Seismic Stratigraphy, Thermal Structure and Tectonic Evolution of the Japan Sea

日本海の音響学的層序とその熱構造およびその構造発達について

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Seismic Stratigraphy, Thermal Structure and Tectonic Evolution of the Japan Sea

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Abstract

Evolution of a back-arc basin from its formation to initiation of closure can be studied in the Japan Sea which is a early-middle Miocene back-arc basin formed at the eastern margin of Asia. There are two main basins in the Japan Sea: the Japan Basin and the Yamato Basin. These two basins differ considerably in their topographic and geophysical characteristics. The Japan Basin shows smooth and flat sea-floor with normal oceanic crust underneath. The Yamato Basin, on the contrary, is characterized by shallower water depth and thick anomalous oceanic crust. It has been suggested that the Japan Basin is the product of sea-floor spreading and the Yamato Basin that of continental crust stretching. It has been indicated that the eastern margin of the Japan Basin is now subject to a convergent process producing a ridge-trough topography related to reverse faulting.

In the first chapter of the thesis, I have tried to provide some constraints to the tectonic evolution of the Yamato Basin based on acoustic stratigraphy and the BSR (Bottom Simulating Reflector) distribution. Thermal structure of the Yamato Basin was proposed from the detection of a diagenetic BSR, opal-A to opal-CT transformation indicative of an isothermal plane of about 40°C. The BSR is seen everywhere in the Yamato Basin, and the surface heat flow values are estimated for whole area of the basin. The calculated surface heat flow indicates a significant thermal anomaly in the Yamato Basin, that has not been detected by previous probe study. The middle part of the Yamato Basin shows elevated heat flow compared with the northern and southern parts. Comparison with thermal structure and acoustic basement

depth suggests that a loose correlation with basement depth with significant perturbation. A basin rifting model based on depth-dependent stretching with highly variable initial rift width is preferred to account such thermal structure.

In the second chapter, I studied the convergent process of the eastern margin of the Japan Sea especially emphasizing its implication to ophiolite emplacement. In the northeastern tip of the Japan Basin, the nascent crustal shortening is ongoing with some thrustings. The tectonic style can be divided into two features, one is a subduction type which involve some back-thrustings, the other is a obduction type. These tectonic styles are important features for the ophiolite emplacement and the nappe tectonics around an island arc. The present-day continuation of the activities is supported by topographic features, abnormal sediment physical properties, seismicity around the Okushiri Ridge, and observations of active faults on land. I propose that the Okushiri Ridge, one of prominent fault-bounded basement highs, was created through a tectonic inversion process from the extension to the compression at around 2 Ma. The inversion of tectonic style, thus, can be an important process for emplacement of some ophiolites and evolution of continental margin.

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Chapter I

Acoustic Stratigraphy and Thermal Structure of the Yamato Basin, Japan Sea

I.1 Introduction

Back-arc basins are generally considered to form as a result of rifting of continental margins or intra-oceanic island arcs (Taylor & Karner, 1983). Although back-arc rifts show some basic similarities in kinematics to continental rifting, back-arc rifts are also characterized by their own features. For example many rifts are short-lived and often associated with subduction of oceanic crust, although some authors believe subduction is not essential requirement for the origin of back-arc rifting.

Back-arc basins have been analyzed in terms of both kinematic and dynamic models. These models however have not been sufficient in explaining the origin of extensional stress regime at back-arc setting or in answering the following fundamental questions. Was a particular back-arc basin rifted due to mantle convection in relation to subduction or the role-back effect of subducting slab? Is the subduction of oceanic lithosphere essential to back-arc basin formation? Although, does initial volcanism characterize the active rifting as a precursor of rifting?

One of the best areas to study such fundamental questions is the Japan Sea back-arc basins. Because the Japan Sea is one of the well surveyed back-arc basins around the world, and also two recent Ocean Drilling Program (ODP) cruises provide an integrated data set that can be used to constrain the evolution of the back-arc basin. The formation of Japan Sea is widely known as caused by the migration and/or rotation of the arc toward trenches or trench retreat, which supported by the paleomagnetic reconstructions (eg. Kawai *et al.*, 1971; Otofuji & Matsuda, 1983).

Although detailed reconstruction of pre-Japan Sea paleogeographic configuration is still quite unsolved (see Niitsuma *et al.*, 1988), timing and general scheme of kinematics are reasonably well constrained. Several models are proposed for the formation of the Japan Sea. These can be divide into two categories, kinematics and dynamics.

Kinematic Models:

Several kinematic models have been proposed for the formation of back-arc basins (eg. Dewey, 1980; Carlson & Melia, 1984). These models require extensional tectonic regime for the initiation of back-arc rifts. There are two types of kinematic models proposed to account for for the opening of the Japan Sea: models which dependent heavily on paleomagnetic data and models in which paleomagnetic data are less important.

Representative work in the first group is modeled by Otofuji & Matsuda (1983) who combined paleomagnetic studies and isotope chronology to proposed a fan shape (or bar room door) opening model for the Japan Sea. The relation between the rotation of the Honshu and the formation of the Japan Sea had also been discussed by Kawai *et al.* (1971). Otofuji & Matsuda (1983) and Otofuji *et al.* (1985) have proposed the timing of the rotations of the NE Japan and the SW Japan respectively. According to their results, the SW Japan rotated clockwise about 54 degrees in 15±1 Ma, and that NE Japan rotated anti-clockwise about 50 degrees in 21-11 Ma. Niitsuma *et al.* (1988), based on paleomagnetic, geologic, and paleogeographic considerations, have also showed that most of Japan Sea, excluding the Tartary Trough, can be created by only the rotation of the SW Japan.

In the second group of models, Lallemand & Jolivet (1985/86) proposed a two step mega-pull-apart basin model for the Japan Sea based on the geological data of Hokkaido and eastern margin of NE Japan. The timing of the formation of mega-pull-apart basin is almost concordant with the formation of the Japan Sea. Tamaki (1985b) suggested the multirift model for the Japan Sea which produced by shallow subduction of oceanic lithosphere from the Pacific side. It may closely relate with the rapid formation model of the Japan Sea based on the some paleomagnetic data (eg. Otofuji & Matsuda, 1983).

Dynamic Models:

Recently, there has been a development in the geodynamic concept of continental rifting. Sengör and Burke (1978) proposed two types of continental rift based on the relative timing between the rifting and the volcanism, in one, the volcanism and usually local doming predates major rift formation so called as an active rift whereas, in the other, rift form first and volcanism follow thereafter so called as a passive rift. The passive rifts relate to the plate kinematics which have no direct connection with the global mantle dynamics. In the study of back-arc basins, this concept of passive rift versus active rift can be applied to make a first-order characterization of back-arc basins.

Models for geodynamics of the Japan Sea opening have tried to explain some of characteristic features of geologic and geophysical observations. Tatsumi *et al.* (1988) and Nohda *et al.* (1988) hypothesized that the hot asthenosphere injected into the continental crust and formed the Japan Sea. This model rationalized the time variant thermal structure of mantle wedge, the migration of volcanic front, and the shift of isotope ratios (Sr and Nd). Shuto (1989) has pointed out the existence of icelandite in the middle Miocene of NE Japan, supporting the occurrence of a mantle diapir beneath NE Japan. Kurasawa & Konda (1986) also suggested the presence of a mantle diapir beneath NE Japan in middle Miocene (16 Ma) based on strontium isotopic ratios of Tertiary volcanic rocks. Miyashiro (1986) presented a new dynamic idea for the formation of back-arc basins, which was called as the "hot region model". This model gave meaningful impacts to the mysterious volcanic episodes, which have no relation to subduction scheme, and to the dynamics of back-arc basin formation. In essences of the hot region model is a variation the former asthenosphere injection model.

It is important to understand, however, that none of these models was constrained from the data of the Japan Sea, simply because these data were not yet available. In 1989, the study of Japan Sea took a new turn with the addition of data from Ocean Drilling Program (ODP). A large volume of data were generated by these cruises (Tamaki, Pisciotto, Allan, *et al.*, 1990; Ingle, Suyehiro, von Breymann, *et al.*, 1990) as well as by pre-cruise site surveys. This paper is an outcome of these combined data sets.

In this paper I will attempt to provide some basic constraints to stratigraphy, structure and thermal regime of the Yamato Basin, a south-cental portion of the Japan Sea, where available data sets are most complete. This paper is organized to provide first a review on geological and geophysical knowledge of the Japan Sea. Then method and data are explained. Acoustic stratigraphy and thermal structure based on a bottom simulating reflector are presented. Considerations will be given to the reliability of such data sets. Some implications to the origin of the Yamato Basin will be discussed.

I.2 Geological and Geophysical Setting of the Japan Sea (Overview)

The Japan Sea was formed in early to middle Miocene as a complex of back-arc basins behind a continental arc of the peripheral of the Asian continent. This section will review the recent studies of the Japan Sea formation based on onland geology, marine geology, and geophysics.

Onland Geology

Voluminous stratigraphical and volcanological studies have accumulated for the Miocene Japanese arc, especially for the Northeast (NE) Japan Arc, Tohoku area. The stratigraphy of NE Japan has been compiled in Kitamura ed. (1986), and they have proposed that NE Japan was constructed from several small blocks possibly reflecting the formation of Japan Sea. These authers also suggest that sevral sedimentary basins abruptly changed from deep to shallow depositional facis.

Kimura (1986) found large unconformities in NE Japan by based on isotope dating and stratigraphical studies. He also suggested the relationship between the stratigraphy and rifting process. There are two significant unconformities for the formation of the Japan Sea, one at 40 Ma and the second at 19 Ma. The hiatus of the 40 Ma unconformity was continued 19 Myrs (40 to 21 Ma?) in the Oga area where is the type locality of the

Neogene stratigraphy of the Japan Sea side of NE Honshu. On the other hand, the hiatus of the 19 Ma unconformity is only 2 Myrs but this unconformity records a drastic change from non-marine to marine deposition. Kimura (1986) further proposed that was a correlation intra-arc basin formation in NE Japan and rifting processes observed in passive continental margins.

Yamaji & Sato (1989) applied the lithospheric stretching model, originally proposed by McKenzie (1978), to NE Japan and proposed that these was a period of initial subsidence 16 to 15 Ma and a period of thermal subsidence 14 to 8 Ma. Yamaji (1990) has also pointed out that rapid rifting of NE Japan was followed by the formation of Japan Sea. Based on these observations he further suggested that the rapid intra-arc rifting was caused by the large temperature dependence of lithosphere rheology and the hot thermal regime of the island arc lithosphere. These are important on restrict to apply a thermal model to the Japan Sea.

It has been suggested that the across-arc variation of volcanism in the NE Japan was caused by different degrees of magma segregation depth and by different degrees of partial melting in the subduction zone (Takahashi & Kushiro, 1983; Tatsumi *et al.*, 1983). Such variations, therefore, should reflect the thermal conditions of the wedge mantle beneath the magmatic arc. Tatsumi *et al.* (1988) suggested that the migration of volcanic front was caused by an episodic change in the thermal condition of the wedge mantle in the middle Miocene. Tsuchiya (1986 and 1990) and Tsuchiya *et al.* (1989) have also described the extensive basaltic magmatism in the middle Miocene along the back-arc side of NE Japan, and pointed out the similarity with volcanic patterns in continental rifts and back-arc basins. Finally the rift zones of the oil field in the NE Japan have been considered to the failed rift zone (Tsuchiya, 1990). Extensional stress field is distinguished in the NE Japan at some around early to middle Miocene, which may be relating with a dynamic change of thermal condition under the NE Japan Arc.

In summary, the geologic data from the land area strongly suggest that around 20 to 15 Ma, there was a phase of rifting in the Japan Sea side of NE Honshu. This rifting was accompanied by a volcanism whose characteristics were quite different from the present mode of arc magmatism being more kin to the volcanism associated with continental rifting. This volcanism may have been related to large thermal structure change in asthenosphere underneath the back-arc side.

Marine Geology and Geophysics

The bathymetry of the Japan Sea can be classified into several basins and ridges with the most prominent features: the Japan Basin, the Yamato Basin, the Tsushima Basin, and the Yamato Ridge (Fig. I-1).

The Yamato Ridge is further divide into three banks. Granites, granodiorites, andesites, and rhyolites have been dredged from the Yamato Ridge, and the granites have yielded radiometric age that range from 110 Ma to 220 Ma (Lelikov & Bersenev, 1973; Vasiliev, 1975). The depth of Moho underneath the Yamato Ridge is considered to over 20 km (Ludwig *et al.*, 1975) based on refraction seismic experiments. Thus, the Yamato Ridge is interpreted as a subsided relict of the continental margin of Eurasia.

The Japan Basin surrounds the Yamato Ridge on northwest and northeast, and the basin has an extremely smooth bathymetry (ranging from 3600 to 3700 m in depth) excluding the Bogorov Seamount.

The Yamato Basin trends northeast to southwest and located at the south of the Yamato Ridge. The relatively smooth seafloor of the Yamato Basin is punctuated by the Yamato Seamount Chain which occurs in the middle of the basin. The water depth of the Yamato Basin ranging from 2700 to 3000 m, which is approximately 500 to 1000 m shallower than the Japan Basin.

Along the western edge of NE Japan Arc, there is a active tectonic zone which is interpreted to be the plate boundary between the Eurasian and North American plates (Nakamura, 1983; Kobayashi, 1983; Seno, 1983; Tamaki & Honza, 1985). Tamaki (1988) has compiled extensive marine geological and geophysical data, and proposed a tectonic evolution of the Japan Sea which has great contributions for the modern Japan Sea studies.

In this section, I discuss geological and geophysical data follow the two main basins of the Japan Sea, the Japan Basin and the Yamato Basin. Especially, I will be integrating seismic reflection and refraction data, heat flow data, magnetic data, and geologic data. It is not including the ODP results which will describe and discuss in the later section.

Japan Basin:

The lithosphere of Japan Basin is created by normal seafloor spreading process during in early Miocene based on the review of the previous studies for the Japan Basin.

There is no large refraction seismic experiment since the middle of 1960's in the Japan Basin. Murauchi (1972) and Ludwig *et al.* (1975) have proposed that the crustal structure of the Japan Basin shows the characteristics of normal oceanic crust. Tamaki & Honza (1985) and Kuramoto (1988) have also suggested that the crust of the Japan Sea exposed along the western wall of the Okushiri Ridge based on the seismic profiles. This interpretation has also recently been support with the observations by the "Shinkai 2000" divings which have reported exposures of oceanic crust in the wall of the Okushiri Ridge (Tokuyama *et al.*, in prep). It is therefore suggested that the Japan Basin was formed by normal seafloor spreading process.

One of the significant age determination methods for the formation of oceanic crust is an estimation of age from heat flow values. Anderson (1980) has also shown that this correlation can be able applied to back-arc basin, and Tamaki (1985a) used the correlations between age and heat flow measurements for the Japan Sea. The average value of the heat flow is a 2.26 HFU (approx. 94.5 mW/m^2), which equivalent to an age of formation of 25 - 28. If the maximum value of heat flow means the youngest age of the formation which is 15 - 17 Ma as an upper limit of the formation age. Tamaki (1985a) was estimated the maximum age of the crust as 30 Ma from the maximum correlated basement depth. It is not overlap with the age which interpreted from heat flow. However the initial formation age is estimated as late Oligocene from above considerations.

Magnetic lineations are very difficult to identify in the Japan Sea (Isezaki, 1986). Kobayashi (1983) discovered a possible weak magnetic lineation, which is parallel to the direction of velocity anisotropy of the upper mantle. Tamaki & Kobayashi (1988) carried out a detailed magnetic survey from the northern tip of the Yamato Basin to the Japan Sea and discovered several short lineations, that suggested the presence of a propagating rift. The lineations trend NE to ENE. The identification of the age is not yet done for the lineations.

Formation age and kinetics have been considered based on geological samples. Siltstone dredged from the Kaiyo Seamount, on the Okushiri Ridge, contained abundant diatom fossils which were identified as belonging to either the *Coscinodiscus yabei* zone (11.58 - 12.90 Ma) or the *Thalassiosira yabei* zone (11.3 - 12.1 Ma) (Sagayama, 1988). The stratigraphy of the Okushiri Ridge has also correlated with the Japan Basin based on seismic reflection data (Kuramoto, 1989). And these data indicate that the dredged siltstone is the oldest sediment in the Japan Basin. In another words, the oceanic crust of the Japan basin was formed before 12 Ma. Miyashita *et al.* (1989) were divided dredged basalt samples from the Okushiri Ridge into five types of basalt based on the assemblage of phenocrysts: olivine; olivine-plagioclase; olivine-plagioclase-clinopyroxene; plagioclase-clinopyroxene; and aphyric basalt. They have also proposed that the size of magma reservoir was relatively small compared to mid-oceanic ridges magma chamber because of the heterogeneous appearance of basalts. Comparison with ongoing rifts examples, the spreading rate should not be so fast.

The acoustic stratigraphy of the Japan Basin has been divided into two units except the acoustic basement which has been interpreted as oceanic crust. The boundary between these two units is a bottom simulating reflector (or BSR) that may correlate with the opal-A to opal-CT transition (Tokuyama *et al.*, submitted by "Marine Geology"). The sediments above this reflector are interpreted to be Pliocene, whereas the sediments below this reflector are considered to be middle Miocene based on Sagayama (1988).

I present additional data here to constrain the structure of the acoustic basement of the Japan Basin. The used single channel profiles were taken during KH-86-2 cruise of Ocean Research Institute, University of Tokyo (Fig. I-2), the lines 7 and 8 are shown in Figures I-3 and I-4 with structural interpretations for the acoustic basements. Both profiles show the water bottom to be extremely flat with a water depth of about 3900 m. Acoustic basement is also observable at 1.5 to 2.0 sec. (two-way traveltimes) below the sea floor. Locally, the acoustic basement is displaced up to about 1 second (two-way traveltime) along high angle normal faults. The structures also show typical horst and graben geometries. These structures are buried by the sediments of the Japan Basin indicating that the normal faults formed before deposition of basin sediments and should reflect the mechanism of the initiation of the Japan Basin. The deformed area is able to be compared with the deepest part of the Japan Basin which originally described by Ishiwada *et al.* (1984). The area shows an elongated trough that trend ENE. The spreading direction estimated from this topography is thus NNW-SSE, which is concordant with the results obtained by the magnetic data of the Japan Basin as discussed above (Tamaki & Kobayashi, 1988).

In summary, the Japan Basin is considered to be floored by normal oceanic crust that formed during seafloor spreading process in late Oligocene to early Miocene.

Yamato Basin:

In 1985, regional scale seismic refraction and reflection experiments were carried out during the Development and Dynamics of Lithosphere Program (DELP) Japan Sea cruise. Katao (1988) analyzed the P-wave velocity structure of the southern Yamato Basin, and concluded that the crust was approximately 18 km in thick which was abnormally thick for normal oceanic crust. Hirata *et al.* (1989) have proposed a possible model for the origin of the thick crust, was generated by the addition of igneous rocks when the regional stress field changed from extension to compression.

Tamaki (1985a) estimated the formation age of the Yamato Basin from the terrestrial heat flow values. The mean heat flow value of the Yamato Basin is 2.34 ±0.30 HFU (approx. 97.8 mW/m^2) which suggests an age of 23 to 24 Ma. The maximum heat flow values suggest an age greater than 10 Ma. It is ambiguous, however, that the estimation of formation age from heat flow value is meaningful for such abnormally thick oceanic crust of the Yamato Basin which may have very different formation mechanisms and heating and /or cooling histories.

Magnetic anomaly data of the Japan Sea have been compiled by Isezaki (1986) and show a very complex pattern and no obvious magnetic lineations in the Japan Sea. Kobayashi (1983), however, found a weak magnetic lineation in the Yamato Basin which is nearly parallel to the axis of elongation of the basin. At present, none of these anomalies has been dated.

Deep Sea Drilling Project (DSDP) Leg 31 drilled at four sites in the Japan Sea but could not reach the basement rocks because of technical problems (Karig, Ingle, *et al.*, 1975). Then geological samples are only taken from the Yamato Seamount Chain, not the basement rocks, and discussed as follow. Volcanic rocks dredged from the Yamato Seamount Chain (Kimura *et al.*, 1987; Kaneoka *et al.*, 1988; Yamashita, 1988), have been divided into two petrological types: alkali basalts and trachyandesites. These two types rocks occur mixed at the Meiyo-Daini seamount in the northeastern tip of the Yamato Basin (Yamashita, 1988). The basalts recovered from the top of the "Yamato-85-2 Knoll" (38°08'N, 135°24'E) (Kimura *et al.*, 1987) is similar to normal back-arc basin basalts in chemical composition, and very similar to the basalts from the active spreading ridges of Mariana Trough. K-Ar and ^{39}Ar-^{40}Ar ages of the dredged samples (Kaneoka, 1988) indicate that the Yamato Seamount Chain shows two peaks: one peak ranges in age from 10 to 15 Ma and the second peak is around 7 Ma. The ages show no correlation with the petrologic characteristics or regionality.

Tokuyama *et al.* (1987) have discussed the acoustic stratigraphy of the Yamato Basin based reflection seismic profiles and drilling results at Site 299 of the DSDP. These works divided the acoustic stratigraphy into six units in the middle part of the basin and three units in the northeastern part of the basin. It can be seen in the seismic profiles that the Yamato Seamount Chain is buried by the entire column of the sediments of the Yamato Basin suggesting that the Yamato Basin crust is older than the Yamato Seamount Chain, whose maximum age is 10-15 Ma. Tamaki (1985a) tried to estimate the formation age of the acoustic basement from the $\sqrt{t}$ law, including a loading correction for sediment loading. However as mentioned above this may not be reasonable because of the abnormally thick crust. Sayanagi *et al.*

(1987) deduced that the Yamato Seamount Chain was not rotated after 6 Ma from the three component magnetic experiments in the Yamato Basin. It also constrained the formation age of the Yamato Basin.

In summary, The Yamato Basin probably at about middle to late Miocene, although, the mechanism of formation is not clear. Abnormally thick oceanic crust, less obvious magnetic lineation and late seamount activity all indicate that normal spreading mechanism, like mid-oceanic ridges was not likely to be responsible for the formation of the Yamato Basin. Thus, it can be concluded that the two main basins of the Japan Sea followed very different basin evolution history.

The heat flow values of the whole Japan Sea show a significant regional differences. Figure I-5 shows all heat probe data of the Japan Sea. In the Japan Basin, it is possible to divide into two region, a "hot" area in the northeast and a "cold" area in the southwest. The average values for these areas are 114.4 and 85.0 mW/m^2 respectively, and the deviations are fairly low. Then there are suggesting formation age of 18-20 Ma and 31-35 Ma. In the Yamato Basin, the heat flow values show less variance and the average is about 100 mW/m^2. Although these ages estimated from heat flow value are not acceptable, because the Yamato Basin has abnormally thick and different origin from normal seafloor spreading ocean.

The main purpose of this paper therefore is to give some basic constraints to the mechanism of the formation of the Yamato Basin based on acoustic stratigraphy and thermal structure. The most of data I used for this study are originally taken and processed for this purpose.

I.3 Data Acquisition and Processing Procedure

The data of this study are mainly composed of two datasets, one is reflection seismic profiles and the other is physical properties of cored sediments from the Yamato Basin by ODP Leg 127. These data were discreetly acquired and processed as basic data, which procedures are described as follow.

The first important set of data used in this study is the reflection seismic data. A large amount of reflection seismic survey lines have been obtained from the Japan Sea. However, the data are restricted within the eastern half of the area (Fig. I-6). At the same time many profiles did not penetrate basement and are only useful for understands the stratigraphy of the sedimentary sections.

Geological Survey of Japan (GSJ) is a pioneer of the Japan Sea's survey, they systematically covered (about five miles interval for each line) the eastern half of the Japan Sea by single channel reflection surveys of GH77-2, GH77-3, GH78-2 and GH78-3 cruises. These results are reported in their cruise reports (Honza ed. 1978a, b, & 1979). Another major investigator, Japan Petroleum Exploration Co. Ltd. (JAPEX) also surveyed along the eastern margin of the Japan Sea using multichannel reflection seismic profiling. Their surveys were usually carried out using a 48 ch. streamer cable and its digital recording configuration with an air-gun (810 in^3) as a controlled sound source. A part of these profiles was reported in Ishiwada *et al.* (1984).

Ocean Research Institute (ORI), University of Tokyo carried out several surveys of reflection seismology in the Japan Sea, for example KT85-15, KH86-2, KT87-6, KT88-9, and KT89-15 cruises. DELP'85 Japan Sea cruise is also used a same equipment. They using a 12 ch. or a 6 ch. streamer cable for multichannel reflection seismic survey. Digital recording system is made by NEC (Nippon Electric Co. Ltd.) which were used both in the multichannel and single-channel surveys. The data used in this study were from all these lines. I used published data for Geological Survey and JAPEX lines.

The ORI and DELP lines were processed at the ORI for this study. In the following section, I describe briefly the outline of data acquisition and processing procedure of ORI's multichannel system, because these reflection seismic profiles have not been published previously. The streamer cable of ORI is composed of several channels, the active section of which group spacing is 50 m in each length and the dead section which comprises from stretch and weight parts. The offset between the sound source and the mid-point of the last channel (ship side) of the streamer cable is usually 250 to 350 m. The sound source is an air-gun (580 or 770 in^3), sometimes using a water-gun or an air-gun array system, shot interval is every 50 m. The recording format is SEG-B and recorded with 1600 BPI on magnetic tapes. The recording length is 8 seconds with 4 m seconds sampling rate.

For in-house processing, the on-board data are converted from SEG-B to SEG-X formats (demultiplex) at ORI. The data are sorted by common depth point traces and are treated by some data enhance methods, deconvolution, time variant filtering, and gain recovering. The stacking velocity is estimated by a constant velocity stacking method. After the normal move out (NMO) correction, the traces are completely stacked. Migration (finite difference method) is applied for the profiles which show fairly strong diffractions (Fig. I-7).

The second type of data I used in this study were the physical properties of sediments I collected as a member of the scientific team of the JOIDES RESOLUTION during the ODP Leg 127. The sampling, measurement, and processing procedures for the physical properties of the cored sediments are described as follow.

Four sites were drilled in the Leg 127 (Fig. I-8): Sites 794 and 797 are situated in the margin of Yamato Basin, Site 795 is located in the northern tip of the Japan Basin, and Site 796 is located on the Okushiri Ridge respectively. The physical properties measured during Leg 127 included:

1) multi-sensor-track (MST) logging of gamma-ray attenuation porosity evaluator (GRAPE) for bulk density, compressional acoustic velocity measurements and magnetic susceptibility;
2) thermal conductivity;
3) Hamilton Frame compressional velocity;
4) electrical resistivity and index properties;
5) grain-size analyses;
6) carbonate content analyses.

Sample selection and spacing were depended on the core recovery, being usually every 1 sample/1 section(1.5 m). P-wave logger transmits a 50 kHz compressional wave pulse through the core at a repetition rate of 1 kHz. Index properties, wet and dry bulk density, grain density, porosity, water contents, void ratio were determined on samples of sediment and rock. Wet samples were weighted using two calibrated Scientech 202 electronic balances, and were measured the volume by a Quantochrome Helium Penta-Pycnometer. Samples were freeze dried for at least 12 hours, and were measured the dry weights and volumes (Fig. I-9). Index properties are calculated as following equations,

Bulk_Density = Sample_Wet_Weight / Sample_Wet_Volume,

$$\text{Grain\_Density} = \frac{\text{Sample\_Dry\_Weight} - \text{Water\_ADJ}}{\text{Sample\_Dry\_Volume} - \dfrac{\text{Water\_ADJ}}{\text{Salt\_Density}}},$$

$$\text{Porosity} = \frac{100 * \text{Corrected\_Water\_Weight}}{\text{Water\_Density} * \text{Sample\_Wet\_Volume}},$$

$$\text{Water\_Content} = \frac{100 * \text{Corrected\_Water\_Weight}}{\text{Sample\_Wet\_Weight} - \text{Corrected\_Water\_Weight}},$$

and

$$\text{Void\_Ratio} = \frac{\text{Corrected\_Water\_Weight}}{\text{Water\_Density} * \text{Sample\_Wet\_Volume} - \text{Corrected\_Water\_Weight}},$$

where:

Salt_Ratio = Salinity / (1000.0 - Salinity),

Salt_Factor = (1000.0 - Salinity) / 1000.0,

Salinity = 35.0,

Corrected_Water_Weight =
(Sample_Wet_Weight - Sample_Dry_Weight) / Salt_Factor, and

Water_ADJ = Corrected_Water_Weight -
(Sample_Wet_Weight - Sample_Dry_Weight).

All values are immediately calculated and are smoothed by five points running mean method of which weights of meaning are 0.5, 0.8, 1.0, 0.8, and 0.5. Thermal conductivity measurements were made on each core using the needle probe technique (Von Herzen & Maxwell, 1959) for the soft to semi-consolidated sediments and the "half-space" technique was applied for the consolidated sediments.

I.4 Lithological Stratigraphy in the Yamato Basin

ODP Leg 127 successfully penetrated the sedimentary sections at Sites 794, 795, and 797. Among them, Sites 794 and 797 were located in the Yamato Basin (Fig. I-10). The lithologies of both sites are similar and cross correlations can be made. Five lithological units were recognized at each site (Fig. I-11). These are briefly described as follow: (1) Quaternary to Pliocene laminated, dark-colored silty clay; (2) Pliocene to upper Miocene diatom ooze, generally bioturbated throughout; (3) middle to upper Miocene bioturbated diatom clay to faintly laminated siliceous claystone and silty claystone, with thin chert layers and minor calcareous layers and nodules; (4) middle to upper (?) Miocene calcareous and siliceous claystone and interbedded tuff with minor phosphate; and (5) lower Miocene volcaniclastic sandstones and siltstones which are graded, planar- to cross-laminated and bioturbated and are interlayered with basalt sills in descending order. This lithological stratigraphy is diachronous with age. In Figure I-11, the dashed line (iso-age) cross the lithological boundary.

Diagenetic phase changes of silica were also identified in each site. The boundary between sediments containing biogenic opal-A (density: 2.0 g/cc) and those embracing opal-CT (density:

2.3 g/cc) was recognized at 294 mbsf (meters before sea floor) in Site 794 and at 299 mbsf in Site 797. Furthermore, the phase boundary from opal-CT to quartz in cored sediments was recognized at 395 mbsf and 426 mbsf for Sites 794 and 797 respectively.

The oldest sediments recovered from the bottom of Site 797, about 900 mbsf, was 19.6 Ma. The lithologic change from shallow water to slope deposits of the Unit 5 to hemipelagic accumulation of the Unit 4 indicates rapid subsidence of the Yamato Basin in early Miocene. This abrupt increase in water depth was clearly marked by the lower middle bathyal sediments that overlie basaltic sills and flows at Site 797. This radical change in bathymetry happened only once since early Miocene in the entire history of the Yamato Basin, suggesting that it may reflect the dynamics of its formation.

I.5 Physical Properties of the Sediments in the Yamato Basin

Physical property measurements were carried out during Leg 127 not only to make correlations with the lithological stratigraphy but to understand the factors which controlled the acoustic properties of sediments. Physical property data used in this study are listed in Appendix-A. Calculated index properties are shown in Figures I-12 and I-13 for Sites 794 and 797 respectively. Thermal conductivities are also shown in the Figures I-14 and I-15 for the each site.

In general, it is recognized that wet bulk density, grain density, and thermal conductivity decrease with depth, whereas porosity and water contents increase with depth down to about 250 mbsf. These trends in physical properties are opposite to the trends observed for normal marine muddy sediments. In the Japan Sea, however, the sediments are dominantly diatomaceous oozes and muds, and this differences may explain the unusual physical properties. For example, diatom tests are generally porous structure and may provide a strong framework which could support a large bulk porosity, therefore the increase in diatom content support the porosity increase unless the diatom framework become altered diagenetically. Furthermore Lee (1973) has demonstrated the compressive strength for diatom oozes. According to the demonstration, the diatom frame is relatively strong and does not fail until about 300 mbsf (or a load of about 14-15 kg/cm^2).

At the opal-A to opal-CT transitional boundary, approximately 294 mbsf, the index properties change abruptly: wet bulk density and thermal conductivity increase, whereas porosity and water contents decrease with depth. According to the grain-size analysis, there is little change in particle size. Then the observed physical properties are not reflecting a change in grain size. Figure I-16 shows the velocity profile which combines P-wave logger data, Hamilton Frame compressional velocity data, and logging data. The combined velocity profile shows no significant gap around the opal-A/CT boundary, less than 5 % jump up of velocity. Below the diagenetic boundary, the variability in the combined velocity increases remarkably, which probably reflect a change in lithology. The individual features of the physical properties from each site are described as follows.

Site 794:

Detail description of physical property is presented with depth as follow.

0-92 mbsf: This section is characterized as highly variable values of all physical properties. The wet bulk density, grain density, and thermal conductivity decrease gradually and the porosity and water contents increase to the bottom of this section with decreasing the degree of amplitude. The variability seems to reflect the changes in lithology such as the frequent ash layers and the dark and bright layers. The opposite sense of physical property gradients is interpreted to reflect the increase in volume of diatom based on smear slide observations.

92-294 mbsf: The bulk density, thermal conductivity, porosity, and water contents show extremely uniform values. The porosity and water contents are still at abnormally high values and increase slightly with depth, suggesting an increase in the diatom content. Because a diatom maintaining a highly porous structure, and able to keep much water in it. The grain density shows more variability, but even the lowest grain density suggests almost pure diatomaceous ooze. The opal-A/CT transition is inferred to be at the bottom of this section, where all physical properties change abruptly.

94-492 mbsf: The porosity and water contents are much lower than in the overlying sediments, and the densities and thermal conductivity are higher. The grain density comes up with the vanishing of diatom.

492-521 mbsf: The lithology of this section is a sub-aqueous tuff, with markedly higher porosity and water contents, and lower bulk density and acoustic velocity than previous unit.

521-646 mbsf: Porosity, water contents, and bulk density follow a compaction trend of normal marine sediments throughout this interval even though igneous sills are often intercalate within the sediments.

Site 797:

The physical properties of Site 797 show almost identical features with the Site 794. The uniformity of the bulk density in the upper 300 m and the pronounced effects of the opal-A/CT transformation, which occurs at nearly the same depth, are clearly seen in the both profiles. Moreover even relatively small variations can be match between the two sites.

0-112 mbsf: The index properties and thermal conductivity show some variability over this interval and the porosity and water contents show a slight linear decrease.

112-302 mbsf : The physical properties change very little through this interval with the densities and thermal conductivity showing little change, and the porosity and water contents slightly increasing with depth. The opal-A/CT transformation can be identified at the bottom of this section and is associated with a significant change of whole physical properties.

302-627 mbsf: Although data points are relatively sparse, the trend of each profile shows a nearly linear trend.

647-800 mbsf: This is a interbedded section between sandstones and sills and the water contents of the sandstones range from 10 to 24%, which are much lower than the value of the sandstones that overlaied the sills. These data may suggest a higher degree of consolidation and/or thermal alteration and dewatering related to interaction between the sandstones and the sills.

At these two sites, the physical property profiles are remarkably uniform in the diatomaceous intervals down to the opal-A/CT diagenetic boundary (about 300 mbsf). The profiles show the diatomaceous sediments undergo little or no compaction at shallow burial depth, which reflects the relatively rigid framework of the diatom tests. Across the diagenetic boundary, the diatoms undergo dissolution and reprecipitation and the physical properties show a relatively large and sharp change. Below this boundary, the sediments seem to have undergone normal compaction with depth, generally decreasing porosity and water contents, and increasing bulk density, thermal conductivity, and acoustic velocity. The diagenetic boundary from opal-CT to quartz also observed, but it is a much weaker anomaly in the physical property data when compare with the opal-A/CT boundary.

The distinct and significant response for the physical properties of the opal-A/CT diagenetic transformation seem to be mainly controlled by temperature. This will be discussed at the following sections.

I.6 Acoustic Stratigraphy of the Yamato Basin

Synthetic seismogram is useful for compare detected seismic section with real geological section (reflecting acoustic impedance of lithology). In this section, acoustic characters are demonstrated by synthetic seismogram based on physical properties measurements of both sites, Site 794 and 797, and acoustic stratigraphy is discussed based on the results.

Physical Properties and Acoustic Characteristics

Synthetic seismogram is useful for establish a seismic stratigraphy. Because it makes possible the acoustic images correlate with real lithology and physical properties of sediments. Then I attempted to make a synthetic seismogram for each drilling site.

In reflection seismology, the reflection coefficient (RC) is shown like the following equation.

$$RC = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

where

Z1=acoustic impedance in the upper layer.

Z2=acoustic impedance in the lower layer.

An acoustic impedance is the product of two variables, velocity and density. The strength of the seismic reflection is directly related to the contrast in acoustic impedance across a boundary. Consequently, all seismic reflections reflect a sudden change of physical properties, especially velocity and density are important factors. Synthetic seismogram is useful in order to compare a model section with a real lithological section, and is significant for the acoustic stratigraphy. The velocity and density data obtained through logging and laboratory measurements can be used to reconstruct the synthetic seismogram.

In first, input wavelet is significant to demonstrate a synthetic seismogram. The most common zero-phase wavelet is the Ricker wavelet (Ricker, 1953), expressed in time domain as

$$f(t) = (1-2\pi^2 V_M{}^2 t^2)e^{-\pi^2 V_M{}^2 t^2},$$

where V_M is the peak frequency. The calculation of synthetic seismogram uses a minimum-phase wavelet for the input wavelet because most of the seismic profiles in this study were taken by air-gun as a controlled sound source. Then the input wavelet used a 20 Hz Ricker type wavelet which has same wave form but does not zero-phase. The computed program is attached in Appendix-B. Figure I-17 shows the results of calculation for the sedimentary intervals of both sites, where AI is acoustic impedance, RC is reflection coefficient. The horizontal axis shows two-way traveltime from the water bottom in seconds. The velocity for Site 794 also used for Site 797 because velocity logs were not obtained at Site 797. The measured velocity and density were converted to a time section and sorted as 10 to 20 msec. interval, then convoluted.

The results of synthetic seismogram shows that there is no significant reflectors in the upper part of both sites, although there is a significant change in the AI and RC at around 0.38 sec. Lithologically, this correlates with the diagenetic boundary of opal-A/opal-CT. As the change in acoustic velocity is relatively insignificant, the change in the density is the major factor for contribution to the reflectivity across this boundary. Below this boundary, the seismograms show several high amplitude changes, including reverse polarities which reflect the variability of physical properties associated with changing lithologies.

It is generally concluded therefore that the acoustic characteristics roughly reflect the physical properties and lithologies at both sites. Especially the opal-A/opal-CT diagenetic boundary is enhanced in the synthetic seismogram because the reflection coefficient is relatively high at the boundary and no significant reflectors around the boundary. The reflector is obviously seen in the seismic profiles what discuss in following section.

Subdivisions of Acoustic Stratigraphy

If the seismic characters in all seismic profiles of the Yamato Basin reflect lithologies that are similar to the lithologies at the drilling sites, then it should be possible to apply the acoustic stratigraphy to the entire Yamato Basin. The acoustic stratigraphy at the drilling sites is propagated into the basin wide area based on acoustic characters which including phase polarity, amplitude, degree scattering, and continuity of reflectors.

The acoustic stratigraphy of the Yamato Basin can be correlated with five sedimentary units and acoustic basement based on the acoustic characters (Fig. I-18), and which is able to correlate the lithologies based on the drilling results of ODP sites. All multichannel seismic profiles and the associated interpretations are shown in Figures I-19 to I-31. The seismic intervals are described and correlated as follow in descending order.

Interval I: This interval is characterized by weak and horizontal stratification and has an approximate thickness of about 200 msec. (two-way traveltimes). The interval velocity is about 1520 m/sec. This interval may be composed mostly of Quaternary sediments, alternation of clays and silty clays as well as a few ash layers. In the northern half part of Yamato Basin, the Toyama Deep Sea Fan deposits, which show clear deep sea channel, natural levee, and over flowed structures are recognized in the seismic profiles (Fig. I-32). The distribution of the Toyama Deep Sea Fan deposits is restricted in the middle to northwestern part of the Yamato Basin where they reach up to 500 msec. The thickness of these sediments decreases to the northwest. The channel axis runs to the eastern margin of the distribution (Fig. I-33).

Interval II: This interval is characterized as a weak or "transparent" interval except one strong reflector. This seismic character reflects a homogeneous lithology (diatomaceous silty clay or diatom ooze) and constant physical properties. The strong reflector interpreted to be the diagenetic boundary, opal-A to opal-CT, as suggested by the synthetic seismogram. It is detected in every profile and identified as a somewhat flat reflector as compare to the topography of acoustic basement. This reflector was previously assigned as a lithologic boundary provided a misconception of basin evolution. The interval velocity of interval II is about 1600 m/sec and this interval has a thickness of 500 to 1000 msec.

Interval III: This interval shows well stratified reflectors which include reverse polarity reflectors in contrast with the previous intervals. An example of this acoustic characteristics is shown in Figure I-34. This interval can be correlated with the alternation of chart and siliceous clay unit obtained by ODP. The interval velocity is about 1750 m/sec and the thickness is around 200 msec.

Interval IV: This interval is characterized by weak or "transparent" stratification, and is distributed to the southern half of the Yamato Basin. This interval reflects the alternating lithologies of silt and sand unit. Thickness is about 100 msec.

Interval V: This interval was not cored by ODP Leg 127. The distribution of this interval is restricted to the area around seamounts, and the thickness of this interval decreases away from the seamounts. Thus, this interval is considered to be apron sediments associated with the seamounts.

Interval VI: This interval is defined as acoustic basement, and includes irregularly stratified low frequency reflectors (see Fig. I-35 as an example). The reflectors show relatively strong and parallel reflection. This interval can be correlated with the alternation of sills and sedimentary units. It is impossible to estimate the thickness of this interval from the seismic reflection profiles, however, wide-angle reflection data of Ludwig *et al.* (1975). suggest that this interval has a seismic velocity of 3.5 to 4.0 km/sec, which suggest the thickness is 1 to 2 km.

Basin-wide Acoustic Stratigraphy

According to the acoustic stratigraphy, some structural and tectonic considerations are applied. In general, the southern part of Yamato Basin is showing deeper water depth (approximately 300-400 m deeper) and thicker sediments (approximately 0.5 sec. thicker) than the northern part. Also the seismic interval IV is only distributed in the southern part (deeper than 4.5 sec.). This observation may suggest that the southern part of Yamato Basin is older than the northern part. There are also depressions in this area in the acoustic basement of the profiles, N4, L39, and L36 in Fig. I-31. These may suggest a failed rift system during the formation of the Yamato Basin, but the evidence is inconclusive.

The significant change of the physical properties at the opal-A/CT diagenetic boundary can be clearly seen in the synthetic seismogram. In fact, the strong reflector can trace in everywhere of the Japan Sea. It is able to recognized that as a bottom simulating reflector (BSR). The analysis of the acoustic stratigraphy of the Yamato Basin suggests that there is a basin-wide diagenetic boundary reflector (BSR) which can be provide an important means to the study of the basin evolution and dynamics.

I.7 Opal-A to Opal-CT Transformation BSR

The transformation from opal-A to opal-CT occurs with increasing burial depth as widely known (eg. Jones & Segnit, 1971; Iijima & Tada, 1981). And also the transformation is primarily controlled by temperature, time, surface area, pore water chemistry, lithology, and permeability (Lewin, 1961; White & Corwin, 1961; Siever, 1962; Mizutani, 1966; Hurd, 1972; Lancelot, 1973; Wollast, 1974; Murata & Nakata, 1974; Kastner *et al.*, 1977). Mizutani (1970) pointed out the most significant factor for the rate of transformation is the reaction temperature from experimental investigation. Hein *et al.* (1978) reported the diagenetic BSR from the Bering Sea. In the Bering Sea deposits, the diagenetic transformation from opal-A to opal-CT is occur at temperatures between 35°C and 50°C, and the range corresponds to a sub-bottom depth of about 600 m. The diagenetic boundary in the Japan Sea can be recognize as a BSR(Bottom Simulating Reflector), which shows a strong normal polarity reflector in the seismic profile. The BSR is almost parallel with the water bottom and occurs as an inter layer of the seismic interval II. However, it is seen in the profiles that the BSR cut the inter-layered reflector in several places. For example, Figure I-36 shows obvious evidence that the BSR cuts other reflectors. The age of the host sediments of the BSR was determined as 8 Ma and 6 Ma for the Sites 794 and 797 respectively. This suggests that the formation of the BSR is not depended on the age but other factors, most probably on the temperature. The depth of the opal A/CT transition from the ODP Leg 127 is plotted at the "temperature depend area" in the age-temperature relationship figure of Tada (1990, in press) (Fig. I-37). This supports that the depth of BSR is closely controlled by the thermal gradient of the Yamato Basin.

During the drilling at the Sites 794 and 797, temperature measurements were attempted using the Barnes/Uyeda instrument, which injected into the virgin sediments. Each run of the measurement showed a fairly good plateau temperature (Figs. I-38-(1) and I-39-(1)). The temperature of the each run was determined by a least squares method, and plotted against depth in Figures I-38-(2) and I-39-(2). The data show an almost linear increase of temperature with depth in the both sites. The best fit thermal gradients are 125 °C/km and 121 °C/km respectively. The temperature measurements were not able to reach to the depth of the opal-A/CT boundary, however, it was possible to linearly estimate the temperatures at each diagenetic boundary because the thermal conductivity maintained nearly constant value from seafloor to the boundary. Then the boundary temperatures was estimated as 38°C and 36°C for Sites 794 and 797 respectively (Fig. I-40). Figure 2-36 shows all estimated temperatures for the depth of BSR and thermal gradients which are including Leg 128 results according to the courtesy of Leg 128 physical property specialists (Ingle, Suyehiro, von Breymann, *et al.*, 1990). It is clear from this figure that the temperatures of the opal-A/CT boundaries observed in the Japan Sea are quite constant, about 40°C, even on the ridge except the Kita-Yamato Trough. And also the BSR is only seen in the seismic interval II everywhere. It should suggest the factor of lithology can be ignored. The BSR of diagenetic transformation from opal-A/CT in the Yamato Basin thus provides an unique opportunity to study the thermal structure of the basin.

I.8 Thermal Structure of the Yamato Basin

The thermal structure of the Yamato Basin was analyzed based on the BSR distribution as an isothermal plane recognized in a number of seismic profiles. Especially dense seismic profiles are located in the hatched area as shown in Fig.I-41, then this investigation will be concentrated inside of it.

Previous Heat Flow Measurements

Previously, a large amount of heat flow measurements were applied to the Japan Sea by Yasui *et al.* (1966) and Yamano *et al.* (1987) using a thermistor probe whose probe length was 1.5 to 4.5 m. These were also compiled into digital data base by Yoshii & Yamano (1983). All measured heat flow values are plotted in Figure I-42. The heat flow values of the Yamato Basin vary small except a value of 223 mW/m^2, with the standard deviation is 14.667, and the mean value is about 96 mW/m^2. Tamaki (1985) estimated the average value of the Yamato Basin as about 98 mW/m^2 after some data corrections. Thus these previous studies treated the Yamato Basin as a thermally uniform basin. However the heat flow measurements were rather concentrated along some seismic profiles and the distribution was obviously biased. An attempt was made here to estimate the thermal structure of the Yamato Basin using the BSR distribution.

Method of BSR Mapping

The depth of diagenetic BSR was picked up from available seismic profiles every five miles interval (Appendix-C). The water bottom depth and acoustic basement depth are also measured simultaneously. The total number of plotted data is over 400. The data quality of available seismic profiles are not same. For example, there is a significant gap of data quality between a single-channel profile and a processed multi-channel profile. An effort was made to interpret the single-channel data based on the the multi-channel profiles, especially at the intersection points. The pick up error of the BSR from the seismic profiles estimates less than 10 msec. The collected data are displayed in Plate I-1, the color coding of dot designates the depth of BSR as two-way travel-time in second. These raw data are normalized into 10 minutes mesh data. The smoothing area is a ring with a minimum radius equal to the distance to the closest datapoint (near data) and a maximum radius equal to 1.25 times distance to the closest datapoint (far data). Then the far data are weighted with 0.15 and combined with near data, and the mean value of the grid was calculated. Plate I-2 shows a smoothed contour map of the depth variation of BSR. It is clearly seen that a shallow BSR area occurs in the middle part and a deep BSR area in the southwestern part. If the sediment velocity above the BSR is same, the "shallow" means high thermal gradient, and the "deep" means low thermal gradient. Then the surface terrestrial heat flow values of the Yamato Basin can be estimated from this BSR depth.

Conversion to Thermal Data

At first, the unit of BSR depth is converted from time to depth by using a combined velocity profile of the Site 794 (Fig. I-16) for every datapoints. In second, the thermal conductivity is also combined from the profiles of both sites (Fig. I-43). The value of thermal conductivity (K) is assumed as follow,

K=0.85; (water bottom to Opal-A/CT boundary),

K=0.511+1.476e-3∗Depth(mbsf); (deeper than Opal-A/CT boundary)

Each heat flow value is calculated with the thermal gradient and thermal conductivity which includes less than 10 % error for the above opal-A/opal-CT boundary, and plotted in Figure I-44. The circle radius reflects the degree of the heat flow, high heat flow is displayed as large circle. The high heat flow values are concentrating around a point of 39°15'N, 136°40'E. This calculated data are also smoothed into 10 minutes mesh data with the same method (Plate I-3). A distinction of the regional heat flow distribution can be made easily, as a high heat flow area versus a low heat flow area in the basin. The feature of high heat flow area shows a slightly elongated shape of east - west direction, on the other hand, the feature of low heat flow area shows a circular shape. The difference of heat flow values between the areas is significantly large, approximately 50 mW/m^2 or more which apparently exceeds any error estimations. Figure I-45 shows the histogram of calculated heat flow values. The total mean value is a 115.7 mW/m^2 (standard deviation = 41.5), which shows slightly higher value compared with the probe data of previous works. The calculated minimum value is a 52.9 mW/m^2, and the maximum value is a 333.0 mW/m^2. Here the estimated heat flow data were compared with the probe data of same location. Yamano *et al.* (1987) measured heat flow values just on the multichannel seismic line, DELP line-B (Fig. I-46). Then the calculated values were able to check with the probe data. Figure I-47 shows the result of the inspection on the line-B. The calculated values match quite well with the probe data within the expected error range which will be discussed later. This inspection strongly suggests the validity of the heat flow estimation from opal-A/CT BSR.

The surface heat flow estimation from diagenetic transition boundary, opal-A to opal-CT, is including some basic errors, the measurement of temperature, the BSR identification from seismic profile, the depth estimation of BSR (equal to the velocity estimation), the measurement of thermal conductivity, and the assumption of the temperature at the depth of BSR as 40°C. The error estimation of BSR depth, thermal conductivity do not exceed about the 10 % of the heat flow value. The most effective factor is the temperature assumption of BSR. As summarized in Fig. 2-36, the temperatures of the boundary obtained from ODP borehole show less than ±5°C variation. The host sediments of BSR look acoustically same in everywhere. The core recovery is fairly good until the boundary, then the depths of diagenetic transition fronts are showing correct values. The temperature difference may originally including a such error. This study assumed the temperature as 40°C and calculated the surface heat flow values.

If the assumed temperature change 1 degree, the surface heat flow value reflect it as about ±4 mW/m^2. Then the constant error of calculated values is estimated as approximately ±20 mW/m^2.

Thermal Structure of the Yamato Basin

The calculated heat flow values from the BSR are compared with all probe data of Yasui *et al.* (1966) and Yamano *et al.* (1987). The algorithm of comparison is quite simple, in first, the calculated data are collected for each probe data from 5 minutes, 10 minutes, 20 minutes, and 30 minutes mesh areas. Then the collected data are calculated into average without weight. The results of comparison between the calculated data and the measured probe data are plotted in Figure I-48. All comparisons are showing fairly good matching. Calculated data have almost no low estimation, however, have some significantly high values, which is not negligible number. The high values are mainly reflecting the high heat flow area in Plate I-3. The reason why the high heat flow values are estimated will discuss at the following section. Temperature profile is estimated for each datapoint on the seismic profiles by using the combined thermal conductivities of both sites (Fig. I-43) and the thermal gradient of each site. The calculation was programmed for satisfy the surface heat flow values (Appendix-D). The 50°C and 100°C isothermal planes are displayed in Plates I-4 and I-5 (Appendix-C). There indicate the existence of the "hot" area and "cold" area in almost same position with the surface heat flow distribution as displayed in Plate I-3. The isothermal lines of 50 and 100°C are plotted on the interpreted seismic profile of DELP line-A. This shows that the surface temperature of the acoustic basement is not constant.

And also the thermal structure is not affected by the seamount activity which emplaced in middle to late Miocene (Kaneoka *et al.*, 1988).

I.9 Discussions

The thermal structure deduced from the BSR distribution thus indicates the existence of hot and cold regions within the Yamato Basin. The difference in the mean surface heat flow exceeds 50 mW/m^2, significantly above the estimated error level. The surface heat flow estimated from the BSR and probe measurements match well except in the middle of the Yamato Basin where the probe value is consistently lower than the BSR estimation. The area is covered by the Toyama Deep Sea Fan deposits. Thus, it is necessary to estimate the influence of the deposits to the thermal structure. First, how long will take the temperature gradient return to a normal conductive profile after the rapid deposition? For example, if the sediments deposit about 100 m in thickness instantaneously, and heat flow value is constant, 100 mW/m^2, the answer will give as follow.

$Q=mct$

where

Q: heat capacity,

m: mass,

c: specific heat (0.8 for quartz), and

t: temperature.

Then

thermal gradient: 120°C/km,

heat flow: 100 mW/m^2 = 2.3*e-6 $cal/cm^2/sec$, and

sediment density: 2.0 g/cc,

the thermal condition will take about 2700 years for return to the normal conductive structure. This is a short time compare with the Pleistocene history of the Toyama Deep Sea Fan deposition, therefore, it is indicating that the temperature profile can be conductive even in the fan depositional area now.

Mizutani (1970) demonstrated the rate of transformation of silica as function of time and temperature. The transformation occur within 10^4 to 10^5 years. Kastner and Gieskes (1982) mentioned that Mg^{+2} and $(OH)^-$ enhance and/or accelerate the rate of transformation, opal-A to opal-CT. These considerations indicated that the formation of the present BSR is likely to be slower than the thermal profile rebound due to rapid fan deposition, but the reaction is not so late and complete within a million years. If the rapid deposition of the fan sedimentation bias the heat flow profile and "fossilize" the BSR depth, the heat flow value estimated from the BSR should be smaller than the probe measurement values. However, the present discrepancy between probe and the BSR shows the relationship which is the other way around. The probe heat flow is lower than the BSR heat flow.

Why do the probe data show low values rather than the calculated values? One possible answer is that the surface porous sediment does not show a purely conductive thermal profile. As the Toyama Deep Sea Fan deposits comprise of rapidly sedimented sand and mud, it is likely that migration of pore fluid is actively taking place. The observation that heat flow discrepancy is larger in the channel axis supports this possibility. A lateral flux of fluid along the permeable horizon may account for uniform thermal profile reducing the heat flow estimate from the probe measurements. The depth estimation of BSR has a little error, because the velocity of the fan deposits is not obtained by ODP drilling. However the difference of velocity from another equivalent unit may be negligible small.

The above discussions suggest that the heat flow estimate from the BSR represent the present state of conductive thermal regime in the Yamato Basin. Then the question is what is the implications of the heat flow distribution in the basin. The north and south region of the Yamato Basin is "cold" and middle part is "hot" as showed in Figures I-49 and I-50. The water depth and the acoustic basement depth are deeper in the southern part than the middle part. The variance of heat flow is significantly high in the middle part rather than the north and south parts (Fig. I-50). The average heat flow values are 109.6, 126.7, and 95.0 mW/m^2 from north to south respectively. Standard deviations are also calculated from north to south, 20.9, 40.02, and 26.02. It is clearly recognized that the high variability exists in the middle section.

The topographies of acoustic basement and the BSR are displayed together in Plate I-6. This comparison suggests that there is a first order correlation between the two: the hot area suggested by the BSR is corresponding to the shallow basement area, and vice versa. There are obvious second order perturbation which makes the correlation coefficient not so high values even change the smoothing area size (Fig. I-51). And also the temperature of top of acoustic basement is not same as showed in Figure I-52. The seamounts in the Yamato Basin do not cause significant thermal effect for the surrounding sediments from the view of depth variation of BSR in the sediments. Thus the heat flow distribution of the basin seems to be affected by two factors: in first order depth to the basement and second order anomalies superposed on this.

The formation mechanism of Yamato Basin has no positive evidence of a sea-floor spreading. The crustal structure of Yamato Basin shows a marked difference from the normal oceanic crust (Katao, 1988; Hirata *et al.*, 1989; Hirata, 1990 (personal communication)). However the thickness of the crust is significantly thinner than surrounding crustal structures such as the Japan Arc and the Yamato Ridge. This requires at least some portion of the continental crust was stretched to form a thinner crust. Thus, I will apply the relationship for crustal thinning and thermal structure to analyze the implications of heat flow distribution.

Several crustal thinning and subsidence models have been proposed for the major rift zones (eg. McKenzie, 1978; Royden & Keen, 1980; Wernicke, 1981; Lister *et al.*, 1986). The most plausible mechanism for the formation of the Yamato Basin should be a crustal stretching model (pure shear model) which originally proposed by McKenzie (1978) adopted for the Great Basin, the Aegean, the North Sea, and the Michigan Basin, because an asymmetry structure is not seen in the Yamato Basin geologically and geophysically. Sleep (1971) had been mentioned the importance of the subsidence history of passive margin which comparable with that of cooling oceanic lithosphere. The simplest stretching model is based on the stretching factor "ß", cause upwelling of hot asthenosphere with continental lithosphere stretching simultaneously. McKenzie (1978) calculated the amount of initial subsidence and the surface heat flow as a function of time. This simple stretching model is given a lot of modifications, adopted into regional rifting problems (eg. Jarvis & McKenzie, 1980; Le Pichon & Sibuet, 1981; Buck *et al.*, 1988). One of significant modification is a depth-dependent stretching model (Rowley & Sahagian, 1986) accounting for the synrift uplift and doming. This model decrease the "ß" with depth.

The Yamato Basin is under almost complete isostatic equivalence based on the gravity investigation (Miyazaki, 1979). The heat flow anomaly in the Yamato Basin can not be explain from the variation of "ß" of simple stretching model. Because the heat flow anomaly shows over 50 mW/m^2, it request five times or more "ß" values in small restricted area. If it is so, it should produce a large basement topography. It is also significant that the the higher heat flow requires more stretching, therefore more crustal subsidence it will need to explain. It could be a critical point to consider the formation mechanism of Yamato Basin. The relation is opposite in the Yamato Basin. The higher heat flow area coincides with the shallower acoustic basement high. Langseth (1990, personal communication) tried to explain the heat flow values on the Sites 794 and 797 from the mixed model of the pure shear model and the variation of initial thickness of lithosphere. This model also fails to explain the heat flow anomaly over 50 mW/m^2, because this order of heat flow anomaly require over 50 km of initial thickness anomaly in the basin. It seems hard to explain the heat flow anomaly.

Then a possible model is a combined model of the depth-dependent stretching model (Rowley & Sahagian, 1986) and the pure shear model with variable initial rift width model (Buck *et al.*, 1988). The depth-dependent stretching will explain the topography and the absolute value of terrestrial heat flow (first order relation) and the initial rift width will account the heat flow variability in narrow space (second order perturbation). Figure I-53 shows an illustrations of the lithospheric stretching model for explain the topography and heat flow anomaly in the Yamato Basin. Figure I-53-(1) shows a continuous nonuniform stretching model of Rowley & Sahagian (1986). The stretching of crust is uniform stretching of which factor is βc as proposed by McKenzie (1978). The stretching factor ($\beta m_{(z)}$) of mantle lithosphere is changing with depth, and is able to show as following equation.

$\beta m_{(z)}=1+(k/(d+2*|Z*\tan\phi|))$,

where

$k=d'-d$.

This stretching factor, $\beta m_{(z)}$, decreases with depth and is everywhere less than βc. Rowley & Sahagian (1986) calculated the initial subsidence of crust on ϕ for various values of βc from some modified equation of McKenzie (1978) (Fig. I-54). They estimated the surface topography and asthenosphere upwelling as shown in the right of illustrations. Figure I-53-(2) changed the crustal stretching factor and ϕ to large. It can obviously estimate the surface topography from McKenzie's equation (McKenzie, 1978) and the asthenospheric upwelling from the above equation of $\beta m_{(z)}$. Figure I-53-(3) modified the initial stretching width to small. This model require the significant asthenospheric upwelling. These variance should be explain the local surface topography and terrestrial heat flow anomalies in the Yamato Basin, which will require numerical simulations to confirm it.

However the knowledge for rift or rift zone configuration is required to perform meaningful simulation. This is not resolved in the seismic profiles of the Yamato Basin. The detailed structures in the basement have been obscured by sills and sediments alternation.

The shape of the heat flow distribution may require some attentions for dynamic approach to the formation model of Yamato Basin. The origin of heat source also may not be linearly distributed along the extension of Yamato Basin but can be some restricted spot like feature. A speculative illustration is shown in Figure I-55, some small plume may be responsible for the formation mechanism of the Yamato Basin. Thus, an isolated rise of such small plume may account for 1) crustal stretching in a restricted area, 2) failure to initiate seafloor spreading and 3) oval shape of high heat flow area. Tatsumi *et al.* (1988) and Nohda *et al.* (1988) were discussed the asthenospheric injection under the Japan Sea. It is meaningful to discuss with these ideas, but the evidence of active rift must present before it.

II.10 Conclusions

Sediment physical property measurements were successfully conducted at the both Sites 794 and 797 in the Yamato Basin. Based on the sediment physical properties and acoustic characters in seismic profiles, an acoustic stratigraphy was provided for whole area of the Yamato Basin. Similar acoustic characteristics were correlated throughout the basin and the diagenetic BSR was also detected everywhere. It is possible to treat the BSR as an isothermal plane of about 40°C. This enables the calculations of the surface heat flow values and the each depth of isothermal planes for the entire area of the Yamato Basin. The anomaly of the calculated heat flow values is significantly high, which has not been detected in previous works. The thermal structure of the Yamato Basin can be explained by a depth-depending stretching of lithosphere with variable initial rift width and/or upwelling of asthenospheric plumes. This paper also demonstrated the use of the opal-A/CT BSR as an indicator for thermal structure of a sedimentary basin.

References

Anderson, R. N., 1980 update of heat flow in the east and southeast Asian seas, in Hayes, D. E. ed., *The Tectonics and Geologic Evolution of Asian Seas and Islands*, Geophys. Monogr. Ser., AGU, Washington, D. C., *23*, 319-326, 1980.

Buck, W. R., F. Martinez, M. S. Steckler, and J. R. Cochran, Thermal consequences of lithospheric extension: pure and simple, *Tectonics*, *7*, 213-234, 1988.

Carlson, R. L., and P. J. Melia, Subduction hinge migration, *Tectonophys.*, *102*, 399-411, 1984.

Dewey, J. F., Episodicity, sequence, and style at convergent plate boundaries, in Stragway, D. W. ed. *The continental crust and its mineral deposits*, Geol. Assoc. of Canada Special Paper, *20*, 553-573, 1980.

Hein, J. R., D. W. Scholl, J. A. Barron, M. G. Jones, and J. Miller, Diagenesis of late Cenozoic diatomaceous deposits and formation of the bottom simulating reflector in the southern Bering Sea, *Sedimentology*, *25*, 155-181, 1978.

Hirata, N., H. Tokuyama, and T. W. Chung, An anomalously thick layering of the crust of the Yamato Basin, southeastern Sea of Japan: the final stage of back-arc spreading, *Tectonophys.*, *165*, 303-314, 1989.

Honza, E. ed., Geological investigation in the northern margin of the Okinawa Trough and the western margin of the Japan Sea, *Geol. Surv. Japan Cruise Rept.*, *10*, p. 79, 1978a.

Honza, E. ed., Geological investigation of the Okhotsk and Japan Seas off Hokkaido, *Geol. Surv. Japan Cruise Rept.*, *11*, p. 72, 1978b.

Honza, E. ed., Geological investigation of the Japan Sea, *Geol. Surv. Japan Cruise Rept.*, *13*, p. 99, 1979.

Hurd, D. C., Factors affecting solution rate of biogenic opal in seawater, *Earth Planet. Sci. Lett.*, *15*, 411-417, 1972.

Iijima, A. and R. Tada, Silica diagenesis of Neogene diatomaceous and volcaniclastic sediments in northern Japan, *Sedimentology*, *28*, 185-200, 1981.

Ingle, J., K. Suyehiro, M. von Breymann, *et al.*, *Proc. ODP, Init. Repts.*, 128: College Station, TX (Ocean Drilling Program), 1990.

Isezaki, N., A magnetic anomaly map of the Japan Sea, *J. Geomag. Geoelectr.*, *38*, 403-410, 1986.

Ishiwada, Y., E. Honza, and K. Tamaki, Sedimentary basins of the Japan Sea, in *Origin and History of Marginal and Inland Seas*, Proceedings of the 27th International Geol. Cong., *23*, 43-65, 1984.

Jarvis, G. and D. P. McKenzie, Sedimentary basin formation with finite extension rates, *Earth Planet. Sci. Lett.*, *48*, 42-52, 1980.

Jones, J. B. and E. R. Segnit, The nature of opal I. Nomenclature and constituent phases, *J. Geol. Soc. Aust.*, *18/1*, 57-68, 1971.

Kaneoka, I., H. Hayashi, T. Iwaguchi, A. Yasuda, Y. Takigami, K. Fujioka, and H. Sakai, K-Ar dating of volcanic rocks dredged from the Yamato Seamount Chain in the Japan Sea, *Bull. Volcanol. Soc. Japan, Ser. 2*, *33*, 213-218, 1988.

Karig, D. E., Ingle, J. C., Jr., *et al.*, *Initial Reports of the Deep Sea Drilling Project*, Washington (U. S. Government Printing Office), *31*, 1975.

Kastner, M. and J. M. Gieskes, Opal-A to opal-CT transformation: A kinetic study, in Iijima, A. *et al.*, ed., *Siliceous deposits in the Pacific region*, Elsevier, 211-227, 1982.

Kastner, M., J. B. Keene, and J. M. Gieskes, Diagenesis of siliceous oozes I. Chemical controls on the rate of opal-A to opal-CT transformation - an experimental study, *Geochim. Cosmochim. Acta*, *41*, 1041-1059, 1977.

Katao, H., Seismic structure and formation of the Yamato Basin, *Bull. Earthq. Res. Inst. Univ. Tokyo*, *63*, 51-86, 1988.

Kawai, N., T. Nakajima, and T. Hirooka, The evolution of the Island Arc of Japan and the formation of granites in the Circum-Pacific belt, *J. Geomag. Geoelectr.*, *23*, 267-293, 1971.

Kimura, K., Chronostratigraphic study of Tertiary NE Japan, *The Earth Monthly*, *8*, 370-375, 1986.*

Kimura, M., T. Matsuda, H. Sato, I. Kaneoka, H. Tokuyama, S. Kuramoto, A. Oshida, K. Shimamura, K. Tamaki, H. Kinoshita, and S. Uyeda, Report on DELP 1985 cruises in the Japan Sea Part VII: Topography and geology of the Yamato Basin and its vicinity, *Bull. Earthq. Res. Inst. Univ. Tokyo*, *62*, 447-483, 1987.

Kitamura, N. ed., *Geological Atlas of Neogene Northeast Japan Arc*, Houbundou, 1986.*

Kobayashi, K., Spreading of the Sea of Japan and drift of Japanese Island Arc: a synthesis and speculation, in *Island Arc, Marginal Seas, and Kuroko Deposits*, Min. Geol. Spec. Issue, *11*, 23-36, 1983.**

Kobayashi, Y., Initiation of plate subduction, *The Earth Monthly*, *5*, 510-514, 1983.*

Kuramoto, S., Estimation of the formation age of the Okushiri Ridge, *Marine Sci. Monthly*, *222*, 669-675, 1988.*

Kurasawa, H. and T. Konda, Strontium isotopic ratios of Tertiary volcanic rocks of northeastern Honshu, Japan: implication for the spreading of the Japan Sea, *J. Geol. Soc. Japan*, *92*, 205-217, 1986.**

Lallemand, S. and L. Jolivet, Japan Sea: a pull-apart basin?, *Earth Planet. Sci. Lett.*, *76*, 375-389, 1985/86.

Lelikov, Ye. P. and I. I. Bersenev, Early Proterozoic gneiss-migmatite complex in the southwestern part of the Sea of Japan, *Doklady Akad. Nauk USSR*, *223*, 74-76, 1973.

Lancelot, Y., Chert and silica diagenesis in sediments from the central Pacific, in *Initial Reports of the Deep Sea Drilling Project*, *Vol. XVII* (P. L. Winterer, J. I. Ewing *et al.*), U. S. Government Printing Office, Washington, 377-405, 1973.

Lee, H., Measurements and estimates of engineering and other physical properties, Leg 19, in Creager, J. S., D. W. Scholl, *et al.*, *Init. Repts. DSDP*: Washington (U. S. Govt. Printing Office), *19*, 701-719, 1973.

Le Pichon and J. C. Sibuet, Passive margins: A model of formation, *J. Geophys. Res.*, *86*, 3708-3720, 1981.

Lewin, J. C., The dissolution of silica from diatom walls, *Geochim. Cosmochim. Acta*, *21*, 182-198, 1961.

Lister, G. S., M. A. Etheridge, and P. A. Symonds, Detachment faulting and the evolution of passive continental margins, *Geology*, *14*, 246-250, 1986.

Ludwig, W. J., S. Murauchi, and R. E. Houtz, Sediment and structure of the Japan Sea, *Geol. Soc. Am. Bull.*, *86*, 651-664, 1975.

McKenzie, D., Some remarks on the development of sedimentary basins, *Earth Planet. Sci. Lett.*, *40*, 25-32, 1978.

Miyashiro, A., Hot region and the origin of marginal basins in the Western Pacific, *Tectonophys.*, *122*, 195-216, 1986.

Miyashita, S., T. Tanaka, H. Momma, H. Tokuyama, W. Soh, S. Kuramoto, and J. Ishii, Observations using the submersibles "SHINKAI 2000" at the northern part of the Okushiri Ridge - A section of the oceanic crust of the Japan Sea -, *JAMSTECTR DEEPSEA RES.*, 85-100, 1989.**

Miyazaki, T., Gravity survey, in Geological investigation of the Japan Sea, *Geol. Surv. Japan Cruise Rept.*, *13*, 27-45, 1979.

Mizutani, S., Transformation of silica under hydrothermal conditions, *Nagoya Univ. J. Earth Sci.*, *14*, 56-88, 1966.

Mizutani, S., Silica minerals in the early stage of diagenesis, *Sedimentology*, *15*, 419-436, 1970.

Murata, K. J. and J. K. Nakata, Cristobalitic stage in the diagenesis of diatomaceous shale, *Science*, *184*, 567-568, 1974.

Murauchi, S., Crustal structure of the Japan Sea, *KAGAKU* (Iwanami), *42*, 367-375, 1972.*

Nakamura, K., Possible nascent trench along the eastern Japan Sea as the convergent boundary between Eurasian and North American plates, *Bull. Earthq. Res. Inst. Univ. Tokyo*, *58*, 711-722, 1983.**

Niitsuma, N., Y. Saito, and A. Taira, Reconstruction of the Japanese Islands before Japan Sea opening, *J. Phys., Earth*, *36*, S133-S142, 1988.

Nohda, S. Y. Tatsumi, Y. Otofuji, T. Matsuda, and K. Ishizaka, Asthenospheric injection and back-arc opening: isotopic evidence from Northeast Japan, *Chem. Geol.*, *68*, 317-327, 1988.

Otofuji, Y., and T. Matsuda, Paleomagnetic evidence for the clockwise rotation of Southwest Japan, *Earth Planet. Sci. Lett.*, *62*, 349-359, 1983.

Otofuji, Y., T. Matsuda, and S. Nohda, Paleomagnetic evidence for the Miocene counter-clockwise rotation of Northeast Japan: rifting process of the Japan Arc, *Earth Planet. Sci. Lett.*, *75*, 265-277, 1985.

Ricker, N., The form and laws of propagation of seismic wavelets, *Geophys.*, *18*, 10-40, 1953.

Rowley, D. B. and D. Sahagian, Depth-dependent stretching: A different approach, *Geology*, *14*, 32-35, 1986.

Royden, L. and C. E. Keen, Rifting process and thermal evolution of the continental margin of eastern Canada determined from subsidence curves, *Earth Planet. Sci. Lett.*, *51*, 343-361, 1980.

Sagayama, T., Diatom assemblage from Kaiyo-kaizan (seamount), northeast margin of the Japan Basin, *J. Geol. Soc. Japan*, *94*, 295-300, 1988.**

Sayanagi, K., N. Isezaki, and Y. Kitahara, Report on DELP 1985 cruises in the Japan Sea Part IV: Geomagnetic anomalies over the seamounts in the Yamato Basin, *Bull. Earthq. Res. Inst. Univ. Tokyo*, *62*, 391-415, 1987.

Sengör, A. M. C. and K. Burke, Relative timing of rifting and volcanism on earth and its tectonic implications, *Geophys. Res. Lett.*, *5*, 419-421, 1978.

Seno, T., A consideration on the "Japan Sea subduction hypothesis" - seismic slip vectors along the Japan Trench -, *J. Seismol. Soc. Japan (ZISIN)* *36*, 270-273, 1983.*

Siever, R., Silica solubility, 0°-200°C, and the diagenesis of siliceous sediments, *J. Geol.*, *70*, 127-150, 1962.

Sleep, N. H., Thermal effects of the formation of Atlantic continental margins by continental breakup, *Royal Astron. Soc. Geophys. J.*, *24*, 325-350, 1971.

Shuto, K., Tertiary volcanism of the Northeast Japan arc in view of hypothesis of the spreading of the Japan Sea, *J. Assoc. Geol. Coll. Japan (Earth Sci.)*, *43*, 28-42, 1989.**

Tada, R., Compaction and cementation in siliceous rocks and their possible effect on bedding enhancement, in *Cycles and Events in Stratigraphy*, Einsel, G., W, Ricken, and A. Seilacher, eds., Springer, 1990, in press.

Takahashi, E. and I. Kushiro, Melting of dry peridotite at high pressure and basalt magma genesis, *Am. Mineral.*, *68*, 859-876, 1983.

Tamaki, K., Age of the Japan Sea, *Chigaku Zasshi*, *94*, 14-29, 1985a.**

Tamaki, K., Two modes of back-arc spreading, *Geology*, *13*, 475-478, 1985b.

Tamaki, K., Geological structure of the Japan Sea and its tectonic implications, *Bull. Geol. Surv. Japan*, *39*, 269-365, 1988.

Tamaki, K. and E. Honza, Incipient subduction and obduction along the eastern margin of the Japan Sea, *Tectonophys.*, *119*, 381-406, 1985.

Tamaki, K. and K. Kobayashi, Magnetic anomaly of the Japan Sea, *Marine Sci. Monthly*, *222*, 705-710, 1988.*

Tamaki, K., K. Pisciotto, J. Allan, *et al.*, *Proc. ODP, Init. Repts.*, 127: College Station, TX (Ocean Drilling Program), 1990.

Tatsumi, Y., M. Sakuyama, H. Fukuyama, and I. Kushiro, Generation of arc basalt magmas and thermal structure of the mantle wedge in subduction zones, *J. Geophys, Res.*, *88*, 5815-5825, 1983.

Tatsumi, Y., S. Nohda, and K. Ishizaka, Secular variation of magma source compositions beneath the Northeast Japan Arc, *Chem. Geol.*, *68*, 309-316, 1988.

Taylor, B. and G. D. Karner, On the evolution of marginal basins, *Rev. Geophys. Spa. Phys.*, *21*, 1727-1741, 1983.

Tokuyama, H., M. Suyemasu, K. Tamaki, E. Nishiyama, S. Kuramoto, K, Suyehiro, H. Kinoshita, and A. Taira, Report on DELP 1985 cruises in the Japan Sea Part III: Seismic reflection studies in the Yamato Basin and the Yamato Rise area, *Bull. Earthq. Res. Inst. Univ. Tokyo*, *62*, 367-390, 1987.

Tsuchiya, N., Submarine igneous activity of basaltic magma during middle Miocene age in the central part of Akita Prefecture, northeast Japan, *Bull. Geol. Surv. Japan*, *37*, 363-366, 1986.**

Tsuchiya, N., Middle Miocene back-arc rift magmatism of basalt in the NE Japan arc, *Bull. Geol. Surv. Japan*, *41*, 473-505, 1990.

Tsuchiya, N., A. Ozawa, and T. Katahira, Two types of Miocene basaltic rocks around Yurihara Oil and Gas Field, southeastern Akita Prefecture, Northeast Japan, *J. Japanese Assoc. Pet. Tec.*, *54*, 179-193, 1989.

Vasilief, B. I., New data on age and mechanism of formation of marginalsea basins and deep-sea trenches in the northwestern Pacific, *Doklady Akad. Nauk USSR*, *225*, 60-62, 1975.

Von Herzen, R. P. and A. E. Maxwell, The measurement of thermal conductivity of deep-sea sediments by a needle probe method, *J. Geophys. Res.*, *65*, 1535-1541, 1959.

Wernicke, B., Low-angle normal faults in the Basin and Range province: Nappe tectonics in an extending orogen, *Nature*, *291*, 645-648, 1981.

White, J. F. and J. F. Corwin, Synthesis and origin of chalcedony, *Am. Miner.*, *46*, 112-119, 1961.

Wollast, R., The silica problem, in *The Sea, Vol. 5* (Ed. by E. D. Goldberg), John Wiley & Sons, New York, 359-392, 1974.

Yamaji, A., Rapid intra-arc rifting in Miocene Northeast Japan, *Tectonics*, *9*, 365-378, 1990.

Yamaji, A. and H. Sato, Miocene subsidence of the Northeast Honshu Arc and its mechanism, *Mem. Geol. Soc. Japan*, *32*, 339-349, 1989.**

Yamano, M., S. Uyeda, M. Uyeshima, M. Kinoshita, S. Nagihara, R. Boh, and H. Fujisawa, Report on DELP 1985 cruises in the Japan Sea Part V: Heat flow measurements, *Bull. Earthq. Res. Inst. Univ. Tokyo*, *62*, 417-432, 1987.

Yamashita, S., Petrological study for the volcanic rocks of seamount in the Yamato Basin, *Marine Sci. Monthly*, *20*, 664-669, 1988.*

Yasui, M., T. Kishii, T. Watanabe, and S. Uyeda, Studies of the thermal state of the earth. The 18th paper: Terrestrial heat flow in the Japan Sea (2), *Bull. Earthq. Res. Inst. Univ. Tokyo*, *44*, 1501-1518, 1966.

Yoshii, T. and M. Yamano, Digital heat flow data file around Japanese Islands, 1983.

* : in Japanese

** : in Japanese with English abstract