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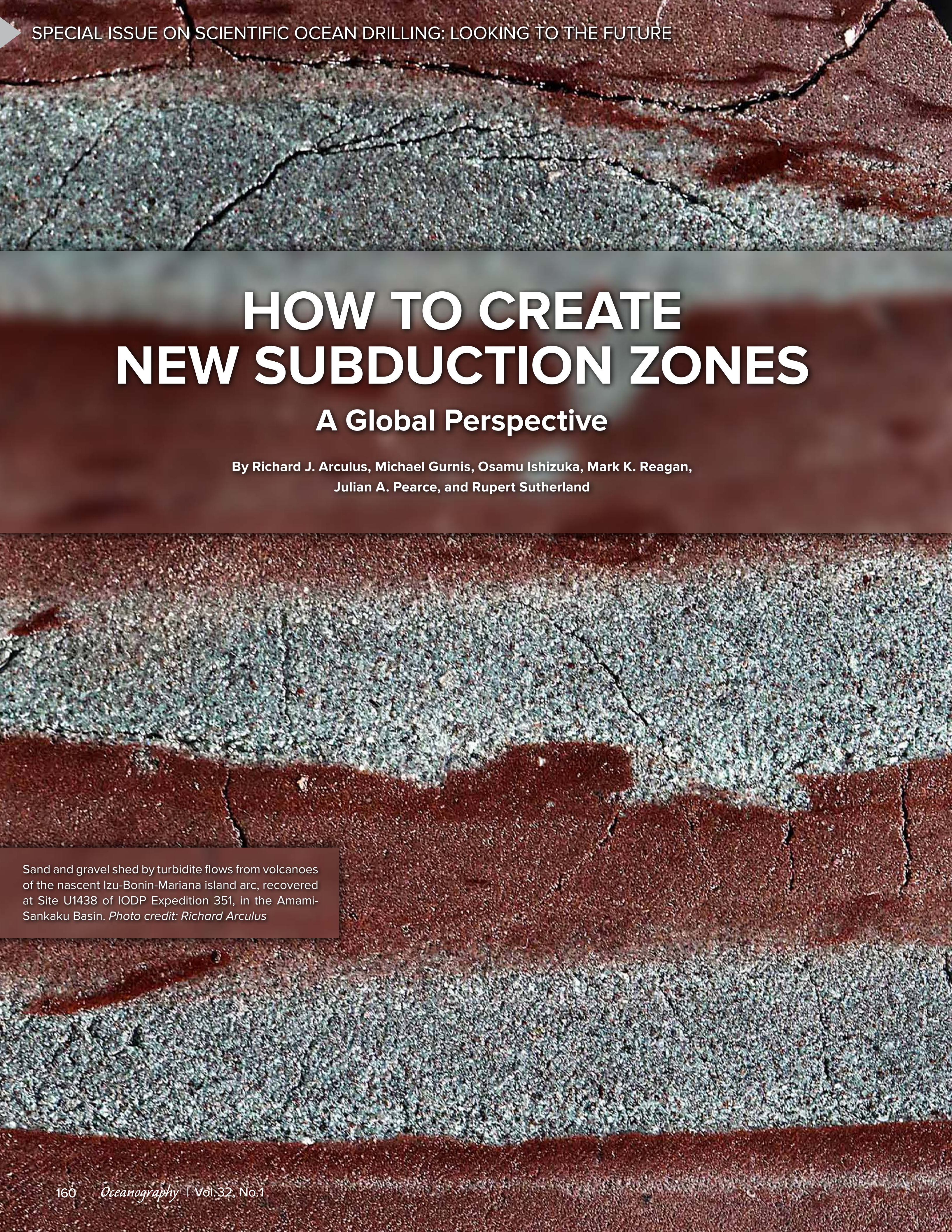
PERMISSIONS

HOW TO CREATE NEW SUBDUCTION ZONES

A Global Perspective

By Richard J. Arculus, Michael Gurnis, Osamu Ishizuka, Mark K. Reagan, Julian A. Pearce, and Rupert Sutherland



Sand and gravel shed by turbidite flows from volcanoes of the nascent Izu-Bonin-Mariana island arc, recovered at Site U1438 of IODP Expedition 351, in the Amami-Sankaku Basin. *Photo credit: Richard Arculus*

ABSTRACT. The association of deep-sea trenches—steeply angled, planar zones where earthquakes occur deep into Earth's interior—and chains, or arcs, of active, explosive volcanoes had been recognized for 90 years prior to the development of plate tectonic theory in the 1960s. Oceanic lithosphere is created at mid-ocean ridge spreading centers and recycled into the mantle at subduction zones, where down-going lithospheric plates dynamically sustain the deep-sea trenches. Study of subduction zone initiation is a challenge because evidence of the processes involved is typically destroyed or buried by later tectonic and crust-forming events. In 2014 and 2017, the International Ocean Discovery Program (IODP) specifically targeted these processes with three back-to-back expeditions to the archetypal Izu-Bonin-Mariana (IBM) intra-oceanic arcs and one expedition to the Tonga-Kermadec (TK) system. Both subduction systems were initiated ~52 million years ago, coincident with a proposed major change of Pacific plate motion. These expeditions explored the tectonism preceding and accompanying subduction initiation and the characteristics of the earliest crust-forming magmatism. Lack of compressive uplift in the overriding plate combined with voluminous basaltic seafloor magmatism in an extensional environment indicates a large component of spontaneous subduction initiation was involved for the IBM. Conversely, a complex range of far-field uplift and depression accompanied the birth of the TK system, indicative of a more distal forcing of subduction initiation. Future scientific ocean drilling is needed to target the three-dimensional aspects of these processes at new converging margins.

INTRODUCTION

In the late nineteenth century, surveying expeditions discovered that there were great depths in the ocean. Their measurements included spot soundings by HMS *Challenger* in 1873 in the Puerto Rico Trench (7,087 m) and in 1875 in the Mariana Trench (8,184 m). The deepest sounding at that time (8,500 m) was reported by Captain George Belknap on USS *Tuscarora*; it marks the first recognition of a linear deep, the Kurile-Kamchatka Trench. By the 1930s and 1940s, it was realized that trenches are associated with all of the volcanic arcs encircling the Pacific, plus those of Indonesia, the Mediterranean, and the Atlantic (Antilles and South Sandwich; Figure 1). The association of these volcanic island chains with ocean deeps, and their positions parallel to one another, had

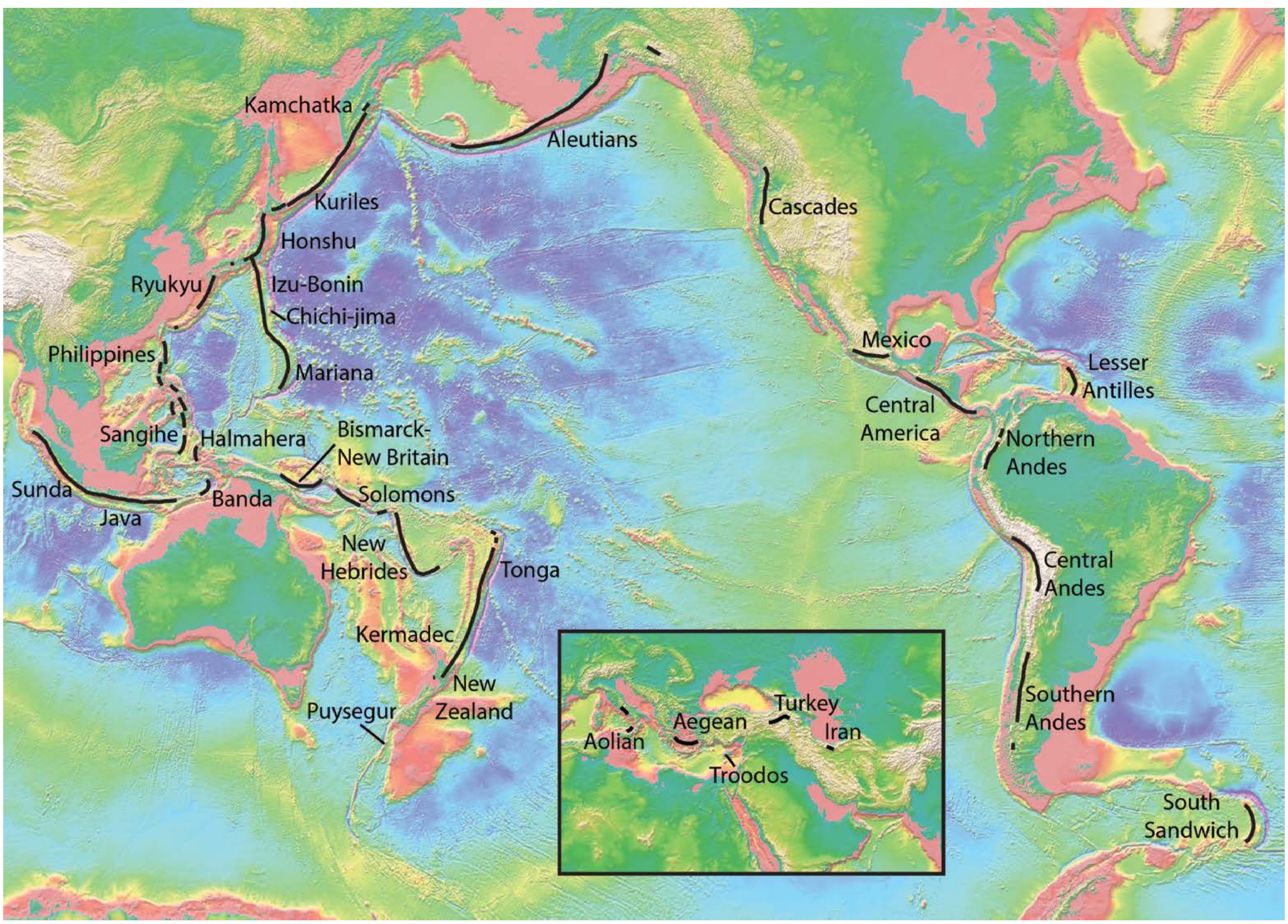


FIGURE 1. Global distribution of island arcs based on the Global Topography base (https://topex.ucsd.edu/marine_topo/). Main panel is centered on the Pacific, with inset showing the Mediterranean and the Middle East.

previously attracted attention. For example, Sollas (1903) demonstrated that an arc of islands could represent the outcrop trace of a planar fault at Earth's spherical surface. Continentward-dipping zones of earthquake foci beneath Japan (Wadati, 1931), the Andes, and Tonga-Kermadec (Benioff, 1949) were recognized as huge thrust faults (Lake, 1931). Benioff (1954) further suggested that the frictional heat generated along these faults was responsible for the volcanism of the island and continental arcs developed above earthquake zones.

In the 1920s to 1930s, submarine-borne gravity measurements in the Indonesian region led by Dutch geophysicist F. Vening Meinesz revealed major negative gravity anomalies along the Sumatra-Java-Banda trenches (Umbgrove, 1945) similar to those subsequently recognized to also exist over other deep-sea trenches. Understanding the significance of radioactive heating of Earth, earthquake and igneous activity, and the characteristics of arc-trench systems was critical in development of a convective hypothesis to account for continental drift (Holmes, 1928). However, it was not until the development of the plate tectonic theory (Hess, 1962; Wilson, 1965; McKenzie and Parker, 1967) that the significance of deep-sea trenches and associated earthquakes and volcanism became generally understood to mark the return (subduction) of tectonic plates (portions of lithosphere) into Earth's interior. Subduction zones can now be defined as locations where two plates converge, as one sinks below the other into Earth's interior. At Earth's surface, the interface between the two plates is typically marked by a deep-sea trench; with increasing depth, subduction zones can be recognized and traced by dipping and planar groupings of earthquakes that are associated both with rocks and sediment in the vicinity of the plate interface, and also brittle failure within the downgoing, colder plate interior.

The paramount importance of subduction zones in terms of overall solid Earth processes is considerable. It has been shown, for example, that most of the driving force behind global plate tectonics derives from subducted plate ("slab") pull rather than "ridge push" (Forsyth and Uyeda, 1975; Conrad and Lithgow-Bertelloni, 2002). The surface of a lithospheric plate carries a carapace of sediment and fluid into Earth's interior that reflects the interactions of rocks with the atmosphere, hydrosphere, and biosphere. Some of these components are returned to the exterior as wedges of sediment that have been scraped off at the trenches, through forearc vents (Fryer, 2012), or via magma genesis within or above the downgoing slab.

All major plate boundaries are ephemeral; they may lengthen or shorten, move relative to one another, or be created and destroyed through time (Dewey, 1975). Subduction zones can vanish, as evident in the Cenozoic demise of the trench associated with the subduction of the Farallon Plate below North America (Atwater, 1970). By using records of paleomagnetic reversals preserved in oceanic crust, observations of seafloor fabric, and a variety of other onshore and offshore data, these events have been reconstructed for the geologic past, with confidence for periods where we have records of the history of plate motions (e.g., back to the Jurassic; Seton et al., 2012), and less so for older times (Matthews et al., 2016a). Knowledge of the processes by which plate boundaries initiate and die is critical to gaining a fuller understanding of how plate tectonics works and how it has shaped our planet through geologic time. And while we have a good understanding of the initiation and development of divergent plate boundaries (i.e., mid-ocean ridges) and straightforward observational opportunities for their study, the same is not true for convergent boundaries and their associated subduction zones. Divergent plate boundaries preserve records of their evolution in the magnetic reversals in the oceanic crust and in the seafloor fabric, but much of the record of subduction initiation is obscured or even destroyed through tectonic erosion, burial, thermal and volcanic overprinting, and other processes at convergent plate boundaries (e.g., Stern, 2004).

The surge in ocean floor exploration of the 1950s–1960s, concurrent with the development of plate tectonic theory, was accompanied by the realization that the compositions of oceanic and continental crust are fundamentally different. The assemblage of rock types (chert-basalt-diabase-gabbro-variably serpentinized peridotite) collectively called an *ophiolite* became key for understanding the origin and development of much more inaccessible in situ oceanic crust (e.g., Gass, 1968). Improvements in analytical techniques for petrological, geochemical, and isotopic studies of magma types led to the realization that subduction zone inputs result in trace element and mineralogical characteristics in convergent margins magmas that are distinct from those of magmas at divergent margins (e.g., Pearce and Cann, 1973). Convergent margin characteristics derive from the input of subducted slab-sourced fluids into the regions of arc magma generation in the wedge of mantle lying between a subducted slab and the overriding plate.

The seminal proposition by Miyashiro (1973) that suggested the Troodos Complex of western Cyprus, an archetypal ophiolite, formed in an island arc rather than at a mid-ocean ridge prompted a torrent of criticism but also a re-examination of the concepts of crustal formation at convergent boundaries. Miyashiro's hypothesis was founded on the similarity of the major element geochemistry of the Troodos Complex with island arcs rather than that of mid-ocean ridges. In particular, the presence of glassy volcanic rocks containing unusually high MgO (>10 wt%) with intermediate (i.e., andesitic) silica (~55 wt% SiO_2) is unlike the basalts and their derivative melts typical of mid-ocean ridges. However, for many geologists, the occurrence on Troodos of a prominent sheeted dike complex represented concurrent magmatism and extension, and the absence of stratovolcanoes with aprons of volcaniclastic debris typical of island arcs seemed incompatible with a convergent margin origin (e.g., Gass et al., 1975).

Two main lines of evidence emerged that have led to current acceptance that most ophiolites formed in convergent margin or so-called "supra-subduction zone" settings (e.g., Pearce, 2003; Dilek and Furnes, 2014). The first, apparently arcane, line of evidence relates to the re-examination (e.g., Kuroda et al., 1978) of the type locality of "boninite" (Petersen, 1891) on the islands of Chichi- and Muko-jima in the Bonin islands located in the modern Izu-Bonin-Mariana (IBM) forearc (Figure 2). Distinctive features of the type boninite are: (1) high MgO (>8 wt%) and low TiO_2 (<0.5 wt%) with intermediate SiO_2 (52–65 wt%) (Le Bas, 2000), and (2) the occurrence of clinoenstatite (Shiraki et al., 1980; Figure 3), an inverted polymorph of high-temperature protoenstatite (Smyth, 1974) that is extremely rare in any other terrestrial igneous rock. Dallwitz et al. (1966) had previously identified clinoenstatite in glassy volcanic rocks on Cape Vogel (Papua New Guinea) but had not realized that they inadvertently discovered boninite (Walker and Cameron, 1983). Cameron et al. (1979) reported boninite on the basis of glass geochemistry in the upper pillow lavas of the Troodos Complex, but noted the absence of clinoenstatite.

The second line of evidence first came from detailed mapping of the IBM forearc islands of Guam (Reagan and Meijer, 1984) and Chichi-jima (Umino, 1985), which revealed igneous basements of near-trench-parallel, boninite sheeted dike-pillow lava complexes. In addition, submarine dredging and examination of the stratigraphy exposed on both trench walls of the current IBM arcs (Dietrich et al., 1978; Ishizuka et al., 2014) revealed a stratigraphy (from deep to shallow) composed of (1) peridotite, (2) minor gabbro, (3) sheeted dikes, (4) low-Ti-K tholeiitic basaltic lava flows, (5) lavas and dikes of boninite, and (6) tholeiitic and so-called "calcalkaline" lavas (see Arculus, 2003). Reagan et al. (2010) reported that the tholeiitic lavas of units 3 and 4 on the trench walls are mid-ocean ridge basalt (MORB)-like in terms of major element and some trace element characteristics but with distinctively lower Ti/V and Yb/V ratios than the latter, interpreted to reflect a significantly different melting environment than that responsible for MORB. The term forearc basalt (FAB) was applied to units 3 and 4 on the basis of their outcrop in the IBM forearc (Reagan et al., 2010). Ishizuka et al. (2011) reported the FAB age range as 52–48 million years old, compared with the oldest boninite at 48.2 million

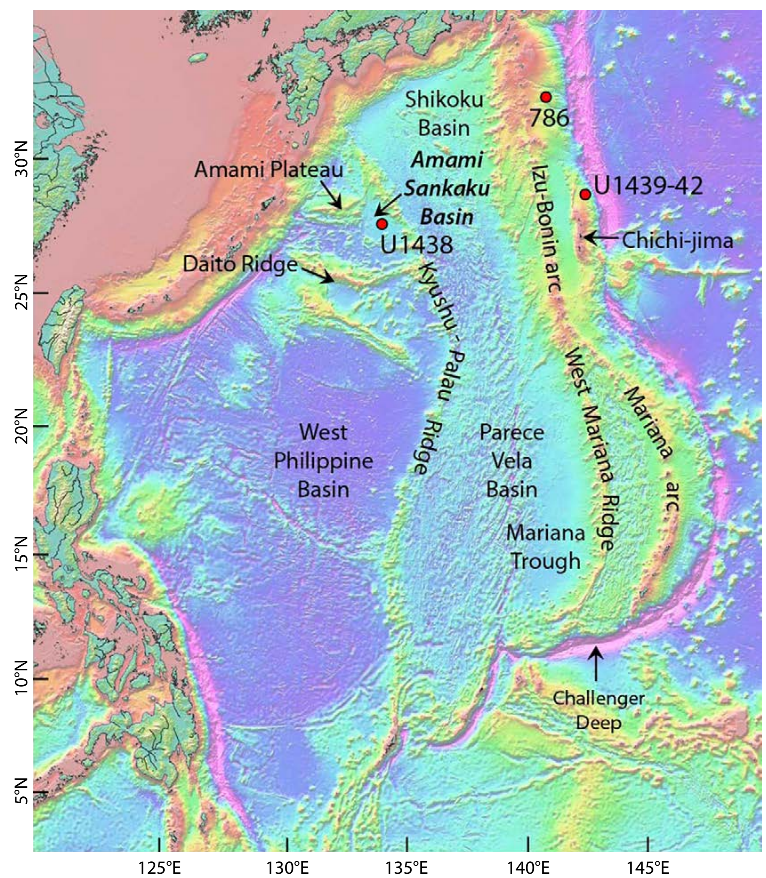


FIGURE 2. Regional context of sites drilled by International Ocean Discovery Program Expeditions (IODP) 351 (Site U1438), 352 (Sites U1439–1442), and Ocean Drilling Program (ODP) Leg 125 (Site 786).

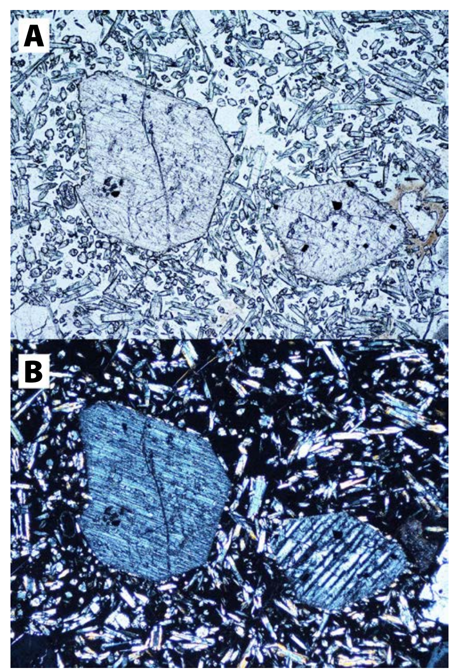


FIGURE 3. Photomicrographs of a thin section of crystal-rich boninite from a pillow lava-dike sequence at Hatsuneura, Chichi-jima. Fields of view are 2.5 mm. (A) Plane-polarized light view with two multiply-twinned clinoenstatite phenocrysts dominating the center of the field in a matrix of clear, isotropic glass and small crystals of pyroxene and olivine. (B) Crossed-polarized light view of the same thin-section.

years old. Thus, the distinctive boninite magma type emplaced under extension in the early growth of the intra-oceanic IBM arcs is convincing evidence that some ophiolites such as the Troodos Complex might have similar origins. Whattam and Stern (2011) interpreted the sequence of early FAB overlain by later boninites or similar lavas to be strong evidence that an ophiolite sequence formed during subduction initiation.

Realization of the significance of subduction zone initiation has stimulated multidisciplinary field, laboratory, and modeling studies to understand the process (Stern and Gerya, 2018). While McKenzie (1977) suggested that "ridges start easily, but trenches do not," Gurnis et al. (2004) pointed out that half of all extant subduction zones initiated in the Cenozoic, and concluded that forces resisting subduction can be overcome in a diversity of settings. Two end-member situations have been identified: spontaneous and induced (Stern, 2004; Gurnis et al., 2004; Figure 4). The former occurs when large density differences exist across lithospheric boundaries (e.g., transform fault conversion; circum-mantle plume head), and the latter when pre-existing plate motions force the development of a new subduction zone (e.g., subduction polarity switch).

One of the largest changes in global plate motions during the Cenozoic may have occurred at ~50 million years ago, as marked by a change in the orientation of the Hawai'i-Emperor seamount chain formed by the Hawai'i mantle plume (Sharp and Clague, 2006; O'Connor et al., 2013). Assuming that plate motion (at least partially) explains this Hawai'i-Emperor Bend, several explanations could be advanced for this change in Pacific Plate motion from NNW to WNW, including (1) the subduction of the Izanagi-Pacific Ridge along eastern Asia (Seton et al., 2015), (2) collision of an intraoceanic arc with southern Asia prior to the arrival of Indian continental crust (Aitchison et al., 2007; Matthews et al., 2016b), (3) the separation of Australia from Antarctica (Whittaker et al., 2007), and (4) the Pacific Plate began to move

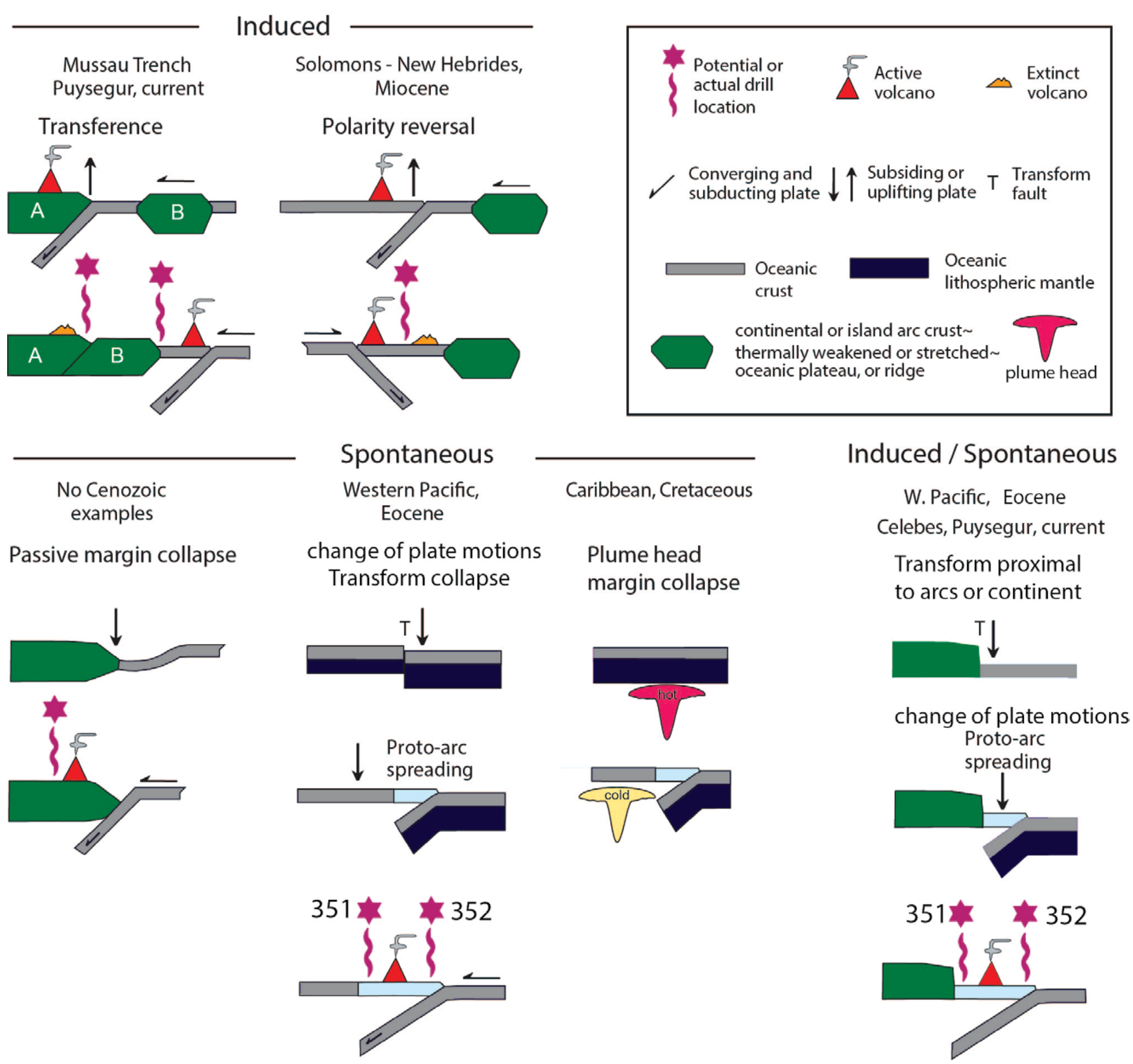


FIGURE 4. Representation after Stern and Gerya (2017) of types of subduction initiation, with specific geographic examples, past and present. Locations of IODP 351 and 352 drill sites are schematically indicated under two types of settings.

toward another or new convergent margin. It is known that subduction zones developed in the western Pacific along a line that extends from Japan in the north, southward through the IBM (Ishizuka et al., 2011; Reagan et al., 2013), to the Tonga-Kermadec (TK) system, albeit with local complications (Meffre et al., 2012; Wu et al., 2016). Seismic tomography (subsurface images made using knowledge of seismic wave propagation) reveals an immense wall of subducted Pacific Plate along this great length of convergent boundaries (Ritsema et al., 2004; C. Li et al., 2008;). Uyeda and Ben Avraham (1972) first proposed conversion of pre-existing transform fault(s) to a transpressional regime at the locus of IBM arc initiation consequent to the change in Pacific Plate motion. Taking into account along-arc strike extension by continued arc-parallel spreading in the West Philippine Basin, Dewey and Casey (2011) developed a model for arc initiation as a trench-ridge-trench triple junction and for formation of a forearc ophiolite complex as now outcrops in the IBM trench walls (Bloomer et al., 1995). The contrast between the settings at subduction initiation of the IBM versus TK systems is significant. For example, while many depict subduction initiation at the IBM as intra-oceanic (e.g., Hall, 2002; Whittaker et al., 2007), it developed at TK at the eastern margin of the rifted fragments of Australia (e.g., Whittaker et al., 2007; Schellart and Spakman, 2012; Meffre et al., 2012; Matthews et al., 2015, 2016b; Figure 5).

A multitude of studies involving extensive geophysical surveys, coring, dredging, and data from previous scientific ocean drilling expeditions provided the stimulus for a campaign by the International Ocean Discovery Program (IODP) to resolve some of the major issues concerning subduction inception and arc initiation in the IBM and TK systems. These issues were identified as first-order research problems in the IODP Science Plan for 2013–2023 (http://www.iodp.org/about-iodp/iodp-science-plan-2013-2023). In 2014, two IODP expeditions targeted the distal rear-arc (Expedition 351) and forearc (Expedition 352) of the Izu-Bonin system (Figure 2) to discover the nature of the arc basement, the spatial and temporal distribution of the earliest magmatism, and the early evolution of the arc. The primary goal of IODP Expedition 371 in 2017 was to date and quantify the deformation and uplift/subsidence of continental ribbons and intervening basins

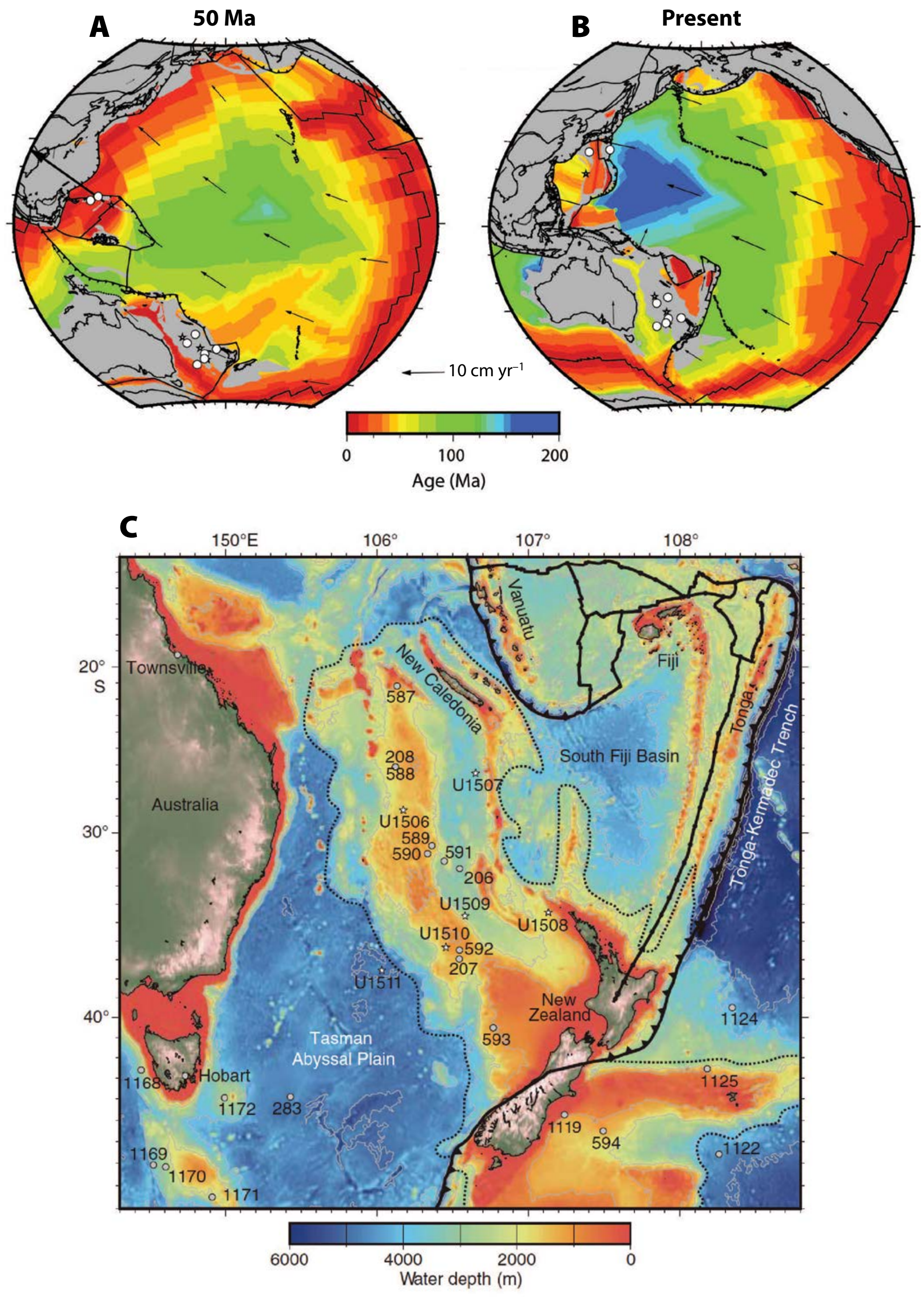


FIGURE 5. Drilling sites, topography, and bathymetry in the Western Pacific. Tectonic features are shown (A) at 50 million years ago (Ma), and (B) at the present day, using the plate tectonic reconstruction of Seton et al. (2012). Velocities are in a moving hotspot frame of reference. The Izanagi-Pacific Ridge at this time had just been subducted beneath Japan and East Asia. Sites from IODP Expeditions 351, 352, and 371 discussed in the text are indicated with larger circles, while selected sites from earlier Deep Sea Drilling Project and ODP legs are marked with stars. This reconstruction does not account for the many discoveries from these recent IODP Expeditions. In this reconstruction, the Pacific Plate has an approximate northwest-trending motion at 50 Ma, which trends to a more westerly motion at 47 Ma. (C) Locations of Expedition 371 sites (stars) along the Tasman Frontier (Sutherland et al., 2017), together with previous deep-sea drilling sites (circles).

between Australia and the TK convergent margin (Figure 5, Tasman Frontier; Sutherland et al., 2017) in order to test the predictions of alternative geodynamic models for subduction inception. In the following sections, we provide some suggestions for future drilling targets to resolve outstanding problems related to western Pacific Eocene subduction initiation and more recently developing systems.

IODP EXPLORES SUBDUCTION INITIATION

Expedition 351: Evidence for the Earliest Evolution of the IBM

The Kyushu-Palau Ridge (KPR) is the oldest remnant arc in the Izu-Bonin-Mariana system, separated 30–25 million years ago from the volcanic IBM front by seafloor spreading in the Parece Vela and Shikoku backarc basins. At its northern end, the KPR strikes across the Amami-Sankaku Basin and forms the eastern boundary of the east-west-striking Mesozoic arc fragments of the Amami Plateau and Daito Ridge (Figure 2). Taylor and Goodliffe (2004) emphasized that the KPR (and hence the inferred juvenile trench) trended at high angles to the Amami Plateau, Daito Ridge, and bounding faults of the Amami-Sankuku Basin. Accordingly, they argued against the inception of the subduction zone and earliest arc at a pre-existing transform fault that was linked to, for example, the Izanagi-Pacific Ridge.

The original aims of IODP Expedition 351 drilling at Site U1438 in the Amami-Sankaku Basin were to explore the pre-arc basement underlying the IBM arc and to recover the history of the early development of the arc preserved in volcaniclastic-rich sediments shed from the growing KPR that, when active, was part of the IBM arc. Prior to IODP Expedition 351, two hypotheses had been put forward for the origin of the reconstructed IBM arc, one in which subduction nucleated spontaneously due to a difference in plate age across a former fracture zone (Stern and Bloomer, 1992) and the other through forced convergence (Gurnis et al., 2004). The two models predicted different histories and ages of the sediments immediately overlying the Amami-Sankaku basement. The simple layered structure of the Amami-Sankaku Basin is composed of ~1.5 km of sediment overlying a normal oceanic crustal thickness of ~6 km (Arculus et al., 2015). The seismic structure of the basement persists eastward beneath the KPR and forms a significant portion of its total thickness. IODP Expedition 351 successfully recovered the targeted sequences—and generated some major surprises (Arculus et al., 2015). The basement (Unit 1) is composed of low-Ti-K tholeiitic basalts ~49 million years in age (Ishizuka et al., 2018) and not Paleocene (66–56 million years old) or older as hypothesized pre-Expedition 351. These basalts overlap in age with the Bonin Ridge boninites (Ishizuka et al., 2006) but are younger than the overall basalt-to-boninite sequence recovered from the present-day IBM forearc by dredging and submersible sampling (Ishizuka et al., 2011) and by IODP Expedition 352 drilling at Sites U1439–U1442 (Reagan et al., 2019).

Conclusions drawn from studies of the petrologic and geochemical characteristics (including radiogenic isotopes) of the Expedition 351 basement basalts (Hickey-Vargas et al., 2018; Yogodzinski et al., 2018) are: (1) they are derived from mantle peridotite source(s) that were highly depleted by melt extraction prior to IBM arc inception ~52 million years ago; (2) the basalts lack the fluid-mobile trace element enrichments typical of most island arc basalts, boninites, or high-Mg andesites (e.g., Schmidt and Jagoutz, 2017); (3) the compositional characteristics of the (micro)phenocrysts of olivine-clinopyroxene-plagioclase-spinel comprise a globally unique data set, reflecting generation of the magmas at relatively high pressures and temperatures under low-redox conditions, followed by rapid transfer to the surface likely under seafloor spreading conditions.

Expedition 352: IBM Forearc Architecture and Construction Timescale

Over a distance of about 13 km, IODP Expedition 352 drilled four sites in the forearc orthogonal to the strike of the Bonin Trench, and recovered a high-fidelity record of crustal generation related to subduction initiation in the Bonin forearc. This was the first expedition dedicated entirely to exploration of the stratigraphy of the IBM forearc. Previous drilling during Ocean Drilling Program (ODP) Leg 125 recovered a sequence of boninite and derivative rocks (e.g., Arculus et al., 1992) at Site 786, located ~270 km north and along the strike of the forearc from those drilled during IODP Expedition 352. A sequence of FABs overlying dikes was recovered at Sites U1440 and U1441, closest to the trench; they were emplaced during near-trench seafloor spreading that accompanied subduction initiation. The basalts are petrologically similar to the FABs retrieved by submersible, dredging, and drilling along the entire length of the IBM forearc (see DeBari et al., 1999; Reagan et al., 2010; Ishizuka et al., 2011). The FABs recovered from the drill cores, together with a compositionally related gabbroic rock collected nearby, have ages of ~51.9–51.3 million years (Reagan et al., 2019). Forearc basalt lavas are generally aphyric, with rare plagioclase and augite phenocrysts. Like the basalts from Site U1438, FABs are highly depleted in incompatible trace elements as a result of ancient melt extraction events (Shervais et al., 2018).

Boninites were drilled furthest from the trench at sites U1439 and U1442. The oldest boninites have compositions that are transitional toward FAB (termed "low-Si boninites," or LSB) and erupted while seafloor spreading continued. These lavas are beneath "high-Si boninites" (HSB) that erupted atop the new oceanic crust and have compositions resembling the boninites on the nearby island of Chichi-jima. HSB ages span 51.3 to 50.3 million years old

(Reagan et al., 2019), placing eruption of the LSB near the age of the nearby FAB. All boninites are formed by flux melting of depleted mantle that involves fluids derived from dehydration and melting of subducted materials. LSB were generated in the presence of melts/fluids from subducting altered Pacific MORB, whereas melts/fluids from subducting sediments were involved with the genesis of HSB (H.Y. Li et al., 2017).

Expedition 371: Exploration of TK Subduction Initiation

IODP Expedition 371 drilled six sites across some of the major structural elements of the Tasman Frontier, including the northern and southern New Caledonia Trough, Reinga Basin, Lord Howe Rise, and Tasman Abyssal Plain (Figure 5). The variable but persistently moderate bathymetry of the Tasman Frontier has ensured preservation of depth-sensitive, fossil-rich records both pre- and post-subduction initiation at ~50 million years ago along the TK arc. Seismic reflection data across the Tasman Frontier reveal episodes of compression, uplift, and subsidence (Sutherland et al., 2017). Results from IODP Expedition 371 show regionally dramatic, Eocene-age vertical motions, with evidence for Eocene-Oligocene faulting and folding (Sutherland et al., 2018). Subduction inception along the proto-TK Arc may have involved elements of both spontaneous and induced elements.

DISCUSSION

Complementing the past multidisciplinary and collaborative approaches to the study of the IBM and TK arcs, the recent IODP scientific ocean drilling expeditions have confirmed some hypotheses regarding crustal architecture, but also produced novel and surprising results. For example, one of the most important conclusions of the collective studies of the IBM system is that the structure and magmatic output of a nascent arc is unlike that of established systems. The latter can be defined as "a chain of concurrently or potentially active volcanic islands, consistently associated but displaced spatially more than 100 km from a deep-sea trench. Much of the eruptive activity is typically explosive. Adjacent to many island arcs in the western Pacific are backarc basins, floored by crustal spreading centers. Some arcs have associated non-volcanic islands between the volcanic arc and trench comprising uplifted basement or trench-accreted sediments" (Arculus, 2009; Figure 6). Implicit in this definition is the notion of a volcanic front marking the trenchward limit of volcanic edifices, a forearc region lacking volcanism, and backarc basins wherein new basaltic ocean crust forms by seafloor spreading. For many arcs, there are also isolated edifices or chains of rear-arc volcanoes not formed through seafloor spreading, such as the Chokai Zone of Japan (Tatsumi, 1989; Tamura et al., 2002), or the cross-chains of the northern IBM arc (Machida et al., 2008). The volcanic front is dominated by subaerial and submarine stratovolcanoes, with extensive aprons of volcaniclastic debris (e.g., Pope et al., 2018).

A persistent chain of stratovolcanoes, geometrically stationary with respect to an adjacent trench and likely fed from plugs or radial dikes (Nakamura, 1977), nevertheless seems incompatible with the presence of an underlying sheeted dike complex. This observation, together with the absence of aprons of volcanic debris, were prime factors in the initial rejection of Miyashiro's (1973) hypothesis that the Troodos Complex formed in an island arc. In fact, the earliest stages of "supra-subduction zone" magmatism might well be unrecognized in the absence of tectonic and geophysical constraints. It turns out that both Miyashiro and his critics were right: the Troodos Complex formed by seafloor spreading but at a convergent plate margin; whether this spreading was in a near-trench setting during subduction initiation remains controversial (Woelki et al., 2018). The accumulating

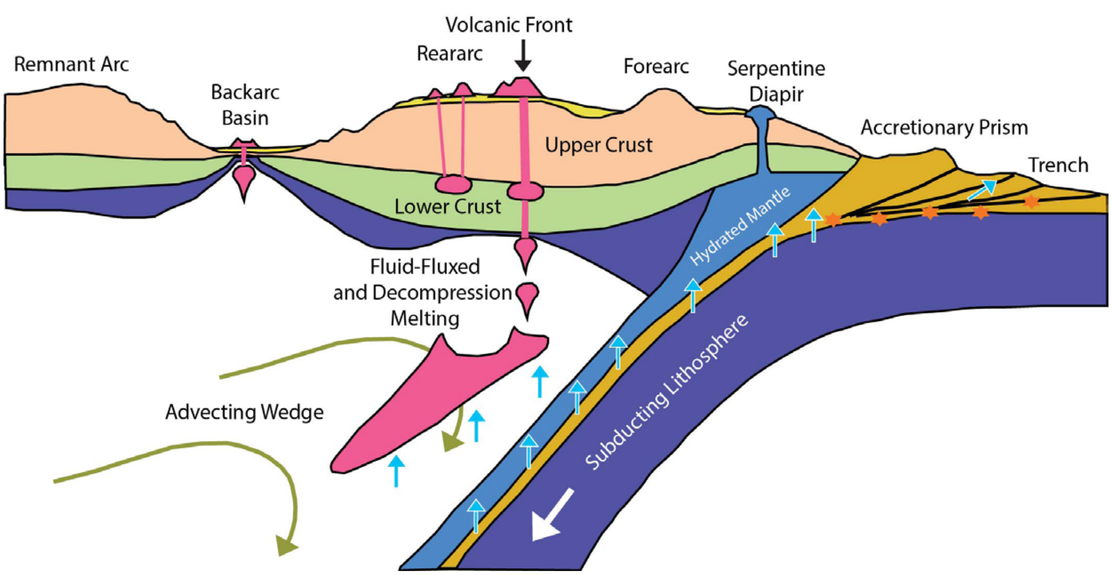


FIGURE 6. Schematic cross section of an island arc from trench to backarc basin. Orange stars represent great earthquakes in the seismogenic portion of the Wadati-Benioff zone. Blue arrows represent movement of hydrous fluids/melts.

evidence clearly supports the model initially proposed by Stern and Bloomer (1992) and recently extended by Stern and Gerya (2018) for the earliest development of the IBM arc. Simply stated, the tholeiitic basalts forming the earliest crust in the IBM arc, sampled at the present-day forearc (Sites U1440 and U1441), were emplaced at one or more spreading ridges underlain by sheeted dike swarms. The architecture of this oceanic crust suggests the basalts formed at a ridge on the overriding plate during subduction initiation (Ishizuka et al., 2014). At this stage, there was no chain of stratovolcanoes, and the concept of a forearc, rear-arc, and backarc for the earliest situation as delimited by a volcanic front cannot be applied. Seen in this context, the basalts drilled at U1438 are younger than FAB and erupted at the same time as boninites along the Bonin Ridge. Reagan et al. (2017, 2019) propose the Amami-Sankaku Basin basement formed through trench-distal magmatism, possibly as a type of later backarc activity, after trench-proximal seafloor spreading ceased, rather than as a continuation of the seafloor spreading that produced the FAB.

Restoring the geometry of the initial stages of magmatism in the proto-IBM arc by closing the backarc basins and forearc rifts places the Amami-Sankaku Basin ~250 km across strike from the Bonin Ridge adjacent to Expedition 352 Sites U1439–1442 (Figure 2). The duration of the earliest period of tholeiitic basalt eruption was less than 1.2 million years at the present location of the Bonin forearc (FAB, 52–48 million years ago; Ishizuka et al., 2011; Reagan et al., 2019), with perhaps two additional million years in the Amami-Sankaku Basin (49–47 million years ago; Ishizuka et al., 2018). The period of boninitic magmatism endured at least from 51 to 44 million years ago on the Bonin Ridge, possibly associated, during the later stages of high-silica boninite eruption, with individual topographically prominent volcanic edifices (Reagan et al., 2017), before transitioning to eruption of the more usual basalts associated with stratovolcanoes (so-called island arc tholeiitic and calcalkalic suites; Ishizuka et al., 2011; Reagan et al., 2019). We note that a slab dipping at ~45° and subducting at 60 mm yr^{-1} (Whittaker et al., 2007; Figure 5) takes ~2.4 million years to reach a depth of 100 km below a volcanic front that is characteristic of mature arcs. This is a relatively short period of time compared with a duration of ~7 million years from the earliest tholeiitic to boninitic magmatism in the case of drill recovery from the present-day forearc to the outcrops on the Bonin Ridge. The processes that drive the transition from seafloor spreading during the nascent arc stages to establishment of the archetypal magmatic arc with a forearc-volcanic front-rear/backarc geometry are not yet understood. However, the processes must reflect the transition from hinged subsidence of the old seafloor, with asthenospheric upwelling into the space created, to true down-dip subduction and a reversal of asthenospheric flow (Stern and Bloomer, 1992). A corollary is that the strike of the KPR is related to the establishment of the volcanic front of a mature magmatic arc, and does not necessarily bear any simple relationship to preexisting ridge-transform segments and their orientations.

Comparison of petrological and geochemical characteristics of the tholeiitic basalts erupted during the initial stages of convergent margin formation with those from mid-ocean ridges and backarc basins is critical for understanding the respective petrogenetic processes involved. We require distinguishing compositional parameters to recognize tholeiitic magmatism associated with subduction inception events in the Mesozoic and older eras (e.g., Buchs et al., 2010). For comparative purposes, we need to know the absolute abundances of major and trace elements allied with isotopic characteristics and constituent mineral compositions of these nascent subduction-related basalts. In this framework, abstracting the most significant results published to date from the IODP expeditions, in combination with previous studies (see references cited earlier), we emphasize five issues.

1. Inception of the IBM system was adjacent to a series of Mesozoic-aged arc-basin systems (Arculus et al., 2015; Leng and Gurnis, 2015). Inception of the TK system was adjacent to a welt of continental crustal ribbons, intervening basins, and older arcs (Meffre et al., 2012; Sutherland et al., 2017). These two systems were not intra-oceanic in the sense of birth surrounded solely by oceanic lithosphere.
2. The earliest lavas accompanying subduction initiation were basalts erupted in a seafloor spreading environment, above sites of asthenospheric upwelling.
3. These early basalts have extremely low abundances of the light (L) relative to the heavy (H) rare earth elements (REE) and small to insignificant enrichment in the most subduction-mobile elements; hence, they lack the large negative Nb anomalies that characterize almost all arc lavas.
4. These early basalts are strikingly radiogenic $^{176}Hf/^{177}Hf$ (εHf ≤ 22.1) at given $^{143}Nd/^{144}Nd$ compared with ocean floor basalts from the Pacific Plate.
5. Clinopyroxene-bearing phenocryst/microphenocryst assemblages in the early basalts reflect rapid transfer from mantle source depths (~30 km) to the surface without the extensive staging that is characteristic of sub-mid-ocean ridge chambers and mush zones.

Elaborating on the significance of the set of geochemical and petrologic characteristics, Figure 7 plots the slopes and curvatures of the chondrite-normalized REE abundances for global MORBs (gray or white circles; O'Neill, 2016) compared with the nascent arc tholeiitic basalts (colored symbols). Quantification of the total shapes of the usual chondrite-normalized abundance plots (see the three insets) is the great advantage of this type of figure. It shows the Amami-Sankaku Basin basalts from IODP Site U1438 define a LREE-depleted limit of the global MORB array. While also highly depleted, FABs are distinct compared with the Amami-Sankaku Basin basalts in having less concave-downward curvatures of the chondrite-normalized LREE abundances and more diverse REE patterns (Shervais et al., 2018). Nevertheless, both the Amami-Sankaku Basin basalts and FABs have Hf-Nd isotopic characteristics requiring mantle source(s) that were more depleted by prior melting than any equivalents tapped beneath the global network of mid-ocean ridges. Development of very high $^{176}Hf/^{177}Hf$ requires an increase in the Lu/Hf ratio of the mantle sources above that of the MORB source(s) and must result from basalt melt extraction combined with the passage of time. There can be a trade-off between the extent of Lu/Hf fractionation and the melting events subsequently associated with subduction, but development of radiogenic Hf must precede the subduction initiation event (Reagan et al. 2010; H.Y. Li et al., 2017; Yogodzinski et al., 2018).

After careful filtering for post-eruptive seawater alteration, Hickey-Vargas et al. (2018) show the abundances of the fluid-mobile trace elements (alkali, alkaline earth, Pb, U, and Th) in the Amami-Sankaku Basin basalts are typical of the most highly depleted MORBs with no evidence of subducted-slab derived inputs. After similar filtering, Shervais et al. (2018) conclude that most FABs lack a subduction influence in their genesis, although some FABs from Site U1441 with elevated Sr (fluid-mobile)/Zr(fluid immobile) (~3.2) likely require some subducted slab-derived water inputs to their mantle sources (Reagan et al., 2017). The presence of negative high-field-strength element anomalies in island arc basalts is commonly interpreted to result from enrichments in La and other LREE of the mantle wedge sources by slab-derived fluids (e.g., Pearce and Peate, 1995). The abundances of elements such as Nb and Ta are then assumed to reflect the pre-enrichment values of the unmodified mantle. The absence of negative anomalies for Nb and Ta in the case of the Amami-Sankaku Basin basalts and FABs can therefore be interpreted as precluding slab-derived additions of the LREE to the mantle sources, therefore ruling out modification of the intrinsic, pre-subduction inception Nd and Hf isotopic characteristics of this sample set.

The mineralogy of IBM FABs and Amami-Sankaku basalts is also distinctive compared with the overwhelming majority of MORBs. The presence of phenocrystic clinopyroxene, for example, is highly unusual compared with the persistent lack of this phase as a phenocryst in primitive (Mg-rich) MORBs (Francis, 1986; Herzberg, 2004). We know that clinopyroxene is involved in the generation of the global MORB compositional array (O'Neill and Jenner, 2012) and is a major constituent of gabbros recovered by scientific ocean drilling, dredging, and submersible sampling of the oceanic crust. Herzberg (2004) notes the so-called "clinopyroxene paradox" is in fact consistent with phase relationships of effectively anhydrous MORB magma. Decompression of a melt saturated with olivine, plagioclase, and clinopyroxene from a crustal magma (melt-crystal mush) chamber at ~2–4 km depth below the seafloor will eliminate clinopyroxene as a near-liquidus phase. The persistence of clinopyroxene in the nascent IBM basalts might be accounted for by more rapid ascent from such depths allied with higher water contents. Clinopyroxenes in the Amami-Sankaku Basin basalts and FABs have lower Na and Ti compared with the rare phenocrysts in MORBs and the abundant compositional data for MOR gabbros; the Amami-Sankaku Basin clinopyroxenes range to more aluminous compositions, whereas the FAB clinopyroxenes are less aluminous than MORB. Spinel compositions in the Amami-Sankaku Basin basalts range from Fe^{3+}-poor, aluminous-chromian

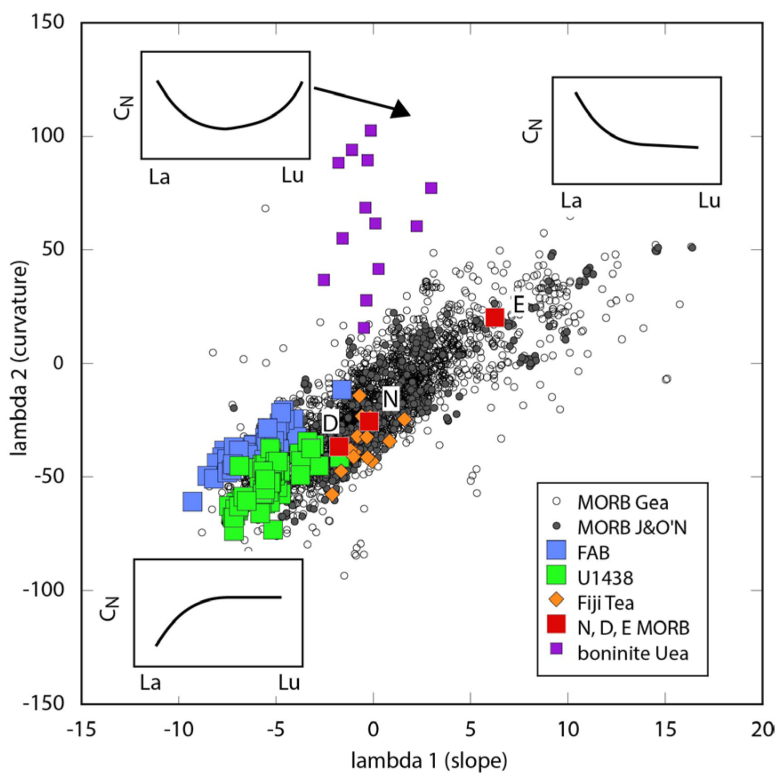


FIGURE 7. Comparison of the curvature (lambda 2) vs. slopes (lambda 1 values) of chondrite-normalized (C_N), rare earth element abundances (O'Neill, 2016) for subduction-inception related magmas compared with mid-ocean ridge basalts. Insets show where representative types of patterns project in the main figure. D = Depleted. E = Enriched. N = Normal. Gea = From Gale et al. (2013). J&O'N = Jenner and O'Neill, 2012. Tea = Todd et al. (2012). Uea = Umino et al. (2015).

to ferrian (magnetite), exceeding the range known in MORBs (Sigurdsson and Schilling, 1976; Barnes and Roeder, 2001), and consistent with higher pressures (or greater depths) of derivation of the Amami-Sankaku Basin basalts than for most MORBs.

Based on the results of Expedition 352, Reagan et al. (2017, 2019) outlined the progression from subduction inception at a transform margin through seafloor spreading and the development of the first chain of individual stratovolcanoes or "typical" arc (Figure 8). Rapid collapse or sinking of the subducting slab leads to decompression of asthenosphere, generating FAB magma with minimal or no material transfers from the slab. Progression to slab-derived flux melting of the wedge proceeds through the generation of the most depleted FAB to boninite over less than 1.2 million years and must reflect changes in the motion of the sinking lithosphere and the advecting mantle above it. This early and fast igneous outpouring of FAB, LSB, and HSB forms the basement of the present-day IBM arc and forearc, and a portion of the welts of remnant arcs, such as the Kyushu-Palau and West Mariana ridges. In terms of crustal growth rates in arcs, this conclusion is important because the flux in the first few million years approached that of mid-ocean ridges (~1,000 km^3 per million years per kilometer of ridge), but diminished once the mature arc, backarc spreading, and the KPR became established.

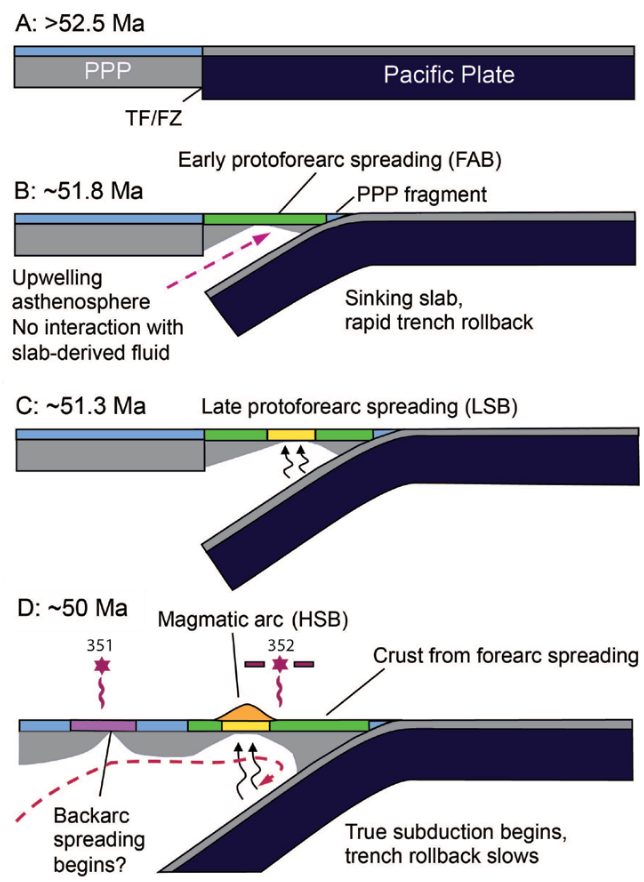


FIGURE 8. Cartoon with time slices after Reagan et al. (2019) of creation and evolution of the Izu-Bonin-Mariana (IBM) crust after subduction initiation. (A) Philippine Sea Plate (PPP)-Pacific Plate in contact prior to subduction initiation along a transform fault/fracture zone (TF/FZ). (B) Subduction inception between 52.5 and 51.9 million years ago (Ma), with asthenospheric upwelling and decompression melting with trench-proximal seafloor spreading and forearc basalt (FAB) generation. (C) Continued Pacific Plate subduction and seafloor spreading generating FAB followed by slab-derived fluid fluxing generating low-silica boninite (LSB). (D) Embryonic arc (chain of stratovolcanoes, advecting wedge, and possibly early trench-distal [backarc] seafloor spreading). IODP Expedition 351 and 352 sites indicated.

The development of the TK system differed from that of the IBM in a number of ways. Crustal elements developed above an eastward–dipping subduction zone in the 57–35 million year old Loyalty-Three Kings arc were thrust over the Norfolk Ridge and are now exposed in New Caledonia (e.g., Cluzel et al., 2018). Meffre et al. (2012) argue that the oldest (~52–48 million years old) igneous rocks (plagiogranites) now in the TK forearc were originally created in a backarc-arc setting. Subduction polarity reversal and collision of the Loyalty-Three Kings arc with New Caledonia placed the 52 million year-aged rocks into the forearc of the TK system. Todd et al. (2012) reported the earliest subaerially exposed magmatic products of the Fiji-TK arc, including island arc tholeiite, boninite, and "early-arc tholeiite" interbedded in outcrops on Viti Levu and Eua (Fiji). The authors interpret these to be products of decompression and flux-enhanced melting of a proto-mantle wedge following subduction inception. For comparison with the forearc and Amami-Sankaku Basin basalts of the IBM system, Figure 7 shows the shapes of the chondrite-normalized abundance patterns of the early arc tholeiites from Fiji. A number of these samples extend into the more LREE-depleted range of global MORB, but are not as extreme as those from the Amami-Sankaku Basin or the IBM forearc.

OUTSTANDING QUESTIONS

We have learned much concerning the creation of new subduction zones over the past five years from a variety of multidisciplinary approaches and focused IODP scientific ocean drilling, but what are the outstanding problems, and what future drilling projects might be undertaken to solve them?

Noting that oceanic lithosphere >10 million years old is unstable gravitationally compared with the underlying mantle (Cloos, 1993), there is broad agreement that Stern's (2004) fundamental division of subduction initiation into spontaneous and induced types is a useful way to approach the issues surrounding creation of convergent margins. Nevertheless, individual examples may well involve a combination of these end members, and it is abundantly clear that subduction inception is intrinsically a three-dimensional process (Zhou et al., 2018). Building on regional geophysical surveys and tectonic syntheses, localized but extensive rock and sediment cores have been recovered that record the operation of fundamental structural and magmatic processes. Identifying the localized as opposed to regional-scale factors then becomes important in overall understanding of these processes. Leng and Gurnis (2015) point out that extensional events in the relatively buoyant Cretaceous-aged arcs (Amami Plateau-Daito Ridge; Figure 2) and, hence, thermal rejuvenation of the region, were important factors leading to subduction initiation along an adjacent transform fault bounding the Mesozoic arcs and comparatively dense Pacific oceanic lithosphere. There is considerable disagreement over whether spontaneous subduction initiation can occur at an old fracture zone absent any other factors (Leng and Gurnis, 2015; Stern and Gerya, 2018). However, the juxtaposition of old Pacific Plate to reheated buoyant relic arcs provides sufficient driving forces for spontaneous initiation (Leng and Gurnis, 2015). In broad terms, the same situation prevailed in the TK system. Other complexities of regional geology in the case of the IBM system concern the impact of the Oki-Daito plume and initiation of spreading in the West Philippine Basin (Ishizuka et al., 2013). There is general agreement that the potential change in azimuth of Pacific Plate motion ~52–50 million years ago coincided with initiation of subduction of the IBM and the TK systems, but the ultimate causal factors are not yet known. Localization of subduction initiation along transform faults bordering preexisting arc terranes and stretched continental ribbons followed. This event can potentially be viewed as a hybrid that included induced processes exploiting along-strike variations in local buoyancy forces.

In the specific case of the IBM system, exploration of the foundations and earliest magmatic products is demonstrably incomplete. We have minimally explored the three-dimensional aspects of the Amami-Sankaku Basin, both in terms of probing the lateral and vertical structure and composition of the basement, as well as through exploring the early stage of arc growth via the KPR output as recorded in the overlying sediments (Straub et al., 2015; Brandl et al., 2017). Combining sample recovery from Deep Sea Drilling Project Leg 60, ODP Leg 125, and IODP Expedition 352 with those from diving and dredging along the IBM forearc, we have the beginnings of an along-strike recovery of crustal sequences associated with subduction initiation. The crust clearly has all of the lithologies found in ophiolites, but the structural and compositional relationships between the units remain poorly known. Penetration to the gabbros that must underlie the sheeted dikes, and ultimately to the underlying mantle remains a priority for understanding the development of the nascent crust after subduction initiation and the precise link between the results of drilling forearc crust and the genesis of supra-subduction ophiolites. Sites closer to the trench than those drilled by Expedition 352 and shown schematically in Figure 8 are the obvious locations.

> "Knowledge of the processes by which plate boundaries initiate and die is critical to gaining a fuller understanding of how plate tectonics works and how it has shaped our planet through geologic time."

The early IBM basalts are a global end member with respect to the degree to which they are depleted in highly incompatible elements, and isotopic compositions convincingly show that this depletion occurred in their mantle sources long before subduction initiation (Yogodzinsky et al., 2018). This opens the possibility that subduction initiation occurred along some sort of geochemical boundary in the mantle, like that represented by the Australia-Antarctic Discordance to the south (Gurnis and Müller, 2003). However, basalts from ophiolites generally are not unusually depleted in incompatible trace elements (e.g., the Samail Ophiolite; Alabaster et al., 1982). Thus, if our conclusion that the IBM forearc is the in situ equivalent of an ophiolite is correct, then strong prior depletion of the mantle is not required for subduction initiation to proceed.

For the TK system, ODP Leg 135 primarily targeted the evolution of the Lau Basin. It is clear, however, from the success of Expedition 352, in combination with the dredging recoveries from the Tonga Trench wall (Bloomer and Fisher, 1987; Meffre et al., 2012), that deep-sea drilling of the TK forearc is of fundamental importance to further understanding of the development of the system.

Globally, there is much interest in further exploring the current tectonism and geophysical characteristics of the

Puysegur-Fiordland boundary between the Australian and Pacific Plates south of New Zealand (e.g., Meckel et al., 2003). This transpressional margin appears to be transitioning from induced (forced) to self-sustained (spontaneous) subduction (Gurnis et al., 2004; Mao et al., 2017). Particular advantages of this region in terms of studying subduction initiation is that the processes are active, the plate kinematics are well constrained, and the geological record is not obscured. Drilling targets will emerge from a number of regional geophysical surveys that have recently been completed.

Also in the Southwest Pacific, the polarity of subduction at the boundary between the Australian and Pacific Plates reversed (Papua New Guinea-Solomon Islands-Vanuatu) following collision of the Ontong Java Plateau with the Vitiaz Trench ~10 million years ago (Petterson et al., 1999). This setting was a target for ODP Leg 134, and is a specific example of a type of induced subduction identified by Stern (2004; Figure 4). A series of multinational geophysical surveys under the auspices of the Circum-Pacific Council for Energy and Mineral Resources in the 1980s revealed much of the fundamental tectonic architecture and geology of this region. There are obvious targets for study of the consequences of polarity reversal such as the sediment record preserved within intra-arc troughs exemplified by the New Georgia Basin.

Exploration of subduction initiation has not yet targeted the many active and developing systems of the Indonesia-Philippines region. Hall (2018) identified many examples of the process from the earliest stages of downward flexure of the oceanic crust to the development of an observable Wadati-Benioff zone. He noted specific cases of subduction initiation propagating along strike from existing subduction zones, as invoked in part by Arculus et al. (2015) for the IBM system, and there are other examples at isolated deeps developed in extensional settings.

In summary, it is clear that we have a multiplicity of global targets for drilling and a potentially coherent ensemble of different examples and stages of subduction initiation. Scientific ocean drilling is the best way to recover the records of subduction initiation, which can potentially be tied to on-land studies of ophiolites. Progress in this field has the potential to transform our understanding of plate tectonics.

REFERENCES

Aitchison, J.C., J.R. Ali, and A.M. Davis. 2007. When and where did India and Asia collide? *Journal of Geophysical Research* 112, B05423, https://doi.org/10.1029/2006JB004706.

Alabaster, T., J.A. Pearce, and J. Malpas. 1982. The volcanic stratigraphy and petrogenesis of the Oman ophiolite complex. *Contributions to Mineralogy and Petrology* 81:168–183, https://doi.org/10.1007/BF00371294.

Arculus, R.J., J.A. Pearce, B.J. Murton, and S.R. van der Laan. 1992. Igneous stratigraphy and major element geochemistry of holes 786A and 786B. Pp. 143–169 in *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 125. P. Fryer, J.A. Pearce, and L.B. Stokking, eds, https://doi.org/10.2973/odp.proc.sr.125.137.1992.

Arculus, R.J. 2003. Use and abuse of the terms calcalkaline and calcalkalic. *Journal of Petrology* 44:929–935, https://doi.org/10.1093/petrology/44.5.929.

Arculus, R.J. 2009. Island Arcs. Pp 481–486 in *Encyclopedia of Islands*. R.G. Gillespie and D.A. Clague, eds, University of California Press.

Arculus, R.J., O. Ishizuka, K.A. Bogus, M. Gurnis, R. Hickey-Vargas, M.H. Aljahdali, A.N. Bandini-Maeder, A.P. Barth, P.A. Brandl, L. Drab, and others. 2015. A record of spontaneous subduction initiation in the Izu-Bonin-Mariana arc. *Nature Geoscience* 8:728–733, https://doi.org/10.1038/ngeo2515.

Atwater, T. 1970. Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. *Geological Society of America Bulletin* 81:3,513–3,535, https://doi.org/10.1130/0016-7606(1970)81[3513:IOPTFT]2.0.CO;2.

Barnes, S.J., and P.L. Roeder. 2001. The range of spinel compositions in terrestrial, mafic and ultramafic rocks. *Journal of Petrology* 42:655–671, https://doi.org/10.1093/petrology/42.12.2279.

Benioff, H. 1949. Seismic evidence for the fault origin of oceanic deeps. *Geological Society of America Bulletin* 60:1,837–1,856, https://doi.org/10.1130/0016-7606(1949)60[1837:SEFTFO]2.0.CO;2.

Benioff, H. 1954. Orogenesis and deep crustal structure: Additional evidence from seismology. *Geological Society of America Bulletin* 65:385–400, https://doi.org/10.1130/0016-7606(1954)65[385:OADCSE]2.0.CO;2.

Bloomer, S.H., and R.L. Fisher. 1987. Petrology and geochemistry of igneous rocks from the Tonga Trench – A non-accreting plate boundary. *Journal of Geology* 95:469–495, https://doi.org/10.1086/629144.

Bloomer, S.H., B. Taylor, C.J. MacLeod, R.J. Stern, P. Fryer, J.W. Hawkins, and L. Johnson. 1995. Early arc volcanism and the ophiolite problem: A perspective from drilling in the western Pacific. Pp 1–30 in *Active Margins and Marginal Basins of the Western Pacific*. B. Taylor and J. Natland, eds, Geophysical Monograph 88, American Geophysical Union, Washington, DC, https://doi.org/10.1029/GM088p0001.

Brandl, P.A., M. Hamada, R.J. Arculus, K. Johnson, K.M. Marsaglia, I.P. Savov, O. Ishizuka, and H. Li. 2017. The arc arises: The link between volcanic output, arc evolution and melt composition. *Earth and Planetary Science Letters* 461:73–84, https://doi.org/10.1016/j.epsl.2016.12.027.

Buchs, D.M., R.J. Arculus, P.O. Baumgartner, C. Baumgartner-Mora, and A. Ulianov. 2010. Late Cretaceous arc development on the SW margin of the Caribbean plate: Insights from the Golfito, Costa Rica, and Azuero, Panama, complexes. *Geochemistry, Geophysics, Geosystems* 11, Q07S24, https://doi.org/10.1029/2009GC002901.

Cameron, W.E., E.G. Nisbet, and V.J. Dietrich. 1979. Boninites, komatiites and ophiolitic basalts. *Nature* 280:550–553, https://doi.org/10.1038/280550a0.

Cloos, M. 1993. Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts. *Geological Society of America Bulletin* 105:715–737, https://doi.org/10.1130/0016-7606(1993)105<0715:LBACOS>2.3.CO;2.

Cluzel., D., M. Whitten, S. Meffre, J.C. Aitchison, and P. Maurizot. 2018. A reappraisal of the Poya Terrane (new Caledonia): Accreted late Cretaceous-Paleocene marginal basin upper crust, passive margin sediments, and early Eocene E-MORB sill complex. *Tectonics* 37:48–70, https://doi.org/10.1002/2017TC004579.

Conrad, C.P., and C. Lithgow-Bertelloni. 2002. How mantle slabs drive plate tectonics. *Science* 298:207–209, https://doi.org/10.1126/science.1074161.

Dallwitz, W.B., D.H. Green, and J.E. Thompson. 1966. Clinoenstatite in a volcanic rock from the Cape Vogel area, Papua. *Journal of Petrology* 7:375–403, https://doi.org/10.1093/petrology/7.3.375.

DeBari, S.M., B. Taylor, K. Spencer, and K. Fujioka. 1999. A trapped Philippine Sea plate origin for MORB from the inner slope of he Izu-Bonin Trench. *Earth and Planetary Science Letters* 174:183–197, https://doi.org/10.1016/S0012-821X(99)00252-6.

Dewey, J.F. 1975. Plate tectonics. *Reviews of Geophysics and Space Physics* 13:326–332, https://doi.org/10.1029/RG013i003p00326.

Dewey, J.F., and J.F. Casey. 2011. The origin of obducted large-slab ophiolitic complexes. Pp. 431–443 in *Arc-Continent Collision*. D. Brown and P.D. Ryan, eds, Frontiers in Earth Sciences, Springer-Verlag.

Dietrich, V.J., R. Emmermann, R. Oberhänsli, and H. Puchelt. 1978. Geochemistry of basaltic and gabbroic rocks from the West Mariana Basin and the Mariana Trench. *Earth and Planetary Science Letters* 39:127–144, https://doi.org/10.1016/0012-821X(78)90149-8.

Dilek, Y., and H. Furnes. 2014. Ophiolites and their origins. *Elements* 10:93–100, https://doi.org/10.2113/gselements.10.2.93.

Forsyth, D., and S. Uyeda. 1975. On the relative importance of the driving forces of plate motion. *Geophysical Journal of the Royal Astronomical Society* 43:163–200, https://doi.org/10.1111/j.1365-246X.1975.tb00631.x.

Francis, D. 1986. The pyroxene paradox in MORB glasses—A signature of picritic parental magmas? *Nature* 319:586–589, https://doi.org/10.1038/319586a0.

Fryer, P. 2012. Serpentinite mud volcanism: Observations, processes, and implications. 2012. *Annual Review of Marine Science* 4:345–373, https://doi.org/10.1146/annurev-marine-120710-100922.

Gale, A., C.A. Dalton, C.H. Langmuir, Y. Su, and J.-G. Schilling. 2013. The mean composition of ocean ridge basalts. *Geochemistry, Geophysics, Geosystems* 13, Q02005, https://doi.org/10.1029/2012GC004334.

Gass, I.G. 1968. Is the Troodos Massif of Cyprus a fragment of Mesozoic ocean floor? *Nature* 220:39–42, https://doi.org/10.1038/220039a0.

Gass, I.G., C.R. Neary, J. Plant, A.H.F. Robertson, K.O. Simonian, J.D. Smewing, E.T.C. Spooner, and R.A.M. Wilson. 1975. Comments on “The Troodos ophiolitic complex was probably formed in an island arc” by A. Miyashiro and subsequent correspondence by A. Hynes and A. Miyashiro. *Earth and Planetary Science Letters* 25:236–238, https://doi.org/10.1016/0012-821X(75)90202-2.

Gurnis, M., and Müller, R.D., 2003. Origin of the Australian-Antarctic Discordance from an ancient slab and mantle wedge. Pp. 417–429 in *Evolution and Dynamics of the Australian Plate*. R.R. Hillis and R.D. Müller, eds, Geological Society of America Special Papers, vol. 372, https://doi.org/10.1130/0-8137-2372-8.417.

Gurnis, M., C. Hall, and L. Lavier. 2004. Evolving force balance during incipient subduction. *Geochemistry, Geophysics, Geosystems* 5(7), Q07001, https://doi.org/10.1029/2003GC000681.

Hall, R. 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations. *Journal of Asian Earth Sciences* 20:353–431, https://doi.org/10.1016/S1367-9120(01)00069-4.

Hall, R. 2018. The subduction initiation stage of the Wilson cycle. In *Fifty years of the Wilson Cycle Concept in Plate Tectonics*. R.W. Wilson, G.A. Houseman, K.J.W. McCaffrey, A.G. Doré, and S.J.H. Buiter, eds, Geological Society of London Special Publications, vol. 470, https://doi.org/10.1144/SP470.3.

Herzberg, C. 2004. Partial crystallization of mid-ocean ridge basalts in the crust and mantle. *Journal of Petrology* 45:2,389–2,405, https://doi.org/10.1093/petrology/egh040.

Hess, H.H. 1962. History of ocean basins. Pp. 599–620 in *Petrologic Studies*. A.E.J. Engle, H.L. James, and B.F. Leonard, eds., Geological Society of America, https://doi.org/10.1130/Petrologic.1962.599.

Hickey-Vargas, R., G.M. Yogodzinski, O. Ishizuka, A. McCarthy, M. Bizimis, Y. Kusano, I.P. Savov, and R.J. Arculus. 2018. Origin of depleted basalts during subduction initiation and early development of the Izu-Bonin-Mariana island arc: Evidence from IODP expedition 351 site U1438, Amami-Sankaku basin. *Geochimica et Cosmochimica Acta* 229:85–111, https://doi.org/10.1016/j.gca.2018.03.007.

Holmes, A. 1928. Radioactivity and Earth movements. *Transactions of the Geological Society of Glasgow* 18:559–606.

Ishizuka, O., J. Kimura, Y. Li, R. Stern, M. Reagan, R. Taylor, Y. Ohara, S. Bloomer, T. Ishii, and U. Hargrove III. 2006. Early stages in the evolution of Izu–Bonin arc volcanism: New age, chemical, and isotopic constraints. *Earth and Planetary Science Letters* 250:385–401, https://doi.org/10.1016/j.epsl.2006.08.007.

Ishizuka, O., K. Tani, and M.K. Reagan, K. Kanayama, S. Umino, Y. Harigane, I. Sakamoto, Y. Miyajima, M. Yuasa, and D.J. Dunkley. 2011. The timescales of subduction initiation and subsequent evolution of an oceanic island arc. *Earth and Planetary Science Letters* 306:229–240, https://doi.org/10.1016/j.epsl.2011.04.006.

Ishizuka, O., R.N. Taylor, Y. Ohara, and M. Yuasa. 2013. Upwelling, rifting, and age-progressive magmatism from the Oki-Daito mantle plume. *Geology* 41:1,011–1,014, https://doi.org/10.1130/G34525.1.

Ishizuka, O., K. Tani, and M.K. Reagan. 2014. Izu-Bonin-Mariana forearc crust as a modern ophiolite analogue. *Elements* 10:115–120, https://doi.org/10.2113/gselements.10.2.115.

Ishizuka, O., R. Hickey-Vargas, R.J. Arculus, G.M. Yogodzinski, I.P. Savov, Y. Kusano, A. McCarthy, P.A. Brandl, and M. Sudo. 2018. Age of Izu-Bonin-Mariana arc basement. *Earth and Planetary Science Letters* 481:80–90, https://doi.org/10.1016/j.epsl.2017.10.023.

Jenner, F.E., and H.St.C. O’Neill. 2012. Analysis of 60 elements in 616 ocean floor basaltic glasses. *Geochemistry, Geophysics, Geosystems* 13, Q02005, https://doi.org/10.1029/2011GC004009.

Kuroda, N., K. Shiraki, and H. Urano. 1978. Boninite as a possible calc-alkalic primary magma. *Bulletin Volcanologique* 41(4):563–575, https://doi.org/10.1007/BF02597387.

Lake, P. 1931. Island arcs and mountain building. *The Geographical Journal* 78:149–157, https://doi.org/10.2307/1784446.

Le Bas, M.J. 2000. IUGS reclassification of the high-Mg and picritic volcanic rocks. *Journal of Petrology* 41:1,467–1,470, https://doi.org/10.1093/petrology/41.10.1467.

Leng, W., and M. Gurnis. 2015. Subduction initiation at relic arcs. *Geophysical Research Letters* 42:7,014–7,021, https://doi.org/10.1002/2015GL064985.

Li, C., R.D. van der Hilst, E.R. Engdahl, and S. Burdick. 2008. A new global model for *P* wave speed variations in Earth’s mantle. *Geochemistry, Geophysics, Geosystems* 9, Q05018, https://doi.org/10.1029/2007GC001806.

Li, H.Y., R. Taylor, J. Prytulak, J. Shervais, J.G. Ryan, M. Godard, M.K. Reagan, and J.A. Pearce. 2017. Isotopic constraints on magma source evolution during subduction initiation; IODP 352 (Izu-Bonin Forearc). *V.M. Goldschmidt Conference: Program and Abstracts*, vol. 27.

Machida, S., T. Ishii, J-I. Kimura, S. Awaji, and Y. Kato. 2008. Petrology and geochemistry of cross-chains in the Izu-Bonin back arc: Three mantle components with contributions of hydrous liquids from a deeply subducted slab. *Geochemistry, Geophysics, Geosystems* 9, Q05002, https://doi.org/10.1029/2007GC001641.

Mao, X., M. Gurnis, and D.A. May. 2017. Subduction initiation with vertical lithospheric heterogeneities and new fault formation. *Geophysical Research Letters* 44:11,349–11,356, https://doi.org/10.1002/2017GL075389.

Matthews, K.J., S.E. Williams, J.M. Whittaker, R.D. Müller, M. Seton, and G.L. Clarke. 2015. Geologic and kinematic constraints on Late Cretaceous to mid-Eocene plate boundaries in the southwest Pacific. *Earth-Science Reviews* 140:72–107, https://doi.org/10.1016/j.earscirev.2014.10.008.

Matthews, K.J., K.T. Maloney, S. Zahirovic, S.E. Williams, M. Seton, and R.D. Müller. 2016a. Global plate boundary evolution and kinematics since the late Paleozoic. *Global and Planetary Change* 146:226–250, https://doi.org/10.1016/j.gloplacha.2016.10.002.

Matthews, K.J., R.D. Müller, and D.T. Sandwell. 2016b. Oceanic microplate formation records the onset of India-Euraisa collision. *Earth and Planetary Science Letters* 433:206–214, https://doi.org/10.1016/j.epsl.2015.10.040.

McKenzie, D.P., and R.L. Parker. 1967. The North Pacific: An example of tectonics on a sphere. *Nature* 216:1,276–1,280, https://doi.org/10.1038/2161276a0.

McKenzie, D.P. 1977. The initiation of trenches: A finite amplitude instability. Pp. 57–61 in *Island Arcs, Deep Sea Trenches and Back-Arc Basins*. M. Talwani and W.C. Pitman III, eds, Maurice Ewing Series, vol. 1, American Geophysical Union, Washington, DC, https://doi.org/10.1029/ME001p0057.

Meckel, T.A., M.F. Coffin, S. Mosher, P. Symonds, G. Bernardel, and P. Mann. 2003. Underthrusting at the Hjort Trench, Australian-Pacific plate boundary: Incipient subduction? *Geochemistry, Geophysics, Geosystems* 4, https://doi.org/10.1029/2002GC000498.

Meffre, S., T.J. Falloon, A.J. Crawford, K. Hoernle, F. Hauff, R.A. Duncan, S.H. Bloomer, and D.J. Wright. 2012. Basalts erupted along the Tongan fore arc during subduction initiation: Evidence from geochronology of dredged rocks from the Tonga fore arc and trench. *Geochemistry, Geophysics, Geosystems* 13, Q12003, https://doi.org/10.1029/2012GC004335.

Miyashiro, A. 1973. The Troodos ophiolitic complex was probably formed in an island arc. *Earth and Planetary Science Letters* 19:218–224, https://doi.org/10.1016/0012-821X(73)90118-0.

Nakamura, K. 1977. Volcanoes as possible indicators of tectonic stress orientation – Principle and proposal. *Journal of Volcanology and Geothermal Research* 2:1–16, https://doi.org/10.1016/0377-0273(77)90012-9.

O’Connor, J.M., B. Steinberger, M. Regelous, A.A. Koppers, J.R. Wijbrans, K.M. Haase, P. Stoffers, W. Jokat, and D. Garbe-Schönberg. 2013. Constraints on past plate and mantle motion from new ages for the Hawaiian-Emperor Seamount Chain. *Geochemistry, Geophysics, Geosystems* 14:4,564–4,584, https://doi.org/10.1002/ggge.20267.

O’Neill, H.St.C., and F.E. Jenner. 2012. The global pattern of trace-element distributions in ocean floor basalts. *Nature* 491:698–705, https://doi.org/10.1038/nature11678.

O’Neill, H.St.C. 2016. The smoothness and shapes of chondrite-normalized rare earth element patterns in basalts. *Journal of Petrology* 57:1,463–1,508, https://doi.org/10.1093/petrology/egw047.

Pearce, J.A., and J.R. Cann. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth and Planetary Science Letters* 19:290–300, https://doi.org/10.1016/0012-821X(73)90129-5.

Pearce, J.A., and D.W. Peate. 1995. Tectonic implications of the composition of volcanic arc magmas. *Annual Review of Earth and Planetary Science* 23:251–285, https://doi.org/10.1146/annurev.ea.23.050195.001343.

Pearce, J.A. 2003. Supra-subduction zone ophiolites: The search for modern analogues. Pp. 269–293 in *Ophiolite Concept and the Evolution of Geological Thought*. Geological Society of America Special Papers, vol. 373, https://doi.org/10.1130/0-8137-2373-6.269.

Petersen, J. 1891. Der boninit von Peel Island. *Jahrbuch der Hamburgischen Wissenschaftlichen Anstalten* 8:341–349.

Petterson, M.G., T. Babbs, C.R. Neal, J.J. Mahoney, A.D. Saunders, R.A. Duncan, D. Tolia, R. Magu, C. Qopoto, H. Mahoa, and D. Natogga. 1999. Geological-tectonic framework of Solomon Islands, SW Pacific: Crustal accretion and growth within an intra-oceanic setting. *Tectonophysics* 301:35–60, https://doi.org/10.1016/S0040-1951(98)00214-5.

Pope, E.L., M. Jutzeler, M.J.B. Cartigny, J. Shreeve, P.J. Talling, I.C. Wright, and R.J. Wysoczanski. 2018. Origin of spectacular fields of submarine sediment waves around volcanic islands. *Earth and Planetary Science Letters* 493:12–24, https://doi.org/10.1016/j.epsl.2018.04.020.

Reagan, M.K., and A. Meijer. 1984. Geology and geochemistry of early arc-volcanic rocks from Guam. *Geological Society of America Bulletin* 95:701–713, https://doi.org/10.1130/0016-7606(1984)95<701:GAGOEA>2.0.CO;2.

Reagan, M.K., O. Ishizuka, R.J. Stern, K.A. Kelley, Y. Ohara, J. Blichert-Toft, S.H. Bloomer, J. Cash, P. Fryer, B.B. Hannan, and others. 2010. Fore-arc basalts and subduction initiation in the Izu-Bonin-Mariana system. *Geochemistry, Geophysics, Geosystems* 11, https://doi.org/10.1029/2009GC002871.

Reagan, M.K., W.C. McClelland, G. Girard, K.R. Goff, D.W. Peate, Y. Ohara, and R.J. Stern. 2013. The geology of the southern Mariana fore-arc crust: Implications for the scale of Eocene volcanism in the western Pacific. *Earth and Planetary Science Letters* 380:41–51, https://doi.org/10.1016/j.epsl.2013.08.013.

Reagan, M.K., J.A. Pearce, K. Petronotis, R.R. Almeev, A.J. Avery, C. Carvallo, T. Chapman, G.L. Christeson, E.C. Ferré, M. Godard, and others. 2017. Subduction initiation and ophiolite crust: New insights from IODP drilling. *International Geology Review* 59:1,439–1,450, https://doi.org/10.1080/00206814.2016.1276482.

Reagan, M.K., D.E. Heaton, M.S. Schmitz, J.A. Pearce, J.W. Shervais, and A.P. Koppers. 2019. Forearc ages reveal extensive short-lived and rapid seafloor spreading following subduction initiation. *Earth and Planetary Science Letters* 506:520–529, https://doi.org/10.1016/j.epsl.2018.11.020.

Ritsema, J., H.J. van Heijst, and J.H. Woodhouse. 2004. Global transition zone tomography. *Journal of Geophysical Research* 109(B2), https://doi.org/10.1029/2003JB002610.

Schellart, W.P., and W. Spakman. 2012. Mantle constraints on the plate tectonic evolution of the Tonga-Kermadec-Hikurangi subduction zone and the South Fiji Basin region. *Australian Journal of Earth Sciences* 59:933–952, https://doi.org/10.1080/08120099.2012.679692.

Schmidt, M.W., and O. Jagoutz. 2017. The global systematics of primitive arc melts. *Geochemistry, Geophysics, Geosystems* 18:2,817–2,854, https://doi.org/10.1002/2016GC006699.

Seton, M., R.D. Müller, S. Zahirovic, C. Gaina, T. Torsvik, G. Shephard, A. Talsma, M. Gurnis, M. Turner, S. Maus, and M. Chandler. 2012. Global continental and ocean basin reconstructions since 200 Ma. *Earth-Science Reviews* 113:212–270, https://doi.org/10.1016/j.earscirev.2012.03.002.

Seton, M., N. Flament, J. Whittaker, R.D. Müller, M. Gurnis, and D.J. Bower. 2015. Ridge subduction sparked reorganization of the Pacific plate-mantle system 60-50 million years ago. *Geophysical Research Letters* 42:1,732–1,740, https://doi.org/10.1002/2015GL063057.

Sharp, W.D., and D.A. Clague. 2006. 50-Ma initiation of Hawaiian-Emperor Bend records major change in Pacific plate motion. *Science* 313:1,281–1,284, https://doi.org/10.1126/science.1128489.

Shervais, J.W., M.K. Reagan, E. Haugen, R. Almeev, J.A. Pearce, J. Prytulak, J.G. Ryan, S.A. Whattam, M. Godard, T. Chapman, and others. 2018. Magmatic response to subduction initiation: Part I. Fore-arc basalts of the Izu-Bonin Arc from IODP Expedition 352. *Geochemistry, Geophysics, Geosystems,* https://doi.org/10.1029/2018GC007731.

Shiraki, K., N. Kuroda, H. Urano, and S. Maruyama. 1980. Clinoenstatite in boninites from the Bonin Islands, Japan. *Nature* 285:31–32, https://doi.org/10.1038/285031a0.

Sigurdsson, H., and J.-G. Schilling. 1976. Spinels in mid-Atlantic Ridge basalts: Chemistry and occurrence. *Earth and Planetary Science Letters* 29:7–20, https://doi.org/10.1016/0012-821X(76)90021-2.

Smyth, J.R. 1974. Experimental study on the polymorphism of enstatite. *American Mineralogist* 59:345–352.

Sollas, W.J. 1903. The figure of the Earth. *Quarterly Journal of the Geological Society* 59:180–188, https://doi.org/10.1144/GSL.JGS.1903.059.01-04.18.

Stern, R.J., and S.H. Bloomer. 1992. Subduction zone infancy: Examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs. *Geological Society of America Bulletin* 104:1,621–1,636, https://doi.org/10.1130/0016-7606(1992)104<1621:SZIEFT>2.3.CO;2.

Stern, R.J. 2004. Subduction initiation: Spontaneous and induced. *Earth and Planetary Science Letters* 226:275–292, https://doi.org/10.1016/j.epsl.2004.08.007.

Stern, R.J., and T. Gerya. 2018. Subduction initiation in nature and models: A review. *Tectonophysics* 746:173–198, https://doi.org/10.1016/j.tecto.2017.10.014.

Straub, S.M., J.D. Woodhead, and R.J. Arculus. 2015. Temporal evolution of the Mariana arc: Wedge and subducted slab controls revealed with a tephra perspective. *Journal of Petrology* 56:409–439, https://doi.org/10.1093/petrology/egv005.

Sutherland, R., J. Collot, F. Bache, S. Henrys, D. Barker, G.H. Browne, M.J.F. Lawrence, H.E.G. Morgans, C.J. Hollis, C. Clowes, and others. 2017. Widespread compression associated with Eocene Tonga-Kermadec subduction initiation. *Geology* 45:355–358, https://doi.org/10.1130/G38617.1.

Sutherland, R., G.R. Dickens, P. Blum, and Expedition 371 Scientists. 2018. *Expedition 371 Preliminary Report: Tasman Frontier Subduction Initiation and Paleogene Climate*. International Ocean Discovery Program, https://doi.org/10.14379/iodp.pr.371.2018.

Tamura, Y., Y. Tatsumi, D. Zhao, Y. Kido, and H. Shukuno. 2002. Hot fingers in the mantle wedge: New insights into magma genesis in subduction zones. *Earth and Planetary Science Letters* 197:105–116, https://doi.org/10.1016/S0012-821X(02)00465-X.

Tatsumi, Y. 1989. Migration of fluid phases and genesis of basalt magmas in subduction zones. *Journal of Geophysical Research* 94:4,697–4,707, https://doi.org/10.1029/JB094iB04p04697.

Taylor, B., and A.M. Goodliffe. 2004. The West Philippine Basin and the initiation of subduction, revisited. *Geophysical Research Letters* 31, L12602, https://doi.org/10.1029/2004GL020136.

Todd, E., J.B. Gill, and J.A. Pearce. 2012. A variably enriched mantle wedge and contrasting melt types during arc stages following subduction initiation in Fiji and Tonga, southwest Pacific. *Earth and Planetary Science Letters* 335–336:180–194, https://doi.org/10.1016/j.epsl.2012.05.006.

Umbgrove, J.H.F. 1945. Different types of island-arcs in the Pacific. *The Geographical Journal* 106:198–209, https://doi.org/10.2307/1788957.

Umino, S. 1985. Volcanic geology of Chichijima, the Bonin islands (Ogasawara islands). *Journal of the Geological Society of Japan* 91:505–523, https://doi.org/10.5575/geosoc.91.505.

Umino, S., K. Kitamura, K. Kanayama, A. Tamura, N. Sakamoto, O. Ishizuka, and S. Arai. 2015. Thermal and chemical evolution of the subarc mantle revealed by spinel-hosted melt inclusions in boninite from the Ogasawara (Bonin) Archipelago. *Geology* 43(2):151–154, https://doi.org/10.1130/G36191.1.

Uyeda, S., and Z. Ben-Avraham. 1972. Origin and development of the Philippine Sea. *Nature Physical Science* 240:176–178, https://doi.org/10.1038/physci240176a0.

Wadati, K. 1931. Shallow and deep earthquakes. *Geophysical Magazine (Tokyo)* 4:231–285.

Walker, D.A., and W.E. Cameron. 1983. Boninite primary magmas: Evidence from the Cape Vogel Peninsula, PNG. *Contributions to Mineralogy and Petrology* 83:150–158, https://doi.org/10.1007/BF00373088.

Whattam, S.A., and R.J. Stern. 2011. The 'subduction initiation rule': A key for linking ophiolites, intra-oceanic forearcs and subduction initiation. *Contributions to Mineralogy and Petrology* 162:1,031–1,045, https://doi.org/10.1007/s00410-011-0638-z.

Whittaker, J.M., R.D. Müller, G. Leitchenkov, H. Stagg, M. Sdrolias, C. Gaina, and A. Goncharov. 2007. Major Australian-Antarctic plate reorganization at Hawaii-Emperor bend time. *Science* 318:83–86, https://doi.org/10.1126/science.1143769.

Wilson, J.T. 1965. A new class of faults and their bearing on continental drift. *Nature* 207:343–347, https://doi.org/10.1038/207343a0.

Woelki, D., M. Regelous, K.M. Haase, R.H.W. Romer, and C. Beier. 2018. Petrogenesis of boninitic lavas from the Troodos Ophiolite, and comparison with Izu-Bonin-Mariana fore-arc crust. *Earth and Planetary Science Letters* 498:203–214, https://doi.org/10.1016/j.epsl.2018.06.041.

Wu, J., J. Suppe, R. Lu, and R. Kanda. 2016. Philippine Sea and East Asian plate tectonics since 52 Ma constrained by new subducted slab reconstruction methods. *Journal of Geophysical Research* 121:4,670–4,741, https://doi.org/10.1002/2016JB012923.

Yogodzinski, G.M., M. Bizimis, R. Hickey-Vargas, A. McCarthy, B.D. Hocking, I.P. Savov, O. Ishizuka, R. Arculus. 2018. Implications of Eocene-age Philippine Sea and forearc basalts for initiation and early history of the Izu-Bonin-Mariana arc. *Geochimica et Cosmochimca Acta* 228:136–156, https://doi.org/10.1016/j.gca.2018.02.047.

Zhou, X., Z.-H. Li, T.V. Gerya, R.J. Stern, Z. Xu, and J. Zhang. 2018. Subduction initiation dynamics along a transform fault control trench curvature and ophiolite ages. *Geology* 46:607–610, https://doi.org/10.1130/G40154.1.

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