequence, which was deposited during and following a volcanic phase that generated abundant fine-grained volcaniclastic sediments. The rapid deposition and sediment coverage associated with this volcanic activity likely facilitated fossil preservation. Fluvial downcutting followed when sediment supply diminished (i.e., Unit 2, which hardly contains fossils as shown in Fig. 12F and G); F, East-west cross-section through the MM-
dominated diet. While the δ13C values of Stegodon tooth enamel samples from MM-LOW and MM-UP are both consistent with the range for grazers, there are significant differences in δ18O between the two levels (Brumm et al., 2016). The positive shift in δ18O values for the MM-UP could be the result of a distinct source of drinking water (i.e., run-off versus lacustrine) or warmer and drier conditions with increased evaporation for the MM-UP.

Pollen samples from both fossil-bearing intervals (Brumm et al., 2016), and phytoliths analysis of four samples from the MM-LOW (van den Bergh et al., 2009a), similarly indicate a grassland-dominated savannah-like landscape with nearby wetlands, as well as scattered patches of forest. The sandstone layers of both MM-LOW and MM-UP frequently contain abundant macro fragments of grassy leaves and strobili of Equisetaceae (horse-tail), the latter usually preferring wet sandy soils (van den Bergh et al., 2009a). The avian fauna from the MM-LOW also points to an open grassy environment, with nearby open water (Brumm et al., 2016; Meijer et al., 2015).

Stone artefacts occur in all excavated layers of the MM-LOW, but are more concentrated in sandy layers 8a and 8b and in pebbly sand layer 4b (Fig. 12E). A description of stone artefacts excavated from the MM-UP (T-32) until 2014 has been summarized previously (Brumm et al., 2016). Since then, a small number of additional stone artefacts have been excavated from MM-UP, resulting in a current total of 162 artefacts. The analysis presented in Appendix H does not include artefacts excavated between 2015 and 2019. Some of the artefacts are lightly to heavily abraded from water-transport, but a significantly high proportion (74.5%) are in fresh, as-struck condition, suggesting minimal dislocation from the nearby sites where they were originally flaked. To date, an analysis of a large assemblage (n = 1680) of in situ stone artefacts from the MM-LOW (Excavations T1 to T8 and T23 and T27) indicates ‘least effort’ reduction of locally available river pebbles and cobbles, resulting in single-platform, multiplatform, and bifacial centripetal cores. Flakes are abundant, some of which are retouched (Brumm et al., 2006, 2010b; Moore and Brumm, 2007).

6.3. Wolo Sege

6.3.1. Wolo Sege site stratigraphy

Wolo Sege is located half a kilometre east of Mata Menge (Appendix A) and occurs in the southwestern corner of a cattle enclosure at the head of a small gully, which is naturally bracketed on three sides by ~ 3-m-high vertical cliff embankments. These embankments substantively expose a ~3-m-high vertical cliff embankments. These fluvialite layers underneath the WST (Fig. 13A–C). A step trench was excavated uphill, from the top of the WST, and covered 26 m of stratigraphy, which enabled a detailed comparison with the nearby Mata Menge sequence (Appendix A, Fig. 2).

Exposed in the step trench, and separated from WST below by a ~0.5 m thick strongly developed palaeosol, are two closely-spaced metre-thick silicic pumice-ash-dominated hyperconcentrated-flood flow deposits correlated with Turakeo and Pu Maso tephras, respectively. The T3-tephra marker is recognised as a discontinuous cm-thick fine ash inter-bed within a well-developed palaeosol intervening between these two tephras. The remainder of the section above Pu Maso Tephra (17m+) is predominantly massive pedogenically-altered silts and variably developed palaeosols with occasional outcropping cm-to dm-thick lenses and shallow scourn-fills of fluvial-bedded cemented sands and gravels (Fig. 2). The coarse-grained cut and fill sequence observed in the MM-LOW at Mata Menge does not occur at Wolo Sege. Fine-grained mudflows sealing off fossil-rich layers as developed in the nearby Mata Menge and Boa Leza sequences (see sections 6.2.1 and 6.4.1) are not developed at Wolo Sege, and the site has not yielded any fossil vertebrates. However, apart from the lithic artefacts found in the archaeological excavations below the WST marker, sparse stone artefacts do also occur at two levels in palaeosols near the top of the Wolo Sege section.

6.3.2. Wolo Sege archaeology

As noted, the Wolo Sege excavations have yielded no faunal remains. However, 168 stone artefacts (including 48 artefacts reported in Brumm et al., 2010a) were recovered within the 2.5-m thick fluvialite sediment sequence intervening between the WST above and breccias of the OKF, below (Fig. 13B–C). Most of the Wolo Sege artefacts occur in situ within the fluvial conglomerate lenses, and consist of small and medium-sized flakes struck from water-rolled cobbles by direct hard-hammer percussion. Three large Acheulean pick-like implements were recovered at Wolo Sege, and are so far the only excavated examples from the So’a Basin sites (Brumm et al., 2006, 2010b; Moore and Brumm, 2007).

6.4. Boa Leza

6.4.1. Boa Leza site stratigraphy

Boa Leza, another of the sites originally excavated by Verhoeven, LOW showing the vertical distribution of fossils excavated within the area indicated with the light blue dashed rectangle in the plan view of Fig. 12G. Each dot represents a fossil specimen with its vertical elevation projected onto the cross section; note that the scale of the projection is the same as in 11E, but smaller than in 11G; fossils occur in all layers but are concentrated in layers 8 and 9; G, Horizontal plan of the 2010–2014 Mata Menge excavations in the MM-LOW, showing the outlines of the trenches and the horizontal coordinates of fossil finds (red dots); green lines indicate profiles shown in Fig. 12E; yellow line shows theorientation of the profile shown in Fig. 12B; dark blue dashed lines indicate the sinusoidal course of the channel-fill Unit 2; note that Trench 16 was dug by an excavator and therefore has very few fossil finds. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
is located 500 m south of Wolo Sege and 675 m southeast of Mata Menge (Appendix A). Verhoeven's site was re-excavated in 1998–99, revealing that S. floresensis fossils and stone artefacts occurred here in a 2 m thick tuffaceous channel cut and fill sequence (Morwood et al., 2009). A ZFT age of 0.84 ± 0.07 Ma was obtained from a homogeneous white silt facies interbedded with fossiliferous coarse pebbly sandstone facies, suggesting broad contemporaneity with the MM-LOW (Morwood et al., 2009; O'Sullivan et al., 2001).

In 2012, we excavated a 1 m wide and 25 m long north-south oriented slot trench (BL1) 8 m east of the 1998 excavations, in order to place the Boa Leza fossil-bearing channel fill sequence in the general stratigraphic scheme. A 2 × 2 m extension (BL1b) was also excavated on the East side of the step trench. These excavations revealed a 7 m thick succession directly overlying the OKF, and in which twenty separate layers could be distinguished, exhibiting a complex cut and fill sequence of fine-grained diamictics or mudflows, pebbly sandstones and reworked tephra beds (Fig. 13D–G). Compared to the nearby sequences at Mata Menge and Wolo Sege, both the WST and Turakeo Tephra are missing in the Boa Leza trench, but the WST is exposed in several outcrops between 130 and 200 m northwest and west of the slot trench. Fluvial downcutting appears to have removed both of these marker tephras at the BL-1 trench site. The presence of a steep ENE dipping erosional surface that cuts down a well-developed palaeosol suggests that the channel axis was approximately oriented NNW–SSE, similar to the channel inferred from the adjacent excavations undertaken in 1998 (Morwood et al., 2009). A prominent boulder channel lag with large intraclasts of the underlying bedrock overlies the erosional surface, which is in turn covered by an interval of intercalating diamictics, cross-beded pebbly sand lenses, and tuffaceous siltstone lenses (Fig. 13F and G), which is a facies association similar to the fossiliferous valley-fill sequence developed at Mata Menge.

6.4.2. Stegodon fauna and archaeology

Stegodon fossils and stone artefacts are mostly associated with either massive-structured clay-rich mudflow or gravelly to silty sand bedded hyperconcentrated-to-flood-flow deposits. In total, 478 fossil specimens were recovered from the Boa Leza trenches BL-1 and BL-1b, of which 119 were representing identifiable skeletal elements and molars of S. floresensis (25%), along with one crocodile tooth, two Hooijeromyx nusatenggaro molars, and a tibiotarsus of a juvenile Eagle Owl, Bubo sp. (Meijer et al., 2015). The remainder are unidentified bone fragments. The more complete and larger Stegodon bones tend to be concentrated at the boundary surfaces of the diamicton layers. Although none of the Stegodon bones were articulated, the left and right humeri, left radius and left ulna of a single subadult individual, plus 23 costa and a number of vertebrae of likely the same individual, were found in close proximity (in a 4 m² area) at the boundary between diamicton layers 6 and 7. This indicates that these Stegodon bones were not transported far by the viscous mudflow that covered them. The minimum number of individuals based on identifiable molars is four individuals.

Four S. floresensis molar fragments from the base of Layer 4 were used for δ13C stable isotope analysis of the enamel. All four samples fall within a narrow range of δ13C values between 0.9 and 1.3‰, reflecting a C₃-dominant (i.e., grass-dominated) diet (Fig. 11; Appendix G). This is within the range of −2.0 to 1.6‰ for samples reported from the MM-LOW (Brumm et al., 2016), but above the range for the Kobatuwa I samples. The cross-beded sandy Layer 4 (Fig. 13D) is largely devoid of fossils, but does contain stone artefacts near its base. A total of 39 in situ stone artefacts were excavated from the BL-1 trenches, which are in addition to the six artefacts excavated from the adjacent Boa Leza excavations in 1998 (Morwood et al., 2009). Detailed analysis of the Boa Leza artefact assemblage has yet to be undertaken.

6.5. Tangi Talo

6.5.1. Tangi Talo site stratigraphy

Tangi Talo (TT) is a significant fossil-bearing site located in the central part of the So’a Basin (Fig. 2) and close to its depocentre (Aziz et al., 2009a; O’Sullivan et al., 2001; van den Bergh, 1999). Here, an expanded sequence of lower OB (Tuff Member) occurs in a −31-m thick hillside exposure that rests unconformably upon lithified volcaniclastic deposits of OKF. Sections revealing such an expanded stratigraphy beneath WST are only developed in the
central and southern parts of the basin. The uppermost part of the TT sequence is dominated by two closely-spaced silicic mass-flow deposits correlated with Wolo Sege (lower) and Turakeo (upper) Tephra. Both tephras are characterized by an upward transition from pyroclastic flow (primary) deposits to overlying reworked (secondary) deposits. The Wolo Sege correlative at this section is here \(^{40}\text{Ar}/^{39}\text{Ar}\)-dated at 0.98 ± 0.02 Ma (SF-FL012-TT7; see Appendix C, Fig. C2), and is indistinguishable from the previously reported \(^{40}\text{Ar}/^{39}\text{Ar}\) age obtained from WST at Wolo Sege (Brumm et al., 2010a). At Tangi Talo, below WST is a ~15-m thick sequence of dominantly fine-textured pedogenically- altered sands, silts, and clays with intervening well-developed palaeosols. A conspicuous white cm-thick silicic ash inter-bed (Wolowawu Tephra) occurs at ~7 m depth below WST.

The lowermost part of the TT sequence (between 15 and 21 m below WST) contains three silicic air-fall ash beds (i.e., TTT-5 [Lowo Lele tephra], TTT-2 and TTT-1) as well as a complex cut-and-fill sequence of a series of clay-rich cohesive mass-flow (mudflow) deposits (Fig. 2). The lowest mudflow (TTT-3 in Fig. 3F) is white in color, with a matrix containing abundant dispersed pumiceous lapilli clasts, and can be traced laterally over several hundreds of metres. Locally, the upper surface of this mudflow is an erosive boundary and lenses of white parallel laminated tuffaceous silt have infilled depressions eroded in the top of this mudflow (see for example Fig. 14B). This pumice mudflow directly overlies a widespread bone bed (Fig. 3F), which represents the main fossiliferous layer at Tangi Talo. At the northern locations the fossil bones are concentrated near the base of the mudflow (Excavations TT-G and TT-L), whereas at the excavations further south (Excavation TT-H and TT-I) the bones are dispersed throughout the pumiceous mudflow, suggesting bones lying on the surface were incorporated into the mudflow downslope. Tephra TTT-5, with its base at 2 m above the main bone bed in Excavation TT-G (Fig. 3F), contains lapilli, whereas TTT-2 and TTT-1 below the bone bed are very fine-grained and incorporated in a 3.5 m thick sequence of pedogenically- altered silts and occasional lenses of fluvial-bedded conglomerates and sands.

The main bone bed and its associated pumice-rich mudflow were excavated at five sites spread out over a horizontal distance of 172 m (Fig. 14A–E). A total station was used to record 3D coordinates of fossils and layer boundaries. The bone layer is dipping between 0.8 and 2° towards the WSW, and the most likely source of the volcanic mudflow is to the east (see Fig. 14E).

Two \(^{40}\text{Ar}/^{39}\text{Ar}\) ages were obtained from this lower interval. Hornblende crystals retrieved from pumice lapilli of Lowo Lele tephra (TTT-5) (Fig. 3F) yielded an age of 1.27 ± 0.03 Ma (SF-FL012-TT7; see Appendix C). Plagioclase crystals, extracted 2 m lower in the sequence from pumice lapilli from the base of the white pumice-rich mudflow deposit that covers and incorporates the bones (TTT-3), yielded an older \(^{40}\text{Ar}/^{39}\text{Ar}\) age of 1.418 ± 0.02 Ma (SF-10/TT001; see Appendix C). As mudflow deposits frequently exhibit channel-marginal and basal erosional contacts, it is possible that older material was entrained in this deposit. This is reflected in the Ar-isotope data, where individual crystals produced a range of apparent \(^{40}\text{Ar}/^{39}\text{Ar}\) ages. However, stepped heating \(^{40}\text{Ar}/^{39}\text{Ar}\) data from individual crystals with older apparent ages indicates thermal loss of radiogenic \(^{40}\text{Ar}\), implying that xenocrysts entrained during eruption were partially reset during emplacement. The 1.4 Ma age represents the youngest population of crystals analysed from the pumiceous mudflow unit and likely represents the emplacement age.

Six palaeomagnetic samples taken below the WST all returned reversed polarities while one sample at 80 cm above the top of the WST has a normal polarity (Fig. 2; see also Yurnaldi et al., 2018). The normal polarity is thought to correspond with the Jaramillo event (1.780–0.990 Ma; Cohen and Gibbard, 2019), while the reversed polarities below the WST correspond with the reversed period of the Matuyama Chron (1.780 Ma – 1.071 Ma). The Cobb Mountain Normal Event at 1.208 to 1.187 Ma is not recognised, which is not surprising considering the low sampling density in this interval. Two palaeomagnetic normal polarities previously reported from the 2 m interval directly underlying the Tangi Talo fossil-bearing horizon were initially interpreted as representing the Jaramillo (Sondaar et al., 1994). Combined with a ZFT age of 0.90 ± 0.07 Ma for the main fossil-bearing layer (Morwood et al., 1998), this interpretation appeared to confirm the age of ~0.90 Ma for the Tangi Talo fauna (Aziz et al., 2009a; Brumm et al., 2010a). However, this young age is incompatible with the revised stratigraphy and new age data reported here, including the recognition of the 1 Ma WST at 18 m above the bone bed, and the \(^{40}\text{Ar}/^{39}\text{Ar}\) age of 1.27 ± 0.03 Ma for the Lowo Lele Tephra (TTT-5) at 2 m above the bone bed. A possible explanation for this anomalous ZFT date is that the sample was under-etched, and therefore not all spontaneous tracks were revealed for age counting, resulting in an erroneous minimum age determination. The two normal polarities directly below the main bone bed reported by Sondaar et al. (1994) could not be replicated by Yurnaldi et al. (2018).

In 2012, a 15 m² excavation was carried out at a site ~300 m northwest of the main bone bed excavations (Excavation F; see Fig. 14A). This excavation revealed vertebrate fossils embedded in a silty fluvial channel-fill that cross-cuts underlying reworked Lowo Lele tephra (~TTT5, 1.27 ± 0.03 Ma) (Fig. 14F and G). The Excavation F fossil assemblage, here designated as TT-UP, is thus slightly younger than the main bone bed at Tangi Talo, hereafter indicated as TT-LOW.

6.5.2. Tangi Talo fauna

The main bone bed at Tangi Talo (TT-LOW) was previously excavated in 1991–92 and 1999 (excavation sectors A–D) (Aziz et al., 2009a; van den Bergh, 1999) and the excavations were extended in 2012 (sectors E, G) and 2013–14 (sectors H, I, K, L).

Fossils are concentrated at the base of an up to 50 cm thick pumice mudflow layer that, as mentioned above, can be traced for at least 172 m from NNE to SSW, and slopes between 0.8 and 2°. In WSW direction (Fig. 14A, E). By 2014, a total of 216 m² of the bone bed had been excavated, yielding a total of 1877 fossil specimens, primarily representing the giant tortoise (Megalochelys sp. (~74% of finds, consisting mostly of broken plastron and carapace fragments); and small pygmy elephant Stegodon sondaari (~16% of finds; see Fig. 3F) (Aziz et al., 2009a; Setiyabudi, 2017; van den Bergh, 1999). Rarer are fossils of Komodo dragon (Varanus komodoensis), including isolated teeth and postcranial elements. Undiagnostic remains of a murine rodent of similar body size as Hooijeromys nasutenggara ([which is common in the younger Mata Menge sites]), isolated crocodile teeth, and a small freshwater turtle (cf. Cuora amboinensis) (Setiyabudi, 2017; Takahashi et al., 2015) have also been identified. The presence of an unidentified giant rat within the TT-LOW fauna, based on incisors, two femur fragments and a tibia fragment, extends the known range of murine rodents on the island by half a million years.

S. sondaari and V. komodoensis fossils are both present in the slightly younger stratigraphic level of Excavation F (number of fossil specimens from TT-UP is 304 specimens) (see Fig. 14D), but Megalochelys fossils are completely absent from TT-UP. Based on the dental remains from this layer, the S. sondaari assemblage of Excavation F comprises an MNI of 35, of which 86% represent
juveniles. This is in sharp contrast with the *S. sondaari* assemblage from TT-LOW (MNI = 52), which has only 35% of the MNI based on fossil teeth representing juveniles. The combined evidence from both levels suggests that *S. sondaari* and *V. komodoensis* persisted in the area following a mass-death event that may be associated with the emplacement of the white pumice-rich mass-flow layer. However, the *Megalochelys* population may have been critically affected by this event, as this species does not re-appear in the slightly younger TT-UP deposits, nor in any of the younger fossil sites in the So'á Basin. However, the absence of *Megalochelys* from the TT-UP could also be due to the much smaller sample size, in addition to the distinct taphonomy of this abandoned channel fill compared to the widespread laharc mass-flow layer for the TT-LOW.

In total, 23 enamel samples of adult *S. sondaari* individuals were analysed for δ13C and δ18O contents (see Appendix G). As adult molar fragments from Excavation F were very rare, only three enamel samples could be obtained from the TT-UP, while the remainder of the samples are from the main Tangi Talo bone-bed (TT-Low). The δ13C values of *S. sondaari* individuals plot in a narrow range (~8.3% to ~3.8%), which is consistent with mixed C3-C4 feeders (see Fig. 11), except for a single individual from the TT-UP that just falls within the range of the other samples (δ13C = ~8.3%). The three samples from TT-UP show comparatively low δ13C values close the lower boundary of the observed range; similarly, these samples also exhibit δ18O values at the higher end of the range. This difference may reflect different climate-vegetation conditions, as both levels are separated by ~100,000 years.

The overall low δ13C values for the *S. sondaari* individuals from both TT-Low and TT-UP are in sharp contrast to δ13C values of *S. floresiensis* from the Sandstone Member, which, except for one specimen from the MM-UP, cluster above ~2.0‰, and are indicative of a predominantly C4 diet. This difference is statistically significant as there is no overlap in values between the two groups (Two-tailed Mann-Whitney U test = 0, p < 0.0001). The S. floresiensis individuals from Kobatua from the top of the Tuff Member have overlapping values between those of Tangi Talo and of Mata Menge/Boa Leza (Fig. 11), suggesting a transition in climate-vegetation conditions.

**6.5.3. Tangi Talo archaeology**

No stone artefacts have been recovered at Tangi Talo, despite the large excavations undertaken at this site (~216 m² in TT-LOW, and ~15 m² in the at least ~100,000 years stratigraphically younger TT-UP). Furthermore, neither the 1-m-wide stepped trench excavated in 2010 that exposed the full stratigraphic sequence up to the WST, nor the fluvial conglomerate that overlies the fossil-bearing channel fill at Excavation F, has yielded a single stone artefact or other proxy evidence for the presence of hominins either at the site (e.g., cut marks on fossil bone) or in the wider landscape. Excavations at other sites in the upper part of the OKF (Excavations T3 at Kobatua-I, T1 at Kobatua-II) likewise did not yield any artefacts or other signs of hominin occupation. In sharp contrast, excavations and fossil sites in fluvial deposits above and directly below the WST, including fluvial conglomerates and pedogenized floodplain sediments, have invariably yielded stone artefacts. For instance, excavations T2 at Kobatua-I, T1 at Kobatua-IV, Wolo Sege Main, Wolo Sege East and Wolo Sege slot trench T1, all excavations in MM-LOW and MM-UP and slot trench T10 at Mata Menge, trench BL-T1 at Boa Leza, and Excavation T1 at Kobatua-I, plus additional sites not dealt with in detail here (Duzu Dhalu, Wolo Milo, Lembah Menge, Wolo Keo, Pauphaadhi, Kopowatu and Ngamapa; see Aziz et al., 2009b; Morwood et al., 1999), have all yielded in situ stone artefacts. This pattern suggests that hominins were not yet established in the So’a Basin at the time when the lower part of the Tuff member was deposited, although absence of direct fossil evidence or proxy evidence in the form of stone artefacts, does not preclude a hominin presence before 1.27 Ma.

To further increase our efforts to test for the presence of in situ stone artefacts in strata with an age of ~1.27 Ma, we performed additional excavations in fluvial sandy and/or pebbly layers that occur stratigraphically directly above the 1.27 Ma Oldo Lele Tephra (TTT-5). In 2014, a 1 × 6 m step trench was excavated 200 m west of Tangi Talo in an attempt to trace back the main fossil bearing layer further west (Excavation J; Fig. 14A). This was a 1 × 5 m large test excavation in a 0.5 m thick fluvial pebbly sandstone layer, which yielded a single *Stegodon sondaari* molar fragment, but no stone artefacts. Although the exact stratigraphic correlation of this trench with the dated Tangi Talo sequence could not be reconstructed, its location is at the same altitude as the main bone bed, combined with the fact that the main bone bed slopes weakly down towards the WST, indicates that this fluvial layer is probably younger than the main bone bed. Another 1 × 5 m trench was excavated in 2017, in a fluvial channel deposit 2-m above the top of the main fossil layer at Tangi Talo (Excavation M; Fig. 14A, H). This excavation was within fluvial cross-bedded pebbly sands and likewise yielded a single rolled *Stegodon sondaari* molar fragment, but again, no stone artefacts, despite the availability of pebbles and cobbles of rock suitable for knapping, such as aphanitic basalt and chaledony. Based on the combined lack of evidence for stone artefacts in the lowermost part of the OB at Tangi Talo and other sequences in the lower part of the Tuff Member, we hypothesise that hominins were not yet present in the So’a Basin prior to
-1.27 Ma. If this hypothesis holds, the first hominin arrival in the basin, and possibly the colonization of Flores itself, would most likely have taken place between ~1.27 Ma and the emplacement of the WST around 1 Ma. Further research into deposits predating 1.3 Ma are necessary to confirm this assessment.

6.6. Mata Go

6.6.1. Mata Go site stratigraphy and archaeology

Mata Go is a roadside quarry in the central part of So’a Basin ~2.3 km south of Tangi Talo (Fig. 2). At this locality, an isolated section of WST is exposed in a small quarry. Here the lowestmost ~3.2 m of WST is exposed and reveals basal surge-fall-flow beds overlying a ~0.30 m thick well-structured palaeosol developed into underlying very coarse-grained (bouldery) channel lag deposits (see Fig. 7D). Along the section, basal surge beds of WST perceptibly ‘pinch-and-swell’ over boulderly obstacles protruding from the surface of the palaeosol (the then ground surface at the time of WST emplacement). During a field survey in 2012, one stone core was noted in situ at the very top of a silty palaeosol, with the basal WST pyroclastic surge sub-unit draped over the protruding core (see Fig. 7E and F). The minimum age of this artefact corresponds with the age of the WST emplacement at ~1 Ma.

6.7. Ulu Mala Kata

6.7.1. Ulu Mala Kata site stratigraphy and palaeontology

Ulu Mala Kata, discovered in 2015, is located along the east bank of the Ae Sesa River, near the confluence with the Lowo Lele River (Fig. 1). Both rivers have incised the OKF basement rocks in this location. A badly damaged Stegodon mandible and an upper molar were found eroding out of riverbank within a weakly consolidated laharc deposit (Fig. 15A–C). This coarse-grained laharc is massive, at least 7 m-thick, and forms a remnant fill terrace along the east side of the Ae Sesa river valley. The laharc deposit commonly contains metre-sized blocks of older Ola Kile breccia that were incorporated during flowage along the Ae Sesay valley. Pumice and charcoal fragments were also entrained within the flow. The source of this laharc deposit is presently unknown. It could have originated from the Ebu Lobo Volcano, which is the main source of the Ae Sesa River, but it is equally possible that this laharc deposit could be derived from a tributary extending eastwards originating in the BCCC. Ula Mala Kata is of great importance because it represents the youngest Stegodon occurrence in the So’a Basin, and extends the local record of Stegodon by 600 ka. The fossils represent a smaller-bodied Stegodon than known from the OBF, and is similar in size and shape to the Late Pleistocene Stegodon florensis insularis that is well-known from Liang Bua (van den Bergh et al., 2008) (see Fig. 15D–G). The Ulu Mala Kata fossils are here attributed to S. florensis insularis (see Appendix 1).

In order to obtain a minimum age for these fossils, we undertook laser ablation multi-collector ICP-MS Uranium-series dating on two enamel/dentine fragments that could not be refitted to the main fossil. One sample consisted of an enamel fragment (UMK15-1a), while the other was an isolated molar ridge fragment (UMK15-1b) that included the worn occlusal surface of one of the worn lower molars that were originally embedded at the front of the mandible distally of the unworn last molars.

The two subsamples yielded overlapping minimum ages of 34.2 + 0.3/-0.5 ka (UMK15-1a) and 31.0 + 0.5/-0.7 ka (UMK15-1b), respectively (see Appendix 2). Two charcoal samples from the laharc provided further support for a Late Pleistocene age, and yielded slightly older but overlapping conventional AMS14C ages of 47,699 ± 1342 bp (WK-48668) and 45,807 ± 1042 bp (WK-48669), respectively, confirming the relatively young age of the terrace fill. These conventional ages would translate to calibrated (OxCal v4.3.2) ages in excess of 49,900 cal BP and 47,250 cal BP, respectively (these are the lower ages at 2σ; the upper boundaries for both samples fall outside the calibration curve). These Stegodon fossils are equivalent in age with the most recent S. florensis insularis record from Liang Bua, estimated at 50 ka (Sutikna et al., 2016, 2018), but could even be several thousand year younger.

7. Discussion

7.1. Silicic tephra source(s)

The occurrence of silicic tephra marker beds within OBF sedi-
men
tary sequences raises obvious questions regarding their erup-
tive origins. Indications of potential source locations can be broadly resolved by combining field observations (i.e., thickness, texture, bedding variations) with comparative glass shard geochemistry. While sporadic tephra beds with uniform field attributes over their lateral extent may be suspected of having a distal (inter-regional) source, the majority of silicic tephra represented within So’a Basin are more likely sourced from adjacent eruptive centres.

7.1.1. Silicic tephra within lower OBF

Sedimentary sequences of lower OBF (Tuff Member) are domi-
nated by metre-to decimetre-thick silicic pyroclastic mass-flow deposits of Wolo Sege, Turakeo and Pu Maso tephras (Figs. 2 and 6). The westward thinning of these deposits across the So’a Basin, coupled with overall textural fining, suggests an eastward source. In addition, the pumice-rich mudflow that covers the main bone bed at Tangi Talo, with its shallow dip towards the WSW, probably has its volcanic source in the east as well. Based on glass shard major element geochemistry determined from electron microprobe (EMP) analysis (Fig. 4, Table 1), these silicic mass-flow deposits typically form a tightly clustered compositional grouping and are indistinguishable (±1 SD). However, individual analyses from each unit typically occupy subtly different domains within that clustered grouping which, in addition to stratigraphic association and sedi-
mentary architecture, permit these mass-flow deposits to be distinguished. Nevertheless, the tight geochemical association suggest that Wolo Sege, Turakeo and Pu Maso Tephra are closely related and likely derived from the same eruptive source. Older (air-fall) tephra (TTT-1, TTT-2, TTT-5 (Lowo Lele) and Wolowawu Tephra) also have strong geochemical affinity with the Wolo Sege-Turakeo-Pu Maso compositional grouping, and are therefore also likely sourced from the same eruptive centre.

Evidence associating this compositional grouping to a potential eruptive source is exposed in a roadside quarry (08°34’27.4”S; 121°18’05.1”E) in the vicinity of Mbai on the northern Flores coastal plain, 26 km north-east of Mata Menge (see Fig. 1 and 16). Here, two prominent silicic deposits are observed separated by a prominent well-structured ~0.4 m thick palaeosol containing con-
spicuous rhyzomorph casts and root moulds. This succession forms the upper portion of an inclined volcanioclastic surface that extends upward from the coastal plain to an eroded rim remnant of an ancestral caldera complex on which the present-day Keli Lambo Volcano is constructed (see Figs. 1 and 16F). The upper silicic de-
posit at Mbai comprises the following sequence: i) an upper 1.4 m thick poorly-sorted, matrix-supported, pumiceous diamict (pyroclastic flow deposit) with the upper part truncated at the present-day ground surface; ii) a middle ~1.3 m thick faintly stratified vitric ash and lapilli layer containing centimetre (cm)-
sized accretionary lapilli (fall deposit); and iii) a basal ~0.26-m-

thick, cross-bedded, well-sorted cm-to mm-bedded vitric sands (surge deposit). The lower silicic unit on which the overlying palaeosol is formed into comprises a ~4.5-m sequence of well-
sorted cm-thick planar-bedded vitric coarse sandy ash. Low-angle cross-beds, pinch-and-swell, scour and rip-up structures together with evidence for constituent density segregation and fines depletion (ash elutriation), collectively indicate successive pyroclastic surge deposition (Fig. 16B–E).

The upper and lower Mbai units are correlated, on the basis of glass shard major-element chemistry (Fig. 17), with Pu Maso and Turakeo deposits from the So'a Basin, respectively. Older pyroclastic deposits at Mbai were not exposed (i.e., Wolo Sege correlative). Nevertheless, the proximal-medial silicic architecture of these two correlatives, along with their corresponding stratigraphic association and occurrence forming part of an inclined depositional surface flanking remnants of an ancestral caldera complex, provides compelling evidence that the majority of lower OBF silicic tephra are sourced from this ancestral Keli Lambo eruptive centre.

7.1.2. Silicic tephra within upper OBF

Four silicic tephra have so far been identified within GLM lacustrine sediments, and are interbedded with numerous tephra and scoria-bearing debris flow deposits of basaltic composition. The silicic deposits interbedded within GLM are usually cm-to dcm- (decimetre) thick and have bedding features consistent with either airfall (primary) or debris-to hyperconcentrated-flow deposition (i.e., Fig. 3C and D). Major-element glass data (Fig. 4, Table 1) for these silicic tephra (i.e., Wulubara, Nata Radang, Poma and Kolopanu) form compositional groupings distinct from those of
Wolo Sege-Turakeo-Pu Maso, suggesting different eruptive sources from those older tephra represented within lower sequences of OBF. One of the four identified silicic deposits of the GLM can be attributed to an intra-Welas caldera source with any certainty. In the vicinity of Nata Radang, in the northwest inner sector of Welas caldera, a 40-m + thick sequence of coarse-grained pyroclastic surge beds can be recognised (Fig. 3A and B). This sequence is associated with a succession of systematically oriented fluvially dissected ridges that are inclined in elevation towards the northwest, and laterally transition to a lava flow deposit (though the contact between the two deposits on the same surface was not observed) originating from a subtly-expressed remnant crater.

Fig. 16. A. Keli Lambo (with a conspicuous summit lava dome ~ 1320-m above-sea-level) is a forested Late Quaternary composite stratovolcano located east of So'a Basin, and constructed upon the eroded remnants of a much older caldera complex; B, C, In a roadside quarry (08° 34’ 27.4” S; 121° 18’ 05.1” E; see Fig. 1B: ‘quarry’) in the vicinity of Mbai adjacent the northern Flores coastal plain, two prominent silicic deposits are observed separated by a prominent well-structured palaeosol; D, E, The lower deposit comprises a ~4.5 m thick sequence of well-sorted, cm-thick, planar to low-angle cross-bedded coarse vitric sandy ash that exhibit pinch-and-swell structures and incorporate large ‘rip-up’ soil clasts (indicated by arrows). The characteristics of this deposit are indicative of successive (turbulent) pyroclastic surge bed emplacement; F. The inclined depositional surface on which these two silicic deposits were emplaced, extends upward from the coastal plain to an eroded rim remnant of an ancestral Keli Lambo caldera complex.
(<0.8-km diameter) breached to the south-east, and located close to
the inner Welas caldera wall.

The glass chemistry of the source-proximal Nata Radang pyro-
clastic surge beds is very similar to that of Poma tephra, and this
similarity may also reflect a localized (i.e., intra-Welas Caldera)
source, though this is yet to be unequivocally established.

The numerous basaltic tephra layers in the GLM likely relate to
the emergence of intra-caldera scoria cones within the ancestral
Welas Caldera lake system.

7.1.3. Inter-regional silicic tephra

Glass shard major-element data from T6 tephra at Mata Menge
as well as T3 tephra from Mata Menge, Lowo Mali and Kopowatu
sections confirm their glass compositions are different to all other
silicic tephra represented within the So’a Basin, and suggest inter-
regional (distal) eruptive sources (Figs. 4 and 5). The distinct
elemental clustering of these tephra is further supported by trace-
element data. Selected T3 and T6 elemental data (i.e., Sr vs Th and
Zr, and Y vs Nb, Ce and Th bivariate plots) were compared against
potential ultra-distal tephra correlatives (i.e., Youngest Toba Tuff
(YTT), Middle Toba Tuff (MTT), Oldest Toba Tuff (OTT) and Unit E
from ODP-758) (Fig. 18; SI Table B3). These are the most widespread
tephra markers so far known from the Indonesian archipelago. T6
tephra does not correlate with any of the well-known Toba-sourced
tephra (YTT, MTT, OTT), though it is geochemically similar to (but
distinguishable from) Unit E. The glass shard composition of T3
tephra is distinctive with a consistently wide elemental spread and
has no resemblance to far-field (i.e., Toba) or regionally- (Keli

Fig. 17. Selected major element compositions (weight percent SiO₂ vs. K₂O and FeO vs. CaO and K₂O) of glass shards from the upper (airfall) unit at Mbai (F14) compared with equivalent elemental data from Pu Maso Tephra (Mata Menge, Pu Maso, Lowo Mali; A-C) and lower (surge) unit at Mbai (F15) compared with equivalent elemental data from Turakeo Tephra (Mata Menge, Pu Maso, Wolo Sege, Tangi Talo and Turakeo reference section; D-F). Pu Maso tephra analyses (transparent grey symbols) are superimposed upon Turakeo tephra analyses (D–F) and further affirm correlation — though Turakeo tephra has a broader major element compositional spread; G, H, Selected trace element compositions Zr vs. Th and Nb of glass shards from the lower surge unit at Mbai (F15) compared with equivalent elemental data from Turakeo Tephra (Mata Menge, Pu Maso and Kobatuwa).
Lambo) and/or locally-derived silicic tephra found within the So’a Basin. On this basis, the distal eruptive origins of both T6 and T3 ash beds currently remain unknown, but this result does not diminish their stratigraphic utility within the overall So’a Basin sedimentary succession.

7.2. Synthesis of faunal changes and palaeoenvironment

This current synthesis of the stratigraphic and dating evidence from the So’a Basin enables a revision of the chronostratigraphic framework, with important implications for the faunal and archaeological sequence and timing of new arrivals and extinctions, as summarized in Fig. 19.

7.2.1. Revised biostratigraphy of Tangi Talo, Kobatuwa and Mata Menge

The earliest evidence of vertebrate fauna on Flores, characterized by the presence of S. sondaari, is the widespread bone bed at Tangi Talo (TT-LOW). The pumice-rich lahar that covers this bone bed and embeds the fossils, was previously thought to be 0.9 Ma old based on palaeomagnetic (Sondaar et al., 1994) and zircon fission-track data (Brumm et al., 2010a; Morwood et al., 1998), but is now firmly dated at 1.4 Ma. In addition, we have now documented a new fossil assemblage (TT-UP) from a slightly younger site at Tangi Talo, Excavation TT-F, with a maximum age of 1.27 Ma.

Previous age estimates for the fossil and artefact assemblages from Kobatuwa-I ranged between \(0.80 \pm 0.09\) Ma and \(0.70 \pm 0.07\) Ma, based on two of zircon fission-track dates of tuffaceous siltstone layers bracketing the fossil-bearing layers. Considering the relatively large error ranges in these fission-track ages, this would correspond with a broad range of between 0.89 and 0.63 Ma for the Kobatuwa assemblage. Based on the new teprostratigraphic correlations, this age range is probably an underestimate, and the Kobatuwa-I fossil and artefact-bearing strata are likely older than the Pu Maso Tephra, which is \(^{40}\text{Ar}/^{39}\text{Ar}\) dated at \(0.81 \pm 0.04\) Ma in the Mata Menge section. These strata are also older than the dated T3 interregional tephra at \(0.90 \pm 0.07\) Ma, suggesting a minimum age of 0.83 Ma for the Kobatuwa assemblage. This minimum age is still in accordance with the ZFT data, but locates the minimum age of Kobatuwa further back in time, indicating that the fossil assemblage and artefacts are certainly older than the ones from the lower fossil-bearing interval at Mata Menge (MM-LOW, see below). At Kobatuwa-I the basal conglomerate (Unit K1, see Figs. 2 and 10; referred to as ‘Unit F’ in Jatmiko...
et al., 2009) contains the oldest record of *S. floresiensis* in the So'a Basin. Although no direct dates are available for this conglomerate, the new tephrostratigraphic correlations indicate that this basal conglomerate was deposited before the emplacement of the Turakeo tephra. The emplacement of the Turakeo Tephra, in turn, occurred before the deposition of the overlying T3 interregional tephra, which is dated at 0.9 ± 0.07 Ma in the Mata Menge sequence. Thus, this basal conglomerate at Kobatuwa-I could be as old as the basal conglomerate lenses underlying the 1 Ma WST at Wolo Sege and Kobatuwa-IV, which also contain stone artefacts but have not yielded any fossils.

At Mata Menge the combined palaeomagnetic evidence and tephro-chronological framework allows us to confidently date the MM-LOW at ~0.77 Ma. *S. floresiensis*, the largest animal on Flores, must also have arrived during that same time interval. After that there appears to be a long period of relative faunal stability, characterized only by the gradual dwarfing of the *S. floresiensis* lineage and possibly a radiation of murine rodents, although it is conceivable that the differences between the Liang Bua and So’a Basin rats are primarily the results of proxy evidence for hominins. A major fauna turnover occurs between 1.3 and 0.9 Ma, and hominins are thought to have arrived between 1.3 and 1.0 Ma ago.

**Fig. 19.** Fauna sequence of Flores, based on a combination of tephrostratigraphic correlations, chronometric age estimates, and paleontological and archaeological data. On the lower left is the Palaeomagnetic and Marine Isotope Record (modified from Head and Gibbard, 2005) spanning the So’a Basin record. The position of dated tephra marker beds from the So’a Basin are included (see Table 2) and the Middle Pleistocene Transition (MPT; ~1.25–0.7 Ma; i.e., Clark et al., 2006) is indicated in light blue shading. Green triangles indicate major glaciations within the MPT including the first major worldwide event (MIS 22; ~870–880 ka) with substantial ice volumes that typify later Pleistocene glaciations (Ehlers and Gibbard, 2007). Note there is a ~300,000 year hiatus between the end of the So’a Basin record and the beginning of the Liang Bua record. Black triangles indicate occurrences of stone artefacts as proxy evidence for hominins. A major fauna turnover occurs between 1.3 and 0.9 Ma, and hominins are thought to have arrived between 1.3 and 1.0 Ma ago. *S. floresiensis*, the largest animal on Flores, must also have arrived during that same time interval. After that there appears to be a long period of relative faunal stability, characterized only by the gradual dwarfing of the *S. floresiensis* lineage and possibly a radiation of murine rodents, although it is conceivable that the differences between the Liang Bua and So’a Basin rats are primarily the results of environmental differences. Note that the youngest occurrence of *S. floresiensis insularis* at the site Ulu Mala Kata in the So’a Basin (not depicted in this figure) is slightly younger than the youngest record in Liang Bua. Known bird taxa have been omitted, as well as several commensal rodents that arrowed to Flores during Neolithic times (10–4.5 ka). Liang Bua data based on Sutikna et al. (2016, 2018). For explanation of the Pleistocene fossil animal icons see Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
Basin (e.g. Boa Leza, Ruda Olo, Ola Bula, Mala Huma, Ngamapa, Paupadhki, Kopo Watu, Dozu Dhalu and Wolo Keo (Sumitomo et al., 2009)) (see Fig. 2). The latest occurrence of S. floresiensis in the OB is in the MM-UP, estimated to be ~ 0.7 Ma. MM-UP is certainly older than 0.65 ± 0.02 Ma, which is the age of the 40Ar/39Ar dated air-fall tephra T-Pica-02 at 15 m above the MM-UP interval in the basal part of the Limestone Member (Brumm et al., 2016). The newly documented fossil-bearing lahar terrace at Ulu Mala Kata, with a calibrated age in excess of 47,250 extends the record of Stegodon in the So’a Basin by ~ 650,000 years, and may represent the last occurrence of Stegodon on Flores.

7.2.2. Fauna sequence

The most common megafauna in the oldest recorded vertebrate assemblage on Flores (from the main bone bed at Tangi Talo (TT-LOW), now dated at ~ 1.4 Ma), are Stegodon sondaari (~16% of fossil specimens) and Megalochelys sp. (~74% of all fossil specimens). Other vertebrates present in this large assemblage are Komodo dragon (Varanus komodoensis), unidentified crocodiles, and a pelvis and marginal carapace fragment of a box turtle (cf. Cuora amboinensis) (Setiyabudi, 2017; Takahashi et al., 2015; van den Bergh, 1999). An unidentified large-bodied murine rodent can now be added to this faunal assemblage, and which extends the earliest record of murine rodents on Flores with more than 500,000 years.

The slightly younger fossil Tangi Talo assemblage from Excavation F (TT-UP) estimated to be ~ 1.27 Ma, still contains S. sondaari (35% of the total number of fossil specimens), V. komodoensis (22% of specimens) and crocodiles (3.3% of specimens). The remainder (39.5%) are unidentified bone fragments, but the site clearly lacks evidence for the presence of Megalochelys, of which small carapace and plastron fragments would have been easily recognizable if they were present. Of the S. sondaari fossils, several long bones, two tusks, a mandible, vertebrae, ribs and 12 articulated caudal vertebrae can be ascribed to a single adult individual, but a large portion of the S. sondaari fossils from TT-UP represents juvenile individuals, such as isolated milk molars and milk tusks. The MNI of S. sondaari, based on dental elements, amounts to 35. Two V. komodoensis thoracic vertebrae were found articulated, and most if not all vertebrae and costa fragments may represent a single individual, hence the relatively large proportion of V. komodoensis fossils in the assemblage, but a MNI of one.

Above TT-UP there is a gap in the fossil record of several hundred thousand years, with the next oldest fossil-bearing layer represented by the basal conglomerate at Kobatuwa-I, which has an estimated age of between 1 and 0.9 Ma (see 7.2.1). This fluvial conglomerate yielded only two rolled molar fragments of a medium to large-sized Stegodon cf. floresiensis (Jatmiko et al., 2009), representing the earliest appearance of this taxon on Flores. The same basal conglomerate at Kobatuwa-I contains stone artefacts, proxy evidence for a hominin presence at this site. These conglomerates may be of similar age as the basal conglomerates from three other sites in the So’a Basin where stone artefacts occur just below the 1 Ma dated WST (Wolo Sege, Kobatuwa-IV, and Mata Go), providing a minimum age for the earliest appearance of hominins.

The fossil assemblage from layers directly on top of the basal conglomerate at Kobatuwa-I (layers I, J, H), is slightly older than the emplacement of the Pu Maso Tephras (Fig. 10), which is dated at 0.81 ± 0.04 Ma. The Kobatuwa-I layers I to H contain abundant S. floresiensis remains, together with crocodiles (possibly Crocodylus siamensis (Setiyabudi, 2017)); V. komodoensis, and lithic artefacts indicating a continuing hominin presence. Two unidentified rodent fossils were also recovered.

The largest fauna assemblage documented from the So’a Basin is from the lower fossil-bearing interval at Mata Menge (MM-LOW), with an age of between 0.77 Ma (the base of the Brunhes Chron) and 0.73 Ma, with this younger age limit representing the upper error range of the ZFT age from the MM-LOW interval as reported by (Morwood et al., 1998). MM-LOW has the same taxa as recorded at Kobatuwa, and likewise contains stone artefacts (Brumm et al., 2010b). Because of the large fossil sample from the MM-LOW interval (11,730 fossil specimens), there are a number of other vertebrates represented that are usually less commonly found in the fossil record, such as several bird species and frogs (Meijer et al., 2015). The birds include various wetlands taxa (a swan Cygnus sp.; a duck Anas cf. gibberifrons; a large rail cf. Gallinula/Fulica; and a lapwing Vanellus sp.) and a medium-sized bird of prey (Hieraedetus sp.) (Meijer et al., 2015).

Most of the diagnostic murine rodent fossils (molars, mandibles and maxillae) from the MM-LOW interval belong to Hoojeromys nusatenggara, which could be a descendant of the unidentifiable giant rat from TT-LOW. H. nusatenggara, first described by Musser (1981) and based on fossil tooth rows from the sites Ola Bula and Boa Leza, is by far the most abundant rodent species documented for the late Early Pleistocene of the So’a Basin, with the exception of a single Speleaomys floresiensis molar from the MM-LOW interval.

Broadly contemporaneous with the MM-LOW is the site of Boa Leza, which, based on its proximity to Mata Menge, its similar sedimentary facies association, and a ZFT date of 0.84 ± 0.07, is not distinguishable from the MM-LOW in either age or depositional environment. Both S. floresiensis and H. nusatenggara have been found at Boa Leza, but not Komodo dragon, which could be due to the much smaller sample size obtained from Boa Leza (478 versus 11,730 fossil specimens, respectively). The Boa Leza assemblage, however, includes an Eagle Owl (Bubo sp.) (Meijer et al., 2015).

The common fauna elements from MM-LOW and Boa Leza continue to be present in the Mata Menge sequence in the MM-UP level, which, with an estimated age ~ 0.7 Ma, represents the youngest record of megafauna in the OB, followed by a gap in the fossil vertebrate record of ~ 650,000 years. The MM-UP assemblage includes a small number of H. floresiensis-like fossils (van den Bergh et al., 2016), and a coracoid of a shelduck (cf. Tadorna) (Meijer et al., 2019), but a large portion of the fossil assemblage from the MM-UP has not yet been analysed in detail.

No vertebrate fossils were recovered from the lacustrine interval at the top of the OB. However, the terrace remnant along the Ae Sesa at the site Ula Mala Kata now provides the youngest, Late Pleistocene megafauna record from the So’a Basin. The Stegodon from this site is smaller than its putative ancestor from the OF, with a size and morphology conform the smaller subspecies S. floresiensis insularis, known from the Late Pleistocene cave deposits in Liang Bua.

The MNI of S. sondaari based on dental elements from the TT-LOW amounts to 52 individuals who died at varying life stages. By assigning each of these 52 individuals to one of five age groups spanning the entire life history of these animals (see van den Bergh, 1999 for the methods used) an age profile of the TT-LOW assemblage was constructed (van der Geer et al., 2017). The resultant profile resembles the Type A age profile of Haynes (Haynes, 1991), which is characterized by a predominance of juvenile individuals and progressively decreasing proportions of successively older age classes. In the TT-LOW, 35% of the individuals represent juveniles with milk teeth (either dp2, dp3 and dp4) in various degrees of occlusal wear. Subsequently older age groups comprise 29% (young adults), 21% (prime adults), 6% (old adults) and 10% (senescent). This age structure of the death assemblage resembles that of a
sttable living population, and is indicative of non-selective mortality, e.g. caused by a catastrophic event affecting the mortality of all age groups equally (Haynes, 1991). The main bone bed at Tangi Talo (TT-LOW) is associated with a large volcanic eruption as represented by the pumice-rich lahar covering the bones. This eruption could therefore account for a local population of S. sondaari being affected by the non-selective mortality of all age groups (Aziz et al., 2009a; van den Bergh, 1999; van der Geer et al., 2017). A partially preserved Megalochelys carapace—plastron with pelvic girdle and left femur and tibia unearthed in 1992 from the main bone bed contained four isolated teeth of V. komodoensis inside, suggesting that Komodo dragons fed on this tortoise carcass. It is also possible that after emplacement of the pumice lahar Komodo dragons dug through this deposit to scavenge the buried animal carcasses. Such scavenging behavior has been observed elsewhere following a major volcanic eruption (Lyman, 1989). The fragmentary and scattered nature of the TT-LOW bone assemblage and the lack of articulated skeletal elements suggests a time gap between death and final burial, as was initially proposed by van den Bergh (1999).

The age structure of the S. sondaari death assemblage from the fluvial channel fill of Excavation F (TT-UP) is quite distinct from that of the TT-LOW. The MNI of TT-UP amounts to at least 35 individuals; 86% of which represent juveniles. This proportion could even be an underestimate, considering that bones of young individuals are less likely to be preserved (Damuth, 1982). The TT-UP age profile corresponds with the Type B of Haynes (1991), in which juveniles greatly outnumber mature individuals. A Type B profile is established when juveniles are disproportionately affected by mortality, but does not suggest a sudden catastrophic event as the main cause of death. Instead, Type B could be the result of predation, possibly by Komodo dragons or crocodiles, or other factors causing selective juvenile mortality, such as food shortages or a period of extreme drought (cf. Haynes, 1991; van der Geer et al., 2014). A direct association with volcanic activity is not evident for the TT-UP, nor are there stone artefacts associated with the TT-UP sequence, which, had they been present, might indicate hominin predation.

It is important to note here that S. sondaari and V. komodoensis both occur in the fluvial channel fill of Excavation F in the TT-UP, and therefore the volcanic event that supposedly generated the earlier mass death (as exemplified by the main bone bed, TT-LOW) apparently had not impacted the entire population of these animals on Flores. However, the volcanic event associated with the lahar that covered the main bone bed of TT-LOW may have wiped out the Megalochelys population, since this taxon has not been recorded in any younger strata throughout the So’a Basin. What eventually caused the extinction of S. sondaari between 1.27 Ma and 0.9 Ma remains speculative, due to the gap in the fossil record. This species’ disappearance from the fossil record could be associated with the later arrival of hominins (predation) and/or interspecific competition following the arrival of the larger S. floreNsis sometime before 0.9 Ma, and/or other indirect ecological impacts caused by this newly-arrived larger proboscidean taxa. An increase in aridity around the Middle Pleistocene transition could also have played a role (see section 7.2.4).

The youngest Stegodon fossils in the So’a Basin are now represented by the S. floreNsis insulareNsis fossils from Ulu Mala Kata. Over a period of more than half a million years, the So’a Basin Stegodon decreased ~30% in linear body size dimensions to reach the size of its Late Pleistocene descendants (van den Bergh et al., 2008). Based on body weight estimates derived from limb bone dimensions, the anatomical changes between the So’a Basin and Liang Bua S. floreNsis would have amounted to a 67% decrease in body weight (van der Geer et al., 2016). This is why the So’a Basin and Liang Bua S. floreNsis have been given distinct chrono-subspecies names: S. floreNsis from the OBF, and S. floreNsis insulareNsis from Liang Bua (van den Bergh et al., 2008; van den Bergh et al., 2009b) and Ulu Mala Kata.

7.2.3. Hominin arrival

The new stratigraphic and dating evidence strongly indicates that the Tangi Talo main bone bed (TT-LOW) is half a million years older than previously thought (Brumm et al., 2010a; Morwood et al., 1998; O’Sullivan et al., 2001; Sondaar et al., 1994), and that the youngest occurrence of S. sondaari (TT-UP) predates the oldest occurrence of stone artefacts by an estimated 250,000 years. When the age of the Tangi Talo fauna was still thought to be ~0.9 Ma (e.g., Aziz et al., 2009a; Brumm et al., 2010a; Morwood et al., 1998), it was assumed that S. sondaari had been present on Flores at least 100,000 years after the arrival of hominins, and therefore that the extinction of S. sondaari and giant tortoise — and the arrival of a new larger-bodied S. floreNsis — occurred during the ensuing 100,000 years. This suggested that the arrival of hominins on Flores did not have any immediate impact on the Stegodon and Mega- lochelys populations (Brumm et al., 2010a). Our revision of the dating of the Tangi Talo fauna now demonstrates there is no evidence of an overlap of 100,000 years. Instead, there is a time gap in the So’a Basin between the latest occurrence of S. sondaari at 1.27 Ma and the earliest record of stone artefacts at slightly older than 1 Ma. At present it cannot be conclusively demonstrated that the Tangi Talo fauna did not overlap in time with the arrival of hominins on Flores. This is because the stratigraphically oldest stone artefacts from directly beneath the WST have a minimum age of 1 Ma, and none of the three sites where this association has been observed (Wolo Sege, Kobatuwa-IV, and Mata Go) have produced fossil evidence. The oldest occurrence of S. floreNsis in the basal conglomerate at Kobatuwa-I could be as old as the artefact-bearing conglomerates at these three sites, though no conclusive evidence provides a minimum age in excess of 1 Ma at Kobatuwa-I, and based on the current data it could be 0.9 Ma. However, given stone artefacts are absent from all excavated sites equivalent in age, or older than, 1.27 Ma (n = 7), it is unlikely that hominins were present before 1.27 Ma. Therefore, it remains an open question whether hominins were involved in the demise of the Early Pleistocene megafauna on Flores.

What about the arrival of modern humans during the Late Pleistocene? In Liang Bua the youngest S. floreNsis insulareNsis fossils are directly overlaid by, and partly embedded in, ash layer LB-T3, which is estimated to be 50 ka (Surikna et al., 2016). The S. floreNsis insulareNsis occurrence from Ulu Mala Kata may be equivalent in age or slightly younger, with a minimum calibrated age of ~47,250 cal BP (upper calibrated age boundary is > 50,000 cal BP), and may represent the youngest recorded occurrence of Stegodon on Flores. This last recorded presence of Stegodon is just a few thousand years older than the earliest evidence for the arrival of modern humans on Flores at ~46 ka cal BP (Surikna et al., 2018) and on Sulawesi north of Flores, where the earliest known cave art is dated to at least 45.5 ka (Brumm et al., 2021).

It is therefore tempting to speculate that modern humans were the main factor in the demise of S. floreNsis, an animal that had shared the island of Flores for almost a million years with H. floreNsis despite fluctuating climatic conditions and major volcanic eruptions. Homo sapiens must have crossed Wallacea on the way to Australia even before 46 ka, as there is now widespread evidence that modern humans were well established on that
continent from around 50 ka (Hamm et al., 2016; Veth et al., 2017), and may have even reached there as early as 65 ka (Clarkson et al., 2017). If this early age for the occupation of Australia can be maintained, it could be possible that H. sapiens initially by-passed Flores taking the northern route via Sulawesi, Seram and Halmahera (Kealy et al., 2017), but archaeological evidence for an occupation as early as 65 ka on these islands, or any Wallacean island for that matter, is so far lacking.

7.2.4. Palaeoenvironmental changes

It is possible that catastrophic volcanic activity, such as the caldera forming eruption that deposited the WST at 1 Ma ago, may have caused or contributed to the eventual disappearance of S. sondaari. However, hominins were already present on Flores when the WST was emplaced, and they continued to be present following this event, with the earliest post-WST record of hominins represented by the lithics in layers I-G at Wolo Sege, and possibly the basal conglomerate (layer K), at Kobatuwa-I. The eruption may therefore have only affected biota surrounding the Kellilambo volcano — including in the So’a Basin — but did not lead to extinction in other parts of Flores. This would allow repopulation of the So’a basin following this volcanic event, at least as far as hominins are concerned.

S. sondaari may have already been extinct when hominins first set foot on the island. Another explanation for the demise of S. sondaari could be a drying climate resulting in an increase of C4 plants in open grassland at the expense of C3 plants in forested areas. C3 vegetation constituted an important part of the diet of S. sondaari, which was a mixed feeder of leafy C3 plants besides C4 grasses (Puspaningrum, 2016). In contrast, S. florens seems to have thrived in a drier, grass-dominated landscape, at least after 0.9 Ma, as demonstrated by the significantly higher δ13C contents of the tooth enamel of S. florens from the Middle Pleistocene Sandstone Member of the OBF (see Fig. 11). The prevalence of an open grassland environment during the Early Middle Pleistocene is supported by other observations, such as the fossil avifauna and a limited set of palynological data (Brumm et al., 2016; Meijer et al., 2015). However, no indicators are currently available for the Early Pleistocene palaeoenvironmental conditions, other than the stable isotope analyses of S. sondaari tooth enamel. The observed difference in diet between S. sondaari and S. florens suggests an increase in relative availability of C4 resources and could signify a significant reduction in rainfall or increased seasonality. Because some of the Kobatuwa individuals before 0.9 Ma were also mixed feeders, S. florens may have been more flexible in its diet, but under drying conditions was eventually forced to primarily feed on grasses. This trend continued into the Late Pleistocene, evidenced by the Liang Bua S. florens insularis, which had reached a similar small body-size as the much older S. sondaari lineage, but had a diet dominated by C4 grasses (Puspaningrum, 2016). On the island of Sumba directly south of Flores a single Stegodon sumbaensis molar from the site Lewa Paku, with an estimated age of ~1 Ma, also had a mixed diet as indicated by a δ13C value of ~4.8‰, and similar to S. sondaari. Although only one early Pleistocene Stegodon individual is known from Sumba, more data is available from the adjacent island of Timor. All Stegodon timorensis molars on Timor are dated as younger than 0.81 Ma (n = 6), and thus of Middle or Late Pleistocene age, had a δ13C above ~2‰ and were grazers (Puspaningrum, 2016). This could indicate that a similar trend of increased aridity could have affected not just Flores, but the wider region of East Nusatenggara. A trend of forested areas being replaced by savannah environments around the Mid-Pleistocene Transition (MPT) has also been demonstrated for both Java and the wider SE Asian region (Louys and Roberts, 2020; Puspaningrum et al., 2020).

A reduction in rainfall is in accordance with Quaternary global climate models, which indicate that between 1.25 and 0.7 Ma ago there was a gradual transition from low amplitude and high-frequency climatic oscillations (~41,000-year cycles) to high amplitude and low frequency oscillations (100,000-year cycles). This resulted in lower overall sea surface temperatures together with increasing aridity and monsoonal intensity in Asia (Clark et al., 2006). In the So’a Basin, Kobatuwa, the oldest site with S. florens, is estimated to be between 1.0 and 0.83 Ma old. This site records a transition and has yielded both mixed C3/C4 individuals and individuals with a higher C4 component in their diet, whereas all of the younger sites are characterized by grazers (S. florens and H. nusatenggara) that primarily fed on C4 resources (Brumm et al., 2016).

High tempo explosive silicic volcanism in the So’a Basin, shifts in faunal composition and diet, and the arrival of humans on Flores (Fig. 19) are all broadly coincident with the onset of the MPT at ~1.25 Ma (Marine Isotope Stages (MIS) 38 (Clark et al., 2006)). In terrestrial realms of the western Pacific and south-east Asia little is known about MPT orbitally-forced biotic effects, though increases in African and Asian aridity and monsoonal intensity have been postulated (Clemens et al., 1996; Head and Gibbard, 2005; Sun et al., 2019; Tiedemann et al., 1994; Williams et al., 1997). Changes in astronomically-forced climate response at the onset of the MPT, leading to overall increase in aridity and/or seasonality between 1.4 and 0.8, as evidenced by the observed shift in herbivore feeding habits, could be a causative factor that impacted browsing insular fauna on Flores such as S. sondaari. However, the arrival of other large mammals (hominins and S. florens), during broadly the same time interval, combined with a significant gap of 400,000 years in the fossil record, complicates determining what factor(s) ultimately led to the extinction of S. sondaari.

7.3. Archaeological observations

The stone artefact assemblages recovered from the So’a Basin sites reflect a similar approach to hard-hammer direct percussion of cobbles and pebbles available in local gravel deposits (Fig. 20). Cores were reduced bifacially, producing centripetal ‘radial’ cores, but were sometimes rotated out of the radial plane, resulting in multiplatform cores. Core reduction was usually non-intensive, and flakes struck from these cores were sometimes retouched. Raw material procurement appears to reflect careful selection for the more siliceous varieties of stones from local gravel deposits; chalcedony and silicified tuff (including opalescent variants) are relatively rare in these gravels, yet compose 10–30% of the flaked-stone assemblages (SI Table H.1). The conjoined flake (Fig. 20–J) and core (Fig. 20–I) from Kobatuwa—and the presence of minimally-reduced ‘assayed cobbles’ at all sites—may indicate that cobbles were partly or entirely reduced at the stone source areas, with tools carried away for use elsewhere.

A comparison of assemblage counts shows similar proportions of artefact types spanning some 300,000 years across a variety of sites and contexts (Fig. 20; Table H.1). This technological stability attests to the importance of the stone technology to hominin adaptation to this insular environment. Although the stone technology was not lost entirely, despite the putative changes to brain structure that may have occurred through the process of island endemism (Falk et al., 2005, 2009), neither are there clear signs of technological innovation in the face of the stresses imposed by the
**Fig. 20.** 2D representations of 3D scans of various stone artefacts excavated in situ at So’a Basin sites. **A,** Multiplatform core from Wolo Sege, Upper Trench, No. A4; **B,** Pick-like multiplatform core from Wolo Sege, Main Trench Conglomerate, No. WS/10/71; **C,** Perforator-like retouched cobble fragment from Kobatuwa, Sector 18, Layer H, No. 72; **D,** Bifacial core from Kobatuwa, sector 16, No. 9; **E,** Multiplatform core from Mata Menge Trench 25 (MM-LOW), No. A107; **F,** Multiplatform core from Mata Menge, Trench 27B (MM-LOW), No. A-1636; **G,** Multiplatform core from Wolo Sege, Main Trench Conglomerate, No. WS/10/116; **H,** Multiplatform core from Mata Menge, Trench 27B (MM-LOW), No. S914; **I,** Bifacial...
dynamic environment, (i.e., volcanism and variable Pleistocene climate). This has larger implications for interpreting hominin stone tool-kits, as it implies that a simple ‘Oldowan-like’ technology is sufficient for a technological adaptation to a dramatically variable environment. One possible exception is the apparent diminution of ‘picks’ at Wolo Sege to small ‘perforators’ at Kobatuwa and Mata Menge (Brumm et al., 2006), and, much later, at Liang Bua (Moore and Brumm, 2009; Moore et al., 2009). However, during surveys large picks made on cobbles have been recovered from the surfaces of eroding contexts of a variety of ages at Mata Menge/Boa Leza, Tangi Talo (at Tangi Talo these surface tools likely originated from the younger part of the sequence exposed in the steep hill slope, equivalent in age with the WST or younger), and elsewhere in the So’a Basin. Given how rare picks are relative to other artefact classes, their absence from excavated assemblages from later deposits may be a sample size effect. Alternatively, the variation may be related to differences in the types of activities that occurred across the excavated sites, although the functions of picks and perforators is presently unknown.

Theoretical and experimental research into early stone tools emphasises that the skills necessary to strike well-controlled flakes — like the tools made by So’a Basin hominins — suggest relatively advanced cognitive abilities, beyond the capabilities of living primates, and unique to the hominin lineage (Moore, 2019). However, the preponderance of bifacial reduction and multiplatform cores at the So’a Basin sites is consistent with simple reduction to produce sharp edges rather than to produce formal tool forms that reflect a hominin ‘mental template’ (Moore and Perston, 2016). The So’a Basin tools are similar in technology and form to the earliest stone tool assemblages from Africa (Moore and Brumm, 2009), and they can be produced without higher-order intentions (Moore, 2011, 2020; Moore and Perston, 2016). Picks and perforators are the possible exception to this, with hints of ‘Acheulean-like’ technology, and documenting the chronology and natures of these tool forms — and the cognitive capacities they might imply — is a priority for further So’a Basin research.

8. Conclusions

Our identification of the Wolo Sege Tephra at Tangi Talo, combined with our new radiometric age results, has led to fresh insights into the insular faunal composition existing during the time the lower Ola Bula sediments were being deposited. This revision of the faunal succession now reveals the earlier interpretation that a fauna turnover occurred at least ~100,000 years after the first arrival of hominins to the island — and which occurred before 1 Ma (Brumm et al., 2010a). Instead, the new chronostratigraphy, which is based on tephrostratigraphic correlations combined with new radiometric ages, indicates that an early Pleistocene insular fauna (comprising the small-bodied proboscidean Stegodon sondaari, the giant tortoise Megalochelys sp., Komodo dragon Varanus komodoensis, a box turtle Cuora cf. ambonensis, crocodiles, and unidentified murine rodents) were present on Flores ~1.4 Ma ago, which is half a million years earlier than had previously been assumed.

The subsequent disappearance of the small-bodied S. sondaari and giant tortoise from the sedimentary record likely occurred before, and/or is coeval with, the earliest occurrence of hominin stone artefacts: the artefacts recovered from beneath the Wolo Sege Tephra, dated at slightly more than 1 Ma, at three different sites in the So’a Basin (Kobatuwa IV, Wolo Sege and Mata Go).

The interval broadly encapsulating the WST is characterized by a closely-spaced succession of explosive eruptions where the So’a Basin was repeatedly inundated by voluminous pyroclastic flow events originating from a now extinct volcanic complex on the east side of the basin, which is most likely the Keli Lambo Volcano. In the aftermath of these successive events, the extensive secondary reworking of these mass-flow deposits indicates sustained landscape instability and readjustment, which in turn would have had important, and recurrent, effects on the So’a Basin vegetation and resident insular fauna. In addition to these volcanic events, climatic changes coinciding with the Early to Middle Pleistocene transition could have contributed to the extinction of S. sondaari and giant tortoise, but further evidence is required to clarify this, as well as the possibility that the arrival of hominins and/or another larger Stegodon species, could also have facilitated these extinctions.

Following the emplacement of the Pu Maso Tephra around 0.8 Ma, the influx of volcanioclastic materials into the So’a Basin from the east either decreased, or stopped altogether. In the western portion of the basin, at Mata Menge and Boa Leza, this reduced sediment supply seems to have resulted in downcutting of the sequence, removing the upper marker tephra layers (Pu Maso and Turakeo tephras), by a fluvial system likely originating from the Welas Caldera. At what age the Welas Caldera started to fill in with a lake and produce the lacustrine sediments at Poma remains unknown, but lake expansion appears coincident with an emergent intra-caldera cone formation (see Fig. 9 a-c). Phreatomagmatic activity associated with initial cone emergence and growth likely displaced the lake waters, causing them to spill into adjacent tributaries and form mudflows of admixed lake and ash sediments. Within the Sandstone Member at Mata Menge and Boa Leza, the cut-and-fill sequence contains multiple metre-thick mudflow units that are interbedded with fluvial sands and gravel layers that contain prolific stone artefacts and fossil bones. This suggests that by 0.77 Ma, which is the age of the lower fossil-bearing interval at Mata Menge, a lake was already present within the Welas Caldera, and perhaps even earlier at the time that the Kobatuwa-I fossil-bearing mudflows and lahars were emplaced. The presence of a permanent water body in the Welas Caldera lake could have attracted hominins, which would explain the abundance of stone tools in the cut-and-fill sequences exposed near Kobatuwa, Mata Menge and Boa Leza.

By 0.65 Ma the lake had expanded to the extent that the remaining subaerial portions of the So’a Basin had become submerged (see Fig. 2A). The ancestral basin outlet (paleo Ae Sesa valley) was likely blocked by rapidly aggregating fluvo-volcanic debris fans extending down the flanks of the Raja Caldera (Fig. 1). However, the exact reasons for this blockage require further investigation. This palaeolake existed for at least 150,000 years, before it drained in response to head-wall erosion with the ancestral Ae Sesa river and its tributaries incising further back within the confines of the basin, while volcanioclastic influxes from the active volcanoes south of the So’a Basin continued to build peripheral aprons of coalescing fluvo-volcanic debris fans. Of special notice is a remnant of a massive coarse-grained lahar exposed in the terrace remnant along the Ae Sesa river at Ulu Mala Kata (Fig. 2), originating from the south and containing fossils attributed to S. floresensis insularis. These Late Pleistocene Stegodon fossils may represent the last dated occurrence of this taxon on Flores and predate the known first appearance date of modern humans in Liang Bua by just a few thousand years. It is now evident that both Stegodon and a lineage of diminutive hominins persisted on the island for almost one million years prior to the arrival of...
**H. sapiens.** Considering the long co-occurrence of these two iconic Flores endemics, it appears increasingly probable that modern humans played a key role in the extinction of both.

**Author contributions**

**Gerrit van den Bergh:** Conceptualization, Methodology, Project administration, Investigation, Formal analysis, Writing – original draft, Writing – Review and editing, Supervision, Funding acquisition. **Brent Alloway:** Conceptualization, Methodology, Investigation, Formal analysis (tephrostratigraphy), Resources, Supervision, Writing – original draft, Writing – Review and editing. **Michael Storey:** Formal analysis, Resources, Investigation, Writing – review and editing. **Ruly Setiawan:** Formal analysis, Investigation, Resources, Project administration. **Dida Yurnaldi:** Formal analysis, Investigation. **Iwan Kurniawan:** Formal analysis, Investigation, Supervision. **Thomas Sutikna:** Investigation, Supervision. **Unggul Prasetyo:** Investigation, Data curation. **Erick Setiabudi:** Formal analysis, Investigation, **Mika Puspaningrum:** Formal analysis, Investigation. **Ifan Yoga:** Investigation, data curation. **Halmi Insani:** Investigation, **Hanneke Meijer:** Formal analysis, Investigation, Writing – Review & editing. **Barry Kohn:** Formal analysis, Investigation, Writing – review and editing. **Brad Pillans:** Investigation, Supervision. **Indra Sutisna:** Formal analysis, Investigation, Data curation. **Anthony Dosseto:** Formal analysis. **Susan Hayes:** Investigation, Writing – original draft, Writing – Review and editing. **John Westgate:** Formal analysis. **Nick Pearce:** Formal analysis. **Fachroel Aziz:** Conceptualization, Investigation, Supervision, Resources. **Rokus Awe Due:** Investigation, Formal analysis. **Michael Morwood:** Conceptualization, Methodology, Project administration, Investigation, Supervision, Funding acquisition.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data availability**

All data are presented in the appendices.

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**Appendix A. Supplementary data**

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**References**


