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Tectonic Process of the Sedimentary Basin Formation and Evolution in the Late Cenozoic Arc-Arc Collision Zone, Central Japan

Akira Takeuchi

1. Introduction

The Japanese archipelagoes in the northwest Pacific consist of southwest Japan arc, Izu - Ogasawara arc, Ryukyu arc and Northeast Japan arc and Krile arc, and the Japan Sea is a marginal sea of northeast Asian continent separated from the northwest Pacific by three islands of Sakhalin, Hokkaido, and Honshu. The thrust-and-fold zones of the Neogene and Quaternary systems in the coastal tectonic belt along the eastern margin of Japan Sea continue their activity until now. Particularly, the seismogenic zone continued from Sakhalin is arrested with the convergent boundary between Amur Plate and the Okhotsk Plate because reverse-fault type of earthquakes with magnitudes larger than 7.4 in Richter's scale have been occurred along this heteromorphic belt every several hundred years. From this point of view to the plate tectonic condition around Japan, the central Japan acts as a multiple junction area unique in the earth, where four pieces of plates, such as the Amur, the Okhotsk, the Philippine Sea, and the Pacific plates, gather and converge together in and around the Japanese archipelagoes (Figure 1). Although the GPS geodetic observations confirmed the presence of the micro-plates [3-5], the structural features of the incipient boundary between the Okhotsk and Amur Plates seemed still immature but recognized as strain accumulated zone along the eastern margin of Japan Sea [6-11].

The Pacific plate have subducted beneath the Okhotsk, the Philippine Sea, and Amur plates which are converging together. In particular, central Japan is the place where the Southwest Japan, the Northeast Japan, the Izu-Ogasawara arcs mutually collide, and therefore the process and mechanism of the development of geologic structures here is quite complicated and hard to be interpreted. Lately, in such situation, the damaging earthquakes of the middle scale have
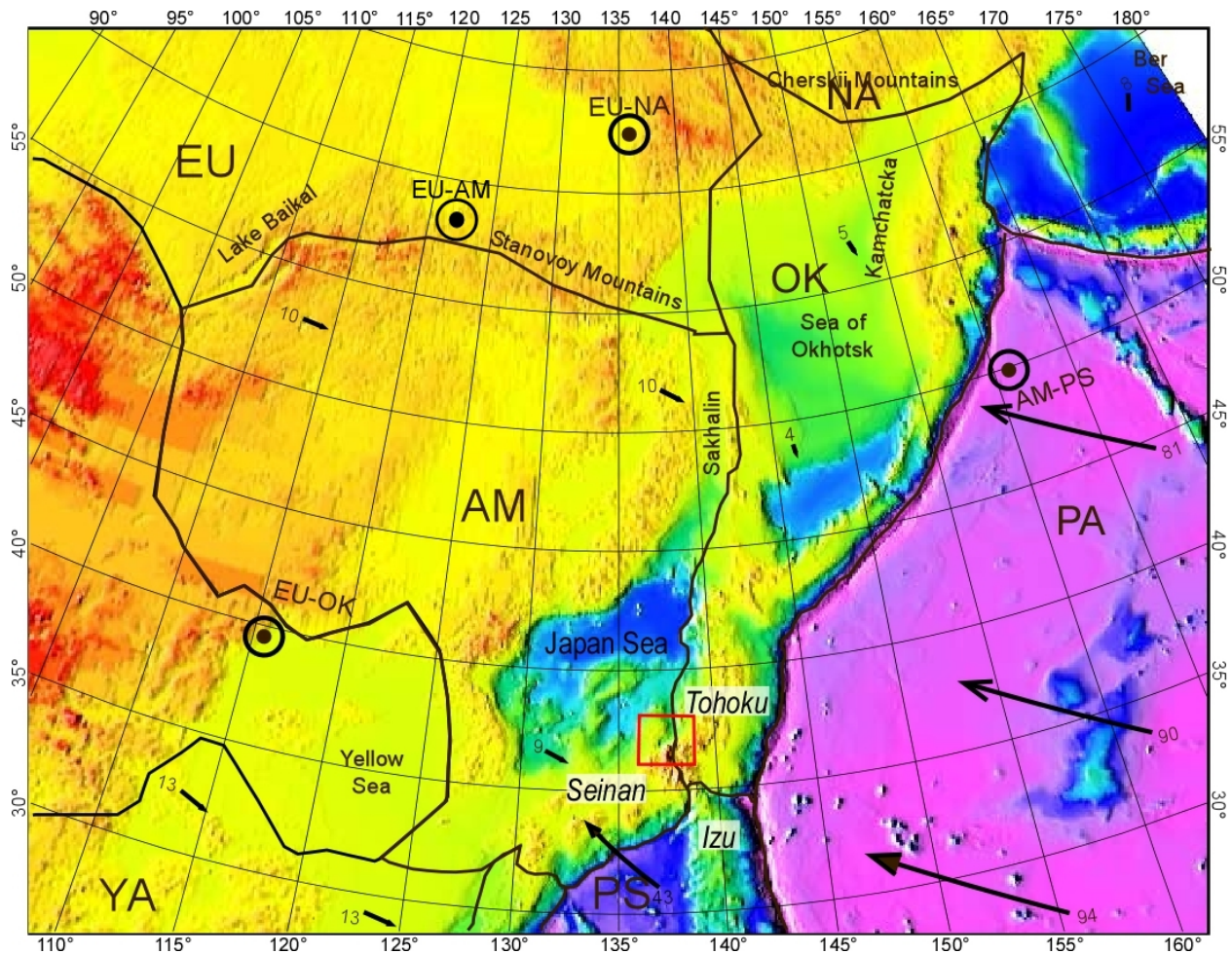
Figure 1. Index Map of Plate Framework in the Northeast Asia. Study area is depicted by open red box. Boundaries of the Okhotsk (OK) and Amur (AM) plates are shown. Surrounding plates include Eurasia (EU), North America (NA), Pacific (PA), Philippine Sea (PS), and Yangtze (YA). Black vectors give model velocities (with numbers in mm/a) relative to plate whose identifier is underlined. Black circles are locations of Euler poles. Simplified from [1] with an addition of Euler pole EU-AM [2].

occurred in the Japan Sea side of the central Japan in succession. In 2004, the Chuetsu earthquake (M_W6.6) occured in the inland Chuetsu area, Niigata Prefecture. Two years and nine months later, in 2007, the Noto Peninsula earthquake (M_W6.7) occurred at a 11km deep hypocenter beneath the west coast of northern Noto Peninsula. Then, only 3.7 months later, the Niigata Prefecture Chuetsu-oki earthquake (M_W6.7) occurred approximately 15km in depth, 32km distant from the epicenter of the 2004 earthquake, attracting an attention to the relations of three earthquakes from a time-space point of view. Furthermore, the Naganoken Hokubu earthquake (M_W 6.35) was generated by the hypocenter 8km in depth at a moment 13 hours 13 minutes after the 2011 off the Pacific coast of Tohoku Earthquake (M_W 9.0) occurred in the Japan Trench on March 11, 2011.

As for the generation style of middle scale and larger earthquakes occurring along the eastern margin of Japan Sea, including the above mentioned earthquakes in central Japan, major listric faults contributed with back arc spreading during the Miocene has been explained as inversion

tectonics which inverted the sense of faulting from normal dip-slip into the reverse slip since the Pliocene. However, the western Noto Peninsula earthquake and the Naganoken Hokubu earthquake were the focal mechanisms that they could not be explained by means of simple inversion tectonics concerning the geologic structure of shallower layers so far. Main shocks of these earthquakes are commonly occuured around 15km in depth, which is almost equivalent to the basal depth of the seismogenic layer.

Since the thick sedimentary cover of the seismogenic layer has been remarkably deformed into faulted and folded structures, the character of tectonics in progress at the Present is questionable whether thin-skinned tectonics or basement-involved tectonics, being concerned with the presence of the detachment surface between the seismogenic layer and the sedimentary cover [12-14]. Thus, this paper discusses the formation process of sedimentary basins in the collision zone between island arcs from the viewpoint of earthquake tectonics about the recent crustal earthquakes. For the purpose of elucidating the active tectonics (crustal movement in progress) along the Japan Sea coast in central Japan, this paper focuses on the specificity of the geologic structure and geomorphology of Eastern Hokuriku district and Fossa Magna - Toyama Trough region, and traces the history of geomorphologic and geologic development in order to propose a comprehensive relation with earthquake occurrence and crustal movement.

## 2. The features and development process of geomorphology and geologic structure

2.1. Target area

The target area for this paper, the Hokuriku-Shin'etsu district, is composed of three adjacent Neogene sedimentary basins located in the Japan Sea side of central Japan including the seabed area (Toyama Trough) between Noto Peninsula and Sado Island (Figure 2). The trough is administratively enclosed by Ishikawa, Toyama, and Niigata Prefectures. During the early to middle Miocene periods the Hokuriku, Shin'etsu, and Niigata basins had developed obliquely upon the basement geologic zones geotectonically belonging to the inner belt of pre-Cenozoic Southwest Japan. Although Shin'etsu, and Niigata basins tends to be treated as a single sedimentary basin, herein, the most part of Niigata basin is excluded from the Fossa Magna area as long as geomorphology and geologic history are concerned [17, 18]. In addition, the north-south trending, narrow basin in the central part of continental slope offing the Japan Sea side of Honshu, the Toyama Trough, borders Northeast Japan and Southwest Japan in the seabed area.

2.2. Tectonic provinces of target area

When a zonal division is available on the basis of regional characteristics of fault distribution such as fault length and orientation, inclination, type of displacement sense (normal, reverse, or strike-slip), and the density of fault distribution in a certain geological age, a tectonic unit in this paper is defined as a fault province. A fault province composed of active faults is called
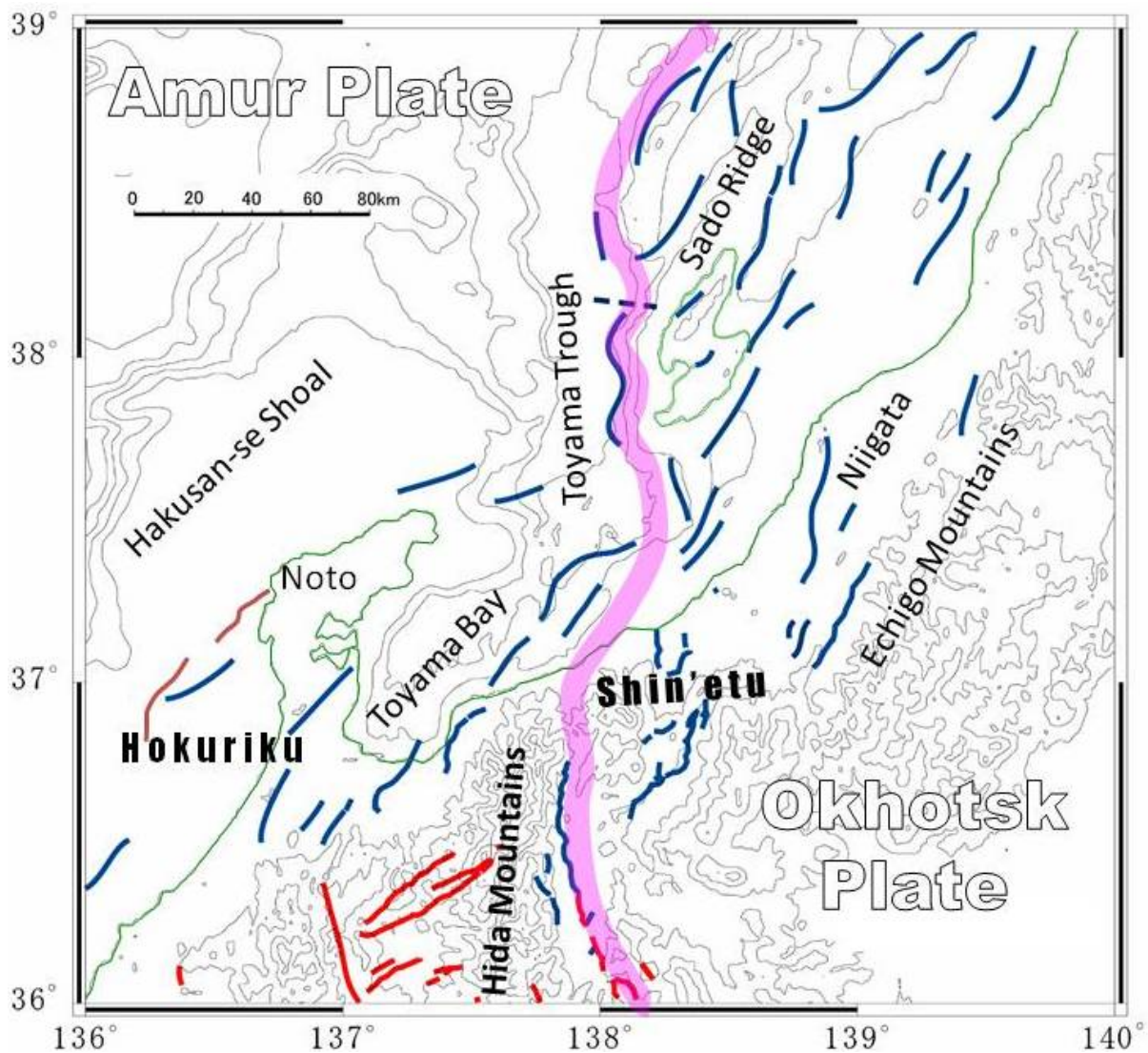
Figure 2. Index Map of Active Faults for the central Japan. Blue line denotes reverse fault, red does strike-slip fault. Thick pink line indicates plate boundary between Amur and Okhotsk plates. Place names are also indicated. Simplified and compiled from [15, 16].

an active fault province which reflects regional characteristics of the seismogenic stress field. From this point of view to the recent crustal movement regionally in a geodetic to geological time scale, a strain concentration zone denotes a geodetic zone where a pattern of displacement field demonstrates a belt of larger strain rate, and geologically it corresponds to a zone where deformation structures such as faults and/or folds develop intensively [6, 9, 19, 20].

Including Mizuho-Fossa Magna folded belt [21], concentrated deformation belts were known in many places in the Cenozoic Japan, but existence of the Niigata - Kobe tectonic belt [19] becomes recognized by the GPS precise geodetic observation network of Geospacial Information Authority of Japan (GSI) having been maintained in and after 1995.

Figure 2 shows active fault distribution [16] and the active fault province [15, 22] of the inner Chubu District. The reverse fault province occupies the inner Tohoku arc and the strike-slip

fault province is located inland area adjacent to the Hida mountain range. Concerning generation of earthquakes in the inland crust, the strong shortening in the Niigata - Kobe tectonic belt lately has attracted attention by intersecting the active fault provinces and the plate boundary between the Amur and Okhotsk plates, Itoigawa - Shizuoka tectonic line as is recognized from Figure 3.
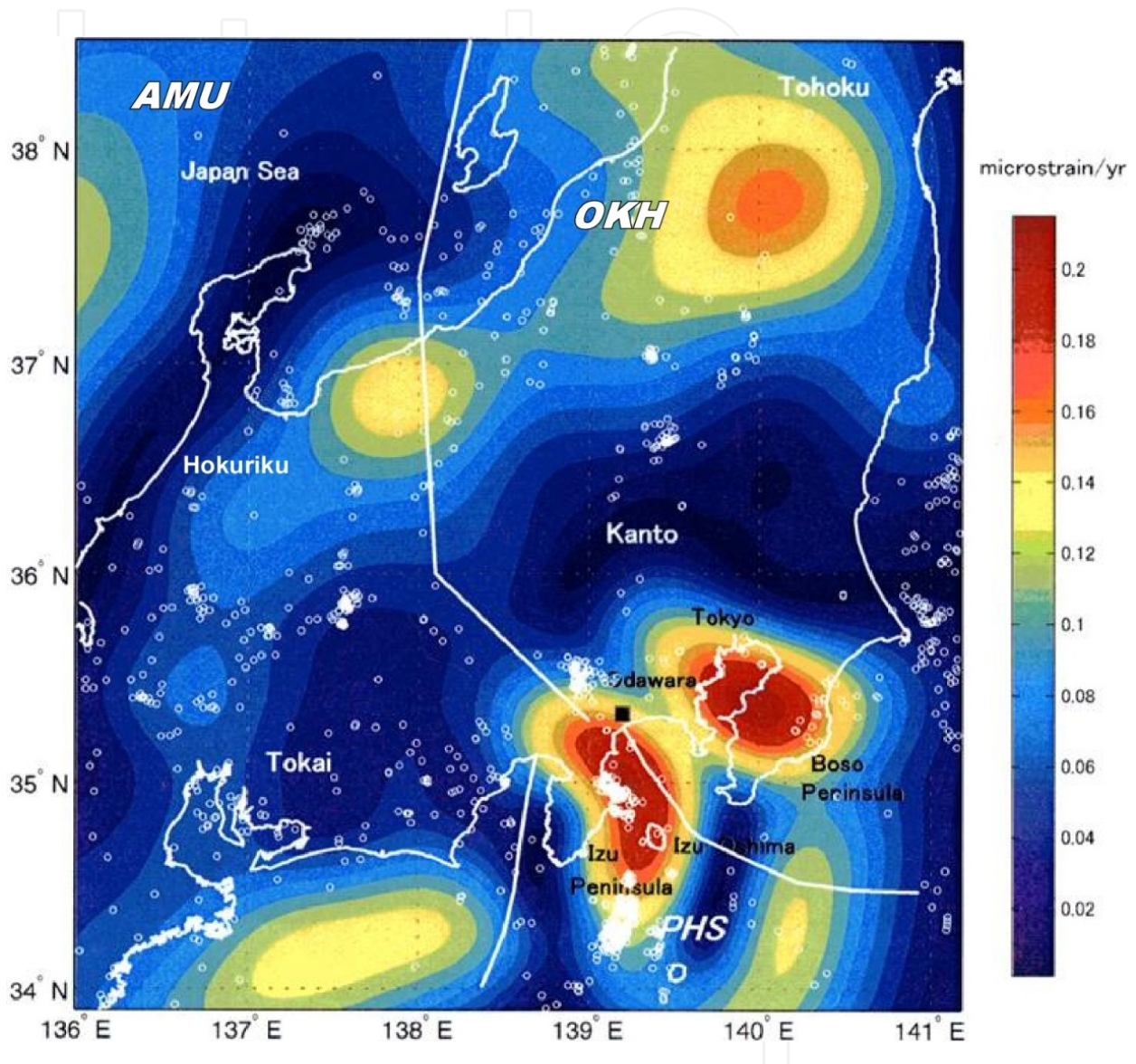
Figure 3. Maximum shear strain rates in central Japan. Estimated from the two-year improved time series data from April 1996 to March 1998 [25]. White circles indicate epicenters of the earthquakes with depths shallower than 30 km and magnitudes greater than 3.0 during the period from January 1996 to March 1998. Note that the strain distribution belt intersects the Itoigawa-Shizuoka tectonic line bounding Amur and Okhotsk plates. This belt corresponds to the Shinanogawa seismic zone and Atotsugawa fault zone in the Niigata Kobe tectonic zone [19].

2.3. Plate tectonic framework

From the plate tectonic point of view, the central Japan acts as a multiple junction area unique in the earth where four pieces of plates, such as the Amur, the Okhotsk, the Philippine Sea,

and the Pacific plates, gather and converge together in and around the Japanese archipelagoes. The border of Amur plate and the Okhotsk plate has just jumped from the west margin of the Hidaka Mountain Range into the eastern margin of Japan Sea at about 0.5Ma. The former plate boundary between the North American plate and the Eurasian plate had been situated in the central Hokkaido where another collision between the Kurile and the Tohoku arcs had performed. As for the Seinan fore-arc, the commencement of subduction with the northing of Philippine Sea plate was represented by the 15Ma intrusions of outer-zone granite and the bended structure of the earlier Nankai trough caused by the paleo-Izu indentation at 15-14Ma. This remarkable transition might have affected the convergent boundary between the Eurasia plate and the North America plate and the both continental plates would be put together in the collision state. Contrastingly, the Pacific plate has continued almost steady subduction along the Japan Trench for the past 40 million years without significant change in the north-westward motion, despite tectonic episodes of back-arc spreading in Japan Sea, Okhotsk Sea and Shikoku Basin.

In the eastern margin of Japan Sea and the Fossa Magna region, the environment of the crustal movement switched totally from the calm period in the late half of Miocene to the Pliocene contraction tectonics. The start of folding in the northern Fossa Magna region dates up by evidence of the paleomagnetism in at least 4Ma [24]. However, the start of folding was much older because of the sedimentological fact that turbidite flowed down the trough-like basins of syncline and the stratigraphic fact that the base of Pliocene andesites (5.4Ma) covered obliquely the anticline which has already begun growth [25-27].

By the way, due to the migration of trench triple junction, the moving direction of the Philippine Sea plate switched at 3Ma from the north direction to northwest [28], and, therefore, the colliding force against the border area between east and west Japan as well as the southern Fossa Magna should have weakened in comparison with the past. The contraction tectonics in the Japan Sea side could be attributed to starting of eastward motion of the Amur plate, because the start of the contractinal tectonics in the eastern margin of Japan Sea was significantly older than 3Ma.

2.4. Time scale setting

As for the upper Cenozoic system distributed over the Hokuriku and Shin'etsu areas, the biochronological stratigraphy was almost established in the 1980s [29-31]. A complicated stratigraphy on terrestrial sediments of the lower Cenozoic system widely distributed in Noto Peninsula has become elucidated based on age-determination data of volcanic rocks [31].

In addition, in late years for the purpose of analysis of the marine paleoenvironment, high precision chronostratigraphy is performed by means of age-marker for the period after the Pleistocene in particular.

Based on the recent advance in the Pliocene stratigraphic correlation and age determination of tephra distributed widely over the central Japan [32, 33], there was large progress for historical studies on the fault activities and upheaval of Hida Mountain ranges [34-36]. In

conformity with these results, this paper also obeys a new definition of the Quaternary period recently revised by the International Stratigraphic Committee (http://quaternary.stratigraphy.org/definitions/).

3. Formation and development of sedimentary basins

The Present Hida Plateau and Noto Peninsula are upheaval zones which expose the basement rocks of pre-Cenozoic system, and are different from the Present coastal plains and near shore waters which comprise the thick sedimentary layers. As for the approximately 5 million years period previous than 1 million years ago, it is thought that the area of Noto Peninsula is a large terriginous flat or is a very shallow archipelago [30], and that this area formed a peninsula after 0.5 Ma [38]. This paper considers the geomorphplogical development of the seabed and coastal places of Japan Sea mainly for block structures of Honshu Island since the Oligocene, with paying attention to the following five stages of crustal movement concerned with a geological development of Southwest Japan west of the Itoigawa-Shizuoka tectonic line. Besides, Northeast Japan saying in this paper includes the northern Fossa Magna region for convenience and excludes the southern Fossa Magna region.

3.1. Rifting phase [32 Ma — 28 Ma]

The drillings into Japan Basin and Yamato Basin conducted in 1989 by International Ocean Drilling Program (ODP) provided an important data related to the timing of formation of the Japan Sea area. According to [39], the formation of the Japan Basin began by thinning of the continental crust in the early Oligocene (32 Ma), and such a tectonic style changed into expanding of the sea floor in the late Oligocene (28 Ma).

3.2. Sea floor spreading phase [28Ma — 18Ma]

The tectonic domain of the sea floor spreading in the Japan Sea area had moved from the widened Japan Basin area to the southwest, and formed both Yamato Basin and Tsushima Basin by crustal expansion, but it ceased in 18 million years ago [39-42]. The rifted structures with trends of north-south direction or northwest-southeast were formed in Toyama Trough and the Hokuriku and Niigata areas in the period from the end of Oligocene to the early Miocene [43-45]. In the Hokuriku district in the middle Early Miocene (20Ma-18Ma), submarine volcanic activities occurred and tearing of the basement, i.e. intra-arc rifting, formed graben-like depressions. According to[46], tectonically distinct boundary between Tohoku and Seinan Honshu arcs had been formed or activated at the end of this phase. Toyama Bay was originally an embayment that branched off the Toyama Trough into the Hokuriku area, and the sea-bottom faults along the coastal line were activated for the period of opening of Japan Sea [9].

3.3. Sedimentary-basin forming stage [18Ma — 15Ma]

Marine sedimentary basins were formed by sudden subsidence to reach 3,000m during this period in the Hokuriku district [30, 47, 48]. These sedimentary basins are located in the almost same places of the Present coastal alluvial plains including Kaga and Toyama Plains.

Intense volcanic activities occurred in the inner belt of Honshu arc on the Japan Sea side of Tohoku region, and submarine volcaniclastics known as 'green tuff' deposited in the period from 24Ma to 14Ma. In detail, around the time of 17Ma, southerly warm current water called 'paleo-Kuroshio' had become to emerge the back arc area, and then in substitution relatively calm subsidence commenced at 16Ma. During the period from 15Ma to 14Ma, marine transgression enlarged the entire intra-arc area, and the bathypelagic black mudstones (Nanatani Formation and its correlatives) were deposited in seabed area where the previous morphologic ups and downs would be buried.

In the Hokuriku district, the depth of the bedrock is at least 2,000m - 3,000m for last Neogene of Kaga - Toyama plains sandwiched between Noto Peninsula and the Hida Highlands [50]. In addition, the zone of relatively high-density rocks such as andesite and basalt lavas occupying the graben-like depressions of the basement is expressed as the narrow zone of highly positive features of Bouguer gravity anomaly [51-54, 35]. These kinds of volcanism are not product of the pervious syn-rift phase of back-arc spreading but of the intra-arc rifting due to commencement of arc volcanism of the Honshu arc [29, 31, 35].

3.4. Basin differentiation phase [15Ma — 5Ma]

Lateral variations in thickness of the middle to upper Miocene strata among the sedimentary basins became remarkable in this period. Spatial variety in sedimentary thickness of individual deposition centers were well documented in the Shin'etsu sedimentary basin, suggesting a syn-sedimentary fault-block movement [25]. In the Hokuriku district, however, the Present-day hilly and mountainous countries including Iouzen-Hodatsu Hill, Imizu Hill, and Yatsuo area and Noto Peninsula bordered the sedimentation basins, where the rates of sedimentation reduced during the time from 15 Ma until 13 Ma[55].

As for the Shimane Peninsula in the San-in district of the western Seinan arc, [56] mentioned that the sedimentary basin had begun its inversion tectonics under the crustal stress field of the north-south compression in 14 million years ago, and the formation of the Shinji folded zone was completed in 6 million years ago [57-59]. The expanse of such the north-south compression field became broader, and the concentrated zone of east-west trending reverse faults and related folds parallel to the Southwest Japan arc developed from San-in to Hokuriku districts in the Japan Sea side from 8 million years ago [60]. The late-Miocene east-westerly deformation zone in the Hokuriku district includes Houdatsu-san Kita fault zone in the southern part of Noto peninsula and Wakayama-gawa fault zone and in northern Noto Peninsula. Landfill underwent ahead through the Hokuriku sedimentary basin from the side of Hida area towards the former Toyama Bay. In the Noto Peninsula, however, nanofossil chronostratigraphy detected several times of hiatuses when glauconites produced on the

seabed after the Middle Miocene [55, 61]. Therefore the Present Toyama Bay is the remains of the Miocene graben half of which had been filled with the sediment [9].

3.5. Evolving stage [5Ma — Present]

Upheaval and subsidence (i.e. undulation of the basement) with axes striking north-south began in the later Pliocene in the eastern part of Southwest Japan, but another tectonic regime of northwest-southeast compression has superposed by the collision with the Izu arc, and the structural trend in the northeast-southwest direction reaches the expression of remarkable current active structure [22, 59, 62, 63]. The fault block movement of this stage is a process of modification where the existing geologic structure change into new one, and is deeply participated in the geomorphology development such as Hida Mountain Ranges, Noto Peninsula, and Toyama Bay in the Present period. This process did not begin at the same time in all the areas of Southwest Japan, but a tendency to migrate from the southeast (the Tokai district) to the northwest (the Hokuriku district and the Kinki district) and to the northeast (the northern Fossa Magna) is recognized [64, 65]. In addition, the inversion process included locally the one of fault-slip sense where former normal faults trending north-south to northeast-southwest directions became re-activated as reverse faults (e.g., Kureha-yama fault: [66]). In the Hokuriku district of the Neogene sedimentary basins, however, alluvial plains continue their sedimentation without performing "basin inversion" like the Miocene Shin'etsu sedimentary basin, where the whole area of subsidence with thick sedimentary layers had changed reversely into the upheaval zone [27-29].

4. Tectonic inversion of sedimentary basins and related faults

The style and degree of basin inversion varies from the Tohoku arc to the Seinan arc. Although any collisional inversion of continental margin rift complexes did not occur in the Japan margin of Amur Plate, the whole basin uplift and major structural inversions with substantial thrust reactivation of earlier extensional structures have performed along the coastal belt of Japan Sea, such as the Shin'etsu basin and Sado ridge on the Tohoku side and Noto and San'in districts on the Seinan side. A gentle inversion of intra-arc rifts has occurred in the Niigata basin. While, in the Hokuriku district, the Miocene sedimentary basins remains as coastal plains or relatively low-lying area where remobilization of earlier master faults is not clear.

Some inversion mechanisms are intrinsic to the existence and lithospheric structure of the basin, and the likelihood of fault reactivation depends on the attitude of the existing fault plane such as the dip and strike to the principal stress axes [67]. If the existing fault were too steep, antithetic accessary faults might develop as new reverse faults in the footwall of the earlier extensional fault.

Figure 4 illustrates the spatial variation of inversion tectonics. The section is obtained by a tomographic inversion method in the analytical line from the western Fukushima through Echigo Plain, Sado Island and Toyama Trough to Yamato Trough [68]. The earlier normal faults are distinctively distributed in the lower part of Toyama Trough to the northwest on the

Hakusan-se Shoal and in the Yamato Trough, while the later inverted reverse faults developed on Sado Island and Niigata sedimentary basin. The latter corresponds to the strain concentration zone along the eastern margin of Japan Sea [9].
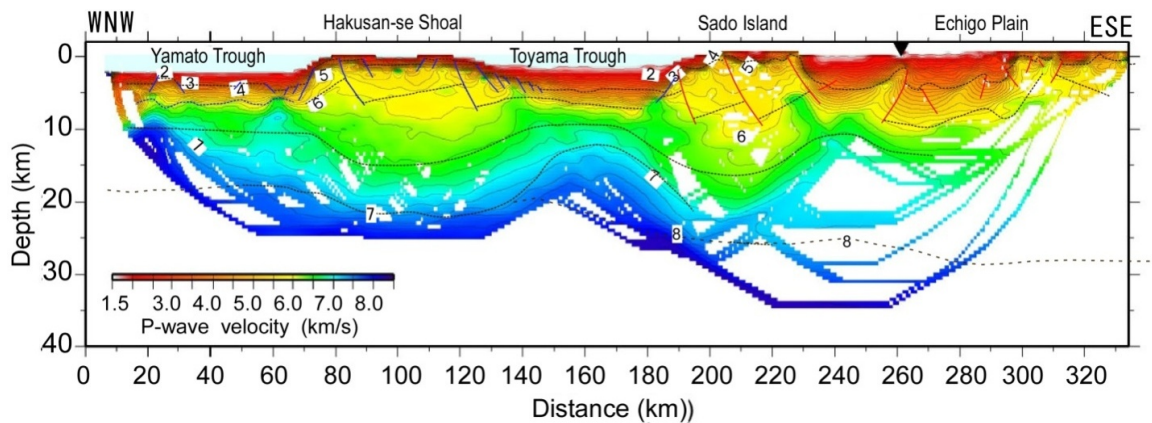
Figure 4. P wave velocity image for the crustal structure. The section is obtained by a tomographic inversion method in the analytical line from the western Fukushima through Echigo Plain, Sado Island and Toyama Trough to Yamato Trough. Faults are distinguished into earlier normal faults (blue) and later inverted reverse faults (red). Note their distinctive distribution. Compiled from [63].

As for the Tohoku arc, the start of eastward motion of Amur Plate at around 5 Ma [69] might have resulted in a new plate boundary along the strain concentration zone since 0.5 Ma. Moreover, [36] examined the U-Pb age data of Kurobegawa granite in the Hida mountain range and concluded that the granites were emplaced incrementally through the amalgamation of many intrusions since the late Miocene up to the latest intrusion event at 0.8 Ma, and that such magmatic intrusions caused rapid uplift and erosion of the Hida mountain range in the Quaternary.

As mentioned already, Japanese archipelagoes forming marginal seas between the northeastern Eurasian Continent and the northwestern Pacific Ocean comprise five island arcs (Kurile, Northeast Japan, Izu-Ogasawara, Southwest Japan, and Ryukyu arcs) which perform collisions each other in their adjacent terminations. Especially in central Japan three arcs (Northeast Japan, Izu-Ogasawara, and southwest Japan arcs) are mutually colliding, where deformed structures and active faults associated with inland crustal earthquakes are concentrated along the fringing zone east and south of Japan Sea. The mobile belt along the Japan margin of Amur Plate runs from Sakhalin - Hokkaido on the Okhotsk plate side, through the volcanic inner zones of the Northeast Japan arc, to the Southwest Japan arc on the Amur plate side [1, 2, 70, 71]. In detail, this belt includes the tectonic zone along eastern margin of Japan Sea, the Noto – San'in tectonic zone, and the Niigata - Kobe tectonic zone. Therefore, such a tectonic phenomenon could not be attributed to back arc compression of a single island-arc due simply to subduction of the oceanic plate on the Pacific side. The belt is situated in a circumference equivalent to the outer margin of the domain of back arc spreading of the Honshu arc.

Such characteristics of deformations and active faults in the inland crust as remarkable along the Japan Sea east margin is not seen at the epicentral and adjacent areas of Mw9.0 class trench-

type earthquakes such as the Chile earthquake (on May 22, 1960 Mw 9.5), the Alaska earthquake (on March 28, 1964 Mw9.2), the Sumatra earthquake (on December 26, 2004 Mw9.0) and others. Conformably, the inland crustal strain accumulation and deformation directly by northwest motion of the Philippine Sea plate is not admitted conspicuous in the inner zone of southwest Japan either. After all the above-mentioned thing is the reason that cannot let the cause of inland East-West compression and the crustal earthquake generation in northeast Japan belong to northwest motion of the Pacific plate directly.

A feature of the tectonic stress field to produce crustal earthquakes can explain this most clearly. As shown in Figure 5, it is significant that a uniform compressional stress field wide spreads over the Japan Sea side of Hokkaido and Honshu, whereas variety of regionality is remarkable as for the Pacific coasts from Hokkaido to Kyushu [72].

5. Summary

5.1. Basin formation

Based on chronostratigraphy of Hokuriku established in late years, geomorphology, geologic structures and history of Hokuriku-Shin'etsu area were briefly summarized as follows.

After the marginal sea, i.e. Japan Sea, had been formed in the back arc area of the Honshu arc during the period from the Oligocene to Miocene time, there occurred broad transgression associated with calming of magma activity followed by cooling in central Japan. As the northward motion of the Philippine Sea plate commenced at around 15Ma, the western half of Honshu arc rotated clockwise with a decrease in area of the Japan Sea, while a buoyant subduction of Izu Arc into Honshu Arc had started.

Consequently, the mega-chasm from Fossa Magna to Toyama Trough was formed above the subducted paleo-Izu arc and the northern extension, and then the single Honshu arc differentiated into the Seinan arc and the Tohoku arc. During this process until 13Ma, the Hokuriku sedimentary basin in the Seinan arc and Shin'etsu and Niigata sedimentary basins in the Tohoku arc were developed in the Japan Sea side in the short term.

5.2. First tectonic inversion

According to [67], it is possible that the tectonic inversion was attributed to temporal variations in stress patterns within plates, resulting from forces caused by changes in plate boundary configuration. The sedimentary basins mentioned above had evolved individually in the period from the late half of middle Miocene to the beginning of the Pliocene. Namely, across-arc contraction tectonics with the E-W trending reverse faults and folds proceeded in the inner zone of Seinan arc, while along-arc subsiding piled up the thick sedimentary sequence in the inner zone of Tohoku arc. The start of buoyant subduction or collision of the Izu arc against the Seinan arc would have changed the configuration and relative motion at nearby plate boundaries as shown in Figure 6.
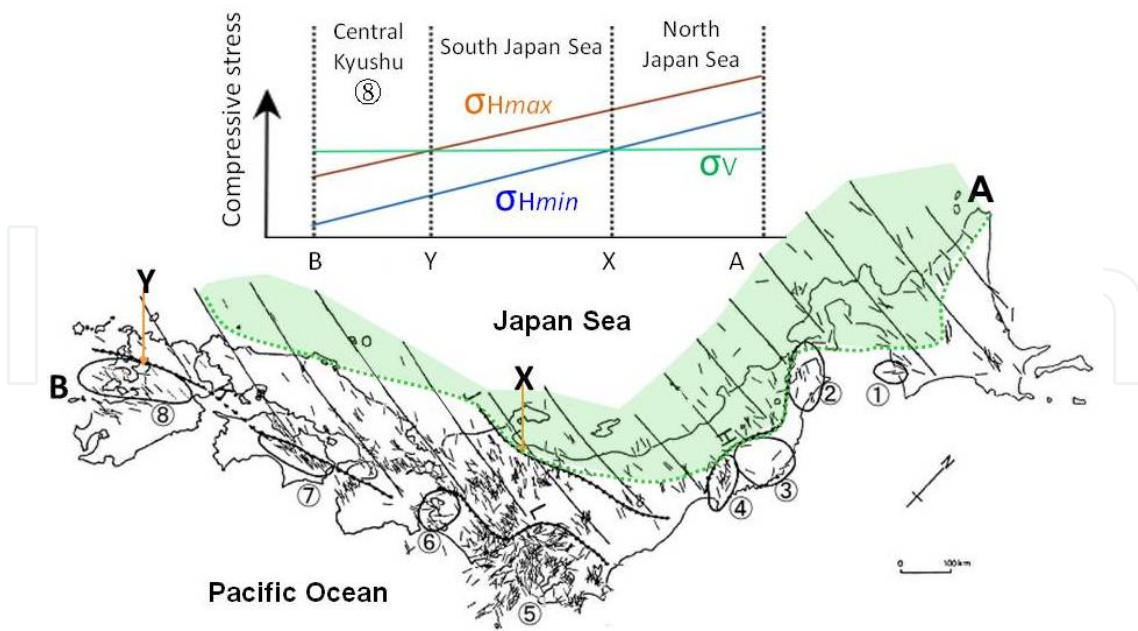
Figure 5. Regional seismogenic stress provinces in Japanese Islands. Inset is a simplified model for variation of fault types due to the along-arc stress gradient of horizontal compression. After [72] with a slight addition.
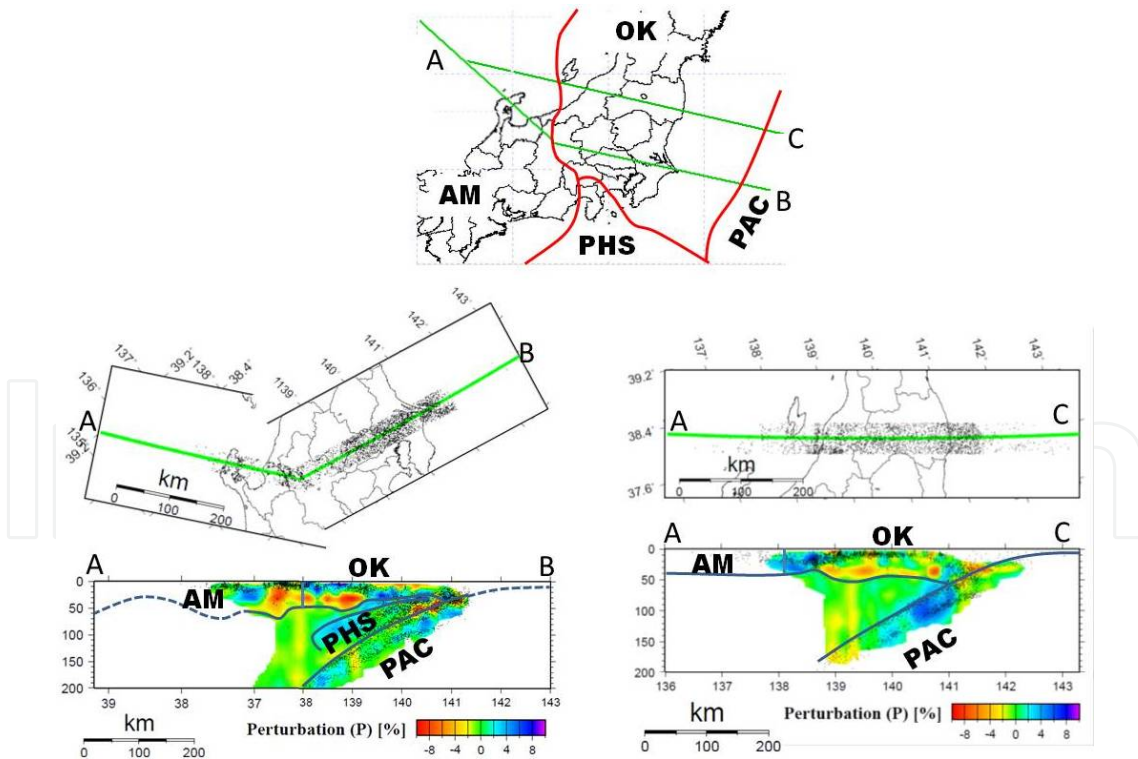
Figure 6. P-wave perturbation structures beneath the central Japan. This section image obtained by high-density seismic stations by seismic tomography using a viewer software developed by NIED to estimate the 3D seismic velocity structure typical of under Japan. Data are quoted from [73]. Tohoku and Seinan arcs are distinctive in rheology structure due to difference in plate configuration.

5.3. Superposition of second inversion

An eastward motion of the Amur plate happened to commence in association with the structural development of Himalaya - Tibetan plateau since the end of Miocene at around 7 Ma. Then the Tohoku, Izu and Seinan arcs started collisions mutually in central Japan, forming a core site of orogeny from where compressional tectonics has gradually spread to *far from the central Fossa Magna to the Niigata*. Therefore, sedimentary basins in the Hokuriku-Shin'etsu area developed deformation structures with reducing the deposition area of clastic sediments and being restricted into the present coastal plains and inland fault-basins. In the Hokuriku-Shin'etsu area after the late Miocene, overlapping of faults and folds in the three structural trends of north-south, east-west, and northeast-southwest is well recognizable and such a superposed structure has been illustrated also by current geomorphology. This intersecting feature has a broad expanse throughout the eastern margin of Japan Sea and is displayed in the seafloor topography conspicuously in particular along the continental slope of Okushiri and the Sado ridges. In addition, Present crustal earthquakes of moderate magnitudes occur by reverse faulting with a sense to promote the geomorphology development of the northeast - southwest direction of hills and mountains surrounding coastal plains evolved from the Miocene sedimentary basin.

5.4. Lateral variation in modes of active tectonics

This paper also noticed the present-day deformed structures and the spatial variety about the existence of basin inversion is also recognized. Namely, in the reverse fault province of Hokuriku, the inversion structure by earlier normal fault which formed the Miocene sedimentary basin is not seen, but typical basin inversion structures are seen in the reverse fault province such as the faults along the western margin of Nagano basin and the middle and northern segment of ISTL in the northern Fossa Magna area.

This cause can be considered as area characteristics of the principal stress axes arrangement by the stress gradient in the seismogenic upper crust. In the former province, stress field is in a state of strong horizontal compression ($\sigma 2 >> \sigma 3 = \sigma V$) and the latter state is somehow neutral ($\sigma 2 \approx \sigma 3$) where a strike-slip faulting is easily exchanged into a reverse faulting ([72]; see Figure 5). Moreover, [35, 48, 74, 75] presented a possible model for the deeper geologic structure, where high-angled block faults among tectonic provinces originated as transform faults and rooted in vertical weak zones in the lower crust beneath the basement of the sedimentary basin.

Based on the sedimentary basin evolution discussed in this paper and in accordance to the results of GPS geodesy and related studies [3-5, 76], the hypothesis of tectonic belt along the eastern margin of Amur Plate [70] is promising for the origin of strain concentration belt running oblique through the zone. This hypothesis includes an eastward motion of the Amur plate with convergence along the east Japan margin and transpression along the west Japan margin as well as its collision in central Japan [1, 2, 71].

6. Conclusion

The development of the thrust/fold belt is attributed not only to horizontal compression but also to vertical block movements as a basement-involved tectonics. In response to the Pliocene and later compression regime, not only master fault but also secondary antithetic faults of the earlier fault-block boundaries are reactivated, and continued differential block movement such as subsiding of the sedimentary basin and uplifting of the igneous provinces.

The Neogene thrust-fault and folded belts in the Tohoku arc comprises the present-day tectonic zone of strain concentration in the sedimentary cover along the eastern margin of Japan Sea and Fossa Magna, while the stress regime of strike-slip faulting occupies the basement as inferred from focal mechanism solutions for small events. In order to account for the tectonic environment, the existence of subducted slab of the Philippine Sea plate, i.e. the paleo-forearc sliver of Izu arc, and related mechanism of rheological accommodation are possibly appreciated to have been worked in the asthenosphere mantle of the late Cenozoic arc-arc collision zone.

In the present study we conclude that an understanding of the tectonics of central Japan arc system provides useful insight into basin formation and evolution in general. The arc-to-arc colliding system in central Japan thus provides one of typical example for understanding how the development of a sedimentary basin is related to plate tectonics, because the GPS geodesy, seismicity, and active fault distribution are constraining the present process better than elsewhere.

Acknowledgements

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