2. Geology and fossil sites of the Soa Basin, Flores, Indonesia.

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Abstract

This paper describes the geology of the Soa Basin, central Flores, in the context of regional plate tectonics, volcanism and uplift, as well as the history of geological research and the main stratigraphic units in the basin itself. The basal breccias of the Ola Kile Formation, formed during the Early Pleistocene, provided a concave structure, in which volcanic, fluvial and lacustrine deposits of the Ola Bula Formation accumulated between 1 million and 650,000 years ago. These have largely remained horizontal and undistorted; and the relative heights of strata largely reflect their relative ages. Localised deposits of vertebrate fossils, including those of *Stegodon florensis*, Komodo dragon, rat and crocodile, also occur in the Ola Bula Formation, mostly in palaeo-channels at times of low lake level, but also associated with palaeo-shorelines. So far 16 such fossil sites have been recorded, most of which also contain stone artefacts that are proxy evidence for hominins. However, stone artefacts are conspicuously absent from Tangi Talo, dated to 900,000 BP and the only fossil site currently known from Flores with pygmy *Stegodon* (*S. sondaari*) and giant tortoise. The Soa Basin sequence may, therefore, document the initial arrival of hominins on Flores.

2.1. Introduction

Flores is located in the middle of the Banda Volcanic Arc system, a string of volcanoes and volcanic islands that delineates an actively subducting zone between the Indian-Australian and Eurasian Plates (Hall 2002; Simandjuntak and Barber, 1996) (Figure 2.1). Subduction of the Indian-Australian Plate has caused the formation, up-lift and volcanism along the southern margin of the overlying Eurasian Plate, resulting in the emergence of a line of volcanic islands and the formation of deep ocean trenches to the south (McCaffrey 1996; Simandjuntak and Barber, 1996; Kopp *et al.*, 2006; Hall 2001).

The initial volcanism that formed Flores was submarine (Burrett *et al.*, 1991). During the Middle Miocene, sandstones and limestones were sub-aqueously deposited within basins that surrounded the volcanic spine of Flores, while subsequent volcanic activity produced widespread volcanic breccias. By the Late Miocene-Early Pliocene, limestones intercalated with volcanic material had been deposited, while extensive, shallow-depth magmatism continued in the Pliocene-Pleistocene and formed numerous calderas (van Bemmelen, 1949; Koesoemadinata *et al.*, 1994; Monk *et al.*, 1997). A volcanic centre, located immediately to the northwest of the Soa Basin, was active around 2.5 my ago and seems responsible for the outpourings of the extensive andesitic breccias that comprise the base rock of the Soa Basin. These outpourings continued until at least 1.66 my (Muraoka *et al.,* 2002: 119, 12, and culminated in the formation of the Welas Caldera. During this volcanic cataclysm a series of dacitic pumice tuffs were deposited as ignimbrites in the Soa Basin. These were overlain by lacustrine and fluviatile sediments in the Early and Middle Pleistocene.

Throughout the entire history of Flores, volcanism and rates of tectonic up-lift have been the dominant factors in shaping the island's landscapes. Sea level fluctuations, associated with glacial and interglacial cycles, are too distant to cause base-level adjustments of the Ae Sissa River system this far inland. Instead, both accumulation and down cutting of the Soa Basin sediments have been determined by rates of tectonic uplift and the nature of river drainage - at times river passage out of the basin was blocked by volcanic processes.

Evidence of uplift on Flores can be seen in the coral-reef exposures along the south coast, such as on Nusa Mules Island; in the raised coral-reef terraces along the north coast; and in the formation of a series of terraces along the Wae Racang River near Liang Bua in West Flores (Westaway, 2006). Similar evidence occurs on the neighboring islands of Sumba, Alor, Atauro and Timor. Uranium-

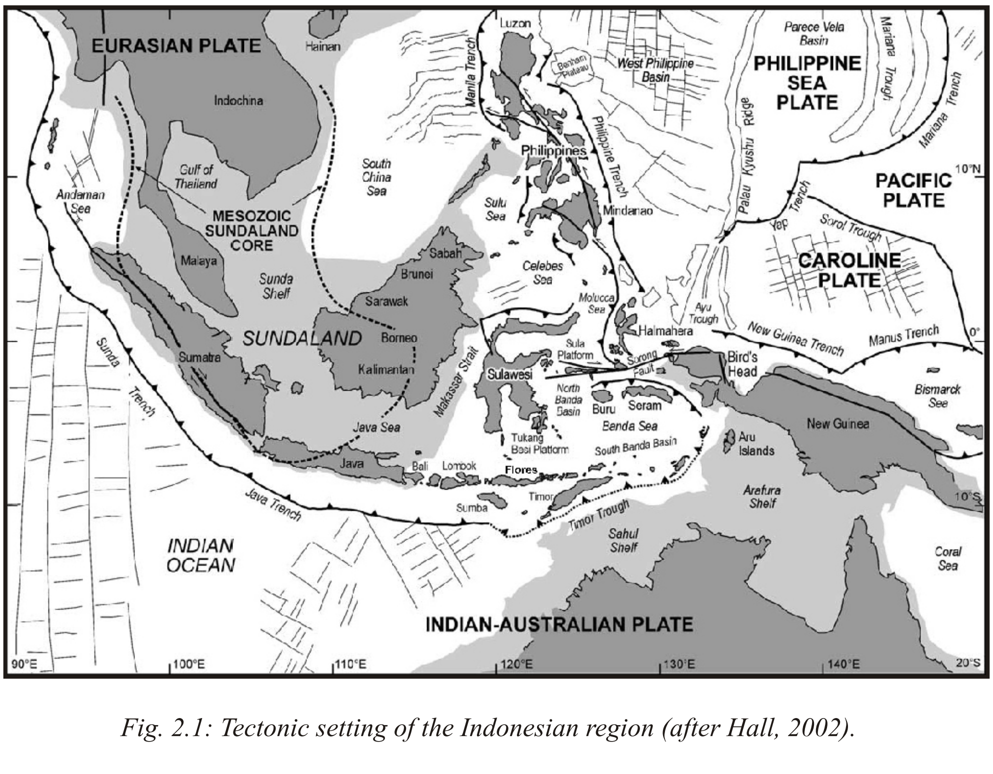

Fig. 2.1: Tectonic setting of the Indonesian region (after Hall, 2002).

series dating of such raised coral terraces provides the most reliable means for estimating tectonic uplift rates. For instance, over the last 1 Ma the raised coral reef terraces at Cape Laundi on Sumba have been uplifted 0.2 to 0.5 mm/yr (Bard *et al.*, 1996, Pirazzoli *et al.*, 1991, 1993), which approximates the 0.47 mm/yr estimates for Atauro (Abbott and Chamalaun, 1981) and 0.3–0.5 mm/yr for Timor (Chappell and Veth, 1978). Given such regional consistency, similar rates of uplift probably characterised Flores. Significantly, Muraoka *et al.* (2002: 09) estimate that two regions of the island were uplifted about 800 metres over the past 2.5 million years (= 0.32 mm/yr).

2.2. Geology of the Soa Basin

The Soa Basin is located between 300 and 370 metres above sea-level immediately to the northwest of Bajawa, the provincial capital for Ngadha Regency in central Flores. It is surrounded by both active and non-active volcanoes and is drained by the Ae Sissa River and its tributaries, which form sub-parallel drainage in the south and a dendritic pattern in the north. The river system runs northeast and exits the basin through a deeply incised gorge, and forms a delta plain on the north coast (Fig. 2.2).

Topographically the Soa Basin is a plateau in which the rivers have dissected valleys that are wide where the less resistant fluvio-lacustrine deposits are being eroded, but form steep gorges where the highly resistant andesitic breccias of the Soa Basin basement are being dissected. The tops of these volcanic breccias often form erosional terraces. The tops of the highest hills in the basin are level and show rounded or flat tops depending on lithology - rounded tops indicate unconsolidated sediments such as tuff or sandy tuff, while flat tops indicate more resistant rocks, usually lacustrine limestones that constitute the top of the basin fill sequence. Aligned hills also form ridges, especially in the southern section of the basin.

Other geological surveys of the area have been undertaken by Ehrat (1925), the Geological Research and Development Centre (Hartono 1961), an Indonesian-Dutch team (van den Bergh 1999) and Muraoka *et al.* (2002): the latter in connection with their assessment of geothermal sources in the region. However, it is difficult to reconcile our dates, stratigraphic evidence and inferred depositional history of the Soa Basin, with those espoused by Muraoka *et al.* (2002), who seem unaware of previous research in the basin, or prior designated names for geological formations. For instance, their 'Welas Tuff' and 'Aesesa Formation' correspond to the basal pumice tuff member and the upper fluvio-lacustrine members of the Ola Bula Formation of Hartono (1961), respectively. They also seem unaware of the andesitic breccias of the Ola Kile Formation that underlie the Ola Bula Formation. By convention, the original names given to these Formations by Hartono (1961) and adopted by van den Bergh (1999) take precedence and will be used exclusively in this paper, though his Gero limestone Formation is here considered as the upper member of the fluvio-lacustrine Ola Bula Formation.

We mapped the entire basin at a scale of 1:50,000, allowing a better understanding of its geological history and highlighting appropriate deposits for radiometric dating (Figure 2.3 plus Appendix A foldout). The mapping was achieved by using aerial photographs and topographic maps to identify boundaries between geological units; extensive ground truthing of all units at precise locations as determined by GPS readings; the study of stratigraphic column samples throughout the basin; and the recording of associated fossil deposits.

Hartono (1961) distinguished four main stratigraphic units within the basin, the Ola Kile Formation, Ola Bula Formation, Gero Limestone Formation and younger volcanic rocks. The basal unit, the Ola Kile, is composed of massive and resistant andesitic breccia with several interbedded tuffaceous siltstones and sandstones, and some lava flows. It was deposited as one or several coalescing volcanic aprons, at least one related to the Welas Caldera volcanic centre (Fig. 2.2). A fission track date of 1.86 million years for a tuff near the top to the Ola Kile Formation is in accordance with the K-Ar ages provided by Muraoka *et al.* (2002), indicating that initial infill of the Soa Basin depression started during the Late Pliocene/Early Pleistocene. Where exposed along the northern edge of the basin, the Ola Kile Formation is at least 75 m thick but its base is not exposed

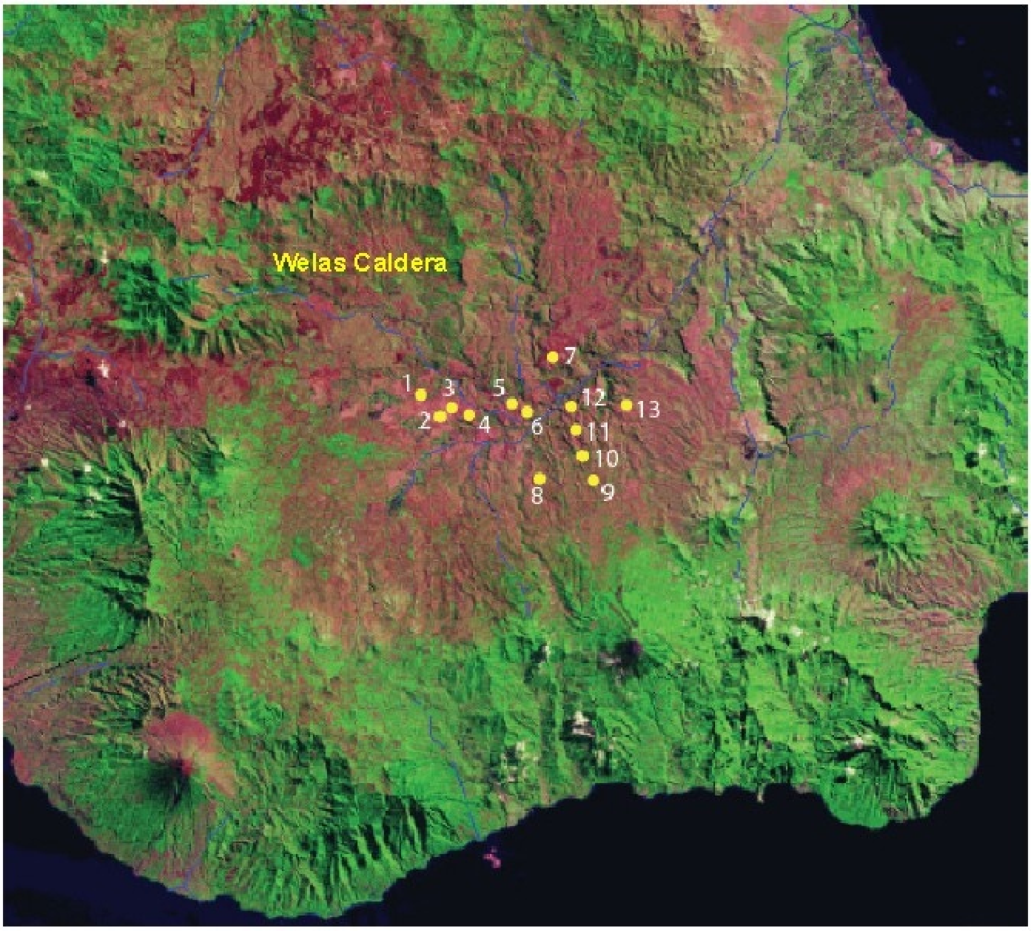

Fig. 2.2: Satellite image of the Soa Basin in West Central Flores, with the most important fossil/archaeological localities. Forested areas are green, Savannah grasslands are red. 1 = Kobatuwa; 2 = Mata Menge; 3 = Lembah Menge; 4 = Boa Leza; 5 = Ola Bula; 6 = Tangi Talo; 7 = Wolo Milo; 8 = Wolo Keo; 9 = Sagala; 10 = Dozu Dhalu; 11 = Kopowatu; 12 = Ngamapa; 13 = Pauphadhi.

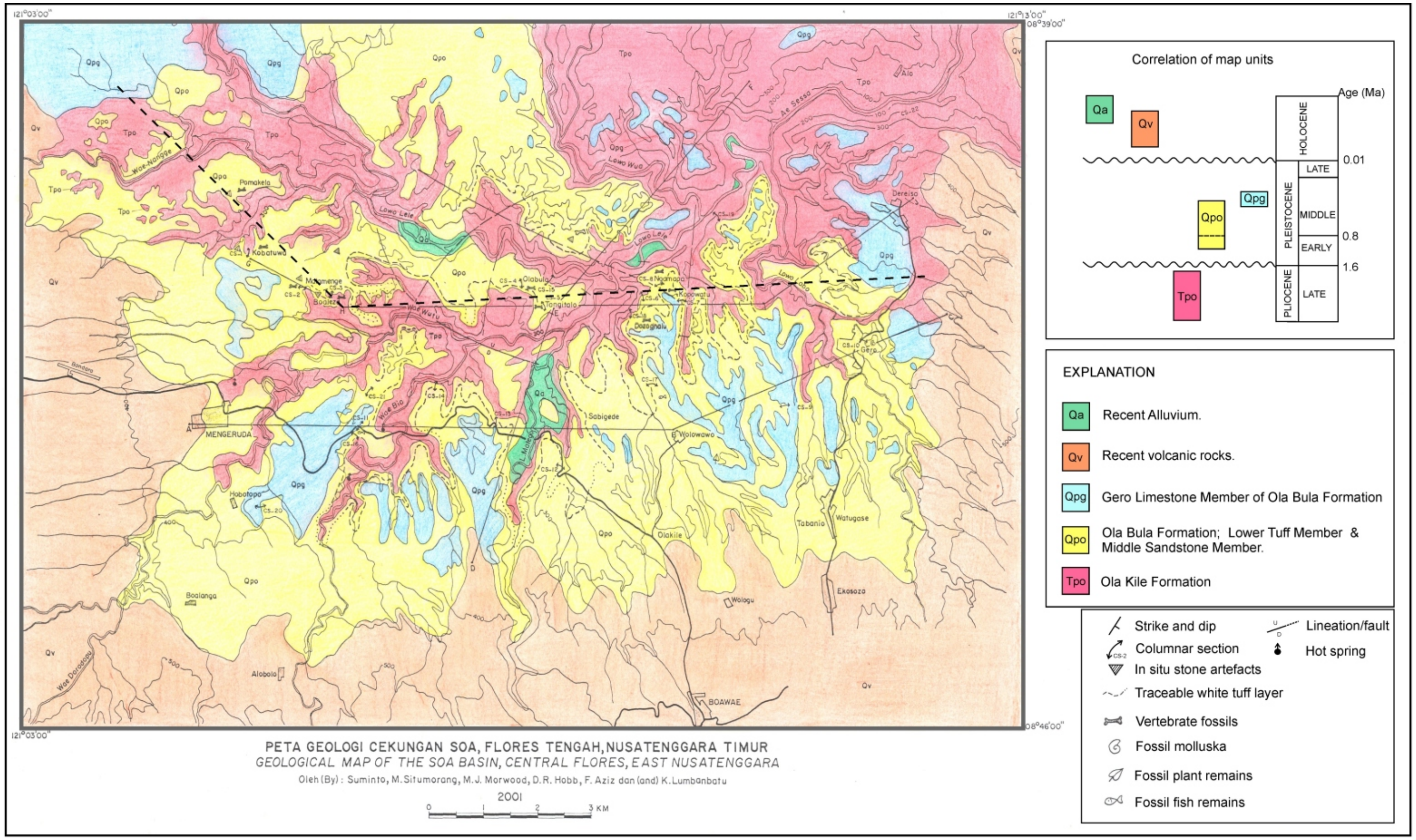

*Fig. 2.3. Geological map of the Soa Basin. Thick dashed line indicates schematic profile shown in **Fig. 2.5***

anywhere. The Formation has an east-to-west strike and a regional dip of 5 degrees to the south resulting from tectonic activity, but possibly partly preserving the dip of the south and southeastward sloping volcanic aprons. Following deposition, and prior to later burial, the upper surface of the Ola Kile was broadly folded and eroded.

The Ola Bula Formation., which unconformably overlies the Ola Kile Formation and fills in much of the two subbasins, consists of as much as 100 m of largely undeformed and flat-lying volcanic and sedimentary deposits, which thin toward the margins of the basin. A fault running east-to-west cuts the Ae Sissa up-stream of the Lowo Mese and Lowo Lele.

Three depositional intervals have been identified within the Ola Bula Formation (Fig. 2.4). A basal tuffaceous interval, which seems to correspond with the Welas Tuff of Muraoka *et al.* (2002), consists largely of volcanic deposits dominated by prominent layers of white pumiceous volcanic tuffs interbedded with tuffaceous silt, and minor sand layers and conglomerate lenses. Some of the pumice layers show clear characteristics of ignimbritic flows, and they are frequently overprinted by red mottling, in particular along the western basin margin near Mata Menge, suggesting extensive periods of non-deposition and soil formation.

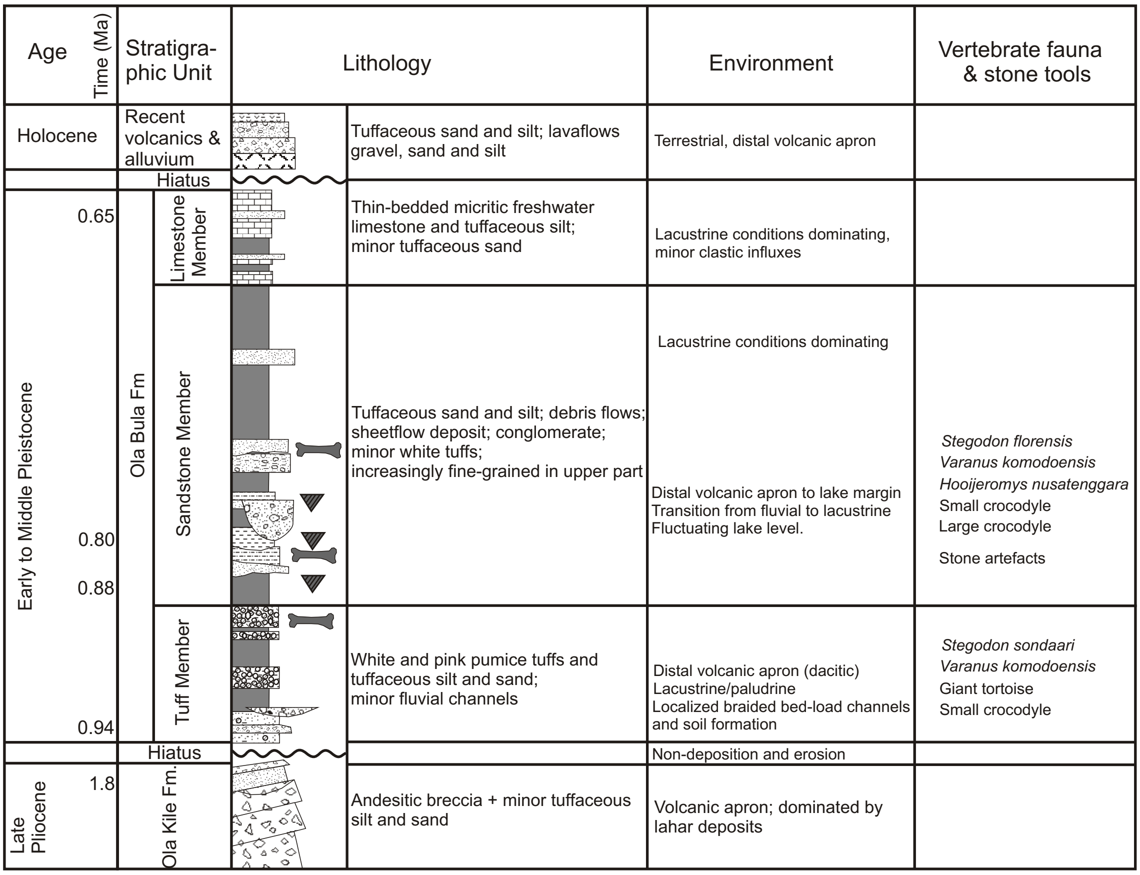

Fig. 2.4. Generalized stratigraphic sequence for the Soa Basin.

The white volcanic tuff interval is very thick in the southeast of the basin in the direction of the Kelindora volcano, which is still active. In the east, the tuffs constitute massive fine-grained white layers with minor, large pumice fragments, possibly deposited in a lacustrine environment. In contrast, around Kobatuwa on the northwestern basin margin near the Welas Caldera, deposition of the Ola Bula Formation started later than in the central part of the basin, and there is no basal tuff member, which was presumably eroded before deposition of the sandstone member began. Sediments of the Ola Bula Formation infilled a pre-existing depression. At present, Tangi Talo is the only known site in the basal tuff interval with fossil vertebrate fossils, which include the remains of *Stegodon sondaari*, giant tortoise and *Varanus komodoensis*.

The tuffaceous interval grades upward into a fluvio-lacustrine interval in which layers of predominantly low-energy siltstones alternate with high-energy sandstones. The sandstone layers are characterized by internal scour and fill structures, and occasionally show parallel laminations and minor crossbedding features. Other facies types occurring in the fluvio-lacustrine interval are reworked tuffs and mudflow deposits. Occasionally the sandstone beds contain concentrations of terrestrial vertebrate fossils, predominantly of *Stegodon florensis* (see below). Freshwater conditions are indicated by evidence for freshwater molluscs, indicative of well-oxidized agitated to occasionally stagnant conditions; crocodiles; mineralized microbial mat laminae; and plant fossils, including horsetails, tree leaves and wood fragments. Along the western margin of the basin, the sequence is condensed and the sandy layers are generally between 0.5 and 2 m thick, indicating that they were deposited in minor streams and as sheetflood deposits. In the central part of the basin, the sandstone member reaches a maximum thickness of about 60 m, and individual sandstone layers are up to 5.5 m deep, indicating much larger river channels. Stone artefacts occur *in situ* in both sandy and fine-grained clastic deposits of the sandstone member.

The sandy interval grades conformably upsection into a limestone interval, up to 40 m thick, of micritic freshwater limestone intercalated with fine-grained sandstones, tuffs and silts. The limestones may exhibit parallel laminations and contain fossils of freshwater algae (oogonia), plants, fish, ostracods and mollusks. The limestone interval was deposited within a lacustrine environment, as indicated by its extensive and horizontal distribution, but the top of some limestone layers show polygonal shrinkage cracks, indicating fluctuating water levels. Hartono (1961) mapped this upper interval as a separate unit, the Gero Formation. On the basis of the gradational nature of the contact between the limestone and the underlying sandy interval, as well as its patchy distribution, it could be considered as the third, upper member of the Ola Bula Formation. However, in the northern part of the basin the Gero limestone interval directly overlies the Ola Kile Formation unconformably – i.e. it is much more extensive than the Ola Bula Formation. The thickest development of the limestone member occurs in the eastern part of the basin, where individual limestone layers may be up to 30 cm deep. Along the western basin margin the limestone interval is thinner (10 m) and consists of thin-bedded layers (1-5 cm thick) alternating with greater amounts of fine-grained clastics and minor sand and tuff layers.

Hartono (1961) claimed that foraminifera occurred in the limestone member, which would suggest small-scale marine transgressions into the basin. However, we could not verify his claim and it is possible that he mistakenly identified the globular calcareous oogonia of Characea as foraminifera (van den Bergh, 1999).

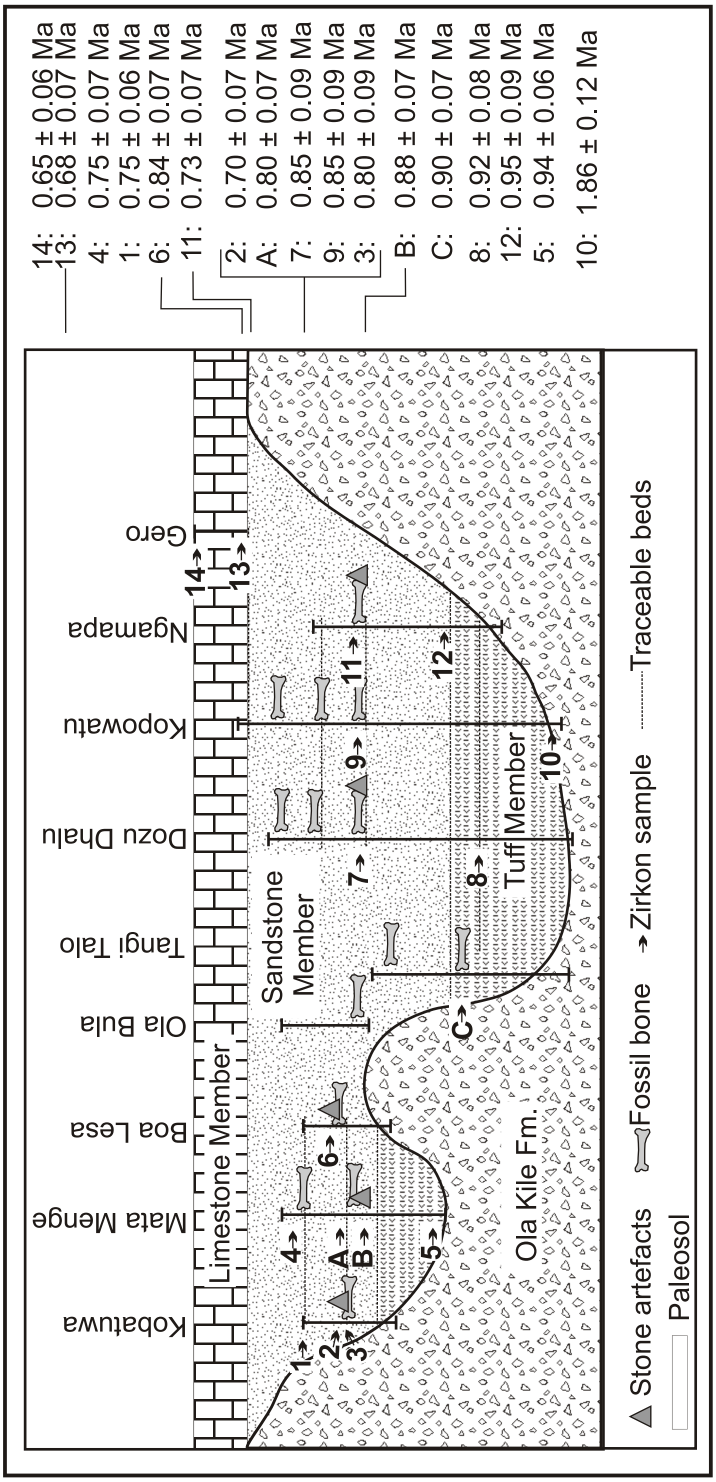

Fig. 2.5. Fission-track ages of the Soa Basin sequence (after O'Sullivan et al., 2001).

Along the southern margin of the Soa Basin, the Ola Bula Formation is unconformably overlaid by recent volcanics. This thin unit (ca 10 m) is composed primarily of andesite and basaltic lavas interbedded with minor sandstone and conglomerate layers consisting of volcanic detritus from the surrounding volcanic uplands.

2.3. Chronology

In order to determine the absolute age of the basin deposits and their fossil localities, we used the fission-track dating method (Fig. 2.5). Of the 14 samples selected from the Ola Bula Formation, eight were from tuffaceous layers below deposits containing stone artefacts, and six were from layers either associated with or located above deposits containing stone artefacts. Three additional samples, two from thin tuffaceous layers near the base and top of the limestone interval, and one from the top of the Ola Kile Formation., were dated in order to determine the minimum and maximum ages, respectively, of the Ola Bula Formation. Although it is possible that the tuffaceous layers sampled have been slightly reworked following deposition, their horizontal extent and lack of internal sedimentary structures, as well as their homogeneity in color and texture, suggest that any reworking was minimal. Therefore, the zircon ages are interpreted as dating the time of deposition for each layer.

The zircon fission track results are consistent throughout the section and become progressively younger upsection (O'Sullivan *et al.*, 2001). Sample ZFT-10 from the top of the Ola Kile Formation yielded an age of 1.86 ± 0.12 Ma (all errors reported at ±1 σ), thus indicating a Late Pliocene minimum age for deposition (Fig. 2.5). Zircon ages from two samples from the tuffaceous interval at or near the base of the Ola Bula of ca. 0.96 - 0.94 Ma indicate that deposition of this unit began during the Early Pleistocene. Farther up section within the basal tuff member of the Ola Bula Formation, zircon ages ranged between 0.92 ± 0.08 Ma and 0.90 ± 0.07 Ma from tuffaceous layers beneath deposits containing stone artefacts. Zircon fission track ages from the fluvio-lacustrine middle sandstone member of the Ola Bula Formation range between 0.88 ± 0.07 and 0.70 ± 0.07 Ma, and stone artefacts occur in deposits spanning this time range. Samples ZFT-13 and ZFT-14, from the overlying Gero limestone member, gave ages of 0.68 ± 0.07 Ma and 0.65 ± 0.06 Ma (Fig. 2.5), indicating that deposition of the Ola Bula Formation ceased in the Middle Pleistocene.

An important point is that, except for the northern part of the Soa Basin, where there is a slight dip to the south, the Ola Bula Formation and the Gero Limestone have remained horizontal. The relative heights of fossil sites and layers within the Ola Bula Formation are, therefore, generally indicative of their relative ages, as confirmed by the fission track results and by age estimates based on the presence of tektites in some strata, palaeomagnetic determinations and the fossil evidence (e.g. Sondaar *et al.*, 1994). However, thick sandstone deposits formed in large, deeply incised channels in the central part of the Soa Basin (e.g. in the Ngamapa and Dozu Dhalu sections) are lower in the sequence and may be contemporaneous with the upper part of the tuff member in the western margin sections (e.g. Mata Menge). In addition, mudflow deposits and fluvial conglomerates are more common along the western basin margin, and the latter may be deeply incised into previously deposited lacustrine sediments - as observed near Mata Menge (see Chapter 4).

2.4. Fossil/archaeological sites in the Soa Basin

We located 16 fossil/archaeological sites in the Ola Bula Formation, including those previously investigated by Maringer and Verhoeven (1970), Sondaar *et al.* (1994) and Morwood *et al.* (1999). In the site survey, we recorded data on stratigraphic and environmental contexts, dimensions, contents, locations and relative heights, and also collected tuffaceous siltstone samples for fission track dating. Equipment used included measuring tapes, compasses, clinometers, an abney level, a Geographical Positioning System (GPS) and an electronic altimeter. For measuring relative heights the altimeter was set each morning at 500 m, which was higher than the actual elevation, at a specific location en route to the field. Barometric changes during the course of each day meant that much cross-checking was required. Sites were also recorded photographically and with digital video. Contributions by researchers from several disciplines (e.g., geology, archaeology, and paleontology) mean that the site-specific, as well as the regional processes responsible for deposition of the sediments within the Soa Basin and excavated finds are now well understood.

From northwest to southeast the fossil sites comprised Wolo Milo, Kobatuwa, Mata Menge, Lemba Menge, Wolo Sege, Boa Lesa, Ola Bula, Tangi Talo, Wolokeo, Dozu Dhalu, Sagala, Deko Weko, Kopowatu, Ngamapa and Pauphadhi. In addition, we also recorded Keli Esu Cave and the abandoned village of Ola Bula. Details on individual sites are given below.

2.4.1. Wolo Milo

Location: 008˚ 40' 57.8' S, 121˚.08' 27.2" E. Surface fossils are exposed on a sandstone platform 45 metres wide. *In situ* artefacts also occur in the above scarp for 10 metres. They are of volcanics, chert and silcrete. The fossil deposits are overlain and underlain by tuffs.

Contents: Fossils include large *Stegodon*. There is also an extensive scatter of stone artefacts on the terrace associated with bone. One *in situ* stone artefact was found.

Relative Height: 456 m. Gero Limestone lies 20 metres above, and the Ola Kile Formation ca. 10 metres below.

Comments: Wolo Milo occurs at the same stratigraphic level relative to the Gero Limestone and Ola Kile Formation as Mata Menge, Boa Lesa and Kobatuwa. The number of fossils, presence of *in situ* artefacts and close proximity of tuffs suitable for dating make Wolo Milo a site with significant research potential.

2.4.2. Kobatuwa

Location: 008.68851˚ S, 121.08790˚ E. Fossils are exposed on a sandstone platform flanking both sides of a deeply incised gully, which runs north to meet the main river channel. The platform is 120 metres long (N - S) and up to 10 metres wide. The well-preserved fossils occur in the uppermost layer of hard coarse sandstone, basically at the interface with the overlying grey siltstone. In one section a white tuffaceous siltstone occurs between the grey siltstone and the coarse sandstone. The natural section along the west bank of the gully shows localised changes in the height of the Ola Kile Formation and the nature of sediments immediately overlying it. At the southern end, the coarse sandstone covers a conglomerate filled palaeo-channel and the Ola Kile Formation lies 2 metres below. Midway along the site the coarse sandstone is 60 cm thick and underlain by a grey siltstone (25 cm), coarse sandstone (25 cm) then the Ola Kile Formation. Following the section along, there are channels in the Ola Kile Formation up to 170 cm deep, infilled with homogeneous grey sandstone, while one section rises to within 25 cm of the present platform surface. At the northern end of the site, the Ola Kile Formation drops down at least 100 cm and a layer of pink tuffaceous siltstone occurs in the resulting depression. This siltstone is relatively soft and has weathered out to undercut the overlying sandstone. Stone artefacts are exposed in the coarse sandstone scarp and in the roof of the undercut. Artefacts also occur beneath the scarp on the slope down to the creek. They are of volcanics, chert and silcrete.

Contents: Fossils include large *Stegodon*, with *in situ* stone artefacts in association

Height: Relative Height: 505 m; True elevation ~332 m. 23 metres below Gero Limestone and between 25 and 200 cm above the Ola Kile Formation.

Comments: The Ola Kile Formation at this site has localised topographic variation (e.g. water channels), and is sealed in by a coarse sandstone layer, which contains stone artefacts. Most of the fossils have been deposited on top of this sandstone layer. Three fission track ages are available for Kobatuwa: a date of 800,000 ± 90,000 BP from a layer of tuff 35 cm below the fossil deposit provides a maximum age for the fossils and associated stone artefacts, while a date of 700,000 ± 70,000 BP for a layer of white tuff 2 metres above the fossil layer provides a minimum age (O'Sullivan, *et al* 2001), and another white tuffaceous silt higher up the slope yielded an age of. 750,000 ± 60,000 BP. Three trenches were excavated at Kobatuwa between 2004-2006, in a research cooperation between the Archaeological Research Centre in Jakarta (ARKENAS), the Geological Survey Institute in Bandung (GSI), and the University of New England, Australia. A more detailed description of the results is provided in Chapter 6 of this volume.

2.4.3. Mata Menge/Lemba Menge

Location: 008.69266˚ S, 121.09563˚ E. Mata Menge lies 1.5 km and 118˚ (southeast) of Kobatuwa on an erosional terrace shaped by a resistant sandstone layer cropping out on a hill slope between the Gero Limestone and the Ola Kile Formation. The fossil deposits are 1.6-2.2 metres thick and are exposed in the face of the terrace scarp. They comprise a fining-upwards sequence of inter-bedded layers and lenses of tuffaceous siltstone and sandstone (see Chaper 4, this volume). Verhoeven conducted excavations here in 1965 and Sondaar *et al.* (1994) in 1992-4. Fossils are also exposed on the terrace flat immediately to the northwest. The site of Lemba Menge, located 120 metres to the east on the other side of a gully, is really part of the same fossil deposit. Verhoeven excavated at Lemba Menge in 1968 (Maringer and Verhoeven 1970: 236).

Contents: Vertebrate fossils include large *Stegodon florensis*, crocodile, giant rat (*Hooijeromys nusatenggara*), and the pelvis of an unidentified bird. Stone artefacts occur *in situ* at both Mata Menge and Lemba Menge (Maringer and Verhoeven 1970: 236; Morwood *et al* 1997; Brumm *et al.,* 2006). They also lie scattered across the sites and in the general vicinity - especially in the gully between Mata Menge and Lemba Menge.

Elevation: Relative Height: 505 m; True elevation: ~332 m. Mata Menge lies 23 metres below Gero Limestone and 8 metres above the Ola Kile Formation. Lemba Menge and the more distant Kobatuwa occur at the same elevation as Mata Menge.

Comments: Some fossils excavated by Verhoeven are in the Catholic Seminary Museum at Ledalero. The location of the stone artefacts that he recovered is not known. Fossils and stone artefacts excavated by Sondaar *et al* (1994) are in the collections of the Geological Survey Institute at Bandung.

Four fission track ages are available for the locale (Morwood *et al.*, 1998; O'Sullivan *et al.*, 2001). The prominent white tuff 18 metres above the site dates to 0.75 $\pm$ 0.07 Ma, while the pink tuff exposed 8 metres below the fossil deposit and immediately above the Ola Kile Formation is 0.94 $\pm$ 0.06 Ma old. Within the site, a layer of tuff sealing off the top of the fossil layer provides a minimum age of 0.80 $\pm$ 0.07 Ma for the fossils and associated stone artefacts, while the pink tuffaceous silt immediately beneath the main fossil deposit yielded a date of 0.88 $\pm$ 0.07 Ma. This silt contains stone artefacts and now provides a minimum age for the first appearance of hominins in the basin (see Chapter 4, this volume; Brummel *et al.,* 2006).

2.4.4 Wolo Sege

Location: 008.40˚ 59.9" S, 121.08˚ 30.3" E. The site lies near the base of the Ola Bula Formation in the western part of the Soa Basin, 540 m and 63° (northeast) of Mata Menge, and stratigraphically ca. 5-10 metres below Mata Menge. It is located in a scarp in a cattle yard at the head of a small gully, surrounded by a series of low hills. A 4 metres high escarpment of resistant tuffaceous silt and ignimbrite/pumice gravel from the lower member of the Old Bula Formation extends along the base of the hills, encircling the gully to the north, west and south. In descending order, the investigated section comprised topsoil, pumice-rich ignimbrite, tuffaceous silts, a 0-80 cm thick fluvial conglomerate, and a 60 cm thick tuffaceous silt. The latter silt interval directly overlies breccias of the Ola Kile Formation.

Contents: Stone artefacts, but no fossils, occur within the conglomerate deposit and underlying tuffaceous silt. In addition, a scatter of stone artefacts occurs across the cattle yard. These were probably eroded from the conglomerate.

Elevation: True elevation: 326 m.

Comments: We undertook a small excavation at this site in 2005 and found stone artefacts at the base of the lowermost tuff directly on top of the Ole Kile Formation.

2.4.5. Boa Lesa

Location: 008.69605˚ S, 121.1005 008˚ E. The site lies 660 metres and 125˚ (southeast) from Mata

Menge. Fossils and stone artefacts occur in a tuffaceous sandstone layer deposited in a channel. These are capped with tuffaceous silt.

Contents: The fossils are of large *Stegodon florensis*. Stone artefacts occur in situ in direct association with the fossils. A scatter of artefacts also lies on the site and in the general vicinity.

Relative Height: 496 m. True elevation ~333 m. Stratigraphic 32 metres below Gero Limestone and 9 metres above the Ola Kile/Ola Bula boundary.

Comments: Verhoeven undertook major excavations here in 1963 and recovered *in situ* stone artefacts (Maringer and Verhoeven 1970: 230). The fossils recovered by Verhoeven are housed in the Catholic Seminary Museum at Ledalero. The museum also has an album of Verhoeven photographs most of which are of the Boa Lesa excavations. On the basis of relative altitude and stratigraphic position, it is the same age as nearby Mata Menge, as confirmed by a fission track date of 0.84 $\pm$ 0.07 Ma for a tuffaceous siltstone overlying the fossil deposit (O'Sullivan *et al.*, 2001). In 1998 and 1999, we re-excavated Boa Lesa to check Verhoeven's findings (see Chapter 5, this volume; Morwood *et al.*, 1999).

2.4.6. Ola Bula

Location: 008.69389˚ S, 121.13305˚ E. The site lies 3.6 km and 086˚ (east) of Boa Lesa on top of the main plateau in the area. Fossils are exposed in a series of sandstone and siltstone layers. The site lies close to and 50 metres above, Tangi Talo.

Contents: Fossils include large *Stegodon florensis*. Stone artefacts of volcanics, silcrete and chert also occur across the site. In a number of locations fossils, stone artefacts and pottery from the upper levels/surface of the plateau have slumped down the sides to the slopes and terraces below.

Relative Height: 465 m. The Ola Bula fossil-bearing deposit is located ca. 60 metres below the Gero Limestone exposed near Mata Menge and 58 metres above the Ola Kile Formation as exposed below Tangi Talo.

Comments: Verhoeven did a major excavation at the site in 1957. His main excavation area measures 21 by 8 metres. He found artefacts on the surface, but none in the excavation (Maringer and Verhoeven 1970: 229). Some of the fossils he excavated are now housed in the Catholic Seminary Museum at Ledalero.

2.4.7. Ola Bula Village

Location: 008.69506˚ S, 121.14007˚ E. (First Hut Cluster) 008.69434˚ S, 121.14274˚ E (Second hut cluster). The remains of a megalithic village occur 780 metres and 100˚ (east southeast) of Ola Bula fossil site. The village is located on a narrow peninsula 123 metres above and overlooking the Ae Sissa River gorge to the NNW and the Ae Bha River to the southeast. The peninsula terminates overlooking the junction of the two rivers to the northeast (075˚) and is precipitous on three sides with a narrow neck joining it to the main Ola Bula plateau to the west. It is on average 60 metres in width and 400 metres in length and has a commanding view of the surrounding country except to the west, where it joins the main plateau. A scatter of stone artefacts and pottery fragments extends across the site and down adjacent scarps. *Stegodon* fossil fragments were also found across the area immediately inside the wall fencing of the village near the first cluster of hut footings. They are associated with an eroded tuff layer just below the eroded remains of hard tuffaceous sandstone. An eroding *Stegodon* jaw and tusk occur in the tuff layer below the sandstone. An occasional thighbone fragment was seen embedded in the hard tuffaceous sandstone outcrops in the area. The fossil fragments appear to have eroded from the sandstone that partially caps the site, which is at the same relative height as the sites of Ngamapa and Kopowatu.

2.4.8. Tangi Talo

Location: 008.69806° S, 121.13611° E. The site lies 510 metres southeast of Ola Bula. It occurs on the hill slope running down from the main plateau to the more precipitous slopes of the Ola Kile Formation, which here forms a gorge along the Ae Bha River 85 metres below. Fossils are eroding out of a pumice-rich tuff layer 35 cm thick, which extends for 100 metres along the slope. Just below the site differential erosion has formed a terrace flat on which fossils, stone artefacts and pottery fragments occur. These are of very mixed ages. In 1994, a 15 metre length of the fossil layer was excavated by Sondaar *et al.* (1994). The resulting scarp is evident at the northern end of the site. Two smaller exposures at the same stratigraphic level on the south and west slopes of the Tangi Talo hillock indicate that this fossil deposit is extensive.

Fig. 2.6: Remains of the pygmy Stegodon sondaari excavated at Tangi Talo in 1994 (Photo: Gert van den Bergh).

Tangi Talo Loc. 2 at 008.7031˚ S, 121.13696˚ E. A flat area measuring 3 by 2 metres

Tangi Talo 2 at 008.69865˚ S, 121.13388˚ E. A slope measuring 6 by 5 metres.

Contents: Fossils include pygmy *Stegodon sondaari*, giant tortoise and Komodo dragon (Figure 2.6). Van den Bergh (1999) also records the occurrence of a small crocodile. It is the oldest fossil site yet located in the Ola Bula Formation and the only one in the basal tuff member. The pygmy *S. sondaari* and giant tortoise have not been reported from other, younger sites.

Relative height: 416 m. 108 metres below Gero Limestone and 8 metres above the top of the Ola Kile Formation.

Comments: A fission track date of 900,000 ± 70,000 BP has been obtained for Tangi Talo (Morwood *et al.*, 1998). The Indonesian-Dutch team excavated the site in 1994, and the Indonesian-Australian team again in 1999 (see Chapter 3, this volume). Stone tools of various types and ages, as well as pottery fragments, lie scattered along the hill slope and adjacent terraces. Recovered examples include proto-handaxes, picks and massive basalt flakes. However, none were observed *in situ*. All appear to have been transported from the slopes above. Nor were any artefacts found in the excavations.

2.4.9. Wolokeo

Location: 008.70926˚ S, 121.14972˚ E. The site occurs over a 2 metre square area on the summit of a knife-edge ridge. Here a scatter of large *Stegodon florensis* fossil fragments and stone tools is exposed on the surface and down the slope. The stone artefacts include an edge-ground implement (= Neolithic). Long grass made recording difficult.

Relative height: 505 m.

2.4.10. Sagala

Location: 008.71167˚ S, 121.15633˚ E. It comprises a scatter of large *Stegodon florensis* fossils exposed for 120 metres on the surface of a sandstone platform. One *in situ Stegodon* tusk was observed but no stone tools. Long grass made recording difficult.

Relative height: 462 m.

2.4.11. Dozu Dhalu

Location: 008.70008˚ S, 121.15400˚ E. The site is located 1920 metres west of Tangi Talo on a spur running down from the main plateau at 335˚ N. The ridge has a number of terraces resulting from differential erosion of the Ola Bula Formation strata. Fossils are exposed on the flat and scarp of the second terrace for 100 metres across the ridge, which is flanked by steep, treed gullies on both sides (Fig. 2.7).

Contents: Fossils include large *Stegodon florensis*, Komodo dragon, snake (?) and giant rat. A sparse scatter of stone artefacts occurs across the site. They are made on volcanics, silcrete, quartzite and chert. One stone artefact was found *in situ* during the 1994 excavation (see Fig. 1.10,

Fig. 2.7. The 1994 and 1997 excavations at Dozu Dhalu revealed a concentration of Stegodon remains (Photo: Gert van den Bergh).

Chapter 1) by the Indonesia-Dutch team, but none were found in situ during the 1997 excavation (Morwood *et al.,* 1999).

Relative Height: 478 m. Stratigraphic 50 metres below the base of the Gero Limestone and 45 metres above the top of the Ola Kile Formation.

Comments: The 1997 excavation provided more detailed information on the site and its contents. A tektite found on the surface of the site indicates a minimum age for the deposits of ca. 0.73 Ma. Two fission track dates are available for the locale: the bone bearing deposits are 0.85 ± 0.09 Ma old, while the prominent white tuff located 20 metres below the fossil strata is 0.92 ± 0.08 Ma old (O'Sullivan *et al.,* 2001).

2.4.12. Kopowatu

Location: 008.69465˚ S, 121.15933˚ E. The site lies 930 metres northeast from Dozu Dhalu. It occurs on a ridge slope in an area about 40 metres wide and at least 100 metres long. Fossils were found eroding from a 3.7 metres thick series of sandstones and siltstones. Bone in the sandstones is highly fragmented, but well-preserved bone occurs in the siltstones. An extensive white tuff layer occurs 20 metres below the fossil deposits. The same tuff layer runs 23 metres below the Dozu Dhalu fossil bone bed.

Contents: Fossils include large *Stegodon florensis*, crocodile and rodent. More detailed investigation is needed to identify additional species. A scatter of stone artefacts, made from volcanics, silcrete and chert, occurs across the site.

Relative Height: 479 m. Stratigraphic 49 metres below the base of the Gero Limestone and 25

Fig. 2.8. A juvenile Stegodon florensis skull excavated at Kopowatu in 1999 (Photos: M.J. Morwood).

metres above the top of the Ola Kile Formation.

Comments: In 1999, we undertook excavations at the site, which yielded a juvenile *Stegodon florensis* skull, - the first documented for this species (van den Bergh *et al.*, 2001; Fig. 2.8) - and an *in situ* stone artefact. A fission track date of 0.85 ± 0.09 Ma was obtained for a tuffaceous siltstone at the top of the fossil deposit (O'Sullivan *et al.*, 2001).

2.4.13. Ngamapa

Location: 008.69169˚ S, 121.15625˚ E. The site lies 930 metres northeast from Dozu Dhalu. It occurs along the flat crest of a ridge about 40 metres across and extends for at least 100 metres. Fossils were found eroding from a coarse sandstone layer 10 cm thick and from the underlying siltstone. Bone in the sandstone is highly fragmented but well-preserved bone occurs in the siltstone. An extensive white tuff layer occurs 2 metres below the fossil deposits.

Contents: Fossils include large *Stegodon*, but more detailed investigation is needed to identify other species. A scatter of stone artefacts occurs across the site. These are made from volcanics, silcrete and chert. One artefact was reported *in situ* by a local informant, Minggus Siga.

Relative Height: 478 m. 50 metres below Gero Limestone, 10 metres above the Ola Kile Formation.

Comments: Two fission track dates are available for the site: the fossil strata date to 730,000 ± 70,000 years BP, while 2 metres below the white tuff layer is 950,000 ± 70,000 years old (O'Sullivan *et al.*, 2001).

2.4.14. Deko Weko

Location: 008.69578˚ S, 121.16371˚ E. It comprises a scatter of large *Stegodon* fossils and stone artefacts, as well as *in situ* fossil exposed for 30 metres along a low scarp of 30 cm thick tuffaceous sandstone overlain by hard conglomerate sandstone ca 50 cm thick. Fragments of bone are also embedded in the conglomerate sandstone. One *in situ Stegodon* tusk was observed, but no *in situ* stone tools.

Relative height: 480 m.

2.4.15. Pauphadhi

Location: 008.68750˚ S, 121.16841˚ E. Discovered by a local informant, Minggus Siga.

The 72 metre fossil exposure occurs in tuffaceous sandstone on two adjacent terraces and the intervening scarp. The scarp is 1 metre high.

Contents: Fossils include large *Stegodon*, but more detailed investigation is needed to identify other species. A scatter of stone artefacts occurs across the site. These are made from volcanics, silcrete and chert. One was recovered *in situ*.

Relative Height: 482 m.

Comments: Pauphadhi is the same relative altitude as Kopowatu, Deko Weko and Dozu Dhalu and is therefore about the same age - 0.85 Ma.

2.4.16. Malahuma

Location: 008.40˚ 59.9" S, 121.08˚ 30.3" E in the Nagarawe area. The 40 metre long fossil exposure occurs in a 60-80 cm thick gravelly sandstone on the slope of a small hill

Contents: Fossils include large *Stegodon*. A scatter of stone artefacts occurs across the site, but none were observed *in situ*.

Relative Height: 482 m.

2.5. Palaeoenvironmental Interpretation

The Soa Basin was shaped during the Pliocene, when the volcanic breccias of the Ola Kile Fm. accumulated. The precise source or sources of these breccias are not known yet, but the volcanic centre represented by the Welas Caldera to the northwest of the basin is likely the main volcano responsible for the thick, massive Ola Kile sequence. Still active volcanoes to the southwest and south may also have been active during this time. Towards the end of the Pliocene, supply of volcanic products decreased while tectonic activity caused southward tilting of the Ola Kile Fm, further shaping the basin in its present form. The upper part of the Ola Kile Fm was partly eroded leading to an unconformable contact between the Ola Kile and the Ola Bula Formations.

Fluviatile, lacustrine and volcanic sediments accumulated in the Soa Basin between ca 1 million and 650,000 years ago. Increased volcanism led to the initial deposition of the lower tuff member between 0.96 and 0.88 Ma, filling in the lower part of the pre-existing basin depression. The tuff member is characterized by a homogeneous, pumice-containing volcaniclastic composition of most of its deposits. The larger components of many layers consist exclusively of pumice fragments. This is one of the criteria used to distinguish syneruptive sediments that are produced geologically instantaneously, following the release of large amounts of pyroclastic fragments during volcanic eruptions (Smith, 1991). During inter-eruption periods, pre-eruption conditions were restored, aggradation ceased and stream beds were incised to form narrower, typically more sinuous, gravel-bedload channels such as represented by the few isolated conglomerate channel-fills observed in the lower member (e.g. at Wolo Sege and below Mata Menge). The member contains ignimbrites formed by hot avalanching pyroclastic flows, e.g. the ignimbrite sealing in the artefact-bearing conglomerate lens at Wolo Sege. Possibly, the lower tuff member is associated with the caldera forming phase of the Welas Caldera, but further research needs to clarify this, because the occurrence of pumice layers overprinted by red palaeosols suggest extended periods of non-deposition, in particular along the western basin margin (e.g. in the interval below Mata Menge).

The taphonomy of the only fossil locality so far encountered within the lower tuff member, Tangi Talo, indicated mass death of the terrestrial vertebrates, such as *Stegodon sondaari* and giant tortoise, shortly after a volcanic eruption (van den Bergh, 1999). As these taxa are not encountered in younger localities, this volcanic eruption may have caused their extinction, though the first hominins to arrive on Flores may have played a role in the demise of these animals as well.

From 0.88 Ma until 0.65 Ma the Soa Basin comprised a large shallow lake or series of lakes for much of the time, presumably when the single drainage outlet was blocked due to volcanic or tectonic activity, or when increased precipitation during wetter periods caused lake levels to rise. Small streams, carrying mostly sandy material, entered in to this lake along its northwestern margin, whereas non-canalized sheet-flows and debris flows also entered the basin from adjacent slopes. The locality Mata Menge is located at a site where such a small stream entered the lake (see Chapter 4, this volume). Localized tuffaceous sediments still accumulated in the lake, rivers, creeks, and waterholes.

Analysis of the stratigraphic and environmental relationships within the basin found that freshwater fossils, as well as the majority of the volcanic tuffs in the upper two members, accumulated during periods of fine-grained silty lacustrine deposition. In contrast, the bones of land animals are not found within these suspension deposits; such creatures would have been confined to the lake margins and higher grounds on the volcanic aprons entering the basin. Their remains occur almost exclusively in sandy facies, or silty lenses associated with sandy facies. Fossils of land animals and stone artefacts have been found only in these localized deposits (Morwood *et al*., 1999). However, a new outlet appears to have periodically been cut by the river, resulting in drainage of the lake and leading to incision of the lacustrine deposits by gravely bed-load channels (see Chapter 4, this volume). In addition, lake levels seem to have fluctuated presumably due to climatic conditions. At such times, terrestrial animals reoccupied the basin, and erosional processes predominated.

Around 0.68 Ma the lake increased in size one final time and the thin-bedded freshwater limestones of the upper limestone member were formed. The deepest part of this lake was located in the eastern part of the basin, whereas along the western basin margin clastic influxes continued, resulting in overall thinner limestone layers and a dominance of fine-grained clastic deposits. Along the northern basin margin the lacustrine limestones were deposited directly on the eroded top surface of the Ola Kile Fm.

In summary, the earliest site, Tangi Talo, located within the tuffaceous interval, contains fossils representing a mass death of an impoverished, highly endemic fauna around 900 ka ago. The taphonomy and age-profile of the death assemblage strongly suggests that they were killed by a major volcanic eruption (van den Bergh, 1999; van den Bergh *et al.*, 2001). There are no associated stone artefacts. All of the other recorded fossil sites in the Ola Bula Fm. are located upsection within the middle sandstone member of the Ola Bula Formation, where they accumulated in localized drainage channels or lake-shore settings, usually sealed in by layers of tuffaceous silt. These sites have similar fossil assemblages, dominated by *Stegodon florensis*, and most also have *in situ* artefacts (Morwood *et al.*, 1999). The vertical sequence of strata and associated stone artefacts in the Soa Basin has, therefore, yielded unambiguous and relatively precise dates for the arrival of hominins on Flores by 880,000 years BP, which coincided with (and possibly caused) the extinction of pygmy *Stegodon sondaari* and giant tortoise, and their replacement by the large-bodied *Stegodon florensis*. Although stone artefacts left by these hominins were at least partly reworked by water currents, their frequent association with a lake margin facies suggests that this environment provided a range of resources that attracted hominins.

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