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The oldest anthropoid primates in SE Asia: Evidence from LA-ICP-MS U–Pb zircon age in the Late Middle Eocene Pondaung Formation, Myanmar

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A B S T R A C T

The Late Middle Eocene Pondaung Formation, central Myanmar hosts the richest deposit of terrestrial mammals in SE Asia. The Pondaung Formation contains anthropoid primates, such as Eosimiidae, Amphipithecidae and the new Afrotarsiidae, plus adapiform primates and is a critical locality in discussions on anthropoid origins and biogeography. The sands of the Pondaung Formation were derived from the erosional unroofing of a dissected andesitic volcanic arc and deposited on the forested floodplains of a large tropical river. Previously, the age of the Pondaung Formation was estimated to be Middle to Late Eocene based on stratigraphic evidence, Late Middle Eocene (Bartonian) based on comparisons with mammals from North America and Europe, 37.2 ± 1.3 Ma and 38.8 ± 1.4 Ma based on fission track dating and 37.4–37.0 Ma based on questionable magnetostratigraphic correlations. Here, we report a new LA-ICP-MS, U–Pb age for zircons from a tuffaceous bed in the Pondaung Formation of 40.31 ± 0.65 Ma and 40.22 ± 0.86 Ma which is slightly older than the debatable magnetostratigraphic ages of 37–36 Ma and 38–39 Ma for the anthropoids from Egypt and Libya. Pending the acquisition of similarly reliable radiometric dates from all the North African and Asian sites, this new date provides support for an Asian origin for the anthropoids. Our new dates are close to the molecular clock date for the origin of the anthropoid primates and may provide a reliable calibration point for the molecular phylogenetic method.

1. Introduction

One of the most important questions in Palaeontology is the origin of the timing and migration of the earliest anthropoids (monkeys, apes and humans). The Late Middle Eocene Pondaung Formation, central Myanmar, is well known globally for its terrestrial mammal fossils which have contributed significant evidence to the debate on the origin and diversification of the anthropoids and other mammalian groups.

Since fossils were first reported by Cotter (1914) and Pilgrim and Cotter (1916), many terrestrial, mammalian fossils have been discovered in the Pondaung Formation (e.g., Takai et al., 2001; Tsubamoto et al., 2002; Takai et al., 2005; Tsubamoto et al., 2006 and references therein). In particular, the presence of a number of anthropoid primates, such as representatives of the Eosimiidae and Amphipithecidae, and adapiform primates, such as the Sivaladapidae, has long attracted the attention of palaeoprimatologists (e.g., Pilgrim, 1927; Colbert, 1937; Ba Maw et al., 1979; Ciochon et al., 1985; Beard et al., 1994; Ciochon and Holroyd, 1994; Beard et al., 1996; Jaeger et al., 1998, 1999; Ciochon et al., 2001; Takai et al., 2001; Ciochon and Gunnell, 2002, 2004; Jaeger et al., 2004; Jaeger and Marivaux, 2005; Takai et al., 2005). Until the last few decades, the oldest definite anthropoids were from North Africa, such as those from the Late Eocene–Early Oligocene Fayum Depression deposits of Egypt, which led to the suggestion of an African origin for the clade (e.g., Kappelman, 1992; Simons, 1995; Miller et al., 2005). In recent years, however, two anthropoid groups, the Eosimiidae and Amphipithecidae, have been discovered in Middle to Late Eocene localities of East and South Asia (e.g., Beard et al., 1994, 1996; Tong, 1997; Chaimanee et al., 1997; Marivaux et al., 2003; Seiffert et al., 2004; Marivaux et al., 2005; Miller et al., 2005; Beard et al., 2007; Marivaux et al., 2008; Beard et al., 2009) and several phylogenetic studies of Palaeogene and Neogene primates have indicated that the Eosimiidae and Amphipithecidae are amongst the oldest anthropoids (e.g., Kay et al., 1997; Ross et al., 1998; Kay et al., 2004a,b; Bajpai et al., 2008).

It is now known that all the earliest anthropoids are found not far from the shores of the Tethyan Ocean and adjacent tropical seas from North Africa, through India to China and South East Asia (Williams et al., 2010). Discoveries in Asia have led to the suggestion of an

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Asian origin (e.g., Jaeger et al., 1998). The oldest possible anthropoids are *Anthrasimias* from the Early Eocene of India and *Altiatlasius* from the Palaeocene of Morocco. However, neither of these genera is well-preserved and their anthropoid affinities are questionable (Williams et al., 2010; Chaimanee et al., 2012).

Recently, a new genus, *Afrasia* has been found in the Pondaung Formation which is "remarkably close" to *Afrotarsius* from the Late Middle Eocene of Libya (Chaimanee et al., 2012). *Afrasia* is placed with *Afrotarsius* in the new Afrotarsiidae within the basal anthropoid clade — the infraorder Eosimiiformes. *Afrasia* is dentally more primitive than the Libyan genus and Chaimanee et al. (2012) suggest that members of the Eosimiiformes dispersed across the Tethyan seas from Asia to Africa during the Middle Eocene. The Libyan *Afrotarsius* is dated as 39–38 Ma on the basis of magnetostratigraphic, biostratigraphic and geological methods (Jaeger et al., 2010).

It is noteworthy that most of the geologic ages of Afro-Asian anthropoid faunas are also estimated either on the basis of palaeontological comparisons of mammals or on less reliable and more easily re-set or debatable dating techniques such as fission track dating and magnetostratigraphy (e.g., Russell and Zhai, 1987; Kappelman, 1992). The age of the Pondaung Formation has been estimated to be Middle to Late Eocene based on stratigraphic evidence (e.g., Bender, 1983), or Late Middle Eocene (Bartonian) based on comparisons with mammals from North America and Europe (e.g., Colbert, 1938; Holroyd and Ciochon, 1994).

Benammi et al. (2002) conducted a magnetostratigraphic study of the Pondaung Formation and found that 74 of their 98 samples yielded a high temperature component. This component has a normal polarity through the formation which they correlated to chron C17n.1n, which has an age between 37.4 and 37 Ma at the Bartonian–Priabonian boundary. However, there is no geophysical reason for this correlation and correlation to older normal chrons is possible such as the C18n1n chron of 39 Ma or even a younger chron C16n2n at 36 Ma.

Apart from these palaeontological and magnetostratigraphic correlations, until recently, there have been no accurate geologic ages available for the Middle to Late Eocene terrestrial faunas in East and Southeast Asia because: (1) no volcanic deposits suitable for radiometric analysis have been found; and (2) none of the deposits, except for those in the Pondaung Formation, have intercalated marine deposits containing index fossils. Tsubamoto et al. (2002, 2009) recently reported a fission-track age of 37.2 ± 1.3 Ma and 38.8 ± 1.4 Ma based on zircon grains obtained from the tuffaceous bed of the Upper Member of the Pondaung Formation. This tuffaceous bed occurs in red claystones, which are located roughly at 300 m below the boundary of the Yaw and Pondaung Formations. The mammal fossils, including primates have been discovered in the same stratigraphic level from the sediments and/or above and below the tuffaceous bed (Suzuki et al., 2006). Here, we report LA-ICP-MS U–Pb zircon ages for this tuffaceous bed in the anthropoid bearing Upper Pondaung Formation which confirms the antiquity of the Pondaung fauna and, pending more robust dating from North Africa, helps support an Asian rather than African origin for the anthropoids.

2. Regional geological setting

Myanmar can be sub-divided into six N–S trending major tectonic domains from west to east: (1) The Arakan (Rakhine) Coastal Strip is an ensimatic fore-deep, (2) the Indo-Burman Ranges represent an outer-arc or fore-arc, (3) the Western Inner-Burman Tertiary Basin is considered to be an inter-arc basin, (4) the Central Volcanic Belt (Central Volcanic Line) represents an inner magmatic–volcanic arc, (5) the Eastern Inner-Burman Tertiary Basin formed as a back-arc basin and (6) the Shan-Tenasserim Massif occurring as the ensialic, Sino-Burman Ranges. The Sagaing Fault forms a tectonically significant boundary between the Eastern Inner-Burman Tertiary Basin (Back-Arc Basin) and the continental, ensialic Sino-Burman Ranges (Bender, 1983; Khin Zaw, 1989, 1990; Fig. 1).

The Arakan (Rakhine) coastal strip comprises Miocene molassic sedimentary rocks that extend northward into the Assam Basin of the Northeastern Indian Ocean (Kyi Khin et al., this issue). The Indo-Burman Ranges form an outer-arc or fore-arc and are underlain by Triassic turbidites and dismembered ophiolites in the east, and tightly folded turbidites of Cretaceous to Early Eocene age in the west. The Central lowlands or Central Basin contain a thickness of up to 15 km of dominantly Tertiary marine and fluviatile sedimentary rocks and are divided into the Western Inner-Burman Tertiary Basin (inter-arc trough) and the Eastern Inner-Burman Tertiary Basin (back-arc trough). Both basins are separated by the Inner Magmatic-Volcanic Arc that contains Cretaceous granitoid plutons (Barley et al., 2003) and the Miocene volcano-sedimentary rocks hosting high-sulfidation epithermal Cu ± Au deposits (e.g., Monywa) in central Myanmar. The Pondaung Formation occurs in the Western Inner-Burman Tertiary Basin (inter-arc trough) (Fig. 1).

3. Local geological and palaeoenvironmental setting

The Pondaung area is characterized by Cenozoic sedimentary rocks which made up a part of the Central Irrawaddy Lowland (Stamp, 1922; Bender, 1983). The Pondaung Formation is conformably overlain by the Yaw Formation (Late Eocene), Shwezetaw Formation (Early Oligocene) and Padaung Formation (Middle Oligocene) and unconformably overlain by the Irrawaddy Formation (Late Miocene–Pliocene) of fluviatile unconsolidated, poorly bedded to thinly bedded sandstone (Bender, 1983; Aye Ko Aung, 1999; Aung Naing Soe et al., 2002; Soe Thura Tun, 2004; Kyaw Linn Oo et al., 2009) (Fig. 2). The Pondaung Formation is underlain by the Tabyin Formation (not shown in Fig. 2) which consists mainly of marine claystones, yielding *Nummulites acutus*, a benthic foraminiferan of Middle Eocene age (Bender, 1983), while the overlying Yaw Formation is mainly composed of deltaic sedimentary rocks consisting of sandstone and shale, and yields benthic foraminifera (e.g., *Nummulites yawensis*, *Discocyclina sella* and *Operculina* sp. cf. *Operculina canalifera*) and molluscs (e.g., *Velates perversus*), which together indicate the Late Eocene (Bender, 1983). The Yaw Formation is overlain by the Shwezetaw Formation and Padaung Formation of shallow marine sandstone with infrequent shale horizons.

The Pondaung Formation is about 2000 m in thickness and consists of alternating mudstone, sandstone, and conglomerate, and is subdivided into the "Lower" and "Upper" Members (Aye Ko Aung, 1999). The "Lower Member," which is about 1500 m in thickness, is dominated by greenish pebbly, often cross-bedded sandstone and variegated mudstone and contains only a few fragments of fossil leaves in its upper part (Aye Ko Aung, 1999). The "Upper Member", which is about 500 m in thickness is dominated by fine- to medium-grained sandstone and multicoloured mudstone. Most of the terrestrial vertebrate fossils have been recovered from the lower half of the "Upper Member." The detailed stratigraphic setting of the Upper Member of the Pondaung Formation is shown in Fig. 3.

Earlier researchers considered the age of the Pondaung mammalian fauna as Late Eocene based on comparisons of the "evolutionary stages" of mammals (e.g., anthracotheres, ruminants, brontotheres, and amynodonts) with those from Europe and North America (e.g., Colbert, 1938; Russell and Zhai, 1987). Later, the Pondaung Formation was interpreted as Late Middle Eocene following the revision of the Eocene/Oligocene geologic time scale (e.g., Berggren et al., 1978; Berggren and Prothero, 1992; Prothero and Swisher, 1992; Holroyd and Ciochon, 1994).

More detailed studies on sedimentary facies associations and a palaeoenvironmental reconstruction of the Pondaung Formation have been undertaken by Aung Naing Soe et al. (2002). They recorded twelve lithofacies in the Pondaung Formation. The primate-bearing uppermost part of the Pondaung Formation, is transitional to the overlying Yaw Formation, and was deposited in a fluvio-deltaic sedimentary environment. Marsh, delta plain and prodelta deposits were recognized. They also showed that primate remains occur in swale-fill sediments,

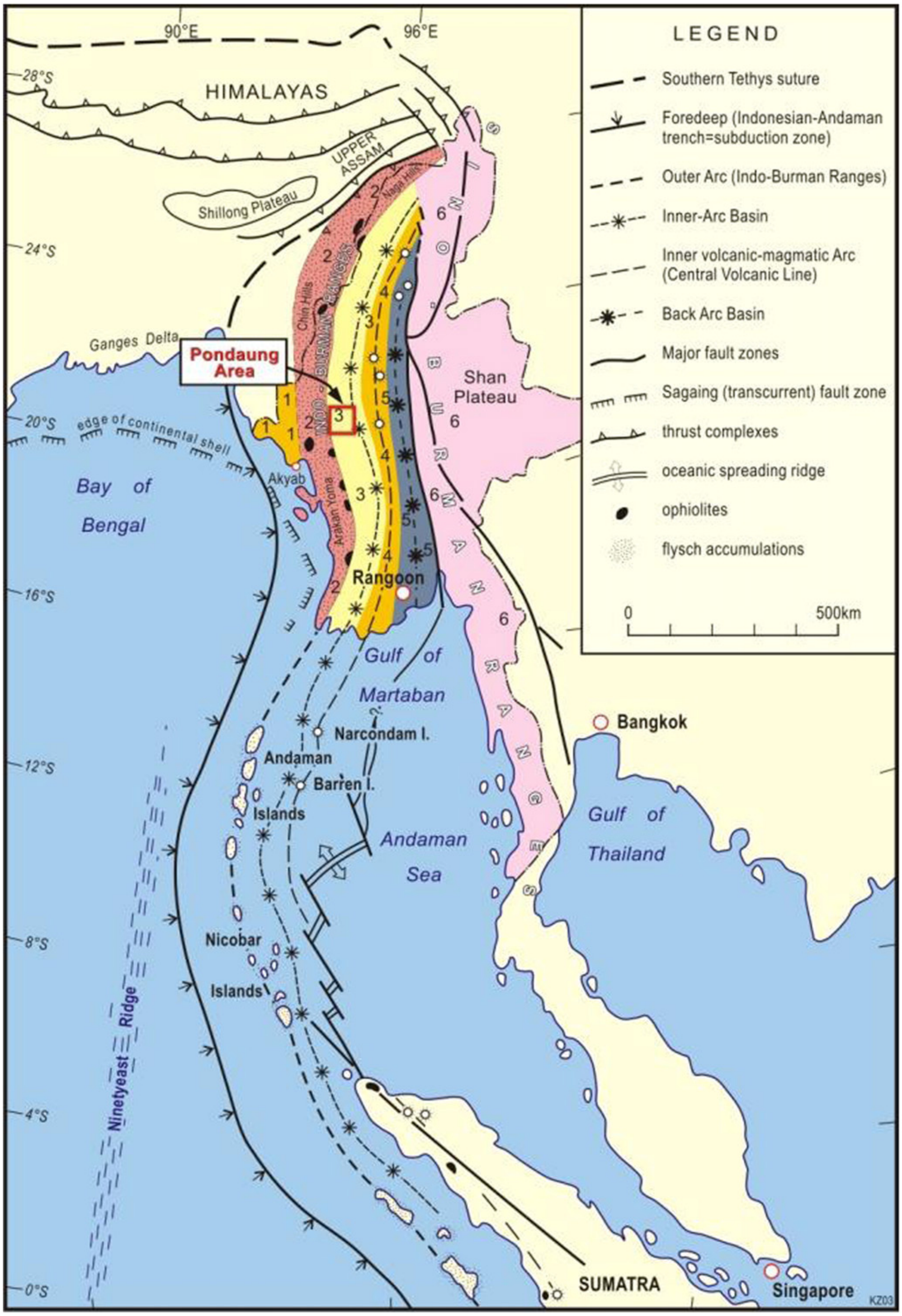

Fig. 1. Regional setting and location map of Pondaung area, Myanmar (after Bender, 1983; Khin Zaw, 1989, 1990). (1) The Arakan (Rakhine) Coastal Strip, (2) the Indo-Burman Ranges, (3) the Western Inner-Burman Tertiary Basin, (4) the Central Volcanic Belt (Central Volcanic Line), (5) the Eastern Inner-Burman Tertiary Basin and (6) the Shan-Tenasserim Massif. The Sagaing Fault forms a tectonically significant boundary between the Eastern Inner-Burman Tertiary Basin and the Sino-Burman Ranges. Note that primate fossil-bearing Pondaung Formation occurs in the Western Inner-Burman Tertiary Basin.

sometimes in carbonate nodules of pedogenic origin and in small crevasse channel deposits in the upper part of the Pondaung Formation. Maung Maung et al. (2005) and Suzuki et al. (2006) recently made a detailed study of the stratigraphic setting and sedimentological characteristics of the primate-bearing "Upper Member" of the Pondaung Formation in the Paukkaung area and also confirmed its fluvio-deltaic palaeoenvironment. Tsubamoto et al. (2006) showed that the Pondaung anthropoids lived in an environment dominated by humid/subhumid, forest/woodland vegetation growing on the well-drained flood plains of a large river system, located not far from the coast of the eastern Tethyan Sea. A forested environment is also supported by the presence of the postcranial skeletons of amphipithecid primates which were arboreal quadrupeds (Ciochon et al., 2001; Marivaux et al., 2003; Kay et al., 2004b; Tsubamoto et al., 2006). The Pondaung fossils are found

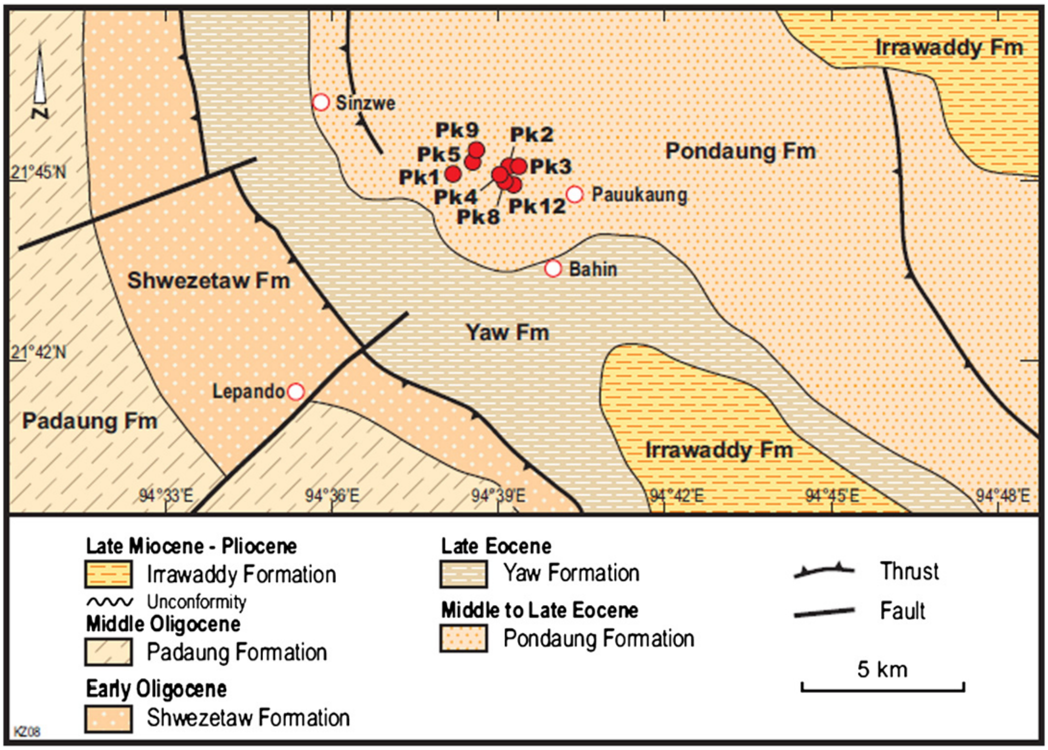

Fig. 2. Geological map of the Pondaung area showing the primate fossil localities and the sampling point of the tuffaceous sandstones (after Aung Naing Soe et al., 2002; Soe Thura Tun, 2004; Suzuki et al., 2006). Pk4 and Pk8 are the sampling points of the tuffaceous sandstones in this work. Pk1 (Sabapondaung Kyitchaung) is the sampling point of the tuffaceous sandstone for Fission Track dating (Tsubamoto et al., 2002). The word "Kyitchaung" stands for fossil locality in Burmese. The detailed stratigraphic locations of the fossil localities are shown in Fig. 3.

at a relatively low latitude (around 21° N at present) and the palaeolatitude was similar (28° ± 7°, Benammi et al., 2002) suggesting warm to hot palaeoclimatic conditions (Tsubamoto et al., 2006).

4. Methods and samples

Maung Maung et al. (2005) and Suzuki et al. (2006) initially studied the stratigraphic relations and positions of the primate fossil-bearing beds of Pk1, Pk2, Pk3, Pk4, Pk5, Pk8, Pk9 and Pk12 in the Paukkaung area and the detailed GPS locations are listed in Tsubamoto et al. (2006). These beds are located in the same stratigraphic level as the primate fossil localities of the Pondaung Formation (Figs. 2 and 3), of which Pk1 and Pk5 have been dated to be 37.2 ± 1.3 Ma and 38.8 ± 1.4 Ma by the fission track method (Table 1) (Tsubamoto et al., 2002, 2009). In this study, two medium-grained tuffaceous sandstone samples are studied from the Pk4 (4–8 East) and Pk8 (4–8 South) localities (see Suzuki et al., 2006 for details) (21° 45′N, 94° 39′E) to the NE of the village of Paukkaung and collected in February 2006. The tuffaceous sandstone samples are from the fossil-bearing Ayoedawpon Taung Claystone (Figs. 3 and 4) and the zircon grains are from a tuffaceous bed as shown in Fig. 4. This tuffaceous bed corresponds to the tuffaceous bed at the Pk1 and Pk5 localities, from which zircon grains were obtained in the previous fission track dating studies (Tsubamoto et al., 2002, 2009).

The LA-ICP-MS method is now widely used for measuring U, Th and Pb isotopic data and precise dating of U–Pb zircon ages (e.g., Fryer et al., 1993; Black et al., 2003, 2004; Jackson et al., 2004; Paton et al., 2010). In this study, we used an Agilent quadrupole ICP-MS with a 193 nm New Wave Laser at CODES, the University of Tasmania. We applied the following method: between 100 and 200 g of rock from each sample was repeatedly sieved and crushed to a grain size < 400 μm. Crushing was performed in a mortar and pestle or a Cr-steel ring mill depending on sample hardness. Heavy minerals were then separated using a gold pan. The heavy mineral residue was then dried. Magnetic and paramagnetic minerals were separated using a Fe–B–Nd magnet. About 20 to 60 zircons were picked from the non-magnetic heavy mineral separate using a single hair from a fine, artist's paint brush, and mounted on double sided sticky tape. Epoxy glue was then poured into a 2.5 cm diameter mould on top of the zircons. The mount was dried for 12 h and polished using clean sandpaper and a clean polishing lap. The samples were then washed in distilled water in an ultrasonic bath. Cathodoluminescence (CL) images of the zircons were also obtained to help with the interpretation of the U–Pb age data. The images were obtained using a FEI Quanta 600 SEM housed at the University of Tasmania (Fig. 5).

Analyses were performed two hours after ignition of the mass spectrometer to enable the machine to stabilise. Four primary (Temora standard of Black et al., 2004) and two secondary standards (91500 standard of Wiedenbeck et al., 1995) were analyzed at the beginning of the session and after every 12 unknown zircons (roughly every hour). Each analysis began with a 30 s blank gas measurement followed by a further 30 s of analysis time when the laser was switched on. Zircons were sampled on 30 μm spots using the laser at 5 Hz and a density of approximately 3 mJ/cm^2. A flow of He carrier gas at a rate of 0.7 l/min carried particles ablated by the laser out of the chamber to be mixed with Ar gas and carried to the plasma torch. Elements measured include ^{96}Zr, ^{146}Nd, ^{178}Hf, ^{202}Hg, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{238}U with each element being measured sequentially every 0.2 s.

The data reduction method used was based on that outlined in detail by Meffre et al. (2007). The average of the background count rates was subtracted from each isotope. Pb and U isotopic ratios were then calculated for each 0.2 s measurement. These ratios were filtered to exclude the top and bottom 1% to eliminate spikes and spurious data. Filtered ratios were then corrected for machine drift, downhole fractionation and mass bias as follows. The machine drift correction was calculated by fitting a line to the primary standard data measured throughout the day and checked by examining the secondary standard data. The downhole fractionation and mass bias correction factors were

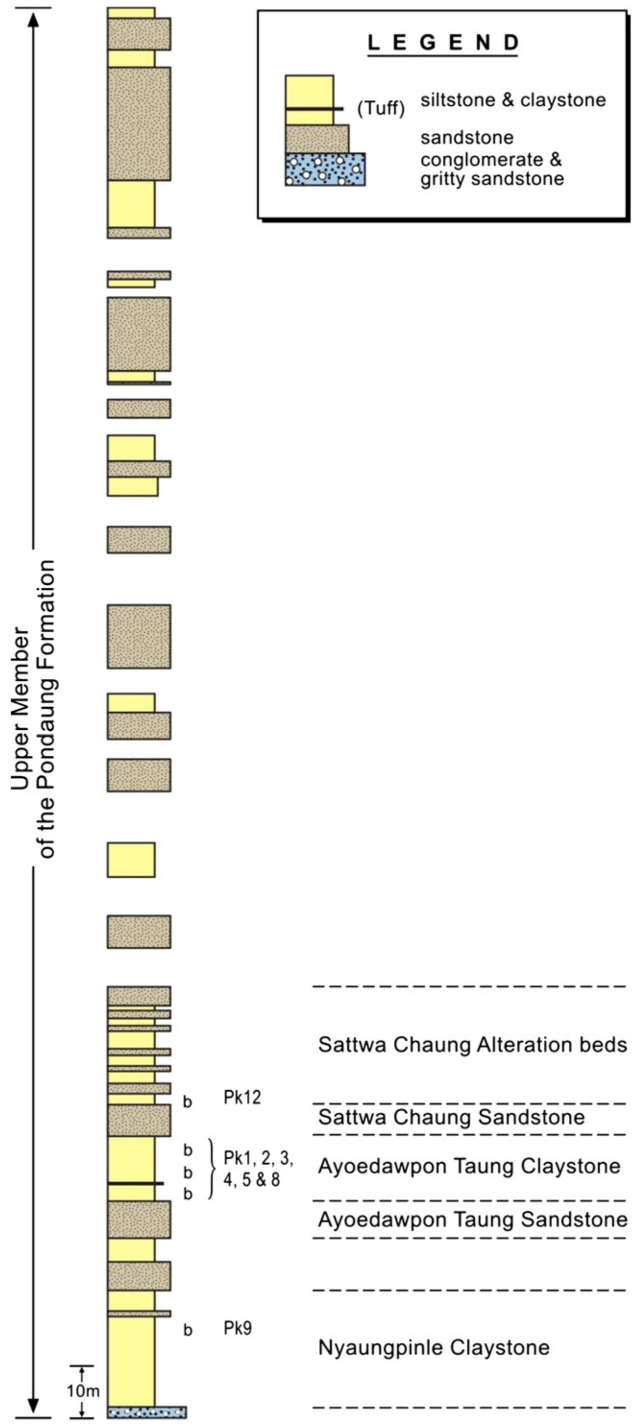

Fig. 3. Summarized columnar section of the Upper Member of the Pondaung Formation. 'b' denotes stratigraphic positions of the fossil localities in the Paukkaung area. Modified after Suzuki et al., 2006.

calculated by plotting the drift corrected ratios on each 0.2 s primary standard measurement. A line was fitted to the data to generate a standard downhole fractionation trend. This trend was used to calculate a set of correction factors which can be applied to the isotope ratios for each 0.2 s measurement on the samples.

After the corrections were applied to the ratios, radiometric ages were calculated for each 0.2 s measurement and plotted against the analysis time. An integration interval was then chosen for the most stable portion of the analysis, to exclude parts with contamination from inclusions. The standard errors quoted were based on the standard error of the measurements within the integration intervals and the errors on the measurement of the standards using similar techniques to that outlined in Paton et al. (2010) where the scatter in the individual primary standard zircons are used empirically to determine the standard error on the samples. Common Pb composition for the ^{207}Pb correction was estimated using the model of Stacey and Kramers (1975) and the uncorrected $^{206}Pb/^{238}U$ age for each individual zircon. For these relatively young zircons with only a small component of common Pb, this provides a relatively robust estimate of the common Pb composition. For samples with more significant common Pb component (e.g. inclusion rich zircons, sphene or apatite), more sophisticated methods of estimating the common Pb composition can be used (see appendix A in Chew et al. (2011) for further discussion). Element abundances were calculated using the method outlined by Kosler (2001) using Zr as the internal standard element, assuming stoichiometric proportions and using the secondary standard 91500 to correct for mass bias using trace element values from the GeoREM database (Black et al., 2003; Jochum and Nohl, 2008). The LA-ICP-MS U–Pb zircon age data in this study are shown in Table 1.

The samples were also analyzed for whole rock major and trace element chemical composition by X-Ray Fluorescence (XRF) method using a PANalytical (Philips) PW 1480 XRF spectrometer at the CODES, University of Tasmania. Major elements were measured from fusion discs, which were prepared at 1100°C in 5%Au/95%Pt crucibles using 0.500 g of sample, 4.500 g of 12–22 Flux (lithium tetraborate–metaborate mix) and 0.0606 g of $LiNO_3$, following the techniques described by Watson (1996) and Robinson (2003).

5. Petrography and LA-ICP-MS results

The unconsolidated sandy materials from Pk4 and 8 were mounted, thin sectioned and examined under the microscope. The samples contain poorly sorted and angular to sub-angular sand-sized grains 10–500 μm in size averaging around 80 μm. The dominant clast population (55 vol.%) is weathered brown glassy volcanic fragments with rare plagioclase micro-phenocrysts. A small proportion of these are vesicular or pumiceous. The samples also contain clasts (25 vol.%) of intermediate felsic volcanics with abundant microlitic plagioclase in a fine-grained devitrified groundmass. Monocrystalline crystals of volcanic quartz (5 vol.%), magnetite (3 vol.%) and feldspar (2 vol.%) are also present. The remainder of the clasts are non-volcanic and include muscovite-quartz schists (5 vol.%), biotite schist (1 vol.%), carbonate fragments (1 vol.%) and polycrystalline quartz (3 vol.%).

The results of the LA-ICP-MS U–Pb zircon study are presented in Table 2. The CL images (Fig. 5) show that the zircons are oscillatory zoned euhedral crystals with characteristics typical of zircons formed in magmatic environments. Some of the crystals show evidence for multiple episodes of growth in a magmatic environment with resorption and dissolution of earlier formed crystals. In some crystals, this can be shown to have occurred late in their growth history as only very thin rims have grown after the resorption. Most of the crystals were analyzed on the larger central zone of the crystals rather than on the rim. Tera-Wasserburg U–Pb zircon concordia plots for the samples are shown in Fig. 6. The zircon from the Pk4 (PK4-8 East) and Pk8 (PK4-8 South) samples yielded absolute ages of 40.31 ± 0.65 Ma (MSWD = 1.6) and 40.22 ± 0.86 Ma (MSWD = 1.8) (Fig. 6).

The sandstone petrography indicates that most of the clasts in the beds near the anthropoid fossils are derived from a single aphyric, volcanic unit of intermediate composition. However, the subordinate volcanic

Table 1
Previous fission-track ages obtained from the Upper Member of the Pondaung Formation. Pk1 and Pk5 are the localities in the Paukkaung area as indicated in Fig. 2.

Locality/name	FT age	Reference
Pk-1	37.2 ± 1.3	Tsubamoto et al. (2002)
Pk-5	38.8 ± 1.4	Tsubamoto et al. (2009)

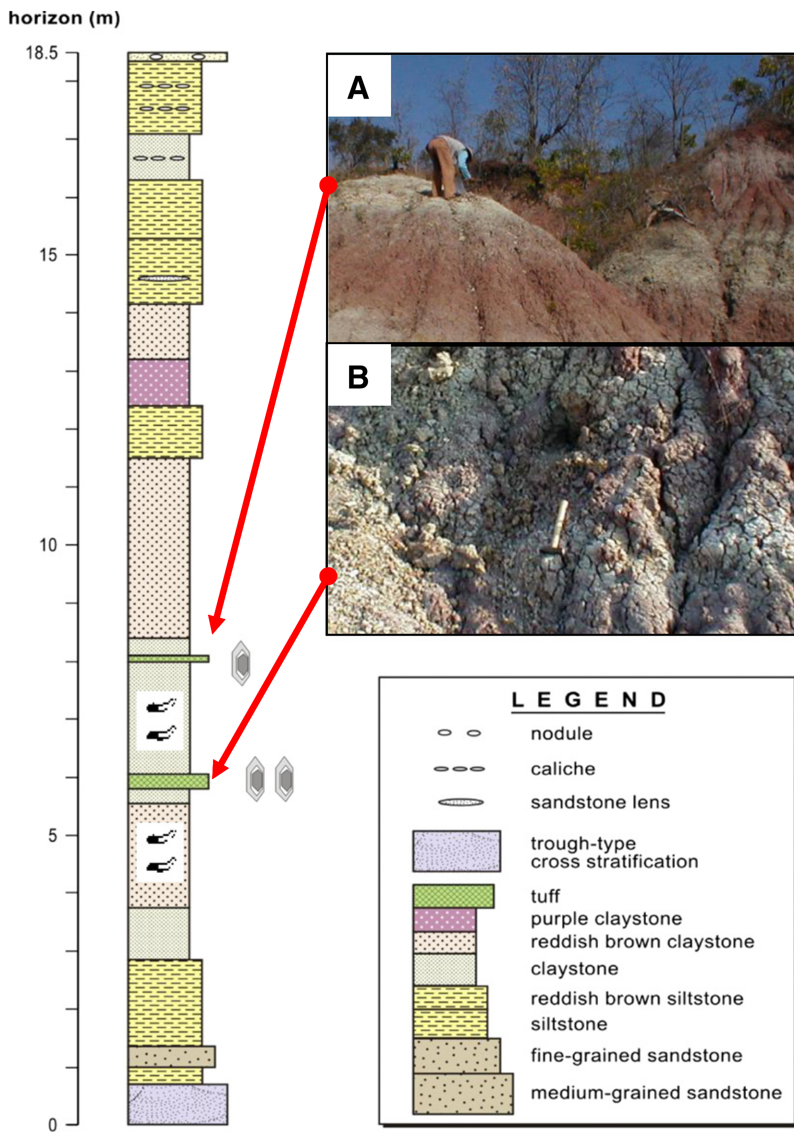

Fig. 4. Detailed stratigraphic section of the Upper Member of the Pondaung Formation showing a detailed columnar section at the Pk4 locality in the Paukkaung area (unpublished data of Hisashi Suzuki and Maung Maung). A. Location of the tuffaceous unit, B. close-up of A.

quartz and schist fragments indicate that other rocks were also supplying material to the basin. Geochemical analyses of the Upper Pondaung tuffaceous sandstones at Paukkaung, which occur above and below the primate-bearing beds, are found to be of andesitic composition (Table 3, Fig. 7) and plot with other intermediate to felsic volcaniclastic sandstone units of the Pondaung Formation from just further north in the Chindwin Basin. Kyaw Linn Oo et al., 2009 established that the Pondaung sandstones were derived from a transitional to dissected magmatic arc, based on sandstone modal analysis, palaeocurrents and provenance studies combined with XRF-immobile trace element and LA-ICP-MS U–Pb zircon geochronology. They also recognized that the arc-related volcaniclastic units of the Pondaung sandstones originated along a convergent continental margin in the Early Middle Eocene (Lutetian) and their detritus was deposited of the Central Myanmar Basin (Kyaw Linn Oo et al., 2009). It is evident that the detrital material in the clastic sequences of the northern Central Myanmar Basin reveals an erosional unroofing history of a calc-alkaline, continental magmatic arc during the fluvial sedimentation of the Pondaung Formation in the Late Middle Eocene (Bartonian) (Allen et al., 2008; Kyaw Linn Oo et al., 2009). These petrological and geochemical data are consistent with the stratigraphic and sedimentological evidence of a fluvio-deltaic palaeoenvironment for the Pondaung primate fossil localities (Aung Naing Soe et al., 2002; Maung Maung et al., 2005).

6. Discussion

The age of deposition of the Pondaung Formation is now constrained by four data sets:

1. The Eocene biostratigraphy above and below the primate fossils.
2. The possible magnetostratigraphic correlation to normal polarity chron C17n1n of 37 Ma
3. The Middle to Late Eocene fission track ages on the zircons.
4. The Late Middle Eocene U–Pb zircon age from the Pk4 and Pk8 localities.

The age of 37.2 ± 1.3 Ma fission-track zircon ages (1 sigma Tsubamoto et al., 2002) is close to the 2 sigma error envelope of the 40.2 ± 0.5 (weighted average of youngest 28 zircons from two samples). Another fission-track date (38.8 ± 1.4) obtained from the Upper Member of the Pondaung Formation (Tsubamoto et al., 2009), has almost the same age as the previous one (Table 2).

The obtained fission-track ages correspond to at a level or just above the Middle and Late Eocene (Lutetian–Bartonian) boundary and are also in agreement with the results of the quantitative comparisons of the Pondaung fauna with other Middle to Late Eocene mammal faunas in East Asia (Tsubamoto et al., 2004). Although there are some

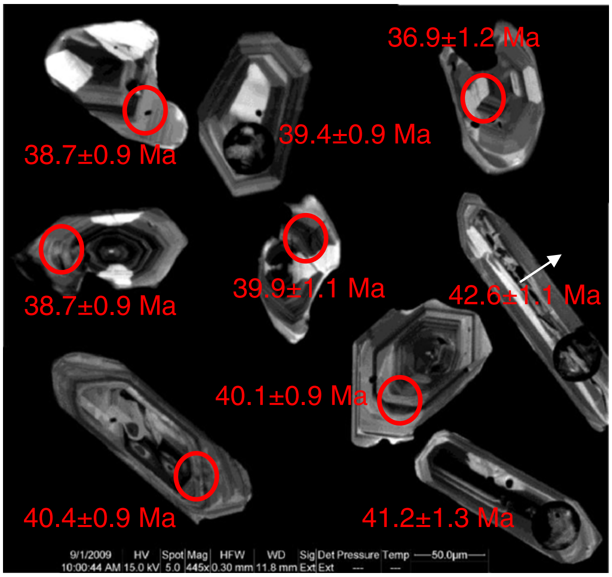

Fig. 5. SEM cathodoluminescence images of zircons from the tuffaceous unit in the Upper Pondaung Formation. White arrow shows area where evidence of truncation and resorption is present. Circular shapes on the crystals are the laser ablation pits where the zircon was analyzed.

absolute ages obtained from the Palaeocene and Early Eocene of China (Russell and Zhai, 1987; Meng et al., 1998; Wang et al., 1998) and North America and from the Oligocene of Mongolia and Inner Mongolia (Evernden et al., 1964; Russell and Zhai, 1987; Meng and McKenna, 1998), this is the first report of a radiometric age from Middle to Late Eocene vertebrate-bearing sediments of SE Asia. In this study, most of the zircons analyzed are concordant or near concordant and plot slightly above concordia due to the presence of a small amount of non-radiogenic Pb (common Pb) (Fig. 6). The zircon U–Pb data from both tuffaceous sandstones suggest two separate phases of zircon formation with the majority of the crystals forming between 40 and 41 Ma and a small proportion (22%) forming 6–8 Ma earlier at 46–48 Ma.

The age difference between fission track and the U–Pb age is therefore 2.7 ± 2.6 Ma (errors added in quadrature) which suggests that the small difference between the two ages is likely to be significant. The age difference, though small, is significant at the 95% confidence level. If the uncertainties in either of the two techniques are even slightly underestimated then the difference between the two techniques will become insignificant. However, there could also be geological reasons for the slight disagreement such as the detrital grain samples in the two studies could have included slightly older detrital zircon grains. Both techniques rely on eruption and erosion of nearby volcanoes and are likely to offer maximum ages for the sandstone rather than dating the deposition of the sediments. The primate-bearing beds are mostly

Table 2
LA-ICP-MS U–Pb analytical results of dating on zircons from the tuffaceous bed in the primate fossil-bearing "Upper Member" of the Pondaung Formation at the pk4 and Pk8 localities as indicated in Fig. 2.

Sample no	$^{206}Pb/^{238}U$ age (Ma)		$^{206}Pb/^{238}U$		$^{208}Pb/^{232}Th$		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		Nd	Hf	Pb	Th	U	Th/U
Analysis no	^{207}Pbcor	+/− 1SE	Ratio	%rse	Ratio	%rse	Ratio	%rse	Ratio	%rse	Ppm	Ppm	Ppm	Ppm	Ppm	
Pk4																
jl04G5	**36.9**	**1.2**	0.0065	2.8%	0.0035	6.8%	0.137	9.4%	0.120	8.9%	2	9329	1	88	115	0.8
jl04G4	**38.7**	**0.9**	0.0063	2.2%	0.0027	5.6%	0.076	8.7%	0.062	8.0%	36	9465	1	92	152	0.6
jl04G2	**39.4**	**0.9**	0.0062	2.1%	0.0019	6.6%	0.054	9.3%	0.041	9.1%	3	9217	1	111	165	0.7
jl04G1	**39.5**	**1.0**	0.0067	2.3%	0.0033	5.6%	0.107	7.0%	0.097	7.0%	91	9310	2	188	247	0.8
jl04G3	**39.5**	**0.6**	0.0061	1.5%	0.0020	3.2%	0.047	5.9%	0.039	5.6%	11	9097	3	390	379	1.0
JN27f11	**39.9**	**1.1**	0.0064	2.6%	0.0023	7.5%	0.075	10.1%	0.059	9.6%	2	9082	1	68	109	0.6
JN27f1	**40.1**	**0.9**	0.0063	2.1%	0.0021	5.0%	0.061	7.3%	0.051	7.1%	2	8977	2	224	275	0.8
JN27f6	**40.4**	**0.9**	0.0064	2.2%	0.0022	4.5%	0.062	8.7%	0.052	7.7%	4	8824	2	176	201	0.9
jl04G6	**40.4**	**0.9**	0.0063	2.1%	0.0022	6.5%	0.047	10.1%	0.039	10.1%	3	9066	1	107	193	0.6
JN27f5	**40.9**	**1.2**	0.0067	2.6%	0.0028	5.7%	0.083	8.8%	0.071	8.4%	10	8604	1	100	134	0.7
JN27f3	**41.2**	**1.3**	0.0066	2.8%	0.0028	10%	0.072	13.9%	0.056	12.7%	1	8352	1	34	85	0.4
JN27f7	**41.3**	**1.1**	0.0065	2.5%	0.0019	7.4%	0.052	11.0%	0.043	10.9%	2	8386	1	70	135	0.5
JN27f10	**41.4**	**1.1**	0.0066	2.5%	0.0022	6.6%	0.062	9.2%	0.052	8.6%	2	9089	1	81	138	0.6
JN27f8	**41.5**	**0.9**	0.0065	2.0%	0.0020	4.1%	0.052	8.9%	0.041	8.0%	7	9846	2	252	229	1.1
JN27f2	**41.7**	**1.1**	0.0065	2.6%	0.0021	5.6%	0.044	11.6%	0.034	11.2%	6	8769	1	114	178	0.6
JN27f9	**42.6**	**1.1**	0.0067	2.5%	0.0020	8.2%	0.055	12.1%	0.045	11.0%	1	8534	1	57	124	0.5
JN27f4	47.5	1.0	0.0075	2.0%	0.0023	3.9%	0.053	8.0%	0.051	7.3%	9	9098	2	250	245	1.0
JN27f12	48.0	0.9	0.0077	1.8%	0.0033	4.3%	0.072	6.2%	0.071	5.8%	1	10,845	2	131	222	0.6
Pk 8																
JN27g4	**37.2**	**1.1**	0.0060	2.8%	0.0020	9.8%	0.070	12.0%	0.047	10.8%	1	8695	1	42	92	0.5
JN27g9	**37.7**	**1.5**	0.0060	3.6%	0.0023	11%	0.069	16.4%	0.049	16.2%	1	9465	1	60	110	0.5
JN27g11	**38.9**	**1.0**	0.0061	2.6%	0.0018	8.8%	0.048	11.6%	0.039	11.3%	2	9738	1	55	103	0.5
JN27g6	**39.8**	**1.0**	0.0063	2.3%	0.0022	7.0%	0.055	11.1%	0.043	10.8%	3	8802	1	69	112	0.6
JN27g12	**39.8**	**0.9**	0.0062	2.1%	0.0024	6.5%	0.053	9.8%	0.043	9.6%	1	9716	1	74	164	0.5
JN27g7	**39.8**	**1.0**	0.0062	2.3%	0.0019	6.2%	0.051	10.3%	0.042	9.7%	4	9441	1	107	153	0.7
JN27g10	**39.9**	**1.1**	0.0062	2.6%	0.0018	7.5%	0.040	15.5%	0.027	14.9%	1	9646	1	84	121	0.7
JN27g5	**40.4**	**0.8**	0.0063	1.9%	0.0017	4.8%	0.049	8.3%	0.042	8.2%	3	8976	2	231	242	1.0
jl04H5	**40.5**	**1.0**	0.0063	2.4%	0.0019	8.5%	0.042	13.2%	0.036	12.4%	1	9358	1	71	124	0.6
JN27g8	**41.2**	**1.0**	0.0065	2.3%	0.0019	8.7%	0.057	10.7%	0.045	10.4%	3	9492	1	58	124	0.5
jl04H1	**41.8**	**1.2**	0.0065	2.7%	0.0019	8.0%	0.041	12.5%	0.035	12.4%	2	8875	1	110	178	0.6
jl04H6	**42.3**	**0.9**	0.0066	2.0%	0.0020	6.3%	0.053	9.8%	0.046	9.4%	3	9317	1	83	118	0.7
jl04H3	44.1	0.9	0.0070	1.9%	0.0023	5.8%	0.064	6.8%	0.061	6.7%	13	9877	1	93	145	0.6
JN27g2	45.1	1.1	0.0071	2.3%	0.0023	6.7%	0.056	10.1%	0.052	9.9%	2	9900	1	67	103	0.7
jl04H4	45.5	0.7	0.0072	1.6%	0.0025	3.1%	0.058	5.6%	0.058	5.4%	17	9680	3	355	383	0.9
JN27g1	46.1	0.8	0.0074	1.6%	0.0025	2.9%	0.067	5.4%	0.066	5.4%	193	10,199	4	526	429	1.2
jl04H2	46.7	0.7	0.0074	1.5%	0.0026	3.9%	0.059	5.1%	0.058	5.2%	12	9407	4	249	475	0.5
JN27g3	48.4	1.4	0.0075	2.8%	0.0019	10%	0.039	17.2%	0.037	16.5%	1	9551	1	36	77	0.5

Numbers in bold were used for age calculations.
SE: Standard error.
^{207}Pbcor: ^{207}Pb corrected $^{206}Pb/^{238}U$ age.

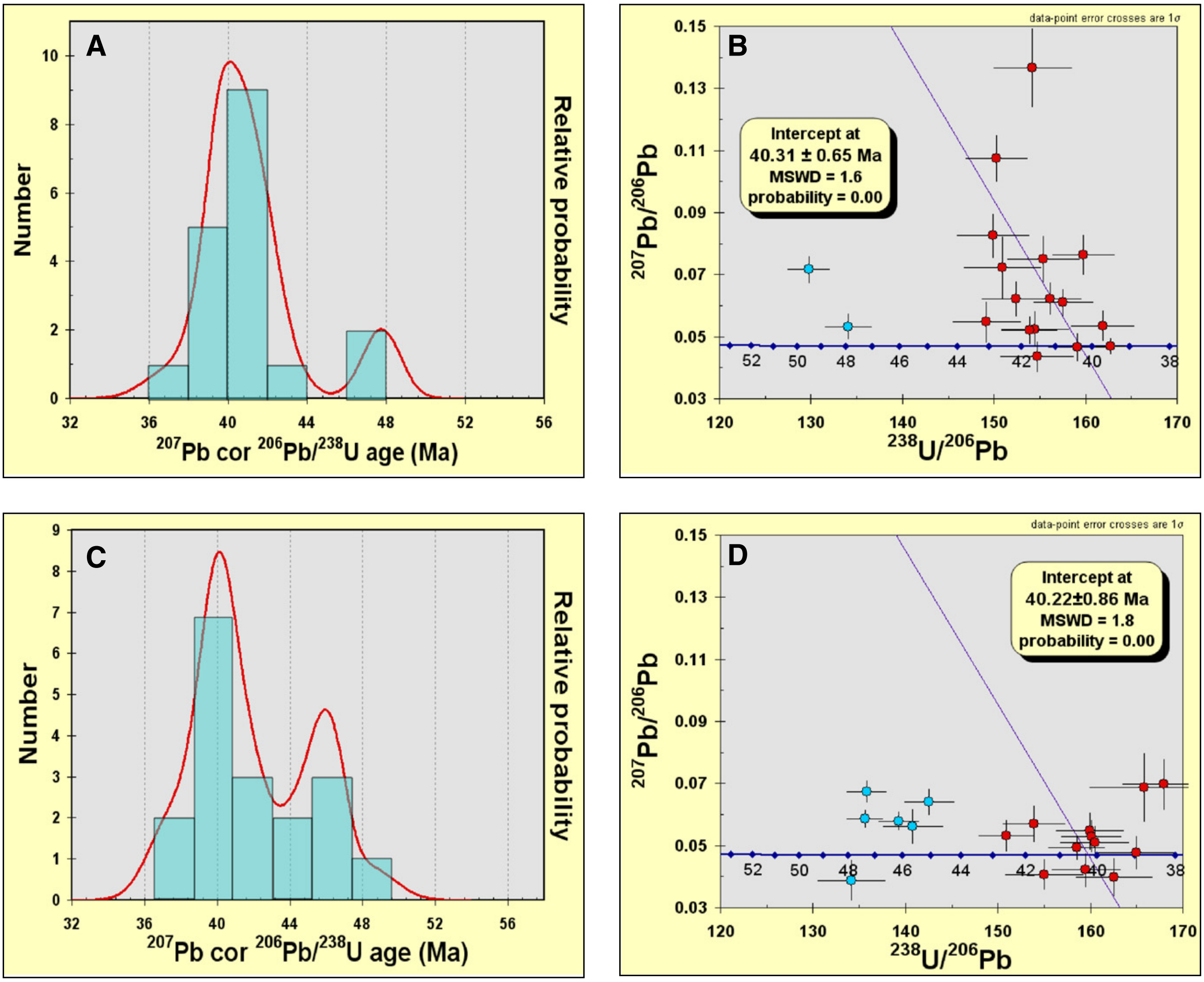

Fig. 6. Tera-Wasserburg U–Pb zircon concordia plots for the Pk4 and Pk8 samples from the Upper member of Pondaung Formation.

below the volcanic sandstone suggesting the age of the fossil primates will be older. The possibility that the primates could have been killed by a volcanic eruption, or associated environmental effects, needs to be investigated later, but the stratigraphic and zircon dating evidence clearly indicates that the Pondaung contains the oldest fossil primates in SE Asia.

Recent studies on primate molecular divergence rates have placed the origin of the anthropoids at before 42.9 Ma (Steiper and Young, 2006) and 43.5 Ma (Perelman et al., 2011). Our provision of a reliable date for the Pondaung fauna may help in calibrating the molecular clock with the geological time scale.

7. Conclusions

The anthropoid-bearing Pondaung Formation contains zircons that give ages of 40.31 $\pm$ 0.65 Ma and 40.22 $\pm$ 0.86 Ma providing one of the few reliable and accurate dates on Eocene anthropoid bearing formations. The oldest definite anthropoids are all Middle Eocene. The anthropoids from the Fayum Depression, Egypt are dated, using magnetostratigraphy and graphic correlation, as close to the base of Chron C17n which in turn is dated as 37.24 Ma (Seiffert et al., 2008). The Libyan anthropoid fauna is estimated at 38 Ma based on magnetostratigraphy and biostratigraphy (Jaeger et al., 2010). However, as with the magnetostratigraphic correlation of the Pondaung Formation the Libyan Dur At-Talah section yields a single (normal) polarity chron which could be correlated with any of several normal chrons in the Eocene. Thus, the anthropoids from the Pondaung Formation may be a few million years older than the oldest definite North African anthropoids and our new date may support arguments for an Asian origin of the anthropoids (Ciochon et al., 1985; Jaeger et al., 1999, 2010; Chaimanee et al., 2012). However, a final resolution of the origin of the anthropoids in either Asia or Africa must await the accurate dating of all the anthropoid bearing sections.

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Table 3
Whole rock XRF major and trace element compositions of Pk4 and Pk8.

Wt.%	Pk4	Pk8
SiO_2	57.09	56.01
TiO_2	0.95	1.02
Al_2O_3	14.89	15.68
Fe_2O_3	4.61	6.82
MnO	0.11	0.04
MgO	2.03	1.77
CaO	2.83	2.20
Na_2O	1.32	1.26
K_2O	0.88	1.09
P_2O_5	0.24	0.56
Loss	14.64	13.59
Total	99.66	100.11
S	<0.01	<0.01
Ppm	**Pk4**	**Pk8**
Sc	16	17
Ba	172	169
V	74	93
Cr	27	34
Ni	37	34
Cu	35	42
Zn	80	86
As	24	17
Rb	38	49
Sr	129	126
Y	100	184
Zr	217	240
Nb	11	11
Sn	3	<2
Pb	25	24
Bi	<2	<2
U	10	22
Th	5	10
La	66	87
Ce	179	239
Nd	113	163

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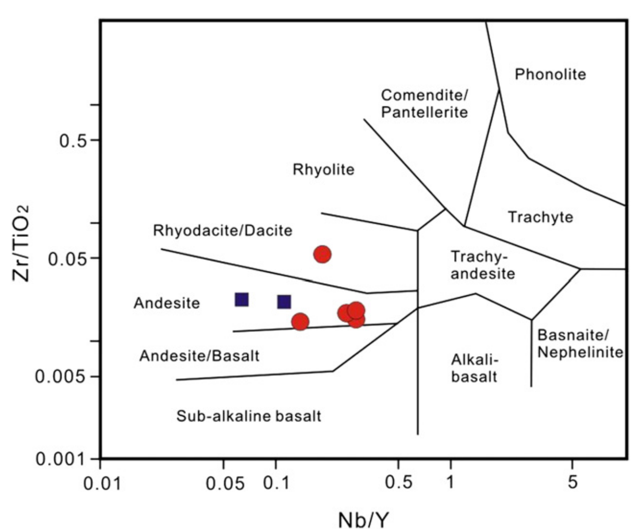

Fig. 7. Zr/TiO_2 vs Nb/Y plot of tuffaceous sandstone (Pk4 and Pk8) from the Paukkaung area (square) together with volcaniclastic sandstone and breccia (circle) from further north in the Chindwin Basin.
Modified after Kyaw Linn Oo et al., 2009.

References

Allen, R., Najman, Y., Carter, A., Barfod, D., Bickle, M., Chapman, H., Garzanti, E., Vezzoli, C., Ando, S., Parrish, R., 2008. Provenenance of the tertiary sedimentary rocks of the Indo-Burman Ranges, Burma (Myanmar): Burman Arc or Himalayan derived? Journal of the Geological Society 165, 1045–1057.

Aung Naing Soe, Myitta, Soe Thura Tun, Aye Ko Aung, Tin Thein, Marandat, B., Ducrocq, S., Jaeger, J.-J., 2002. Sedimentary facies of the lateMiddle Eocene Pondaung Formation (centralMyanmar) and the paleoenvironments of its anthropoid primates. General Palaeontology 1, 153–160.

Aye Ko Aung, 1999. Revision on the stratigraphy and age of the primates-bearing Pondaung Formation. In: Pondaung Fossil Expedition Team (Ed.), Proceedings of the Pondaung Fossil Expedition Team. Office of Strategic Studies, Ministry of Defence, Yangon, Myanmar, pp. 131–151.

Ba Maw, Ciochon, R.L., Savage, D.E., 1979. Late Eocene of Burma yields earliest anthropoid primate, Pondaungia cotteri. Nature 282, 65–67.

Bajpai, S., Kay, R.F., Williams, B.A., Das, D.P., Kapur, V., Tiwari, B.N., 2008. The oldest Asian record of Anthropoidea. Proceedings of the National Academy of Sciences of the United States of America 105, 11093–11098.

Barley, M.E., Khin Zaw, Pickard, A.L., Rak, P., Doyle, M.G., 2003. Jurassic to Miocene magmatism and metamorphism in the Mogok metamorphic belt: implications for the India-Eurasia collision in Myanmar. Tectonics 22, 1019–1030.

Beard, K.C., Qi, T., Dawson, M.R., Wang, B., Li, C., 1994. A diverse new primate fauna from middle Eocene fissure-fillings in southeastern China. Nature 368, 604–609.

Beard, K.C., Tong, Y., Dawson, M.R., Wang, J., Huang, X., 1996. Earliest complete dentition of an anthropoid primate from the late middle Eocene of Shanxi Province, China. Science 272, 82–85.

Beard, K.C., Marivaux, L., Soe Thura Tun, Aung Naing Soe, Chaimanee, Y., Wanna Htoon, Marandat, B., Htun Htun Aung, Jaeger, J.-J., 2007. New sivaladapid primates from the Eocene Pondaung Formation of Myanmar and the anthropoid status of Amphipithecidae. Bulletin Carnegie Museum Natural History 39, 67–76.

Beard, K.C., Marivaux, L., Chaimanee, Y., Jaeger, J.-J., Marandat, B., Tafforeau, P., Aung Naing Soe, Soe Thura Tun, Aung Aung Kyaw, 2009. A new primate from the Eocene Pondaung Formation of Myanmar and the monophyly of Burmese amphipithecids. Proceedings of the Royal Society B 276, 3285–3294. http://dx.doi.org/10.1098/rspb.2009.0836.

Benammi, M., Aung Naing Soe, Than Tun, Bo Bo, Chaimanee, Y., Ducrocq, S., Tin Thein, Jaeger, J.-J., 2002. First magnetostratigraphic study of the Pondaung Formation: implications for the age of the Middle Eocene anthropoids of Myanmar. Journal of Geology 110, 748–756.

Bender, F., 1983. Geology of Burma. Borntraeger, Berlin 293.

Berggren, W.A., Prothero, D.R., 1992. Eocene–Oligocene climatic and biotic evolution: an overview. In: Prothero, D.R., Berggren, W.A. (Eds.), Eocene–Oligocene Climatic and Biotic Evolution. Princeton University Press, Princeton, pp. 1–28.

Berggren, W.A., McKenna, M.C., Hardenbol, J., Obradovich, J.D., 1978. Revised Paleogene polarity time scale. Journal of Geology 86, 67–81.

Black, L.P., Kamo, S.L., Allen, C.M., Aleinikoff, J.N., Davis, D.W., Korsch, R.J., Foudoulis, C., 2003. TEMORA 1: a new zircon standard for Phanerozoic U–Pb geochronology. Chemical Geology 200, 155–170.

Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., Mundil, R., Campbell, I.H., Korsch, R.J., Williams, I.S., Foudoulis, C., 2004. Improved $^{206}Pb/^{238}U$ microprobe geochronology by the monitoring of a trace-element related matrix effect; SHRIMP, ID-TIMS, ELA-ICP-MS, and oxygen isotope documentation for a series of zircon standards. Chemical Geology 205, 115–140.

Chaimanee, Y., Suteethorn, W., Jaeger, J.-J., Ducrocq, S., 1997. A new Late Eocene anthropoid primate from Thailand. Nature 385, 429–431.

Chaimanee, Y., Chavasseau, O., Beard, C., Aung Aung Kyaw, Aung Naing Soe, Chit Sein, Lazzari, V., Marivaux, L., Marandat, B., Min Swe, Rugbumrung, M., Thit Lwin, Valentin, X., Zin Maung Maung Thein, Jaeger, J.-J., 2012. Late Middle Eocene primate from Myanmar and the initial anthropoid colonization of Africa. Proceedings of the National Academy of Sciences of the United States of America. http://dx.doi.org/10.1073/pnas.1200644109 (www.pnas.org/cgi).

Chew, D.M., Sylvester, P.J., Tubrett, M.N., 2011. U–Pb and Th–Pb dating of apatite by LA-ICPMS. Chemical Geology 280, 200–216.

Ciochon, R.L., Gunnell, G.F., 2002. Eocene primates from Myanmar: historical perspectives on the origin of Anthropoidea. Evolutionary Anthropology 11, 156–168.

Ciochon, R.L., Gunnell, G.F., 2004. Eocene large-bodied primates of Myanmar and Thailand: morphological considerations and phylogenetic affinities. In: Ross, C.F., Kay, R.F. (Eds.), Anthropoid Origins: New Visions. Kluwer/Plenum Publishers, New York, pp. 249–282.

Ciochon, R.D., Holroyd, P.A., 1994. The Asian origin of Anthropoidea revisited. In: Fleagle, J.G., Kay, R.F. (Eds.), Anthropoid Origins. Plenum Press, New York, pp. 143–162.

Ciochon, R.L., Savage, D.E., Thaw Tint, Ba Maw, 1985. Anthropoid origins in Asia? New discovery of *Amphipithecus* from the Eocene of Burma. Science 229, 756–759.

Ciochon, R.L., Gingerich, P.D., Gunnell, G.F., Simmon, E.L., 2001. Primate postcrania from the late Middle Eocene of Myanmar. Proceedings of the National Academy of Sciences of the United States of America 98, 7672–7677.

Colbert, E.H., 1937. A new primate from the upper Eocene Pondaung Formation of Burma. American Museum Novitates 951, 1–18.

Colbert, E.H., 1938. Fossil mammals from Burma in the American Museum of Natural History. Bulletin of the American Museum of Natural History 74, 255–436.

Cotter, G. de P., 1914. Some newly discovered coal seams near the Yaw River, Pakokku district, Upper Burma. Records of the Geological Survey of India 44, 163–185.

Evernden, J.F., Savage, D.E., Curtis, G.H., James, G.T., 1964. Potassium–argon dates and the Cenozoic mammalian chronology of North America. American Journal of Science 262, 145–198.

Fryer, B.J., Jackson, S.E., Longerich, H.P., 1993. The application of laser Ablation Microprobe-Inductively Coupled Plasma-Mass Spectrometry (LAM-ICP-MS) to in situ (U)–Pb geochronology. Chemical Geology 109, 1–8.

Holroyd, P.A., Ciochon, R.L., 1994. Relative ages of Eocene primate-bearing deposits of Asia. In: Fleagle, J.G., Kay, R.F. (Eds.), Anthropoid Origins. Plenum Press, New York, pp. 123–141.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. Chemical Geology 211, 47–69.

Jaeger, J.-J., Marivaux, L., 2005. Shaking the earliest branches of anthropoid primate evolution. Science 310, 244–245.

Jaeger, J.-J., Aung Naing Soe, Aye Ko Aung, Benammi, M., Chaimanee, Y., Ducrocq, R.-M., Than Tun, Tin Thein, Ducrocq, S., 1998. New Myanmar middle Eocene anthropoids. An Asian origin for catarrhines? Comptes Rendus de l'Academie des Sciences de Paris 321, 953–959.

Jaeger, J.-J., Tin Thein, Benammi, M., Chaimanee, Y., Aung Naing Soe, Thit Lwin, Than Tun, San Wai, Ducrocq, S., 1999. A new primate from the middle Eocene of Myanmar and the Asian early origin of anthropoids. Science 286, 528–530.

Jaeger, J.-J., Chaimanee, Y., Tafforeau, P., Ducrocq, S., Aung Naing Soe, Marivaux, L., Sudre, J., Soe Thura Tun, Wanna Htoon, Marandat, B., 2004. Systematics and paleobiology of the anthropoid primate Pondaungia from the late middle Eocene of Myanmar. Comptes Rendus Palevol 3, 241–253.

Jaeger, J.-J., Beard, C., Chaimanee, Y., Salem, M., Benammi, M., Hlal, O., Coster, P., Bilal, A.A., Duringer, P., Schuster, M., Valentin, X., Marandar, B., Marivaux, L., Metais, E., Hammuda, O., Brunet, M., 2010. Late middle Eocene epoch of Libya yields earliest known radiation of African anthropoids. Nature 467, 1095–1098.

Jochum, K.P., Nohl, U., 2008. Reference materials in geochemistry and environmental research and the GeoReM database. Chemical Geology 253, 50–53.

Kappelman, J., 1992. The age of the Fayum primates as determined by paleomagnetic reversal stratigraphy. Journal of Human Evolution 22, 495503.

Kay, R.F., Ross, C., Williams, B.A., 1997. Anthropoid origins. Science 275, 797–804.

Kay, R.F., Williams, B.A., Ross, C.F., Takai, M., Shigehara, N., 2004a. Anthropoid origins: a phylogenetic analysis. In: Ross, C.F., Kay, R.F. (Eds.), Anthropoid Origins: New Visions. Kulwer Academic/Plenum Publishers, New York, pp. 91–135.

Kay, R.F., Schmitt, D., Vinyard, C.J., Perry, J.M.G., Shigehara, N., Takai, M., Egi, N., 2004b. The Paleobiology of Amphipithecidae, South Asian late Eocene primates. Journal of Human Evolution 46, 3–24.

Khin Zaw, 1989. Comments on transcurrent movements in the Myanmar–Andaman sea region. Geology 17, 93–95.

Khin Zaw, 1990. Geological, petrological and geochemical characteristics of granitoid rocks in Myanmar: with special reference to W–Sn mineralisation and their tectonic setting. SE Asian Journal of Earth Sciences 4, 293–335.

Kosler, J., 2001. Laser-ablation ICPMS study of metamorphic minerals and processes. In: Sylvester, P.J. (Ed.), Laser-ablation-ICPMS in the earth sciences: principles and applications: Mineralogical Association of Canada, 29, pp. 185–202.

Kyaw Linn Oo, Khin Zaw, Myitta, Day Wa Aung, 2009. Tectonic setting of Podaung sandstones, Southern Chindwin Basin, Myanmar: evidence from XRF-major and trace element geochemical analysis and LA ICP-MS geochronology. 11th Regional Congress on Geology, Mineral and Energy Resources of Southeast Asia (GEOSEA), 8–10 June, Kuala Lumpur, Malaysia. Abstract volume, pp. 56–57.

Marivaux, L., Chaimanee, Y., Ducrocq, S., Marandat, B., Sudre, J., Aung Naing Soe, Soe Thura Tun, Wanna Htoon, Jaeger, J.-J., 2003. The anthropoid status of a primate from late Middle Eocene Pondaung Formation (Central Myanmar): tarsal evidence. Proceedings of the National Academy of Sciences of the United States of America 100, 13173–13178.

Marivaux, L., Ducrocq, S., Jaeger, J.-J., Marandat, B., Sudre, J., Chaimanee, Y., Soe Thura Tun, Wanna Htoon, Aung Naing Soe, 2005. New remains of *Pondaungimys anomaluropsis* (Rodentia, Anomaluroidea) from the latest Middle Eocene Pondaung Formation of Central Myanmar. Journal of Vertebrate Paleontology 25, 214–227.

Marivaux, L., Beard, K.C., Chaimanee, Y., Jaeger, J.-J., Marandat, B., Aung Naing Soe, Soe Thura Tun, Aung Aung Kyaw, 2008. Proximal Femoral Anatomy of a Sivaladapid Primate from the Late Middle Eocene Pondaung Formation (Central Myanmar). http://dx.doi.org/10.1002/ajpa.20866.

Maung Maung, Thaung Htike, Tsubamoto, Suzuki, H., Chit Sein, Egi, N., Zaw Win, Zin Maung Maung Thein, Aye Ko Aung, 2005. Stratigraphy of the primate-bearing beds of the Eocene Pondaung Formation at Paukkaung area, Myanmar. Anthropological Science 113, 11–15.

Meffre, S., Scott, R.J., Glen, R.A., Squire, R.J., 2007. Re-evaluation of contact relationships between Ordovician volcanic belts and the quartz-rich turbidites of the Lachlan Orogen. Australian Journal of Earth Sciences 54, 363–383.

Meng, J., McKenna, M.C., 1998. Faunal turnovers of Paleogene mammals from the Mongolian Plateau. Nature 394, 364–367.

Meng, J., Zhai, R., Wyss, A.R., 1998. The late Paleocene Bayan Ulan fauna of inner Mongolia, China: Bull. Carnegie Museum of Natural History 34, 148–185.

Miller, E.L., Gunnell, G.F., Martin, R.D., 2005. Deep time and the search for anthropoid origins. Yearbook of Physical Anthropology 48, 60–95.

Paton, C., Woodhead, J.D., Hellstrom, J.C., Hergt, J.M., Greig, A., Maas, R., 2010. Improved laser ablation U–Pb zircon geochronology through robust downhole fractionation correction. Geochemistry, Geophysics, Geosystems 11, 1–36.

Perelman, P., Johnson, W., Roos, C., Seuanez, H., Honath, J., Moreira, M., Kessing, B., Pontius, J., Roelke, M., Rumpler, Y., Schneider, M., Silva, A., O'Brien, S., Pecon-Slattery, J., 2011. A molecular phylogeny of living primates. PLoS Genetics 7, e1001342. http://dx.doi.org/10.1371/journal.pgen1001342.

Pilgrim, G.E., 1927. A *Sivapithecus* palate and other primate fossils from India. Palaeontologia Indica, New Series 14, 1–26.

Pilgrim, G.E., Cotter, G. de P., 1916. Some newly discovered Eocene mammals from Burma. Records of the Geological Survey of India 47, 42–77.

Prothero, D.R., Swisher, C.C.I.I.I., 1992. Magnetostratigraphy and geochronology of the terrestrial Eocene–Oligocene transition in North America. In: Prothero, D.R., Berggren, W.A. (Eds.), Eocene–Oligocene Climatic and Biotic Evolution. Princeton University Press, Princeton, pp. 46–73.

Robinson, P., 2003. XRF analysis of flux-fused discs. 5th International Conference on the Analysis of Geological and Environmental Materials: Abstracts, 90.

Ross, C., Williams, B.A., Kay, R.F., 1998. Phylogenetic analysis of anthropoid relationships. Journal of Human Evolution 35, 221–306.

Russell, D.E., Zhai, R., 1987. The Paleogene of Asia: mammals and stratigraphy. Mémoires du Muséum National d'Histoire Naturelle, Série C 52, 1–488.

Seiffert, E.R., Simons, E.L., Simons, C.V., 2004. Phylogenetic, biogeographic, and adaptive implications of new fossil evidence bearing on crown anthropoid origins and early stem catarrhine evolution. In: Ross, C., Kay, R.F. (Eds.), Anthropoid Origins: New Visions. Kluwer Academic/Plenum, New York, pp. 157–181.

Seiffert, E.R., Bown, T.M., Clyde, W.C., Simons, E., 2008. Geology, paleoenvironment and age of Birket Qarun Locality 2 (BQ-2), Fayum Depression, Egypt. In: Fleagle, J.G., Gilbert, C.C. (Eds.), Elwyn Simons: A Search for Origins. Springer, Berlin, pp. 71–86.

Simons, E.L., 1995. Egyptian Oligocene primates: a review. Yearbook of Physical Anthropology 38, 199–238.

Soe Thura Tun, 2004. The earth that bears the primates: geology of the Pondaung Primates area revisited. Journal of the Myanmar Academy of Earth and Science 2, 136–147.

Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters 26, 207–221.

Stamp, L.D., 1922. An outline of the tertiary geology of Burma. Geological Magazine 59, 481–501.

Steiper, M., Young, N., 2006. Primate molecular divergence dates. Molecular Phylogenetics and Evolution 41, 384–394.

Suzuki, H., Maung Maung, Zaw Win, Tsubamoto, T., Zin Maung Maung Thein, Egi, N., Takai, M., Shigehara, N., 2006. Stratigraphic positions of the Eocene vertebrate localities in the Paukkaung area (Pondaung Formation, central Myanmar). Asian Paleoprimatology 4, 67–74.

Takai, M., Shigehara, N., Aye Ko Aung, Soe Thura Tun, Aung Naing Soe, Tsubamoto, T., Tin Thein, 2001. A new anthropoid from the latest middle Eocene of Pondaung, central Myanmar. Journal of Human Evolution 40, 393–409.

Takai, M., Chit Sein, Tsubamoto, T., Egi, N., Maung Maung, Shigehara, N., 2005. A new eosimiid from the latest middle Eocene in Pondaung, central Myanmar. Anthropological Science 113, 17–25.

Tong, Y., 1997. Middle Eocene small mammals from Liguanqiao basin of Henan Province and Yuanqu basin of Shanxi Province, central China. Palaeontologia Sinica 186, 1–256.

Tsubamoto, T., Takai, M., Shigehara, N., Egi, N., Soe Thura Tun, Aye Ko Aung, Maung Maung, Danhara, T., Suzuki, H., 2002. Fission-track zircon age of the Eocene Pondaung Formation, Myanmar. Journal of Human Evolution 42, 361–369.

Tsubamoto, T., Takai, M., Egi, N., 2004. Quantitative analyses of biogeography and faunal evolution of middle to late Eocene mammals in East Asia. Journal of Vertebrate Paleontology 24, 657–667.

Tsubamoto, T., Egi, N., Takai, M., Shigehara, N., Suzuki, H., Nishimura, T., Ugai, H., Maung Maung, Chit Sein, Soe Thura Tun, Aung Naing Soe, Aye Ko Aung, Tin Thein, Thaung Htike, Zin Maung Maung Thein, 2006. A summary of the Pondaung fossil expeditions. Asian Paleontology 4, 1–66.

Tsubamoto, T., Zin Maung Maung Thein, Thein, Suzuki, H., Maung Maung, Iwano, H., Danhara, T., Takai, M., 2009. Fission-track ages of the Upper Member of the Pondaung Formation, Paukkaung area, central Myanmar. 116th Annual Meeting of the Geological Society of Japan Okayama, Japan: Abstract, vol. 203.

Wang, Y., Hu, Y., Chow, M., Li, C., 1998. Chinese Paleocene mammal faunas and their correlation. Bulletin of Carnegie Museum of Natural History 34, 89–123.

Watson, J.S., 1996. Fast, simple method of powder pellet preparation for X-ray fluorescence analysis. X-Ray Spectrometry 25, 173–174.

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Vonquadt, A., Roddick, J.C., Speigel, W., 1995. 3 Natural zircon standards for U–Th–Pb, Lu–Hf, trace-element and REE analyses. Geostandards Newsletter 19, 1–23.

Williams, B.A., Kay, R.F., Kirk, E.C., 2010. New perspectives on anthropoid origins. Proceedings of the National Academy of Sciences of the United States of America 107, 4797–4804.