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Tectonic constraints on formation and evolution of microplates in the Indian and Pacific Oceans: reviews and statistical inferences

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ABSTRACT: Oceanic plates are growing through narrow boundaries, such as mid-ocean ridges and transform faults. However, the discovery of diffuse plate boundary suggests another type of plate boundary that accommodates difference in plate motion via internal deformation. Along the Central and Southeast Indian ridges, for example, the Capricorn and Macquarie microplates exhibit widespread diffuse boundaries and hence divide the Indo-Australian Plate further into the Indian, Australian, Capricorn, and Macquarie plates. As for microplates distributed along the East Pacific Rise and Pacific-Antarctic Ridge in the Pacific Ocean, however, the typical plate boundaries surrounding the given microplate are distinctly established. Global plate reorganization involving the changes in plate motion or in spreading direction can be accommodated by forming a microplate through ridge extinction, ridge propagation, and pseudofault formation. However, relations between these tectonic processes have not been quantitatively assessed. In particular, we aim to examine tectonic constrains on the formation processes of microplates with diffuse plate boundary. In this study, we compare plate size, plate age, full-spreading rates, thermal structures, total rotation, and rotation rate for the 9 microplates including extinct plates (i.e., Capricorn, Macquarie, and Mammerickx* microplates in the Indian and Southern Oceans; Galapagos, Easter, Juan Fernandez, Bauer*, Friday*, and Selkirk* microplates in the Pacific Ocean; extinct plates are denoted with asterisks). From this comparison, we find that the microplate formation would require certain tectonic conditions (e.g., full-spreading rates faster than 70–80 mm/yr and rotation rates faster than 5–6°/m.y.) to evolve into an independent and rigid plate with respect to the neighboring plates. If the conditions are not met, the same tectonic reorganization would result in a microplate with diffuse plate boundaries.

Key words: microplate, ridge propagation, diffuse plate boundary, plate reorganization

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1. INTRODUCTION

The Earth's lithosphere is ideally considered as a rigid plate that rotates about an imaginary central axis with respect to the other counterpart plate on a sphere without internal deformation (Morgan, 1968; Hellinger, 1981; Bird, 2003). Previous studies have defined 52 tectonic plates on the Earth that can be divided into two groups: one consisting of seven large plates covering approximately 94% of the Earth's surface, and the other consisting of smaller plates following a fractal distribution (Bird, 2003; Morra et al., 2013). These tectonic plates are generally distinguished by narrow and distinct boundaries, such as mid-ocean ridge, transform fault, and trench. However, the presence of widespread intraplate earthquakes and internally scattered motions within a plate have suggested an alternative concept: a diffuse plate boundary exhibiting internal deformation of the given plate (Wiens et al., 1985; Gordon et al., 1990; Royer and Gordon, 1997; Conder and Forsyth, 2001).

After a diffuse plate boundary was first recognized in the North America-South America and East African Rift system (e.g., Chase, 1978), it has been widely applied to describing diffuse boundaries between oceanic plates (Wiens et al., 1985; Gordon et al., 1990; Royer and Gordon, 1997; Conder and Forsyth, 2001; Cande and Stock, 2004; Gordon et al., 2008; Gordon, 2009). For example, the Capricorn Plate near the Rodrigues Triple Junction (RTJ) exhibits three diffuse zones with respect to the Indian and

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Australian plates (Fig. 1a). Similarly, the diffuse zone of the Macquarie Plate near the Macquarie Triple Junction (MTJ) is located within the Australian Plate (Royer and Gordon, 1997; Cande and Stock, 2004; Gordon et al., 2008; Gordon, 2009; Choi et al., 2017). Both the Capricorn and Macquarie plates, interestingly, have evolved around the given triple junctions and sub-divided the Indo-Australian Plate. These plates are regarded as microplates because they exhibit independent plate motions with respect to the Australian Plate (Matthews et al., 2016; Choi et al., 2017). The difference in plate motions, however, is accommodated by the diffuse plate boundaries characterized by wide distribution of intraplate earthquakes (Royer and Gordon, 1997; Cande and Stock, 2004; Gordon et al., 2008; Gordon, 2009; Choi et al., 2017) (Fig. 1). These imply that such diffuse plate boundaries may not be transient to accommodate any given differences in plate motion, rather persistent along with local- and global-scale plate tectonic motions.

In the Pacific Ocean, on the other hand, numerous small-scale plates are distinguished from their surrounding plates by relatively narrow and distinct plate boundaries (Fig. 1). Plate reorganization generally involves with a change in spreading direction of the mid-ocean ridge, which induces deformation of the oceanic lithosphere at the corresponding spreading centers (e.g., Matthews et al., 2016; Choi et al., 2017). A significant change in plate motion (e.g., more than 10° change in spreading direction) often initiates overlapping spreading centers from ridge propagation regime in the given seafloor geometry. Such plate reorganization can lead to microplate formation associated with the rapid rotation of overlapping zones bordered by propagating rifts and dying ridges, and the subsequent territorial growth, which eventually result in the tectonic separation of a microplate from its principal plate (Naar and Hey, 1991; Schouten et al., 1993; Bird and Naar, 1994; Hey et al., 1995; Bird et al., 1998; Bird et al., 1999). In addition to plate reorganization, microplate formation can be also triggered by a fast-spreading mid-ocean ridge system interacting with a plume, which enhances ridge propagation through a thin and weak lithosphere produced by the given plume activity (Hey et al., 2004; Matthews et al., 2016). Episodic triple junction migration, furthermore, can contributes to ridge propagation and microplate formation (e.g., Juan Fernandez and Friday microplates in Fig. 1b) (Tebbens et al., 1997; Tebbens and Cande, 1997; Bird et al., 1999; Hey, 2004; Matthews et al., 2016).

Because previous studies suggested that microplate formation may require a series of tectonic interactions (e.g., fast rift propagation or triple junction migration) and conditions (e.g., thickness of oceanic lithosphere) during major plate reorganization, the microplate formation can be regarded as a special tectonic event compared to a plate formation with diffuse plate boundaries

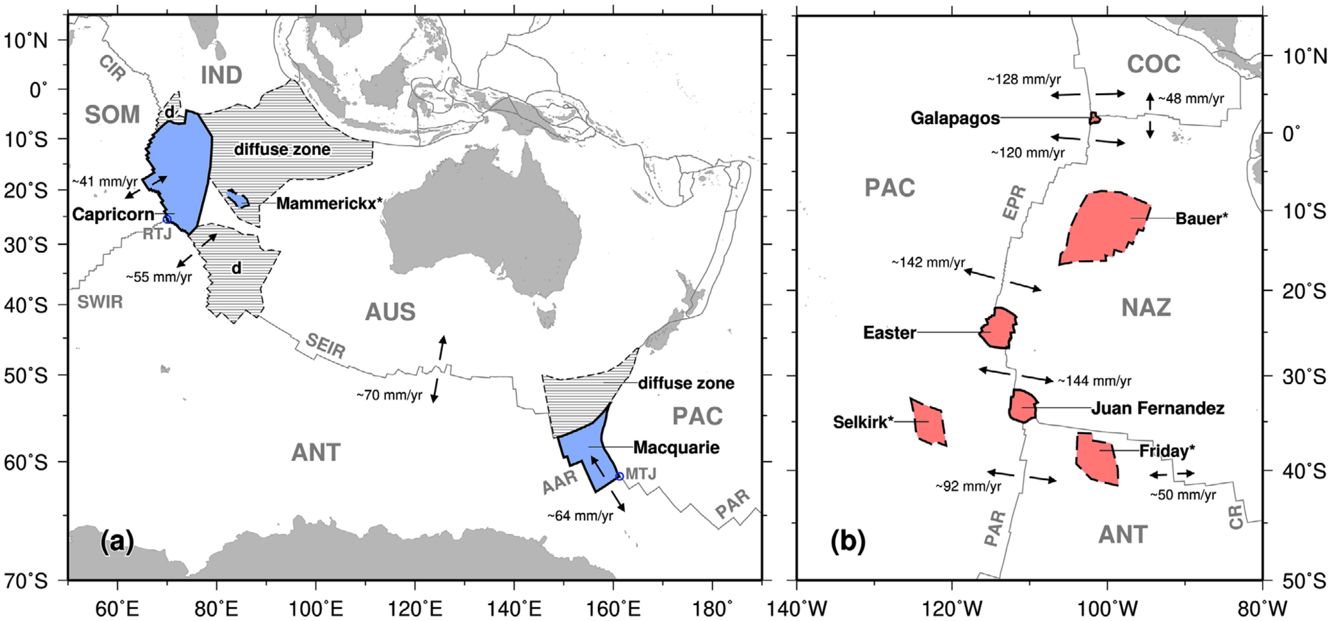

Fig. 1. The location of the microplates used in this study, the distribution of major tectonic plates around them, and the representative full-spreading rates of each region are shown. (a) Small tectonic plates along the Central and Southeast Indian ridges are marked with pale blue, whereas the shaded areas enclosed by dotted lines indicate a diffuse zone facing the microplates characterized by a widespread seismic zone. PAC: Pacific Plate; AUS: Australian Plate; ANT: Antarctic Plate; SOM: Somalia Plate; IND: India Plate; MTJ: Macquarie Triple Junction of the Australian-Antarctic-Pacific plates; RTJ: Rodrigues Triple Junction of the Australian-Indian-Somalian plates; PAR: Pacific-Antarctic Ridge; AAR: Australian-Antarctic Ridge; SEIR: Southeast Indian Ridge; SWIR: Southwest Indian Ridge; CIR: Central Indian Ridge. (b) Microplates in the Pacific Ocean are shown in pale red. COC: Cocos Plate; NAZ: Nazca Plate; EPR: East Pacific Rise; CR: Chile Ridge. In both figures, the plates bounded by bold lines along with a pale color represent the active plates, while the colored areas bounded by dotted lines indicate the extinct plates, with asterisk after their names.

(e.g., Neves et al., 2003; Hey, 2004; Matthews et al., 2016). In this study, we examine the available global datasets of topography (version 18.1 of Smith and Sandwell, 1997), gravity (version 23.1 of Sandwell et al., 2014), seafloor magnetic picks (Seton et al., 2014), plate rotation models (Cande et al., 1995; Bird, 2003; DeMets et al., 2010), and seismic tomography models (Ritsema et al., 2011; French and Romanowicz, 2015) to constrain tectonic characteristics of microplates. Based on the estimated constraints, we aim to infer statistically the tectonic environments modulating the formation and evolution of microplates. In particular, we consider first the active plates having independent plate motion, including the Capricorn and Macquarie microplates along the Central and Southeast Indian ridges, the Galapagos, Easter, and Juan Fernandez microplates in the Pacific Ocean. In addition, we examine the extinct microplates exhibiting no independent plate motion (denoted with asterisks) as follows: the Mammerickx Microplate* in the eastern Indian Ocean, and the Bauer Microplate*, Friday Microplate*, and Selkirk Microplate* in the Pacific Ocean (Fig. 1).

2. MICROPLATES

2.1. Pacific Ocean

2.1.1. Galapagos Microplate

In the Pacific Ocean, many recently formed microplates exist along the East Pacific Rise (EPR), the fastest divergent plate boundary in the global ridge system. The Galapagos Microplate is one of those Pacific microplates, located at ~2°N on the northern EPR bounded by three major tectonic plates: the Pacific Plate to the west, the Cocos Plate to the northeast, and the Nazca Plate to the southeast (Fig. 1). In the north of the Galapagos Microplate, the full-spreading rate between the Pacific and Cocos plates is reported to be ~128 mm/yr for 0.78 Ma, whereas the spreading rate in the south, between the Pacific and Nazca plates, is approximately 114–123 mm/yr (Hey et al., 1995; Bird et al., 1998; DeMets et al., 2010) (Fig. 1). The Cocos-Nazca plates, however, spreads at a full-spreading rate of ~48 mm/yr (DeMets et al., 2010).

Based on the seafloor magnetic data, the formation age of the Galapagos Microplate was estimated as ~1 Ma by developing from a ridge-ridge-ridge (RRR) or ridge-ridge-fault (RRF) type of triple junction (Lonsdale, 1988; Rusby and Searle, 1995). Since ~1 Ma, the overlapping rift zones with large offsets developed in the northern part of the Pacific-Nazca EPR started to migrate toward the north, while the rift zones with small offsets in the southern part of the Pacific-Cocos moved to the south. Such tectonic reorganization left the V-shaped trails at the eastern margin of the Galapagos Microplate (Fig. 2f), implying the occurrence of complicated deformation as pseudofaults or oblique fracture zones due to the propagation of Cocos-Nazca boundary. Lastly, the microplate has gradually undergone approximately 5–10° clockwise rotation (Lonsdale, 1988).

2.1.2. Easter Microplate

The Easter Microplate is located between the Pacific and Nazca plates at ~25°S on the west of Easter Island, the middle of the EPR (Fig. 1). In the vicinity of the Easter Microplate, the full-spreading rate of the EPR has been reported to be ~142–143 mm/yr in the north of the Easter Microplate and ~144–149 mm/yr in the south (Naar and Hey, 1991; Hey et al., 1995; Bird et al., 1998; DeMets et al., 2010).

The initiation time of the Easter Microplate was estimated between magnetic anomaly 3A and anomaly 3, corresponding to ~6–5 Ma in geological timescale (Naar and Hey, 1991; Bird and Naar, 1994; Rusby and Searle, 1995; Bird et al., 1998). In the early stage, the Easter Microplate started out as a large rift system propagating northward rapidly from the current position of the southern boundary of the microplate (Fig. 2c), inducing a significant deformation of the oceanic lithosphere along the EPR. After such fast-propagating state, the microplate has undergone a clockwise rotation of ~45° since approximately 3 Ma (Naar and Hey, 1991; Bird and Naar, 1994; Rusby and Searle, 1995; Bird et al., 1998).

During the period of 6–5 Ma, the global plate motions were reorganized around the Pacific Plate accompanied with sudden changes in spreading direction of the EPR and Pacific-Antarctic Ridge (PAR) (Naar and Hey, 1991; Bird and Naar, 1994; Cande et al., 1995; Rusby and Searle, 1995; Wessel and Kroenke, 2000; Neves et al., 2003). In addition, the clockwise rotation of ~20° in spreading direction and the increase in spreading rate occurred at the Southeast Indian Ridge (SEIR) at the same period (Cande and Kent, 1992; Choi et al., 2017). The previous studies hypothesized that these major tectonic events initiated the formation of several microplates along the EPR and PAR, such as the Easter and Juan Fernandez microplates (Naar and Hey, 1991; Bird and Naar, 1994; Rusby and Searle, 1995; Bird et al., 1998).

2.1.3. Juan Fernandez Microplate

The Juan Fernandez Microplate is located at ~33°S, where the EPR is connected to the PAR. Here the EPR is the divergent boundary between the Pacific and Nazca plates, whereas the PAR is the divergent boundary between the Pacific and Antarctic plates. Thus, the Juan Fernandez Microplate is surrounded by the Pacific, Antarctic and Nazca plates (Fig. 1). Such tectonic conditions result in a large difference in spreading rates from the north and to the south of this microplate because the EPR spreads much faster than the PAR. In the north of the Juan Fernandez Microplate, the estimated full-spreading rate is ~142–149 mm/yr,

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while the spreading rate in the south reaches ~94–95 mm/yr (Hey et al., 1995; Bird et al., 1998; DeMets et al., 2010).

Similar to the Easter Microplate, the formation of Juan Fernandez Microplate started around the magnetic anomaly 3A (Bird and Naar, 1994; Bird et al., 1998) through an initial tectonic setting characterized with ridge propagation and intra-transform spreading, which were induced by the 6 Ma plate reorganization accompanied with the migration of the Pacific-Antarctic-Nazca/Farallon triple junction (Tebbens et al., 1997; Tebben and Cande, 1997; Bird et al., 1999; Matthews et al., 2016) (Fig. 2d). The kinematic evolution of the microplate involving with the growth and reorganization of the propagating spreading centers resulted in significant changes in the rotation rate of microplate, ranging from 7 to 29 °/m.y. (Bird et al., 1998).

2.1.4. Bauer Microplate*

Although the Bauer Microplate is the largest microplate observed in the Pacific Ocean, it is an extinct microplate located inside the Nazca Plate, at ~12°S east of the EPR (Fig. 1). This microplate exhibits no further territorial expansion after the active growth period of 17–6 Ma (Tebbens and Cande, 1997; Blais et al., 2002; Eakins and Lonsdale, 2003).

The eastern boundary of the Bauer Microplate is the Galapagos Rise, an extinct ridge whose western boundary is considered as a part of the past EPR (Eakins and Lonsdale, 2003). The Bauer Microplate was initiated at ~17 Ma via the lengthening and overlapping ridge axes of the Galapagos Rise and the EPR (Fig. 2g). In particular, the EPR exhibited the spreading rate of 130–200 mm/yr during the microplate formation. The initial 100–200 km wide overlapping zone, generated as the Galapagos Rise in the east propagated to the south and the EPR in the west propagated to the north (Fig. 2g), grew into a microplate with a counterclockwise rotation of ~25° and its subsequent territorial expansion. Around 6 Ma, the Galapagos Rise ceased spreading as the microplate was captured by the Nazca Plate (Eakins and Lonsdale, 2003).

2.1.5. Friday Microplate*

The Friday Microplate is also an extinct plate located east of the PAR, at ~39°S inside the Antarctic Plate (Fig. 1). Before its microplate formation, a single triple junction of the Pacific, Antarctic, and Nazca/Farallon plates was present at chron 5C (~16 Ma). After a ridge propagation started from a large offset during the chron 5A (~12 Ma) plate reorganization, the Friday microplate completed its tectonic adjustments at the chron 5o (~11 Ma), forming the conjugate pseudofaults, termed as the Friday and Crusoe troughs (Tebbens et al., 1997; Tebbens and Cande, 1997; Matthews et al., 2016) (Fig. 2h). This formation processes formed new three triple junctions around the microplate, similar to the Juan Fernandez Microplate of the present day (Tebbens and Cande, 1997).

After the microplate formation, both ridge axes of the western and eastern boundaries of the microplate continued to spread until they were captured as the northernmost PAR in the west and the northernmost Chile Ridge in the east (Fig. 2h). During its territorial expansion accompanied with a clockwise rotation of ~10°, the Friday Microplate created the asymmetrically distributed pseudofaults as observed in the present day (Tebbens et al., 1997; Matthews et al., 2016) (Fig. 2h). Finally, the kinematic evolution resulted in the microplate extinction with no failed ridge and a northward stepwise triple junction migration (Tebbens et al., 1997; Tebbens and Cande, 1997) (Fig. 2h).

2.1.6. Selkirk Microplate*

Selkirk Microplate is an extinct plate associated with the plate motion between the Pacific-Nazca plates and placed inside the Pacific Plate at ~35°S, west of the PAR (Fig. 1). The Selkirk Microplate originated around 24 Ma via a northward propagating rift from the Mocha transform fault, which is the southern boundary of the microplate (Tebbens and Cande, 1997; Blais et al., 2002) (Fig. 2e). At the early stage of growth, the core of the microplate was captured by the Nazca Plate, while the Selkirk Microplate accreted to the Pacific Plate through the northward propagation of the eastern rift and continuous eastward migration of the corresponding spreading ridge (Blais et al., 2002). In the western boundary of the microplate, southward propagating rift with a fan-shaped opening structure approached the offset, and intersected to the Mocha Fracture Zone (Fig. 2e). The Selkirk Microplate appears to have undergone a clockwise rotation of about 20°. The extinction process of this microplate was similar to that of the Bauer Microplate, which is related to the kinematic evolution of plate motion between the Pacific and Nazca plates (Blais et al., 2002).

2.2. Indian and Southern Oceans

2.2.1. Macquarie Microplate

Because the plate motions between Australian and Antarctic plates constrained by seafloor magnetic picks exhibit inconsistency along the east of the Balleny Fracture Zone, the Macquarie Microplate at approximately 150–160°E and 60°S is proposed as a microplate with independent plate motion (Cande and Stock, 2004) (Fig. 1). The Macquarie Microplate is bounded by the Australian-Antarctic Ridge (AAR) to the south and a diffuse boundary of widespread seismicity zone to the north (Cande and Stock, 2004; Choi et al., 2017) (Fig. 2b).

Using the high-resolution shipboard magnetics, the motion of the Macquarie Microplate was redefined over the eight

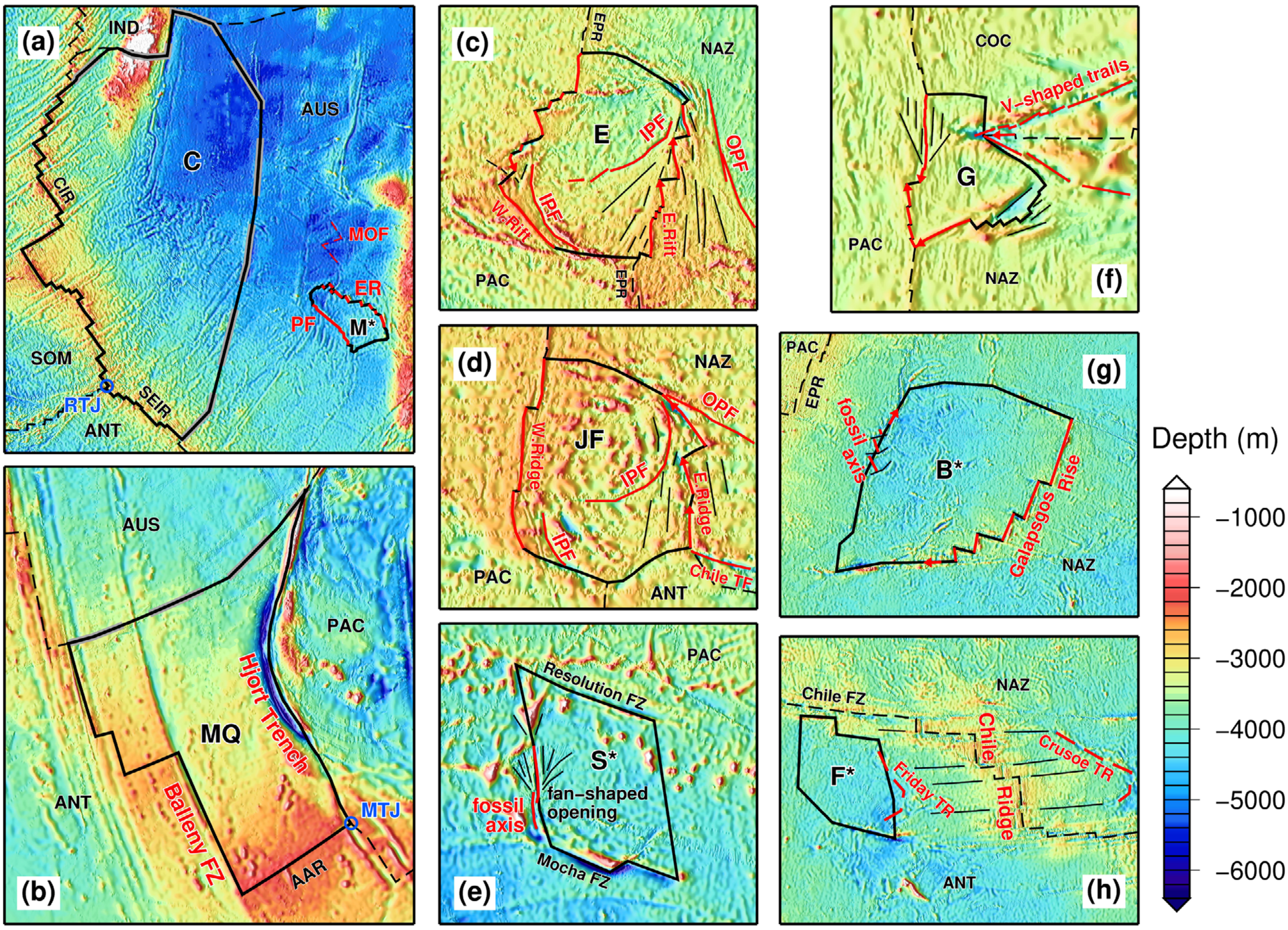

Fig. 2. The simplified tectonic features of distinct and diffuse microplates based on the satellite-derived global topography (version 18.1 of Smith and Sandwell, 1997). Black bold lines indicate the tectonic boundary of distinct and diffuse microplates; darkgray dashed lines in (a) and (b) show a boundary with a diffuse zone. The digital global plate boundary from Bird (2003) is shown as black dashed lines. The principal tectonic features and seafloor traces are emphasized by red lines. (a) Capricorn Microplate (= C) and Mammerickx Microplate (= M*) in the Indian Ocean. AUS: Australian Plate; ANT: Antarctic Plate; SOM: Somalia Plate; IND: India Plate; RTJ: Rodrigues Triple Junction; CIR: Central Indian Ridge; SEIR: Southeast Indian Ridge; ER: extinct ridge; PF: pseudofault; MOF: migrating offset fabric. (b) Macquarie Microplate (= MQ) in the Southern Ocean. PAC: Pacific Plate; MTJ: Macquarie Triple Junction; AAR: Australian-Antarctic Ridge; Balleny FZ: Balleny Fracture Zone. (c) Easter Microplate (= E) in the Pacific Ocean. NAZ: Nazca Plate; EPR: East Pacific Rise; IPF: inner pseudofault; OPF: outer pseudofault; E.Rift: east rift; W.Rift: west rift. (d) Juan Fernandez Microplate (= JF) in the Pacific Ocean. E.Ridge: east ridge; W.Ridge: west ridge; Chile TF: Chile Transform Fault. (e) Selkirk Microplate (= S*) in the Pacific Ocean. Mocha FZ: Mocha Fracture Zone; Resolution FZ: Resolution Fracture Zone. (f) Galapagos Microplate (= G) in the Pacific Ocean. COC: Cocos Plate. (g) Bauer Microplate (= B*) in the Pacific Ocean. (h) Friday Microplate (= F*) in the Pacific Ocean. Friday TR: Friday Trough; Crusoe TR: Crusoe Trough; Chile FZ: Chile Fracture Zone. See the text for the detailed descriptions. * indicates extinct plates.

magnetic anomalies (1o, 2, 2Ay, 2Ao, 3y, 3o, 3Ay, and 3Ao) (Choi et al., 2017). Such more finely divided magnetic picks revealed that the plate was initiated around 6.24 Ma via a rapid rift propagation and/or MTJ migration, forming an asymmetric pseudofault as a linear trough near the MTJ east of the Macquarie Microplate (Choi et al., 2017). At the time of microplate formation, the relatively young oceanic lithosphere formed at the AAR was also too buoyant to be subducted at the Hjort Trench (Fig. 2b), which might induce a counterclockwise rotation of ~10° in the Australian-Antarctic spreading direction. Finally, the Macquarie Microplate has continued to move in the changed NNW-SSE spreading direction, independently from the Australian Plate motion and to grow larger as new lithosphere is constantly generated at the AAR (Choi et al., 2017).

2.2.2. Capricorn Microplate

The Indo-Australian Plate, initially considered as a single large plate, has been redefined as being composed of multiple plates with wide diffuse plate boundaries, which have undergone internal tectonic deformation manifested by widespread occurrence of intraplate earthquakes (Royer and Gordon, 1997; Conder and Forsyth, 2001; Gordon et al., 2008; Gordon, 2009). Near the RTJ, the Capricorn Microplate located around 70–80°E and 10–25°S has diffuse zones as large as the Capricorn Microplate or

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larger, at the boundary with the Australian Plate, and a small diffuse boundary with the Indian Plate (Fig. 1).

Although this microplate behaves as an independent plate, owing to its large size and the presence of several wide diffuse zones bounded by major plates (Figs. 1 and 2a), less than about 1° rotation relative to the Australian Plate and less than 3° rotation relative to the Indian Plate are estimated for the past 11 Ma (Royer and Gordon, 1997).

2.2.3. Mammerickx Microplate*

Unlike the above microplates with diffuse zones distributed along the Central and Southeast Indian ridges, the Mammerickx Microplate is an extinct Pacific-type microplate located around ~85°E and ~22°S in the eastern Indian Ocean (Fig. 1). The previous studies suggested that its formation was associated with the initial soft India-Eurasia collision (Gibbons et al., 2015; Matthews et al., 2016). The microplate originated at ~47 Ma along the Indian-Antarctic ridge, whose full-spreading rate was estimated to exceed 100 mm/yr at that time. In the early stage, the conjugate pseudofaults and extinct ridge traces were formed during the fast propagation of the newly generated ridge (Fig. 2a). The Mammerickx Microplate experienced a ~25° counterclockwise rotation prior to the extinction of the dying ridge (Matthews et al., 2016).

3. ESTIMATION OF TECTONIC PARAMETERS

In order to quantify various tectonic parameters associated with formation of microplates, we examine the following global datasets. To determine the plate boundaries, we basically used the global digital model of plate boundaries constructed by Bird (2003). However, because the extinct plates (e.g., Bauer Microplate), the recently recognized microplate (e.g., Mammerickx Microplate), and the diffuse boundary (e.g., a part of Macquarie Microplate) are not included to the digital dataset of Bird (2003), we manually traced the Bauer, Friday, Selkirk, and Mammerickx microplates and the diffuse boundaries of Capricorn and Macquarie microplates using the satellite-derived gravity data (version 23.1 of Sandwell et al., 2014). The boundaries we used for this study are displayed in Figure 2. The surface area of a given plate was then computed by the *gmtspatial* program of GMT (Generic Mapping Tools) software.

The plate age, full-spreading rates, total rotation, and average rotation rates were obtained from the previous studies for each plate of interest as described in section 2. The seafloor magnetic picks from Seton et al. (2014) were complementally utilized to estimate the plate age. The MORVEL (Mid-Ocean Ridge VELocity) for constraining the current motion of global tectonic plates was used as a reference model to estimate the spreading rates at the plate boundaries of the given microplate (DeMets et al., 2010). We also examined the global tomography models, S40RTS (Ritsema et al., 2011) and SEMUCB (French and Romanowicz, 2015), as a proxy to the thermal structures beneath the microplates. The estimated tectonic parameters in this study are listed in Table 1. Lastly, we categorize further the examined microplates into 'distinct' and 'diffuse' microplates based on plate boundary types. The former is bounded by narrow and distinct plate boundaries (e.g., Easter Microplate), while the latter is bordered by diffuse plate boundaries (e.g., Macquarie Microplate). In the subsequent comparison analyses, we aim to quantify differences, if any, between the formation and evolution processes of these distinct and diffuse microplates.

4. RESULTS AND DISCUSSION

4.1. Comparison of Plate Size

Formation of microplates is commonly associated with topographical changes in the mid-ocean ridge, such as propagating rift and overlapping spreading centers (Lonsdale, 1988; Naar and Hey, 1991; Schouten et al., 1993; Hey et al., 1995; Rusby and Searle, 1995; Neves et al., 2003). The total length of the ridges associated with microplate formations, thus, could be a tectonic factor to determine the territorial expansion of the distinct and diffuse microplates. Furthermore, Morra et al. (2013) suggested that the critical size of small tectonic plates, distinct from the major tectonic plates of the Earth's surface, is approximately $10^{7.5}$ km^2 (i.e., ~3.2×10^7 km^2 in different notation). Such small tectonic plates (< $10^{7.5}$ km^2) appear to be irregularly formed by uncorrelated tectonic events. The number of global small tectonic plates varied from 18 to 31 during the last 60 Ma, although no apparent pattern was characterized in the number and spatial distribution of such small tectonic plates (Morra et al., 2013). However, the previous study did not include the specifics of the microplates as examined in this study. Thus, we computed the size of the distinct and diffuse microplates (Table 1) to examine if the size of distinct and diffuse microplates would follow the previous relation (Morra et al., 2013) and if the total length of spreading ridges would be a critical factor to the tectonic expansion of the given distinct and diffuse microplates.

In Figure 3, we compare the surface areas of the distinct and diffuse microplates estimated from their corresponding plate boundaries. There are large uncertainties for the areas of the Capricorn and Macquarie microplates because their plate boundaries are dependent on the definition of the diffuse zone they are in contact with. The largest plates in size among all the plates examined in this study are the Capricorn Microplate (~2.5×10^6 km^2) between the diffuse microplates and the Bauer Microplate (~8.5×10^5 km^2) among the distinct microplates (Fig. 3). Except for the two plates, other microplates are very small in

Table 1. Tectonic parameters associated with the formation of the microplates

	Plate size (km^2)	Age (Ma)	Full-spreading rates (mm/yr)	Total rotation (degree)	Rotation rate (degree/m.y.)	Triggers for microplate formation
Galapagos	14,560	1.0–0	114–123;128	6.0	6.0 [5.0–10.0]	– plate reorganization – triple junction migration
Easter	166,621	6.0–0	142–149	90.6	15.0	– plate reorganization
Juan Fernandez	97,635	6.0–0	93–149	81.8	13.6 [7.0–29.0]	– plate reorganization – triple junction migration
Bauer*	853,791	17.0–6.0	130–160	25.0	2.27 [2.0–5.0]	– plate reorganization
Friday*	193,018	16.0–11.0	71–92.4	10.0	1.98	– plate reorganization – triple junction migration
Selkirk*	141,126	24.0–20.8	80	20.0	6.25	– plate reorganization
Macquarie	302,307	6.24–0	60–70	7.79	1.19 [1.08–1.29]	– plate reorganization – triple junction migration
Capricorn	2,555,270	11.0–0	35–47.5;52–58	2.64	0.16 [0.07–0.24]	– plate reorganization
Mammerickx*	91,089	47.3–43.4	75–105	25.0	6.41	– plate reorganization – triple junction migration – plume activity

* indicates extinct plates.

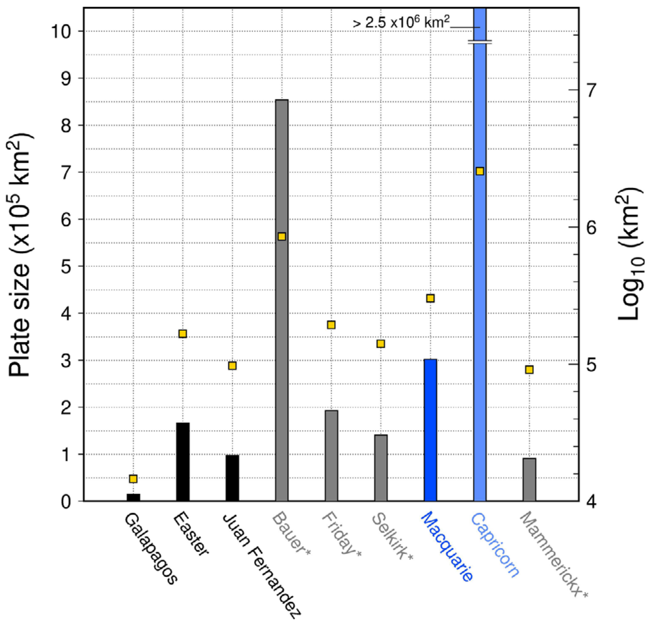

Fig. 3. The sizes of distinct and diffuse microplates are shown by the vertical bars (left Y-axis) and the yellow squares with logarithm format (right Y-axis). All of the microplates are far below $10^{7.5}$ km^2 (or about 3.2×10^7 km^2), the reference area for the small tectonic plates defined by Morra et al. (2013), except for the Capricorn and Bauer microplates; all the plates examined here are under $\sim 3.0 \times 10^5$ km^2 (or less than $\sim 10^{5.5}$ km^2). The distinct microplates are marked with a series of black-gray colored bars, while the diffuse microplates are shown with a series of blue colored bars. In particular, gray bars and an asterisk after its name indicate the extinct plates.

area, less than $\sim 3.0 \times 10^5$ km^2 (i.e., $\sim 10^{5.5}$ km^2) (Fig. 3). Thus, we find the size of the microplates is generally much small than the previously defined small tectonic plates (Morra et al., 2003). This further implies that a newly forming microplate needs to compete with the pre-existed plate for its terrestrial growth, which appears to be limited to the estimated area of $\sim 10^{5.5}$ km^2.

From the reviews discussed above, we find the responses of the ridge system (e.g., propagating rifts) to a given tectonic trigger (e.g., plate motion reorganization) is essential to the formation processes of the microplates. Here we simplify the irregular shape of plate boundaries as a square and consider one side of the square as a set of spreading ridges. The size analysis on the examined microplates, thus, implies that the critical length of ridges for a given plate to maintain the territorial growth is ~600 km. As the steady-state upwelling system at the ridges feeds seafloor spreading and hence generation of new lithosphere, the divergent boundary for a microplate is needed to be long enough to maintain the independent motion and territorial growth. However, such ridge system may not exceed the estimated length of ~600 km because the propagating rifts need to be continued over such a long distance by competing with the neighboring plate motion. With the given the size limit of the microplates ($\sim 10^{5.5}$ km^2), thus, the propagating rifts synchronous with the formation of microplate appear to be limited in ~600 km distance.

We find that the microplates examined in this study have not been successful to achieve the territorial expansion for evolving into larger plates. Compared to the distinct microplates with narrow plate boundary accommodating a rapid change in plate motion, the diffuse microplates tend to maintain territorial expansion by continuously undergoing local- and global plate motion changes and hence generally exhibit the larger size (Fig. 3). Nonetheless, the interplay between the given tectonic environments and complex tectonic reorganization would enhance or impede the growth of microplate (e.g., Bird, 2003; Sornette and Pisarenko, 2003; Morra, 2013).

4.2. Comparison of Age

The age comparison result shows that the extinct microplates

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are slightly older than the active plates (Table 1). The Mammerickx Microplate in the eastern Indian Ocean, for example, was active from ~47 Ma when the initial soft Indian-Eurasian collision was occurred (Gibbons et al., 2015; Matthews et al., 2016). The extinct plates in the Pacific Ocean were active for about 24–6 Ma during the major plate reorganization events happened at ~24 Ma, ~12 Ma, and ~6 Ma (Tebbens et al., 1997; Tebbens and Cande, 1997; Blais et al., 2002; Eakins and Lonsdale, 2003) (Figs. 4 and 5). The active microplates, which continued their territorial expansion with independent plate motion, are mostly associated with the plate reorganization events at ~6 Ma and ~1 Ma (Naar and Hey, 1991; Cande and Kent, 1992; Bird and Naar, 1994; Cande et al., 1995; Rusby and Searle, 1995; Bird et al., 1998; Wessel and Kroenke, 2000; Neves et al., 2003; Choi et al., 2017), except for the Capricorn Microplate originated at ~11 Ma (Royer and Gordon, 1997) (Figs. 4 and 5).

The magnetic picks in the study areas are color-labelled in Figure 4 according to the geomagnetic reversal timescale (Gee and Kent, 2007). These data are one of the raw datasets utilized to determine the seafloor age accompanied with plate reconstruction models (Seton et al., 2014). Interestingly, our comparison based on the magnetic picks illustrates the main difference between the distinct and diffuse microplates as follows. The active and extinct microplates in the Pacific Ocean were initially formed in the vicinity of mid-ocean ridges with relatively fast-spreading rates, which in turn were sensitive to the changes in global tectonic plate motion. The magnetic picks within a given microplate, thus, inherently represent its age (Figs. 4 and 5). However, the diffuse microplates were formed when an existing plate underwent a distinctly independent motion induced by a tectonic trigger such as global plate motion change. Because the lithospheric deformation associated with such independent plate motion occurs at a large

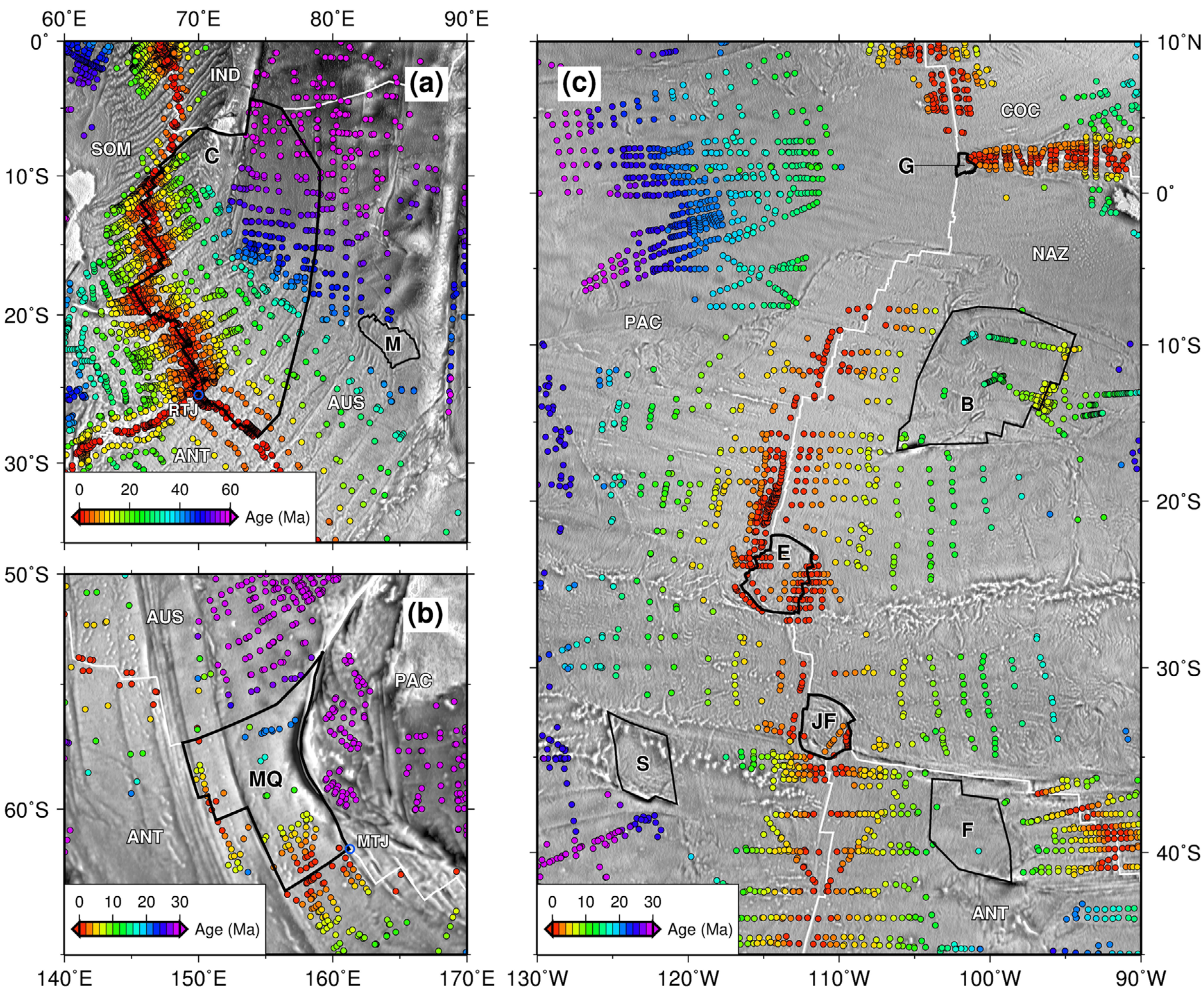

Fig. 4. Magnetic picks identified by the previous studies (Seton et al., 2014). In particular, the data from Choi et al. (2017) and Choi et al. (unpublished manuscript) were complementally used for the area around the Macquarie Microplate. White solid lines show the plate boundaries, and the distinct and diffuse microplates are bounded by black solid lines. (a) Magnetic picks near the RTJ. C: Capricorn Microplate; M: Mammerickx Microplate (b) Magnetic picks near the MTJ. MQ: Macquarie Microplate (c) Magnetic picks in the eastern Pacific Ocean. G: Galapagos Microplate; E: Easter Microplate; JF: Juan Fernandez Microplate; B: Bauer Microplate; F: Friday Microplate; S: Selkirk Microplate.

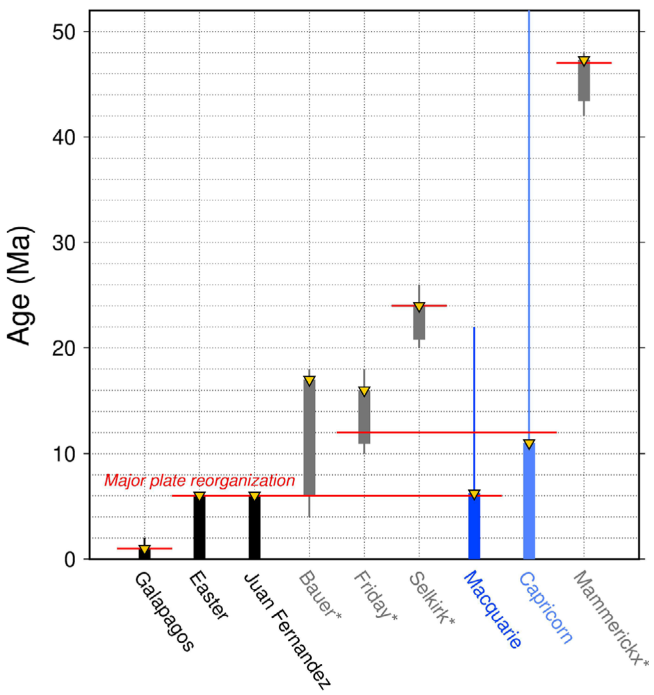

Fig. 5. The formation ages of the distinct and diffuse microplates are marked with yellow inverted triangles. whereas the duration of territorial growth is shown by vertical bar. The vertical thin lines indicate the seafloor ages within the area of the plates, which are estimated by global magnetic picks (Seton et al., 2014; Choi et al., 2017; Choi et al., unpublished manuscript). The red lines indicate when major tectonic events for plate reorganization occurred.

distance from the spreading center, a diffuse zone with widespread intraplate seismicity is formed instead. Consequently, the global magnetic picks within the diffuse microplate areas can be significantly different from the ages when the diffuse microplates actually started to behave as an independent plate (Figs. 4 and 5).

The age comparison result indicates that the formation age of diffuse microplates may not be constrained by the diffuse zones bordering with other plates. The age of the entire area of the diffuse microplates, furthermore, might be much older than the actual formation age. This indicates that any topographic changes such as an overlapping spreading center or a propagating rift in a mid-ocean ridge are neither directly involved in the formation of diffuse microplates nor are they determining factors for the area of the diffuse microplates, although a change in global motion could have been the main driver of its formation, like in the case of distinct microplates. For this reason, it would be reasonable to consider the Mammerickx Microplate in the eastern Indian Ocean as an extinct Pacific-type microplate, unlike other diffuse microplates along the Central and Southeast Indian ridges, based on the distribution of the magnetic picks (Figs. 4 and 5). For the formation of distinct microplates, a relatively young and thin lithosphere is a crucial tectonic condition because propagating rifts and overlapping spreading ridges can be easily developed and transformed into a tectonic plate boundary. For the formation of diffuse microplates, however, the diffuse zones accommodate such plate motion difference with the neighboring plates, exhibiting internal deformation in an already formed plate.

4.3. Comparison of Full-spreading Rates

The formation of microplates is typically associated with rapid rotation of oceanic lithosphere and topographical changes in the mid-ocean ridge, accompanied by propagating rifts and overlapping spreading centers. Such topographical changes in the vicinity of the spreading ridge can be enhanced by fast-spreading systems, rather than by slow-spreading systems (Lonsdale, 1988; Naar and Hey, 1991; Schouten et al., 1993; Hey et al., 1995; Rusby and Searle, 1995; Neves et al., 2003).

Comparison of the full-spreading rates of the spreading ridges examined in this study (Table 1) shows a significant difference in spreading rates between the distinct and diffuse microplates (Fig. 6). Based on the full-spreading rates, the global spreading ridges are usually divided into five systems as follows: ultraslow (< 20 mm/yr), slow (20–55 mm/yr), intermediate (55–75 mm/yr), fast (75–180 mm/yr), and super-fast spreading ridges (> 180 mm/yr) (Dick et al., 2003). Lithospheric thickness beneath the slow-spreading ridges (e.g., Mid-Atlantic Ridge (MAR)) generally reaches about 4 km, whereas the sub-ridge lithosphere at the fast-spreading systems (e.g., EPR) is only about 1 km thick (Neves et al., 2003). As the plate strength is proportional to the square of lithospheric thickness (Byerlee, 1978; Neves et al., 2003), we can presume that ~16 times greater force is required at the slow-spreading ridge than at the fast-spreading ridge to break the plate (Neves et al., 2003). In addition, in the process of the formation and growth of propagating rifts, the large variation of full-spreading rates along the rift (i.e., ranging between > 100 mm/yr at the rift tail to 0 mm/yr at the rift tip) can provide sufficient brittle lithospheric thickness required to drive the rotation of the microplate (Neves et al., 2003). Our comparison on spreading rates is also consistent with the previous findings as the full-spreading rates of the microplates are systematically faster than ~70–80 mm/yr (Fig. 6). In particular, as noted above, the Mammerickx Microplate was formed when the spreading rates between the Indian-Antarctic plates were 75–105 mm/yr (Cande and Patriat, 2015; Matthews et al., 2016). These findings imply the distinct microplate can only be formed and evolved when the given spreading rate exceeds ~70 mm/yr, although both distinct and diffuse microplates can be initiated due to an identical tectonic trigger.

4.4. Comparison of Thermal Structures

In addition to the lithospheric thickness that determines the

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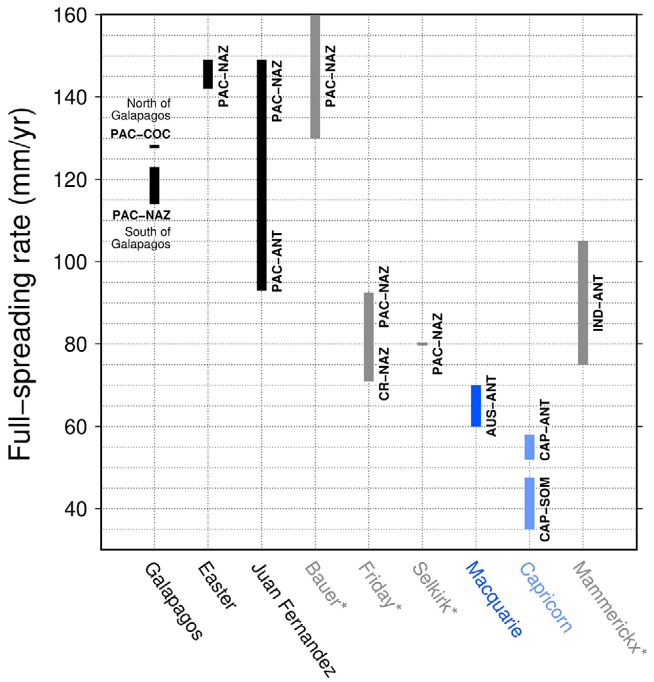

Fig. 6. Comparison of the full-spreading rates at the divergent boundaries surrounding the distinct and diffuse microplates. The range of vertical bars indicates the variation in the spreading rates at the boundaries which is in contact with the distinct and diffuse microplates. The full-spreading rates of 70–80 mm/yr are regarded a critical condition for the formation of distinct microplates.

plate strength to resist an external force trying to break the plate and for a new plate, lithospheric strength is also thermally controlled near the spreading axis (e.g., Phipps Morgan et al., 1987). For example, a hot, thin, and weak lithosphere associated with fast-spreading rates and plume activity can enhance ridge propagation and microplate formation (Hey, 2004; Matthews et al., 2016). To characterize thermal effects of lithosphere on the formation and evolution of microplates, we utilize S-wave seismic tomography models as a proxy of the thermal structure beneath the studied plates.

In Figure 7, based on the present-day location of the distinct and diffuse microplates, the tomography models, S40RTS (Ritsema et al., 2011) and SEMUCB (French and Romanowicz, 2015), by depth are compared. At 100 km depth, the low-velocity zones of the S-wave are coherently distributed with mid-ocean ridges, indicating the presence of steady-state upwelling areas beneath the spreading ridges (e.g., Courtillot et al., 2003; Park et al., 2019). Such short-wavelength variation along the spreading ridge is better captured by the SEMUCB model. With the S40RTS model, the regional variations including the effects due to subducting plates are better captured (Fig. 7). In particular, the EPR system is placed above the lowest velocity zone of the S-wave at all the depth (more enhanced at 100 km depth), implying that such a relatively hotter lithosphere or upper mantle may reduce thickness and brittle strength of the plate and hence become prone to form

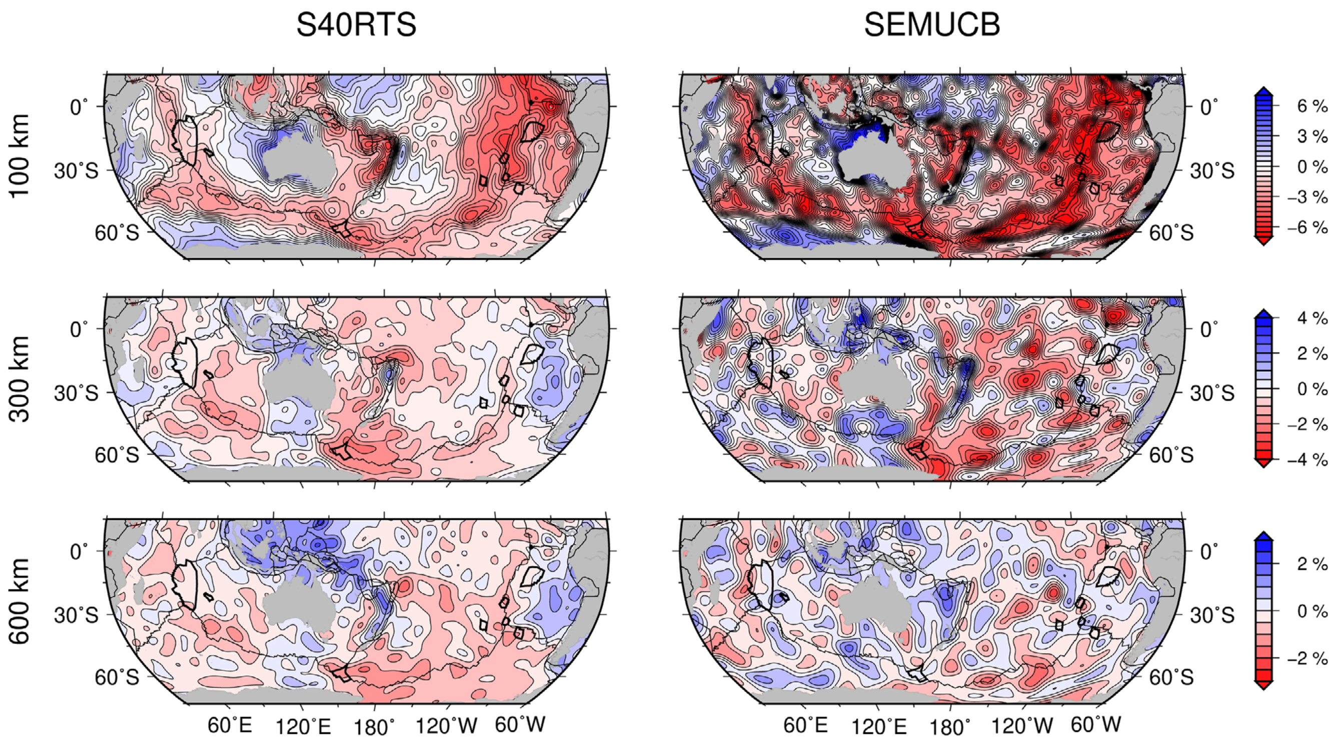

Fig. 7. Comparison of tomography models, S40RTS (Ritsema et al., 2011) and SEMUCB (French and Romanowicz, 2015) by depths. Black solid lines indicate the plate boundaries (Bird et al., 2003) and the distinct and diffuse microplates in the Indian, Southern, and Pacific Oceans are shown bounded by thick solid lines. The vertical scale bars indicate the variation of S-wave velocities.

a microplate. However, we find no clear systematic difference in the tomography models (at 100 km, 300 km, and 600 km depths) between the distinct and diffuse microplates (Fig. 7). Nonetheless, it requires further studies to quantify correlations between thermal structure and formation of distinct and diffuse microplates.

4.5. Comparison of Total Rotation and Rotation Rates

The plate motion change affects ridge morphology, microplate formation with rotation, rift propagation involving ridge jumps and pseudofaults (e.g., Matthews et al., 2016), as well as inducing the migration of spreading axes (Bird and Naar, 1994; Tebbens and Cande, 1997; Bird et al., 1998). The previous studies confirm that the development of overlapping spreading centers with ridge propagation is closely related with microplate formation (e.g., Naar and Hey, 1991; Bird and Naar, 1994; Tebbens and Cande, 1997; Bird et al., 1998; Blais et al., 2002; Eakins and Lonsdale, 2003; Matthews et al., 2016). However, the plate motions and its associated changes can be represented by the total rotation and its rate estimated at the corresponding Euler pole (Naar and Hey, 1991; Tebbens et al., 1997; Tebbens and Cande, 1997; Bird et al., 1998).

We compared the total rotation and rotation rate of the distinct and diffuse microplates (Table 1), based on the plate reconstruction models of the previous studies. While the Galapagos Microplate experienced only a total rotation of about 6° (Lonsdale, 1988) (Fig. 8a) in a relatively young age of ~1 Ma (Figs. 3 and 4), the Juan Fernandez Microplate was rotated ~82° during the corresponding formation processes (Bird et al., 1998) (Fig. 8a). As for the diffuse microplates, the Capricorn and Macquarie microplates in the Indian and Southern Oceans have undergone the total rotation of less than 10°. In particular, the Capricorn Microplate has experienced a rotation of less than ~3° with respect to the Indian Plate and less than ~1° with respect to the Australian Plate (Royer and Gordon, 1997) (Fig. 8a). It is interesting to note that the amount of total rotation for the Capricorn Microplate is the smallest among the nine plates analyzed in this study, although it is the oldest plate surrounded by a series of widespread deformation zone. The Macquarie Microplate also showed a rotation of less than ~8° with respect to the Antarctic Plate and less than ~7° for the Australian Plate (Choi et al., 2017) (Fig. 8a). Thus, there seems to be little correlation between the total rotation and the formation of the distinct and diffuse microplates.

However, the rotation rates can be used as an indicator to differentiate the formation processes of the distinct and diffuse microplates. For the distinct microplates located in the Pacific Ocean, the rotation rates exceed ~6.0 °/m.y. (Fig. 8b), which may be tectonically correlated with the given hot and thin oceanic lithospheres (e.g., Fig. 7). Including the Mammerickx Microplate (~6.4 °/m.y.), the distinct microplates mostly exhibit rotation rates of more than ~5.0 °/m.y. at least, except for the Friday (less than 2.0 °/m.y.) and Bauer (~2.3 °/m.y.) microplates. However, the Bauer Microplate was rotated at ~5.0 °/m.y. at the initial stage of the formation (Eakins and Lonsdale, 2003). The Easter and Juan Fernandez microplates characterized by large total rotation of ~45° and ~82°, respectively (Fig. 8a), also exhibit high rotation rate of ~15 °/m.y. (Fig. 8b).

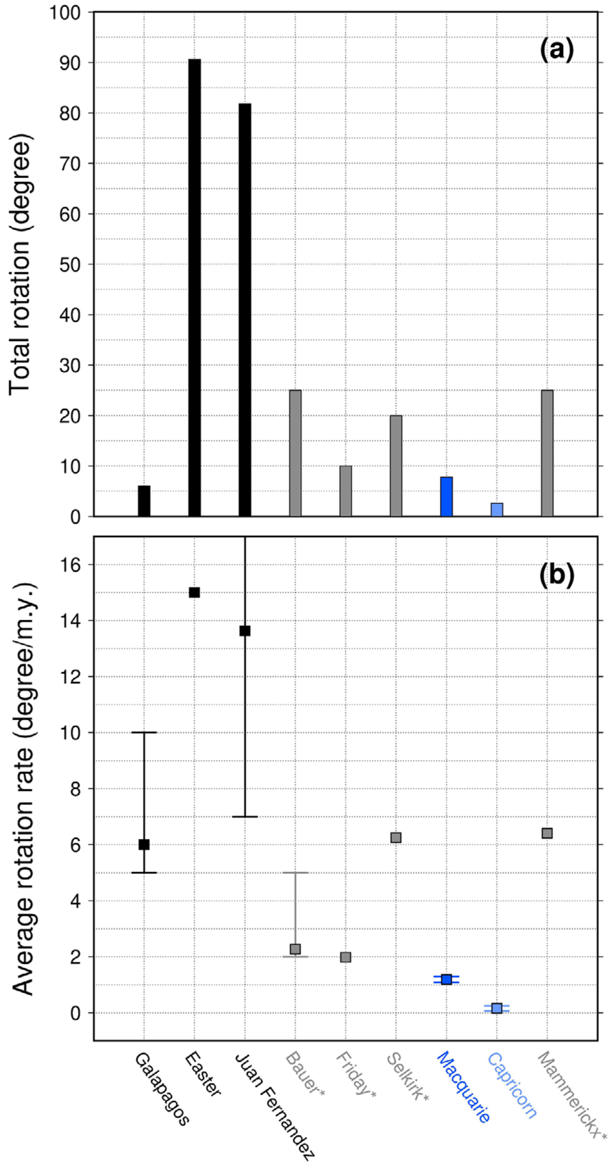

Fig. 8. (a) Total rotation amount of the distinct and diffuse microplates at the time they are/were active through the generation and territorial growth. Except for the Galapagos Microplate with age of ~1 Ma, all the distinct microplates have/had undergone at least ~10° rotations during the entire growth process of microplate, and the diffuse microplates have not. (b) Average rotation rates of the microplates. The distinct microplates mostly exhibit a rotation rate of about 5–6 °/m.y. or higher, and the diffuse microplates have a rotation rate of around 1 °/m.y or less. The range bars indicate the variation in the rotation rate within the active period of the plate.

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In contrast, the Capricorn and Macquarie microplates have the rotation rates of ~0.3° or less and ~1.3° or less, respectively (Fig. 8b). These rotation rates may be too small to cause brittle deformation and form any new narrow and distinct plate boundaries. Eventually, the Capricorn and Macquarie plates have remained as diffuse microplates with undergoing internal deformation. Thus, a rotation rate of approximately 5–6 °/m.y. or higher could be the minimum requirement for the evolving into a distinct microplate from a diffuse microplate.

5. SUMMARY

Microplate formation appears to be associated with the following major tectonic environmental indicators: plate reorganization, ridge propagation, fast-spreading ridge system, plume activity, and triple junction migration (Tebbens et al., 1997; Tebbens and Cande, 1997; Bird et al., 1999; Hey et al., 2004; Matthews et al., 2016). However, relations between these indicators have not been quantitatively assessed. In particular, we aimed to examine plausibility to differentiate the formation processes of distinct and diffuse microplates. During comparison, we found that the formation of diffuse microplates would be a default response to the given tectonic triggers to initiate microplate formation. We also found that the distinct microplate formation would require certain tectonic conditions to evolve into an independent and ridge plate with respect to the neighboring plates. If the conditions were not met, the same triggers would result in a microplate with diffuse plate boundaries. In this study, we used the following six tectonic parameters for comparison: plate size, plate age, full-spreading rates, thermal structures, total rotation, and rotation rate. The results are summarized as follows:

(1) Areas of less than $10^{5.5}$ km^2 (~3.0×10^5 km^2) and the ridge length of ~600 km appears to be the limiting factors for microplate formation. With any given tectonic triggers (e.g., plate reorganization), the area with such limited length of the ridge system is required to initiate and form a ridge and independent plate from its former principal plates.

(2) Full-spreading rates should exceed 70–80 mm/yr to grow into a microplate. The distinct plate boundaries of microplates would require a fast-spreading system, which may enhance ridge propagation in the relatively young, thin, and weak lithosphere and hence brittle deformation of the lithosphere accompanied with rapid rotation.

(3) Total rotation of more than 10° and rotation rate of more than 5–6 °/m.y. appears to be associated with the formation of distinct microplates. The total rotation and rotation rates during distinct microplate formation resulted from frequent ridge propagation and hence were much larger than those of diffuse microplates. For the estimated slow rotation rates, the diffuse microplates would be not evolved into a distinct microplate due to the thicker lithosphere.

In summary, microplate formation via ridge propagation and rapid rotation depends on whether the oceanic lithosphere is made brittle by the external forces induced by the changes in tectonic conditions. The physical property of the lithosphere in turn depends on the thickness and thermal structure of the given plate. If its size and age get too large and old, the thickening of the lithosphere will favor to form diffuse plate boundary, not distinct plate boundaries. Similarly, the fast-spreading system would produce thin oceanic lithosphere which is more prone to brittle deformation. As for thermal structures of upper mantle, a further study is required to fully assess relations between the global tomography variation and formation of distinct and diffuse microplates.

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