Back-Arc Basins

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Earth's geology is fashioned to a large degree at lithospheric plate boundaries by the types of relative motion between adjacent plates. At divergent plate boundaries, such as mid-ocean ridges, mafic basaltic lavas erupt, forming the seafloor that underlies most of the ocean basins. At convergent boundaries, such as subduction zones, oceanic lithosphere is consumed at deep-sea trenches, leading to the eruption of chains of andesitic arc volcanoes near the edge of the overriding plate. Back-arc basins are especially diverse geologic settings because they inherently involve both of these types of plate boundaries.

Back-arc basins are extensional basins formed behind subduction zones by rifting volcanic arcs and accreting new volcanic seafloor (Karig, 1970). Most back-arc basins are located behind the western limb of the Pacific Ocean (Figure 1) along current and past convergent boundaries. Many important aspects of back-arc crustal formation are similar to those of mid-ocean settings, including seafloor spreading, hydrothermal activity, and vent fauna communities. However, back-arc basins differ from mid-ocean ridges in several aspects, mainly due to their proximity to convergent plate boundaries. Although back-arc basins make up far less of Earth's surface compared to open-ocean basins, they show a wide variety of spreading styles and lithospheric compositions. This diversity makes them important areas for studying crustal-accretion and related processes as well as the biological communities that inhabit these remote settings.

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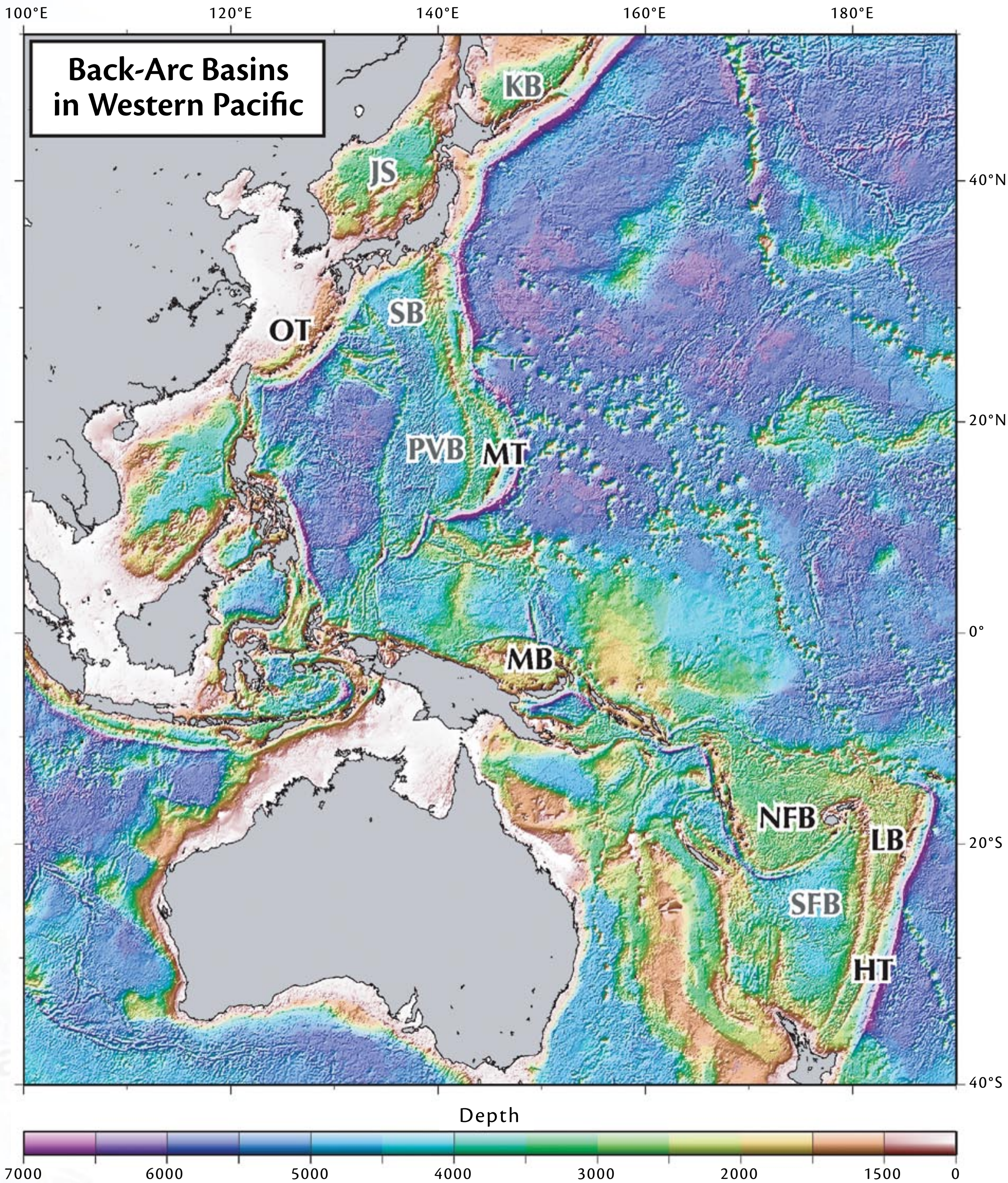

Figure 1. Distribution of back-arc basins in the western Pacific. Most back-arc basins are located along the western margin of the Pacific Ocean. HT = Havre Trough, JS = Japan Sea, KB = Kurile Basin, LB = Lau Basin, MB = Manus Basin, MT = Mariana Trough, NFB = North Fiji Basin, PVB = Parece Vela Basin, SB = Shikoku Basin, SFB = South Fiji Basin, and OT = Okinawa Trough. Basins whose names appear in gray are not currently active rifting/spreading systems.

BACK-ARC BASIN FORMATION

Why and how extensional basins open near the boundaries between convergent plates, and suddenly stop opening, have long been outstanding questions in plate tectonics. Figure 2 illustrates two general concepts of back-arc basin formation. In one scenario, the subducting plate can sink into the mantle faster than it converges with the overriding plate. In this case, the trench is said to "roll back" from the overriding plate (Elsasser, 1971; Moberly, 1972), in the process breaking off a smaller "arc" or "forearc" plate that remains in contact with the trench while the remaining part of the overriding plate trails behind. Alternatively, the overriding plate may move away from the trench; the slab acts as a sea anchor in the mantle (Scholz and Campos, 1995), resisting the migration of the trench with the retreating overriding plate. Again, a small plate breaks off from the overriding plate and remains in contact with the subducting plate along the trench. Both of these mechanisms may operate at the same time.

When arc systems rift, the breakup generally occurs in the vicinity of the arc volcanic front (Molnar and Atwater, 1978) (Figure 2), defined as the trenchward limit and usually the maximum locus of arc volcanism (Tatsumi, 1986; Tatsumi and Eggins, 1995). The arc volcanic front is a region of thickened crust, melt emplacement, high heat flow, and large gravitational stresses, all of which tend to favor breakup in this area if stresses become extensional. Nevertheless, breakup is not always exactly centered on the arc volcanic front and may occur within ±50 km (Taylor and Karner, 1983) so that some systems rift behind the arc and others in the forearc. The reasons for this variability are not clear, but the local weaknesses in the overriding plate are not the only factors controlling breakup. Other effects, such as the motion and geometry of the subducting slab and coupling with the mantle wedge during breakup, may also be important. After breakup, some basins, such as the Mariana Trough, appear to have initiated rifting at a central area and then grown by widening and propagation, that is, the progressive extension of the rift along strike into the arc volcanic front (Stern et al., 1984). Other basins, such as the Havre Trough, appear to be opening more uniformly along their entire lengths (Delteil et al., 2002).

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An interesting but poorly understood aspect of back-arc basin development is that it often appears to be episodic. Back-arc basins may form and grow for periods of up to tens of millions of years and then become extinct, only to begin a new cycle of arc rifting and spreading a few million years later. This sequence is well developed in the Philippine Sea (Figure 3), where subduction developed and formed a volcanic arc that later rifted, forming the Parece Vela and Shikoku Basins (Okino et al., 1998; Okino et al., 1999; Okino et al., 1994). These basins ceased opening and a new volcanic arc grew, which again rifted to form rift basins in the Bonin Arc and seafloor spreading in the Mariana Trough. In the wake of these basins, the Kyushu-Palau and West Mariana Ridges were left as remnant or inactive arcs.

KINEMATICS OF BACK-ARC BASINS

As we have seen, the opening and evolution of back-arc basins can be a response to far-field stresses, as when the overriding plate is pulled away from the trench,

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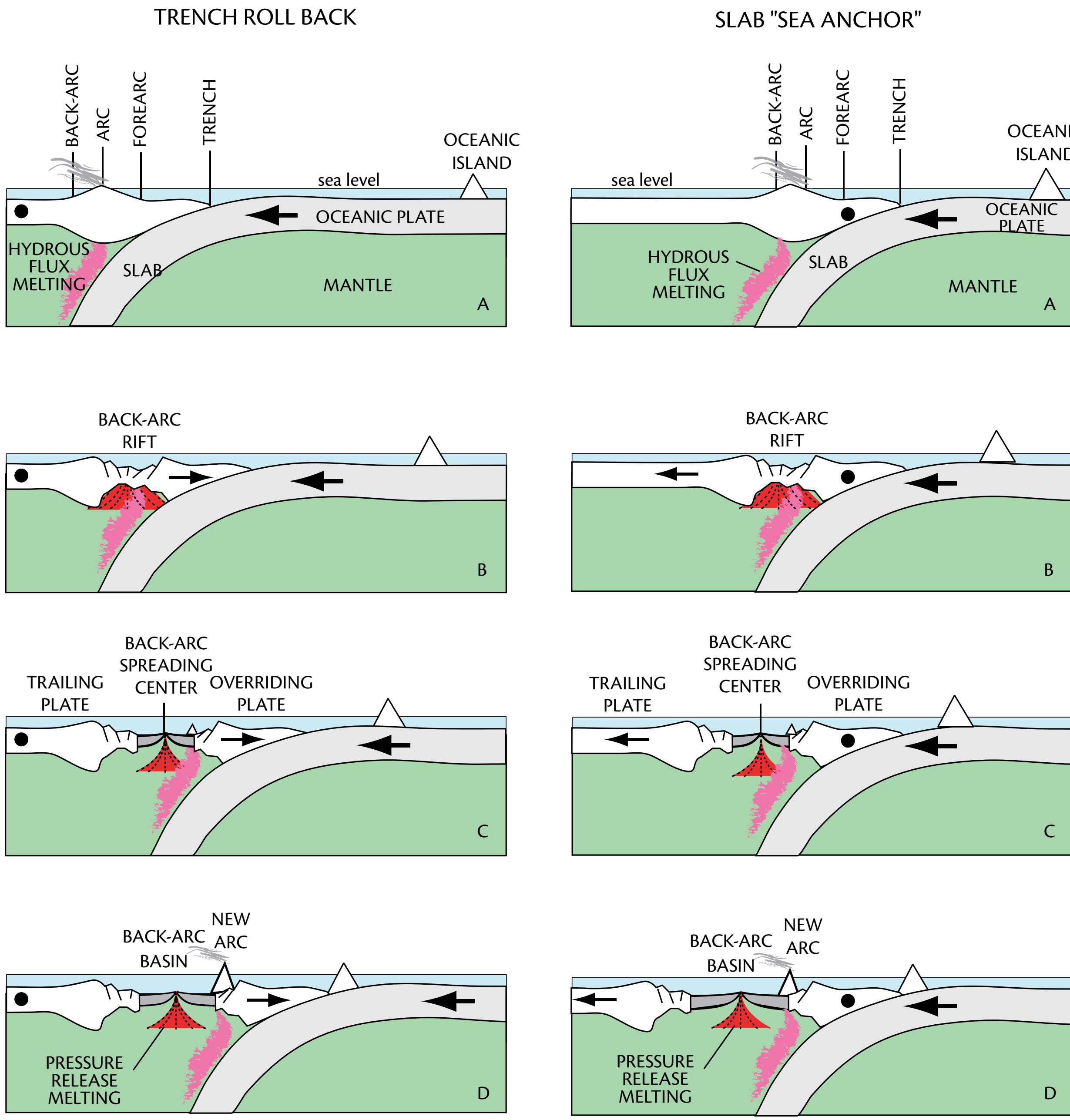

Figure 2. Modes of back-arc basin opening. The panels from top to bottom show a schematic time sequence of back-arc basin opening. Left-hand panels show the case of slab roll back (Elsasser, 1971; Moberly, 1972) in which the trailing plate is considered fixed (indicated by black dot) and the trench hinge moves relatively seaward (indicated by small right-pointing arrow), breaking off a section of the overriding plate that moves with the trench from a trailing plate that remains fixed. Despite the oceanward motion of the trench, the oceanic plate itself continues to converge with both the trailing and overriding plates as indicated by the relative motion of the oceanic island toward the left (large arrow). In the right-hand panels, the trench hinge is considered to resist motion (black dot) because of a slab "sea anchor" force (Scholz and Campos, 1995). In panels B–D, what becomes the "trailing" plate begins to move toward the left (indicated by small arrow), creating a relative opening with respect to the overriding plate. In both cases, mantle melting initially results from hydrous fluxing from fluids released by the slab (pink pattern in panels A). As extension begins (panels B) and the arc plate is rifted and thinned, the underlying mantle begins to rise to fill the space created. This action initiates pressure-release melting (red pattern and dashed lines indicate mantle advection). Once breakup occurs, the separating overriding and trailing plates continue to drive mantle advection and pressure-release melting. Note that hydrous flux melting may continue throughout and that arc and spreading-center melt sources may be initially quite close but separate with time (panels B–D).

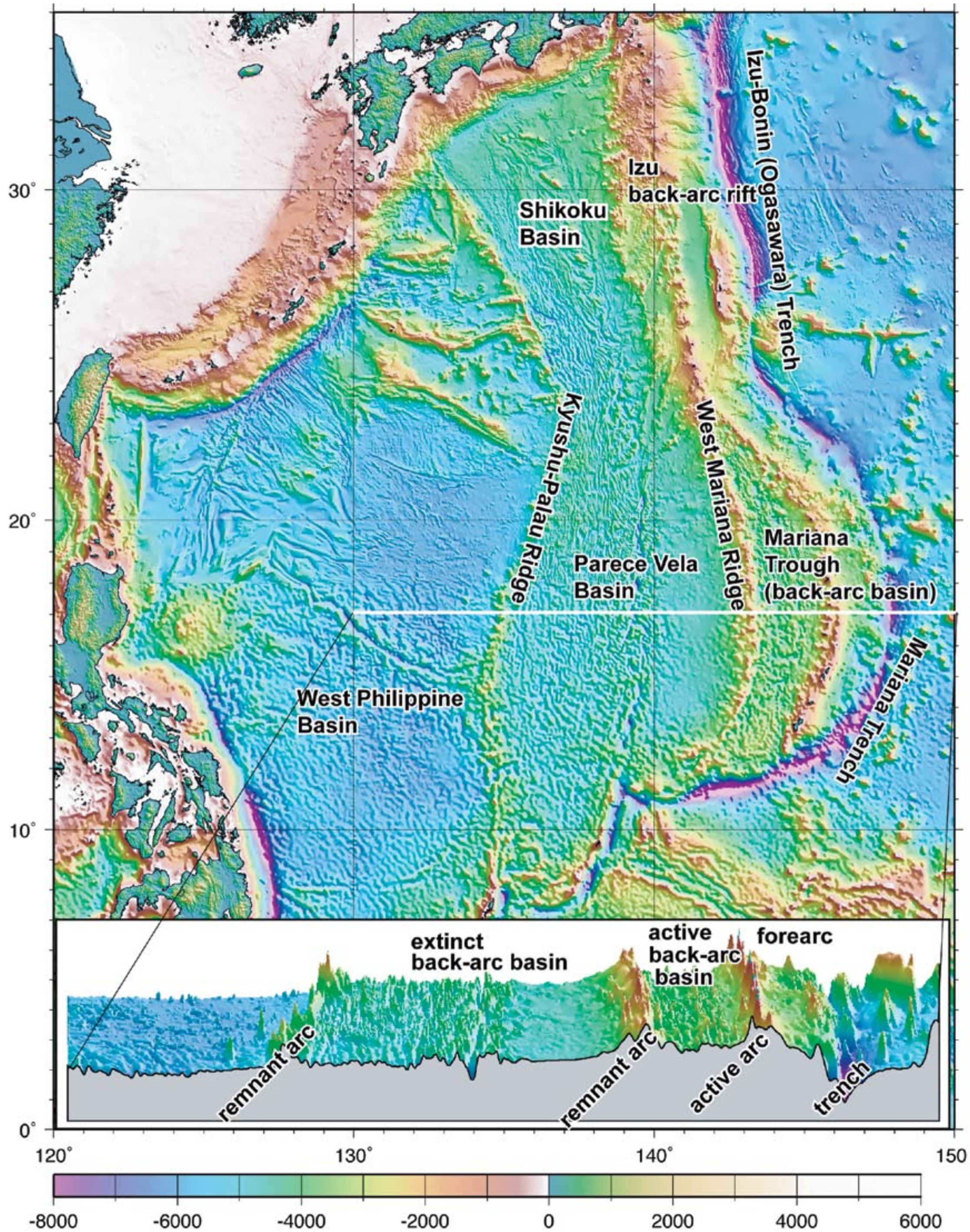

Figure 3. Episodic back-arc basin formation in the Philippine Sea. The Shikoku and Parece Vela Basins rifted and opened from late Oligocene to Middle Miocene, splitting the paleo Izu-Bonin-Mariana arc. The Izu back-arc rift zone and the Mariana Trough are current extensional back-arc areas. *Compiled bathymetry data from JTOPO1 (Marine Information Research Center, Japan)*

and also to changes in proximal stresses, as when the trench and slab roll back away from the overriding plate. In both cases, the trench itself can change shape in plan view during basin opening. This change in shape can lead to a different behavior from typical "plate tectonic" kinematics, which describes the movement of lithospheric plates approximated as rotations about axes or "poles" that pass through the center of the earth. For example, when continents rupture and move apart and a new ocean basin forms in between the original boundaries of the rift, the conjugate margins can be brought back together to a close approximation by a simple rotation of one plate with respect to the other. In contrast, the reconstructed conjugate margins of back-arc basins often do not fit well when brought back together, indicating nonrigid behavior of lithosphere.

This nonrigid behavior can be seen in the case of the development of the Philippine Sea. The Bonin and Mariana arcs represent the conjugate margins to the Kyushu-Palau Ridge (Figure 3). Their rather complex evolution (Okino et al., 1999) and discordant shapes on a map show that these conjugate features cannot be reconstructed by simple rotations without large mismatches. Even early geologic mapping (Karig et al., 1978) indicated that the Mariana arc is undergoing large deformation rather than a simple rigid rotation away from the conjugate West Mariana Ridge. Nonrigid tectonic behavior is seen even in geologically "instantaneous" GPS measurements in the Mariana Trough where the Mariana arc "plate" shows arc-parallel deformation (Kato et al., 2003). Still other basins, such as the Lau Basin west of Tonga, appear to be currently opening by a rigid rotation of the Tonga Ridge away from the Australian Plate (Bevis et al., 1995). Even here, however, examination of the larger system, consisting of the Lau and Havre back-arc basins, shows that its evolution requires distinct opening kinematics even though its component adjoining basins are both surrounded by the larger Pacific and Australian plates and share a continuous Tonga-Kermadec Trench (Figure 1).

These examples illustrate the importance of changes in the plan geometry of the trench itself in back-arc kinematics rather than simply the relative motions between the larger trailing plate and the trench. Because the trench itself can change shape as the back-arc basin opens, the overriding arc plate must accommodate these changes by deforming. This is not true of the trailing plate however, as it is decoupled by the spreading center from stresses induced by the trench. Thus, the two flanks of a back-arc basin separated by a spreading center need not be symmetric. A well-developed example of this asymmetry is evident in the southernmost Mariana Trough. Here, the overriding arc plate is fractured at large angles to the trench and back-arc spreading center, but the trailing plate is not and displays seafloor fabric that is conformable with the shape of the spreading center (Martinez et al., 2000). Asymmetric spreading, well documented in the central Mariana Trough (Deschamps and Fujiwara, 2003), can favor the spreading axis remaining close to the volcanic arc. This spreading-axis location, in turn, may facilitate deformation of the overriding arc plate by minimizing its growth rate.

> ...diversity not only broadens the magnitude of the controlling variables that can be studied, but also presents them in new combinations not found in the open oceans.

MAGMATISM

As discussed above, back-arc basins develop by first rifting near the arc volcanic front and later forming seafloor-spreading centers. This evolution suggests that construction of crust within back-arc basins may be influenced by at least two distinct melt-generation processes that vary in influence during the evolution and growth of these basins: that which supplies arc volcanism and that which forms the crust at seafloor-spreading centers (see Figure 2). Arc volcanism is thought to be largely produced by hydrous melting (Kushiro et al., 1968; Tatsumi and Eggins, 1995). This melting occurs when the sinking lithospheric slab at a subduction zone encounters higher pressures and temperatures that lead to metamorphic breakdown of hydrous minerals and the release of water into the mantle wedge (Schmidt and Poli, 1998). As the water enters the hot mantle wedge above the slab, it lowers the mantle solidus temperature, leading to melting (Grove et al., 2006). The melts are then thought to rise buoyantly, subparallel to the slab through the mantle wedge to the arc volcanic front (Tamura et al., 2002). In contrast, at seafloor-spreading centers, the lithospheric plates are viscously coupled to deeper ductile mantle. As the lithospheric plates separate, they are thought to actively drive mantle upwelling to the spreading axis at a rate proportional to the spreading rate. Decreasing pressure in the hot upwelling mantle causes it to partly melt in a process referred to as "pressure-release melting" (Langmuir et al., 1992). Thus, as back-arc basins form and widen, the magmatic centers may be initially close to the arc volcanic front and strongly influenced by hydrous flux melting; as they separate from the arc with time, magma production evolves toward mainly pressure-release melting. Crustal compositions may thus also change correspondingly from felsic compositions (andesite and dacite) (Sinton et al., 2003), with strong slab chemical influence, toward mafic mid-ocean ridge basalts (MORB) that characterize seafloor spreading in the open oceans (Gribble et al., 1998).

These effects have been noted in several back-arc basins (Martinez and Taylor, 2002; 2003), but are perhaps best displayed in the Lau Basin where the Eastern Lau Spreading Center has a simple geometry progressively approaching the arc volcanic front from north to south as the basin narrows (Zellmer and Taylor, 2001). Correspondingly, the magma chemistry changes from basaltic to andesitic (Vallier et al., 1991) with an increasing slab signature (Pearce et al., 1995). The southward-increasing arc proximity also dramatically changes the spreading center's melt productivity and, correspondingly, its morphology changes from a deep, flat axis to a peaked, shallow axial high, although spreading rates in this same interval decrease by over a factor of two (Martinez et al., 2006). Highly variable basin morphology is also observed in the older Lau Basin flanks and may similarly reflect the interplay between spreading centers and a heterogeneous, subduction-influenced mantle during the complex opening history of the basin (Martinez and Taylor, 2006).

> Back-arc basins ... present rich and diverse settings in which to examine and test our understanding of mantle melting and crustal accretion and their effects on the construction of the oceanic crust and lithosphere.

In addition to these systematic changes with arc proximity, geochemically and isotopically enriched lavas that are distinct from normal back-arc basin basalts are reported from the Shikoku, South China, and West Philippine Basins (Sato et al., 2002). In the Shikoku Basin, these lavas erupted during the last stage of spreading and after the cessation of spreading, and are now recognized in the Kinan Seamount Chain (Sato et al., 2002) and as the basaltic sills drilled at Deep Sea Drilling Project Site 444 (Hickey-Vargas, 1998). These lavas have enriched-MORB (E-MORB)- to ocean island basalt (OIB)-like geochemistry, with isotopic characteristics suggesting mixing of a MORB source and an OIB source. Post-spreading enriched magmatism may be a common process during the last stage and after the cessation of back-arc spreading (Sato et al., 2002). The possible explanation for this enriched magmatism is that mantle upwelling induced by back-arc spreading might not stop immediately after cessation of back-arc spreading, but instead may continue for some period of time.

Further information on melt-generation processes in back-arc basins can be obtained through analyses of serpentinized peridotites found in rare "tectonic windows," which directly expose the mantle through faulting. Tectonic windows in back-arc settings, however, are only known in the Philippine Sea. One is in the "central graben" of the active Mariana Trough spreading center (Ohara et al., 2002), and several others are near the axis of the extinct Parece Vela Basin spreading center (Ohara et al., 2003; Ohara, 2006). Although these Philippine

Sea back-arc basin peridotites underwent some later melt/fluid impregnation, the residual composition of the minerals in the peridotites follows the global abyssal peridotite compositional trend from nearly undepleted (Parece Vela Basin) to moderately depleted (Mariana Trough) mantle signatures (Ohara, 2006). These variations indicate differences between magma formation and transport processes beneath the two basins. In the now-extinct Parece Vela spreading center, melting may have been greatly suppressed in the dying rift environment because of the thick and cold lithosphere and closely spaced fracture zones, whereas the Mariana Trough shows more typical depletions associated with active spreading segment ends.

HYDROTHERMAL ACTIVITY

Although less studied than at mid-ocean ridges, hydrothermal activity has been long known at arc and back-arc settings (see review in Ishibashi and Urabe, 1995). Because of the greater range of crustal chemistry in back-arc basins relative to mid-ocean ridges, the character of back-arc hydrothermal systems also shows a greater diversity. Back-arc hydrothermal systems frequently display greater magmatic contribution than do mid-ocean settings. Back-arc systems are also tectonic analogs of economically important Kuroko-type volcanic massive sulfide deposits (Ishibashi and Urabe, 1995). The most complete survey to date of hydrothermal activity along a back-arc spreading center was carried out along the Eastern Lau Spreading Center in the Lau Basin (Wiens et al., 2005). The results show a remarkably high density of vents along the ridge axis (nearly 30 vents over a < 400-km length) inferred from a survey of hydrothermal plumes (mainly derived from particulate matter emitted by black smokers) in the water column (Baker et al., 2006). Remarkably, the plume incidence (fraction of ridge length overlain by hydrothermal plumes) increases to the north, with increasing spreading rate, although seismic evidence (Harding et al., 2000) indicates that magma in the crust decreases to the north and almost disappears in the segments with the greatest plume incidence (Baker et al., 2006). This observation is difficult to reconcile with models that view hydrothermal activity as primarily driven by freezing magma (Cann and Strens, 1982). The observations suggest that mantle heat extraction, perhaps facilitated by greater faulting in this tectonic environment, is enhancing hydrothermal activity (Martinez et al., 2006). The apparent high density and chemical diversity of back-arc hydrothermal activity, at least along the Eastern Lau Spreading Center, suggest that back-arc spreading centers are key sites for the study of vent biology.

> As some back-arc basin sites are so remarkably different chemically, these hydrothermal systems provide an unprecedented opportunity to explore the extent of the unusual microbial biodiversity at deep-sea vents.

VENT ECOSYSTEMS

The spatial complexity and physicochemical heterogeneity inherently associated with back-arc basins (Tivey, this issue) provide a great diversity of niches for invertebrate and microbial colonization. As a consequence, many new taxa and types of communities have been described from these geologically unique areas. In general, invertebrates such as mussels (*Bathymodiolus spp.*) and provannid gastropods (*Alvinoconcha hessleri, Ifremeria nautilei*) dominate the ecosystem at back-arc basins (Figure 4) (Tunnicliffe, 1991; Desbruyères et al., 1994; Pranal et al., 1996). Sessile tubeworms (*Lamellibrachia, Alaysia, Arcovestia* spp.), although present, are only rarely documented (e.g., Manus Basin, Southward and Galkin, 1997; Lau Basin south of Hine Hina at 22°32´S and 176°43´W, Desbruyères et al., 1994; and recently from the Eastern Lau Spreading Center, author Reysenbach, personal observation). Barnacles are often prevalent and represented by several types, including the primitive species *Eochionelasmus ohtai* and *Neobrachylepas*

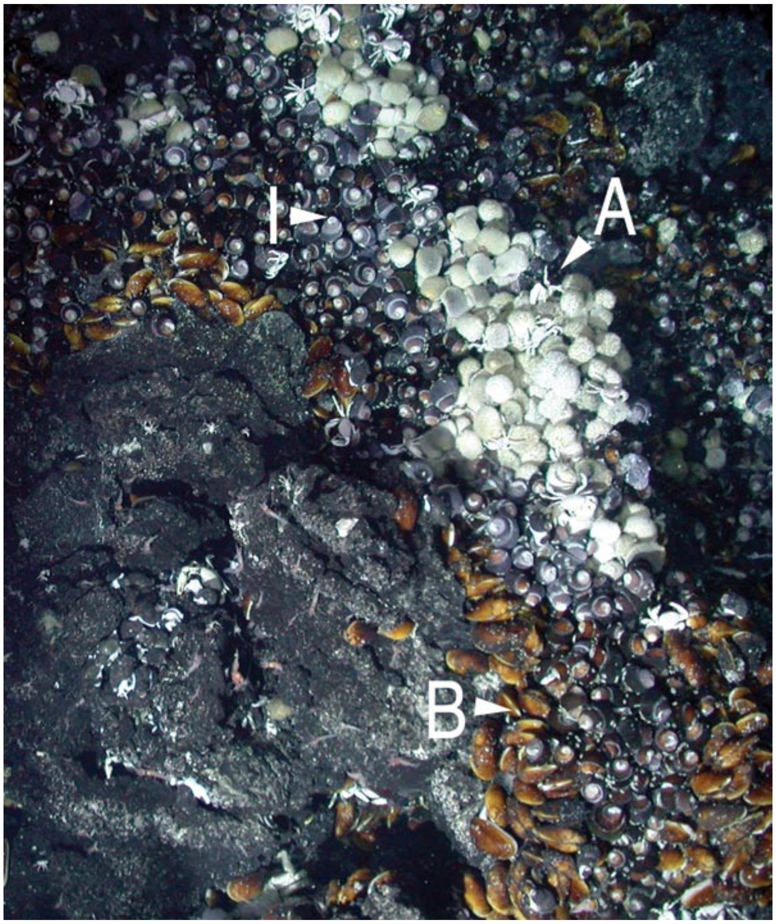

Figure 4. Spatial zonation of the three dominant invertebrate taxa at vent sites in the North Fiji Basin. *Alvinoconcha* snails (A) live in close proximity to venting fluid, while *Ifremeria* snails (I) and *Bathymodiolus* mussels (B) live just outside of the hottest zone, almost always with *Bathymodiolus* on the perimeter. Other taxa, such as *Austinograea* crabs, can be seen.

replica (Newman and Yamaguchi, 1995; Yamaguchi and Newman, 1997; Newman, 2000). Other more typical and conspicuous vent community inhabitants include *Chorocaris* shrimp, *Austinograea* crabs, *Lepetodrilus* limpets, and various fish. This distribution, if not an artifact of the relatively localized exploration of back-arc basins in the western Pacific, may be the direct result of the biogeographic isolation of back-arc basins. Many species common to other biogeographic provinces, such as *Riftia pachyptila*, serpulid worms, and members of the bivalve family Veiscoymidae, are noticeably absent. The influence of the arc on the geology, and hence rock substrate (andesitic versus basaltic), deposit composition, and hydrothermal fluid chemistry (pH, sulfide, and metals in particular), likely affects colonization at back-arc basins.

Similar to mid-ocean hydrothermal vent ecosystems, chemoautotrophic bacteria form the base of the food chain, primarily as endosymbionts in all three dominant molluscs at back-arc basins (*Bathymodiolus, Alvinoconcha,* and *Ifremeria)*. Differences in the requirements and capabilities of the internal symbionts likely affect the distribution of these taxa. For example, at sites in the North Fiji Basin, these dominant mollusc taxa exist in "bulls-eye" formation with *Alvinoconcha* living close to the vent effluent at 12°–30°C (and presumably the highest sulfide concentrations), *Ifremeria* in the middle at 7°–11°C, with *Bathymodiolus* on the outer edge at 4°C. Although all three invertebrate species possess symbionts within the gamma-Proteobacteria, sulfide uptake rates were quite variable between taxa and correlated with the assumed available sulfide in each respective zone (author Goffredi, personal observation). Thus, each species likely segregates in the optimal chemical regime not only for its own physiological function/tolerance, but for its symbionts as well.

The microbial diversity at deep-sea vents is tightly coupled to the geochemistry of venting fluids and the mineralogy of the resulting deposits. The heterogeneity of geochemistry and geology at back-arc basins provides a unique opportunity for microbial ecologists to explore the influence of geology and geochemistry on patterns of microbial diversity. It is therefore surprising that relatively little microbiological work has been done at back-arc basins. However, studies at different back-arc basins are providing some emerging patterns in the free-living microbial diversity of these areas as well as the framework for future comparative diversity analyses.

Like at most deep-sea vent sites, epsilon Proteobacteria dominate many of the habitats, including the outer edges of chimney structures. Until recently, none of this diverse group of vent-related epsilon-Proteobacteria could be grown in the laboratory. However, Ken Takai, Satoshi Nakagawa, Fumio Inagaki and others in the past five years have isolated numerous representatives of this group from back-arc basins, primarily from the Okinawa Trough deep-sea vents (e.g., Takai et al., 2003; Inagaki et al., 2003, 2004; Miroshnichenko et al., 2004; Nakagawa et al., 2005a; 2005b). This back-arc basin-related research provided a valuable contribution to the overall understanding of the metabolic role of the epsilon Proteobacteria from deep-sea vents. Additionally, numerous other vent-related Archaea and Bacteria have been isolated or detected at back-arc basins, such as the until-recently uncultivated, deep-sea endemic lineage DHVE2, and cultured groups such as Thermotogales, Thermococcales, and Aquificales. Within the Aquificales there seem to be some back-arc-basin-dominant groups emerging. *Persephonella marina* appears to be the dominant isolate from the East Pacific Rise and other spreading centers (Reysenbach et al., 2002), although it has never been isolated from western Pacific vents (Lau Basin, Manus Basin, or Okinawa Trough). Instead, at back-arc basins, *P. hydrogeniphila* is the more prevalent isolate, and other previously shallow marine genera such as *Hydrogenivirga* have been grown from these environments (author Reysenbach, unpublished data; Satoshi Nakagawa, JAMSTEC, *pers. comm.*, 2006).

As some back-arc basin sites are so remarkably different chemically, these hydrothermal systems provide an unprecedented opportunity to explore the extent of the unusual microbial biodiversity at deep-sea vents. For example, at some sites in the Okinawa Trough, sediments have liquid CO_2 and CO_2 hydrates, providing an unusual niche for microorganisms. Several sites are also very briny, providing conditions for the discovery of extreme halophiles such as the archaeum *Haloarcula* from active sulfide chimneys collected from the PACMANUS hydrothermal vent area in the eastern Manus Basin (Takai et al., 2001). Additionally, as is the case along the Valu Fa Ridge at sites like Mariner, because of the complex geology and geochemistry, end-member fluids have a very low pH (~ 2.5) (Fouquet et al., 1993; Ishibashi et al., 2006) and are rich in metals such as Zn, Pb, Cu, and Cd. These conditions will no doubt select for microbes resistant to heavy metals (Llanos et al., 2000) and for acidophiles. Recently, a small subunit rRNA gene sequence detected in environmental samples collected from Mariner deep-sea vent was determined to be most closely related to extreme acidophiles such as *Thermoplasma*, *Picrophilus,* and *Ferroplasma*. Although Reysenbach et al. (2006) were unable to culture this organism, they did isolate the first strictly acidophilic thermophile, *Aciduliprofundum boonei*, from these samples; it is the first representative of a deep-sea endemic archaeal lineage detected at almost all deep-sea vent sites explored. This discovery points to the importance of back-arc basins for providing alternative microbial niches that then perhaps help address more general differences and similarities of global patterns of microbial biodiversity at deep-sea vents.

...the variability of magmatic and tectonic regimes occurring within back-arc environments gives rise to an unrivalled diversity of hydrothermal vent systems and affords the opportunity to examine the conditions that sustain the broad diversity of biological communities inhabiting these systems.

SUMMARY

The close association of convergent and divergent plate-boundary processes at back-arc basins results in greater tectonic, geologic, and geochemical diversity in these settings than is typically found at open-ocean seafloor-spreading centers. This diversity not only broadens the magnitude of the controlling variables that can be studied, but also presents them in new combinations not found in the open oceans. Back-arc basins thus present rich and diverse settings in which to examine and test our understanding of mantle melting and crustal accretion and their effects on the construction of the oceanic crust and lithosphere. Further, the variability of magmatic and tectonic regimes occurring within back-arc environments gives rise to an unrivalled diversity of hydrothermal vent systems and affords the opportunity to examine the conditions that sustain the broad diversity of biological communities inhabiting these systems.

ACKNOWLEDGEMENTS

We thank Paul Craddock for a thorough and constructive review. Research for this paper was supported by National Science Foundation Grants 0242077 and 0242038.

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