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Cenozoic Evolution of the Sulu Sea Arc-Basin System: An Overview

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Key Points:

- Age and geochemical data compilation for the circum-Sulu Sea region summarized 7 Cenozoic (Mid Eocene to Pleistocene) magmatic phases
- After Palawan Continental Terrane accretion, Sulu Sea back-arc basin was opened by Celebes Sea subduction (~21 Ma) and rollback (17-9 Ma)
- Northern Borneo underwent intraplate extension and magmatism after ~9 Ma, and the Sulu Sea subducted along Sulu-Negros trench from ~4 Ma

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Abstract The Cenozoic Sulu Sea arc-basin system is situated in the tectonic junction between the South China Sea (SCS), northern Borneo, Palawan Continental Terrane, Philippine Mobile Belt, and Celebes Sea. We compare new/published geochronological and geochemical data from across the circum-Sulu Sea region, and summarize seven major magmatic phases from the Middle Eocene to Pleistocene. The Middle Eocene (42.65 Ma) Sabah ophiolite and Eocene-Oligocene (34-33 Ma) Central Palawan ophiolite have MORB-IAT-transitional features, representing an intraoceanic subduction setting in the Paleogene northern Borneo and central-southern Palawan. After the SCS opening (~32 Ma) and ridge jump (~25 Ma), late-stage Proto-SCS subduction (24-21 Ma) may have formed the Panay arc andesite and the BABB magmatism in SW Zamboanga peninsula. Starting of final convergence between the Palawan Continental Terrane and northern Borneo-SW Philippines (~21 Ma) likely caused regional uplift/thrusting, forming the Top Crocker Unconformity and triggering the NW-dipping Celebes Sea subduction. The subduction may have formed arc magmatism (21-18 Ma) in the Cagayan ridge and its continuation in Panay and NE Sabah, and opened the NW Sulu Sea back-arc basin through continental crust attenuation. Subduction rollback likely occurred in 17-14 Ma and 13-9 Ma, shifting arc magmatism southeast to the Sulu ridge and opening the SE Sulu Sea back-arc basin. NW-dipping Celebes Sea subduction largely ceased after ~9 Ma, followed by extension-related uplift/exhumation and 4-0.2 Ma intraplate volcanism in northern Borneo. SE-dipping Sulu Sea subduction likely occurred along the Negros-Sulu trenches, and produced arc volcanism from ~4 Ma.

Plain Language Summary The Sulu Sea and the adjacent sea basins (e.g., Celebes and SCS) are situated at the junction between the Eurasian, Philippine Sea, and Indo-Australian plates. The opening and closure (when Australia-Eurasia eventually collide) of these basins represent the final tectonic episode of the Neo-Tethys, an ocean that separates the northern and southern continents. When and how these sea basins were created are long disputed. Here we present a regional tectonic reconstruction model by compiling new/published radiometric age and chemical data of major igneous suites from across the circum-Sulu Sea region. Our model suggests that the Sulu Sea was formed by the NW-dipping Celebes Sea subduction at ~21 Ma, in response to the collision between the South China-derived Palawan Continental Terrane and northern Borneo-SW Philippines. The Sulu Sea basin may have continued to expand till ~9 Ma, when NW-dipping subduction of the Celebes Sea stopped. Afterward, to the west of the Sulu Sea, within-plate extension in northern Borneo occurred and continues to the present-day; whereas to the east, subduction of the Sulu Sea may have occurred along the Negros-Sulu trenches, and produced arc volcanism from ~4 Ma.

1. Introduction

The Western Pacific is featured by its many island arc chains and marginal sea basins tectonically positioned between the Eurasia, Pacific, and India-Australian plates. These sea basins (e.g., South China, Banda, Molucca, Celebes, Sulu) are mostly developed in the Cenozoic, especially since the Middle Eocene when

India-Asia collided and Australia pressed north toward Sundaland, representing the final phase of the Neo-Tethys closure (Advokaat et al., 2018; Hall, 2002, 2012; Pubellier & Morley, 2014; Zaw et al., 2014). However, knowledge about the age and evolution of these basins, and how they interacted with the surrounding geological terranes, remains inadequate. For the Sulu Sea, its formation is variably linked to the subduction of the Proto-South China Sea (SCS) (after Hall and Breitfeld [2017]'s definition), SCS, and/or Celebes Sea, or represents a marginal basin similar to the SCS (Hutchison, 2004; Liu et al., 2014; Rangin, 1989; Rangin & Silver, 1990). Constraining the evolution timeline of the Sulu Sea is dependent on those of the surrounding terranes and sea basins, which are equally enigmatic. For instance, the NW Borneo-Palawan troughs were long regarded to be a still-active or relatively young subduction trench (e.g., Hamilton, 1979; Hesse et al., 2009; Hutchison, 2010; Simons et al., 2007), yet more-recent studies suggest that they were formed by gravity-driven flexure of the sediment wedge (e.g., Hall, 2013; Hall & Breitfeld, 2017). Timing of the (Proto)-SCS seafloor spreading and subduction remains unclear (e.g., Advokaat et al., 2018; Briais et al., 1993; Pubellier & Morley, 2014; Sibuet et al., 2016), and so is the collision of the Palawan Continental Terrane (including northern Palawan, western Mindoro(-Tablas), NW Panay, Reed Bank-Dangerous Grounds) with the Philippine Mobile Belt and northern Borneo. Suggested ages of the collision range widely from late Early Miocene (~20 Ma) (Yumul, Dimalanta, et al., 2009) to Late Miocene (~10 Ma) (Fan & Zhao, 2018). Different hypotheses on the timing of ocean basin opening/subduction and terrane collision are not necessarily mutual exclusive, as such events can be diachronous, particularly across such a vast region. This, however, highlights the importance to elucidate the tectonic timeline through compiling and comparing geological data from across the region.

In this study, we present zircon U-Pb-Hf isotope and whole-rock geochemical data on the newly identified Middle Eocene and early Late Miocene magmatism from northern Borneo. New and published geochronological/geochemical data of various magmatic suites from the circum-Sulu Sea region, including the Sulu Sea basin and Sulu-Cagayan arcs (northern Borneo, Sulu-Cagayan ridges, Panay, Negros, SW Zamboanga peninsula) (Figure 1), were compared to reveal any magmatic evolution trends and to synthesize a regional tectonic reconstruction model (Figure 11). In the model, the geological terrane definition is based on the GPlate tectonic model (EarthByte Group) (Matthews et al., 2016; Müller et al., 2018), while the paleolatitudes of geological terranes follow Hall (2012), which are in turn based on paleomagnetic evidence (e.g., Hall, Ali, et al., 1995; Hall, Fuller, et al., 1995). Timing of the key tectonic events in the model, for example, starting/cessation of Sulu Sea back-arc basin opening, is based on our age compilation and geological interpretations.

2. Tectonic Subdivisions of the Sulu Arc-Basin System

2.1. Sulu Sea

The Sulu and Celebes Seas are bounded by Borneo to the west, Sulawesi to the south, Philippine Mobile Belt to the east, and Palawan Continental Terrane to the north. The two sea basins are separated along the Sulu ridge, and the Sulu Sea is further subdivided along the ENE-trending Cagayan ridge into the NW and SE Sulu Sea basins (Figure 1) (Hutchison, 1992; Rangin & Silver, 1990; Rangin et al., 1990).

Seismic survey revealed thicker crust in the NW Sulu Sea (>10 km) than the SE Sulu Sea (~6 km), and the former is also considerably shallower (1,000–1,800 m deep) than the latter (greatest depth: 4,500–5,000 m) (Murauchi et al., 1973; Rangin & Silver, 1990). Interpreted paleomagnetic anomalies of the SE Sulu Sea basement range from C7 (23.96 Ma) in the northwest to C5 (9.79 Ma) in the southeast (Gradstein et al., 2012; Roeser, 1991; Shyu et al., 1991). The Ocean Drilling Program (ODP Leg 124) has drilled one hole in the SE Sulu Sea (Site 768), which penetrated ~1,046 m of sedimentary and pyroclastic rocks, and ~222 m of basement rocks (pillow/massive basalts, dolerite, and micro-gabbros) (Figures 1 and 2). The oldest sediments overlying the basement are late Early Miocene claystone with thin turbidite interbeds (Scherer, 1991). The claystone is overlain by thick (~197 m) volcaniclastics, comprising mainly dacitic-rhyolitic tuff and lapillistone interpreted to have erupted in a shallow marine-subaerial environment. The overlying brown claystone contains late Early to early Middle Miocene radiolarian and has low carbonate contents, suggesting sub-CCD (carbonate compensation depth) deposition and hence regional subsidence. After the Miocene,

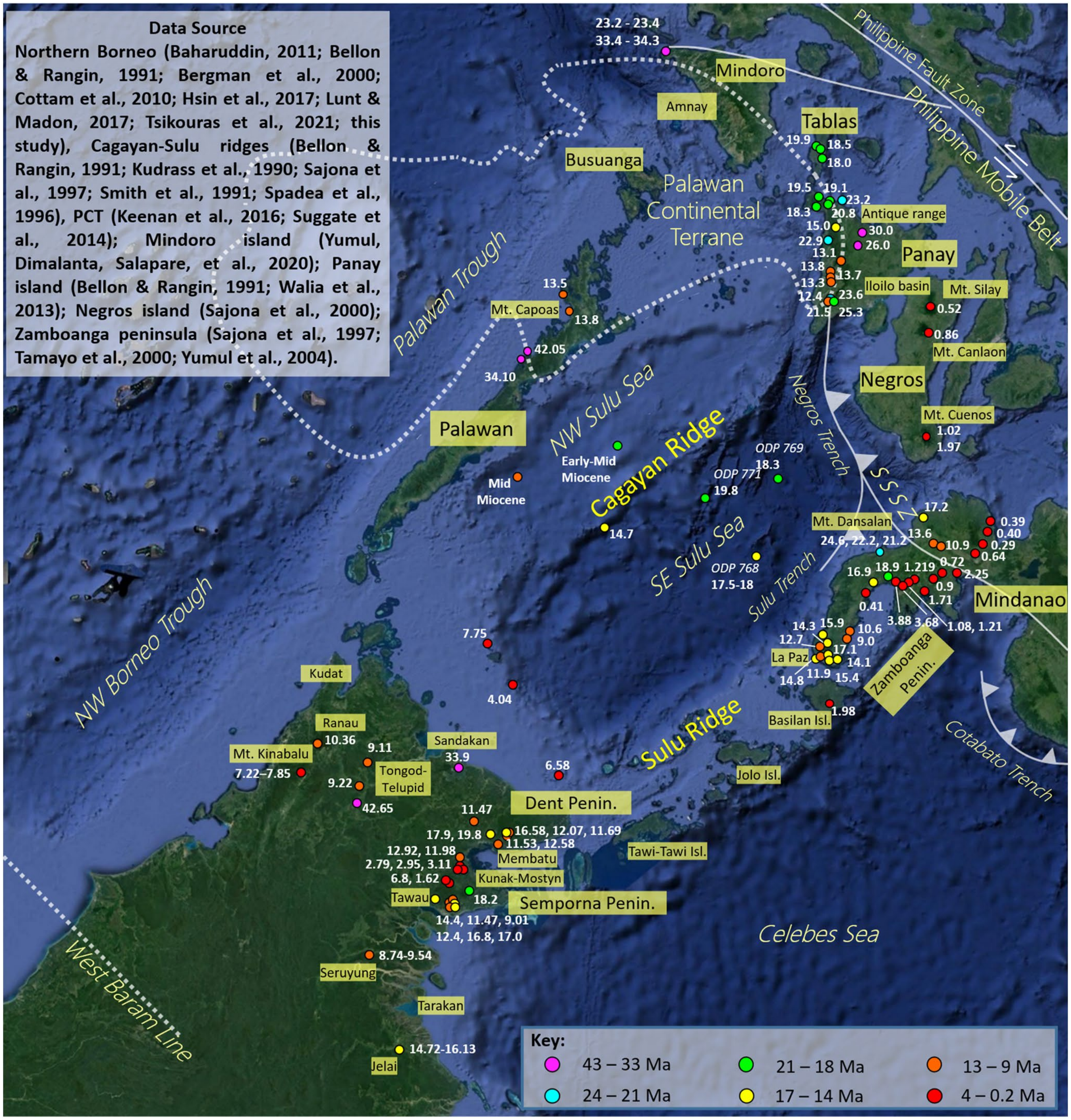

Figure 1. Google Earth topographic image of the circum-Sulu Sea region, showing new/published magmatic ages and major structures.

pelagic carbonates first appeared at ~2.4 Ma and gradually dominated at ~1.9 Ma (paleomagnetic age), suggesting rapid CCD deepening (e.g., Nichols et al., 1990; Pouclet et al., 1991; Silver & Rangin, 1991).

2.2. SW Sulu Arc (Northern Borneo)

The northern Borneo in this study encompasses the Seruyung-Jelai area (North Kalimantan, Indonesia), together with the Tongod-Telupid area and Dent and Semporna peninsulas (Sabah, East Malaysia), all

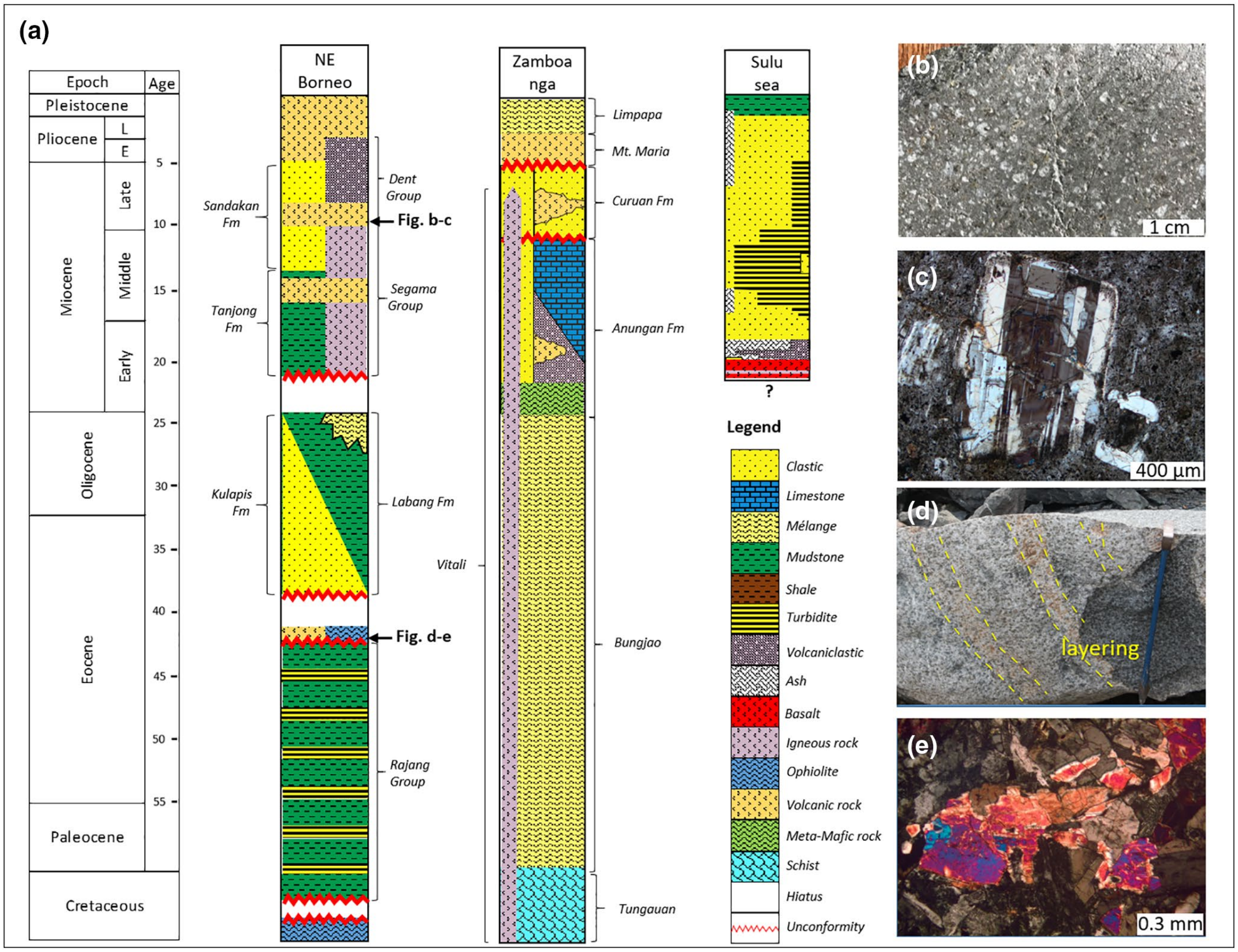

Figure 2. (a) Stratigraphic comparison from different parts of the Sulu arc-basin system (modified after Hall, 2013; Spadea et al., 1991a; Yumul et al., 2004); (b)–(e) Photos/microphotographs of: (b) Plagioclase-pyric basaltic-andesite core sample (Seruyung); (c) Plagioclase phenocrysts in devitrified groundmass (Seruyung; crossed-polar); (d) Eocene gabbro block in Miocene mélange (Tongod-Telupid); (e) Gabbro with cumulate texture (Tongod-Telupid; crossed-polar).

located east of the West Baram Line (Figure 1). NE North Kalimantan is extensively covered by tropical rain forest and swamp, and the Seruyung Au deposit (from which samples S1–S8 were collected; Figures 1 and 2) represents one of the rare outcrops in the region. Seruyung lies on the ENE-trending Sembakung lineament, which controls the local fault development and (basaltic-)andesite lava/tuff emplacement. The Seruyung (basaltic-)andesite was loosely attributed to Miocene by stratigraphic correlation (JRN, personal communication 2018). The Jelai volcanics are exposed ∼50 km south of Seruyung. Like Seruyung, the Jelai lavas/pyroclastics are mainly basaltic-andesitic, but as to be described later these two nearby volcanic suites have rather different ages and geochemistry. The Jelai volcanics lie unconformably above the Upper Eocene-Middle Miocene Sebakung Formation (Fm.) shallow-marine clastics and reef limestone, and are overlain unconformably by the Langap Fm. lacustrine clastics (Baharuddin, 2011; Heryanto et al., 1995; Sulistyawan et al., 2013).

The Sabah basement rocks comprise various Triassic-Jurassic (250.7-178.6 Ma) granites and metamorphic units in Segama valley (Burton-Johnson et al., 2020; Dhonau & Hutchison, 1966; Graves et al., 2000; Leong, 1977, 1998). Mafic-ultramafic rocks in central-northern Sabah were long interpreted to be ophiolitic (Omang, 1995, 1996; Omang & Barber, 1996; Omang et al., 1994), but Imai and Ozawa (1991) and Tsikouras et al. (2021) argued that while some do have a typical ophiolitic assemblage (serpentinized peridotites, amphibolite schist/gneiss, gabbro, sheeted dykes, pillow basalts), others may have a continental origin. These ophiolitic rocks are commonly in faulted contact with the "Chert-Spilite Formation" (Jasin et al., 1985; Leong, 1977), a term not adopted in some subsequent studies because these lithologies may have different origins (Jasin, 1992; Jasin & Tongkul, 2013). The radiolarian cherts in Darvel bay/Telupid yielded Early Cretaceous (Valanginian-Barremian: 139.8-126.3 Ma) ages, while those in Baliojong valley and Kudat peninsula yielded Early Late Cretaceous (Barremian-Cenomanian) ages (Jasin, 1992). The Upper Eocene-Oligocene Crocker and Trusmadi Formations (eqv. Labang Formation in central-eastern Sabah) comprise deep pelagic sediments, and are overlain by the Lower Miocene Kudat Fm. clastic sediments across the Top-Crocker Unconformity (TCU). Although the TCU is sometimes used interchangeably with the term Base Miocene Unconformity, the unconformity does not always located in the base Miocene, for example, sediments below the TCU were dated to be post-24.3 Ma (fossil age) or 20 Ma (Rb-Sr age) (Lunt, 2019; Wade et al., 2011, and references therein). Formation of the TCU is interpreted to signify either the collision between the Palawan Continental Terrane and northern Borneo-SW Philippines (Hall et al., 2008; Van Hattum et al., 2013) or the SCS spreading-ridge jump (Lunt & Madon, 2017), although how the latter generated the TCU was not specified.

In northernmost Sabah, the highly sandy Kudat Formation contains heavy mineral (including kyanite and garnet)-bearing sediments that are absent in the Crocker/Labang Fm. flysch over most of Sabah, and is probably sourced from north of Borneo, for example, kyanite-bearing garnet amphibolite in the pre-Middle Eocene Central Palawan ophiolite (Encarnación et al., 1995; Van Hattum et al., 2006, 2013). Sediment deposition is disputed to be before (e.g., Van Hattum et al., 2013) or after (Lunt, 2019) the TCU formation. Above the TCU, another prominent unconformity in Sabah-southern Palawan is the Deep Regional Unconformity (DRU; 14-12 Ma), which was originally associated with the end SCS spreading (Hutchison, 2004; Levell, 1987), but later also attributed to a Mid-Miocene pause in regional compression (Sabah Orogeny) (Lunt & Madon, 2017, and references therein). The Middle Miocene Unconformity (MMU) was occasionally used interchangeably with the DRU. While the MMU is clearly defined in offshore Sarawak, its referred ages differ (16-12 Ma) at different places in Sabah and SW Philippines (Lunt, 2019; Steuer et al., 2014). Another regional unconformity, termed the Shallow Regional Unconformity (SRU), may have developed at 11-10 Ma by a regional extension event (Hall, 2013). In eastern Sabah, volcanics in the Dent and Semporna peninsulas were feldspar K-Ar dated to be 18.8-17.9 and 18.2-14.4 Ma, respectively (Bergman et al., 2000). A much younger, dominantly basaltic volcanism at Tawau and Kunak-Mostyn was dated at Pliocene (whole-rock K-Ar age: 3.11-2.79 Ma) (Rangin et al., 1990) to Pleistocene (zircon U-Pb age: ~0.5 Ma) (Hsin et al., 2017).

2.3. Central Sulu Arc (Sulu-Cagayan Ridges)

The Sulu ridge is geographically divided into the western (Sibutu and Tawi-Tawi islands), central (Jolo and Marungas islands), and eastern (Basilan island and SW Zamboanga peninsula) segments (e.g., Castillo et al., 2007). Little is known about the western segment, except that the Tawi-Tawi islands contain possible dismembered ophiolites and some Ni mining projects. Volcanics in the central segment consist mainly of aphyric to olivine-/plagioclase-phyric basalts and (basaltic-)andesites. Volcanics in the eastern segment vary from basaltic to rhyolitic, and include aphyric or olivine-phyric basalt, andesite, and porphyritic dacite/rhyolite with plagioclase and amphibole phenocrysts (Castillo et al., 2007; Sajona et al., 1996, 1997). The Sulu trench lies offshore of the NE Sulu ridge, and south of the NNW-trending Negros trench. A seismic-interpreted accretionary complex is present on the NW-flank of the Sulu ridge (Rangin & Silver, 1991; Schlüter et al., 1996), albeit few geological data of this complex are available. There is no report of its on-shore occurrence in SE Sabah or SW Zamboanga peninsula.

Around 250 km northwest of the Sulu ridge lies the submerged Cagayan ridge remnant arc (Figure 1). Two holes (ODP Site 769 and 771) were drilled on the SE flank of the ridge. The oldest rocks recovered are basaltic-andesitic lapillistone and tuff, probably erupted in a subaerial/shallow marine environment with minimal sediment reworking. These volcaniclastics were constrained to be Early Miocene by the overlying early Middle Miocene (foram and radiolarian age) claystone, coeval with the SE Sulu Sea volcaniclastics (Site 768) (Kudrass et al., 1990; Nichols et al., 1990; Spadea et al., 1991b).

2.4. NE Sulu Arc (Panay Island-SW Zamboanga Peninsula) and Palawan Continental Terrane

The Buruanga peninsula in NW Panay is considered as part of the Palawan Continental Terrane, while the rest of Panay is likely part of the NE Sulu arc and Philippine Mobile Belt (Figure 1) (Gabo et al., 2009; Yumul, Dimalanta, et al., 2009). At Buruanga, pre-Cenozoic stratigraphy includes Middle Jurassic pelagic chert (Unidos Fm.) and limestone (Gibon Fm.), and the Mid-/Upper-Jurassic Saboncogon Fm. siliceous mudstone-sandstone (Zamoras et al., 2008). The Gibon Fm. limestone is intruded by the Patria quartz diorite, which yielded consistent Early Miocene whole rock/biotite K-Ar (20.9-19.5 Ma) (Bellon & Rangin, 1991) and zircon U-Pb (18.3 ± 0.2 Ma) (Walia et al., 2013) ages. Across the Nabas thrust fault in the southern Antique Range, the Cretaceous-Early Eocene Antique Ophiolite comprises tectonic slices of serpentinized peridotites, layered/isotropic gabbros, (rare) sheeted-dikes, pillow/sheet-flow basalts, and chert (Tamayo et al., 2001; Yumul et al., 2013). The ophiolite is unconformably overlain by the Miocene Lagdo Fm. andesitic breccias and clastics. The northern Antique range is dominated by Miocene volcaniclastics, basaltic flows, and deep marine clastics. These Miocene rocks are overlain by Pliocene-recent shallow marine to terrestrial clastics (Rangin et al., 1989; Walia et al., 2013; Zamoras et al., 2008).

The SW Zamboanga peninsula borders with the Philippine Mobile Belt along the Siayan-Sindangan suture zone (SSSZ) (aka. Sindangan-Cotabato-Daguma lineament), an ancient suture zone and still-active sinistral fault (Figure 1). The peninsula is suggested to contain a continental basement that becomes more ophiolitic toward the northeast (Tamayo et al., 2000). Close to the SSSZ, the basement comprises a mélange with metaultramafic clasts. Above that lies the metagreywackes, quartz-(chlorite)-sericite schists and epidote-amphibolite of the Mt. Dansalan Metamorphics. The Metamorphics and the Lower to Middle Miocene Camanga Sediments (sandstone-siltstone interbeds and limestone) are overlain by the Miocene-Pliocene Ipil (porphyritic-)andesite and tuffaceous sandstone (Yumul et al., 2004, and reference therein).

Away from the SSSZ in the SW Zamboanga peninsula, the basement comprises the Tungauan schist and Baugiao mélange. The Baugiao mélange contains clasts of metavolcanics/sediments, marble, metamorphic rocks (slate, phyllite, low-grade schist), and harzburgite in a serpentinite matrix. The mélange is unconformably overlain by the Anungan Formation, which contains a lower sedimentary member with Early-/Mid-Miocene nanofossils, a middle volcanic member with andesitic-dacitic pyroclastic-lava interbeds (whole-rock K-Ar age: 18.2–12.7 Ma), and an upper crystalline/fossiliferous limestone member attributed also to be Early to Middle Miocene. The Anungan Formation is unconformably overlain by the Curuan Fm. clastics and andesites (Yumul et al., 2004, and reference therein). These sequences are unconformably overlain by the Mt. Maria andesitic-dacitic flows and tuffs (whole-rock K-Ar age: 3.88-0.34 Ma) (Sajona et al., 1996, 1997) (Figure 2).

3. Samples and Methods

3.1. Sample Descriptions

In this study, eight (basaltic-)andesite samples were collected from Seruyung (3.653547°N, 116.716511°E; North Kalimantan), together with three cumulate gabbro-dolerite from Tongod-Tulupid (5.420056°N, 116.975442°E; Sabah), and two andesite-dacite from Ruwai (1.534479S, 111.301324°E) and Beruang Kenan (0.616667°N; 113.416667°E) (Central Kalimantan). As to be explained later, both Central Kalimantan samples yielded Devonian ages and may represent deeper crustal rocks in northern Borneo, from which the Devonian inherited zircons in the Eocene Tongod-Tulupid gabbros were derived. The Seruyung samples are plagioclase-phyric (basaltic-)andesite, with 50%–60% plagioclase and 10%–15% pyroxene phenocrysts in a glassy groundmass (10%–30%). Minor (<5% each) glass shards and Fe-Ti oxides are also present. The Tongod-Tulupid layered gabbro samples were collected from boulders in the predominantly Miocene ophiolite (Lai, 2020). The samples are medium-grained, and have 50% plagioclase, 35% clinopyroxene, 10% hornblende, and accessory (<5%) Fe-Ti oxides. The Ruwai and Beruang Kenan andesitic-dacitic volcanics were intruded by Cretaceous and Miocene granitoids (Lai et al., 2020). The rocks contain phenocrysts of feldspars (50%–60%), quartz (10%), and minor (<5%) volcanic lithics, pyroxene, and hornblende set in a devitrified groundmass (20%–30%).

3.2. LA-ICP-MS Zircon U-Pb Dating

Separated by conventional density and magnetic separation technique, zircons from 11 samples (Seruyung = 8, Tongod-Tulupid = 1, Central Kalimantan = 2) were U-Pb dated with a Resonetics RESOlution S-155 laser ablation (LA) system coupled with an Agilent 7900 ICP-MS, at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS). Each analysis (29 μm spot-size) comprises a 20–30 s laser-off background signal acquisition, followed by a 50 s laser-on sample data acquisition. Helium was used as the carrier gas, and NIST 610 standard for external calibration and Si as an internal standard. The primary 91500 (Wiedenbeck et al., 1995) and secondary Plesovice (Sláma et al., 2008) zircon standards were analyzed between every five unknowns. For the Plesovice zircon, the concordia age (346.1 ± 2.9 Ma) yielded in our analyses is consistent (<3% error) with the recommended value (ID-TIMS: 337.13 ± 0.37 Ma) (Sláma et al., 2008). Analytical precision is commonly ∼4%. Off-line selection and integration of the background and analyte signals, together with time-drift correction and quantitative calibration, were done with ICPMSDataCal. Only zircon spots with concordant or nearly concordant ages (<15% discordance) were considered. Detailed analytical conditions and procedures for both U-Pb and Hf isotope analyses are as described in Xu et al. (2019, and references therein).

3.3. LA-MC-ICP-MS Zircon Hf Isotope Analysis

The analysis was performed with a Resonetics RESOlution M-50 193 nm LA system coupled with a Thermo Scientific Neptune Plus multicollector (MC)-ICP-MS at the GIGCAS. Zircon Hf isotope analysis spots from all the 11 dated samples were selected close to the U-Pb spot in the same age domain (no inherited core or growth rim found in CL imaging). Analytical conditions include 45 μm beam size, 4 J cm^{-2} energy density, 6 Hz repetition rate, and helium as the carrier gas. Each analysis consists of 400 cycles (integration time = 0.131 s/cycle), and comprises 28 s laser-off gas blank background measurement, followed by 30 s laser-on sample signal collection. The ^{180}Hf gas blank was below 0.2 mv during our analysis, and ^{173}Yb and ^{175}Lu were used to correct the isobaric interference of ^{176}Yb and ^{176}Lu on ^{176}Hf. Natural $^{176}Yb/^{173}Yb$ (0.79381) and $^{176}Lu/^{175}Lu$ (0.02656) ratios were used in the correction (Segal et al., 2003). The mass bias factor of Yb was calculated from the measured $^{173}Yb/^{171}Yb$ and the natural ratio (1.13268), while those of Lu and Yb are assumed to be the same. The $^{176}Hf/^{177}Hf$ mass bias was normalized to $^{179}Hf/^{177}Hf$ (0.7325) with an exponential law. Analyses of the Plešovice zircon ($n = 40$, measured between every five unknowns) yielded a weighted mean $^{176}Hf/^{177}Hf$ of 0.282484 ± 0.000011 (2 SD), consistent (within errors) with the recommended value (0.282482 ± 0.000013; 2 SD) (Sláma et al., 2008).

3.4. Whole-Rock Geochemical Analysis

The analysis was conducted at the Bureau Veritas Laboratory in Vancouver, Canada. The Seruyung ($n = 8$) and Tongod-Tulupid ($n = 3$) samples were crushed and pulverized to 200 mesh. The powdered samples were digested by Li-borate fusion. Concentrations of major element oxides and trace elements (including REEs) were measured with ICP-ES and ICP-MS, respectively. Detailed analytical procedures followed the *AA Litho Package*. The ioGAS™—REFLEX program was used for data analysis and visualization.

4. Results

4.1. Zircon U-Pb-Hf Isotopes

Zircons from the Seruyung (basaltic-)andesite (S1–S8) are mostly short prismatic and euhedral. Euhedral grains are 50–200 μm long and 40–100 μm wide. The zircons have oscillatory/sector zoning but lack inherited core. They (from all eight samples) have $^{206}Pb/^{238}U$ ages of 8.5–11.1 Ma (no inherited zircons), yielding similar weighted average ages of 8.90–10.15 Ma (Figure 3). The samples yielded largely positive εHf(t) (1.07–8.47), and have predominantly Mesoproterozoic-Neoproterozoic (0.55–1.69, mostly 0.70–1.18 Ga) two-stage model ages (T_{DM2}), which assume that the parental magma was produced from the average continental

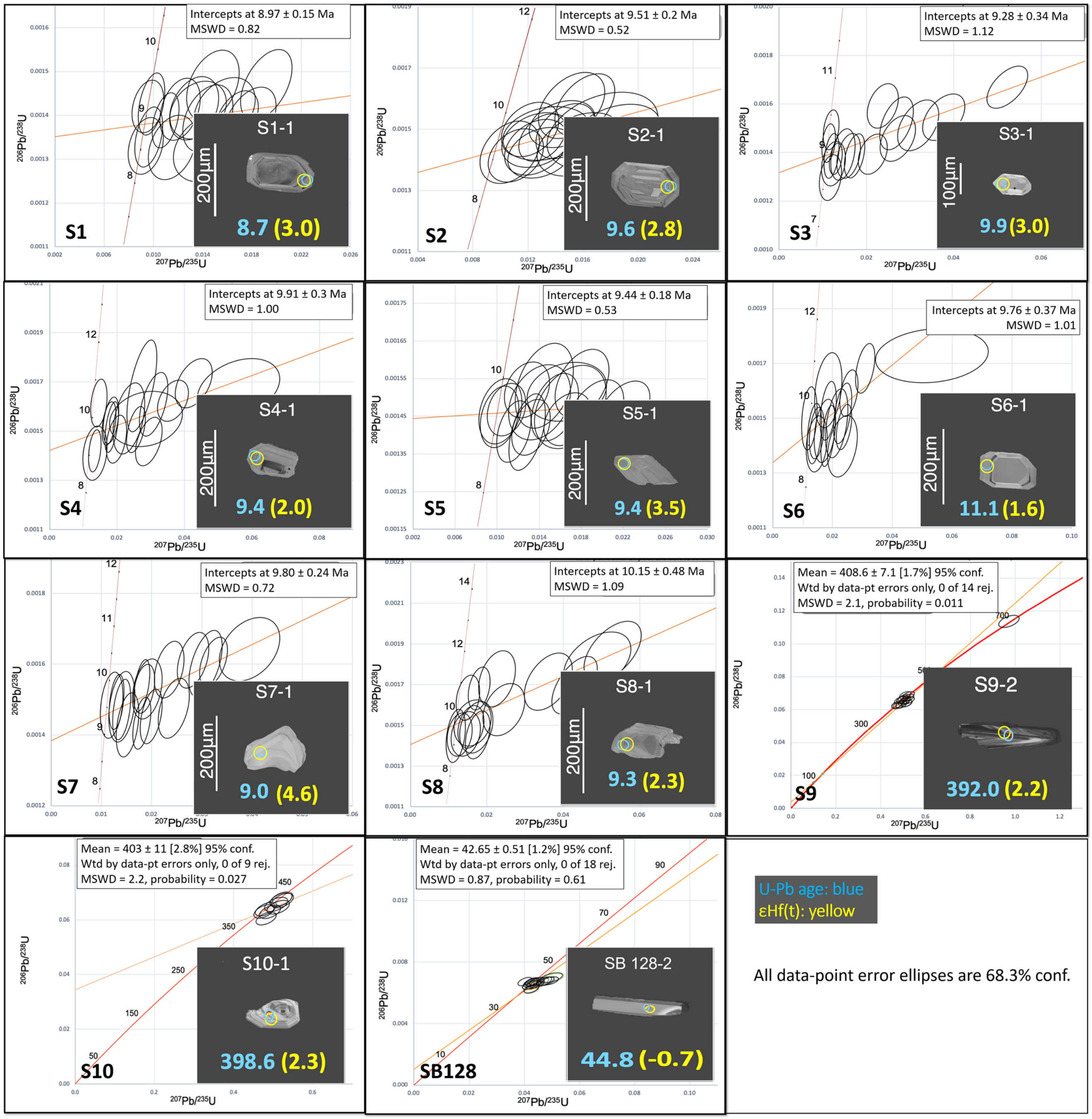

Figure 3. Zircon U-Pb concordia diagrams and representative CL images of the Seruyung basaltic-andesite (S1–S8), Central Kalimantan andesitic-dacitic volcanics (S9 and S10), and Tongod-Tulupid gabbro (SB128).

crust ($^{176}Lu/^{177}Hf = 0.015$) sourced from the depleted mantle (Spencer et al., 2020, and references therein) (Lai, 2020).

Zircons from the Sabah gabbro (SB128) are prismatic/elongated (100–200 μm long and 20–50 μm wide), but many are broken grains. Oscillatory/sector zoning is uncommon, and inherited core is absent. Other than two inherited zircons (392.4 and 395.5 Ma), most zircons (18 out of 20) yielded Eocene $^{206}Pb/^{238}U$ ages (40.0–44.8 Ma) and a weighted average age of 42.65 ± 0.51 Ma (MSWD = 1.2) (Figure 3). Most zircons have εHf(t) = -3.84 to 6.69, and Mesoproterozoic-Neoproterozoic T_{DM2} (0.69–1.66, mostly 0.69–1.27 Ga).

Zircons from the two Central Kalimantan samples (S9–S10) are mostly anhedral or broken fragments (up to 100 μm long). Oscillatory/sector zoning is present but uncommon. The main zircon cluster from the Beruang Kanan (S9) and Ruwai (S10) samples yielded similar weighted average ages of 408.6 ± 7.1 Ma (MSWD = 2.1; n = 14) and 403.0 ± 11.0 Ma (MSWD = 2.2; n = 9), respectively (Figure 3). Sample S9 has five younger zircons (9.5, 9.7, 101.1, 133.4, and 133.8), which are coeval with the intruding granitic dykes/veins and may have brought into the sample by the veins. Sample S10 contains one Proterozoic inherited zircon (1782.3 Ma). As for Hf isotopes, Sample S9 has εHf(t) = −4.16 to 7.62 and T_{DM2} = 0.80–1.66 Ga, while sample S10 has εHf(t) = −8.65 to 6.69 and most T_{DM2} = 1.07–1.56 Ga (Lai, 2020).

4.2. Whole-Rock Geochemistry

The Seruyung (basaltic)-andesites have medium MgO and low-medium SiO_2 and TiO_2 contents. Positive correlations of SiO_2 with many incompatible elements (Th, La, Zr, Nb), and negative correlations with MgO, CaO, TiO_2, P_2O_5, and Sr indicate fractionation of pyroxene, plagioclase, apatite, and Fe-Ti oxides. The Tongod-Telupid gabbros have lower SiO_2 and certain incompatible trace element (e.g., La, Zr, and Nb) contents than the Seruyung (basaltic)-andesite, and are also less fractionated (lower La/Yb) and alkali (lower K_2O and Nb/Y) (Figure 4; Lai, 2020). More trace element compositional features are to be described in Section 5.

5. Magmatic Phases in the Cenozoic Sulu Arc-Basin System

Very few geochronological studies were conducted on the Sulu arc-basin system in the past two decades. Published ages are mainly whole-rock or mineral K-Ar (some Ar-Ar) ages, and we have supplemented that with our new LA-ICP-MS zircon U-Pb ages. Although K-Ar isotope systematics is susceptible to resettling by postmagmatic thermal (alteration/metamorphism) events and weathering, we suggest that the published K-Ar ages are reasonably reliable because they are as follows: 1) consistent in different studies and across different parts of the Sulu arc-basin system; 2) supported by our new zircon U-Pb ages and published (radiolarian, magnetic-anomaly, zircon U-Pb) ages; 3) unlikely to be modified by postmagmatic alteration/metamorphism. For instance, the early Late Miocene and Plio-Pleistocene K-Ar ages are clearly separated by a 4–11 Myr gap, instead of connected by a scattered age spectrum typical of (partial) age resetting. The same logic applies to the other magmatic phases, which are with clear and consistent age gaps (and/or geochemical distinction) across the circum-Sulu Sea region. The new/published age (n = 127) and geochemical (n = 230) data compilation has distinguished seven major magmatic phases in the (I-II) pre-Middle Oligocene (43 Ma and 34-33 Ma), (III) Late Oligocene-early Early Miocene (24-21 Ma), (IV) mid Early Miocene (21-18 Ma), (V) late Early Miocene-Middle Miocene (17-14 Ma), (VI) early Late Miocene (13-9 Ma), and (VII) Pliocene-Pleistocene (4-0.2 Ma) (Figures 5–9).

5.1. Phase I–II: Pre-Middle Oligocene (pre-33 Ma)

The Middle Eocene (42.65 ± 0.51 Ma) Tongod-Telupid (Sabah) cumulate gabbro blocks in this study (Figures 1 and 2) were situated in a mélange dominated by ophiolitic mafic-ultramafic rocks of Late Miocene age (Lai, 2020). In other places of Eastern Sabah, the ophiolitic mélange contains also clasts of Cretaceous radiolarian cherts (Aitchison, 1994; Asis & Jasin, 2012; Jasin, 2000) in a mudstone matrix (Jasin et al., 1995). The ~42.65 Ma age is broadly coeval with the recently reported Telupid gabbros (47 ± 2–42.5 ± 0.3 Ma) (Chien et al., 2019) and the Central Palawan granite (42 ± 0.5 Ma) (Suggate et al., 2014). The Tongod-Telupid gabbro is largely MORB-island arc tholeiite (IAT)-transitional, resembling the nearby Darvel bay (Group II) basalts of Omang (1996) (Figure 6). Although without reliable radiometric age, these Darvel bay basalts occur as clasts in Eocene sediments with Cretaceous radiolarian chert (Rangin et al., 1990), implying possible early Cenozoic formation. Different from the reported Telupid gabbros that have high and positive εHf(t) (22-16 Ma) (Chien et al., 2019), our Tongod-Telupid gabbro has considerably lower εHf(t) (mostly -3.5 to +6.3), which altogether suggest a mantle-derived depleted source with various degrees of crustal input. Crustal input is also supported by the presence of Devonian (395.5-392.4 Ma) inherited zircons in the gabbro, which are coeval with our newly discovered andesitic-dacitic volcanics in Central Kalimantan. These

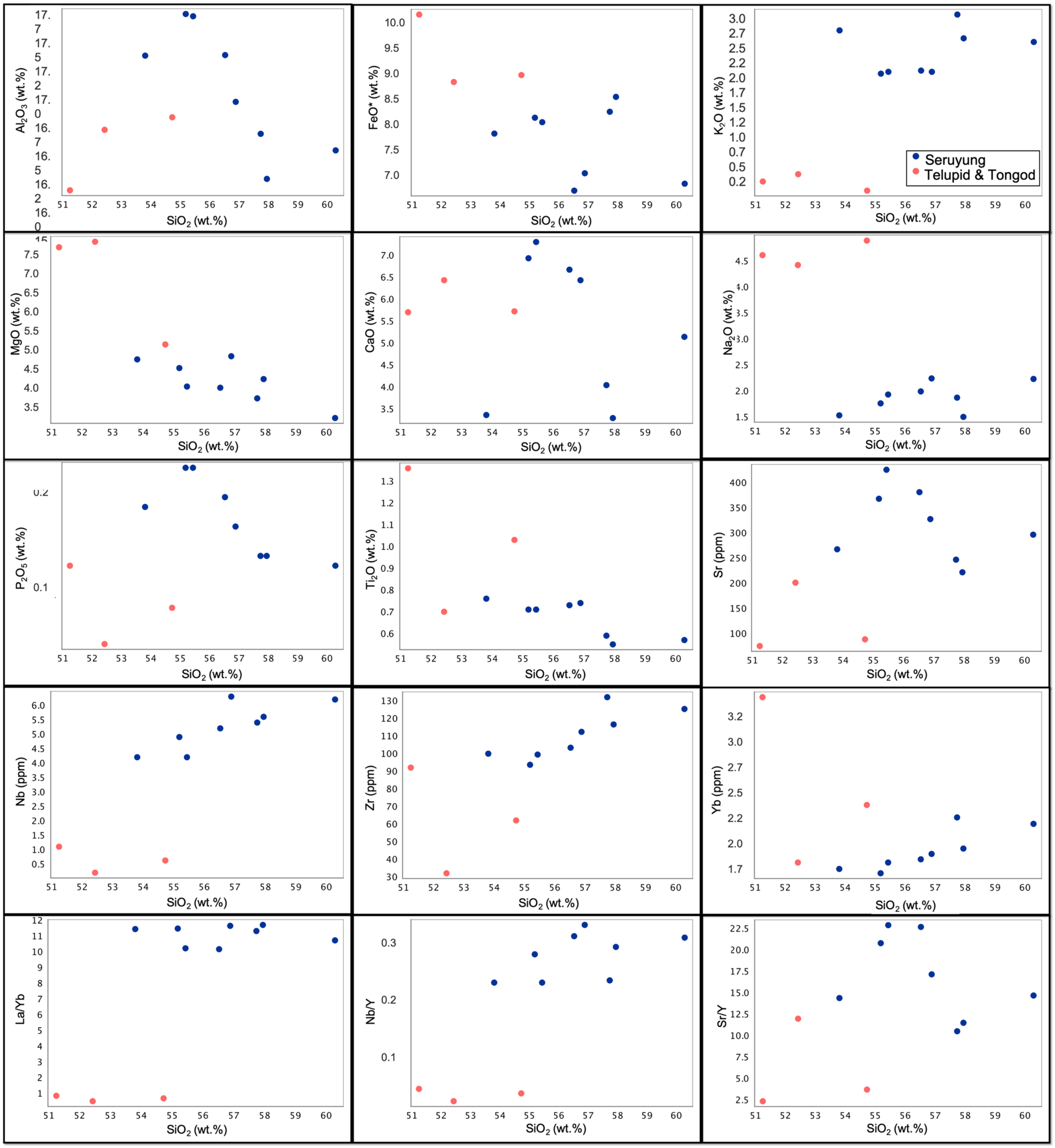

Figure 4. Harker-type diagrams for the Seruyung basaltic-andesite and Tongod-Tulupid gabbro samples.

Devonian volcanics represent the oldest reported magmatism in the whole of Borneo, and could represent a source for the Devonian inherited zircons. Devonian rocks were also reported in the Lower Devonian coral and stromatoporoid-bearing limestone blocks in SW Borneo (Rutten, 1940; Sugiaman & Andria, 1999). Consequently, instead of a MOR setting (Chien et al., 2019), we prefer a back-arc basin (BAB) setting for the Middle Eocene magmatism, which agrees with its MORB-IAT character (Figure 6). The Sandakan andesitic

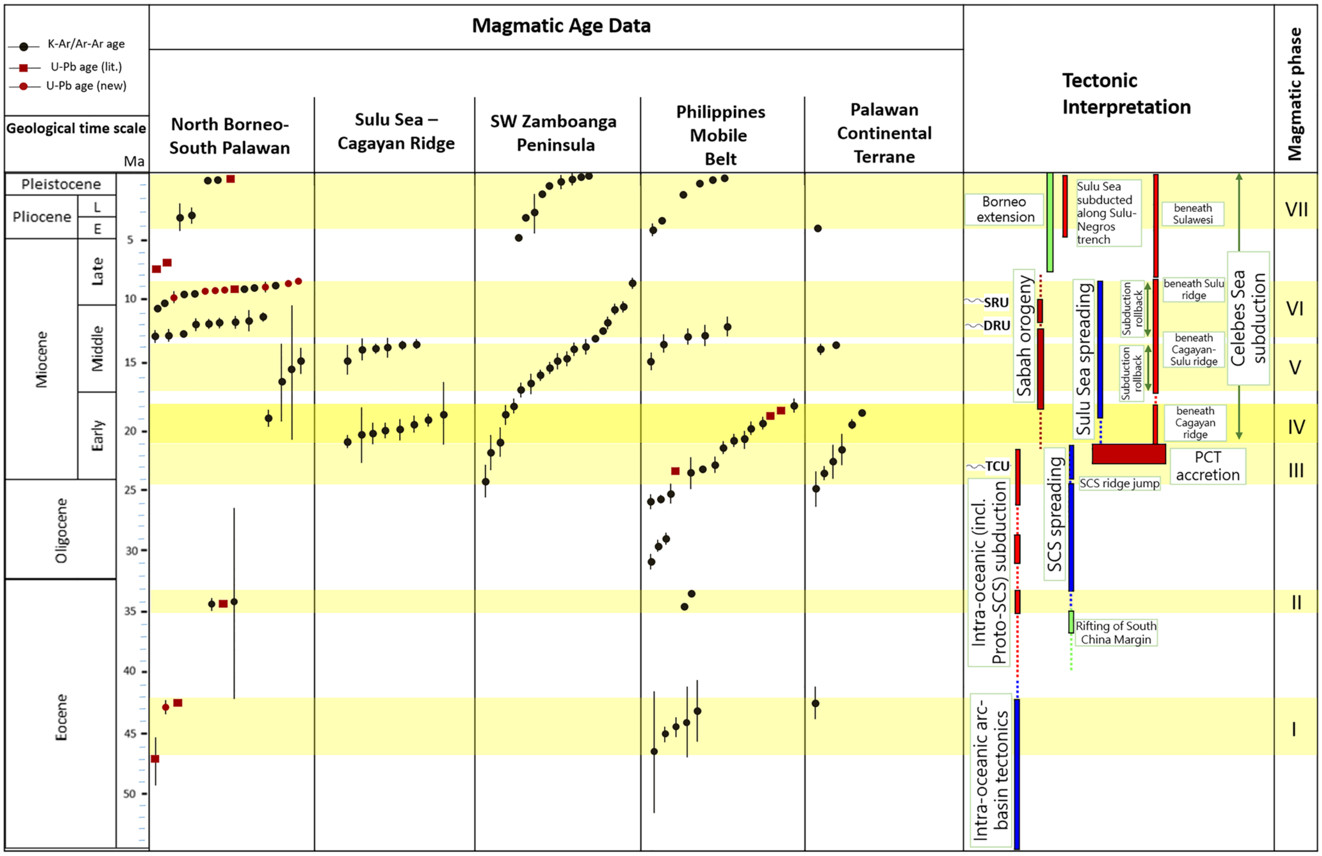

Figure 5. Box-plot of magmatic ages from across the circum-Sulu Sea region. Timeline of interpreted regional tectonic events is shown in the far-right column. Data source as in Figure 1.

tuff (33.9 ± 7.7 Ma; Swauger et al., 1995) is largely coeval with the ophiolites in Mindoro (Amnay; zircon U-Pb age: 34.3-33.4 Ma) (Yu et al., 2020; Yumul, Dimalanta, et al., 2020) and central Palawan (zircon U-Pb age: 34.1 Ma) (Keenan et al., 2016; Yumul, Jumawan, et al., 2009). Although no published geochemical data are available for the Sandakan andesitic tuff, the MORB(-IAT) and E-MORB-like signature of the Amnay and Central Palawan ophiolites are suggestive of a BAB setting (Jumawan, 1999; Keenan et al., 2016; Perez et al., 2013).

5.2. Phase III: Early Miocene (24-21 Ma)

Major Cenozoic magmatism in the circum-Sulu Sea region began with the latest Oligocene Mt. Dansalan amphibolite (interpreted gabbro protolith) in the Zamboanga peninsula (amphibole K-Ar age: 24.6-21.2 Ma) (Tamayo et al., 2000). These ages are likely robust because broadly coeval ages were also reported in the adjacent Panay, notably the Iloilo basalt-andesite basement rocks (K-Ar age: 26.2-21.5 Ma) (Bellon & Rangin, 1991) and the Lagdo Fm. andesitic tuff (zircon U-Pb age: ~23.2 Ma) (Walia et al., 2013). In the Th/Yb versus Nb/Yb diagram, the Mt. Dansalan metagabbros (Tamayo et al., 2000; Yumul et al., 2004) fall between the mantle array (MORB-end) and oceanic arc field (Figure 7; Pearce, 2014). The rocks have distinct arc-type negative Nb, Zr, and Ti anomalies. Subduction features, including enrichments of large ion lithophile elements (LILEs) over high-field strength elements (HFSEs), positive Pb-Sr anomalies (albeit can also be seafloor metasomatism related), and negative Nb-Ta and Ti anomalies, are also present in the Lagdo Fm. andesitic tuff (Walia et al., 2013) (Figure 7), and the Iloilo basalt-andesite are largely arc calc-alkaline (Bellon & Rangin, 1991). No Phase III magmatic rocks are reported in northern Borneo. We suggest that this

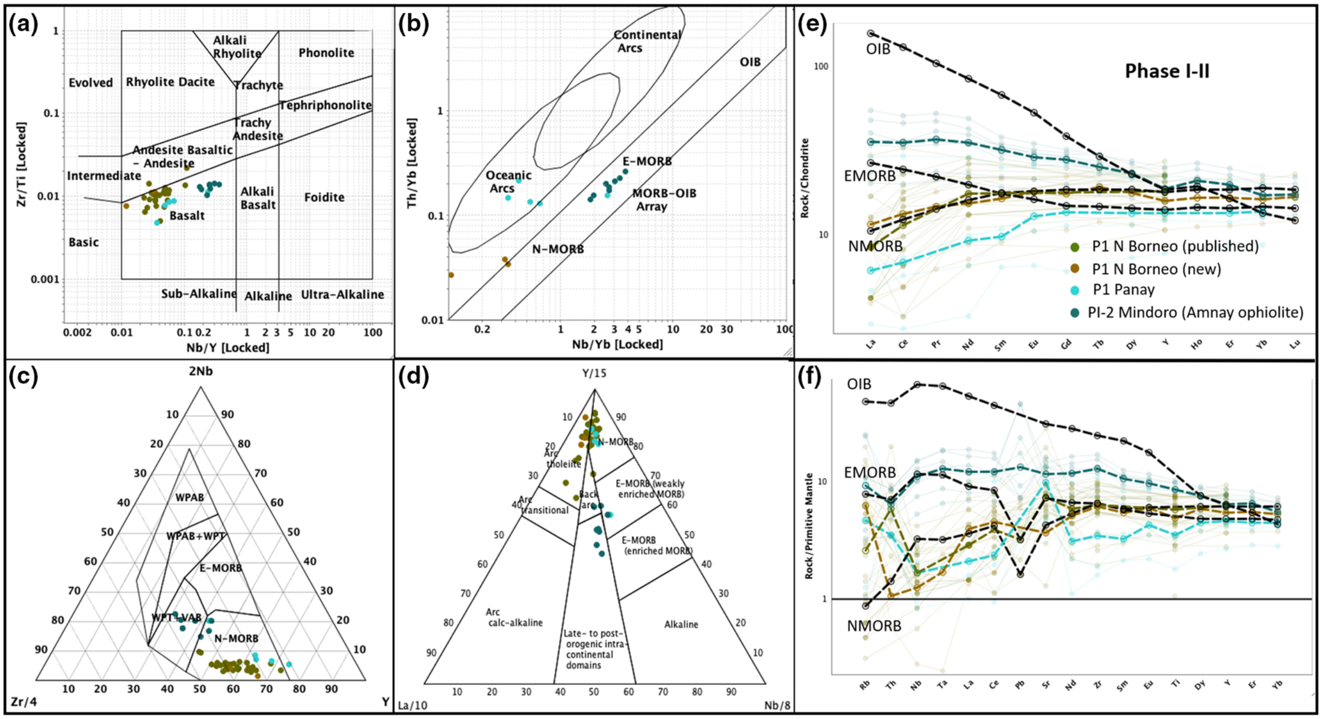

Figure 6. Geochemical diagrams for Phase I–II (>33 Ma) magmatism: (a) Zr/Ti versus Nb/Y (Pearce, 1996); (b) Th/Yb versus Nb/Yb (Pearce, 2014); (c) Ternary Zr-Nb-Y (Meschede, 1986); (d) Ternary La-Nb-Y (Cabanis & Lecolle, 1989); (e) Chondrite-normalized REE patterns; (f) Primitive-mantle (PM)-normalized multielement patterns. Chondrite-/PM-normalizing values are from Sun and McDonough (1989). Data source for Figures 6–10 are given in the text and Lai, 2020.

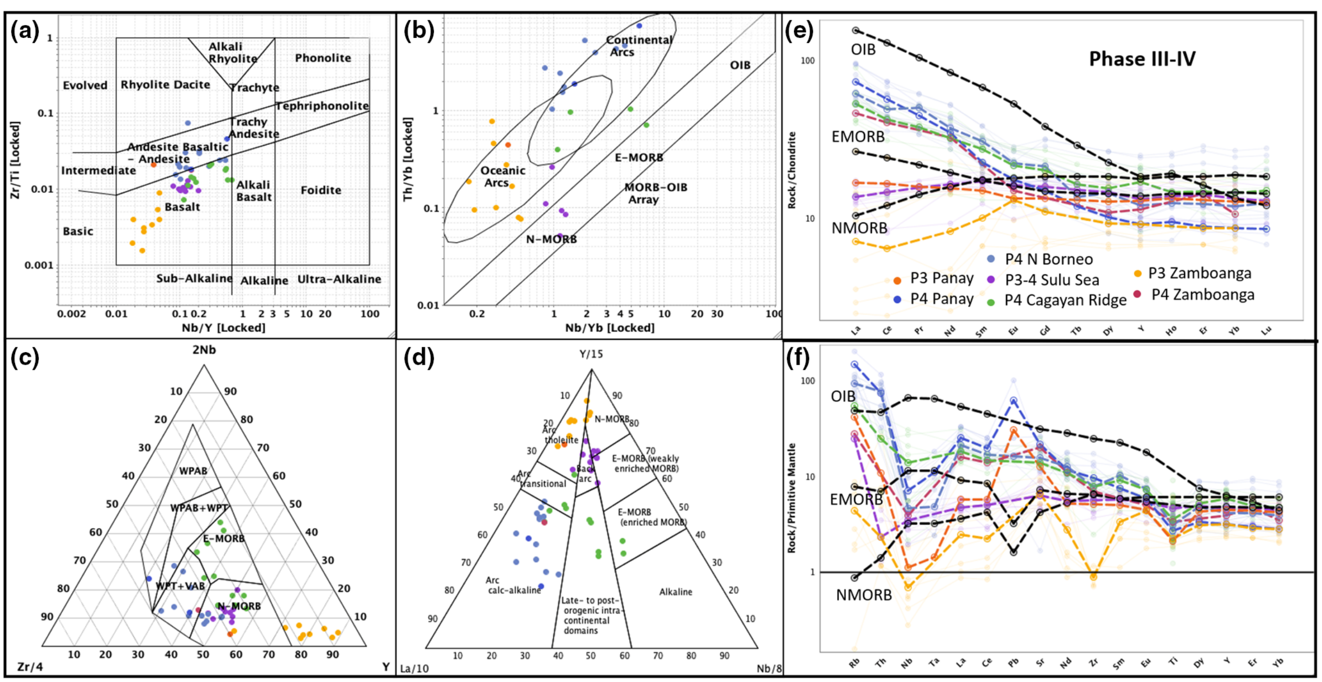

Figure 7. Geochemical diagrams for Phase III (24-21 Ma) and Phase IV (21-18 Ma) magmatism: (a) Zr/Ti versus Nb/Y; (b) Th/Yb versus Nb/Yb; (c) Zr-Nb-Y; (d) La-Nb-Y; (e) Chondrite-normalized REE patterns; (f) PM-normalized multielement patterns.

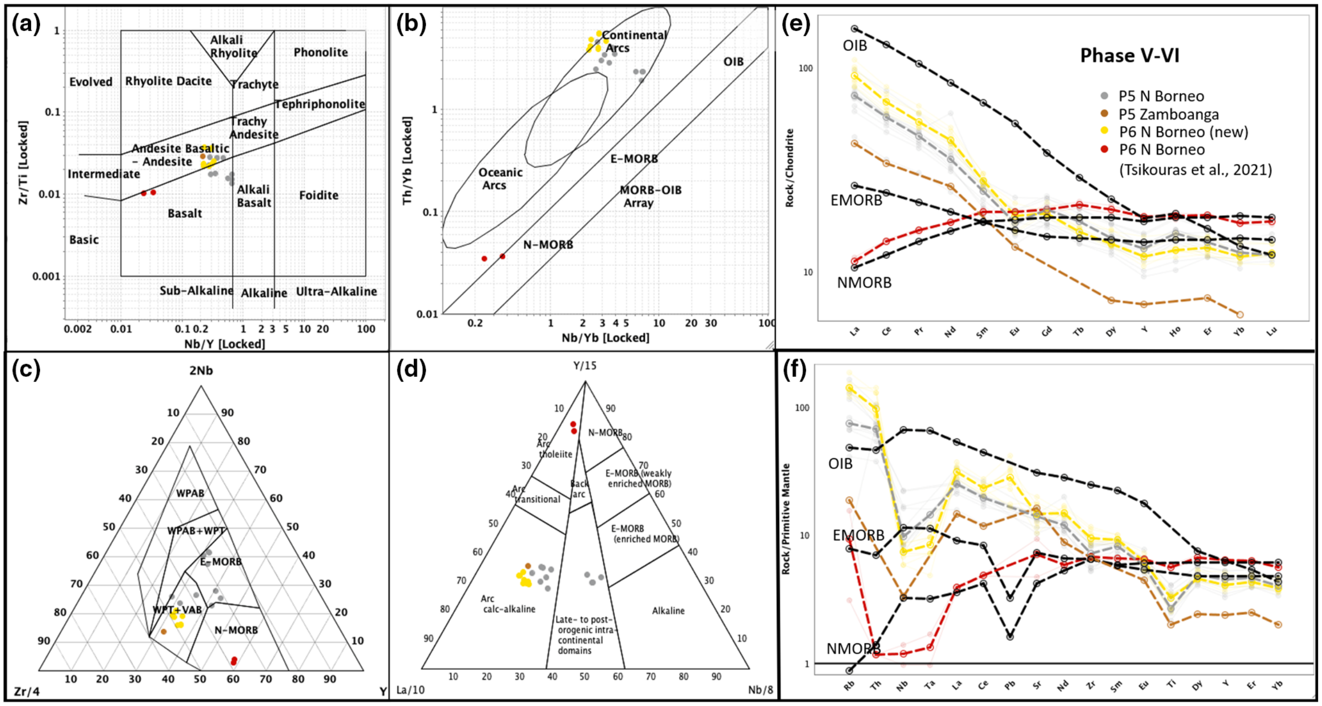

Figure 8. Geochemical diagrams for Phase V (17-14 Ma) and Phase VI (13-9 Ma) magmatism: (a) Zr/Ti versus Nb/Y; (b) Th/Yb versus Nb/Yb; (c) Zr-Nb-Y; (d) La-Nb-Y; (e) Chondrite-normalized REE patterns; (f) PM-normalized multielement patterns.

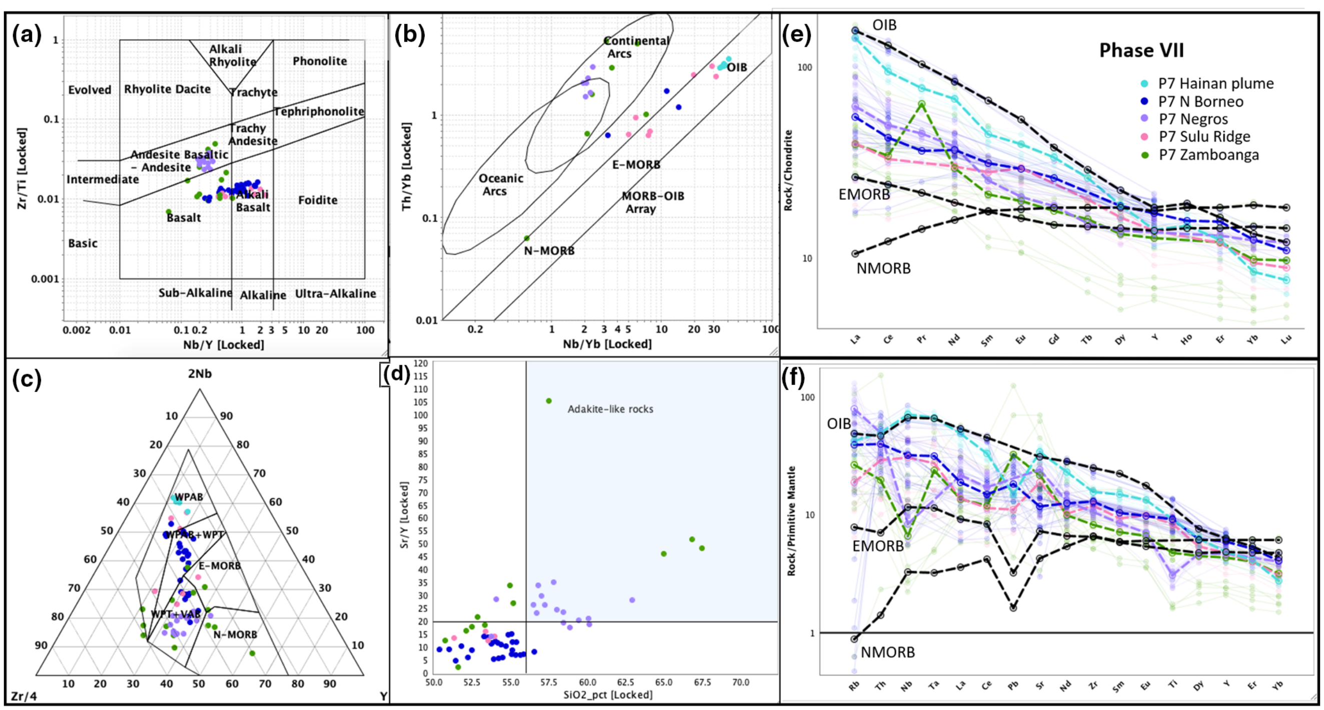

Figure 9. Geochemical diagrams for Phase VII (4-0.2 Ma) magmatism: (a) Zr/Ti versus Nb/Y; (b) Th/Yb versus Nb/Yb; (c) Zr-Nb-Y; (d) Sr/Y versus SiO_2 (Richards et al., 2012); (e) Chondrite-normalized REE patterns; (f) PM-normalized multielement patterns. Data from Hainan plume basalt are also shown for comparison.

Phase III magmatic gap in northern Borneo is likely genuine, since no 24-21 Ma inherited zircons are found in younger rocks analyzed in this study or in Tsikouras et al. (2021) (Figure 3; Lai, 2020).

5.3. Phase IV: Mid-Early Miocene (21-18 Ma)

There is no (or narrow <1 Myr) age gap between Phase III and IV, yet Phase IV magmatism is different from Phase III in terms of its much wider spatial distribution (covering also northern Borneo-Cagayan ridge) and its dominantly calc-alkaline intermediate compositions. The oldest Phase IV rocks are the Cagayan ridge (basaltic-)andesite (Site 769: 20.83-19.48 Ma; Site 771: 20.90 and 18.78 Ma) (Figures 1 and 5) (Bellon & Rangin, 1991). In its northern continuation in Panay, similar ages were reported from the Fragante Fm. tuffaceous sandstone (~19.1 Ma) and Patria quartz diorite (~18.3 Ma). Phase IV arc andesite was reported in SW Zamboanga peninsula (~18.95 Ma) (Sajona et al., 1997), which is coeval (within error) with the oldest Anungan Fm. volcanics (~18.2 Ma) (Yumul et al., 2004). In northern Borneo, andesitic-dacitic lavas/tuffs from the Dent (~18.8 Ma) and Semporna (~18.2 Ma) peninsulas have also similar ages (Bergman et al., 2000).

Geochemically, all the Early Miocene (Phase IV–V) Sulu Sea basalts are MORB-like tholeiitic. The rocks have mostly low Th/Yb and Nb/Yb ratios, and fall on/near the mantle array near the N-MORB (including BABB) end (Figure 7). These rocks also show N-MORB-like total (Σ) REE contents with nearly unfractionated patterns. In the primitive-mantle (PM)-normalized multielement diagrams (Sun & McDonough, 1989), the basalts are similar to BAB (IAT-MORB-transitional), notably in their elevated Rb and Th contents, positive Sr anomalies and negative Nb and Ti anomalies. The rocks show no discernible Eu anomalies. In northern Borneo, the Tungku andesite (Bergman et al., 2000) is geochemically similar to many coeval Cagayan ridge (basaltic-)andesites (Spadea et al., 1996). These rocks are featured by LREE and LILE enrichments between E-MORB and OIB, and HREE and HFSE contents around/below average OIB. The rocks have distinct negative Nb and Ti anomalies, and fall mainly into the continental arc field. Some other Cagayan ridge (basaltic-)andesite samples are E-MORB or N-MORB-like, with the latter mimicking the Sulu Sea BABB. The two Phase-IV Panay diorite samples reported by Walia et al. (2013) show similar arc-type affinity, including very high LREE/HREE and LILE/HFSE enrichments, positive Pb(-Sr) anomalies and negative Nb and Ti anomalies (Figure 7).

5.4. Phase V: Late Early Miocene-Middle Miocene (17-14 Ma)

Our age compilation suggests a short (~1 Myr) magmatic hiatus at 18-17 Ma, consistent with the paucity of volcanic materials in the late-Early Miocene clastics from the Cagayan ridge (Pouclet et al., 1991). (Basaltic-)andesite volcanism likely resumed at Jelai (feldspar K-Ar age: 16.13-14.72 Ma) (Baharuddin, 2011) and Tawau (16.3 and 14.4 Ma) (Bergman et al., 2000) in northern Borneo (Figure 1). Concurrently, the Anungan Fm. volcanics (17.1, 15.9-15.4, 14.8-14.1 Ma) (Yumul et al., 2004) and other volcanics in the central (~16.89 Ma) and SW (~14.94 Ma) parts of the Zamboanga peninsula (Sajona et al., 1997) were also erupted. Slightly younger volcanism was also reported in the Cagayan ridge Site 769 (15.07 and 14.25 Ma) and Site 771 (14.23 and 13.84 Ma) (Bellon & Rangin, 1991), but the volcanism there (and in Panay, except for the Valderrama unit) largely ceased after ~14 Ma (Bellon & Rangin, 1991), and took no part in Phase VI and VII (Figures 1 and 5).

Similar to their Phase IV counterparts, most Phase V (basaltic-)andesites in northern Borneo are featured by continental-arc-type high Th/Yb and Nb/Yb ratios (Figure 8). However, some Jelai basaltic-andesites (Sulistyawan et al., 2013) are distinctly less evolved (lower Zr/Ti), more alkali (higher Nb/Y), and have higher Nb contents, showing affinity transitional between typical calc-alkaline arc basalts (IAB) and alkali OIB. In the Th/Yb versus Nb/Yb diagram, these samples fall close to the mantle array between average E-MORB and OIB (Figure 8).

5.5. Phase VI: Early Late Miocene (13-9 Ma)

After another short magmatic gap in 14-13 Ma, andesite-dacite magmatism resumed at Kunak (Tungku Fm.: ~12.92 Ma) and Membatu (12.58 and 11.50 Ma) in northern Borneo, and probably intensified at 12-9 Ma, with coeval volcanics widely documented at Kunak (~11.8 Ma), Membatu (~11.69 Ma), and Tawau (11.61 and 9.01 Ma) in SE Sabah (Bergman et al., 2000; Rangin et al., 1990). Similar ages are recorded further inland in the Sabah ophiolite at Tongod (9.22 Ma) and Telupid (9.11 Ma) (Lai, 2020) (Tsikouras et al., 2021), and arc (basaltic-)andesite in Seruyung 10.15-8.90 Ma (this study). In the SW Zamboanga peninsula, the youngest Anungan Fm. volcanics at La Paz were dated at ~12.7 Ma, and the unconformably overlying Curuan Fm. volcanics at 10.6-9.0 Ma. Although coeval magmatism likely occurred also along the Sulu ridge that connects northern Borneo and Zamboanga peninsula, the few age data published (predominantly from the central-northeastern part) are all Plio-Pleistocene, which can be caused by insufficient sampling (Figures 1 and 5).

Phase VI (basaltic-)andesite in northern Borneo have elevated Th/Yb and Nb/Yb ratios, resembling typical continental arc rocks. These rocks have also E-MORB- to OIB-like LREE and LILE enrichments and HREE and HFSE depletions, and negative Nb-Ta, Zr, Ti, and Eu anomalies (Figure 8). For the Seruyung (basaltic-) andesite (this study) and Miocene Sabah ophiolite (Tsikouras et al., 2021), their zircon εHf(t) values are largely positive (Lai, 2020). This suggests a predominantly mantle-derived depleted source, which is supported by the lack of inherited zircons in these rocks. The high-Nb, IAB-OIB-transitional basaltic-andesites in Phase V are absent in Phase VI.

5.6. Phase VII: Pliocene-Pleistocene (4-0.2 Ma)

Phase VI magmatism was likely followed by a long magmatic quiescence till the late Pliocene (~4 Ma), as indicated also by the lack of volcaniclastic input in the Dent Gp. sediments (Lunt & Madon, 2017). In northern Borneo, the Kunak-Mostyn basalt was dated at 3.11-2.79 Ma (Bergman et al., 2000; Rangin et al., 1990), and much younger zircon U-Pb (~0.5 Ma) and C-14 (carbonized tree fossils in volcanics: 27-24 ka) ages were reported in SE Sabah (Hsin et al., 2017; Kirk, 1968). This suggests that regional volcanism persisted till at least late Pleistocene. In the SW Zamboanga peninsula, the Mt. Maria volcanics yielded K-Ar ages of 3.88-3.55, 1.71-1.08, 0.90, and 0.34 Ma (Sajona et al., 1997; Yumul et al., 2004). Volcanics in the NE Sulu ridge (Basilan island) were dated at ~1.98 Ma (Sajona et al., 1997), while those in the nearby Negros yielded 1.97-0.52 Ma (Sajona et al., 2000) (Figure 1).

Phase VII volcanics in northern Borneo and Sulu ridge are largely alkaline/marginally alkaline basalts ($Nb/Y > 0.5$). These rocks are similarly LREE- and LILE-enriched (many OIB-like), and they have more-depleted HREEs and HFSEs than OIB or MORB. They are featured by high-Nb content, and absence of negative Nb-Ta or Eu anomalies. In the Th/Yb versus Nb/Yb diagram, these (marginally)alkaline basalts fall on/close to the mantle array between the average E-MORB and OIB, and in the within-plate basalt (WPB) field in tectonic discrimination diagrams (James et al., 2019; Macpherson et al., 2010; Sajona et al., 1997) (Figure 9). In SW Philippines (Zamboanga peninsula and Negros), although some Phase VII samples show similar WPB features to their northern Borneo counterparts, most samples are more evolved and less alkaline ($Nb/Y < 0.5$). They show arc calc-alkaline (e.g., negative Nb and Ti anomalies) or adakite-like (e.g., high Sr/Y, low Y) characters (Richards et al., 2012; Sajona et al., 1996, 1997; Solidum et al., 2003), and fall inside/near the continental arc field (Figure 9). Compilation of published Sr-Nd-Pb isotope data suggests that the northern Borneo basalts have lower $^{143}Nd/^{144}Nd$, but higher $^{87}Sr/^{86}Sr$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios than coeval volcanics in SW Philippines. The northern Borneo isotope data trend toward EMII, whereas the SW Philippines data trend toward the Indian-MORB-like Sulu Sea basalts (Figure 10) (Castillo et al., 2007; Macpherson et al., 2010; Spadea et al., 1996).

6. Tectonomagmatic Evolution of Sulu Sea Arc-Basin System

6.1. Intra-Pacific Oceanic Arc Magmatism (Pre-40 Ma)

The Sulu Sea evolution may have had its root in the Proto-SCS subduction, which brought the Palawan Continental Terrane from SE South China to form the northwestern boundary of the Sulu Sea basin (Almasco et al., 2000). The Proto-SCS is believed to be a Mesozoic ocean largely eliminated by subduction (Hall & Breitfeld, 2017; Hinz et al., 1991). Zahirovic et al. (2014, and references therein) suggested that the Proto-SCS was a BAB opened at ~65 Ma by the Paleo-Pacific (Izanagi) slab-rollback, yet detrital zircon U-Pb age and mineral assemblage suggest a common Cretaceous-Eocene provenance between the Palawan Continental

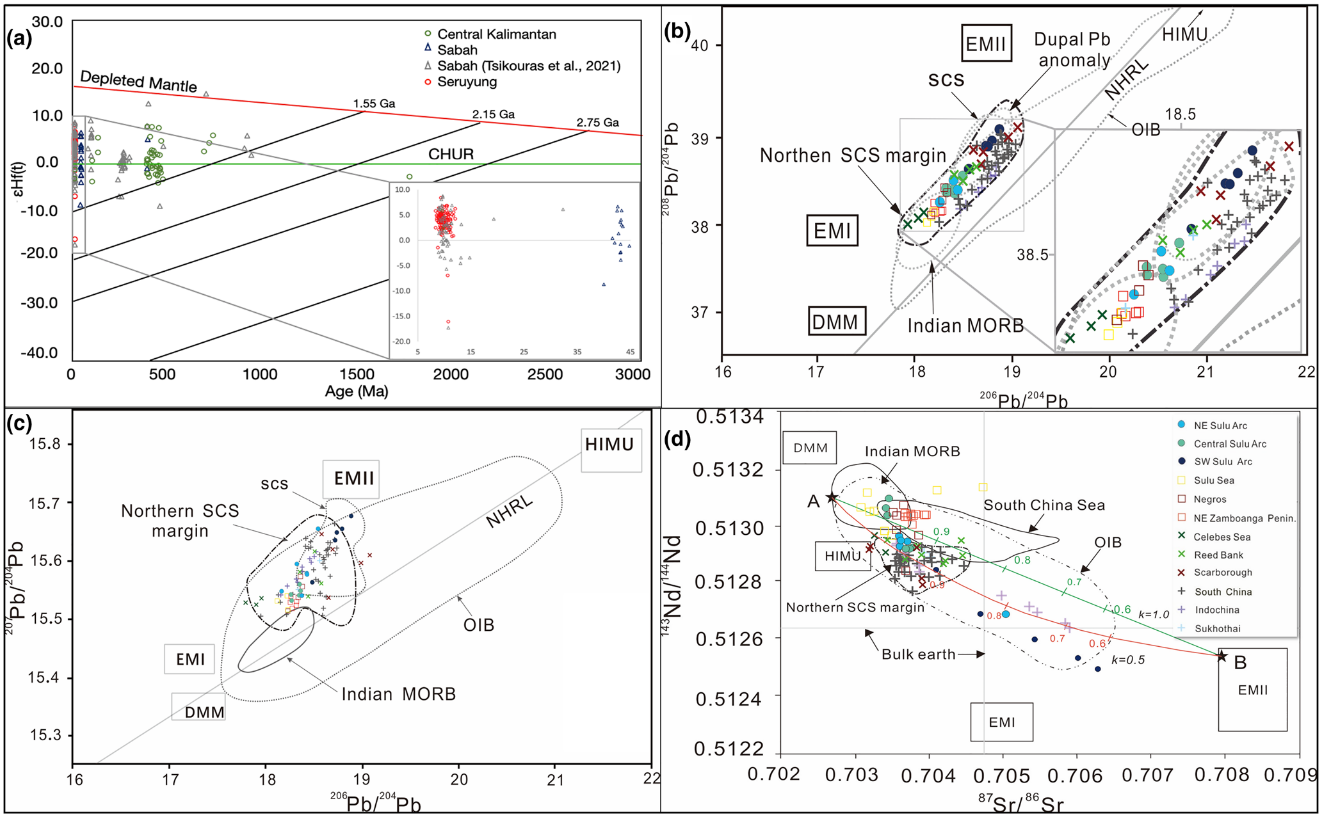

Figure 10. (a) Zircon εHf(t) versus U-Pb age plot for Phase I and VI volcanics from northern Borneo. Data of Devonian Central Kalimantan volcanics (this study) and Miocene Sabah ophiolites (Lai, 2020) (Tsikouras et al., 2021) are shown for comparison; plots of (b) ^{87}Sr/^{86}Sr versus ^{143}Nd/^{144}Nd, (c) ^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb, and (d) ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb for the Plio-Pleistocene volcanics in the circum-Sulu Sea region. Data from Late Cenozoic WPB units in South China-mainland SE Asia are also shown for comparison.

Terrane and SE South China Block (Shao et al., 2017). The Palawan Continental Terrane is variably placed in the north (Hall, 2002) or south side (Morley, 2012; Zahirovic et al., 2014) of the Proto-SCS. Based on the Palawan Continental Terrane-South China provenance link, we consider the former configuration is more likely (Figure 11).

In northern Borneo, our Tongod-Telupid gabbro (42.65 Ma) is broadly coeval with the BAB-type ophiolite (whole-rock K-Ar age: 43.8 ± 2.2) (Fuller et al., 1991; Keenan et al., 2016) and granite (~42 Ma) (Suggate et al., 2014) in central Palawan (Figure 5). As afore-discussed, the wide-range (mainly positive) zircon εHf(t) values and the Devonian inherited zircons in the Tongod-Telupid gabbro indicate a depleted mantle source with crustal input, which together with the central Palawan BABB and arc granite suggest an intraoceanic subduction setting in the Cretaceous-Eocene central Palawan-northern Borneo.

6.2. Continental Margin Rifting of South China and SCS Opening (36-33 Ma)

Timing of the SCS predrift extension and seafloor spreading remains enigmatic. Apatite fission track and (U-Th-Sm)/He dating suggests an Eocene (53-36 Ma) extension in SE South China, although it may have started as early as 66 Ma (Cao et al., 2020; Franke et al., 2011; Sales et al., 1997; Suggate et al., 2014) or 61.5 Ma (Su et al., 1989). Huang et al. (2013) reported ~35.5 Ma (Ar-Ar age) mantle upwelling-related basaltic magmatism in eastern Guangdong. The onset of SCS spreading is marked by widespread breakup-unconformity in northeastern SCS, for example, 37-30 Ma (near Taiwan), 33-32 Ma, and 28-27 Ma (eastern and western Pearl River estuary basin, respectively), 33-32 Ma (Reed Bank-Palawan), and ~28 Ma (Reed Bank) (Franke, 2012). Barckhausen et al. (2014) suggested a ~32 Ma spreading-onset in the central SCS, followed by a ridge jump at ~25 Ma. Similarly, deep-tow magnetic anomalies and core analyses by C. F.

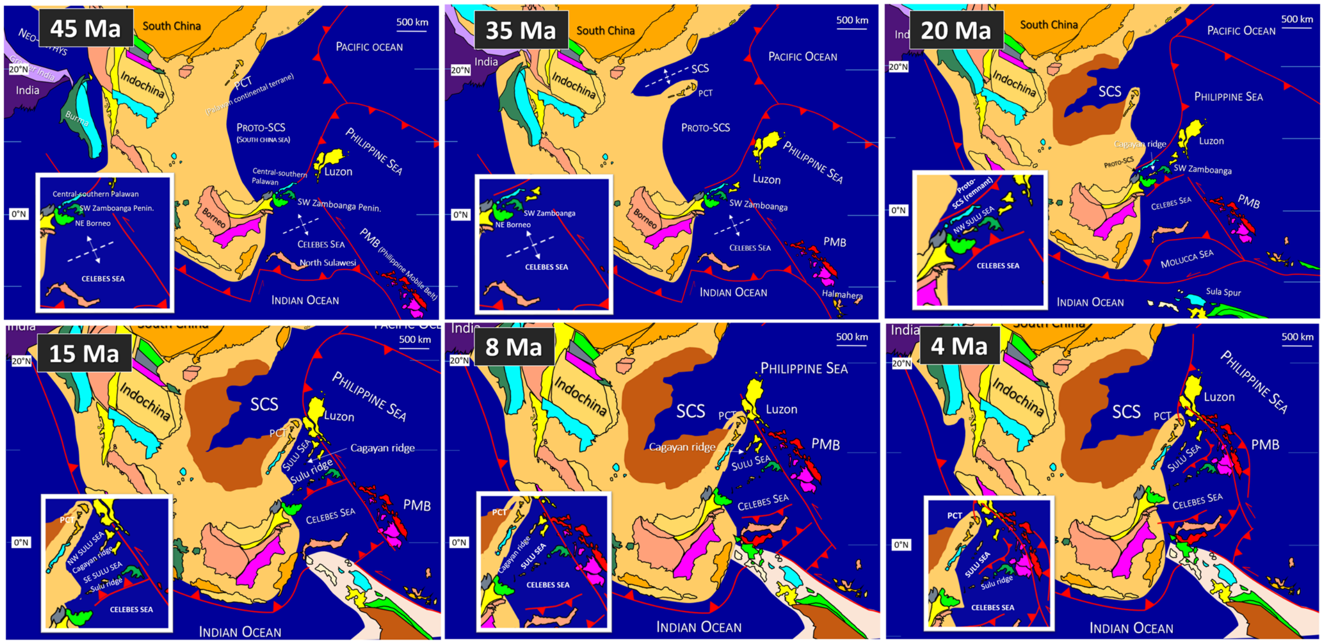

Figure 11. Tectonic reconstruction diagram for the circum-Sulu Sea region (modified after Hall, 2013; Matthews et al., 2016; Müller et al., 2018; Witts et al., 2012).

Li et al. (2014) suggested a ~33 Ma spreading-onset in the northeastern SCS, albeit with 1–2 Myr variation along the continent-ocean boundary. We consider that the SCS opening (especially toward the later stage) was at least partly driven by the Proto-SCS subduction. The subduction may have generated a Late Eocene magmatic arc in northern Borneo, but is largely eroded/recycled by the Palawan Continental Terrane collision-related uplift save the Sandakan andesitic tuff (~33.9 Ma; Swauger et al., 1995). Onset of the SCS spreading (34-32 Ma) coincides temporally with the Oligocene decoupling of Palawan Continental Terrane-South China detrital provenance (Shao et al., 2017), and signifies the southward drift of Palawan Continental Terrane toward the present location (Figure 11).

6.3. Final Proto-SCS Subduction and Palawan Continental Terrane Accretion (25-21 Ma)

The SCS spreading likely terminated when the Palawan Continental Terrane collided with northern Borneo-SW Philippines, yet when that actually happened is still unclear. Some magnetic anomaly studies placed the spreading cessation at ~20.5 Ma (Barckhausen et al., 2014) or ~15.5 Ma (Briais et al., 1993), yet Sibuet et al. (2016) argued that the masking of spreading fabric by postspreading magmatism (10-3.5 Ma) can affect the anomalies (Tu et al., 1992; Zhao et al., 2018). The Palawan Continental Terrane accretion is variably suggested to be end-Eocene to Miocene: Steuer et al. (2013) and Aurelio et al. (2014) constrained the Palawan ophiolite emplacement to be end-Eocene to ~23 Ma, based on the thrust-related metamorphism of Eocene turbidites and the sealing of thrust by the Lower Miocene Pagasa Formation, respectively. A tectonic wedge was then formed by underthrusting of the Upper Oligocene-Lower Miocene Nido limestone beneath the Burdigalian syn-thrust sediments. Termination of the wedge formation, and thus the accretion-related compression in central-southern Palawan, is constrained by the MMU (Aurelio et al., 2014), whose age is not well-constrained in SW Philippines as afore-mentioned. Meanwhile, Walia et al. (2013) proposed a much later start (15-14 Ma) for the collision based on zircon and apatite fission track dating from NW Panay. The authors interpreted the ~18.3 Ma diorite from NW Panay to be subduction-related, yet similar-age (~19.5 Ma) quartz diorite (also from NW Panay) was interpreted to be syn-collisional by some earlier studies (Bellon & Rangin, 1991; Yumul, Dimalanta, et al., 2009).

Based on the least-disputed geological facts that: (1) SCS ridge jump occurred after ~23.6 Ma, which likely brought the seafloor spreading closer (and probably more orthogonal) to northern Borneo-SW Philippines; (2) Final convergence between Palawan Continental Terrane and northern Borneo-SW Philippines started after ~25 Ma, which caused major uplift/thrusting, and the formation of TCU and the Kudat Formation (Lunt, 2019, and references therein); (3) Arc-type andesitic magmatism (Lagdo Fm. ~23.2 Ma) occurred in NW Panay (Walia et al., 2013), and BAB-type magmatism (Mt. Dansalan: 24.6-21.2 Ma) in SW Zamboanga peninsula (Tamayo et al., 2000), we suggest that (1) the SCS ridge jump and the consequent SE-directed compression may have subducted the remaining Proto-SCS beneath SW Philippines, forming the Lagdo Fm. andesites and Mt. Dansalan BAB-type mafic rocks. The ~10° counterclockwise rotation (~23 Ma) modeled by Advokaat et al. (2018) may have also caused by the convergence, and/or by the collision of the Sula Spur (SE Sulawesi) with Sundaland (Advokaat et al., 2014); (2) the Palawan Continental Terrane accretion may have started in the Early Miocene (~21 Ma), soon after the above-mentioned arc-/BAB-type magmatism had ceased. The accretion may have been slightly diachronous at different parts of the Palawan Continental Terrane, causing the age variation in metamorphism, syn-/postcollisional magmatism and ophiolite emplacement at different parts of the region (Yumul, Dimalanta, et al., 2009); (3) convergent (late-subduction and collision) tectonics likely started in central Palawan, and produced the uplift that formed the TCU and shed sediments (including heavy metamorphic minerals) south for the Kudat Fm. sandstones (Figure 11). Exact timing of the collision is difficult to pinpoint as crustal shortening/uplift can also be subduction-related, for example, orogenesis of the Andes (Oncken et al., 2006; Schepers et al., 2017) and Tibet (Kapp & DeCelles, 2019; S. Li et al., 2020), and time-lag between the collision onset and upper-crustal shortening has been reported (S. Li et al., 2020). In northern Borneo, the NE-SW-directed compression in northern-central Sabah and its southward weakening also support a SW-ward propagated convergence (Lunt, 2019; Lunt & Madon, 2017; Tongkul, 1997). We argue that the upcoming Phase IV (21-18 Ma) and Phase V–VI (17-9 Ma) arc magmatism was formed by the initial Celebes Sea subduction and its subsequent slab-rollback, respectively.

6.4. Celebes Sea Subduction and Initial Opening of Sulu Sea (21-18 Ma)

After the collision, regional stress gradually changed from N-S directed to NW-SE directed (Lunt & Madon, 2017; Tongkul, 1997), which we consider to have initiated the NW-dipping Celebes Sea subduction. Whether the Sulu arc was formed by south-dipping Sulu Sea subduction (Bellon & Rangin, 1991; Rangin & Silver, 1991; Schlüter et al., 2001) or north-dipping Celebes Sea subduction (Hall, 1996, 2002, 2012, 2013) is long disputed. Main support for the former comes from the seismic-interpreted occurrence of accretionary prism at the NW-flank of the Sulu ridge, yet as aforementioned (Section 2) there is little geological evidence for its actual existence. The suggested Miocene south-dipping subduction, which eliminated the southern half of the SE Sulu Sea basin, would have generated back-arc extension SE of the Sulu arc, together with major transform faults along the NE- and SW-margin of the Sulu Sea to accommodate the subduction tectonics. However, neither is apparent in regional topographic/bathymetric images or was previously reported (Hall, 2018; Hall & Spakman, 2015), except for some local transform faults in the Balabac Strait (Cullen, 2010). The Miocene south-dipping model cannot explain also the Late Miocene back-arc basin opening represented by the Tongod-Telupid ophiolite (Lai, 2020), or the Phase V–VI arc magmatism in Jelai and Seruyung, which is located far from the Sulu Sea basin or any reported ophiolite occurrence in northern Borneo (Figure 1).

These abovementioned phenomena, nevertheless, can be explained by a north-dipping subduction model. Although no published seismic data is available to decipher whether a fossilized accretionary prism exists at the SE-flank of the Sulu arc, the Mid-Miocene uplifting and sedimentary transition (from open-sea to clastic deltaic) in the western Tarakan basin resemble more a forearc-accretionary compressional tectonics than a back-arc extension one (Noda, 2016; Satyana et al., 1999). We do not dispute the occurrence of SE-ward subduction of the Sulu Sea, but consider that to have occurred much later (Plio-Pleistocene) and confined only to the south-eastern SE Sulu Sea basin along the Negros-Sulu trenches. The young and immature subduction system can explain the absence of back-arc spreading southeast of the Sulu ridge, the Plio-Pleistocene Negros-SW Zamboanga arc magmatism, and the absence of a regional dextral fault along the SW Sulu Sea margin.

For the timing of the Sulu Sea opening, magnetics modeling by Roeser (1991) suggested that predrift extension may have started in 35-30 Ma (early Oligocene; 0.6 cm/yr half-spreading rate). According to the model, the oldest oceanic crust occurs in the northwestern SE Sulu Sea, equivalent to anomaly C7 (23.96 Ma;

Gradstein et al., 2012). By using inverted Moho and Curie-point depths, Liu et al. (2014) further pushed forward the basin-opening onset and cessation to Late Eocene-Early Oligocene and Middle Miocene, respectively. However, drilling at Site 769 (within the interpreted oldest part of the basin) did not recover any oceanic basement rocks, which casts doubt on the reliability of magnetic anomaly interpretations. Besides, no rocks older than ~21 Ma (radiometric or fossil age) were reported in the Sulu Sea basin (Figure 1; Lai, 2020) (Rangin & Silver, 1991; Roeser, 1991; Scherer, 1991).

Based on our magmatic age compilation, we postulate that the Sulu Sea seafloor spreading occurred at 21-9 Ma (Figures 5 and 11). Early subduction and premagmatic (pre-21 Ma) extension may have opened the NW Sulu Sea BAB, as supported by the highly attenuated continental crust (Kudrass et al., 1990; Smith, 1991; Spadea et al., 1991a, 1996) and Early- to Middle Miocene pelagic sediment cover (Lunt & Madon, 2017 and references therein). Opening of the SE Sulu Sea likely started later, possibly at ~18.8 Ma (paleomagneto-biostratigraphic age) (Nichols et al., 1990) or ~18 Ma (calcareous nannofossils) (Shyu et al., 1991). Early Celebes Sea subduction may have formed Stage IV (21-18 Ma) arc andesitic-dacitic volcanics and diorite along the Panay-Cagayan ridge-NE Sabah line. The Cagayan arc was likely exposed or shallow-submerged due to the Early Miocene regional uplift, as indicated by the strong subaerial weathering (reddening) and lack of sediment reworking in some pyroclastics from Sites 769 and 771 (Nichols et al., 1990). Interpreted forearc high-Mg basalts from SW Panay may have also been part of this arc assemblage, although no age data are available (Cruz et al., 1989).

6.5. Subduction Rollback and Main-Stage Sulu Sea Opening (17-9 Ma)

There appears to be a magmatic younging trend (albeit not without age overlap) from NW to SE in the circum-Sulu Sea region (Figures 1 and 5), which likely reflects rollback of the subducting Celebes Sea slab, as first proposed by Hall (2013). We suggest that the NW Sulu Sea basin opening was gradually terminated by the post-18 Ma subduction rollback, while the SE Sulu Sea opening likely continued well into the Tortonian (till ~9 Ma), as indicated by Phase VI Sulu arc magmatism. The shorter opening lifespan of the NW Sulu Sea basin can explain why the basin is smaller and shallower than its south-eastern counterpart, and why it is not floored by oceanic crust like in mature back-arc basins.

The Sabah Orogeny may have extended well into the Middle Miocene, possibly driven by late-stage SCS rifting (e.g., at Bunguran trough), and formed the Pagasa tectonic wedge (16-12 Ma) in offshore SW Palawan (Aurelio et al., 2014; C. F. Li et al., 2014; Lunt, 2019). The compression likely lasted till the formation of DRU (14-12 Ma), when the region underwent major subsidence and NW-dipping listric fault development (Aurelio et al., 2014). In northern Palawan, the termination of compression is evidenced by the emplacement of postcollisional Capoas granite (13.8-13.5 Ma) (Suggate et al., 2014). Such compression-to-extension transition may have jointly contributed by postorogenic gravitational collapse after the Palawan Continental Terrane accretion, gravity-driven flexural response of the sediment wedge (resembling the present-day NW Borneo-Palawan troughs; Hall, 2013), as well as rollback of the subducting Celebes Sea slab. The SE-retreat of subduction front may have cut off magmatism in the Panay-Cagayan ridge after ~14 Ma, shifted arc magmatism to the SW Zamboanga peninsular-Sulu ridge-SE Sabah line, and further enlarged the SW Sulu Sea basin. Arc magmatism may have extended further SE locally to North Kalimantan in 16-14 Ma (Jelai), and again in 10-9 Ma (Seruyung). The rollback and back-arc rifting may have also extended into central Sabah, forming the Late Miocene Tongod-Telupid BAB-type ophiolite. The IAB-OIB-transitional Jelai basaltic-andesites likely reflects possible near-trench entrainment of deeper and more-enriched mantle during the slab rollback, or slab-tearing/fracturing similar to the northernmost Miocene Ryukyu arc (Kiminami et al., 2017).

It is noteworthy that Lunt and Madon (2017, and references therein) had identified a 14-13 Ma subsidence (or transgressive) event in eastern Sabah, based on fossil evidence from the reefal limestone and its overlying claystone beds. The proposed subsidence/transgression is coeval with the magmatic gap, which we suggest to be linked to the second rollback episode. The Cagayan ridge may have gradually submerged through the multiphase regional subsidence. Our age compilation suggests that arc magmatism, and thus the NW-dipping Celebes Sea subduction, largely ceased after ~9 Ma (Figures 1 and 5). The ~9 Ma arc magmatic cessation correlates well with the youngest back-arc spreading (C5, 9.79 Ma) recorded in the southern SE Sulu Sea basin (Roeser, 1991). Although the exact cause remains unclear, the NW-dipping subduction termination is broadly coeval with the starting of south-dipping subduction beneath Sulawesi along the North Sulawesi trench, as indicated by the intermediate-felsic arc magmatism in the North Arm (from ~9 Ma) (Advokaat et al., 2017, 2014; Hall, 2018; Rudyawan et al., 2014). The Celebes Sea may have also subducted eastward beneath the Cotabato trench (Hall, 2018; Yumul, Armada, et al., 2020). We consider that the south- and east-dipping subduction of the Celebes Sea may have changed the regional stress field and halted its NW-dipping subduction (Figure 11).

6.6. Regional Extension and OIB Magmatism (8 Ma–Present)

Borneo has likely undergone major extension after ~10 Ma, as evidenced by the development of SRU and low-angle detachments (Hall, 2013), and the almost-synchronous (thus rapid) emplacement (zircon U-Pb age: 7.85-7.22 Ma) and cooling ($^{40}Ar/^{39}Ar$ biotite age: 7.63-7.32 Ma) of the Mt. Kinabalu pluton (Cottam et al., 2010, 2013). Intraplate volcanism likely extended southwest to Kelian (East Kalimantan; K-Ar age: 0.97 ± 0.02 Ma) (Abidin, 1996; Davies et al., 2008) and west to the Usun Apau plateau (Sarawak; Ar-Ar age: 4.1-3.9 Ma and 2.1 Ma) (Cullen et al., 2013). The Mt. Kinabalu pluton was likely emplaced under a NW-SE extensional regime (Burton-Johnson et al., 2017, 2019), and the Late Miocene-recent extension in the upper part of the NW Borneo Shelf is balanced by NW-directed thrusting in the deep marine section (Hesse et al., 2009), which altogether suggest a predominantly SCS-directed orogenic collapse. On the opposite side of the Sulu Sea, the SW Zamboanga peninsula may have collided with the Philippine Mobile Belt at ~5 Ma (Pubellier et al., 1991), and the subduction along the Philippine trench started propagating south from ~8 Ma, reaching Leyte at ~3.5 Ma (Ozawa et al., 2004). The consequent postcollisional tectonics and subduction pull may have brought the region around Zamboanga peninsula under extension.

Magmatism resumed after ~4 Ma in the region, especially along the Zamboanga peninsula-Sulu ridge-SE Sabah (Castillo et al., 2007; James et al., 2019; Macpherson et al., 2010; Sajona et al., 1997) and Negros (Sajona et al., 2000; Solidum et al., 2003). As afore-discussed, Plio-Pleistocene volcanics in the SW Philippines have more subduction-related geochemical and Sr-Nd-Pb isotope features than those in northern Borneo (Figure 10). The Sulu Sea basin is suggested by some authors to have subducted along the Negros-Sulu trenches in the latest Miocene to Pliocene (Holloway, 1981; Sajona et al., 2000). If subduction did occur, our age compilation suggests that it likely started at ~4 Ma. The subduction is also evidenced by the first appearance (~2.4 Ma) of pelagic carbonates from Site 768, which suggests basin subsidence around it (Nichols et al., 1990). The SE-dipping subduction may have subjected eastern Sabah (overriding plate) to further extension, triggering the intraplate OIB-type volcanism there (Figure 11).

Late Cenozoic OIB-type intraplate magmatism is also widely distributed in South China-SCS-mainland SE Asia (e.g., northern SCS margin, Reed Bank, Scarborough, Indochina), and is often interpreted to be linked to the Hainan plume activity (Hoang et al., 2018; Yan et al., 2018; Zhang et al., 2020, and references therein). Apart from the OIB-type geochemical signature, many of these OIB-type magmatic units have also very similar Sr-Nd-Pb isotope compositions to the Plio-Pleistocene basalts in northern Borneo, and formed a trend toward EMII (Figure 10). Whether the Hainan plume has any genetic link with the Plio-Pleistocene magmatism in northern Borneo would require further investigation.

7. Conclusions

Through magmatic age and geochemical data comparison across the circum-Sulu Sea region, we suggest that the Sulu Sea opening had commenced at ~21 Ma, when the Celebes Sea subducted northwest in response to the final convergence between Palawan Continental Terrane and northern Borneo-SW Philippines. Early subduction may have formed the NW Sulu Sea basin, followed by subduction rollback that formed the SE Sulu Sea basin. The subduction rollback is accompanied by the SE-retreat of magmatic front from the Panay-Cagayan ridge-NE Sabah line to the SW Zamboanga peninsular-Sulu ridge-SE Sabah/North Kalimantan line. NW-dipping Celebes Sea subduction largely ceased after ~9 Ma, and was immediately followed by rapid uplifting in Borneo, causing the Mt. Kinabalu pluton emplacement/exhumation and intraplate volcanism in eastern and northern Borneo. Subduction of the SE Sulu Sea along the Negros-Sulu trenches may have started in ~4 Ma, forming the Plio-Pleistocene arc and adakitic volcanism in SW Philippines.

Data Availability Statement

Data sets for this research are available in these in-text data citation references: Lai (2020), "Geochron Geochem Data Compilation_Circum-Sulu Sea," Mendeley Data, V1, https://doi.org/10.17632/wmp3ng3n57.1.

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