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Notes
Reinitiation of subduction and magmatic responses in SW Japan during Neogene time

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ABSTRACT

Southwestern Japan during Paleogene time was affected by subduction of the Kula and Pacific plates beneath the eastern margin of Eurasia, followed by a brief episode of transform faulting to allow the Shikoku Basin to open at 27–15 Ma. Subsequent opening of the Japan Sea back-arc basin in middle Miocene time broke Japan away from Eurasia, and SW Japan rotated clockwise ~45º as it drifted south (17–15 Ma). Southward drift required subduction of the Philippine Sea plate beneath SW Japan, leading to the formation of a magmatic arc. Subduction of the hot Shikoku Basin lithosphere and spreading ridge resulted in distinctive volcanism in the SW Japan forearc between 17 and 12 Ma. This volcanism included mid-oceanic-rise basalt (MORB)-like intrusions and oceanic-island basalt (OIB)-type alkali basalts, felsic plutons in the accretionary prism, and high-magnesium andesites along the Setouchi forearc basin. Mafic magmas in the outermost forearc originated from the subducted Shikoku Basin spreading ridge, whereas Setouchi high-magnesium andesites (HMA) may have resulted from the interaction of melts of the subducted Philippine Sea plate with the overlying mantle. Felsic magmas in the forearc resulted from melting of Shimanto Belt sediments caused by intrusion of HMA magmas. Persistent rear-arc volcanism was caused by upwelling asthenosphere associated with opening of the Sea of Japan. Rear-arc volcanism began ca. 25 Ma as rift-fill low-alkali tholeiite volcanism and was replaced gradually after 12 Ma by alkali basalt volcanism. Upwelling-related alkali volcanism continues up to the present, whereas forearc volcanism ceased at 12 Ma. The volcanic arc narrowed with time as the Philippine Sea slab descended and slowly cooled. Adakitic dacites erupted after 1.7 Ma above the 100-km-depth contour of the subducted Philippine Sea plate, suggesting that melting resulted from interaction of the slab with upwelling asthenosphere. Interactions between upwelled rear-arc asthenosphere and subduction of the hot Philippine Sea slab appear to have been the main controls of magmatism for the Neogene SW Japan arc.

Keywords: Neogene, back-arc basin opening, volcanism, SW Japan, subduction reinitiation.

INTRODUCTION

The formation of a subduction zone is a singular event in the tectonic history of any region. Once formed, subduction zones tend to persist for many millions of years. Scientists agree that once subduction is under way it will continue until unusually buoyant crust is introduced into the system (Closs, 1993), so that subduction zones generally end dramatically, with the crashing of continents and raising of mountain ranges (Burke et al., 1977). As a result of such spectacular events, the termination of subduction is widely appreciated and readily envisioned by geologists, largely because the geologic evidence for why, when, and how subduction ends is sufficiently well preserved that a detailed history can be resolved. The same cannot be said for the beginning of subduction, which generally begins beneath thousands of meters of seawater and for which the subaerial manifestations such as arc volcanism can take several millions of years to develop once a lithospheric slab begins to descend into the mantle. Consequently, and in spite of its importance, we have not yet developed diagnostic criteria for identifying past episodes of subduction initiation. We have learned that the best place for studying subduction initiation is the subduction “nursery” of the Western Pacific, where many subduction zones began in the Cenozoic (Stern, 2004). In that spirit, we present here what we think is an outstanding example of subduction reinitiation along the southern margin of SW Japan during middle Miocene time and use this to explain several aspects of the tectonic and magmatic evolution of this region. We summarize tectonic and magmatic development of the SW Japan arc in Neogene time including a response to subduction of hot Shikoku Basin seafloor and progressive changes in the location and composition of SW Japan lavas as responses to subduction of Shikoku Basin lithosphere and upwelling back-arc basin asthenosphere.

We are not the first to argue that subduction began beneath SW Japan ca. 15 Ma; this hypothesis is widely acknowledged in the Japanese scientific literature, especially among those working on the remarkable igneous record of SW Japan (Maruyama et al., 1997; Taira, 2001; Takahashi, 1986; Tatsumi and Hanyu, 2003). The intent of this overview is to synthesize the igneous record for SW Japan, much of it published in regional Japanese journals, for English-speaking audiences and use this to examine and refine paleogeographic models, which presently are controversial. Furthermore, if we are correct that this is an example of subduction initiation, then SW Japan is worthy of the attention of the global community interested...
in this problem, particularly since so much of it is above sea level, where it is relatively easy to study. We also hope that this synthesis provides a context for the international effort to understand the evolution of the SW Japan convergent margin, which is an important component of the U.S. National Science Foundation-MARGINS initiative and a top priority objective of the Integrated Ocean Drilling Project.

TECTONIC SETTING

The following sections present the tectonic evolution of the region, focusing mainly on Neogene time. We first outline tectonic developments in the region just prior to the critical time, 15 Ma, when subduction of the Philippine Sea plate began beneath SW Japan (Maruyama et al., 1997; Taira, 2001). These events include opening of the Sea of Japan and opening of the Shikoku–Parece Vela Basin. We outline several kinematic models for the evolution of the Philippine Sea plate. We then present the sequence of events observed on land in SW Japan and in the Izu-Bonin-Mariana (IBM) collision zone in central Japan and explain these as a consequence of subduction initiation.

Opening of the Sea of Japan

The opening of the Sea of Japan back-arc basin required the southward displacement of a portion of eastern Asia (the Japan basin trends E-W), forming Japan (Maruyama et al., 1997; Taira, 2001). The Sea of Japan could not have opened without an active subduction zone on the southwestern flank of what is now Japan (Fig. 1), so understanding Sea of Japan opening history constrains SW Japan arc evolution. There is controversy about when the opening happened, which we will explore here. Eight tectonic phases have been identified (Tamaki et al., 1992): (1) Initial rifting and subsidence between 32 and 23 Ma; (2) Rapid subsidence to bathyal depths in early Miocene time (23–19 Ma), at rates far exceeding those expected for thermal subsidence; (3) Slow, thermal subsidence in the mid-Miocene (19–15 Ma); (4) Renewed rapid subsidence, indicating fault control later in the middle Miocene (15–12.5 Ma); (5) A third phase of thermal subsidence (12.5–10 Ma); (6) Uplift beginning in late Miocene time (10–7.5 Ma); (7) Acceleration of uplift and compressional deformation along the margins of the Sea of Japan ca. 5 Ma; and (8) Accelerating uplift beginning 2 Ma. The principal episode of spreading is thought to have occurred ca. 20 Ma, although this is difficult to reconcile with paleomagnetic evidence for the ~45° clockwise rotation of SW Japan at 15 Ma (Jolivet and Tamaki, 1992; Otofuji et al., 1991). Biostratigraphic ages of sediments immediately above basaltic basement are sometimes significantly younger than 40Ar/39Ar ages at ODP sites 794 (20–21 Ma versus 15–16 Ma), 795 (17–24 Ma versus 13–15 Ma), and 797 (18–19 Ma versus 17–18.5 Ma) (Burckle et al., 1992; Kaneoka et al., 1992).

Figure 1. Tectonic map of the Pacific plate, Philippine Sea plate, Sea of Japan, and Japan arcs. Abbreviations: ERP—Eurasia plate, NAP—North America plate, PAP—Pacific plate, PSP—Philippine Sea plate, thin lines with numbers—depths of slab surfaces of the Pacific and Philippine Sea plates.
have occurred between 16 and 15 Ma (Otofuji et al., 1991; Otofuji et al., 1994; Otsuki, 1989). We thus prefer to use the oldest biostratigraphic ages of 17–15 Ma to constrain the Sea of Japan opening at least for the SW Japan arc, because these ages approximate rapid rotation of the SW Japan arc, presumably marking when back-arc basin seafloor spreading freed it from the Asian mainland (Fig. 1). This interpretation is consistent with the fact that rear-arc rift sediments in the Matsue area (Fig. 2) changed from terrigenous and brackish water facies to open marine sediments at ca. 16.0–15.3 Ma, suggesting deepening of the region now occupied by the Sea of Japan (Kano et al., 1994b), accompanied by submarine igneous activity in the rift zone between 17 and 16 Ma (Furuyama et al., 1997; Imaoka and Itaya, 2004).

**Evolution of the IBM Arc System and Opening of the Shikoku Basin**

The development of the IBM arc system (Fig. 1A) exerted two important controls on
the evolution of the SW Japan subduction zone:
(1) it was associated with a broad zone of very young (and hot) lithosphere during mid-Tertiary time (the Shikoku Basin); and (2) it produced thickened arc crust. Both of these features resisted subduction beneath SW Japan and should have produced indelible tectonic markers in the overriding SW Japan lithosphere when they were subducted, as discussed in a later section. The focus of this section is simply to outline the evolution of the IBM arc system, including the Shikoku Basin.

Because the IBM arc system has always been an arc system under strong extension, its components encompass a broad area about the size of India, spanning from the Kyushu-Palau ridge (KPR) to the IBM trench (Fig. 1A). The early history has been outlined (Bloomer et al., 1995; Stern and Bloomer, 1992) and concluded that the IBM subduction zone began as part of a hemispheric-scale founding of old, dense lithosphere in the Western Pacific. This simple model of how subduction began depends in part on the orientation of spreading centers and fracture zones, needed to localize large-scale lithosphere founding. Stern and Bloomer (1992) preferred an E-W—spreading “Tethyan” spreading regime and a N-S fracture zone in which the IBM subduction zone nucleated, but paleomagnetic data suggests that the IBM arc system has rotated ~90° clockwise since the early Oligocene (Hall et al., 1995; Seno and Maruyama, 1984). Paleomagnetic results further indicate that the IBM arc at 50 Ma lay near the equator and was oriented more E-W than N-S as it is today (Hall et al., 1995; Seno and Maruyama, 1984). Regardless of this controversy, subduction initiation for IBM is constrained by the age of forearc igneous basement to have begun by ca. 50 Ma (Bloomer et al., 1995). During this stage, the forearc was the site of igneous activity, including the eruption of depleted tholeiites, boninites, and associated low-K rhyodacites (Hickey and Frey, 1982; Stern et al., 1991; Taylor et al., 1994).

The IBM arc was established until ca. 30 Ma, when it began to rift in the south to form the Parece Vela Basin. Spreading propagated north and south from this point, resulting in the “bowed-out” appearance of the Parece Vela Basin in the northern part (Taylor, 1992) (Fig. 1A). This rifting event also split off the KPR as a “remnant arc” from the active IBM arc. The Shikoku Basin began to form a few million years later. Nucleation of spreading to form the Shikoku Basin apparently began in the northernmost IBM arc ca. 27 Ma (Okino et al., 1994) and propagated southeastward. Orientation of the spreading system changed to northerly at ca. 23 Ma, and east-west spreading with transform offsets occurred after that. Taylor (1992) suggests that Shikoku Basin spreading may not have begun until ca. 22 Ma. Propagating Shikoku and north Parece Vela Basin spreading ridges met ca. 20 Ma. After ca. 19 Ma, the Shikoku Basin spreading ridge rotated counterclockwise. Spreading in the combined Shikoku–north Parece Vela system stopped at ca. 15 Ma, for unknown reasons. An attractive explanation is that spreading stopped when the ridge began to be subducted beneath SW Japan.

**Collison of the IBM Arc and Kyushu-Palau Ridge with SW Japan**

The arc crust of the northern IBM arc is ~22 km thick (Suyehiro et al., 1996), thicker than the ~15 km thickness thought to be necessary to jam subduction zones (Cloos, 1993). Crust of the KPR to the west is somewhat thinner, ~15 km thick (Lin et al., 1989), but still thick enough to significantly resist subduction. Attempted subduction of these thickened crustal sections should have deformed the accretionary prism or other parts of the crust in the shallow part of the subduction zone hanging wall (e.g., Taira, 2001). The first signs of this collision should define when the NE Philippine Sea plate began to be subducted beneath SW Japan. Understanding migration of the locus of these two collisions with time also provides an independent constraint on paleomagnetic models, some of which predict several hundred km of clockwise rotation of the Philippine Sea plate—and thus the KPR and IBM collision zones—since mid-Miocene times.

As expected, the KPR collision zone is much more subtle than the IBM collision zone. Kimura (1996) concludes that the collision occurred in middle to late Miocene time. The location of the KPR collision zone and the present northern terminus of the KPR are the same, indicating negligible migration of the KPR relative to the Nankai Trench since mid-to late Miocene time.

The IBM collision zone (ICZ) is caused by the attempted subduction of thickened arc crust at the northeasternmost corner of the Philippine Sea plate (Figs. 1A and 1B), which also marks Earth’s only TTT (Trench-Trench-Trench) triple junction. The north end of the IBM arc enters the Nankai Trench subduction zone at a rate of ~4 cm/yr but the ~22-km-thick IBM crust is too thick and buoyant to be readily subducted. Instead, the northern end of IBM is plunging end-on into southern Honshu (Fig. 1). This collision has been occurring at about the same place since ca. 15 Ma (Itoh, 1986). The deformation is partly accommodated by orocinal bending of margin-parallel lithotectonic belts in southern Honshu, such as the Cretaceous-Paleogene accretionary prism (Niitsuma, 1989).

Even though the IBM arc crust has acted for the most part as a rigid indentor during the collision, it is also being deformed and thickened. Cumulative thickening has almost doubled the crust, from ~22 km thick at 32°15’N to >40 km thick (Soh et al., 1998) in the collision zone. Uplift has exhumed the deep infrastructure. The Tanzawa plutonic complex in the collision zone is interpreted as the exposed middle crust of the IBM arc and has been explicitly linked to the ~10-km-thick layer with 6–6.3 km/sec velocity midcrustal layer identified from the refraction profile at 32°15’N in the oceanic Izu arc section (Taira et al., 1998). K-Ar ages for biotites, hornblende, and whole rocks range from 4.6 to 10.7 Ma (Kawate and Ariana, 1998).

The IBM and KPR collision zones indicate that collision with—and by implication, subduction of the NE Philippine Sea plate beneath—SW Japan began ca. 15 Ma, and that there has been little oblique convergence since that time. There has been negligible lateral migration of features on the Philippine Sea plate relative to Japan since 15 Ma (Hibbard and Karig, 1990a; Takahashi and Saito, 1998; Takahashi and Saito, 1999). The situation today is collinear to coplanar NE Japan–IBM subduction zone dipping beneath the SW Japan subduction zone (Ishida, 1992). This is best explained as indicating that the NE Japan–IBM subduction zone is older than the SW Japan subduction zone, requiring the younger subduction to descend through the mantle wedge above the older Pacific plate slab.

**BASEMENT GEOLOGY OF SW JAPAN**

The SW Japan area is geographically classified into the Oki, San-in, Sanyo, Setouchi, and Outer zones as the trench is approached (Fig. 2). Basement for the Oki, San-in, and Sanyo zones consists of the pre-Jurassic terranes. These are aligned trench subparallel ENE-WSW and young southwestward. Jurassic basement underlies the Setouchi area, which also parallels the trench and is bordered to the south by a major fault, the Median Tectonic Line (MTL in Fig. 2). The region between the MTL and the Butsuzo Tectonic Line (BTL) is underlain by a Triassic to Jurassic metamorphic terrain in the north and accreted terranes of the same age in the south. South of the BTL lies the Shimanto Belt, a late Cretaceous–Miocene accretionary complex (Ichikawa, 1990). This consists of melange and turbidites, which range in age between 140 Ma and 15 Ma. Southward younging of the accretionary prism is the prime structure of the terrain and suggests that continuous subduction
took place along the southern margin of the SW Japan arc (Isozaki, 1996).

The Setouchi, San-in, and Sanyo areas experienced intense plutonic activity between 135 and 50 Ma (Imaoka et al., 1994; Nakajima, 1996). This developed a granodioritic batholith comparable in volume with the Sierra Nevada batholith of California. This plutonism affected SW Japan and can be traced from northern Kyushu into eastern Korea and China. The SW Japan batholith is thought to represent Andean-style magmatism that occurred when SW Japan was adjacent to China and Korea (Nakajima, 1996).

A subordinate episode of felsic volcano-plutonic activity occurred between 42 and 30 Ma along the San-in zone. This igneous activity was still of the arc type, but the narrow distribution of these igneous rocks along the east and west sides of the present Sea of Japan is thought to indicate a plutonic precursor to the Sea of Japan opening (Kagami et al., 1999).

**LATE CENOZOIC MAGMATISM IN THE SW JAPAN ARC**

Understanding the relationship between late Cenozoic tectonics and magmatism in the SW Japan arc requires reconciling temporal, spatial, and compositional variations of volcanism. Published radiometric ages were compiled (Fig. 2). Along-arc projection of the Outer zone and Setouchi zone during the episode of forearc magmatism (17–12 Ma; Fig. 2B) is highlighted in Figure 3. We hereafter identify four major stages of late Cenozoic volcanic activity in SW Japan as (1) Initial rifting of the Sea of Japan back-arc basin (25–17 Ma); (2) During opening of the Sea of Japan back-arc basin (17–12 Ma); (3) Late Tertiary volcanic arc (12–4 Ma); and (4) Late Pliocene–Holocene volcanic arc (4–0 Ma) stages. These are also referred to as stages I–IV in the following discussion. Some general comments about the generation of the different suites are sprinkled throughout the discussion.

**Initial Rifting of the Sea of Japan Back-Arc Basin (Stage I, 25–17 Ma)**

Before the Sea of Japan back-arc basin opened, volcanism was restricted to the Oki and San-in zones (Fig. 2A), where low alkali tholeiitic (LAT) mafic to felsic magmas erupted (Fig. 4). Lavas of this stage preserved along the Sea of Japan coast are intercalated with terrestrial to brackish-water sediments (Kano et al., 1994b). Marine equivalents of these sediments were deposited in a narrow rift zone parallel to the Sea of Japan coast, which is now located between the Oki ridge (underlain by thick continental crust) and SW Japan (Tanaka and Ogusa, 1981). Volcanism in this stage is regarded as related to initial rifting of the Sea of Japan back-arc basin (Pouclet et al., 1995; Uto et al., 1994).

![Figure 3. Volcanic activity along the SW Japan forearc during Sea of Japan opening. Alk—alkali basalt, HMA—high-magnesium andesite, NFM HMA—Northern Fossa Magna high magnesium andesite. PSP—Philippine Sea plate, MORB—mid-oceanic-ridge basalt, MTL—median Tectonic Line, BTL—Butsuzo Tactonic Line, ISTL—Itoigawa-Shizuoka Tactonic Line. Age and rock-type data sources same as in Figure 2.](https://gsabulletin.gsapubs.org)}}
Volcanic activity after 17 Ma dramatically changed, affecting almost the entire SW Japan area, including the rear-arc rift San-in zone, the intra-arc Setouchi zone, and the forearc Outer zone. Magmatism began ca. 16.5 Ma over 1000 km along the SW Japan forearc and continued until 12 Ma. The Outer zone was affected by intense igneous activity from ca. 17 Ma to 12 Ma (Figs. 2B and 3). Because forearc magmatism commenced suddenly, in association with rapid opening of the Sea of Japan, and continued for ~5 m.y., we adopt the age range of 17–12 Ma as defining stage II.

Figure 4. Total alkali versus silica plots for volcanic rocks of five zones and four stages. Thin dotted lines define rock suite boundaries (LeMaitre et al., 1989), thick lines indicate alkali-tholeiite rock suite boundary (LeMaitre et al., 1989; MacDonald and Katsura, 1964). For data sources, see the text.
In the Outer zone, I- and S-type felsic igneous rocks (Chapell and White, 1974) were emplaced between 17 and 12 Ma (Figs. 2B, 3, and 4). Between the MTL and BTL, I-type igneous rocks occurred exclusively, whereas S-type intrusions occur south of the BTL (Nakada and Takahashi, 1979; Takahashi, 1986; Terakado et al., 1988).

Three mafic intrusions occur along the Pacific coast of SW Japan, the Ashizurimisaki, Murotomisaki, and Shionomisaki Complexes (Figs. 2B and 3). The Ashizurimisaki Complex consists of alkali dolerite to gabбро-bearing syenite to quartz syenite with an alkali granite ring complex (Murakami et al., 1983). A-type granite associated with the Ashizurimisaki Complex (Imaoka et al., 1991; Murakami et al., 1983) is ca. 12–14 Ma (Shibata and Nozawa, 1987). The Murotomisaki Complex consists of MORB-like LAT dolerite and gabбро intruded in Shimanto sediments (Miyake, 1985b) and has an age of 14.4 Ma (Hamamoto and Sato, 1987). The Shionomisaki Complex also consists of tholeiitic basalts, dolerite, granophyre, quartz porphyry, and rhyolite (Miyake and Hisatomi, 1985). The Shionomisaki is also MORB-like (Miyake and Hisatomi, 1985) (Fig. 4) and 15–13 Ma age (Iwano et al., 2000).

Three HMA dikes were also reported in the Outer zone of the Kii Peninsula (Fig. 2B). One of these dikes intrudes N6 (Nano-fossil zone 6) Miocene sediments (17–16 Ma) and shows a magnetic azimuth of 40°E, consistent with rotation of SW Japan after 16.5–15 Ma (Miyake, 1985a; Miyake et al., 1988). This precedes most HMA magmatism occurred after the rotation of SW Japan. A 17.7 Ma lamprophyre dike at Shingu in central Shikoku, also precedes the rotation of SW Japan (Uto et al., 1987) (Fig. 2B). Due to the possibility of significant assimilation, this age should be regarded with suspicion, but alkali volcanism in the forearc is also reported from the Ashizurimisaki (Murakami et al., 1983) and Shitara areas at 14–12 Ma in central Japan (Sugihara and Fujimaki, 2002) and from Tanegashima, south of Kyushu at 16 ± 2 Ma (Taneda and Kinoshita, 1972) (Fig. 3).

Late Tertiary Volcanic Arc (Stage III, 12–4 Ma)

Igneous activity in the forearc of SW Japan ceased after 12 Ma, and rear-arc alkalic volcanism dominated until Quaternary time (Figs. 2C and 2D). Stage III monogenetic alkali basalt complexes are scattered over the Sanyo and San-in zones (Iwamori, 1992; Iwamori, 2000; Kimura et al., 2003; Uto, 1989; Uto, 1996). These clusters of mostly monogenetic volcanoes are 15–40 km in diameter and consist of scattered small lava flows, cinder cones, and dikes. Voluminous intermediate to felsic lavas erupted in the Matsue area (Fig. 4). Strong alkaline volcanic activity also occurred on Oki Island between 7 and 4 Ma (Figs. 2C and 4). Volcanic activity that was confined to rear-arc rifts in the San-in and Oki zones before this stage continued but LAT lavas were replaced by transitional to alkali basalts (here called alkali basalts for simplicity, see Fig. 4). Only alkali basalts erupted in the Sanyo zone, and this style of volcanic activity expanded to the southeast. This temporal geochemical change occurring in the rear-arc rift along with expansion of alkali basalt volcanism toward the trench suggest progressive change in magma source throughout stages I to III in SW Japan.

Late Pliocene–Holocene Volcanic Arc (Stage IV, 4 Ma–Present)

There is almost no volcanic activity between 4 and 3 Ma in the SW Japan arc. After this hiatus, volcanism resumed in the San-in and Oki zones, but not in the Sanyo zone (Kimura et al., 2003) (Figs. 2D and 4). Monogenetic alkali basalt volcanism is largely associated with subalkali intermediate rocks in clusters such as Kannabe-Genbudo (Furuyama et al., 1993b) and Abu (Kakubuchi et al., 2000) (Fig. 2C). Adakitic dacites (Morrис, 1995) have erupted since 1.7 Ma at Ooe-takayama (1.7 Ma) (Kimura et al., 2003), Daisen (1.0–0 Ma) (Kimura et al., 2003; Tsukui et al., 1985), Aonoyama Volcano Group (1.2–0.02 Ma) (Furuyama et al., 2002; Kamata et al., 1988), and Sambe (0.1–0 Ma) (Kimura et al., 2003; Kimura et al., 1999a).

Adakitic centers define an arcuate zone (Fig. 2D), which approximates the surface projection of the leading edge of the Philippine Sea plate (Morrис, 1995; Nakashishi et al., 2002; Ochi et al., 2001). North of the adakite zone, alkali basalt activity continues up to the present, at Kannabe-Genbudo, Daikonjima, Abu, and Oki Islands.

PETROGENESIS OF IGNEOUS ROCKS AND TECTONIC IMPLICATIONS

SW Japan magma types are classified into alkali basalt and evolved equivalents; LAT basalt to felsic magma; HMA; MORB-like basalt; I-type and S-type felsic magmas; and very small volumes of A-type felsic magma. Although comprehensive trace element and isotope data sets do not yet exist for all the rock suites, existing data allow valuable insights into late Cenozoic magma sources and thermal structure beneath the arc. We here summarize and evaluate existing models for the origins of the different rock suites in an effort to reconcile petrogenetic models with the tectonic evolution of the SW Japan arc. Because the major element compositions are summarized as part of the general classification (Fig. 4), the emphasis in the following discussion is on trace element and isotope compositions.

Stage I

LAT basalt erupted during stage I on Oki Island (19 Ma) (Uto et al., 1994) and Matsue (25 Ma) (Kimura et al., 2004, personal commun.). The Oki basalt has a high-K shoshonitic signature with elevated abundances of large ion lithophile elements (LILEs) Rb, Ba, and Sr, although abundances of other elements including rare earth elements (REEs) and high field strength elements (HFSEs) are similar to Enriched-MORB (Fig. 5). Matsue LAT basalt has similar element abundance with E-MORB in most of the elements with elevated abundances in Ba, Sr, and Pb. LAT basalt from the Tango area (Figs. 2A and 2B) also has similar REE abundances with Oki LAT (Kimura et al., 2004, personal commun.). These features are somewhat different from typical arc-type subalkali basalts and have affinities with rift zone lavas erupted through thick continental crust. Elevated LILEs with relative depletion in HFSEs could be inherited from the characteristics of metasomatized continental lithosphere or result from contamination of magmas by continental crust (Uto et al., 1994; Wilson, 1989). This view is supported because the initial rifting to form the Sea of Japan affected sialic China continental crust (Uto et al., 1994).

Stage II

Alkali basalts began to erupt in the Oki zone (Kimura et al., 2004, personal commun.) following the opening of the Sea of Japan. The trace element composition of Oki Island alkali basalts is identical with typical oceanic-island basalt (OIB) (Sun and McDonough, 1989) (Fig. 5). Alkali basalts from Iki Island have similar trace-element characteristics. Basanite lavas from the island are extremely elevated in LREE (Aoki, 1959; Aoki, 1970), but other incompatible elements are similar to other alkali basalts in Oki zone. Note that the ages of Iki basalts yield K-Ar ages from 15 Ma to 0.6 Ma (Sano, 1995). The age of the Iki basanite lavas is not yet clear. However, other OIB-type alkalic lavas fall in the age range of stages II to IV. The origin of SW Japan alkali basalts of all stages is controversial and may have resulted from either
Figure 5. N-MORB normalized incompatible trace element plots for volcanic rocks of five zones and four stages. Normalization factors and order of element from Pearce and Parkinson (1993). E-MORB and OIB data from Sun and McDonough (1989). Sources of data are listed in the text. LAT—low-alkali tholeiite, HMA—high-magnesium andesite, MORB—mid-oceanic-ridge basalt, OIB—oceanic-island basalt.

an asthenospheric mantle plume (although this would have had great difficulty traversing the subducted Pacific plate slab) or represent melting of lithospheric mantle as a result of heating or secondary convection associated with the Sea of Japan opening (King and Anderson, 1998). We tentatively interpret that SW Japan OIB resulted from melting subcontinental mantle asthenosphere, but the precise mode of generation is not critical for understanding Neogene subduction re-initiation beneath SW Japan.

LAT basalts from the Matsue rear-arc rift (Kimura et al., 2004, personal commun.; Miyake, 1994) (ca. 16–15 Ma) have relatively high LILE abundances with relatively low REEs and HFSEs, and the oldest sample is very similar to E-MORB except for highly incompatible LILEs and Sr (Fig. 5). These basalts have major element compositions that are intermediate between LAT and calc-alkalic suites (Miyake, 1994; Morris et al., 1990; Morris et al., 1999; Uto et al., 1994). In this context, Matsue LAT basalts are transitional between oceanic tholeiite and arc basalt and are similar to back-arc basin tholeiites (Taylor and Martinez, 2003). One sample shows strong depletion in HFSEs down to MORB levels (Kimura et al., 2004, personal commun.) (Fig. 5). Basalts with arclike trace element signatures erupted on the Yamato Bank between 26 and 22 Ma, whereas MORB-like tholeitic basalts dominated in the Yamato Basin before and after opening (22–13 Ma) (Poucle et al., 1995). The transitional nature of LAT basalt in SW Japan may reflect contributions from the continental lithosphere, which was metasomatized by subduction at the Asian continental margin (Miyake, 1994; Morris et al., 1990; Morris et al., 1999; Uto et al., 1994).

The Setouchi HMA suite was first thought to form by melting hydrated upper mantle (Ishizaka and Carlson, 1983; Tatsumi, 1982; Tatsumi and Ishizaka, 1982). Setouchi HMA (Fig. 5) is now thought to include melts from the subducted slab (Shimoda and Tatsumi, 1999; Shimoda et al., 1998; Tatsumi and Hanyu, 2003). Trace element patterns of Setouchi HMA (JA-2 igneous rock standard of the Geological Survey of Japan, data by Kimura et al., 2004, personal commun.)
are very similar to SW Japan adakitic dacite, although HMA have lower concentrations of Sr and slightly higher HREE abundances (Fig. 5) (Kimura et al., 2004, personal commun.). Even so, HMA have steeper REE patterns than other arc andesites, and together with the elevated Pb and isotopic evidence (Shimoda and Tatsumi, 1999; Shimoda et al., 1998; Tatsumi and Hanyu, 2003), indicate derivation of Setouchi HMAs by mixing between melts of hydrous upper mantle and subducted sediments. Paleomagnetic directions suggest that Outer zone HMAs are precursors of Setouchi HMA activity, and this further suggests very rapid injection of the subducted Philippine Sea plate beneath the Outer and Setouchi zones within only ~1 m.y.

I- and S-type forearc felsic magmas have similar trace element patterns (not shown) in spite of contrasting major element compositions. However, the two suites define a continuum in terms of alumina saturation index (Murata and Yoshida, 1985; Nakada and Takahashi, 1979). The origin of these felsic melts is controversial. Based on spatial correlation between different suites and basement geology (S-type in the Shimanto Belt, I-type in the Sambagawa Belt), S-type is considered to result from melting arkose or metasediment, and I-type was derived from melting granodiorite or amphibolite (Murata and Yoshida, 1985). A trace element and isotopic study suggests that Outer zone S-type felsic magma was produced by mixing between sediment melt and HMAs intruded in Shimanto accretionary complex sediments (Shinjo et al., 2003). The most mafic andesite from the Ishizuchi I-type igneous complex has elevated MgO (4.14 wt% at SiO₂ = 59.73 wt%) for an evolved andesite (Yoshida et al., 1994). Considering the similarities in trace element patterns to the Setouchi HMAs, some I-type felsic rocks may also have been derived by fractional crystallization of HMA or by mixing between HMA magmas and silicic magmas produced by melting of felsic upper crust. The origins of individual S- and I-type igneous bodies are beyond the scope of this paper, but we suggest that the HMAs show temporal-spatial relationships such that voluminous HMAs may be parents to voluminous forearc felsic melts.

MORB-like and alkali suites characterize Outer zone mafics (Fig. 4). Trace element data for the Munomisaki and Shionomisaki Complexes (Shinjo et al., 2003) suggests that the gabbros are comparable to E-MORB (Miyake, 1985b) (Fig. 5). This is further supported by Nd-Sr iso- tope compositions of the Shionomisaki Complex, which are MORB-like (Terakado et al., 1988). The extinct Shikoku Basin spreading ridge is presently located immediately south of the Munomisaki and Shionomisaki (Fig. 3), supporting the idea that the forearc MORBs (Fig. 3) were derived from drying and just-subducted spreading ridges (Hibbard and Karig, 1990b; Miyake, 1985b; Takahashi, 1986). The Ashizurumisaki alkali dolerite has OIB-like trace element patterns (Shinjoe et al., 2003) with MORB-like isotopic compositions (Terakado et al., 1988), consistent with off-ridge alkali volcanism associated with the subducted ridge, although it has high LILE and Pb, due perhaps to crustal contamination from Shikanto sediments.

All of these features of magmatism indicate a close relationship between stage II forearc igneous activity and subduction of young and hot Shikoku Basin lithosphere, including a spreading ridge. The broad outbreak of stage II volcanism across SW Japan is consistent with a subduction reinitiation event. Forearc volcanism is identified as a hallmark of subduction initiation as a result of strong extension in the hanging wall (Gurnis et al., 2004).

Stage III

The Oki (Kimura et al., 2004, personal commun.), San-in (Iwamori, 1992; Kimura et al., 2004, personal commun.; Tatsumi et al., 1999), and Sanyo (Iwamori, 1992) zones are characterized by alkali suite magmas in stage III, although some are transitional between LAT and alkali basalt (Figs. 4 and 5). These alkali basalts occasionally have slightly positive anomalies in Ba, Sr, and Pb but do not show HFSE depletions except for slightly negative Zr and Hf spikes (Fig. 5). Although these possess the chemical signatures of arc magmas (Pearce, 1983; Pearce and Parkinson, 1993) to some extent, OIB signatures predominate. Strongly alkaline basalts, such as the Hiba alkali basalt and Hamada nephelinite, show strong depletions in Zr and K with or without Nb depletion. These trace element signatures are similar to Iki Island basanite (Aoki, 1970) and may be due to metasomatism of the source (Iwamori, 1992), such as carbonate fluid metasomatism (Tatsumi et al., 1999).

LAT changed to alkali activity between 19 and 12 Ma in the SW Japan rear-arc region, coincident with a similar change in the Sea of Japan basins at 17–13 Ma, and all of these changes were related in space and time with the opening of the Sea of Japan (Poulet et al., 1995). LAT basalt is produced by melting upper mantle peridotite at depths of ~60 km (Kushiro, 1973). Upwelling of asthenosphere could have caused episodic volcanism. OIB source mantle melted continuously during and after the opening, resulting in a change to dominant alkali basalt volcanism after 17 Ma. OIB-type alkalic magmatism became more important in stages II–III. Island arc signatures shown in some of the alkali basalts may be due to fluid from the subducted Philippine Sea plate (Iwamori, 1992) or sediment melt from the Pacific plate (Cousens and Allan, 1992). This chemical signature may also be inherited from remnants of the subcontinental lithospheric mantle, which was previously metasomatized by slab fluids (Miyake, 1994; Morris and Kagami, 1989; Tatsumoto and Nakamura, 1991; Uto et al., 1994) as the signals appear to be stronger in the area with thicker subcontinental lithosphere. We suggest that these spatial changes are related to the southward migration of a thermal anomaly or mantle plume that continued even after the Sea of Japan opening.

Stage IV

OIB-type alkali volcanism continues today in the Oki zone (Kimura et al., 2004, personal commun.; Kimura et al., 2003). In the San-in zone, adakite volcanic activity began after 1.7 Ma (Kimura et al., 2003) (Figs. 2D and 5). Two adakitic dacies from Daisen and Aonoyama (Kimura et al., 2004, personal commun.) are shown in Figure 5. The chemical characteristics, including major and trace elements, are typical of adakite, with strong depletions in HREE (Defant and Drummond, 1990; Morris, 1995). Alkali basalt activity in the San-in zone continued as well, but some of these have HFSE-depleted signatures (Kimura et al., 2004, personal commun.) (Fig. 5). At Genbudo-Kannabe and Abu, typical OIB-type basalts erupted (Kakubuchi et al., 1995b; Kakubuchi et al., 2000; Kimura et al., 2004, personal commun.; Kimura et al., 2003). In contrast, other alkali centers such as Yokota and Daikonjima have strong HFSE depletions (Fig. 5). Both types coexist in the Abu region (Kakubuchi et al., 2000).

There is an obvious arcuate distribution of adakites (Fig. 2D). Adakites replaced alkali basalts near Yokota-Daisen at ca. 1 Ma (Kimura et al., 2003), consistent with the passage of the subducted Philippine Sea plate through the hot mantle that previously generated alkali basalt magmas, and initiation of adakite magmatism as the subducted slab interacted with this hot mantle and melted (Kimura et al., 2003; Morris, 1995). Alkali basalts with HFSE-depleted chemical signatures erupted near the Daisen, Sambé, and Aonoyama adakitic centers (Fig. 2D), whereas OIB-type alkali basalts erupted further away, except for those near Abu. These relationships suggest that the Philippine Sea plate slab was increasingly affecting the SW Japan rear-arc region, first affecting the OIB source mantle by addition of fluid (HFSE-depleted alkali basalts) and then by melting to form adakites.
PALEOGEOGRAPHY

Previous Models

There is general acknowledgment that the Philippine Sea plate formed when subduction began in the IBM trench, ca. 43–50 Ma. However, there is fundamental disagreement about the orientation of this trench and that of the other important marker of Eocene configurations, the Central Basin Fault, which was a spreading ridge all through Paleogene time. Uyeda and Ben-Avraham (1972) showed the Central Basin Fault as an E-W–oriented spreading ridge system, an idea expanded on by Hilde et al. (1977), who show it as an eastern remnant of a Tethyan spreading system. Stern and Bloomer (1992) proposed that a N-S–trending fracture zone collapsed in Eocene time to begin subduction along the IBM trench. In this scenario, the Philippine Sea plate has not rotated very much since Eocene time. Those simple models are inconsistent with paleomagnetic data, which imply a clockwise rotation of the Philippine Sea plate. Seno and Maruyama (1984) infer clockwise rotation of the Philippine Sea plate. This model does not require an active subduction zone along the NW Philippine Sea plate before Miocene time. The Hibbard and Karig (1990a) model requires no rotation of the Philippine Sea plate; instead, they infer that SW Japan during early Miocene time (ca. 24 Ma) subducted the Pacific plate and that voluminous late Miocene magmatism in SW Japan indicates that subduction of the Philippine Sea plate began at ca. 15 Ma. Hall (2002) and Hall et al. (1995) infer significant clockwise rotation of the Philippine Sea plate but require that the Philippine Sea plate migrated northward hundreds of kilometers relative to SW Japan. In their model, the northern margin of the Philippine Sea plate from 25 to 15 Ma moved ~1700 km NE along the Ryukyu Trench. Yamaji and Yoshida (1998) proposed that several aspects in the magmatic and tectonic evolution of SW Japan are best explained by a transform at the north end of the Philippine Sea plate, which reorganized into a ridge-ridge-ridge triple junction. This triple junction was subducted at ca. 15 Ma to cause the widespread volcanic activity in the SW Japan forearc region about this time. There are several paleogeographic models offered to explain unusual forearc volcanism in SW Japan at 15 Ma (e.g., Hibbard and Karig, 1990b; Seno and Maruyama, 1984; Taïra, 2001; Tatsumi and Hanyu, 2003). None of these models address the late Cenozoic magmatic evolution of the SW Japan arc.

Subduction Rate of the Philippine Sea Plate Over the Past 17 m.y.

For a paleogeographic reconstruction, the motion of the Philippine Sea plate leading edge in the late Cenozoic provides an important constraint. As the northeastern margin of the plate is defined by the IBM arc and the arc positions in the Neogene is a matter of debate, important constraints can be inferred from the position of the subducted Philippine Sea plate slab that is now beneath SW Japan. Below, the space-time evolution of subduction-related igneous activity in SW Japan is used to track the progress of the Philippine Sea plate as it was subducted during Neogene time (Figs. 6 and 7; also see Figs. 2 and 3).

Stage I

The exact position of the Philippine Sea plate leading edge in this stage is not clear. However, we can indirectly track the slab as it descends during Neogene time from changes in volcano locations and magma compositions. There is no evidence of Cenozoic volcanism older than 17 Ma in the forearc of SW Japan. There are in situ MORB-like lavas in the Shimanto accretionary prism between Kyushu and SW Japan, but these range in age between 100 and 65 Ma (Osozawa and Yoshida, 1997). The MORB intrusions of this time are believed to be oblique subduction of a spreading ridge between Pacific-Kula plates in the Cretaceous before the Philippine Sea plate arrived at the present position. The long quiescence of volcanic activity between 65 and 17 Ma and the sudden occurrence of forearc volcanism in middle Miocene time lead us to conclude that the Eurasia plate–Philippine Sea plate boundary in early Miocene time was defmed by a transform fault. Further reasoning for this model is discussed below. Prior to opening of the Sea of Japan, the SW Japan arc lithosphere was the margin of Eurasia, and initial riftin g volcanism took place in what is now the rear-arc region (Figs. 6 and 7A).

Stage II

A convergent plate boundary along SW Japan is required to accommodate opening of the Sea of Japan and to permit large-scale rotation of the arc, so subduction must have been under way by 17 Ma. Initial descent of the Philippine Sea plate beneath SW Japan is marked by an unusual episode of igneous activity in the forearc. Researchers argue that

![Figure 6. Age compilation of Cenozoic igneous rocks in SW Japan. Subsidence uplift of the Sea of Japan adopted from Tamaki et al. (1992). LAT—low-alkali tholeiite, HMA—high-magnesium andesite, thin dashed line—possible southeastern margin of the Sea of Japan back-arc basin mantle asthenosphere, thick dashed line—trace of the Philippine Sea plate slab leading edge, with arrows indicating subduction rate for each interval. Note that this section projects age data of the SW Japan arc shown in Figure 2 onto an across-arc section. Setouchi and Outer zone ages are projections of entire forearc igneous rock distribution shown in Figure 3. For clarity, ages of San-in and Sanyo zones during stage IV are projected only in the central part of SW Japan. Age ranges of each square are summarized from Kimura et al. (2003).]
Figure 7. Diagrams showing Neogene development of the upper mantle structure and volcanism beneath SW Japan. Alk—alkali basalt, HMA—high-magnesium andesite, LAT—low alkali tholeiite. Figure modified from Kimura et al. (2003). MORB—mid-oceanic-ridge basalt, ADK—adakite.
subduction of young, hot Shikoku Basin lithosphere induced this magmatism (Hibbard and Karig, 1990a; Shimoda and Tatsumi, 1999; Shimoda et al., 1998; Shinjoe, 1997; Takahashi, 1986; Tatsumi and Ishizaka, 1982; Yamaji and Yoshida, 1998) (Figs. 6 and 7B), but subduction initiation events are often characterized by forearc volcanism (Stern, 2004). The first few million years of subduction must have been very rapid (>10 cm/year; Fig. 6) in order for the Philippine Sea lithosphere to arrive beneath the Setouchi zone and cause HMA magmatism by 16–15 Ma (Tatsumi et al., 2003) (Figs. 6 and 7B). The rapid (>15 cm/year) rotation of SW Japan (Otofuji et al., 1991) is associated with rapid subduction. Upwelling of rear-arc mantle asthenosphere and rear-arc volcanism migrated southeastward, but a spatial gap between back-arc and subduction-related forearc volcanism suggests that these were independent magmatic expressions (Figs. 6 and 7B).

Stage III

The penetration rate of the Philippine Sea plate appears to have slowed to ~0.9 cm/year during stage III. Further migration of rear-arc volcanism southeastward is seen by the appearance of OIB-type volcanism in the Sanyo zone (Figs. 6 and 7C). During the stage III episode of slow subduction, volcanic activity was limited to rear-arc, monogenetic alkali basalt volcanoes. Such volcanic activity can be caused by low compression stress in the arc, which is consistent with slow plate convergence. Progressive penetration of the Philippine Sea plate terminated alkali basalt volcanism in the Sanyo zone by ca. 4 Ma (Kimura et al., 2003). Cessation of volcanism in the forearc and narrowing of the rear-arc zone of volcanism indicate forearc cooling as the Philippine Sea plate continued to subduct.

Stage IV

Subduction of the Philippine Sea plate accelerated ca. 5 Ma to 4 cm/year, comparable with the present subduction rate (Kamata and Kodama, 1999) (Figs. 6 and 7D). Tomographic imaging of the mantle beneath SW Japan defines the leading edge of the subducted Philippine Sea plate (Ochi et al., 2001), and we can use this to reconstruct the progressive subduction of the slab. The leading edge of the slab is now almost directly beneath Oki Island at 150 km depth. The subducted slab is ~350 km long. If the present subduction rate, 4 cm/year, has been constant over the last 4 m.y., then the leading edge of the 4 Ma slab should have been located about 160 km southeast of its present position. This approximately correlates to the position of the stage III volcanic front and supports our estimated subduction rate for stage IV.

If the subduction rate was constant before 4 Ma, the Philippine Sea plate leading edge should have been offshore of the Outer zone before 10 Ma, which is not supported by the forearc subduction volcanism in stage II. This also supports our assessment of very slow subduction during stage III.

The slab depth from tomography contradicts the idea that the leading edge of the Philippine Sea slab immediately correlates to the adakite zone (Morris, 1995). However, the slab is located ~100 km beneath adakite centers, which is consistent with the idea that slab melting occurs by dehydration melting of basaltic oceanic crust at the transition from amphibolite to eclogite (Drummond and Defant, 1990). Magmatism in the rear-arc region progressed from OIB-type alkali basalt through arc-signature alkali basalts to adakites during this stage, suggesting gradual heating of the slab, which first dehydrated and then melted. Similar heating of subducted plate edges has been suggested for the generation of adakites at the Aleutian-Kamchatka arc junction (Yogodzinski et al., 2001).

BACK-ARC OPENING SUBDUCTION REINITIATION MODEL

Taking the Neogene magmatic history of the SW Japan into account, we propose a paleogeographic model for Japan since 36 Ma. Below, we compare this with magmatic activity in the NE Japan and Ryukyu arcs. Neogene magmatism in these arcs, along with that of the IBM arc (Haraguchi et al., 2003), is summarized in Figure 8.

Continental Arc Stage (Stage 0: 36–25 Ma)

Andean-style continental arc magmatism continued from 135 Ma up to at least ca. 50 Ma. The duration corresponds to the age of the SW Japan batholith and in situ MORB intrusins in the forearc Shimanto accretionary prism (100–65 Ma) due to subduction of the Kula-Pacific ridge (Maruyama et al., 1997; Nakajima, 1996; Osozawa and Yoshida, 1997). This subduction at its later stages involved the Pacific plate, and it is not clear when it stopped. Andean-style subduction may have continued until ca. 30 Ma, if we include 42–30 Ma plutonism (Kagami et al., 1999) (Fig. 9A). Almost all Oligocene igneous rocks in both SW and NE Japan arcs belong to the subalkaline suite. They are clearly subduction related, with negative Nb anomalies and enrichments in LILEs (Nakajima et al., 1995; Omura et al., 1988; Uto et al., 1994; Yoshida et al., 1995). The volcanic arc during this time defined a continental arc, encompassing NE Japan and the modern rear-arc region of SW Japan, including central Japan and northern offshore Kyushu. Recent studies of Oligocene volcanics (28–24 Ma) from the Noto Peninsula suggest that HMA and adakites as well as LAT with depleted Nd-Sr isotopic compositions occurred (Uematsu et al., 1995).

Volcanism also occurred in the southern Ryukyu arc near Taiwan but not farther north. This volcanic arc was separated from the SW and NE Japan arcs (Fig. 9A). Southern Ryukyu plutons in this age range (40–19 Ma) have volcanic arc granite (VAG) signatures, which replaced within-plate granite (WPG) activity of 70–50 Ma (Kato et al., 1992; Kawano, 1992; Shinjo et al., 1999). This suggests that the Philippine Sea plate began to subduct around 40 Ma in the southern Ryukyu arc. If our paleogeographic model is correct, the northern termination of the IBM arc should have been located north of the southern Ryukyu arc (Fig. 9A). Shikoku Basin opening began somewhere near Kyushu in the later part of this stage, and this opening was permitted by development of a transform fault between Eurasia plate and Philippine Sea plate.

Initial Rifting Stage (Stage 1: 25–17 Ma)

Distribution of early Miocene volcanics is almost coincident with that of the preceding Oligocene arc except in the northern part of NE Japan. This suggests that the early Miocene volcanic arc belonged to the initial rifting stage, similar to stage I volcanism in SW Japan, leading to formation of the Sea of Japan back-arc basin (Pouclet et al., 1995; Seno and Maruyama, 1984).

Shikoku Basin spreading occurred between 27 and 18 Ma, and spreading propagated from north to south (Nakanishi et al., 1992; Okino et al., 1994). We think that the Shikoku Basin spreading was not allowed due to fixation if the NW edge of the Philippine Sea plate already subducted beneath SW Japan, so our model requires that the Shikoku Basin was separated from the Ryukyu Trench or that at least this part of the Eurasia plate–Philippine Sea plate boundary was a transform fault. Other constraints for reconstructing the position of the Shikoku Basin prior to subduction initiation are: (1) The width of the northernmost Shikoku Basin (now subducted) should have been similar to the length of the stage II forearc magmatic arc; (2) Forearc magmatism occurred over a 1000 km about the same time as rapid rotation of SW Japan; (3) Forearc magmatism indicates a similar amount of crust was subducted everywhere beneath the SW Japan arc; and (4) The total subducted length of the Philippine Sea slab beneath SW Japan is ~400 km.
Our preferred reconstruction places the Shikoku Basin spreading ridge at 17 Ma, almost perpendicular to the Nankai transform (Fig. 9B). This allows the triple junction of the Pacific–Eurasia-Philippine Sea plates to migrate NE during stage I. In this regard, our model is a modification of Seno and Maruyama’s (1984) model. At the same time that the Nankai transform allowed the PSP to rotate clockwise and the Shikoku Basin to open, the western PSP could have been obliquely subducted beneath the SW Ryukyu arc (Fig. 9B). An accretionary prism should have developed continuously during this stage in the Ryukyu arc, but transform motion along the Nankai Trench should have yielded a distinctive sedimentary succession off SW Japan. As little is known about the formation of the SW Japan accretionary prism during earliest Neogene time, testing this suggestion must await further observations.

Sea of Japan Opening Stage (Stage II: 17–12 Ma)

NE Japan during stage II was also distinctive (Figs. 8 and 9C). Paleomagnetic evidence suggests anticlockwise rotation of the NE Japan arc (Hamano and Tousha, 1986). Although subalkali magmatism continued, arc volcanism broadened into the forearc with eruption of LAT basalts in the rear arc (Nakajima et al., 1995; Ohki et al., 1994; Ohki et al., 1993; Yoshida et al., 1995). Rear-arc basalts erupted ca. 15 Ma reveal a depleted DM endmember source that differed from the mantle source of stage I, which had nearly Bulk Earth Nd-Sr isotopic composition (Nakajima et al., 1995; Nohda et al., 1988; Nohda and Wasserburg, 1981; Ohki et al., 1994; Ohki et al., 1993). This change suggests participation of asthenospheric mantle that upwelled in association with Yamato Basin opening at ca. 17 Ma (Pouclet et al., 1995) affected arc sources. This coincided with changes in basalt chemistry in the SW Japan rear arc (17–12 Ma), where magmatism changed from isotopically enriched LAT to depleted alkaline suites. Alkaline suites are not observed in NE Japan, but the change from enriched to depleted isotopic signatures is similar. This difference may be due to the thicker continental crust of SW Japan and Sea of Japan islands, which could have prevented shallow mantle melting.

Figure 8. Comparison of igneous activity between Ryukyu, SW Japan, and NE Japan arcs. HMA—high-magnesium andesite, PSP—Philippine Sea plate, PAP—Pacific plate, BAB—back-arc basin, thick dotted line—boundary distinguishing whether Pacific or Philippine Sea plates are responsible for associated volcanic activity. For references, see text.

Igneous activity in central and southern Kyushu was also characterized by HMA (Nagao et al., 1999), I-type, and S-type felsic magmas (Nakada and Takahashi, 1979). A lamprophyre dike was also intruded at Tanegashima (Taneda and Kinoshita, 1972) (Fig. 9C). In this context, SW Japan forearc activity continued into southern Kyushu. Volcanic activity in the Ryukyu arc during this stage involved the entire arc (Fig. 9B) and was characterized by arc-type subalkali lavas except for an E-MORB–like HMA at the south end of the arc (Kato et al., 1992; Shinjo et al., 1999; Shinjo et al., 2000). During stage II, the Ryukyu arc joined with the SW Japan arc and arc volcanism in Ryukyu was related to oblique Philippine Sea slab subduction (Shinjo et al., 2000).

Late Tertiary Volcanic Arc Stage (Stage III: 12–4 Ma)

After the cessation of forearc volcanism in SW Japan, intense alkaline monogenetic volcanism took place there and in northwestern Kyushu and SW Japan (Hoang and Uto, 2003; Matsumoto et al., 1992; Nagao et al.,...
Figure 9. Tectonic evolution and temporal variation of igneous activity in Ryukyu, SW Japan, and NE Japan arcs during Cenozoic time. Age data and lava chemistry are mainly based on Nakajima et al. (1995), Ohki et al. (1993, 1994), Sakuyama and Nesbitt (1986), Yoshida et al. (1995) for NE Japan arc; Kaneko (1995), Kimura and Yoshida (1999), Kimura et al. (1999b), Omura et al. (1988), Ujike and Stix (2000) for Hokuriku area and central Japan; Matsumoto (1992), Matsumoto et al. (1992), Nagao et al. (1999) for Kyushu; Daishi (1992), Shinjo et al. (2000) for Ryukyus and references therein. LAT—low alkali tholeiite, HMA—high-magnesium andesite, ERP—Eurasia plate, PAP—Pacific plate, PSP—Philippine Sea plate, thick solid line—plate boundary, thick broken line—spreading ridge, shaded line—leading edge of subducted Philippine Sea plate, thin solid line—depth contour of present surface of subducted Pacific plate; tectonic map of the Sea of Japan is from Tamaki et al. (1992). Moving directions of the Pacific and Philippine Sea plates are shown as solid arrows. Opening of the Sea of Japan and rotation of the SW and NE Japan arcs are shown by open arrows on panel (C). MORB—mid-oceanic-ridge basalt, BTL—Butsuzo Tectonic Line.
Late Pliocene–Holocene Volcanic Arc Stage
(Stage IV: 4–0 Ma)

Accelerated subduction of the Philippine Sea slab (4 cm/year) began ca. 4 Ma, for reasons that we do not understand. During this episode, the volcanic arc of SW Japan continued to narrow. Rear-arc mantle asthenosphere continued to interact with the subducted slab to produce arc-type alkali and adakite magmas at ~100 km depth (Fig. 9E). The alkali basalt province expanded westward to the center of the Korean Peninsula.

Opening of the Okinawa Trough (4–2 Ma) (Sibuet et al., 1995) was also induced during this episode perhaps by acceleration of Philippine Sea plate subduction. This was related to arc volcanism in the forearc and alkali basalt activity in the rear arc of the northern extension of the trough (Shinjo et al., 2000). The northern continuation of the Ryukyu forearc extends to northeastern Kyushu, where it defines a sub-arc volcanic chain lying 100 km above the subducted Philippine Sea slab (Fig. 9E).

During this stage, NE and central Japan was continuously a magmatic arc induced by the subducting Pacific plate (Kaneko, 1995; Kimura and Yoshida, 1999; Kimura et al., 1999b; Sakuyama and Nesbitt, 1986; Shibata and Nakamura, 1997; Ujike and Stix, 2000). The Philippine Sea slab descends above the Pacific plate beneath central Japan, cooling the mantle wedge, which narrows the volcanic arc (Iwamori, 2000). A slab tear may have occurred beneath the Fuji volcano due to indentation of the slab (Aizawa et al., 2004). Fragmentation of the slab also occurred, separating shallowly inclined segments beneath SW Japan and a more steeply inclined Kyushu segment (Ishida, 1992). The spatial correlation between the present Shikoku Basin, the shallow subduction region, and distribution of adakites suggests that presently subducted Shikoku Basin is still buoyant and may be hotter compared to the other segments (Fig. 9E).

The tectonic reconstructions noted above are consistent with the magmatic response between the three arcs over the past 25 m.y. Further tests obviously await accumulation of additional geochemical evidence.

CONCLUSIONS

A review of age and geochemical data for igneous rocks in SW Japan over the past 25 m.y., along with some new data, are integrated with a review of tectonic development of the Sea of Japan, other parts of Japan, and evolution of the Philippine Sea plate. Volcanic activity is classified into (1) Stage I: Initial rifing of the Sea of Japan (25–17 Ma); (2) Stage II: During opening of the Sea of Japan (17–12 Ma); (3) Stage III: Late Tertiary volcanic arc (12–4 Ma); and (4) Stage IV: Late Pliocene–Holocene volcanic arc (4–0 Ma). LAT volcanism in developing rift zones characterized stage I. Back-arc extension to form the Sea of Japan was associated with erosion of isotopically depleted LAT to alkali basalt volcanism, and this extension occurred at the same time that subduction of the Shikoku Basin began. Stage II was marked by subduction of young, hot oceanic lithosphere, which interacted with the overlying mantle to cause widespread HMA magmatism. HMA magmas either erupted with minor crustal contamination or melted accreted sediments to produce felsic magmas during stage II. Subduction of the Shikoku Basin spreading ridge also produced MORB-like tholeiitic basalt and off-ridge alkali basalt magmas at the Pacific coast. Subduction ultimately cooled the upper mantle, causing narrowing of the rear-arc volcanic region in stage III, and further subduction caused the slab to penetrate into mantle asthenosphere and melt during stage IV. The development history of the SW Japan arc was compared with that of the NE Japan and Ryukyu arcs over a similar time, and as a result of all these considerations, a paleogeographic model of the northwestern Pacific in the late Cenozoic was proposed. Reinitiation of subduction associated with back-arc basin opening began ca. 17 Ma was the critical event responsible for forming the modern SW Japan volcanic arc.

REFERENCES CITED


Errata

A recent software upgrade caused unforeseen and unfortunate errors in a number of figures in the July/August 2005 issue (v. 117, no. 7/8). Following are the articles that were affected and their corrected figures. GSA Bulletin regrets the error.

Processes of oscillatory basin filling and excavation in a tectonically active orogen: Quebrada del Toro Basin, NW Argentina
George E. Hilley and Manfred R. Strecker
(v. 117, no. 7/8, p. 887–901, doi: 10.1130/B25602.1)

Figure 1 (right). Tectonic map of the central Andes (modified after Isacks, 1988). The internally drained Altiplano-Puna plateau is bordered by a series of intramontane basins within the Cordillera Oriental and Sierras Pampeans. Box shows the location of Figure 2, Star denotes Quebrada del Toro.

Figure 3 (below). (A) Geologic units and structures of the Toro basin. Sierra Pasha consists of Cambro-Ordovician quartzites and Precambrian weakly metamorphosed Puncoviscana Formation (adapted from Marrett and Strecker, 2000, and references therein). (B) Shaded relief topography of Toro basin (SRTM data, U.S. Geological Survey) showing location of photographs in Figure 5 (letters with arrows), the locations of Figures 4 and 6, and the location of the paleomagnetic stratigraphic site (PS) reported in Viramonte et al. (1994) and Reynolds et al. (2000).
Stratigraphic and geochemical evolution of an oceanic arc upper crustal section: The Jurassic Talkeetna Volcanic Formation, south-central Alaska
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Figure 1. Tectonic map of Alaska and NW Canada showing the major exotic terranes accreted to cratonic North America. The study region is located within the Peninsular Terrane of south-central Alaska, sandwiched between Wrangellia to the north and the Cretaceous accretionary complexes exposed within the Chugach Terrane to the south (modified after Beikman, 1992). Terrane boundaries are all faulted.
Figure 4. Geological map of the Matanuska Valley and western Copper River Basin showing the exposures of Talkeetna Volcanic Formation studied east of the Matanuska Glacier, on Sheep Mountain, in the region of East Boulder Creek and in the Horn Mountains. The trace of the Matanuska Valley may reflect the presence of a major E-W trending strike-slip fault. Map modified after Beikman (1992).
Figure 5. (A) Geological map of Talkeetna Mountains between the Little Oshetna River and the Oshetna River. Map modified after Grantz (1960). (B) Cross section through the top of the Talkeetna Volcanic Formation immediately under marine Middle Jurassic sedimentary rocks. Vertical exaggeration ×2.
Figure 6. Geological cross sections through the Talkeetna Volcanic Formation at (A) East of the Matanuska River, (B) at Sheep Mountain, (C) in the vicinity of East Boulder Creek, and (D) in the Horn Mountains. See Figure 4 for precise locations. Unshaded stratigraphic levels are not exposed and are unknown. No vertical exaggeration.
Figure 7. Proposed composite stratigraphy for the entire Talkeetna Volcanic Formation compiled from measured sections on the various massifs considered in this study. Sections are schematic and do not represent individual bed thicknesses, instead showing the overall character of the section.
Figure 8. Sedimentary logs from the stratigraphic base of the Talkeetna Volcanic Formation (A) at Willow Mountain and (B) South of the Matanuska River, East of the Matanuska Glacier. The symbols used for the rocks are the same as for Figure 7. See Figure 4 for precise locations. Black stars indicate location of samples. Sedimentary logs from the stratigraphic top of the Talkeetna Volcanic Formation, under the Middle Jurassic Tuxedni Formation, are shown in (C) Sheep Mountain, (D) Little Oshetna River, (E) East Boulder Creek, and (F) Horn Mountains. Note striking facies differences between different areas of similar stratigraphic equivalence.
Reinitiation of subduction and magmatic responses in SW Japan during Neogene time
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Figure 1. Tectonic map of the Pacific plate, Philippine Sea plate, Sea of Japan, and Japan arcs. Abbreviations: ERP—Eurasia plate, NAP—North America plate, PAP—Pacific plate, PSP—Philippine Sea plate, thin lines with numbers—depths of slab surfaces of the Pacific and Philippine Sea plates.
Figure 9. Tectonic evolution and temporal variation of igneous activity in Ryukyu, SW Japan, and NE Japan arcs during Cenozoic time. Age data and lava chemistry are mainly based on Nakajima et al. (1995), Ohki et al. (1993, 1994), Sakuyama and Nesbitt (1986), Yoshida et al. (1995) for NE Japan arc; Kaneko (1995), Kimura and Yoshida (1999), Kimura et al. (1999b), Omura et al. (1988), Ujike and Stix (2000) for Hokuriku area and central Japan; Matsumoto (1992), Matsumoto et al. (1992), Nagao et al. (1999) for Kyushu; Daishi (1992), Shinjo et al. (2000) for Ryukyus and references therein. LAT—low alkali tholeiite, HMA—high-magnesium andesite, ERP—Eurasia plate, PAP—Pacific plate, PSP—Philippine Sea plate, thick solid line—plate boundary, thick broken line—spreading ridge, shaded line—leading edge of subducted Philippine Sea plate, thin solid line—depth contour of present surface of subducted Pacific plate; tectonic map of the Sea of Japan is from Tamaki et al. (1992). Moving directions of the Pacific and Philippine Sea plates are shown as solid arrows. Opening of the Sea of Japan and rotation of the SW and NE Japan arcs are shown by open arrows on panel (C). MORB—mid-oceanic-ridge basalt, BTL—Butuzo Tectonic Line.
Late Quaternary eolian and alluvial response to paleoclimate, Canyonlands, southeastern Utah


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Figure 4. Map and generalized cross section of alluvial deposits along a portion of Salt Creek (location on Fig. 1).