Chapter 5

Tectonic Synthesis: A Plate Reconstruction Model of the NW Pacific Region Since 100 Ma

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Additional information is available at the end of the chapter

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Abstract

Based on the results of interdisciplinary study from Chapters 1–4, a plate tectonic model of the northwestern Pacific region since 100 Ma is presented in this chapter. The evolution of the Pacific margin is viewed as a longstanding history of migration/amalgamation of allochthonous blocks onto the subduction zone. Such a process inevitably provoked diverse tectonic events, spatiotemporal positions of which have been discussed in this book. In order to reconcile paradoxical discrepancies in the docking process of arc fragments, the authors introduce a marginal sea plate with a spreading center that was alive in the Cretaceous. Oblique subduction of the ridge caused specific migratory igneous activity along the rim of the overriding plates, together with flips of shearing direction. Arc-trench systems on the eastern and western sides of the marginal sea plate developed following different timelines and were eventually mixed up during the plate's closure that prompted formation of a coincident Oligocene clinounconformity widespread on the Eurasian margin. Since the demise of the hypothetical plate, the tectonic regime of the northwestern Pacific margin has been controlled by the growth, namely, the rotational history and modes of convergence of the Philippine Sea Plate.

Keywords: plate motion, marginal sea, northwestern Pacific, Philippine Sea Plate, tectonics

1. Introduction

The authors' in-depth research has described a variety of tectonic events around the northwestern Pacific margin since the late Mesozoic. The architecture of the forearc basins of the Japanese archipelago depicted by high-resolution seismic profiles is indicative of a regional Oligocene unconformity related to a prevailing compressive regime (Chapter 1). A paleomagnetic investigation of the Mesozoic strata in south central Hokkaido showed significant northward transportation of crustal blocks since the Early Cretaceous and their amalgamation/collision with the continental margin with different timings by the late Paleogene (Chapter 2). Petrological and geochemical studies of the voluminous Late Jurassic to Early Cretaceous igneous rocks in Hokkaido have confirmed a typical island-arc affinity of andesitic volcanics and found signatures that suggest a collision of oceanic island arcs and seafloor spreading on the convergent margin (Chapter 3). Descriptions of microscale cracking and the magnetic fabrics of a Late Cretaceous granitic pluton, combined with an azimuthal observation of dike swarms, suggest drastic changes in the stress regimes around the Eurasian margin from the Late Cretaceous to Early Paleogene (Chapter 4).

These remarkable episodes should be closely related to the plate tectonic configuration because the northwestern Pacific has been a site of the birth and demise of oceanic plates since the late Mesozoic. As shown by Engebretson et al. [1], extremely rapid northward migration of the Izanagi Plate is key to understanding the intensive Cretaceous deformation process on plate margins. Temporal changes in the Pacific Plate's motion have controlled the formation and deformation of island arcs through the Cenozoic. Precise paleoreconstruction is difficult, however, because the Pacific Basin is surrounded by convergent margins where the evidence of geologic phenomena has been sucked deep into the interior of the earth. In this chapter, the authors attempt to construct a new kinematic model of plate motions for the northwestern Pacific region (**Figure 1**) based on our research and previous studies giving constraints on the timeline of thermal and structural events on active margins and clues to the whereabouts of allochthonous terranes since 100 Ma.

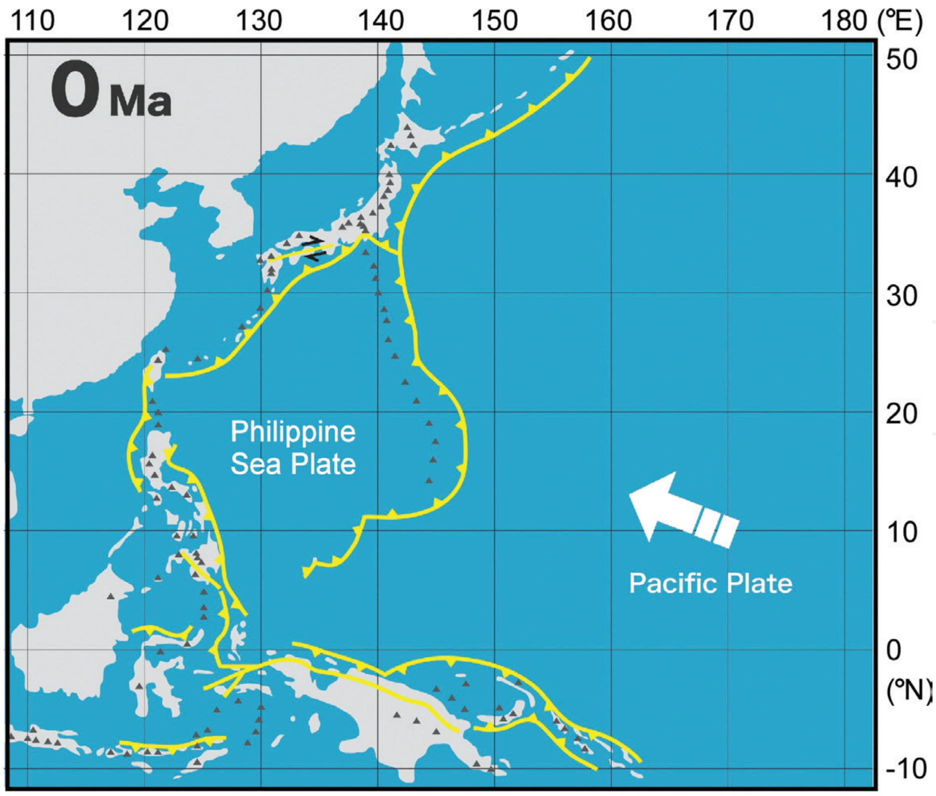

Figure 1. Present status of the plate reconstruction area of the NW Pacific region.

2. Constraints on plate reconstructions

We place a special emphasis on the chronicle of Cretaceous tectonic events because the ubiquitous, continuous sedimentary records of the present-day Asian continental margin are helpful in verifying our tectonic model. **Figure 2** summarizes the tectonic and/or thermal episodes on the northwestern Pacific margin throughout the period. In the following sections, highly diverse and somewhat self-contradictory event sequences are described one by one.

2.1. N-S transportation and amalgamation

In addition to the lateral motion of Hokkaido's constituents discussed in Chapter 2, significant northward migration has been reported from other areas of the Far East. Bazhenov et al. [2] did a paleomagnetic analysis of the Campanian-Maastrichtian tuffaceous siltstones and sandstones of island arc affinity from the Chayka Formation, which is distributed in south Sakhalin, and determined a paleolatitude of 27°N (**Figure 2**). They posited intra-oceanic motion of hypothetical island arcs with the Pacific Plate and their docking at the Eurasian margin at ca. 30 Ma. Another reliable paleomagnetic work focusing on Sakhalin, however, suggested that the island has a complicated structure, as does Hokkaido. Weaver et al. [3] compared their paleomagnetic inclination data with the apparent polar wander paths of major plates and concluded that a part of south Sakhalin probably evolved with the North American Plate or the Eurasian Plate. Thus, multiple origins of the northwestern Pacific landmasses have been deduced at a wide geographic scope. Northerly motion of oceanic plates also provoked intermittent development of accretionary complexes (**Figure 2**) such as the Samarkinsk terrane in Sikhote Alin [4] and the Naizawa

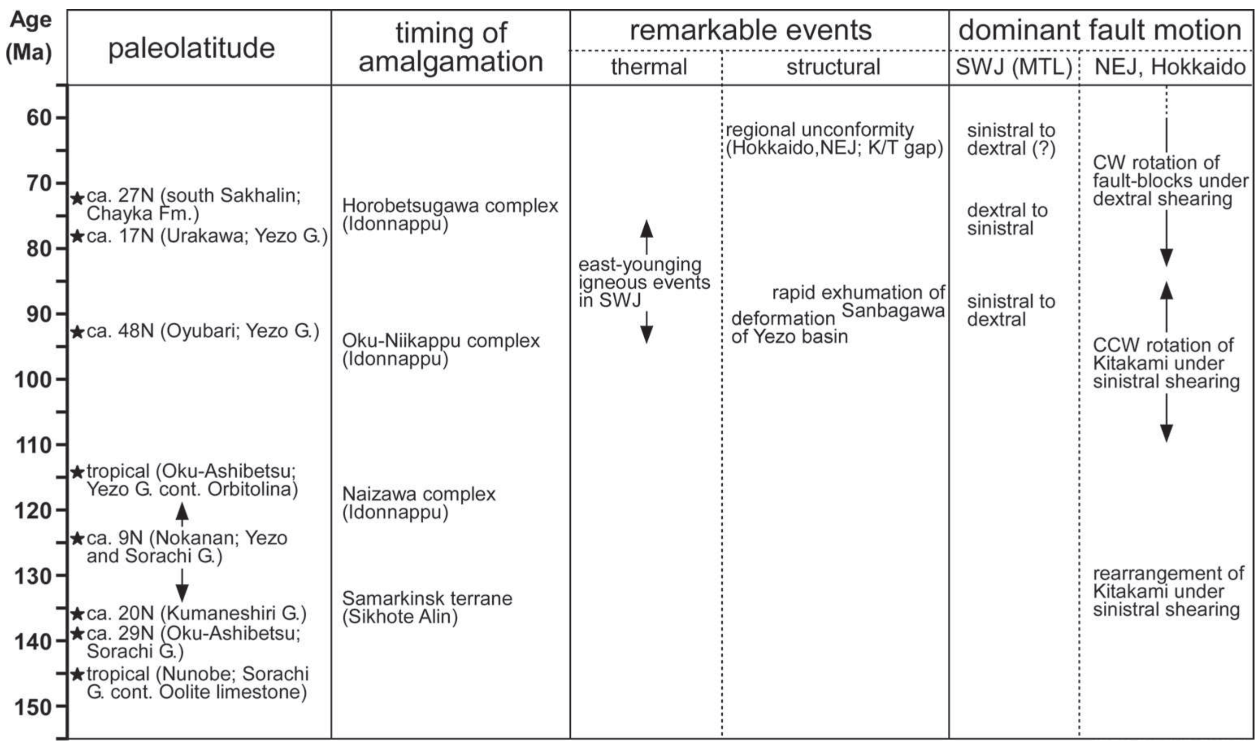

Figure 2. Tectonic and/or thermal episodes on the NW Pacific margin through the Cretaceous period.

and Horobetsugawa complexes in Hokkaido [5] in ascending order. Ueda and Miyashita [6] interpreted the Oku-Niikappu complex in the Cretaceous accretionary terranes of Hokkaido as a fragmented remnant island arc that moved with an oceanic plate and collided against the continent.

2.2. Thermal events

The eastern margin of Eurasia was a site of voluminous igneous activity in the Late Cretaceous. Radiometric ages of these rocks show a clear trend of being younger toward the northeast. Kinoshita [7] assumed that ridge subduction affected this conspicuous magmatism. He took two magmatic belts with different spatiotemporal development trends into account and attributed them to the subduction of the Farallon-Izanagi and Kula-Pacific ridges. Ridge subduction is a so-called “ace in the hole” to explain inscrutable events on convergent margins. Wallis et al. [8] reported an astonishing result that the Lu-Hf ages of eclogite samples obtained from the Sanbagawa metamorphic rocks in southwest Japan were centered at 89–88 Ma. This was identical to the Ar-Ar phengite ages of the same unit, which requires an extremely rapid exhumation of the metamorphosed terrane on the forearc. Their concept was that the approaching Izanagi-Pacific ridge triggered an anomalous uplift of the accretionary prism.

2.3. Structural events

Not only the southern part of the Cretaceous continental margin but also the northern part as well underwent intensive uplift. Tamaki et al. [9] executed one-dimensional basin modeling based on organic maturation. They investigated the vitrinite reflectance and T_{max} parameter values from Rock-Eval pyrolysis of the Yezo Group in the Oyubari area of central Hokkaido. Tamaki and Itoh [10] obtained paleomagnetic inclinations for that group, showing an affinity for a coeval paleolatitude with the North China Block [11]. They suggested notably low, constant maturation throughout the thick study section, which was confirmed by various biomarker analyses. This requires an anomalously rapid burial, probably related to thrust-stacking and/or large-scale slumping, followed by a prompt tilting/exhumation event (**Figure 2**).

In a wider geographic view, central Hokkaido has been an area of syn-accretionary exhumation. Ueda [12] demonstrated that the Early Cretaceous Iwashimizu complex in the Kamuikotan metamorphic zone, to the east of the Oyubari area, had been exhumed as a result of repetitive duplex-forming compression and extensional unroofing during the subduction of seamounts. Ando and Tomosugi [13] confirmed a younger unconformity between the Upper Maastrichtian and Upper Paleocene around the western rim of central Hokkaido and the Pacific coast of northeast Japan. The intensive deformation of the forearc probably propagated westward from the Cretaceous to the earliest Paleogene. The youngest event of the K/T unconformity is ubiquitous in the Yezo sedimentary basin. Ando [14] stated that the stacking patterns of the sequences and the timing of sequence boundaries agree with the oscillation patterns of the Haq curves, which fact led him to assume global eustasy control over the regional event.

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2.4. Dominant sense of faulting on plate margins

As discussed in Chapter 4, the paleostress regime of southwest Japan indicates repetitive shifts in the strike-slip of the arc-bisecting Median Tectonic Line under the influence of fluctuating oceanic plate convergence from the Late Cretaceous to the early Paleogene. On the other hand, in the Early Cretaceous, northeast Japan was governed by sinistral shearing stress provoked by a rapid northward motion of the Izanagi Plate. Based on an elaborate work of structural geology in northeast Japan, Sasaki [15] determined a predeformation configuration of its forearc (Kitakami massif) restoring left-lateral displacements on arc-parallel faults (**Figure 2**).

The strong sinistral phase was replaced by a dextral phase in the Late Cretaceous. Based on the counterclockwise and then clockwise rotational sequence of a large pluton in northeast Japan revealed by paleomagnetic methods, Itoh et al. [16] argued that switching from left- to right-lateral slips on arc-parallel faults resulted in a ball-bearing clockwise motion of crustal blocks. Such a deformation mode spread over the forearc basin of northeast Japan [17] and Hokkaido and lingered through the Paleogene. This was shown by numerical modeling of pull-apart basin formation in Hokkaido [18]. Its timeline is totally discordant from that of southwest Japan. In summary, the southwestern and northeastern parts of the Japan arc seem to have belonged to different convergent margins around the Cretaceous period.

3. Reconstructions

By reviewing the Cretaceous episodes, we have recognized anew that the present-day island arcs on the northwestern Pacific margin are a hodgepodge of allochthonous and autochthonous blocks that experienced various tectonic events. For example, a long-accepted theory posits that central Hokkaido consists of a volcanic arc associated with an accretionary complex overlain by forearc basin sediments that developed somewhere on the Pacific margin during late Mesozoic era. However, the authors' paleomagnetic study (Chapter 2) revealed that the ancient "forearc" of the Sorachi-Yezo Belt contains crustal blocks derived from low latitudes, although they cannot be discriminated from in situ coeval units by clear geologic boundaries. The evolutionary process of the "backarc" of the Oshima Belt is in an even more serious turmoil. Our paleomagnetic data on the Early Cretaceous Kumaneshiri Group suggest northward transportation of the volcanic arc, whereas some of the clastics in the terrane definitely originated from the Asian craton. Kawamura et al. [19] reported SHRIMP U-Pb ages of detrital zircon grains separated from Jurassic sandstones at ca. 1800 and 2500 Ma and confirmed a Proterozoic/Archean clastic provenance for the Oshima Belt.

As shown in **Figure 3**, the authors introduce a marginal sea plate between the mother continent and the major oceanic plates to construct a model that can reconcile the varied timings of the collision/amalgamation of crustal blocks onto the continental rim and the conspicuous magmatism that is probably related to ridge subduction. Now we are ready to present a plate tectonic chronicle for the northwestern Pacific region from 100 to 10 Ma. The animations of the reconstruction (a complete set at 5-m.y. intervals) that accompany the following section are

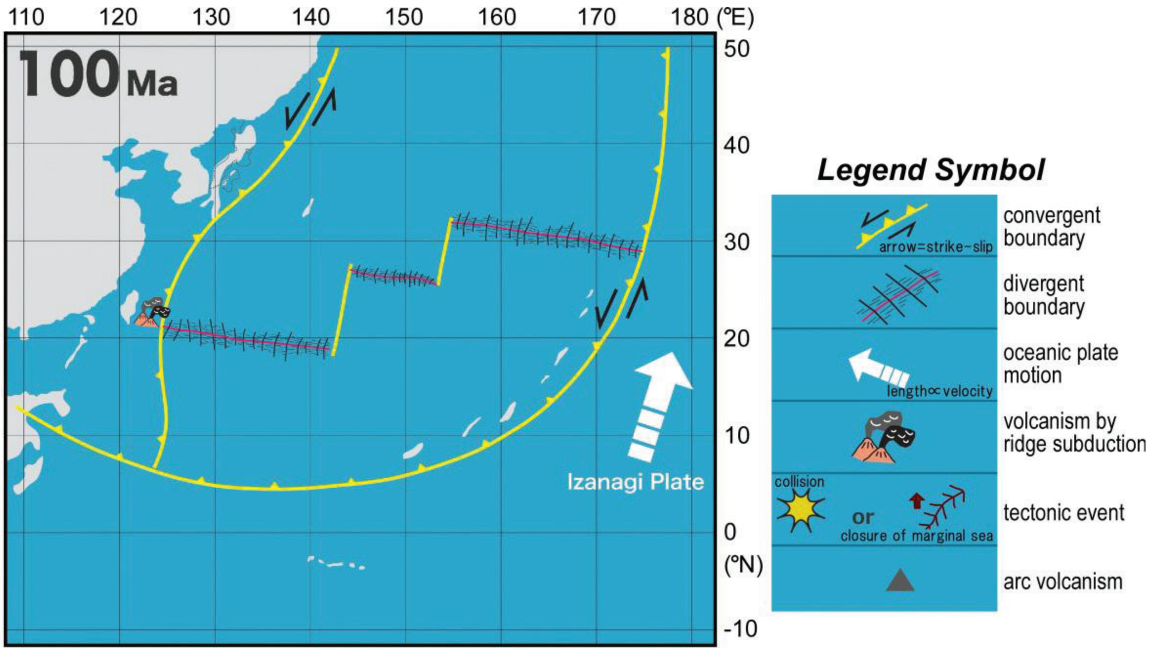

Figure 3. Reconstruction at 100 Ma.

available at OPERA: Osaka Prefecture University Education and Research Archives (http://hdl.handle.net/10466/14970).

3.1. 100 to 80 Ma

At the beginning of the Late Cretaceous, the present northwestern Pacific region was governed by the Izanagi Plate, which was characterized by quite rapid northward movement (**Figure 3**; [1]). This was promptly replaced by the westerly moving Pacific Plate (**Figure 4**). Their configuration between epochs was interpolated based on the reconstruction cartoons of Ref. [1] and calibrated by their linear velocity tables.

The eastern margin of Eurasia experienced voluminous igneous activity in the Late Cretaceous that has a clear trend toward younger activity as we move northeast. We value Kinoshita's [7] original hypothesis, assuming the effect of Kula-Pacific ridge subduction. However, the Kula-Pacific ridge's pathway in his theory does not fit with Engebretson's [1] plate reconstruction. In its place, we assume a spreading center within the newly introduced marginal sea plate. In our model, the ridge moves at a pace concordant with the time-progressive plutonism on the continental margin. It is plausible that rapid northerly migration of the Izanagi-Pacific ridge caused intense short-lived igneous activities in the Late Cretaceous along the eastern boundary of the marginal sea plate (including a major portion of the present northeast Japan forearc) (**Figure 4**), which Kinoshita [7] originally interpreted as the Farallon-Izanagi ridge effect.

Based on a detailed stratigraphic study of the Late Jurassic to Early Cretaceous Sorachi Group in central Hokkaido, Takashima et al. [20] proposed a tropical to subtropical origin of the terranes in the northern territory based on frequent occurrences of oolitic limestone and other paleontological evidence. Although the precise paleoposition of the landmass on the marginal sea plate is

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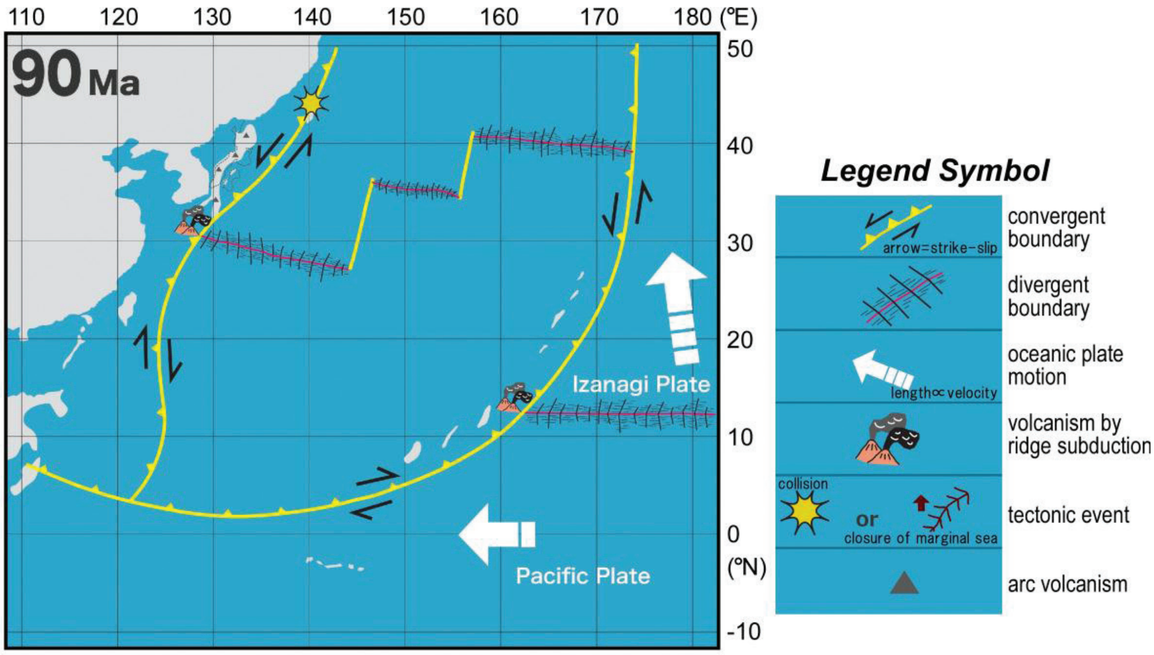

Figure 4. Reconstruction at 90 Ma.

still difficult to estimate, we regard their findings as an essential constraint in the reconstruction model. The eastern boundary of the marginal sea plate was also a site of intensive wrench deformation caused by highly oblique subduction of the Izanagi Plate. Sasaki's [15] structural analysis provides us with a clue to estimate an effective range for this wrench deformation event.

Paleomagnetic analyses by Tamaki and Itoh [10] clearly showed that the muddy sediments of the Late Cretaceous Yezo Group obtained from the Oyubari area in central Hokkaido have a geographical affinity to the mother Eurasian continent. We, hence, assume that some of the crustal blocks composing the present Japanese archipelago were settled on the margin of the mother continent for a long time and placed them upon the western convergent boundary of the newly introduced marginal sea plate.

As shown in **Figure 4**, an intraoceanic remnant arc collided against the continental margin at ca. 90 Ma after Ref. [6]. Their theory leads us to imagine an intensive deformation event in the Late Cretaceous on the Eurasian margin, facing the northwesterly moving marginal sea plate.

Collision of a remnant arc mentioned above inevitably provoked strong deformation of the forearc region. A geochemical expedition by Tamaki et al. [9] clarified that the indented rim of the continent was intensively deformed, which is recorded as an anomalously rapid burial of the Yezo forearc basin and a prompt exhumation accompanied by the buildup of overturned structures. This is a significant tectonic episode in the Late Cretaceous, and we anticipate that more geological findings can be related with this event.

This period was marked not only by a collision of landmasses upon the northern portion of the continental margin but also by a growing influence of the spreading center of the marginal sea plate. Wallis et al. [8] obtained Lu-Hf ages centered at 89–88 Ma for eclogite samples of the Sanbagawa metamorphic rocks in southwest Japan, identical to Ar-Ar phengite ages of the same unit. These ages require an extremely rapid exhumation of the metamorphosed terrane on the forearc. Their original concept was that the approaching Izanagi-Pacific ridge triggered uplift of the accretionary prism. Our alternative interpretation for the integrated thermochronological results is that the northerly moving spreading center of the hypothetical marginal sea plate caused the island arc to pop up.

Conventional wisdom holds that southwest Japan was a stable component of the eastern Eurasian margin before the Miocene backarc opening of the Japan Sea. Under this condition, the fact that its deformation structure seems to indicate multiple directional shifts of shear through the Late Cretaceous is quite enigmatic. Tokiwa [21] explicitly described the sequence of stress-strain state wobbles within the island arc based on a detailed analysis of deformation structure of an accretionary prism on its forearc. He suggested a flickering shift of sinistral-to-dextral (90–85 Ma) and dextral-to-sinistral (75–70 Ma) deformation on the same convergent margin. The northerly moving spreading center of the assumed marginal sea plate in our model acts as a toggle switch to solve the paradox, namely, segments of the convergent margin on its opposite sides show shear in reverse directions as shown in our reconstructions (e.g., **Figure 4**).

3.2. 80 to 60 Ma

Throughout the final stage of the Cretaceous and early Paleogene, the Pacific Plate was characterized by moderate northwesterly convergence as depicted in our reconstructions at 80 and 70 Ma (**Figures 5** and **6**). Its motion vector was calibrated based on the linear velocity tables of Ref. [1]. It is well known that a regional unconformity, the so-called "K/T Gap", developed in this period around the northwestern Pacific [14]. We have not yet found a drastic change in plate motion or continental collision related to this significant event.

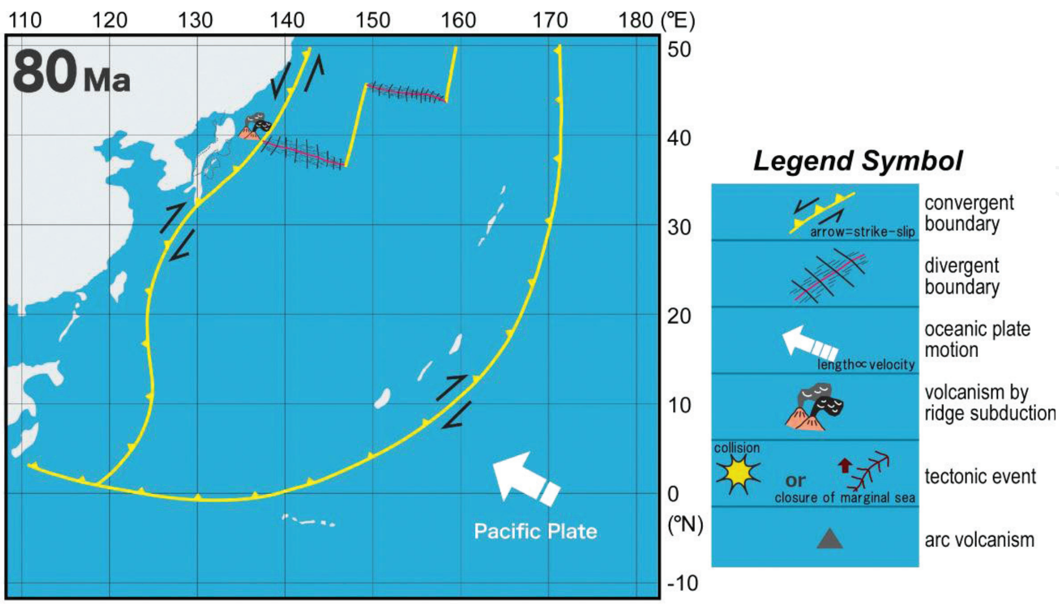

Figure 5. Reconstruction at 80 Ma.

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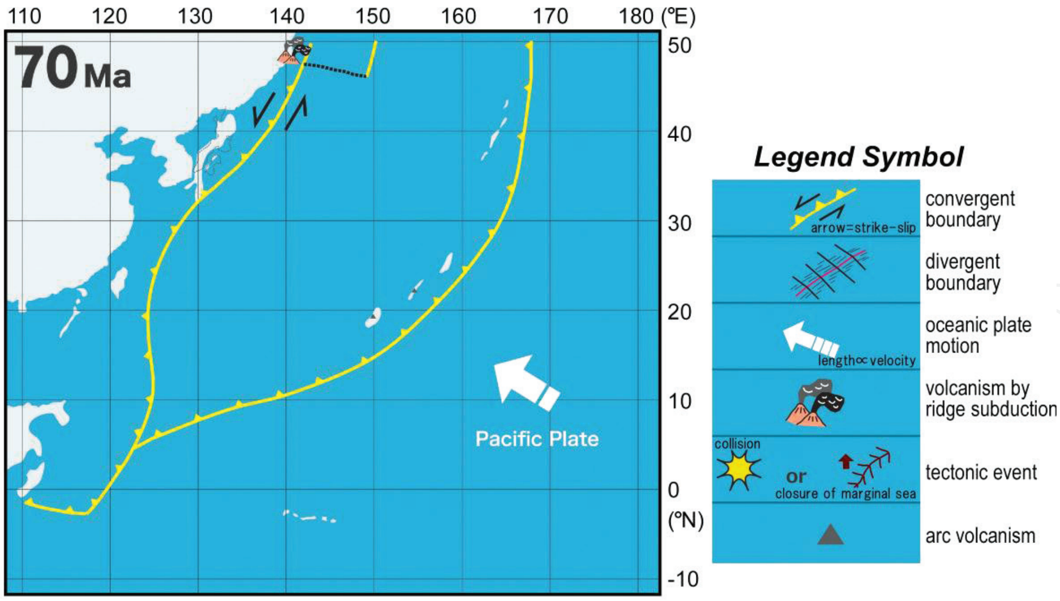

Figure 6. Reconstruction at 70 Ma.

Westerly motion of the Pacific Plate in this period may have provoked right-lateral wrench deformation of the forearc of northeast Japan, as depicted by the complex rotation sequence of a large pluton in Kamaishi revealed in the paleomagnetic research of Ref. [16]. It seems that temporal changes in the sense of the oblique convergence of the oceanic plates affected the whole forearc as presented by a paleomagnetic study of subsurface core samples by Itoh and Tsuru [17]. To evaluate rotational motions related to the forearc wrenching proposed in previous structural studies, they did paleomagnetic measurements of core samples obtained from the MITI Sanriku-oki, an exploration borehole on the forearc shelf of northeast Japan. The Eocene and Late Cretaceous cores were successfully oriented by correlating the bedding planes on the core surface with sidewall imaging, or by northing calibration, referring to the mean declination of secondary normal magnetization. Their primary directions of magnetization were corrected for tectonic tilting. Comparison with contemporaneous reference directions indicated an 87° counterclockwise rotation between the late Campanian and Eocene, and a 42° clockwise rotation thereafter. Although this sequence of rotational motions is similar to that revealed for the pluton on land (cf. [16]), sinistral wrenching seems to have lingered longer on the shelf, which may be related to a time lag in fault activity. As for the western convergent margin, Tokiwa [21] suggested the second shift of shear deformation in southwest Japan from dextral to sinistral (75–70 Ma), which is related to the demise of the spreading center on the marginal sea plate (**Figure 6**).

The low latitude origin of the Late Cretaceous Yezo Group was clearly indicated by a paleomagnetic study by Tamaki et al. [22] executed in south central Hokkaido. Their results infer that a certain part of the northeastern Japan arc may have been deposited on a remote forearc on the eastern side of the marginal sea plate. Considerable northward transportation of a part of Sakhalin was shown by a paleomagnetic study in Ref. [2]. The paleolatitudes of that study fit with the convergent trajectory of the Pacific Plate. Another paleomagnetic study in

Ref. [3], however, suggested that Sakhalin contains autochthonous blocks. Careful paleomagnetic measurements executed on the latest Cretaceous to early Paleocene volcaniclastic rocks by Otofuji et al. [23] revealed a tropical origin of a forearc component of northeast Japan. Their paleolatitudes, deduced from paleomagnetic inclinations, however, are significantly lower than those expected from the trajectory of the Pacific Plate. Our model implies that the studied landmass was on the southern part of the boundary between the marginal sea and Pacific Plates.

3.3. 60 to 40 Ma

No reliable paleostress trend for the earliest Paleogene around southwest Japan has been published. We discussed the trend in this book based on microscopic fracture network in Late Cretaceous plutonic rocks (Chapter 4). A possible shift of shear direction from sinistral to dextral is shown in our reconstructions (**Figures 6** and **7**). Although the driving force of the transient stress state has not been identified, the early Paleogene is a period when an asthenospheric injection provoked crustal thinning and formation of intracontinental basins and deformation of the convergent margin [24]. Such an event may have triggered the change in stress state.

From 55 Ma to the present, a reliable, exquisite plate reconstruction model including the southern part of our modeled area was submitted by Hall [25]. According to his compilation, some of today's components of Southeast Asia were confined adjacent to the approaching India, and spreading of the marginal sea in the Pacific region remained stagnant at around 55 Ma. The Philippine Sea Plate had begun to emerge in the equatorial Pacific region at 50 Ma (**Figure 8**). In the southern Pacific, Australia began to migrate northward at around 45 Ma, generating new convergent margins fringing around the Sundaland. The spreading centers in the Celebes Sea and Philippine Sea were active under a backarc setting.

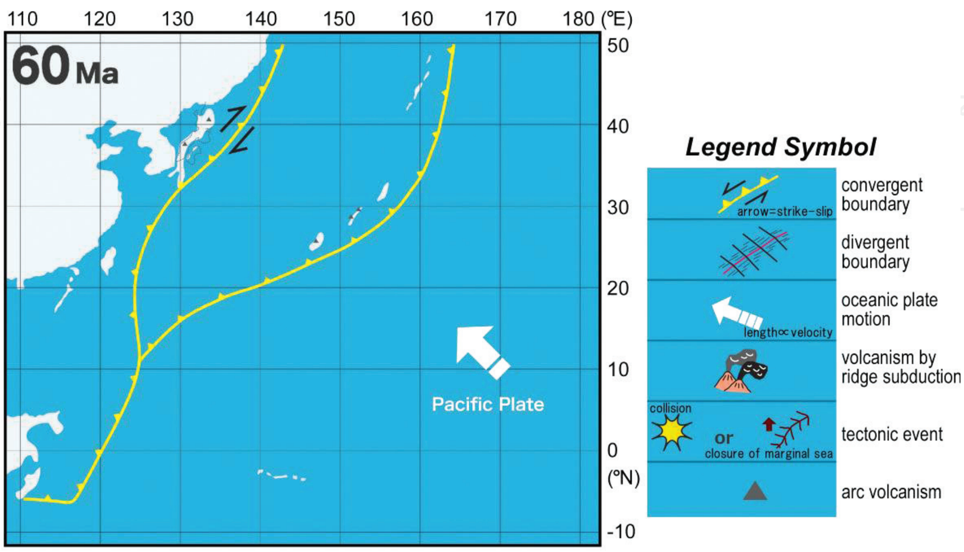

Figure 7. Reconstruction at 60 Ma.

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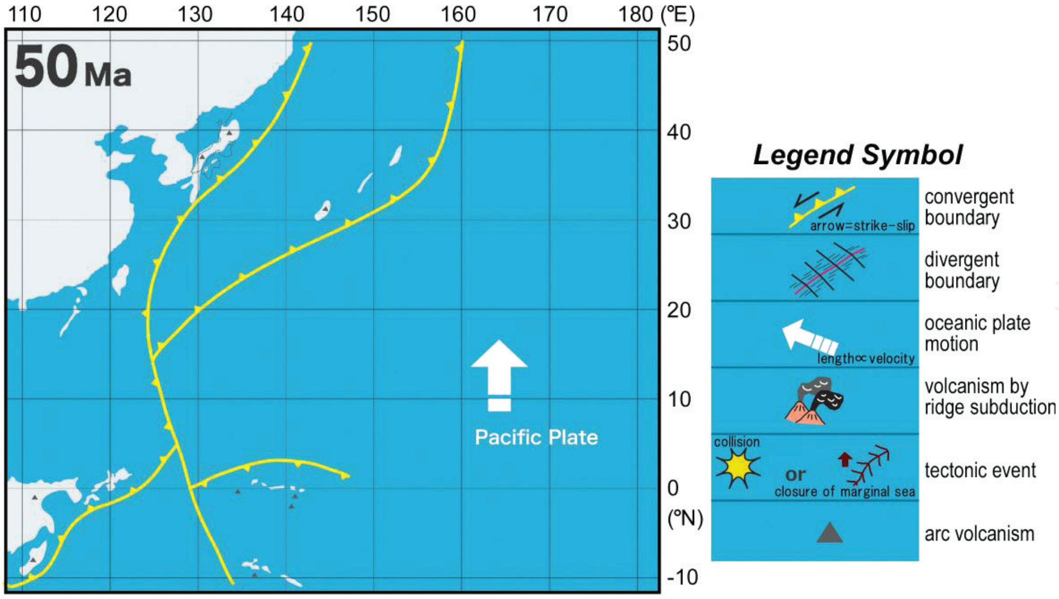

Figure 8. Reconstruction at 50 Ma.

3.4. 40 to 20 Ma

As expressed by the famous bight between the Emperor Sea Mount Chain and the Hawaiian Islands, the Pacific Plate shifted its motion counterclockwise around 45–40 Ma (**Figure 9**). Since then, the Pacific Plate has been steadily moving westward. Its linear velocity in each epoch was calibrated based on data tables in Ref. [1].

After the Middle Eocene development of fluvial to estuarine basins buried by coal-bearing clastics, central Hokkaido and the forearc area of northeast Japan became a site of intermittent subsidence [26]. Our model relates this phenomenon to shifting of the Pacific Plate motion

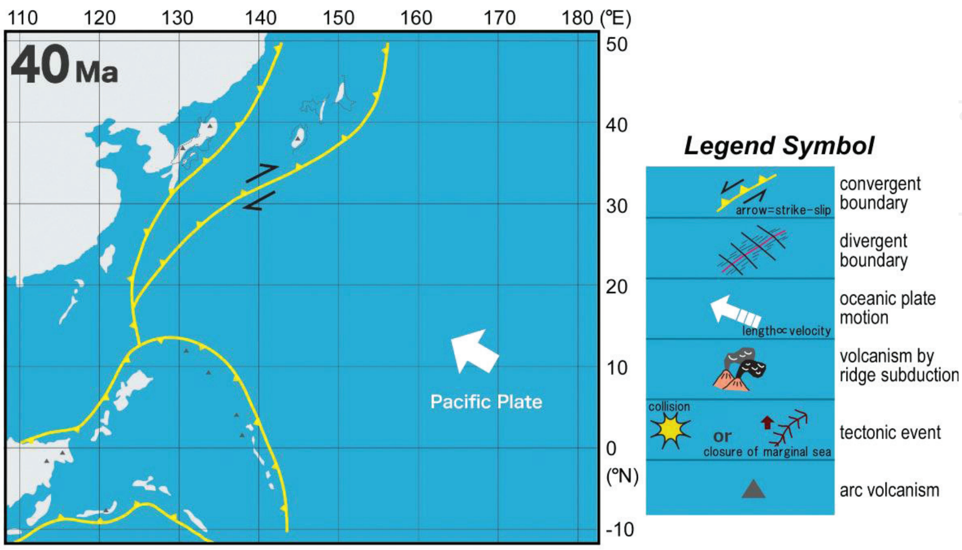

Figure 9. Reconstruction at 40 Ma.

and prevailing dextral shear on the eastern border of the marginal sea plate. Numerical models constructed in a geophysical study suggested that several transcurrent faults with dextral slips can restore the actual spatiotemporal distribution of the sedimentary basins throughout the Paleogene [18].

The most noted Paleogene tectonic event around the northwestern Pacific margin is the formation of the regional Oligocene unconformity (Ounc; [26]), a systematic description of which is given in Chapter 1. Our reconstruction regarded this event as an effect of strong compressive stress raised by the closure of the marginal sea plate and subsequent collision of island arcs at ca. 30 Ma (**Figure 10**). At that point, all of the components of the present-day arc-trench system had arrived at the northwestern Pacific margin.

The proto-Philippine Sea Plate continued to expand at 40 Ma [25]. The azimuth of its spreading center had been fixed in an eastwest direction. To the west, India was about to collide against Eurasia. At 35 Ma, divergence in the Celebes Sea became stagnant, whereas the east-west trending ridge in the proto-Philippine Sea continued to spread. The early phase of the formation of the Philippine Sea Plate had come to an end by ca. 30 Ma. The marginal sea was surrounded by subduction zones.

In Hall's [25, 27] reconstruction, the Philippine Sea Plate began to rotate clockwise around the beginning of the Miocene (24 Ma) accompanied with strike-slip (sinistral) motion in northern New Guinea. We can see an embryotic spreading center along the northeastern margin of the plate. It seems, however, that many ambiguous points remain with regard to the kinematic model of the rotation event. Recently, Kimura et al. [28] advocated that the Philippine Sea Plate swiftly rotated clockwise nearly simultaneous with the clockwise motion of southwest Japan driven by the Miocene backarc opening of the Japan Sea. On the other hand, Yamazaki et al. [29] stated that the main rotation phase of the Philippine Sea Plate took place before 25 Ma based on newly obtained paleomagnetic data from the northwestern part of the plate. The authors refrain from giving final judgment on such a chaotic condition because further investigation based on firm geochronological information is needed.

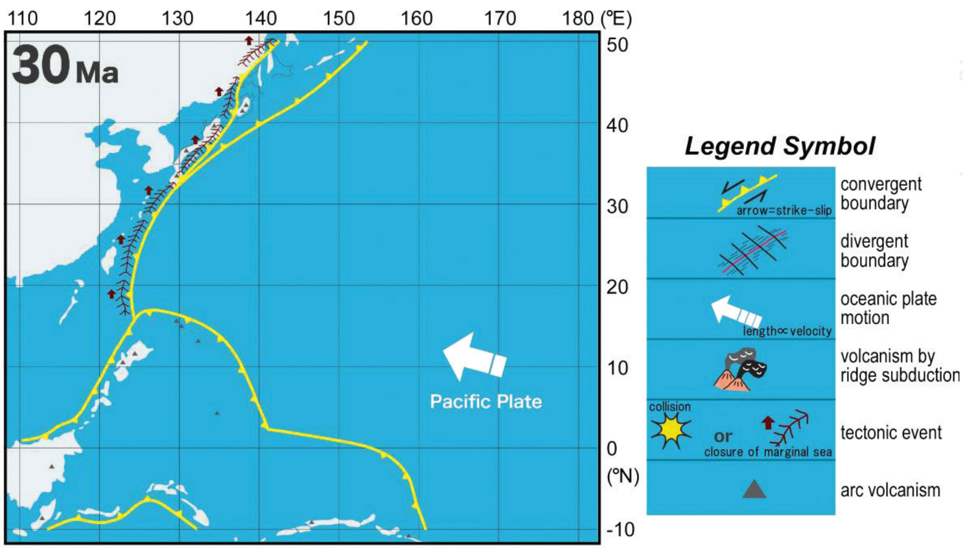

Figure 10. Reconstruction at 30 Ma.

3.5. 20 Ma to present

An interpretation of reflection seismic data covering the offshore forearc region of northeast Japan [17] depicted a series of transcurrent faults cutting slantwise through the arc. Based on a conspicuous trend of offshore geomagnetic anomalies, the distribution of Paleogene arc volcanism and a provenance study of the coeval detritus within forearc basins, Itoh and Tsuru [17] restored the arc-arc junction, and advocated more than 200 km of dextral displacement on the fault zone since the Oligocene period. Its ongoing status is delineated in the reconstruction at 20 Ma (**Figure 11**).

In addition to prevailing dextral motion on an arc-bisecting fault zone, numerical modeling by Kusumoto et al. [18] clarified that an eastwest compression and reverse fault motion must have emerged to restore the configuration of the elongate basin of the Middle Miocene Kawabata Formation in central Hokkaido. This may be linked to the initiation of the collision between the Kurile and northeast Japan arcs.

Although some ambiguous points remain, energetic paleomagnetic studies by Otofuji and his colleagues (e.g., [30]) confirmed that the rifting and backarc opening in the Japan Sea occurred in a relatively short period not later than 15 Ma. The spatiotemporal distribution of marine sediments on the Japanese backarc supports their working hypothesis. A paleomagnetic study in the eastern part of southwest Japan revealed that arc bending had occurred after the Japan Sea backarc opening. Based on a reconstruction of terrane arrangement, Itoh [31] argued that the collision of the proto-Izu arc had precipitated the bending event, which is a significant constraint on the coeval position of the eastern margin of the Philippine Sea Plate. Geological evidence in the South Fossa Magna tectonic zone suggests multiple collisions of landmasses on the Izu-Bonin arc, namely the Kushigatayama, Misaka, Tanzawa, and present Izu Peninsula [32]. It seems that the eastern margin of the Philippine Sea Plate has been anchored in front of the easternmost part of southwest Japan since 15 Ma.

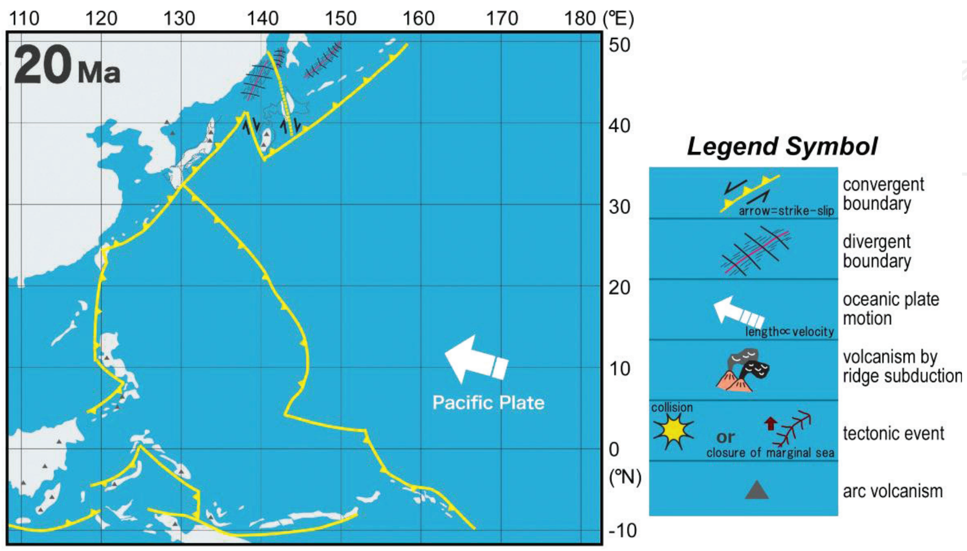

Figure 11. Reconstruction at 20 Ma.

Regardless of the theories described in the previous section we adopt, clockwise rotation of the Philippine Sea Plate and spreading of the Shikoku Basin were about to terminate by 15 Ma. Within the Philippine Sea Plate, extension of the Sula Spur was still active, forming the North Banda Sea by ca. 10 Ma. To the west of our mapped area, the Java Trench subduction zone began to roll back, causing extension of the Sundaland Margin [25]. At around 5 Ma, the South Banda Sea was being formed, whereas the Molucca Sea subduction was almost complete and the Halmahera and Sangihe arcs were about to collide. We can see volcanism as a precursor to rifting on the Mariana arc (**Figure 12**). A marine geological survey and geomagnetic anomaly modeling revealed the latest rifting event in the Okinawa Trough since the end of Pliocene [33]. Our model incorporates its configuration. Spreading on the Mariana arc still continues now, and the basin floor is widening [25].

Around southwest Japan, the most remarkable event in the second half of this interval is a strong contraction on its backarc side and the formation of a regional unconformity. Itoh and Nagasaki [34], based on interpretation of seismic reflection data, clarified that an eastwest folded zone on land continues onto the whole backarc shelf. Although the driving force of the tectonic episode has not been fully elucidated, some hypothesize that revitalized subduction of the Philippine Sea Plate is responsible for the regional arc deformation (e.g., [28]). If this is the case, the motion history of the oceanic plate should be reexamined in light of deformation trends on the convergent margin.

Based on submarine geomorphology and geology around the collision front of the Izu Peninsula, Nakamura et al. [35] advocated that a counterclockwise shift of the converging direction of the Philippine Sea Plate occurred around 2–1 Ma. Their finding has a great significance in the field of active tectonics because west-northwestward motion of the oceanic

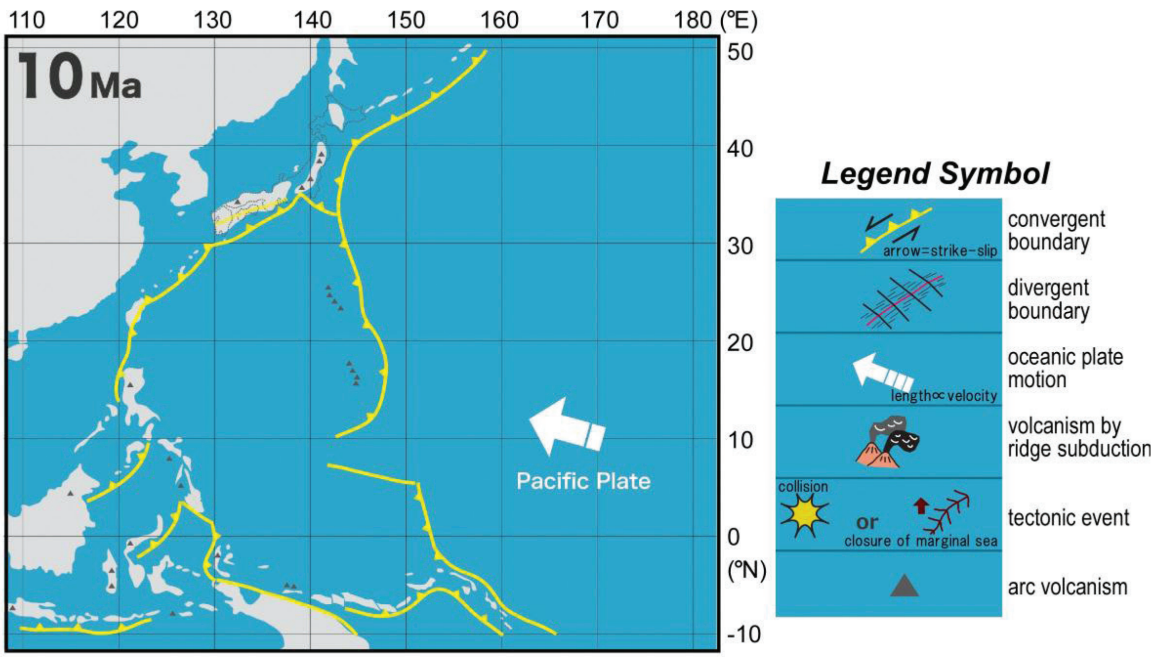

Figure 12. Reconstruction at 10 Ma.

plate enhances right-lateral slips on the arc-bisecting Median Tectonic Line and development of intra-arc basins controlled by activity on numerous secondary faults in southwest Japan. A temporal change in the motion of the Philippine Sea Plate also caused extensive wrench deformation of southwest Japan. Based on an integrated analysis of seismic data, geological and geomorphological evidence, Itoh et al. [36] clarified that the island arc is a continental sliver put between regional transcurrent faults with active dextral slips. A closer look at the spatiotemporal deformation trends in southwest Japan [37] shows a complex pattern of contraction and extension features, which are comprehensively understood as the effect of a transient converging azimuth and migration of the Euler pole of the Philippine Sea Plate. Further investigation of tectonic episodes on the circum-Pacific convergent margins will pave the way for improved plate reconstruction.

4. Conclusions

Our thoroughgoing examination has indicated the spatiotemporal positions of diverse tectonic events around the northwestern Pacific. The evolution of the Pacific margin is viewed as a history of migration/amalgamation of allochthonous blocks onto the subduction zone. In order to reconcile paradoxical discrepancies in the docking process of genetically grouped arc components like the "forearc basin", the authors introduced a marginal sea plate with a spreading center that was alive in the Cretaceous. Oblique subduction of the ridge caused specific migratory igneous activity along the rim of the overriding plates, together with flips of shearing direction. Arc-trench systems on the eastern and western sides of the marginal sea plate developed following different timelines and were eventually mixed up during the Oligocene closure of the plate. This phenomenon is now recognized as a coincident regional clinounconformity on the Eurasian margin. Since the demise of the hypothetical plate, the tectonic regime of the northwestern Pacific margin has been controlled by the growth of the Philippine Sea Plate. Accurate restoration of its rotational history and modes of convergence should be pursued through further quantitative research on the geodynamics of active circum-Pacific margins.

As for the present result, a live show is available on the platform of Dagik Earth (three-dimensional digital globe), which is a project by the visualization group of the earth science hub of Kyoto University (http://earth.dagik.org). Anyone can access our plate model (http://dagik.org/menu/land/Dagik_NWPacific_100my/e) as animated cartoons by means of a web browser.

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