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No seamount subduction, no magmatic arc?

XiaoBo He[1*], JunTao Tao[1], Yi Cao[2], FaBin Pan[2], EnYuan He[3], LingMin Cao[3], and YiXian Zheng[4]

[1]Department of Ocean Exploration & Technology, Zhejiang Ocean University, Zhoushan Zhejiang 316022, China;

[2]School of Earth Sciences, China University of Geosciences, Wuhan 430074, China;

[3]Key Laboratory of Ocean and Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China;

[4]Department of Marine Sciences, Zhejiang University, Zhoushan Zhejiang 316021, China

Key Points:

- Seamount subduction plays an important role in transporting a considerable flux of water into the deep mantle.
- Arc magmatism is likely related to seamount dehydration.
- The arc gap can be attributed to a subducting slab not being accompanied by seamounts.

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Abstract: Water is essential for the formation of a magmatic arc by lowering the melting temperature of materials in the mantle wedge. As such, it is logical to attribute the absence of a magmatic arc to insufficient water released from the subducting plate, although a number of other factors may cause volcanic arc quiescence as well, such as a slab window or flat slab subduction. In this contribution, we present a possible but testable correlation between the occurrence of a magmatic arc and seamount subduction in light of bathymetric data obtained near trenches. This correlation, if it holds true, in turn means that a magmatic arc is unlikely to occur when the subducting slabs have not been severely fractured and that one of the main reasons for excluding effects such as the slab window or flat slab subduction may be that the plate is not accompanied by seamounts. Therefore, the role that seamount subduction plays in recycling water back into the mantle deserves more attention from the earth sciences community.

Keywords: seamount subduction; arc volcano; slab dehydration; slab faulting; bathymetric anomaly

1. Introduction

Subduction zones act as the most important sites of mass and energy exchange in the earth system, with significant implications for the evolution of the Earth's surface and interior (e.g., Stern, 2002). In subduction zones, lithospheric plates are descending into the mantle, leading to earthquakes and magmatic arc volcanoes. Magmatic arcs are surface manifestations of hot materials rising upward from deep inside the mantle, as a result of the solidus temperature being lowered by water released from the descending slabs (e.g., Katz et al., 2003). This process helps cool the planet and plays a key role in the overall differentiation of the planet, including the formation of the atmosphere (e.g., Paterson and Ducea, 2015). Magmatic arcs are also natural laboratories for studying the growth of continental crusts (e.g., Attia et al., 2020). In essence, magmatic arcs are the product of water cycling between the oceans and the solid earth. As such, studying magmatic arc volcanoes can shed light on the water contents in the mantle. Specifically, nearly all arc volcanoes are sourced from mafic magmas that contain 2–6 wt% H_2O, with a global average of 3.9 ± 0.4 wt% H_2O. One possibility is that magmas rise from the mantle with variable H_2O contents (>4 wt%; Plank et al., 2013).

One puzzling aspect of the evolution of magmatic arcs is the mechanisms that result in their absence, causing magmatic arc gaps to form along the arc strike (Figure 1). A number of mechanisms have been proposed to explain the magmatic arc gap in different tectonic settings: (1) a slab window (gap; e.g., Castellanos et al., 2018), which can be attributed to factors such as aseismic ridge subduction (e.g., Rosenbaum and Mo, 2011), whereby no slab sits below the arc when the window has largely developed; (2) flat slab subduction (e.g., Figure 1; Rondenay et al., 2010; Chuang L et al., 2017; Manea et al., 2017), which leads to a cold environment with no sufficient mantle wedge existing above the flat slab; (3) oceanic crust underthrusting (Tang GJ et al., 2021), which is somehow equivalent to the flat slab scenario by causing no melting of mantle wedge materials; (4) removal of the subducting crust at shallow depths (Yang JF et al., 2020) so that the water fails to move into the deep mantle; (5) the extrusion of lavas inhibited at a prevailing compressional regime (Yumul et al., 2020), whereby the magma becomes trapped in the mantle; and (6) adjustment of the subducted slab by steepening (Ku YP et al., 2009), which represents a period of arc migration that leads to changes in the temperature and pressure conditions in the mantle wedge. However, the existing mechanisms still do not sufficiently account for the magmatic arc gaps that occur widely at the western

Correspondence to: X. B. He, xiaobo.he@zjou.edu.cn
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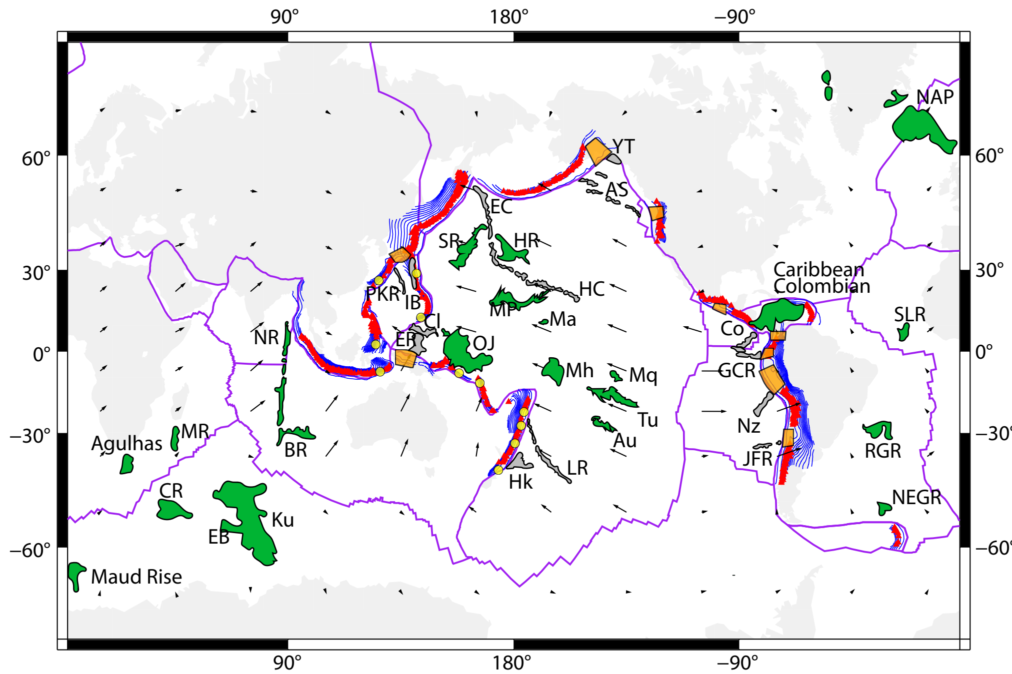

Figure 1. Distributions of arc volcanoes (red triangles), prominent arc gaps (yellow circles), slab flattening areas (orange shaded quadrilaterals), major oceanic plateaus or seamounts (in green; Kerr, 2014), and subducting arcs, ridges, or seamount chains (Gutscher et al., 2000). Magmatic arc volcanoes are provided by the National Oceanic and Atmospheric Administration and modified from Syracuse and Abers (2006). The subduction zone geometry model shown as blue lines is Slab2 (Hayes et al., 2018). Absolute plate velocities in a mantle reference frame are shown as black arrows (Müller et al., 2019). Abbreviations: CR, Conrad Rise; MR, Madagascar Rise; EB, Elan Bank; Ku, Kerguelen Plateau; BR, Broken Ridge; NR, Ninetyeast Ridge; PKR, Palau–Kyushu Ridge; IB, Izu–Bonin Arc; ER, Euripik Rise; CI, Caroline Plateau; OJ, Ontong Java Plateau; LR, Louisville Ridge; Hk, Hikurangi Plateau; Au, Austral Plateau; Tu, Tuamotu Plateau; Mq, Marquesas Plateau; Mh, Manihiki Plateau; Ma, Magellan Rise; MP, Mid-Pacific Mountains; HC, Hawaiian Chain; HR, Hess Rise; SR, Shatsky Rise; EC, Emperor Chain; Co, Cocos Ridge; GCR, Galápagos–Carnegie Ridge; Nz, Nazca Ridge; JFR, Juan Fernández Ridge; RGR, Rio Grande Rise; NEGR, Northeast Georgia Rise; SLR, Sierra Leone Rise; NAP, North Atlantic Province.

Pacific subduction zone, such as the typical one near the Challenger Deep and another in the middle of the Izu–Bonin trench (Figure 1).

Here we propose that the magmatic arc gap is caused by subduction of a "dry" slab and that such a subducting slab is dry because of insufficient hydration as a consequence of slab subduction unaccompanied by seamounts. The foundation that establishes the relationship between seamount subduction and the generation of magmatic arcs lies in (1) the possible spatial correlation that exists between arcs and the abundant seamounts near trenches and (2) a growing body of evidence suggesting that highly hydrated seamounts exist in subduction zones. We will explore these lines of evidence fully in the following sections.

2. The Linkage Between Magmatic Arcs and Seamount Dehydration

Because magmatic arcs are the result of slab dehydration, a logical explanation for magmatic quiescence is that magmatic arcs are due to an insufficient release of water from the subducting slabs. To understand the cause of a magmatic arc gap, we need to explain why the descending slab has not been well hydrated. Here we suggest a possible spatial correlation between the arcs present and the abundant seamounts near trenches, as exemplified by the Izu–Bonin–Mariana, Ryukyu, and Tonga–Kermadec subduction zones (Figure 2). It is also clear that magmatic gaps appear to be spatially correlated with trenches that are not characterized by the arrival of seamounts (Figure 2). Specifically, a striking volcanic gap is seen in the southernmost Mariana subduction zone, where a relatively smooth seafloor without notable seamounts can be observed at the trench–outer rise area near the Challenger Deep.

Note that there is a distance between the arc and the trench. Thus, the fact that seamounts are seen near trenches prior to subduction does not necessarily indicate that the seamounts are subducting underneath the arcs. Our suggestion assumes that seamounts often appear in groups on the seafloor. A typical area with seamounts emerging in large numbers is in the South China Sea (e.g., Zhao MH et al., 2018; Zhao YH et al., 2020; Qian SP et al., 2021), strongly suggesting the possibility that seamount subduction exists when several seamounts are observed prior to subduction. This is likely true, as exemplified by the central Mariana and Izu-Bonin forearcs (Oakley et al., 2008). Therefore, a causal linkage perhaps exists between the magmatic arc and seamount dehydration. In other words, the water content associated with seamount subduction is likely much higher than that solely from normal slab dehydration. This may be due to the difference in fracture density between seamounts and the slab. We explain this aspect in more detail in Section 4.2.

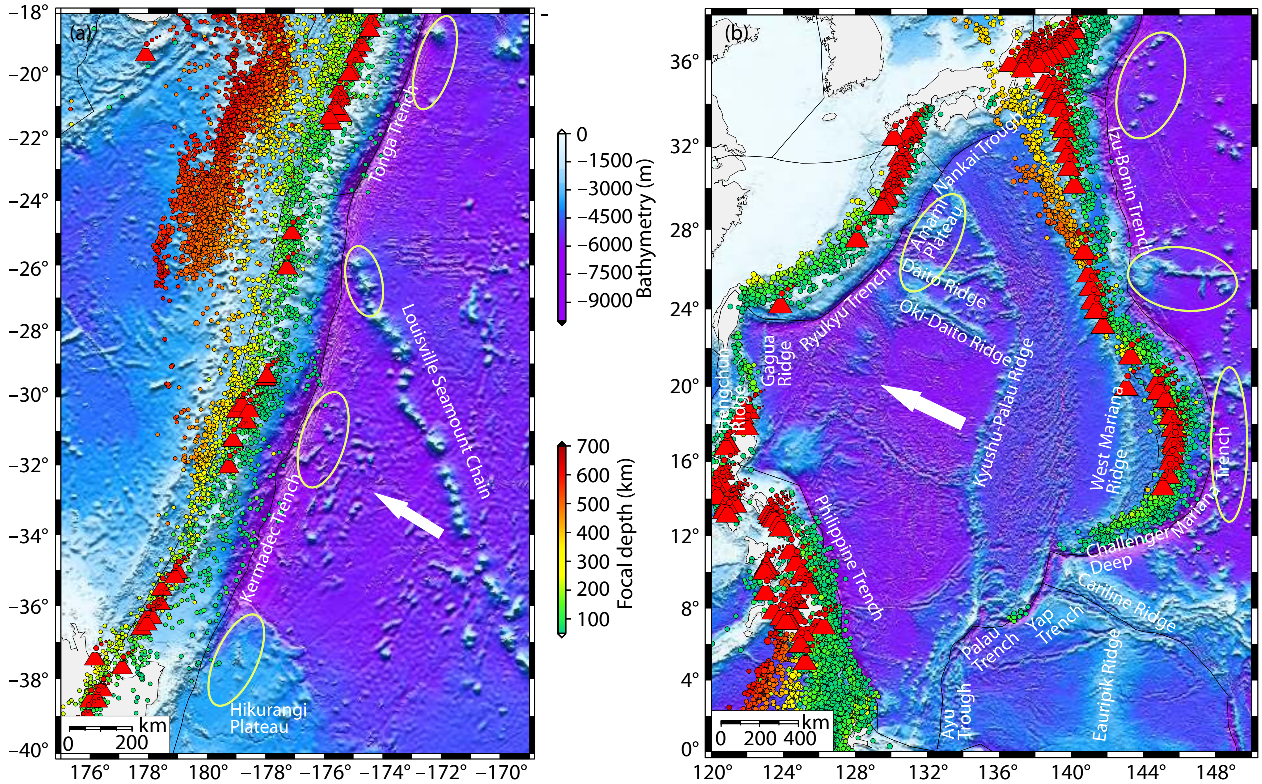

Figure 2. Map of bathymetry, seismicity, and arc volcanoes in the Tonga–Kermadec subduction zone (a) and circum-Philippine Sea subduction zones (b). The ellipses delineate the seamount-rich areas near trenches.

3. Existing Evidence for Hydrous Seamounts in Subduction Zones

To demonstrate that seamount subduction is capable of accounting for dehydration-triggered magmatic arcs, we collected evidence showing the existence of hydrous seamounts in subduction zones. A recent work using passive and controlled-source seafloor electromagnetic data collected in a region of active seamount subduction at the northern Hikurangi Margin, New Zealand, showed that 3.2 to 4.7 times more water was subducted compared with the normal, unfaulted oceanic lithosphere (Chesley et al., 2021). In an earlier study using seismic wide-angle reflection and refraction data collected in the trench–outer rise region offshore of Nicaragua, Ivandic et al. (2010) found a prominent slow-velocity anomaly within the crust beneath two seamounts, suggesting that water percolation and circulation had increased the porosity. Kopp et al. (2004) observed similar anomalous low upper-mantle velocities attributable to faulting-related lithosphere hydration beneath the O'Higgins seamount group and the Juan Fernández Ridge. The fluid-rich Yakutat oceanic plateau, confined to at least the upper crust, can also explain the slab buoyancy, and thereby the flat subduction (Petersen et al., 2021), along with a spectrum of other characteristics of low-frequency earthquakes, intraslab seismicity, and tectonic structures in central Alaska (Chuang et al., 2017). Collectively, all the lines of existing evidence suggest that subducting seamounts represent an underappreciated mechanism for transporting a considerable flux of water to the forearc and deep mantle.

4. How a Seamount Is Hydrated

The hydration of seamounts is considered to occur through a two-stage process: (1) initial hydration when they are formed and (2) faulting-related hydration resulting from seamount–trench interactions. The latter stage is thought to play a dominant role in hydration by hydrating the interior of the seamount as well as the vicinity where it occurs.

4.1 Seamounts Are Hydrated When They Are Formed

Park and Rye (2019a, b) proposed the "metasomatic underplating" model and argued that crustal fractures develop during hot spot magma ascent, which allows seawater to infiltrate and serpentinize the sub-Moho mantle. This process could account for the 5–10 km anisotropic layer lying between the crust and mantle beneath volcanic islands (seamounts). If this is the case, seamounts are hydrated when they are formed in the middle oceanic floor.

4.2 Seamounts Are Hydrated as They Interact with Trenches

It is well known that incoming plates are subjected to hydration through faulting-related processes associated with outer rise bending (e.g., Cai C et al., 2018; Wan KY et al., 2019; Zhu GH et al., 2021). Therefore, faulting related to trench–slab interactions can also be appreciated as a source of hydration. In other words, more intense deformation leads to more faults, and thereby more hydration. A series of numerical experiments (e.g., Baba et al., 2001; Zhang JY et al., 2022) revealed that intense deformation was localized around the subducting seamounts during seamount–trench collisions, which facilitated slab fracturing. A high-angle normal fault intersecting the slab was also observed just ahead of the subducting seamount in northern Ryukyu, where oceanic plateaus are subducting (Arai et al., 2017). All the numerical and natural observations support extensive fracturing of the subducting seamounts.

To understand whether the developed fractures can be observed in the trench–outer rise region, we examined bathymetric data collected at the East Caroline Ridge (Figure 3a) and the Juan Fernández Ridge (Figure 3b). Unlike trench-parallel normal faulting, which is widely developed for incoming plates at the outer rise, trench-normal and plate motion-parallel signatures are also observed in these two settings (Figure 3). This scenario is consistent with the prediction that in areas mostly locked by friction, the faults in the incoming plates are oriented nearly perpendicularly to the trench (Li SS and Freymueller, 2018). Such a scenario may have very important implications for intraplate intermediate-depth seismicity in subduction zones (e.g., Geersen et al., 2022).

More important, it has been suggested that 3.2 to 4.7 times more water is carried into the deep mantle by a subducting seamount compared with the normal, unfaulted oceanic lithosphere (Chesley et al., 2021). One possible explanation for the high degree of hydration for seamounts is that seamounts and their margins must be subjected to greater fracturing; this explanation is consistent with the notion that subducting seamounts are prone to aseismic creep and small earthquakes as a result of the development of a fracture network during subduction (Wang KL and Bilek, 2011, 2014). This scenario is further supported by a local observation showing the existence of the Louisville earthquake gap (a 200-km-wide reduction in earthquake [$M_w > 5$] numbers; Bassett and Watts, 2015) and enhanced volcanic activity associated with the subduction of the Louisville seamount chain in the middle of the Tonga–Kermadec trench. Therefore, our model directly links the seismicity to arc volcanism in a seamount subduction zone.

It is also worth mentioning that sufficient hydration is not limited to seamounts only, but is applicable to subduction of other types of bathymetric anomalies as well, such as continental margins, island arcs, fracture zones, spreading ridges, and oceanic plateaus. The key process that hydrates the incoming slabs well is the formation of faults, which facilitates water transport into the slabs through trench–slab interactions, whereas the arrival of bathymetric anomalies in trenches is conducive to fault generation.

5. Summary

In this contribution, we present the hypothesis that magmatic arc gaps are likely due to the subduction of a dry slab that has avoided sufficient hydration and that this insufficient hydration is perhaps caused by subducting slabs that are not accompanied by seamounts. That is, the seamounts play a vital role in slab fracturing, and thereby slab hydration, when they encounter subduction zones. Therefore, seamounts serve as the most important carriers of water back into the mantle. If this is the case, the slab hydration resulting from outer-rise bending alone is not sufficient to produce magmatic arc volcanoes. In the future, more seismic and electromagnetic images along with numerical modeling will shed light on the role that seamount subduction plays in the generation of volcanic arcs.

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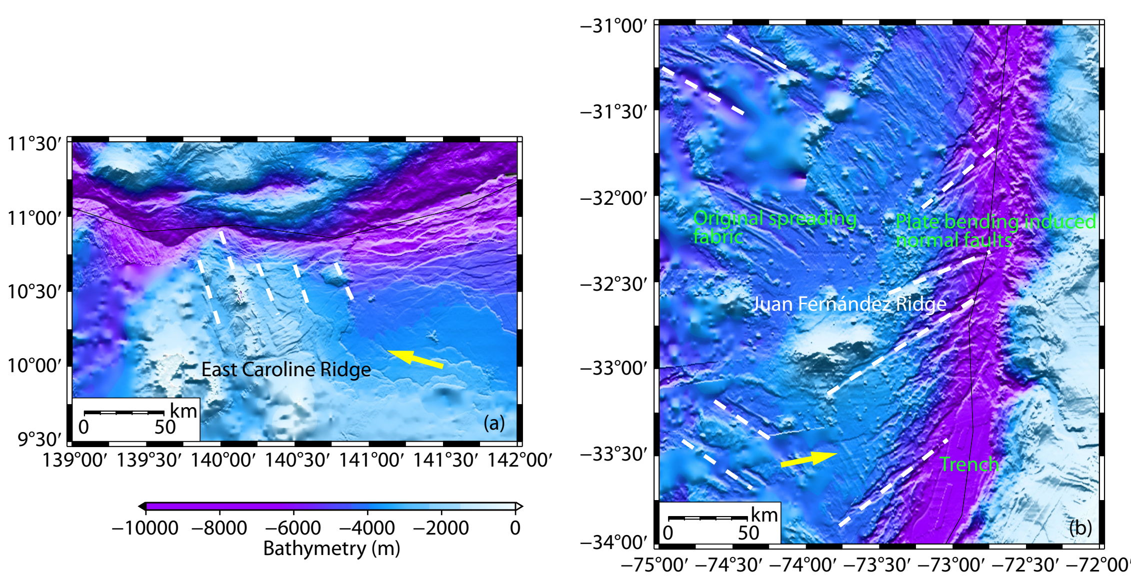

Figure 3. High-resolution bathymetric image of the East Caroline Ridge (a) and the Juan Fernández Ridge (b). Bathymetric data are available at https://download.gebco.net. The dashed white lines indicate the recognized plate-bending-induced normal faulting and original spreading fabric.

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