Multiple tectonic events in the Miocene Japan arc : The Heike microplate hypothesis

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It was a time of unrest for the Japan arc about 15 Myr ago. Magmatism, large-scale topography, and stress regime changed with the rapid paleomagnetic rotation of SW Japan. Magmatic zone expanded oceanward, while the event in NE Japan was older by one million years than in SW Japan. Stress regime in SW Japan changed from tensional to compressional just after the magmatism began.

Here, a plate kinematic model is presented to account for the events with special reference to the magmatism in SW Japan as a key phenomenon. The magmatism has been ascribed to the subduction of the young Philippine Sea plate. Instead, it is suggested here that the hot mantle plumes that rose under the drifting Japan arc were the cause of the magmatism. A hypothetical microplate, named the Heike, is introduced in the paper. It is assumed that the plate was detached from the Pacific plate at ~19 Ma and began anticlockwise rotation. The rotation resulted in a leaky transform boundary between the Heike and Pacific plates, creating a slab window that activated fore-arc magmatism NE Japan. Namely, hot mantle materials were raised to compensate the retreat of the Heike slab, and supplied heat to the magmas. Hot and volatile-rich plume was raised from the Pacific slab via the other slab window under western SW Japan by the roll back of the slab, activating the widespread magmatism in SW Japan. The microplate was demised at 15 Ma and the young and buoyant Shikoku Basin begun subduction. The buoyant subduction uplifted SW Japan and switched stress state in the arc. Our plate model is consistent with the superfast Japan Sea opening inferred from paleomagnetic data.

Keywords: Miocene tectonics, SW Japan arc, Fore-arc magmatism, Ridge subduction, Microplate, Plate reconstruction, Japan Sea opening

I. Introduction

Middle Miocene magmatism in the frontal SW Japan arc has been taken as a typical example of near trench magmatism that is ascribed to the subduction of the hot and young Philippine Sea Plate. The Shikoku Basin, the northeastern part of the plate (Fig. 1) had been spreading until the magmatism (Seno and Maruyama, 1984). However, plate models presented for the magmatism are inconsistent with the onshore geology of Japan including the spatial and temporal distribution of igneous activities. Here, we synthesize the onshore

geology of SW Japan and present a new plate model, in which the widespread Middle Miocene magmatism is accounted for by the passive upwelling of hot asthenosphere accompanied by the retreat of a subducting slab that is consistent with superfast backarc spreading in the Japan Sea suggested by Otofuiji *et al.* (1995a).

Although weak and sporadic magmatism can occur in frontal arc without any other tectonism, *e.g.*, the Mariana fore-arc (Marlow *et al.*, 1992), magmatism in the youthful Shimanto accretionary complex, SW Japan (Taira *et al.*, 1988) was heated simultaneously

in a regional-scale at ~ 15 Ma and left a number of plutons and volcanic rocks between the Yakushima Island and Fossa Magna region (Fig. 1). The term 'near trench magmatism' is used in this paper referring to the Middle Miocene magmatism in the Shimanto Belt. What is enigmatic is that magmatic activity at that time was not restricted within the belt but was widespread in the entire Honshu Island as well as in the northern Ryukyu arc.

The regional near trench magmatism was explained by Marshak and Karig (1977), invoking the migration of a trench-ridge-trench (TRT) triple junction along the Nankai Trough. It follows that their model requires an age progression of the magmatism along the trench. However, Shibata (1978) showed that the magmatism was simultaneous (Fig. 2). It is suggested by Takahashi (1981) that the magmatism was accompanied by the transition from transform to convergent plate boundary at the Nankai Trough—the Shikoku Basin did not subduct under the SW Japan before the magmatism. However, it was found that the spreading direction in the Shikoku Basin changed a few times. Three phases of spreading are identified by Okino *et al.* (1994) from marine magnetic anomalies in the basin: asymmetric or fan-shaped spreading, symmetric E-W spreading and NE-SW spreading in historical order. The variable spreading should have resulted in divergence or convergence at the paleo-Nankai trough. The transform model is not satisfactory.

The Pacific Plate is assumed by Hibbard and Karig (1990) to have subducted at the trough before the magmatism. They argue that their model account for the temporal variations of stress field and for the rise of young accretionary prism above sea level, as they consider that the Shimanto Belt was uplifted shortly before the magmatism. However, the belt was uplifted to a shallow marine depth in

the Early Miocene (Kato, 1989). We will show, instead, that the uplift seems to be unrelated to the magmatism. Instead, successive arc-wide subsidence and uplift with amplitudes of many hundred meters should be noted (Kano and Nakano, 1985; Yamamoto and Hoshizumi, 1988).

Previous authors invoked the youthfulness of the Shikoku Basin to account for the magmatism. However, the simultaneity of the activity along the strike-length of 800 km is enigmatic (Underwood *et al.*, 1992). Recent observations revealed that near trench magmatism occurs only in the vicinity of the TRT triple junction in front of the Solomon Islands (Taylor and Exon 1987) and of southern Chile (Forsythe *et al.*, 1986; Cande *et al.*, 1987): the subducting lithosphere that is younger than a few m.y. old is able to cause such anomalous magmatism. Marine magnetic anomalies show that spreading in the Shikoku Basin began earlier than the magmatism by ten million years (Okino *et al.*, 1994), too old to cause the wide spread magmatism.

The timing of the tectonic events is critically assessed in the following sections, *i.e.*, fore-arc magmatism, vertical movements, paleomagnetic rotation and transition of stress field. In this paper, we hypothesize a microplate that, we believe, played tricks upon the Japan arc when it was demised under the arc. The microplate gave a strong control to the tectonics of the Japan arc only for a few million years, but was eventually demised. In this paper we call the microplate the Heike after the family that had Japan under their despotic rule for a short period but perished in battle in the 12th Century. For age controls, the bio-chronostratigraphy correlated by Berggren *et al.* (1985) and Oda (1986) is used in this work.

Fig. 1. Tectonic map around Japan. Marine magnetic lineations after Nakanishi *et al.* (1992), Chamot-Rooke *et al.* (1987) and Okino *et al.* (1994). The SW and NE Japan Arcs are bounded by the fold and thrust belt in the Fossa Magna region, Central Japan. QVF, Quaternary volcanic front; A, Ashizuri; I, Ishizuchi; K, Kumano; M, Muroto; O, MITI Omaezaki-oki well; OK, Okinawa; P, Pohang; S, Shitara; T, Tanegashima; Y, Yakushima.

II. Tectonic events in early Middle Miocene SW Japan

1. Widespread magmatism

The fore-arc magmatism occurred not only along the entire length of the SW Japan arc but also in the northern Ryukyu arc. The western end of the magmatic zone is defined by the granite pluton in the Yakushima Island off south Kyushu, Ryukyu arc (Fig. 1). Granites in the Fossa Magna Region (Shibata *et al.*, 1984) mark the other end of the zone. High magnesian andesites that represent the magmatism were recently discovered in the region also (Miyake *et al.*, 1995). Figure 2 shows the ages of Middle Miocene igneous rocks in SW Japan, showing simultaneity along the arc.

The magmatic province is subdivided into three zones: the outer zone in the trench side, the San'in-Hokuriku area along Japan Sea coast, and the Setouchi magmatic Belt in-between, (Fig. 1). In this paper we call the outer zone as the Kumano magmatic Belt after a large cauldron. The Kumano Belt more or less overlaps the Shimanto Belt. S-type granites are the main members of the Kumano Belt that are often associated with funnel-type cauldrons (Takahashi *et al.*, 1980; Murakami *et al.*, 1989). Volcanic rocks are also found in the belt. By contrast, the Setouchi Belt is characterized by the occurrence of high magnesian andesites (Tatsumi and Ishizaka, 1982). Valles-type cauldrons associated with I-type granites were produced in the early phase of the activity (Aramaki *et al.*, 1977; Nakada and Takahashi, 1979; Takahashi *et al.*, 1980).

Melting experiment of high magnesian andesites suggests that the melt reached equilibrium with mantle rocks at 1000–1100°C and at a depth of 30–50 km (Tatsumi, 1982). Olivine andesites in the belt also suggest temperatures at 1060–1230°C for the same depths (Kawasaki *et al.*, 1994). The granite magma

Fig. 3. Paleothermal regime under the Kumano and Setouchi Belts. See text in detail. Dash: subsurface temperature under the Japan Sea coast of NE Japan after Kushiro (1988).

was produced at ~700°C and 20 km under the Kumano area (Murata, 1984). S-type granitic magma in the southwestern Shikoku Island was formed at a depth of ~20 km and 840–880°C (Dai *et al.*, 1993). Both of these granitic magma intruded the Shimanto Belt and exhibit slightly colder temperature conditions than that under the Setouchi Belt. A dike of high magnesian andesite is reported by Miyake *et al.* (1985) in the Kumano Belt. Vitrite reflectance (an index of organic diagenesis) of the Southern Shimanto rocks that are exposed in the Muroto Peninsula indicates paleotemperatures at 140–320°C (Mori and Taguchi, 1988; Underwood *et al.*, 1992, 1993b; DiTullio *et al.*, 1993; Laughland and Underwood, 1993). The burial depth of the rocks is estimated at 2–4 km by Hibbard *et al.* (1993). Figure 3 shows the paleogeothermal regime estimated from vitrite reflectance and Petrology. These temperatures are as high as those under the present volcanic NE Japan arc that is estimated petrologically by Kushiro (1990).

2. Arc magmatism prior to the near-trench magmatism

Early Miocene magmatism was characterized by two types of activity in the SW Japan arc: (1) a chain of cauldrons and/or granites along the present Japan Sea coast (Kano and Nakano, 1985; Sakai, 1993) and (2) lamprophyre dikes in the frontal arc at 16–18 Ma (Taneda and Kinoshita, 1972; Uto *et al.*, 1987). There are two lamprophyre dikes, one in the Setouchi and the other in the Kumano Belt. They yield K–Ar ages at 17.7 ± 0.5 (Uto *et al.*, 1987) and 16 ± 2 Ma (Taneda and Kinoshita, 1972), respectively. Such alkaline magma is thought to be formed with minor degrees of partial melting (Kushiro, 1983), suggesting lower geothermal gradients before the near-trench magmatism.

3. Timing of widespread magmatism

The volcanic rocks in the Setouchi Belt rest on shallow marine sediments that are assigned to Blow's (1969) foraminifer zones from N. 6 through N. 8 (Yoshida, 1992). The volcanism onset at a time between the first appearance horizons of *Praeorbulina glomerosa* (~16.0 Ma) and *Orbulina saturalis* (15.3 Ma). The oldest rocks of the activity yield radiometric ages at 15–15.5 Ma (Tsunakawa *et al.*, 1983; Matsuda *et al.*, 1986; Tazaki *et al.*, 1992), consistent with the fossil age. The youngest radiometric ages in the Setouchi Belt concentrate between 11 and 12 Ma (Tatsumi *et al.*, 1980). Yet, the main phase of magmatism seems to have terminated around 13 Ma in the Setouchi Belt. The onset of magmatism in the Kumano Belt is constrained less accurately. The plutonic and volcanic rocks in the Cape of Shiono-misaki represent the earliest activity that is correlated to the foraminifer zone N. 8 (15.3–16.8 Ma) (Hisatomi, 1981). Their radiometric ages fall in a range around 14 Ma in the belt (Shibata, 1978).

4. Vertical movement of the SW Japan Arc

Just before the near-trench magmatism, the SW Japan arc was subject to a rapid and regional vertical movement (Kano *et al.*, 1991). The Shimanto Belt was uplifted to shallow marine depth by the time of foraminifer zone N. 8 (~16 Ma). To show the gross pattern of vertical movement, we compiled paleo water depth (paleobathymetry) of sedimentary basins estimated from benthic fossil faunas with a few exceptions of which neritic environments were assessed from depositional facies (Fig. 4).

Our compilation shows that the uplift of the Shimanto accretionary belt was not as simultaneous in the belt as the onset of the magmatism. The belt was partly raised by 23 Ma and truncated by shallow marine, fore-arc basin sediments with sharp unconformity by 16 Ma (Fig. 4). As an example, the accretion complexes are covered by shallow, fore-arc basin sediments at the Cape of Ashizuri (Kimura, 1985). On the other hand, sedimentation in lower bathyal or abyssal environments were continuing in the south Kyushu Shimanto Belt (Kato, 1985). At the MITI Omaezaki-oki well, off Central Japan, where the basal part of the drilled units consists of Paleogene Shimanto rocks. They yield fossil benthic foraminifers indicating paleobathymetry greater than 2,000 m (Kato *et al.*, 1989). The unit is overlain by Early Miocene (17–18 Ma) mudstone that yield shallow marine fossil fauna. Accordingly, uplift was not simultaneous in the belt (Fig. 5). The SW Japan arc subsided and then uplifted as a whole at the beginning of the magmatism (Fig. 4). The inner arc was inundated by seawater at 16–17 Ma. The San'in and Hokuriku districts along the Japan Sea coast submerged from non-marine to upper-middle bathyal environments (200–1,000 m below sea level) within the N. 8 zone but were rapidly uplifted near sea level by the base of the N. 9 zone (~15.3 Ma) (Nomura, 1986b; Nakagawa and Chiji, 1988;

Fig. 4. Paleobathymetry inferred from fossil fauna or from depositional facies. The Shimanto accretionary complex was gradually uplifted to the sea level by ~17 Ma. SW Japan was flooded at ~16 Ma. Marine transgression reached at its climax at ~15.5 Ma but the arc was raised above sea level by ~15 Ma. Data sources: Akimoto (1991), Funayama (1988), Hasegawa and Takahashi (1992), Huang and Okamoto (1979), Katto and Taira (1978), Kimura (1985), Nakagawa (1985), Nomura (1992), Sugiyama *et al.* (1982), Yamazaki (1992).

Fig. 5. Time table of Miocene tectonic events in SW Japan. See text in detail.

Kano *et al.*, 1991). The Setouchi district also experienced the same sense of movements with smaller paleobathymetric amplitudes. Based on fossil molluscan fauna, Shibata (1985) estimates the maximum water depth at a few hundred meters in the N. 8 zone. The magmatic activity of the Setouchi Belt onset just after marine regression at the base of N. 9 zone (Yoshida, 1992). The Miocene paleobathymetric variation at the MITI Omaezaki-oki well was consistent with those in the San'in-Hokuriku area (Fig. 3): the N. 7-8 (16-17 Ma)

sediments yield fossil benthic foraminifers, which are indicative of paleodepths at 500-2,000 m, whereas the N. 8-9 (14.5-16 Ma) sediments yield shallower fossil fauna (200-1,000 m) (Kato *et al.*, 1989). The short-lived subsidence left sediments as thick as many hundred meters.

Magmatism in the Kumano Belt began under the sea but the belt was uplifted above sea-level in the N. 9 zone (Hisatomi, 1981). Granitic plutons were rapidly unroofed in the Kumano area shortly after their intrusion (Hasebe *et al.*, 1993). Cauldrons in the

Kumano Belt were formed following the marine regression.

5. Paleostress Regime

Tectonic stress changed from tensional to compressional shortly before the fore-arc magmatism. The magmatism commenced under tensional stress field, but changed simultaneously with the paleobathymetric rebound. Such tensional paleostresses are evidenced in the Setouchi Belt by half grabens, *e.g.*, the Kameyama Basin (Miyamura *et al.*, 1983) and by dikes (Tsunakawa, 1985; Yamamoto, 1991). The dikes and grabens run parallel to the arc, suggesting across-arc tensional stresses. Such dikes crop out typically in the Shitara area, Central Japan (Fig. 1) and yield K-Ar ages at 15.1 ± 0.5 Ma (Tsunakawa *et al.*, 1983a; Takada, 1987). Those dikes were outcome of the earliest phase of magmatism in the Setouchi Belt. A high magnesian andesite dike that is parallel to the arc is also found to the west of Kumano pluton (Miyake *et al.*, 1985). Grabens at 17–18 Ma are also found in the Island of Oki, off the San'in area (Yamazaki, 1992). These observations indicate that the magmatism began in extensional stress state.

Compressional stress regime followed the tensional state with the onset of the fore-arc magmatism. This is evidenced by thrust faults in northwest Shikoku where the Kuma Group, most of which is of Early Miocene in Age (Kashima and Takechi, 1996). The group is cut by the faults that is in turn covered by the base of the volcanic rocks of the Setouchi belt (Takeda, 1996). In addition, the compressional stress regime is indicated by dike swarms perpendicular to the arc (Tsunakawa, 1985; Kano *et al.*, 1991). The oldest swarms of them are dated at 13.9 ± 0.4 and 14.6 ± 0.6 Ma (Tsunakawa *et al.*, 1983b). Compressional deformation was concentrated between the Island of Kyushu and Korean Peninsula at ~ 15 Ma (Katsura, 1992). Compressional stress appears to

have peaked in the end of Miocene Epoch as Japan Sea sediments are folded and truncated by Pliocene ones off San'in district (Tai, 1973; Tanaka and Ogusa, 1981; Kano *et al.*, 1993; Yamamoto, 1993; Itoh, 1995). Yet, the folding began to glow from 15 Ma (Yamauchi and Yoshitani, 1981; Kano and Yoshida, 1985; Nomura, 1986a).

Dike swarms in the Matsue area, San'in district, suggest that the transition in the stress regime was simultaneous with the paleobathymetric rebound (Kano *et al.*, 1994). Rhyolite dikes, which are parallel to the arc and suggest tensional stress, penetrate the deep marine rhyolitic volcanics of the Kuri Formation, and the rhyolites yield fission-track ages at 15.3 and 14.8 Ma. After the regression the subaerial Omori Volcanics deposited with the intrusion of dikes perpendicular to the arc. Conclusively, stress regime changed from tensional to compressional with the paleobathymetric rebound at 15 Ma (Kano *et al.*, 1991).

6. Paleomagnetic Rotation of SW Japan

There are a number of paleomagnetic data today (Hayashida and Itoh, 1984; Otofujii and Matsuda, 1983; Torii, 1983) that support a clockwise rotation of SW Japan that was suggested by Kawai *et al.* (1961). Yet, Kawai and his coworkers inferred that the rotation was Cretaceous in age, radiometric dating in tandem with paleomagnetic measurements revealed it as a Miocene event. There were only a small number of grabens developed in SW Japan, also suggesting that the main part of SW Japan rotated without severe intra-arc deformations. The movement may have begun as early as ~ 26 Ma (Nakajima *et al.*, 1990) but mostly between 16 and 14 Ma (Hayashida *et al.*, 1991; Otofujii *et al.*, 1991).

The fore-arc magmatism onset during the rapid rotation of SW Japan. This is evidenced by the Kumano Plutonic Rocks and the Murou Welded Tuffs. They are consistently rotated

the pre-rotation units in the SW Japan block (Torii, 1983; Torii and Ishikawa, 1986).

The eastern part of SW Japan arc also showed differential rotation from the main part of the arc: the area rotated opposite direction after 14 Ma probably by the collision of the Izu-Bonin arc against the Japan arc (Itoh, 1988).

III. Discussion

The widespread magmatism and a variety of accompanying tectonic events are reviewed in the previous sections. The temporal variation of the large-scale topography places critical constraints for their interpretation. There was an across-arc variation of paleobathymetry in the period of the N. 8-9 zones. The variation cannot be explained by eustasy alone. Eustasy played a minor role in the transgression over SW Japan: tectonic subsidence was more significant (Hiroki, 1995). There are fault-bounded grabens formed before or during the marine transgression (Itoh *et al.*, 1994).

The subsidence was coeval with that in the NE Japan Volcanic arc (Yamaji and Sato, 1989; Yamaji, 1990). The volcanic NE Japan arc remained in the deep sea until the Late Miocene and the frontal arc stayed near the sea-level, whereas SW Japan was raised above sea level by 15 Ma. Accordingly, a sharp contrast in large-scale topography between the SW and NE Japan arcs appeared with the onset of the fore arc magmatism in SW Japan (Kano *et al.*, 1991).

The marine regression at 15 Ma was of regional-scale, and most likely of tectonic uplift in origin. Eustatic fall appears not to account for the full amplitude. In addition, the regression in SW Japan was not contemporaneous with the third-order sea-level fluctuations suggested from the stratigraphy of the NE Japan frontal arc (Yanagisawa *et al.*, 1989) and from Hokkaido Island, northern Japan (Hoyanagi *et al.*, 1995). The frontal-arc stayed

near sea-level in the Middle Miocene. Simultaneous regression did not happen along the Korean continental margin either, where more stable tectonism is expected than in SW Japan arc. Submarine sedimentation lasted until ~12 Ma in the Pohang Basin, Korea (Ingle, 1992).

Therefore, tectonic uplift was probably the primary cause for the regression. However, Crustal thickening seems not to account for the event. Tectonic deformation is negligible in and around SW Japan at that time. In most areas in the Setouchi and San'in-Hokuriku districts, younger and non-marine volcanics overlie older and marine sediments without significant stratigraphic truncation (Kano *et al.*, 1991). Accordingly, the arc was uplifted with little tectonic deformations.

1. Plate reconstruction

Here we put all the geological data together and present a plate kinematic model. The magmatism onset simultaneously along the entire SW Japan and in northern Ryukyu arcs. The magmatism began with the uplift of the arc and was followed by the transition of tectonic stress from tensional to compressional. To explain these observations, we present a plate kinematics that is an extension of Hibbard and Karig' (1990) model. They assumed that (1) the Pacific Plate was subducted under SW and NE Japan while the Philippine Sea Plate migrated northward, and (2) the Philippine Sea Plate began to subduct under SW Japan at ~15 Ma. Since then the youthful Shikoku Basin gave rise to the magmatism, they interpret.

On the basis of stratigraphy and geologic structures, a convergent plate boundary is also suspected between the Shimanto Belt (Japan arc) and the northern end of the Izu-Bonin arc before 15 Ma (Koyama, 1991), as the block consists of bathyal or abyssal deposits as well as igneous rocks (Akimoto, 1991). The arrival of the Izu-Bonin arc at the Fossa Magna region

is suggested by Saito *et al.* (1992) who revealed that the Izu-Bonin arc began to supply volcanic materials at 14–15 Ma to the southern Boso Peninsula, southern NE Japan arc (Fig. 1). Hibbard and Karig's model is consistent with these observations as well as the simultaneity of the magmatism but contradicts its spatial extent (Underwood *et al.*, 1992). The magmatism was too extensive.

We assume a microplate, called the Heike that was subducting under Japan before the magmatism (Fig. 6). The plate is also assumed to have been detached at around 20 Ma along a fracture zone from the Pacific Plate to form a leaky transform fault. In late Cenozoic, the Pacific Plate that subducted under Japan has had the magnetic anomalies called Japanese lineation set that are faulted along NNW-SSE trending fracture zones (Nakanishi *et al.*, 1992). It is hypothesized that the microplate was detached along an unlocked fracture zone from the Pacific Plate. The consumption of the Heike plate resulted in the collision of SW Japan against the young and buoyant Shikoku Basin. Prior to the collision, there was a divergent boundary between the Heike and Philippine Sea Plates. When the Heike was demised, this spreading axis caused the near trench magmatism along the entire length of the trench off SW Japan. However, the ridge subduction alone seems not to account for the Middle Miocene magmatism. The paleogeothermal gradient under the Setouchi Belt was probably higher than the Kumano Belt (see previous section). The ridge-trench interaction should have resulted in the hotter Kumano Belt. We will return to this problem later.

The evolution of the large-scale topography is consistent with this plate model. The amplitude of arc's dynamic topography increases with the age of the subducting lithosphere (Mitrovica *et al.*, 1989; Gurnis, 1992;

Otsuki, 1992). The old Pacific Plate subducted before the event. The Heike microplate departed from the Pacific Plate, so that the microplate had old oceanic lithosphere. The young Philippine Sea Plate began subduction at 15 Ma to raise the SW Japan arc by a few hundred meters. The NE Japan volcanic arc remained deep under the sea because the old Pacific Plate followed the event.

2. Implications for superfast Japan Sea opening

Paleomagnetists argue that spreading in the Japan Sea backarc basin was as fast as tens of cm/yr (Otofuiji *et al.*, 1985). Some researchers doubt the rotation because the paleomagnetism suggest surprisingly fast, however, recent GPS measurements reveals that superfast back-arc spreading can happen (Bevis *et al.*, 1993), so that the superfast opening of the Japan Sea is assumed in our model.

In our model, Japan Sea opened as a back-arc basin of the Heike Plate after ~20 Ma. There are marine sediments and basalts discovered at the ODP sites 794, 795 and 797 in the Japan Sea and were dated at 19–20 Ma (Tamaki *et al.*, 1992). Accordingly, the back-arc opening might have started earlier than the detachment of the Heike from the Pacific Plate. The term 'opening' is used here because it is still unclear whether the marine basin appeared as a result of spreading or of rifting in the Japan Sea. In any case, the opening was accelerated at 16–17 Ma and peaked at around 15 Ma (Nakajima *et al.*, 1990; Hayashida *et al.*, 1991).

Narrow slabs have tendency to roll back easier than wide slabs, because they should shove underlying mantle aside (Dvorkin *et al.*, 1993). It is easy for the mantle to pass by the sides of the slab. In addition, the Heike Plate, which detached from the Pacific Plate, had old and dense lithosphere created in the Jurassic. The negative buoyancy of the very old slab

Fig. 6. Palinspatic plate model. The pivot of the rotation of SW Japan is also shown. IBA, Izu-Bonin arc; KP, Kyushu-Palau Paleo arc.

should have encouraged the trench to retreat. The deeper mantle was passively raised by the sinking Heike slab (Fig. 7). These effects may have prompted superfast back-arc opening in the Japan Sea. We suggest that the rapid

back-arc opening might have been controlled by the Heike Plate. It should be noted that the position of a subduction zone is determined by the intersection between the surfaces of the Earth and a slab. A sinking slab can carry the

Fig. 7. Schematic showing rapid asthenospheric flow onto the old and dense Heike subducting slab through slab windows. The SW Japan arc rotated with its pivot near the junction of the SW Japan and Ryukyu arcs. See text in detail.

zone oceanward. The slab under Japan might have become easier to tear down after the detachment of the Heike Plate than before, because the asthenosphere became possible to flow into the wedge mantle under SW Japan. By contrast, the Philippine Sea slab was younger and more buoyant, so that its roll back was retarded. Paleomagnetic studies show that the SW Japan arc rotated with its pivot in the Kyushu Island (Ishikawa, 1997). The contact of the Heike and Philippine Sea plate off the island of Kyushu may have prevented the Heike slab to rollback, placing the pivot there (Fig. 7).

3. Implications for widespread magmatism

Narrow slabs roll back easily because deep mantle can ascend by their sides. This accounts also for the widespread magmatism. The passive, hot mantle flow into the mantle wedge raised the temperature under SW Japan. The subduction of the leaky transform fault between the Heike and Pacific might have the volcanic front in NE Japan migrate oceanward. The front lay near the axis of NE Japan at 17–

20 Ma but stepped to the present Pacific coast at 16–17 Ma (Fig. 1), about one million year earlier than the widespread magmatism in SW Japan (Ohguchi *et al.*, 1989; Ohki *et al.*, 1993). The Tomari Andesite (13–15 Ma; Watanabe *et al.*, 1993) is an example of such a fore arc magmatism. The volcanic rocks along the Pacific coast that deposited at 14–16 Ma have anomalous geochemical signatures relative to island-arc volcanics. They are characterized by basalts with high FeO^* and of TiO_2 and low $\text{K}_2\text{O}/\text{TiO}_2$ and by icelanditic dacites (Takahashi, 1986). The slab window between the Pacific and Heike slabs gave a way to rise hot and dry mantle plume from the area under the Pacific and Heike slabs to shallow depths. Fore-arc magmatism including icelandites indicates asthenospheric upwelling around 16 Ma (Takahashi *et al.*, 1995).

On the other hand, wet asthenosphere may have been provided into the wedge mantle under western SW Japan from the fluxed mantle above the Pacific slab (Fig. 7). The geothermal gradient under the western part of the

Setouchi Belt was steepened presumably by this inflow. The high magnesian andesites are distributed mainly in the western part of the Setouchi Belt, whereas the eruption of the magma was rarer in the eastern part (Shiraki, 1995). The distribution is consistent with the difference of the inflows at the both sides of the Heike slab. The mantle upwelling between the Heike and Pacific slabs did not supply enough water to produce such magmas.

The demise of the Heike Plate made the Japan arc abort backarc spreading. The successive collision of the Philippine Sea Plate might have brought the backarc from tensional to compressional stress states. Spreading in the Shikoku Basin was blocked probably because the northern part of the basin began subduction at 15 Ma.

At the end of the article, it should be noted how to verify the present plate model. This model depends on paleomagnetist's hypothesis that the main part of SW Japan drifted as a coherent block (*e.g.*, Kawai, *et al.*, 1961; Otofujii *et al.*, 1985). SW Japan seems to have been deformed much less than NE Japan, because there are a small number of tectonic features such as half grabens. But, actually, several grabens have been identified there, such as the Kabuto Basin in central SW Japan (Miyamura *et al.*, 1981). The quantification of the amount of Early to Middle Miocene intra-arc deformation would be a way to verify the model. The model depends also on a variety of tectonic events and their timing. The increase and improvement of time controls may provide another way to verify the present plate model also.

IV. Conclusion

We put forward a microplate named the Heike to explain the widespread magmatism in the Middle Miocene SW Japan arc. The roll back of the Heike slab may have caused pas-

sive mantle upwelling that resulted in the widespread magmatism. The magmatism onset between 15 and 16 Ma along the entire length of the SW Japan and northern Ryukyu arcs. The oceanward migration of the volcanic front in NE Japan that predated the magmatism in SW Japan by 1-2 million years is also consistent with our plate model. Paleomagnetic rotation, rapid vertical movements, and succession of stress regime from tension to compression, all of these events were coeval and in accord with the onset of magmatism in our plate model. The spreading in the Shikoku Basin might have been stopped by the subduction of the northern border of the basin under SW Japan.

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日本列島周辺の中新世プレート運動：平家プレート仮説

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日本海拡大の末期，すなわち 1500 万年ほど前に，いくつものテクトニックな事件が，日本弧を舞台として相次いで起こった。広域的な昇降・応力場の転換・火成活動・古地磁気回転・激しい断層運動などである。それらを制約条件として，日本列島周辺のプレート運動を復元した。太平洋プレートから分離したマイクロプレートが 1500 万年前に日本弧の下に沈み込んで消えたとすると，それらの制約をみたし，さらに古地磁気から推定された日本海の超高速拡大をも説明できることを示す。中期中新世初期における日本弧の広域的火成活動は，マイクロプレートの後退を補償するかたちで湧きあがったマントルプリュームに原因を求めることができる。