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Cretaceous to Holocene forearc evolution in Japan and its implication to crustal dynamics

The forearc tectonic evolution of Japan since Cretaceous time has revealed three important tectonic processes: the formation of a sedimentary accretionary prism, crustal accretion and imbrication, and subduction erosion. The accretion of sediments seems to have been controlled mainly by the input of sediment into a trench, as has been documented in the Shimanto Belt and the Nankai accretionary prism. Crustal accretion and imbrication have been taking place at a collision zone between arcs. These processes are associated with the collision and subduction of hot and rheologically weak lithosphere of the arc. Subduction erosion of forearc slopes has been documented in the Japan Trench in relation to the subduction of graben features and seamounts.

The most important inference drawn from the forearc evolution of the Japanese islands is that the majority of the continental crust in these island arcs was formed by the accretion of sediments and the intrusion of granites and that a part of this was eroded later and subducted. This process offers a global implication as to how continental crust has evolved throughout the Earth's history.

Introduction

The Cretaceous to Cenozoic tectonic evolution of the forearc areas of the Japanese arc and trench systems has been controlled dominantly by three tectonic processes: (1) the formation of accretionary prisms that are made up sedimentary sequences composed of material scraped from the subducting oceanic plate and tectonic slivers of oceanic materials, (2) the crustal accretion and imbrication at a collision zone between arcs, and (3) the subduction erosion of forearc slopes. The first process is best documented in the southwestern Japan arc, where it is represented by the development of the Cretaceous to Tertiary Shimanto accretionary prism and by the current accretion in the Nankai Trough (Taira, 1985; Ogawa, 1985; Taira and others, 1988) (fig. 1). The second process has been in progress since the middle Miocene at a collision boundary between the Izu-Bonin arc and the Honshu arc (Ogawa and others, 1985; Amano, 1986). The third process has been demonstrated by recent investigation of the sea floor by submersibles and SeaBeam mapping, especially during the Japanese-French Kaiko Project, which has revealed large-scale gravity collapse of the forearc slope in the Japan Trench (Cadet and others, 1987; Von Huene and Lallemand, 1990; Kobayashi and others, 1991).

Figure 1.—Present framework of the arc-trench systems around the Japanese islands. Arrow shows direction of plate movement. Barbed line shows the subduction zone. Abbreviations: ICZ, Izu collision zone; Sr, Suruga Trough; Zn, Zenu Ridge; Sg, Sagami Trough; Ks, Kyushu; Sk, Shikoku; Hk, Hokkaido; Erimo Smt, Erimo Seamount.

In this brief account, we review these three important tectonic processes in the forearcs and trenches of the Japanese arc and trench systems. In addition, we discuss their implications to crustal evolution in general.

Evolution of the Shimanto accretionary prism

During most of Mesozoic to early Miocene time, a continental arc at the eastern margin of the Asian continent probably extended from southern China to the northeastern Siberian region (Taira and others, 1989) (fig. 2). Most of the basement rocks of the present-day Japanese arc were formed during this period of subduction tectonism,

Figure 2.—Tectonic evolution of the Japanese islands since the Late Cretaceous (taken from Taira and others, 1989). Arrow shows direction of plate movement. Heavy line is the subduction zone. Abbreviations: SB, Shikoku Basin; IZB, Izu-Bonin arc; ICZ, Izu collision zone.

which included both the formation of accretionary prisms and the intrusion of granites (Taira and others, 1989). The Cretaceous and early Miocene part of the accretionary prism is called the Shimanto Belt (see Taira and Ogawa, 1988, for a general introduction). Extending from central Honshu to the Ryukyu Islands, the belt is about 1,800 km along its strike and has a maximum width of 100 km, so it is the largest structural element of the Japanese islands.

The Shimanto Belt is one of the most studied accretionary prisms in the world. The age of the subducted oceanic plate, the nature of the oceanic and infilled-trench sedimentary sequence, and the style of deformation are well constrained by the large amount of data that has been collected.

The Shimanto Belt is composed of two main lithologies: a relatively coherent turbidite sequence and a highly deformed *mélange* belt. These lithologies occur in a repeated fashion that is similar to the structure of a fold and thrust belt, and they systematically become younger oceanward. A key to the understanding of the origin of the Shimanto Belt lies in the *mélange* belt, which includes tectonic slivers of basaltic pillow lavas, nanno-ooze limestones, radiolarian cherts, red pelagic shales, and varicolored hemipelagic shales and volcanic ash layers that are dispersed in a highly sheared argillaceous matrix. Considerable effort, mainly based on radiolarian biostratigraphy, has been carried out in order to determine the geologic age of these lithologies. By dating the infilled-trench sedimentary sequence and the pelagic and hemipelagic sediments, we have been able to reconstruct the trench stratigraphy throughout the evolution of the Shimanto Belt.

The best documented example of plate stratigraphy has been obtained from the island of Shikoku (Taira and others, 1988) (fig. 3). Here, dating of Cretaceous *mélange* lithologies by the use of microfossils indicates that nannofossil-bearing limestone and radiolarian cherts are Valanginian (130 Ma) to Cenomanian (100 Ma) in age. varicolored shales are Coniacian to Santonian (80 Ma), and the argillaceous *mélange* matrix is Campanian (70 Ma). The adjacent coherent turbidite unit (trench deposits) also dates from the Campanian. Paleomagnetic analysis of these rocks has revealed that Valanginian pillow lavas and nannofossil limestones were formed at equatorial latitudes, whereas the coherent turbidite units of Campanian age (70 Ma) were deposited more or less at their current position of latitude (30° N.) (Kodama and others, 1983). Thus, we think that an ocean floor originated at the equatorial latitude at 130 Ma, that it moved at least 3,000 km, and that it then was subducted at 70 Ma. The dating of *mélange* lithologies throughout the Shimanto Belt has revealed a systematic change of oceanic-plate stratigraphy through time: a time progressive decrease of age difference between the basal pelagic unit and the sedimentary sequence in the trench. This suggests that the juvenile oceanic lithosphere was subducted during most of Paleogene, which constrained the plate reconstruction of the western Pacific Ocean to Cretaceous to Tertiary time.

On the basis of such a firm foundation for tectonic evolution, more detailed structural analyses are being done for the Shimanto Belt. These analyses include the study of the structural evolution in relation to plate kinematics (Nishi, 1988; DiTullio and Byrne, 1990), *mélange* fabrics (Kimura and Mukai, 1989; Kano and others, 1991).

Figure 3.—Reconstructed plate stratigraphy from *mélange* belt of the Shimanto Belt, island of Shikoku, Japan (taken from Taira and others, 1988). Abbreviations: Valang, Valanginian; Haut., Hauterivian; Barr., Barremian; Apt., Aptian; Alb., Albian; Cenom., Cenomanian; Turon., Turonian; Coniac, Coniacian; Sant., Santonian; Camp., Campanian; ls, limestone.

duplex structure (Murata, 1991), effect of ridge subduction (Hibbard and Karig, 1990), nature of underplated basaltic rocks (Ogawa and Taniguchi, 1989), and thermal evolution (Komatsu and others, 1991). We envision that such continuous efforts on the study of the Shimanto Belt will set a standard for geological, geochemical, and geophysical models for the evolution of an accretionary prism.

The subduction at the continental margin of eastern Asia from Cretaceous to Paleogene time was followed by successive events of dramatic tectonic evolution: the eastward migration of the Izu-Bonin arc and the spreading of the Shikoku Basin, the rotation of the southwestern and northeastern Japan arcs and the spreading of the Sea of Japan, and the subsequent collision of the Izu-Bonin arc against Honshu (fig. 2).

Nankai accretionary prism

The present-day subduction zone of the Shikoku Basin is represented by the Nankai Trough, where we can observe the development of a typical accretionary prism. A large amount of data on this prism has resulted from concentrated marine geological and geophysical investigations, such as drilling done by the Deep Sea Drilling Project and the Ocean Drilling Project (ODP) (Kagami and others, 1985; Taira and others, 1991), SeaBeam mapping and submersible diving carried out during the Japanese-French Kaiko Project (Kaiko I Research Group, 1986; Kobayashi and others, 1990; Le Pichon and others, 1990), the two-ship seismic experiments done by Japan and the United States (Moore and others, 1990; Stoffa and others, in press), and the IZANAGI long-range side-scan survey (Ashi and others, 1990).

Basically, two layers of sediments are being subducted below the forearc in the Nankai Trough: an upper turbidite sequence and a lower hemipelagic sequence that together form a 1–2-km-thick pile of sediments (fig. 4A). The turbidites in Nankai were supplied westward from the Suruga Trough drainage area, especially from the Fuji River. This sediment transport avenue is the result of the arc-arc collision between the Izu-Bonin arc and the Honshu arc (Taira and Niitsuma, 1985).

The results of ODP Leg 131, which penetrated the entire sedimentary sequence from the toe of the prism to the basaltic basement, characterized the nature of the décollement (Taira and others, 1991). We found a sharp offset of physical properties. The porosity above the décollement was 30 percent, and it increased to 40 percent below the 19-m-thick décollement zone. The sediments above the décollement are highly deformed because of the nearly horizontal compression oriented in a northwest-southeast direction, whereas the sediment below the décollement was little deformed. These observations indicate that the basal décollement of the Nankai accretionary prism is an overpressured zone that acts as a seal and prohibits drainage of the underthrust sequence. In addition, the basal décollement is a distinct stress discontinuity.

Submersible diving carried out during the Kaiko Project and the Kaiko-Nankai Project in the eastern Nankai Trough have revealed the widespread occurrence of seepage-related biological communities that are represented by the giant clam *Calyplogena*, which is found together with calcareous cemented clasts. Detailed measurements near the surface of the geothermal gradient in the biological communities were interpreted to show a large flux of methane-rich porewater, which cannot be explained easily by dewatering of the underlying sediment (Le Pichon and others, 1990). Le Pichon and others (1990) have proposed the existence of shallow, near-surface convection as a way of accounting for this extra expulsion of water. The role of fluids in the structural and geochemical evolution of an accretionary prism

is an important unsolved problem, and the Nankai Trough provides one of the best fields for such investigation.

Arc-arc collision and crustal imbrication

After the opening of the Shikoku Basin, the Izu-Bonin arc collided against the island of Honshu and produced a zone of repeated slices of arc crust and infilled-trough sequence that is called the Izu collision zone (fig. 1) (Soh and others, 1991). The Izu collision zone has been an active collision and accretion zone for several million years and has undergone progressive tectonic deformation that probably was initiated during the opening of the Sea of Japan at about 15 Ma in the middle Miocene (Taira and others, 1989). This collision-related deformation has resulted in the formation of thrust-bound tectonic crustal segments that range up to several tens of kilometers in size and consist of volcanic and volcanoclastic successions from the Izu-Bonin arc.

Relatively short lived foreland basins, which are filled by an overall upward-coarsening sedimentary sequence, have developed along the boundary thrust faults. This sedimentary sequence is represented by hemipelagic, deep-water shales at the base that are intercalated with volcanoclastic and turbidite debris-flow deposits in the middle and have fan-delta to delta-plain fluvial deposits at the top. The overall thickness of the sequence reaches more than 5 km and was deposited over a period of a million years. The basin-filling sediments tend to be younger in age progressively from north to south, and they range from middle Miocene to Pleistocene. The thrust movements that generated the foreland basins are thought to have shifted southward as time passed, which we interpret as the incremental migration of the plate boundary that was caused by the incorporation of the frontal segment of the Izu-Bonin arc into the Honshu arc (Taira and others, 1989). The forearc part of the Izu-Bonin arc was accreted along the Sagami Trough and formed an accretionary complex called the Miura Group (Ogawa and others, 1985; Ogawa and Taniguchi, 1988; Soh and others, 1991), which represents one of the rare examples of a young and shallow-level accretionary prism that is exposed on land.

Collision-related deformation has extended beyond the Izu collision zone to the nearby Philippine Sea plate in the northern Shikoku Basin (fig. 1). A linear topographic high, the Zenisu Ridge, extends from the northeastern Shikoku Basin to the Izu-Bonin arc a few tens of kilometers seaward of the Nankai Trough. The ridge formed from the rupture caused by the uplift of the Shikoku Basin oceanic crust as a result of intraplate compressive tectonism (Le Pichon and others, 1987).

The Izu collision zone provided a unique tectonic setting for the collision and subduction of hot and rheologically weak lithosphere (Lallemant and others, 1989). Crustal imbrication and the infilling of foreland basins produced a repeated succession of volcanic piles and sediment. These lithologies are quite different from those of the sediment-dominated accretionary prisms in the Shimanto Belt and the Nankai Trough. The documentation of these two contrasting accretionary processes, sediment accretion in contrast to crustal accretion, is an important result of Cretaceous to Cenozoic accretionary tectonism in Japan.

Subduction erosion in the Japan Trench

The Japan Trench is 7–8 km deep and is sediment starved. The seaward slope of the trench is characterized by well-developed half-graben structures on the subducting ocean plate (fig. 4B).

Figure 4.—Seismic-reflection profiles from the Nankai Trough (A) and the Japan Trench (B) (taken from Taira and others, 1990). Abbreviations: TWT(s), two-way traveltime, in seconds; BSR, bottom simulating reflector (gas hydrate phase transition).

The landward slope of the trench is steep, the mean slope angle being 7° , and it commonly has a steeper upper slope that is characterized by benched topography. SeaBeam topographic mapping shows that the landward slope of the Japan Trench is dominated by large-scale gravity collapse (Cadet and others, 1987; Kobayashi and others, 1991). The topography is characterized by steep concave scours, large blocks of slope material, and a debris apron on the trench floor.

The most spectacular examples of the landward topography of the Japan Trench are associated with the subduction of a seamount near the junction of the Japan and Kuril Trenches (figs. 1 and 5). The inner trench wall in this area shows signs of a seamount that has been subject to indentation and gravity failure. A large embayment that has enormous scours is observed to the north of the Erimo Seamount, which is part of a seamount train that is approaching the trench axis. Yamazaki and Okamura (1989) investigated this area further by using

Figure 5.—Schematic illustration of forearc erosion processes observed in the Japan Trench (taken from Taira and others, 1990).

magnetic-anomaly studies, and they suggested that a seamount of about the same size as Erimo Seamount is buried beneath the irregular topography that has been created partly by slope failure. Southeast of Erimo, the inner wall of the Japan Trench comprises a series of crescent-shaped escarpments and intervening hummocky terrain, and it has lobate topography that is indicative of a huge submarine landslide complex. The slide, 50 km by 40 km, probably resulted from seamount subduction (Fujioka and Taira, 1989; Taira and others, 1990).

These studies reveal that the lower part of the landward slope of the Japan Trench is mechanically very weak, probably owing to overpressuring, and is, therefore, subject to frequent, massive gravity failure (Von Huene and Culotta, 1989). The slump debris and collapsed material filled the graben depression, which was brought eventually to the subduction zone. The seismic images suggest that the décollement of the plate boundary developed within the upper part of the trench's sedimentary sequence and that most of the sediment filling the graben seems to have been subducted deeper (see figure 4B).

The subduction erosion of the forearc slopes seems to have persisted since Miocene time, as documented by the large subsidence

of the forearc region (Von Huene and others, 1982). The material removed by this process is estimated on the basis of model calculations to be about 50 km²/m.y. (Von Huene and Lallemand, 1990).

Implications to crustal dynamics

The forearc tectonic history observed in Japan from Cretaceous to Cenozoic time can be classified as follows:

- (1) The accretion of thick sedimentary sequences and the development of accretionary prisms represented by the Cretaceous to Paleogene history of the Shimanto Belt and the present-day Nankai Trough.
- (2) Crustal accretion and imbrication in relation to the collision and subduction of the island arc after the Miocene.
- (3) Subduction erosion of the forearc in the Japan Trench after the Miocene.

We would like to point out that the majority of the crust in the Japanese island arcs, which shows a crustal profile as thick as 40 km, is composed dominantly of accretionary prism sediments and granitic

intrusive rocks. We suggest that sediment accretion is a fundamental process for the growth of continental crust.

The cause of crustal accretion and tectonic erosion can be related to the mode of plate subduction, which shows different thermal and rheological properties. Subduction of hot and rheologically weak lithosphere, such as that found in an island arc, causes crustal imbrication. Subduction of mature and cold lithosphere, along with the development of horst and graben structures and sediment starvation, enhances forearc erosion and sediment subduction.

Such tectonic processes as these should be reconsidered in a time-progressive manner with respect to the Earth's thermal history: subduction of "hot" lithosphere in Archean time and subduction of cooler lithosphere in Phanerozoic time. Crustal imbrication in the Izu collision zone can be viewed as a direct analogy to the subduction tectonism of the early Earth. This has important implications regarding the origin of Archean crust, such as greenstone-granite terranes (Hoffman, 1991; Taira and others, in press). On the other hand, tectonic erosion and sediment subduction in the Japan Trench can be interpreted as characteristic of subduction tectonism in later phases of the Earth's history.

Sediment accretion, as documented in the Shimanto Belt and the Nankai Trough, is controlled mainly by the input of sediment into the trench. Thus, this process could have occurred throughout the history of the Earth. This general inference further implies that the material put into the asthenosphere should have changed throughout the Earth's history. Most of the upper crustal materials would have been delaminated and imbricated at the convergent boundary in the early Earth. On the other hand, in a later phase of the Earth's history, plate subduction could have conveyed a relatively larger proportion of supracrustal materials to the mantle. Such a gross change in subduction tectonism and the cycle of materials through the course of the evolution of the Earth should have affected the nature of magmatism, mantle composition, and heterogeneity of the mantle. We conclude that the tectonic history of subduction observed in the Japanese arc systems can be related to global crustal dynamics and the evolution of the Earth, although further detailed study is necessary to assess this important issue.

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