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Do microcontinents nucleate subduction initiation?

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ABSTRACT

Subduction initiation is a pivotal process in plate tectonics. Models of subduction initiation include the collapse of passive margins, oceanic transform faults, inversion of oceanic core complexes, and ridge failure but have ignored the potential effects of continental crust relicts within the oceanic crust. In this paper, we explore the role of microcontinents on subduction initiation through two-dimensional thermo-mechanical numerical modeling. We consider three scenarios with variable ages of oceanic crust surrounding the microcontinent and parametrically examine the microcontinent characteristics (size, crustal thickness, thermal gradient, and rheology), oceanic plate age, and convergence rates. Results suggest that moderate-size (≥300 km) microcontinents can nucleate subduction initiation at the junction between continental and oceanic plates. A large part of the microcontinent would be dragged into the subduction zone, and the subsequent asthenosphere upwellings would incorporate part of the microcontinent. Our numerical models add a new hypothetical scenario for subduction initiation, especially for those places where a young and buoyant plate subducts beneath an older and denser oceanic plate. Moreover, they can explain the origin of exotic crust materials and ultrahigh-pressure minerals in supra–subduction zone ophiolites.

INTRODUCTION

Subduction is arguably the fundamental force driving plate tectonics on Earth (e.g., Guilmette et al., 2018). Direct records of subduction initiation are rarely observed in either modern tectonic settings or ancient orogens, which makes the mechanisms responsible for subduction initiation enigmatic and controversial (Stern, 2004; Crameri et al., 2020). Hypotheses for subduction initiation include its development in passive margins and intraoceanic settings (e.g., Stern and Gerya, 2018). Collapse of passive continental margins is an intuitive idea regarding formation of new subduction zones because it closes the Wilson cycle loop with sinking of the oldest pieces of oceanic crust (e.g., Zhong and Li, 2019). However, rheological strengths in passive margins may resist the lithospheric collapse, unless such margins were sufficiently weakened (e.g., Nikolaeva et al., 2011; Bercovici and Mulyukova, 2021). Recent studies have proposed that subduction at weakened passive margins may result from the lateral propagation of intraoceanic subduction zones rather than actual initiation (a.k.a. "infection"; Zhou et al., 2020). Research in intraoceanic settings suggests that subduction initiation nucleates at lithospheric weak zones such as major transforms or other oceanic faults (Stern and Gerya, 2018). This may happen regardless of whether initiation is spontaneous—oceanic lithosphere collapses when it becomes denser than the mantle—or induced—where plate convergence forces a plate to subduct (Stern, 2004). In both scenarios, the older and denser oceanic plate would underthrust beneath the younger and buoyant plate (Stern and Gerya, 2018). However, some real cases of subduction initiation like the North Luzon arc (Fig. 1), where the younger South China Sea plate subducts beneath the older western Philippine Sea plate (Shao et al., 2015), challenge this hypothesis. Supra–subduction zone (SSZ) ophiolites, oceanic lithosphere tectonically emplaced into orogens, are generally suggested to document ancient subduction initiation of intraoceanic arcs (Whattam and Stern, 2011). Crustal minerals (e.g., zircons) and ultrahigh-pressure (UHP) minerals (e.g., diamonds) have been recovered from the upper-mantle sections of SSZ ophiolites (e.g., Yang et al., 2007; Yamamoto et al., 2013; Belousova et al., 2015). The existing geodynamic models of subduction initiation struggle to explain the origin of these exotic minerals in the SSZ ophiolites.

Old zircon xenocrysts occur in modern oceanic arcs such as the Solomon Islands (Tapster et al., 2014) and Luzon arc (Shao et al., 2015), indicating that cryptic and older continental crust exists in some juvenile oceanic arcs (Shao et al., 2015). Microcontinents represent isolated continental pieces stranding in oceanic lithosphere and are ubiquitous in both modern ocean basins and ancient orogens (Torsvik et al., 2013; Xiao et al., 2015). They have been widely studied to understand their formation (Müller et al., 2001; Whittaker et al., 2016; Molnar et al., 2018) and their accretion to convergent margins (Moresi et al., 2014; Gün et al., 2021). Microcontinents are generally weaker and more buoyant than the surrounding oceanic lithosphere (Molnar, 1988; Gün et al., 2021), with strong rheological contrasts but not too much lithospheric strength. We hypothesize that such obstacles may represent potential loci for subduction initiation. In tectonic reconstructions of the northern Luzon and the Puysegur (New Zealand) subduction zones, microcontinents were postulated as a factor in

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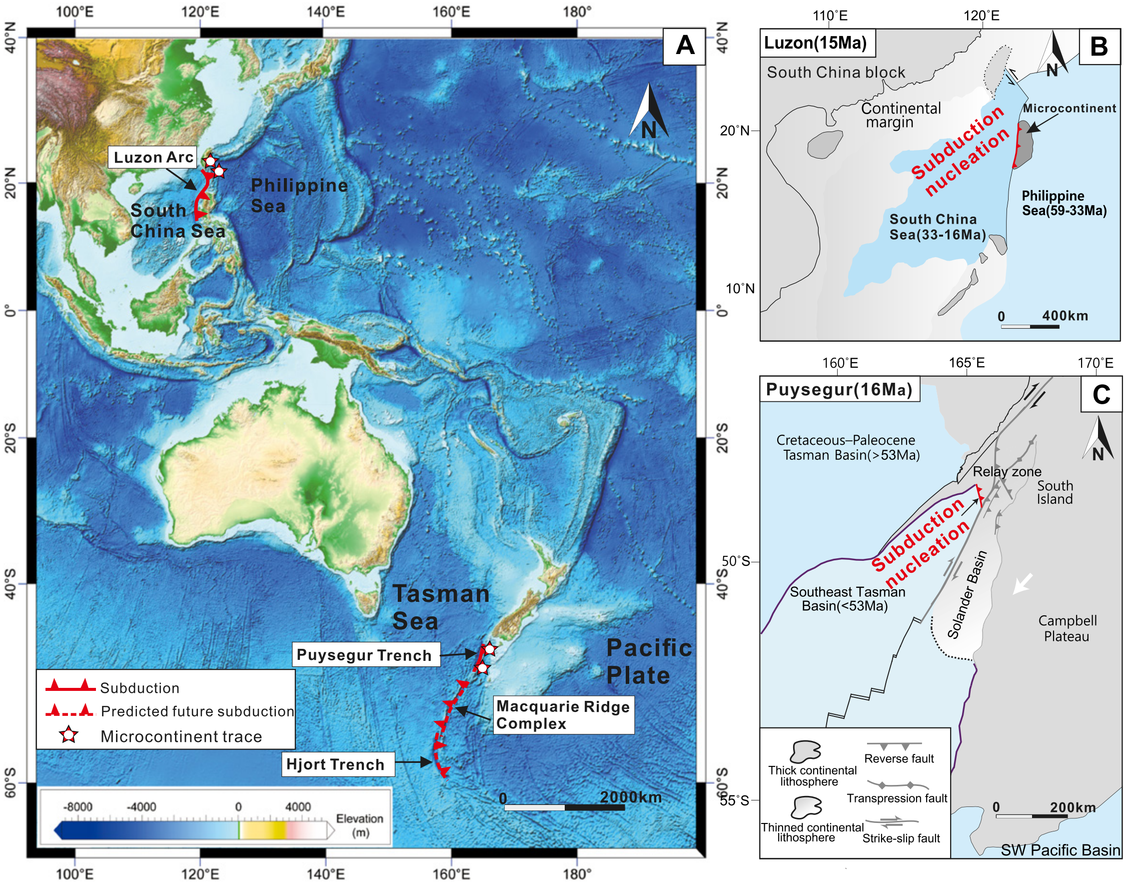

Figure 1. (A) Possible convergent margins where microcontinent facilitated subduction initiation. (B) Tectonic reconstruction of Luzon subduction initiation at 15 Ma (after Shao et al., 2015). The age ranges for the South China Sea and Philippine Sea represent the time of seafloor spreading. (C) Plate reconstruction showing setting of Puysegur subduction initiation at 16 Ma (after Shuck et al., 2022).

where subduction initiated (Shao et al., 2015; Gurnis et al., 2019; Fig. 1).

In this paper, we explore the role of microcontinents in nucleating subduction initiation by numerical modeling with I2VIS, a two-dimensional thermo-mechanical code (Gerya and Yuen, 2003). We first conducted three models with variable age of oceanic crust surrounding the microcontinent, according to the different mechanisms of microcontinent formation, and parametrically examined in one of them thermal gradient, rheology, and crust thickness of the microcontinent, oceanic plate age, convergence rate, and size of the microcontinent to explore the subduction initiation mechanism of microcontinents. The models predict subduction nucleation along the edge of the medium microcontinents and explain why the younger

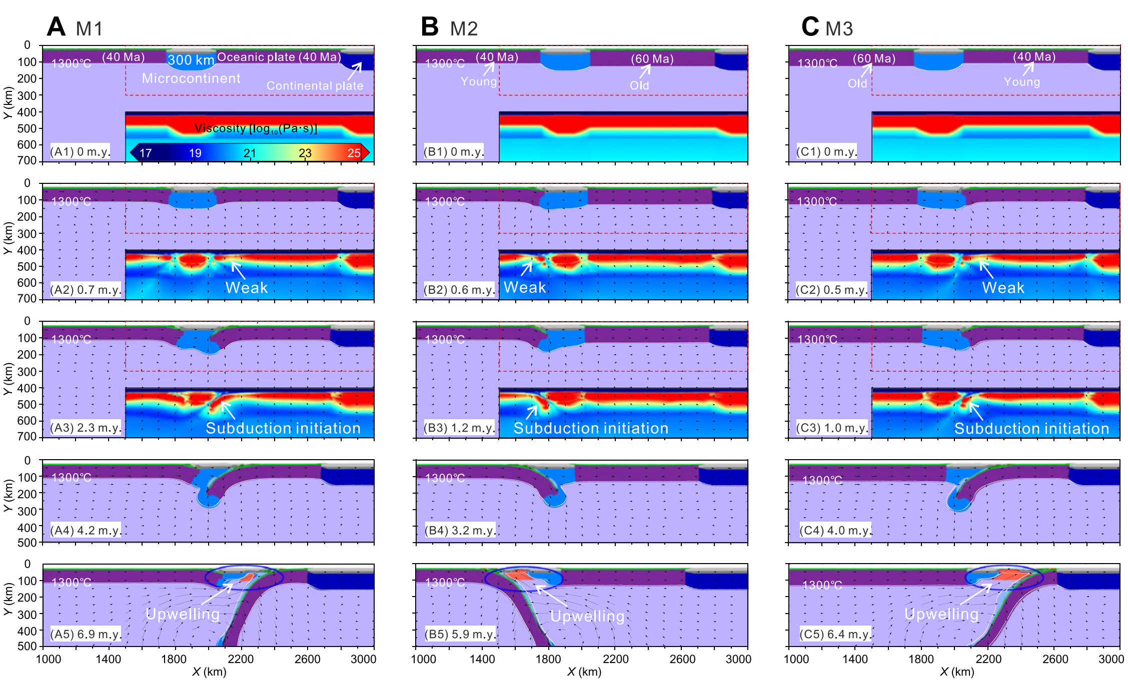

Figure 2. Numerical model evolution of composition and viscosity (in the red box area) showing subduction initiation along the edge of the microcontinent. The three models (M1, M2, and M3) are selected to simulate the three most common conditions associated with microcontinent formation, and they are the same except for the age of the oceanic plate surrounding the microcontinent. (A) Both are 40 Ma. (B) On the left of the microcontinent is 40 Ma, and on the right is 60 Ma. (C) On the left of the microcontinent is 60 Ma, and on the right is 40 Ma. The solid line with black arrow represents the velocity field; the length of the solid line represents the relative size of the velocity.

buoyant oceanic plate could subduct beneath the older denser oceanic plate and the origin of crustal materials and UHP minerals in the SSZ ophiolites.

NUMERICAL MODEL RESULTS

The models consist of four tectonic units: a continent plate with a passive margin, and a microcontinent surrounded by two oceanic plates, as shown in Figure S1 in the Supplemental Material[1]. We tested a range of models and selected three references to simulate the three most common conditions associated with microcontinent formation (see the Supplemental Material for numerical parameters):

Model M1 (Fig. 2A): Rotational extension due to relative motion of diverging plates combined with preexisting linear lithospheric weaknesses could separate microcontinents from passive margins during the last phases of continental breakup (Molnar et al., 2018). In this scenario, the oceanic crust on both sides of microcontinents should be similar in age. In M1, the age of the oceanic plate surrounding the microcontinent is fixed at 40 Ma on both sides.

Model M2 (Fig. 2B): Müller et al. (2001) suggested that the impingement of a mantle plume adjacent to an active spreading ridge could cause renewed continent rifting followed by microcontinent separation. In this scenario, the earlier active spreading ridge would be extinct in favor of the new seafloor spreading. The oceanic crust between the microcontinent and continent therefore would be older than that toward the spreading ridge. M2 consists of a 60 Ma oceanic plate facing the continent and a 40 Ma oceanic plate of 40 Ma on the oceanward side of the microcontinent.

Model M3 (Fig. 2C): Plate tectonic reorganization could separate microcontinents from a passive margin modified by preceding mantle plume activity (Whittaker et al., 2016). In this scenario, the oceanic crust between the microcontinent and continent would be younger than that toward the spreading ridge. Our M3 set includes an oceanic plate of 40 Ma facing the continent in contrast to a 60 Ma oceanic plate on the ocean side.

All three models result in an induced subduction initiation within a few million years (~3 m.y.) located at one of the boundaries of the microcontinent (Fig. 2). The viscosity contrast between the microcontinent and the adjacent oceanic plate (Fig. 2) could localize deformation at this weak interface rather than at stronger passive margins during plate convergence. Thermal and compositional density differences between the microcontinent and oceanic plate facilitate the shearing and rupture of the continent-ocean contact zone, and then one of the oceanic plates begins to sink under the microcontinent (Fig. S2). The sinking oceanic slab could release fluids with increasing depth, temperature, and pressure, which would drastically reduce the effective friction coefficient of the weak interface and promote the nucleation of a self-sustained subduction zone (van der Lee et al., 2008). A large part of the microcontinent is sheared and dragged into the subduction zone by the negative buoyancy of the subducted slab as subduction continues (Fig. 2). This is because the weak continental lithosphere of the microcontinent is more inclined to suffer internal deformation than the surrounding oceanic lithosphere (Molnar, 1988; Gün et al., 2021). In models M2 and M3, the younger oceanic plate, rather than older one, sinks into the mantle (Figs. 2B and 2C). This is due to the boundary between the younger oceanic plate and microcontinent being weaker than such between the older oceanic plate and microcontinent as well as the passive margin (Figs. 2B2 and 2C2). In addition, the strength of the oceanic plate increases with increasing age (Cloetingh et al., 1982), and thus it is easier for the younger oceanic plate to bend and initiate subduction. Hot asthenosphere upwellings and decompression melting during subduction initiation are clearly demonstrated in our models (Fig. 2). In M2, numerical models with different age offsets of the oceanic plates predict similar subduction initiation of the younger oceanic plate along the edge of the microcontinents (Fig. S3A). If the microcontinents are removed,

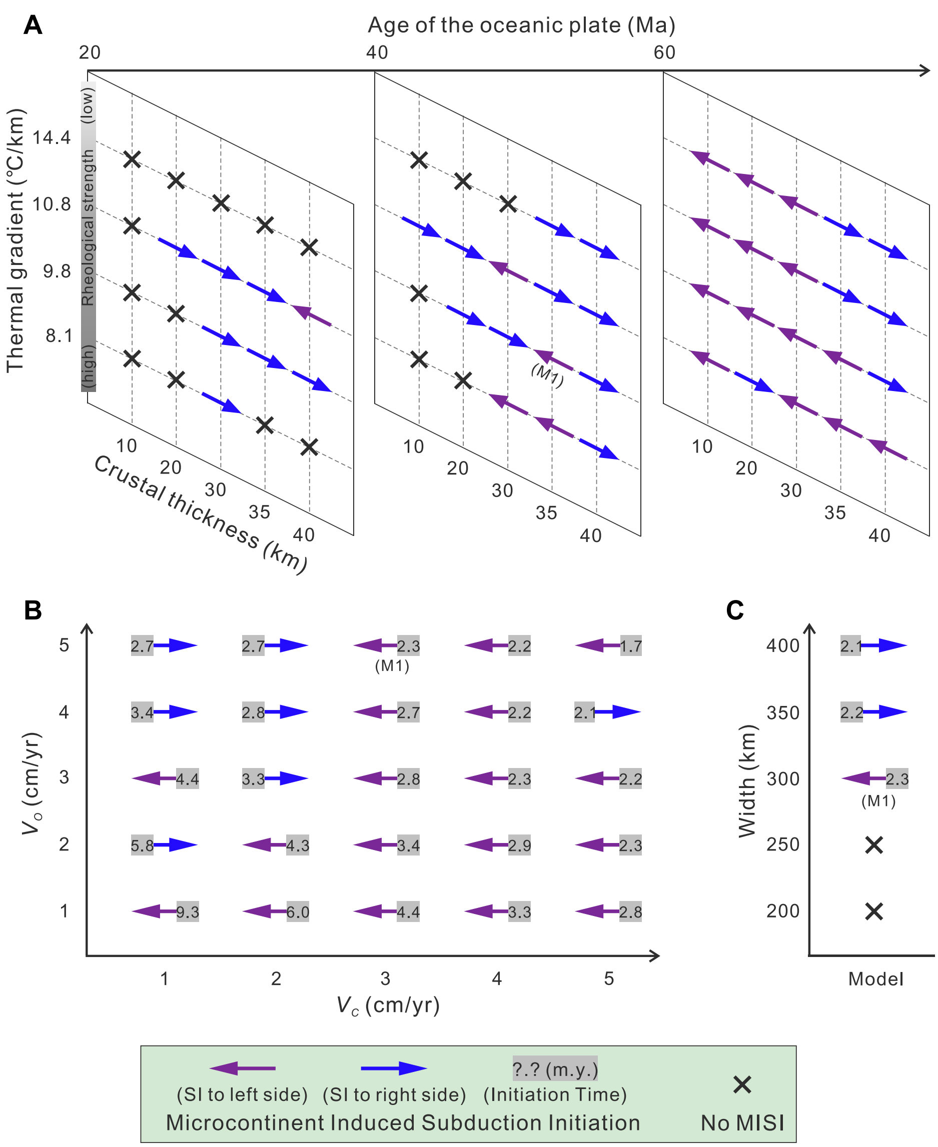

Figure 3. Parametric results in comparison to reference model M1. (A) Results from variation of thermal gradient, rheology, and crust thickness of the microcontinent as well as oceanic plate age. (B) Results from variation of convergence rates. V_c and V_o represent the convergence rates of continental and oceanic plates, respectively. (C) Comparison of models with variously sized microcontinents. MISI—microcontinent-induced subduction initiation.

[1]Supplemental Material. Numerical modeling method, Table S1, and Figures S1–S3. Please visit https://doi.org/10.1130/GEOL.S.22756013 to access the supplemental material, and contact editing@geosociety.org with any questions.

the model results suggest the older oceanic plate would subduct beneath the younger oceanic plate (Fig. S3B).

We investigated the effects of thermal gradient, rheology, and crust thickness of the microcontinent, oceanic plate age, convergence rates, and size of the microcontinent with respect to the reference model M1. Our results suggest that oceanic plate age plays a crucial role in microcontinent-induced subduction initiation (Fig. 3A). Subduction initiation along the edge of the microcontinent is more likely as oceanic plate ages. Thermal gradient, rheology, and crust thickness of the microcontinent mainly determine the subduction polarity (Fig. 3A); e.g., when the oceanic plate is 60 Ma, thinner microcontinents ($\leq$30 km) nucleate mainly left-dipping subduction, whereas thicker microcontinents ($>$30 km) mainly nucleate right-dipping subduction. Convergence rates could control timing and polarity of microcontinent-induced subduction initiation (Fig. 3B). The convergence rate is generally negatively correlated with subduction initiation timing. When the convergence rate of the continent plate is $>$3 cm/yr, the microcontinents nucleate mainly left-dipping subduction. When continental plate convergence rate is $<$3 cm/yr, left-dipping subduction changes into right-dipping subduction with increasing convergence rate of the oceanic plate. A microcontinent width $\geq$300 km seems to be a requirement for nucleating microcontinent-induced subduction initiation (Fig. 3C).

DISCUSSION

Our modeling is a first test of the hypothesis that microcontinents embedded within the oceanic lithosphere can nucleate subduction. According to our results, the edges of microcontinents may seed subduction initiation more easily than in stable passive continental margins. In addition, our study suggests that a younger oceanic plate more easily subducts under the microcontinent, consistent with observed present-day subduction of a younger oceanic slab beneath an older oceanic slab. Our results also suggest that large portions of the microcontinent nucleating subduction may be dragged into the mantle during the first stages of the subduction processes. Such a feature may explain why the role of the microcontinent in subduction initiation has been largely underestimated in previous studies.

Our modeling results can help resolve the contested subduction initiation settings in Luzon and Puysegur. The Luzon arc system results from the eastward subduction of the South China Sea plate beneath the West Philippine Basin part of the Philippine Sea plate (Fig. 1A). Seafloor spreading took place in the West Philippine Basin at 59–33 Ma (e.g., Deschamps and Lallemand, 2002) and in the South China Sea at ca. 33–16 Ma (Briais et al., 1993). The oldest age of Luzon arc volcanism indicates that the South China Sea plate likely initiated subduction ca. 18–16 Ma (Shao et al., 2015). Occurrence of old zircons (0.2–3 Ga) in the young lavas indicates underlying microcontinents in the Luzon arc and Gagua Ridge of the Philippine Sea (e.g., Qian et al., 2021). These microcontinents likely rifted from the South China block during opening of the South China Sea and then drifted to the western margin of the Philippine Sea (Shao et al., 2015; Qian et al., 2021). Subduction initiation apparently occurred along the western margin of the microcontinent (Fig. 1B; Shao et al., 2015). Both polarity and occurrence of the inherited zircons in arc volcanics are consistent with our modeling results.

The Puysegur subduction zone marks the northern Australian-Pacific plate boundary south of New Zealand (Fig. 1A). New Zealand separated from the Gondwana margin through Tasmania seafloor spreading ca. 110–90 Ma (Kula et al., 2007; Hoernle et al., 2020). Spreading of the Tasman Sea ceased ca. 52 Ma, followed by a renewed seafloor spreading along the Pacific-Australia margin at 45–30 Ma (Gurnis et al., 2019; Shuck et al., 2022). Starting ca. 30 Ma, changes in relative motion between the Australian and Pacific plates caused this divergent plate boundary to change to dextral strike-slip movement accompanied by a transpressive relay zone at Puysegur Bank (Lallemand and Arcay, 2021). Puysegur subduction initiated ca. 20–16 Ma along this relay zone and involved underthrusting of Australian oceanic lithosphere beneath the Pacific plate (Gurnis et al., 2019; Lallemand and Arcay, 2021; Fig. 1C). New geophysical results show that the overriding Pacific plate is block-faulted and extended continental crust rather than oceanic in nature along much of the plate boundary where subduction initiated (Gurnis et al., 2019). The microcontinent apparently played a significant role in nucleating the Puysegur subduction initiation (Gurnis et al., 2019), consistent with our modeling results. In addition to the Puysegur subduction zone, convergence and underthrusting possibly associated with subduction initiation are also observed to the southwest along the Macquarie Ridge Complex and Hjort Trench region (Lallemand and Arcay, 2021). The oceanic crust is $\sim$20 m.y. older on the west near Macquarie Island (ca. 30 versus ca. 10 Ma), has similar ages on both sides near the northern segment of the Hjort Trench (ca. 20 Ma), and is 20 m.y. older on the east near the southern segment of the Hjort Trench (ca. 10 Ma versus ca. 30 Ma) (Lallemand and Arcay, 2021). It is noteworthy that the deepest troughs, the predicted future subduction initiation sites, are located on the side of the young oceanic crust (Fig. 1A). Thus, we speculate that continental fragments may exist in the Macquarie and Hjort regions similar to those in the Puysegur region, facilitating subduction initiation.

Finally, our modeling results provide a new tectonic scenario explaining why crustal materials and UHP minerals occur in SSZ ophiolites (Fig. 4). When subduction initiates along the microcontinents, part of the microcontinent is dragged and foundered into the mantle. The asthenospheric upwelling, which forms the mantle part of the SSZ ophiolite, could incorporate part of these crust materials and UHP minerals from the microcontinents, as our modeling shows (Fig. 4B). The UHP minerals were probably transported to the lithospheric depths of the microcontinents through plume activity before their incorporation into ophiolites. Our suggestion is evidenced by the presence of ultra-refractory geochemical features similar to those of cratonic mantle peridotites (Huang et al., 2020), old re-depletion model ages (Shi et al., 2007), and Precambrian zircons (Yama-

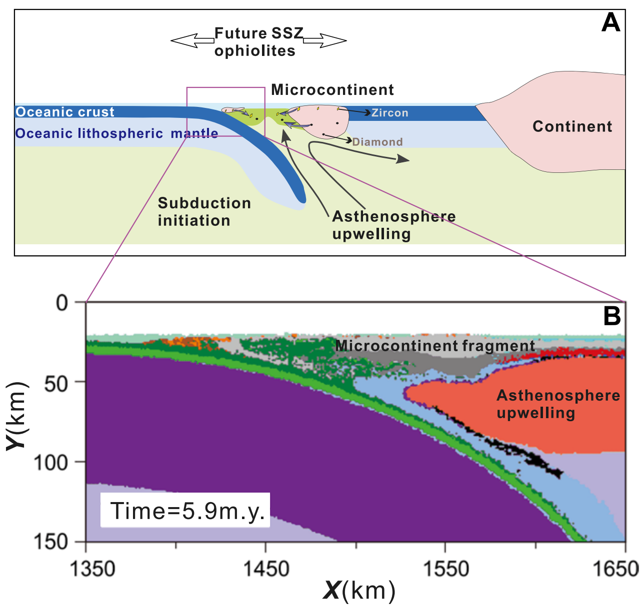

Figure 4. (A) Cartoon showing the origin of crustal materials and ultrahigh-pressure minerals in supra–subduction zone (SSZ) ophiolites. (B) Model M2 snapshot at 5.9 m.y. The purple and blue arrows represent the left and right directions of the subduction initiation, respectively.

moto et al., 2013) in the mantle part of various SSZ ophiolites.

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