THE GEOLOGICAL SOCIETY
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Tracing Argoland in eastern Tethys and implications for India-Asia convergence

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ABSTRACT

Incremental accretion of continental fragments from East Gondwana to Eurasia resulted in the growth of Asia and rise of the Tibetan Plateau, yet its detailed evolution remains uncertain. Argoland, a continental fragment that rifted from NW Australia during the Late Jurassic, played a key role in the initial opening of the Indian Ocean and the evolution of eastern Tethys. However, its present identity remains elusive, with East Java-West Sulawesi currently assumed to be the most likely option. To constrain the missing Argoland and its role in India-Asia convergence, we report new detrital zircon data from Sulawesi, Indonesia, and West Burma, Myanmar, and synthesize literature results from relevant regions in Southeast Asia, which (>15,000) reveal age profiles of West Sulawesi, the central Sulawesi metamorphic belt, and southeast Borneo comparable to that of Bird's Head, New Guinea, whereas age patterns of West Burma and East/West Java are similar to those of NW Australia. Notably, the most dominant age populations in NW Australia are rarely detected in Sulawesi and Borneo. These observations, combined with previous geological records and recent paleomagnetic data, suggest that West Burma is the mysterious Argoland, opposing the currently favored East Java-West Sulawesi model, with East Java and West Sulawesi probably having originated from NW Australia and Bird's Head, respectively. We estimate an average northward motion of ~6–8 cm/yr for West Burma, which split from NW Australia to approach the equator during ca. 155–95 Ma, shedding new light on the reconstruction and breakup of northern East Gondwana, progressive building of Southeast Asia, and India-Asia convergence.

INTRODUCTION

A fundamental but challenging task in geology is the paleogeographic reconstruction of East Gondwana. Its northern margin has been dismembered into a series of continental fragments and then accreted to Eurasia at the expense of the Tethys oceans, resulting in the progressive growth of Asia and rise of the Tibetan Plateau (Metcalfe, 1996, 2011; Chung et al., 1998, 2005; Royden et al., 2008; Burrett et al., 2014; Müller et al., 2016; Zahirovic et al., 2016; Kapp and DeCelles, 2019). Despite significant advances in the last decades, the detailed evolution—including origin, drifting, and accretion—of some East Gondwana-derived continental fragments is still poorly constrained due to a paucity of reliable evidence, among them the missing Argoland (or Argo) continental block (e.g., Hall, 2012; Metcalfe, 2017).

Sandwiched between the Java Trench to the north and the submerged Scott and Exmouth Plateaus to the south, the Argo Abyssal Plain (Fig. 1) forms a ~600-km-wide and ~5.7-km-deep ocean basin offshore NW Australia north of the Canning Basin. The Argo Abyssal Plain has attracted attention as it preserves the oldest Indian oceanic crust and thus holds key information regarding initial opening of the Indian Ocean and late stages of eastern Tethys (Heirtzler et al., 1978; Heine and Müller, 2005; Gibbons et al., 2012; Zahirovic et al., 2016). Combined evidence from borehole, sedimentology, geochronology, and seafloor magnetic lineations establishes that seafloor spreading in the Argo Abyssal Plain and rifting of Argoland from NW Australia commenced at ca. 160–155 Ma (Heine and Müller, 2005; Gibbons et al., 2015). However, the present identity of Argoland remains enigmatic; competing theories vary from the West Burma model based mainly on uncertain stratigraphic correlations (Metcalfe, 1996) to the East Java-West Sulawesi model, which relies primarily on NW Australia-like zircon age profiles from East Java and the presence of several Archean-Proterozoic zircons in West Sulawesi (Smyth et al., 2007; Hall, 2012, 2017). Metcalfe (2011) switched to the East Java-West Sulawesi model, pointing out little direct evidence for the West Burma model and interpreting West Burma as part of Cathaysia in the late Paleozoic (Barber and Crow, 2009; Hall, 2012, 2017); nevertheless, some tectonic reconstructions continue to follow the assumptions of Metcalfe (1996) and identify West Burma as Argoland (Gibbons et al., 2012, 2015) without strong supporting evidence.

Assuming that East Java-West Sulawesi is an elongated continental block, the East Java-West Sulawesi model is currently prevailing (Metcalfe, 2011, 2017; Hall, 2012, 2017; Zahirovic et al., 2016). However, this model faces serious challenges from recent studies that reveal Bird's Head, New Guinea, rather than NW Australia, affinities for the Malino and Palu metamorphic complexes in northern West Sulawesi (Fig. 2A) (van Leeuwen et al., 2007, 2016; Hennig et al., 2016), although East Java has a zircon age profile similar to those of NW Australia (Smyth et al., 2007). Without good reason, Hennig et al. (2016) intentionally separated NW Sulawesi from West Sulawesi so as not to conflict with the East Java-West Sulawesi model. However, Bird's Head-like zircon age profiles are also found in other parts of West Sulawesi (see Discussion section), which suggests that the whole of West Sulawesi was probably of Bird's Head origin. In addition, the occurrence of several ancient zircons in West Sulawesi does not

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GSA Bulletin; https://doi.org/10.1130/B35772.1; 6 figures; 1 supplemental file.

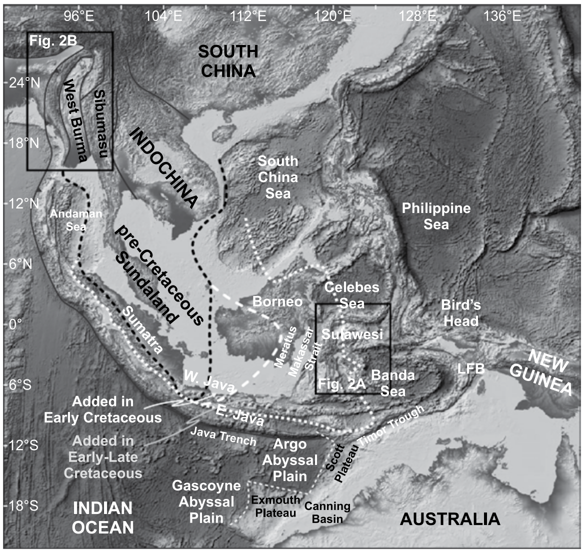

Figure 1. Simplified geological map of Southeast Asia, modified after ETOPO1 of the National Oceanic and Atmospheric Administration, USA. Thick dotted lines illustrate the progressive growth of Southeast Asia (Hall, 2012). LFB—Lengguru Fold Belt.

necessitate a linkage between West Sulawesi and NW Australia (or Argoland), because Archean-Proterozoic zircons occur almost everywhere on Earth. Moreover, there is no geophysical evidence substantiating a continental connection between East Java and West Sulawesi; in fact, the continental sliver/basement beneath West Sulawesi was probably limited between 4°S and 1°N (Elburg et al., 2003) with no further southward extension, let alone a connection with East Java (~6–8°S). Most significantly, the assumed East Java-West Sulawesi combination, which is >1500 km in length (Smyth et al., 2007), is too large to fit into the Argo Abyssal Plain, which is ~600 km wide, or the reconstruction of Argo by Hall (2012). Collectively, the two models above were both built on inconclusive observations or assumptions; thus, further investigations are needed to test them.

Robust provenance analysis of the two candidates can help resolve this long-standing enigma. Detrital zircons from (meta)sedimentary rocks have been extensively utilized to provide provenance information about terranes (Cawood and Nemchin, 2000; Cawood et al., 2003; Gehrels et al., 2011; Zhu et al., 2011; Zhang et al., 2015, 2016, 2019a, 2019b; Han et al., 2016a, 2016b; Morón et al., 2019), and age patterns of Precambrian zircons as specific detrital fingerprints are particularly useful in testing connectivity between terranes (Zhang et al., 2018; Shaanan et al., 2019). Given that NW Australia is characterized by the preponderance of ca. 1300–1000 Ma and 600–500 Ma age populations (Cawood and Nemchin, 2000; Zhu et al., 2011; Zhang et al., 2018; Morón et al., 2019), such age spectra are reasonably expected in Argoland. Thus, we carried out a detrital zircon study on Triassic basement rocks in Sulawesi and Triassic-Cenozoic sedimentary rocks in West Burma, supplemented with available data from related regions in Southeast Asia, to test the existing models and trace the remnants of Argoland in eastern Tethys. Additionally, by

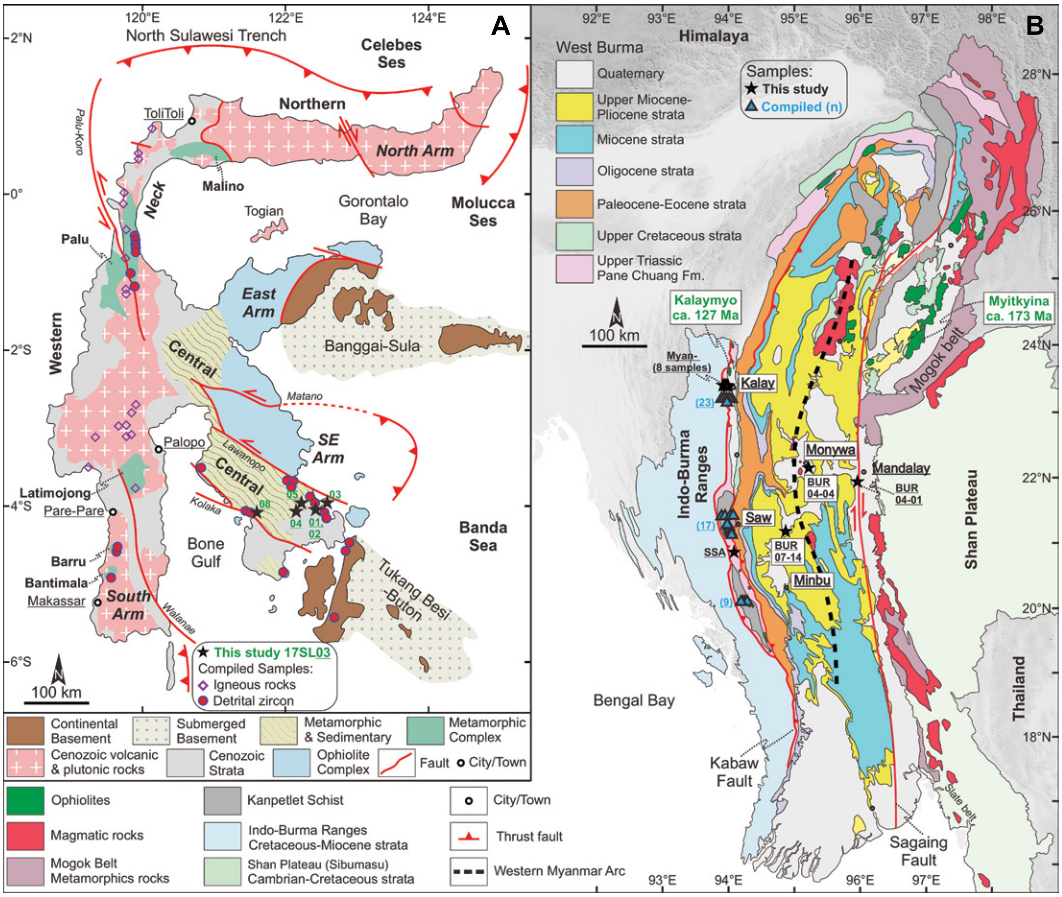

Figure 2. (A) Simplified geological map of Sulawesi, modified after Maulana et al. (2019), shows samples from the present study and compiled samples from West Sulawesi (Hennig et al., 2016; van Leeuwen et al., 2016; Jaya et al., 2017; White et al., 2017) and the central Sulawesi metamorphic belt (Decker et al., 2017). (B) Simplified geological map of Burma, modified after Cai et al. (2019), shows samples from the present study and compiled samples (Sevastjanova et al., 2016; Yao et al., 2017). Ages (ca. 173 Ma and 127 Ma) of ophiolites are from Liu et al. (2016). n—number of samples.

incorporating previous geological observations and recent paleomagnetic data (Barley et al., 2003; Liu et al., 2016; Westerweel et al., 2019), we aim to illustrate the northward motion of Argoland and decipher its role in India-Asia convergence.

GEOLOGICAL BACKGROUND

Sulawesi

Situated in the heart of the Indonesian archipelago, Sulawesi has experienced a complex evolution since the Triassic (Polvé et al., 1997; Elburg and Foden, 1998; Parkinson et al., 1998; Elburg et al., 2003; Hennig et al., 2016; Jaya et al., 2017; Böhnke et al., 2019; Maulana et al., 2019; Zhang et al., 2020). The island includes six tectonic units, i.e., the northern Sulawesi arc, West/Western Sulawesi, the central Sulawesi metamorphic belt, eastern Sulawesi ophiolites (most of East Arm and SE Arm), and two continental fragments of Banggai-Sula and Tukang Besi-Buton (Fig. 2A). The northern Sulawesi arc occupies most of the North Arm of Sulawesi, where widespread Cenozoic island arc magmatic rocks intruded or overlaid Eocene oceanic crust (e.g., Elburg and Foden, 1998). The central Sulawesi metamorphic belt comprises mainly (meta)sedimentary rocks that were formed by the accretion of West Sulawesi to Sundaland (or specifically Borneo) during the Early Cretaceous (Parkinson, 1998; Parkinson et al., 1998), followed by emplacement of the eastern Sulawesi ophiolites probably during the Oligocene to Miocene and subsequent docking of the two microcontinents likely during the Miocene (Polvé et al., 1997; Parkinson, 1998; Elburg et al., 2003; Hall, 2012), which might have resulted in Oligocene to Miocene re-metamorphism of some rocks in the central Sulawesi metamorphic belt. For detailed geology of Sulawesi, see Polvé et al. (1997), Elburg et al. (2003), van Leeuwen et al. (2016), and references therein.

Characterized by widespread Cenozoic magmatic rocks and several metamorphic complexes (i.e., the Malino, Palu, Latimojong, Barru, and Bantimala), West Sulawesi was inferred to have rifted from Gondwana during the Jurassic and accreted to Eurasia during the Cretaceous (Elburg et al., 2003; van Leeuwen et al., 2007, 2016; Hall, 2012; Hennig et al., 2016; Jaya et al., 2017; Maulana et al., 2019). The central Sulawesi metamorphic belt crops out in the central part and SE Arm of Sulawesi, where the Pompangeo schist complex occurs as the most extensive component, with equivalent Mekongga, Mendoke, and Rumbia complexes limited in the SE Arm (Parkinson et al., 1998). Source materials (or protoliths) of these schist complexes are found along the eastern margin, including the Upper Triassic Meluhu Formation, which consists mainly of sandstone, siltstone, and mudstone deposited in a rift graben (Surono and Bachri, 2002).

Although different in protolith and metamorphic pressure-temperature conditions, the metamorphic/schist complexes in West Sulawesi and the central Sulawesi metamorphic belt underwent coeval regional metamorphism during ca. 130–110 Ma and may represent exhumed relics of the same continental fragment that collided with Borneo during the Early Cretaceous (Parkinson et al., 1998; Böhnke et al., 2019; Maulana et al., 2019). West Sulawesi separated from Borneo during the opening of the Makassar Strait during the Eocene; this was followed by a relative counter-clockwise rotation of the SE Arm that resulted in the opening of the Bone Gulf and thus separation of the SE from the South Arm during the Miocene (Camplin and Hall, 2014).

Burma

Burma, or Myanmar, may be divided into three major tectonic units, from east to west: East Burma (including the Shan Plateau and the Mogok metamorphic belt), West Burma, and the Indo-Burma Ranges (Fig. 2B) (Barley et al., 2003; Mitchell et al., 2012; Morley et al., 2020). East Burma occupies part of the Sibumasu terrane that rifted from northern Gondwana during the Early Permian and collided with Indochina during the Triassic (Metcalfe, 1996, 2011; Cai et al., 2017). West Burma may be interpreted as a continental block that was separated from Cathaysia (Barber and Crow, 2009; Hall, 2012, 2017) or New Guinea-Australia (Cai et al., 2017, 2019; Yao et al., 2017). The Indo-Burma Ranges consist mainly of Cretaceous ophiolitic rocks and Cretaceous-Miocene marine/continental strata that may be interpreted as an accretionary complex resulting from eastward subduction of the Neo-Tethyan/Indian plate (Mitchell et al., 2012; Cai et al., 2019; Licht et al., 2019; Morley et al., 2020). For detailed geology of Burma, see Mitchell et al. (2012), Morley et al. (2020), and references therein.

West Burma is bounded by the Indo-Burma Ranges to the west and the dextral strike-slip Sagaing Fault to the east (Fig. 2B). The Upper Triassic Pane Chaung Formation and the Kanpetlet Schist, covered by Cenozoic strata, crop out as the oldest rocks in West Burma (Westerweel et al., 2019) and contain abundant Permian-Triassic detrital zircons that were inferred to have been sourced from SE Asia (Sevastjanova et al., 2016) or New Guinea-Australia (Cai et al., 2017, 2019; Yao et al., 2017), although some researchers tend to interpret the Pane Chaung Formation as a separate continental fragment of Indian origin (i.e., Mt. Victoria Land) (e.g., Mitchell, 1986; Morley et al., 2020). We follow the considerations of Westerweel et al. (2019) and Sevastjanova et al. (2016) and identify the Pane Chaung Formation as the basement of West Burma because (1) the Pane Chaung Formation shows a NW Australia-like pre-Triassic detrital zircon age profile distinct from those of the Tethyan Himalaya and Qiangtang terranes (Sevastjanova et al., 2016; Yao et al., 2017; Zhang et al., 2018; this study) and (2) the abundant Triassic detrital zircons of the Pane Chaung Formation cannot be well explained by the Indian-origin model. During the Cretaceous, Neo-Tethyan subduction resulted in an Andean-type continental arc in West Burma, as evidenced by arc magmatism in Western Myanmar (or Wuntho-Popa) Arc with a main magmatic pulse during 110–80 Ma that was followed by a subordinate event during 70–40 Ma (Mitchell et al., 2012; Wang et al., 2014; Gardiner et al., 2015). A series of studies suggests that the Western Myanmar Arc may correlate with the Gangdese batholiths in south Tibet because of similarities in formation mechanism, magmatic pulse, geochemistry, and isotopic compositions (Mitchell et al., 2012; Wang et al., 2014; Gardiner et al., 2015; Liu et al., 2016; Zhang et al., 2019a).

SAMPLING, DATA COMPILATION, AND ANALYTICAL METHODS

This study focuses mainly on pre-Cretaceous zircon age patterns to determine the provenance characteristics of West Sulawesi, the central Sulawesi metamorphic belt, and West Burma, as younger ages are related to tectonomagmatic events after accretion to Southeast Asia. Six representative samples were collected from the Triassic basement in the central Sulawesi metamorphic belt (Figs. 2A and 3; Fig. S1 in the Supplemental Material[1]), including two greenschist facies meta-sandstones (17SL01 and 17SL02) from the basement underlying the Upper Triassic Meluhu Formation, three sandstones (17SL03–17SL05) from the Meluhu Formation, and one greenschist facies mica-schist (17SL08) from the Triassic Mekongga complex (see GPS positions in Table S1; see footnote 1). In West Sulawesi, we combined all available detrital and inherited zircons (1683 analyses from 41 magmatic and (meta)sedimentary samples; see locations in Fig. 2A) from Ceno-

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[1] Supplemental Material. Supplementary Figures S1 and S2 and Table S1. Please visit https://doi.org/10.1130/GSAB.S.13063754 to access the supplemental material, and contact editing@geosociety.org with any questions.

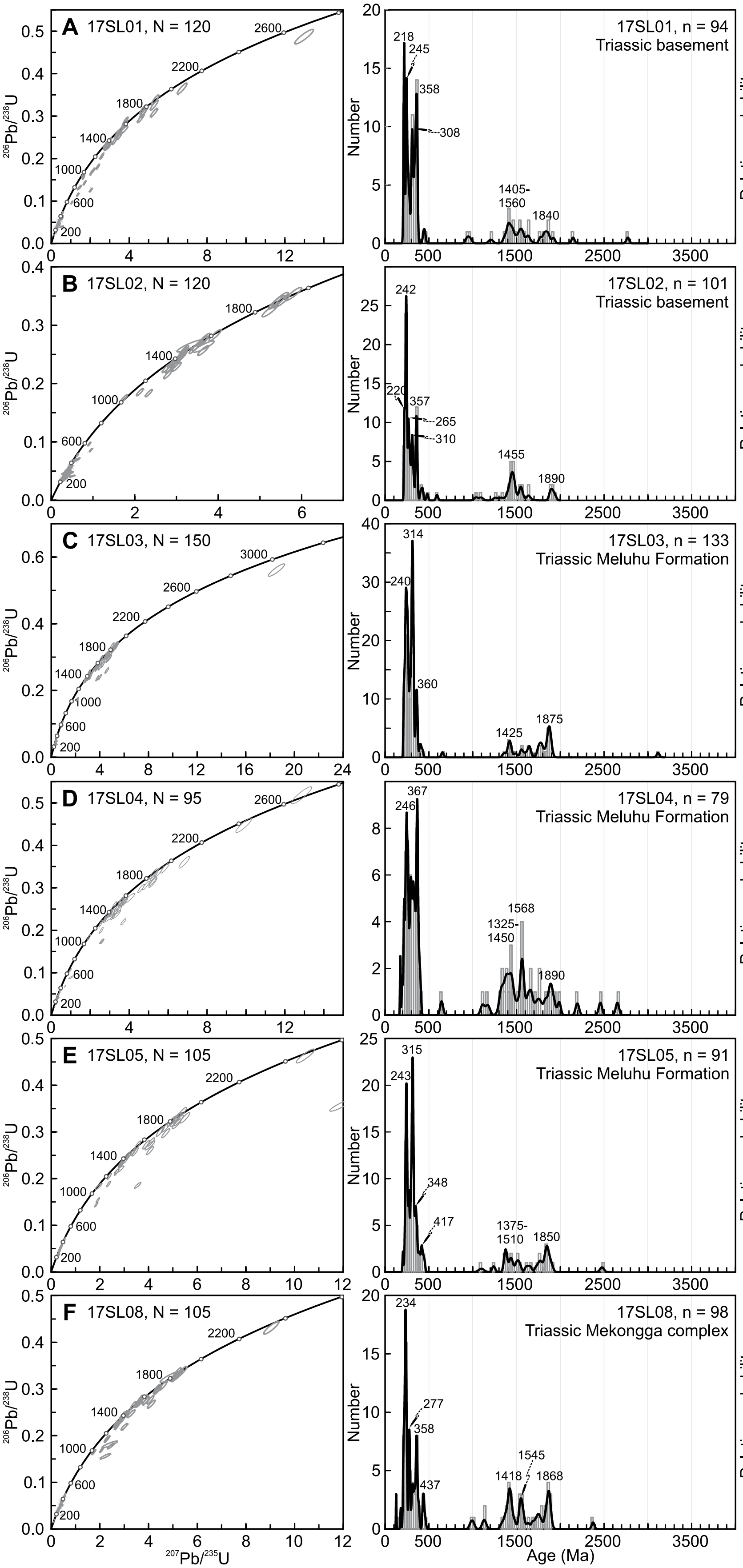

Figure 3. Concordia and relative probability diagrams for samples from Sulawesi in this study. N—number of analyses; n—number of concordant analyses.

zoic magmatic and sedimentary rocks (Hennig et al., 2016; van Leeuwen et al., 2016; Jaya et al., 2017; White et al., 2017) to provide a zircon age profile for West Sulawesi.

From West Burma, 12 representative samples were collected (Figs. 2B and 4; see GPS positions and ages of strata in Table S1), including seven sandstones (Myan-01, Myan-03, Myan-07, Myan-11, Myan-Pg1, Myan-KK, and SSA) and two conglomerates (Myan-09 and Myan-Pg2) from Late Triassic to Miocene strata and three Irrawaddy River sediment samples (BUR04-01, BUR04-04, and BUR04-14).

To determine the source terranes for West Sulawesi, the central Sulawesi metamorphic belt, and West Burma, we compiled detrital zircon data from Bird's Head (Decker et al., 2017), SE Borneo (Witts et al., 2012), West Burma (Yao et al., 2017; Zhang et al., 2018), East Java (Smyth et al., 2007), West Java (Clements and Hall, 2011), and Western Australia (Zhu et al., 2011; Zhang et al., 2018; and references therein).

All of the 18 samples from Sulawesi and West Burma were crushed for selection of detrital zircons; unfortunately, there were no thin sections or other heavy minerals. Zircon grains were separated using standard density and magnetic techniques. They were randomly handpicked and embedded in epoxy resin and then polished to expose interiors. Using an Agilent 7500s Q inductively coupled plasma-mass spectrometer (ICP-MS) attached with a Photon Machines Analyte G2 laser ablation system at the Department of Geosciences, National Taiwan University, Taipei, ~100–150 grains from each sample were conducted for laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) U-Pb isotopic analysis with LA spot size of 35 μm, repetition rate of 7–8 Hz, and energy fluence of 4–5 J/cm^2. Applied analytical procedures are similar to those reported by Chiu et al. (2009), and standard zircons 91500 and Plešovice were analyzed (every 10 unknowns) to monitor instrumental conditions, which yielded weighted mean ages of 1067.3 ± 4.1 Ma (^{207}Pb/^{235}U; 2σ; $n = 70$) and 333.1 ± 2.0 Ma (^{206}Pb/^{238}U; 2σ; $n = 50$), respectively, which match with the recommended values (Jackson et al., 2004; Sláma et al., 2008). GLITTER (v.4.4; www.glitter-gemoc.com) and Isoplot (v. 3.0) (Ludwig, 2003) were used to deal with measured values and to plot concordia and relative probability density diagrams with common lead correction for each zircon following the

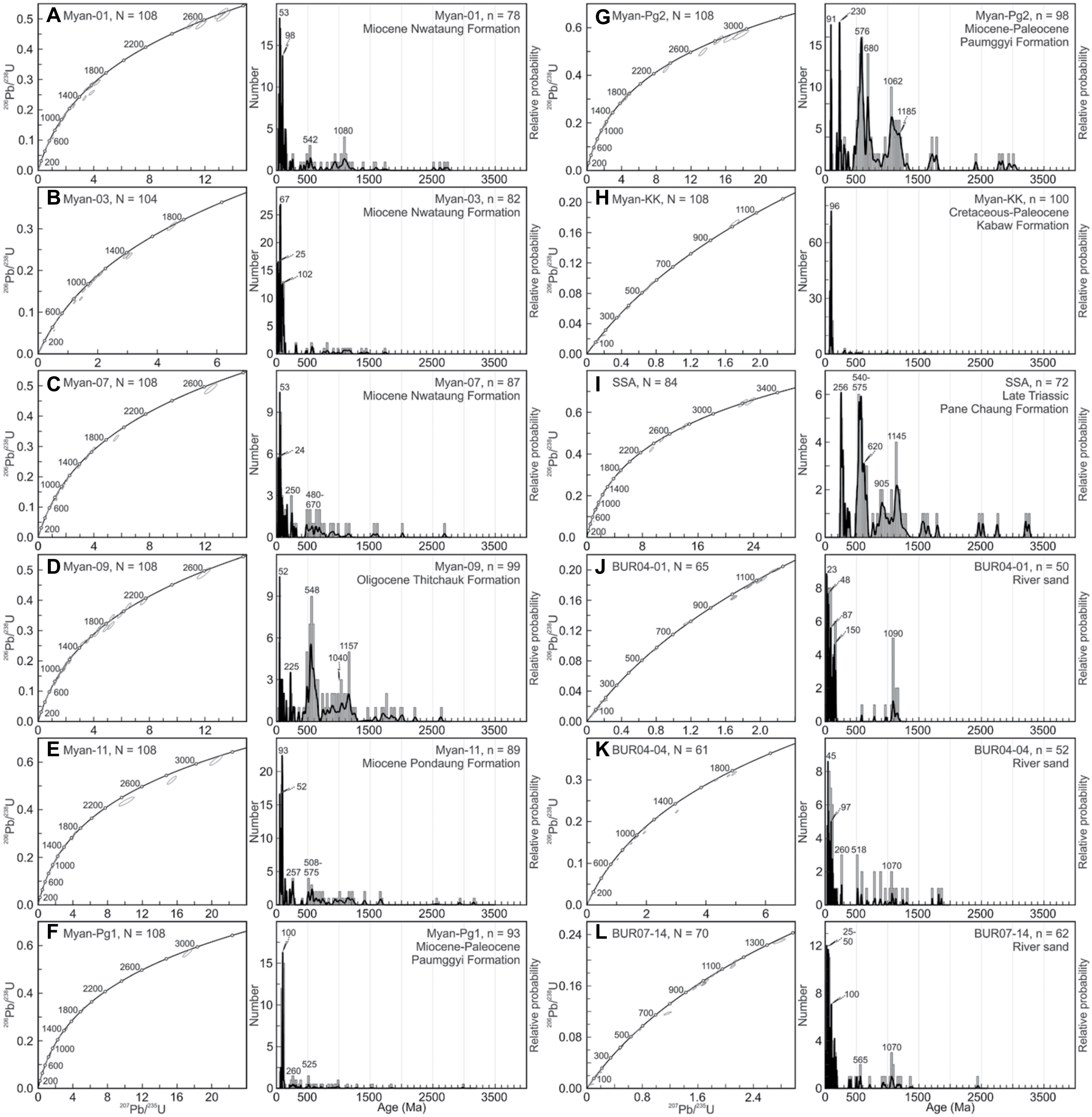

Figure 4. Concordia and relative probability diagrams for samples from West Burma in this study. N—number of analyses; n—number of concordant analyses.

methods of Andersen (2002). Some unreliable/abnormal analyses (particularly the <200 Ma analyses) were filtered and excluded from discussion. Generally, we consider ages with ≤10% discordance as concordant and prefer ^{206}Pb/^{238}U ages for <1000 Ma grains and ^{207}Pb/^{206}Pb ages for >1000 Ma grains.

RESULTS

From the central Sulawesi metamorphic belt, a total of 695 zircons were subjected to LA-ICP-MS U-Pb dating, yielding 596 concordant results (Fig. 3; Table S1). The youngest grains (215–204 Ma; n = 17) and age peaks (220–218 Ma) indicate Late Triassic maximum depositional ages for the sequences, which agree with previous stratigraphic constraints (Surono and Bachri, 2002). The six samples show similar age profiles (Fig. 3), further matching well with that (the gray curve in Fig. 5A; n = 1061) of clastics from the same area (Decker et al., 2017),

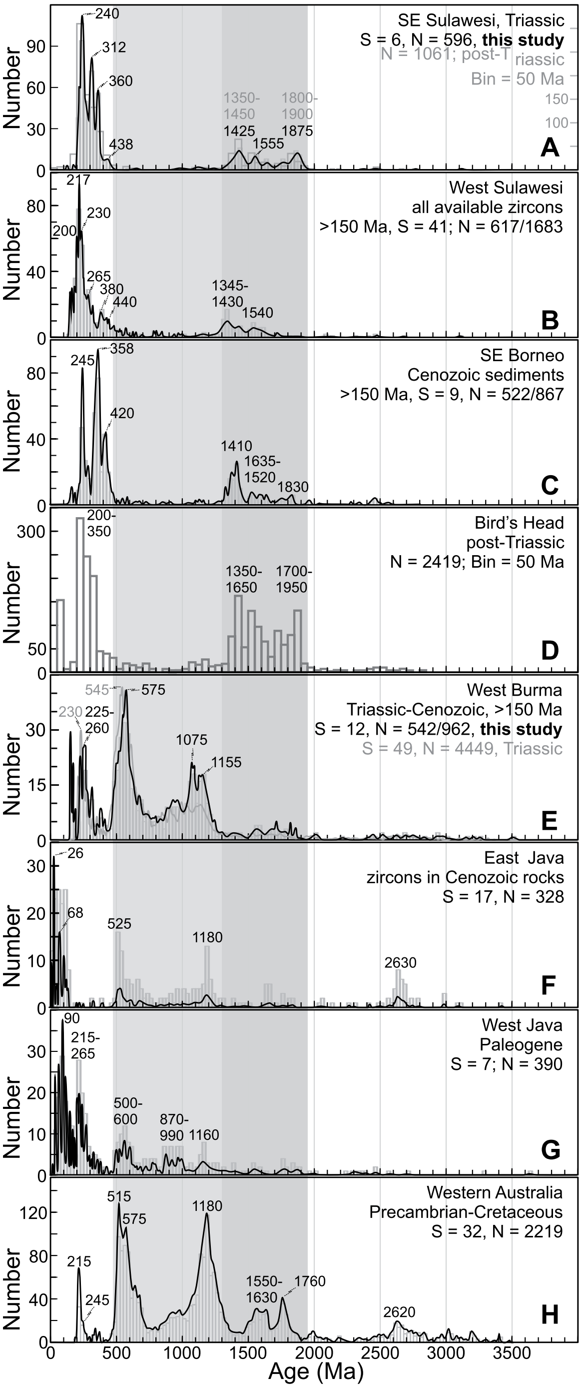

Figure 5. Zircon age profiles for Sulawesi, West Burma, and related regions. Our new data from Sulawesi and West Burma are provided in Table S1 (see footnote 1) with compiled data from SE Sulawesi in gray (Decker et al., 2017), West Sulawesi (Hennig et al., 2016; van Leeuwen et al., 2016; Jaya et al., 2017; White et al., 2017), Bird's Head (Decker et al., 2017), SE Borneo (Witts et al., 2012), West Burma (in gray) (Sevastjanova et al., 2016; Yao et al., 2017), East Java (Smyth et al., 2007), West Java (Clements and Hall, 2011), and Western Australia (Zhu et al., 2011; Zhang et al., 2018). The detailed data for Bird's Head are not available; Figure 5D is modified after Decker et al. (2017). Bin width is 25 Ma if not stated. S—number of samples; N—number of concordant analyses.

and thus supporting a common provenance for the Meluhu Formation and the Pompangeo/Mekongga complexes in the central Sulawesi metamorphic belt (Parkinson et al., 1998). Therefore, the combined age profile can best depict the provenance signatures of the central Sulawesi metamorphic belt. Taken together, detrital zircons from the central Sulawesi metamorphic belt show a prominent age population of ca. 440–200 Ma with three subordinate age populations of ca. 1900–1800 Ma, 1600–1500 Ma, and 1450–1350 Ma (Fig. 5A). Strikingly, 1300–500 Ma zircons are rarely detected.

A similar age distribution can be found in (meta)sedimentary and magmatic rocks across West Sulawesi (see locations in Fig. 2A) (Hennig et al., 2016; van Leeuwen et al., 2016; Jaya et al., 2017; White et al., 2017), and all available pre-Cretaceous zircons define major age populations of ca. 1600–1300 Ma and 440–200 Ma that may characterize the continental basement of West Sulawesi (Fig. 5B). The similarities in age spectra most likely reflect the same origin/provenance for West Sulawesi and the central Sulawesi metamorphic belt. The scarcity of 1.9–1.8 Ga zircons in West Sulawesi probably results from insufficient analyses (mostly <40) of individual samples in previous studies (Hennig et al., 2016; van Leeuwen et al., 2016; Jaya et al., 2017; White et al., 2017). Similar age populations are further evidenced by our dating of magmatic and sedimentary rocks across West Sulawesi (Fig. S2; see footnote 1) (e.g., Zhang et al., 2020).

From West Burma, a total of 1140 zircons were analyzed and yielded 962 concordant results (Table S1; Fig. 4) with pre-Cretaceous (>150 Ma) zircons exhibiting two dominant age populations of ca. 650–500 Ma (peak at 575 Ma) and 1155–1075 Ma and one subordinate age population of ca. 260–225 Ma (Fig. 5E). Such an age pattern is similar to that (the gray curve in Fig. 5E; n = 4449; 49 samples) of Triassic (meta)sedimentary rocks from nearby regions (see locations in Fig. 2B) (Sevastjanova et al., 2016; Yao et al., 2017), and thus together they can characterize the provenance signatures of West Burma.

According to Andersen (2005), the rate of failure to detect minor (e.g., 2% and less) age populations is almost zero with ~600 and ~960 concordant analyses for the central Sulawesi metamorphic belt and West Burma, respectively, in this study. Considering that our observations are consistent with previous results from the same/nearby regions (Hennig et al., 2016; Sevastjanova et al., 2016; van Leeuwen et al., 2016; Decker et al., 2017; Jaya et al., 2017; White et al., 2017; Yao et al., 2017), we are confident that the above age patterns of Sulawesi (including the central Sulawesi metamorphic belt and West Sulawesi) and West Burma may best illustrate their provenance signatures. In addition, the marked differences in major age populations of Sulawesi and West Burma, as well as those of Bird's Head and NW Australia, are readily identified by visual comparison (Fig. 3).

DISCUSSION

Origin of West Sulawesi and the Central Sulawesi Metamorphic Belt

Given their coeval metamorphism (ca. 130–110 Ma; Parkinson et al., 1998; Böhnke et al., 2019; Maulana et al., 2019) and consistent age profiles (Figs. 3 and 5; Fig. S2), West Sulawesi and the central Sulawesi metamorphic belt probably belong to the same continental fragment that collided with Borneo along the Meratus suture during the Early Cretaceous (Parkinson et al., 1998; Maulana et al., 2019).

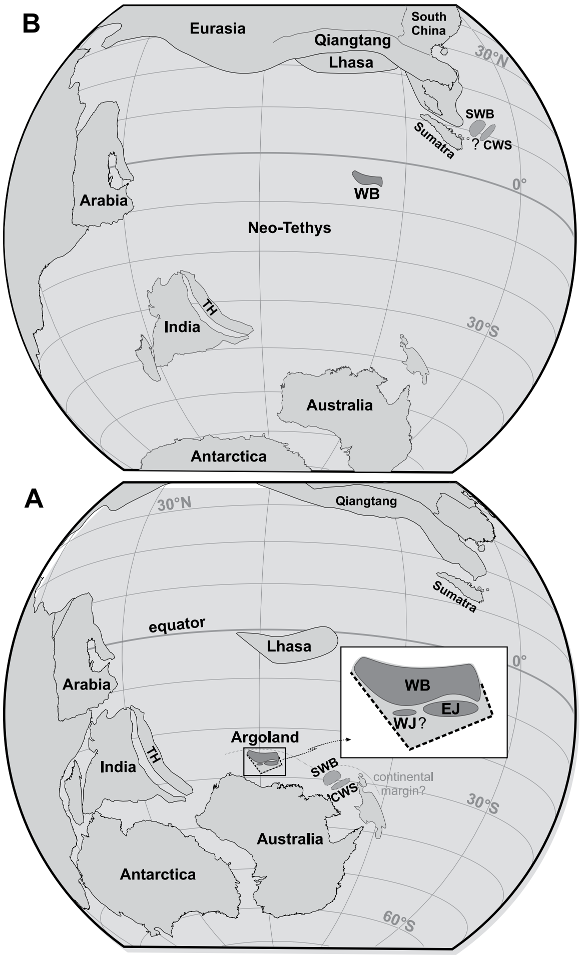

Figure 6. A tentative reconstruction of northern East Gondwana at (A) ca. 180 Ma and (B) ca. 95 Ma. Note that the ^{40}Ar/^{39}Ar ages of ca. 95 Ma should be further tested by zircon U-Pb isotopic analysis. The reconstruction is modified after Zhang et al. (2019a), Li et al. (2016), and Westerweel et al. (2019); positions of Southwest Borneo and West Sulawesi are after Jaya et al. (2017), and outlines of terranes are for reference only. CWS—Central Sulawesi metamorphic belt and West Sulawesi; E/WJ East/West Java; SWB Southwest Borneo; WB—West Burma.

Further supporting evidence arises from SE Borneo displaying a similar pre-Cretaceous age profile (Fig. 5C) (Witts et al., 2012). The central Sulawesi metamorphic belt probably separated from West Sulawesi during the opening of the Bone Gulf during the Miocene (Camplin and Hall, 2014).

Current models assume East Java-West Sulawesi as Argoland offshore NW Australia (Metcalfe, 2011, 2017; Hall, 2012, 2017; Zahirovic et al., 2016). In that case, West Sulawesi would have received substantial ca. 1300–500 Ma zircons that dominate Precambrian-Cretaceous sequences within/around NW Australia (Cawood and Nemchin, 2000; Zhu et al., 2011; Zhang et al., 2018; Morón et al., 2019). However, this is not the case. All existing data testify to the scarcity of 1300–500 Ma grains in Sulawesi and 1450–1350 Ma zircons/rocks in NW Australia (Fig. 5), which is inconsistent with a NW Australian origin for West Sulawesi and the central Sulawesi metamorphic belt. The above observations cannot be satisfactorily explained by sedimentary mixing or other factors that can bias detrital zircon records (cf. Cawood et al., 2003; Fedo et al., 2003) but may be best explained by a straightforward deduction that the continental fragment of West Sulawesi and the central Sulawesi metamorphic belt was not geographically adjacent to NW Australia. Clearly, West Sulawesi cannot be part of Argoland.

The age distributions of West Sulawesi and the central Sulawesi metamorphic belt match well with that of Bird's Head, New Guinea (Fig. 5D) (Decker et al., 2017). We also identify Bird's Head-like Carboniferous-Triassic age populations in the Malino (NW Sulawesi) and the Bantimala (South Sulawesi) areas (Fig. S2), coincident with previous findings in NW Sulawesi (van Leeuwen et al., 2007, 2016; Hennig et al., 2016). These findings provide strong evidence that the continental fragment underneath West Sulawesi (from north to south) and the central Sulawesi metamorphic belt was probably linked to, or in the vicinity of, the Bird's Head Peninsula before its separation from East Gondwana (Fig. 6A).

Tracing the Remnants of Argoland

Mesoproterozoic to Cambrian orogenic events (e.g., the Albany-Fraser, Kuunga, and Pinjarra) prevail in Western Australia, with ca. 1300–1000 Ma and 600–500 Ma zircons dominating sediments within/around NW Australia as they do in the Canning, Carnarvon, and Perth basins (Cawood and Nemchin, 2000; Zhu et al., 2011; Morón et al., 2019). Therefore, it is reasonable to expect abundant 1300–500 Ma zircons in Argoland as it was once located close to the Canning basin; this may be used as a criterion for tracing the remnants of Argoland.

Such age profiles have been documented in Paleozoic strata of the Lhasa terrane (Leier et al., 2007; Zhu et al., 2011), late Paleozoic to Cenozoic strata of Sumatra (Zhang et al., 2018), Triassic-Cenozoic sequences of West Burma (Fig. 5E) (Yao et al., 2017; Zhang et al., 2018), inherited zircons from Cenozoic magmatism of East Java (Fig. 5F) (Smyth et al., 2007), and Paleogene sediments of West Java (Fig. 5G) (Clements and Hall, 2011), which implies a common provenance from Western Australia for these terranes, among which may hide the remnants of Argoland. By contrast, age spectra of SE/NW Borneo (Witts et al., 2012; Breitfeld and Hall, 2018) and West Sulawesi (Fig. 5B), as well as Banda Arc (Zimmermann and Hall, 2016), are quite unlike those of NW Australia. Note that Mesozoic-Cenozoic sedimentary rocks of the Lengguru Fold Belt (see Fig. 1) also contain substantial Western Australia-derived 1300–500 Ma zircons, which has been attributed to a shift in drainage system during Jurassic-Cretaceous times (Decker et al., 2017). Therefore, the Lengguru Fold Belt is herein not considered as part of Argoland.

Recent paleomagnetic data corroborate an equatorial paleolatitude at ca. 180 Ma for the Lhasa terrane (Li et al., 2016), which is inconsistent with Late Jurassic separation of Argoland. Likewise, East/West Sumatra cannot be Argoland, because East/West Sumatra had accreted to Southeast Asia during the Triassic as further evidenced by Late Triassic to Cretaceous Meso-/Neo-Tethys oceanic subduction-related arc magmatism (McCourt et al., 1996; Zhang et al., 2018, 2019a), and the Woyla Nappe of Sumatra is excluded as it is generally regarded as an intra-oceanic arc (e.g., Barber and Crow, 2009; Hall, 2012). By contrast, NW Australia-like age patterns discovered in East and West Java (Figs. 5F and 5G) (Smyth et al., 2007; Clements and Hall, 2011) may be clues for the presence of dismembered slivers of Argoland lying beneath them (Fig. 6A).

West Burma was ruled out as Argoland relying principally on some unverified Permian fusulinids in Burma (Thura Oo et al., 2002) and an assumption that regards it as the continuation of

West Sumatra, which originated from Cathaysia and accreted to Eurasia during the Triassic (Barber and Crow, 2009; Metcalfe, 2011, 2017; Sevastjanova et al., 2016; Hall, 2017). In this model, Metcalfe (2011) postulated a Cathaysian affinity for the fusulinids, which, however, disagrees with the Late Permian paleogeographic reconstruction by Thura Oo et al. (2002) that located West Burma close to NW Australia. Notably, many confusions surround the fusulinids as they were reported without any systematic description (Thura Oo et al., 2002); the exact age, location, taxonomy, and affinity still remain ambiguous, as explicitly pointed out later by Metcalfe (2017). In addition, the prerequisite (i.e., a >1700 km transcurrent fault to transport West Burma-West Sumatra outboard Southeast Asia during the Triassic) in the Cathaysia origin model lacks supporting evidence (Gibbons et al., 2015; Zhang et al., 2018). Moreover, West Burma shows age patterns resembling those of NW Australia (Fig. 5E) (Cai et al., 2017; Yao et al., 2017; Zhang et al., 2018) rather than those of Cathaysia/Indochina (overwhelmingly dominated by ca. 970–960 Ma zircons with negligible ca. 600–500 Ma grains; e.g., Xu et al., 2013), which cannot be adequately explained by the Cathaysia origin model.

West Burma was previously inferred to have attached to Southeast Asia during the Triassic relying mainly on two equivocal justifications, i.e., the occurrences of Permian-Triassic detrital zircons and Cr spinel in the sedimentary rocks of West Burma, which were assumed to be rare in Western Australia (Sevastjanova et al., 2016). However, this is not the case. In fact, Permian-Triassic detrital zircon age peaks and magmatic rocks of this age have been documented in the Carnarvon Basin of NW Australia (e.g., Veevers and Tewari, 1995; Lewis and Sircombe, 2013) and the Bird's Head-West Papua region (Decker et al., 2017; Jost et al., 2018) as well as in the Banda Arc (Zimmermann and Hall, 2016). Similarly, detrital spinel has been detected in the Jurassic-Cretaceous sediments of the Canning Basin of NW Australia (Boyd and Teakle, 2016), and the so-called rareness of detrital Cr spinel in Western Australia (Sevastjanova et al., 2016) may be attributed to insufficient heavy mineral studies in the region. In addition, Sevastjanova et al. (2016) solely cited Cawood and Nemchin (2000) for the scarcity of detrital Cr spinel in Western Australia. However, such a conclusion was never made by the authors (Cawood and Nemchin, 2000), who only analyzed nine sedimentary samples from the northern Perth Basin.

Most crucially, the findings related to ca. 173 Ma ophiolites to the east of West Burma (Liu et al., 2016) and ca. 170–120 Ma subduction-related, I-type tonalite-granodiorite batholiths on the western margin of East Burma (Barley et al., 2003) that are indicative of the existence of Middle Jurassic-Early Cretaceous oceanic subduction between West and East Burma contradict a Triassic docking of West Burma to Southeast Asia. Collectively, there is so far little concrete evidence for West Burma having a Cathaysian origin or a Triassic accretion to Southeast Asia. Therefore, Permian-Triassic detrital zircons in West Burma are most likely to have sourced from the West Papua region (Cai et al., 2017; Yao et al., 2017; Aitchison et al., 2019) rather than from Southeast Asia (Sevastjanova et al., 2016).

Alternatively, in the context of size and age profile, West Burma appears to be the most viable candidate for Argoland. Thus, we propose a tentative reconstruction involving a Late Jurassic (ca. 155 Ma) separation from NW Australia for West Burma (Fig. 6), consistent with existing geological observations (Barley et al., 2003; Liu et al., 2016) and more importantly recent paleomagnetic data revealing a paleolatitude of 5.0 ± 4.7°S at ca. 95 Ma for West Burma (Westerweel et al., 2019); these factors are difficult to explain in any previous models involving a Triassic docking of West Burma to Southeast Asia. It should be noted that the ages of ca. 95 Ma (i.e., 97–87 Ma) are $^{40}Ar/^{39}Ar$ dates on andesite, diorite, and granodiorite from West Burma (Westerweel et al., 2019), which represent the cooling rather than crystallization ages of the magmatic rocks, although they are sometimes within error of each other. Consequently, more reliable/precise dating methods (e.g., zircon U-Pb isotopic analysis) are needed to test or better constrain the formation time(s) of the magmatism, which are of critical importance and may lead to significant changes in tectonic reconstructions.

Tectonic Implications

Combining substantial zircon age data (n > 15,000) from relevant regions in Southeast Asia and newly published paleomagnetic constraints, we provide the first evidence sustaining West Burma (rather than East Java-West Sulawesi) as the mysterious Argoland (Fig. 6A), although more investigations from other perspectives, especially more detailed paleomagnetic studies in eastern Tethys, are needed to further substantiate our model. If true, the new reconstruction would fundamentally change our understanding of the tectonic evolution—including origin, drifting, and accretion—of the West Burma terrane. Crucially, West Burma (as Argoland), once situated in a vital location between Australia and India, may preserve key geological records regarding the breakup of East Gondwana and its relation to late stages of eastern Tethys and the opening of the Indian Ocean. In addition, the new reconstruction would significantly impact investigations of paleoenvironmental change and biodiversity in West Burma and Southeast Asia (Licht et al., 2019; Westerweel et al., 2019) by suggesting a brand-new growth scenario for Southeast Asia in which West Burma most likely accreted during the Late Cretaceous (Metcalfe, 1996; Yao et al., 2017), resulting in the significant clockwise rotation of West Burma since ca. 80 Ma (Westerweel et al., 2019) and a magmatic gap between ca. 80 Ma and 70 Ma (Mitchell et al., 2012; Wang et al., 2014; Gardiner et al., 2015). Accordingly, previous tectonic reconstructions involving a Triassic accretion for West Burma (Hall, 2012; Metcalfe, 2017) should be amended; the competing geodynamic models for India-Asia collision (Royden et al., 2008; van Hinsbergen et al., 2012; Ingalls et al., 2016) require revisions in the interpretation of Asian lithosphere deformation.

We estimate an average northward transport speed of ~6–8 cm/yr during ca. 155–95 Ma for West Burma (Fig. 6), comparable with those (~7 cm/yr and ~6 cm/yr, respectively) of the northern Qiangtang and the Lhasa terranes (Li et al., 2016; Song et al., 2017) that also originated from northern East Gondwana. The similarities in average drifting speed likely result from the same or similar driving mechanism(s), such as slab pull of the Tethyan oceanic plates. Such a northward drifting from NW Australia to southern Eurasia for West Burma with a paleolatitude of ~5.0°S at ca. 95 Ma (Westerweel et al., 2019) refutes it as part of the near-equatorial Trans-Tethyan subduction system located at ~0°–10°N at that time (Hall, 2012). This consideration is further supported by the fact that the Western Myanmar Arc of West Burma is an Andean-type continental arc (Mitchell et al., 2012; Licht et al., 2019) that is distinct from the Incertus and the Kohistan intra-oceanic arcs. In addition, there is no geological/geophysical evidence supporting the existence of such a huge and continuous Trans-Tethyan subduction system. Given that the detailed sedimentology, geochemistry, petrography, and geochronology of Western Myanmar forearc basins disapprove an early Paleogene India-West Burma collision (Licht et al., 2019), tectonic reconstructions involving an early India-West Burma docking before the India-Asia collision seem unlikely.

Additionally, contemporaneous with the northward motion of the Indian plate, West Burma probably shared a similar acceleration in northward convergence rate with India during the Late Cretaceous. Therefore, a detailed migration history of West Burma may not only shed light on the driving mechanism(s) for convergences between East Gondwanan continental blocks (i.e., Qiangtang, Lhasa, Sulawesi, etc.) and southern Eurasia but also provide a wealth of information on the trigger(s) for the anomalously fast northward motion of the India plate (Jagoutz et al., 2015) as well as timing of the India-Asia collision, rise of the Tibetan Plateau, and Asian lithosphere deformation (Westerweel et al., 2019).

CONCLUSIONS

Our new detrital zircon data from Sulawesi and West Burma, along with available results from relevant regions in Southeast Asia, reveal that West Sulawesi, the Central Sulawesi metamorphic belt, and SE Borneo show age profiles similar to that of Bird's Head (New Guinea), contrasting with West Burma and East/West Java exhibiting age patterns comparable to those of NW Australia. Considering that the most dominant age populations in NW Australia are rarely detected in Sulawesi and Borneo, we suggest that West Sulawesi and East Java most probably originated from Bird's Head and NW Australia, respectively, and thus should no longer be considered as a united block representing Argoland. In the context of size, age profile, geological records, and recent paleomagnetic data, West Burma emerges as the best candidate for Argoland. This new tectonic reconstruction implies a Late Jurassic separation from NW Australia, a Late Cretaceous accretion to Eurasia, and an average northward transport speed of ~6–8 cm/yr during ca. 155–95 Ma for West Burma. A better and detailed evolution of West Burma will advance our understanding of the reconstruction and breakup of northern East Gondwana, the initial opening of the Indian Ocean, and the progressive building of Southeast Asia.

ACKNOWLEDGMENTS

We appreciate the constructive comments from the editors (Professors Rob Strachan and Fu-Yuan Wu) and two anonymous reviewers. This study was funded by the Academia Sinica and Ministry of Science and Technology (grant MOST-108-2639-M-001-002-ASP), Taiwan. Emily Hung, Jia-Huei Chen, and Yi-Ju Hsin are thanked for helping to analyze the samples.

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Science Editor: Rob Strachan
Associate Editor: Fu-Yuan Wu

Manuscript Received 2 June 2020
Revised Manuscript Received 18 August 2020
Manuscript Accepted 29 September 2020

Printed in the USA