Age Estimation of the Japan Sea on the Basis of Stratigraphy, Basement Depth, and Heat Flow Data

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Ages of the Japan and the Yamato Basins in the Japan Sea were examined on the basis of three independent methods; stratigraphic consideration of the basin sediments, age-depth correlation, and age-heat flow correlation. Basement depths of the Japan and the Yamato Basins after sediment loading correction were compared with those of other marginal seas in the Western Pacific whose ages are well constrained. The age estimations by age-depth correlation and age-heat flow correlation show good coincidence in the Japan Basin. The age estimation of the Yamato Basin, however, shows a discrepancy among the three methods; the basement depth shows an age range from 6 Ma to 0 Ma, sediment stratigraphy shows that of about 10 Ma, and heat flow data show the age from 30 Ma to just over 10 Ma. This discrepancy can be explained by the thick accumulation of Neogene volcanoclastics which are represented as acoustic basements on seismic reflection records with a refraction velocity of 3.5 km/sec. The final estimated age of the Japan and the Yamato Basins is identical with a range of 30 Ma or older to 15 Ma or slightly younger.

1. Introduction

The age of the Japan Sea has been controversial with estimates ranging from Mesozoic (e.g., GNIBIDENKO, 1979), to Early-Middle Miocene time (e.g., OTOFUJI *et al.*, 1985a), while ages of most of other marginal seas in the Western Pacific have been identified. This ambiguity makes an obstacle for the study of the Cenozoic tectonic evolution of the Japanese islands and the Western Pacific. The age of the Japan Sea will present an important constraint for the tectonic evolution of the Western Pacific.

The age of the ocean floor is obtained by the identification of magnetic anomaly lineations and the age determination of basement rocks by deep sea drilling. Ages of most of the marginal seas in the Western Pacific have been determined by these two methods. Both of these two methods, however, are not successful for the Japan Sea. The magnetic anomaly pattern of the Japan Sea, which is complicated with weak amplitude is difficult to identify (e.g., ISEZAKI and UYEDA, 1973). Four DSDP holes of the Japan Sea did not reach the basement in the basin area (Fig. 1) (KARIG and INGLE, Jr., 1975).

There are some other methods to constrain the age of the ocean floor. Basement depth, heat flow value, and lithospheric thickness are good indicators for this. They have simple correlations with the age of the ocean floor in terms of square root of age

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Fig. 1. Topography of the Japan Sea with DSDP Leg 31 sites.

(PARSONS and SCLATER, 1977; YOSHII *et al.*, 1976). These correlations have been established in such major oceans as the Pacific, Indian, and Atlantic Oceans, but have still been controversial in the marginal sea basins. Such correlation is the result of the cooling effect of the lithosphere according to its age gradient after the formation at the mid-oceanic ridge. In the context of plate tectonics, the formation of the marginal seas is caused by sea floor spreading analogous to the process along mid-oceanic ridges. This suggests the possibility that such correlation is applicable to the marginal sea basins such as the Japan and the Yamato Basins.

Abundant sampling data and DSDP drilling data are available in the Japan Sea. Sediment stratigraphy of the basin area can be deduced from the bottom sampling data, drilling data, and seismic reflection profiles. The age estimation of the bottom of

the sediments using the stratigraphy well constrains the age of the underlying basement. Thus, the sediment stratigraphy also presents constraints for the formation age of the Japan Sea. In this paper, I discuss and estimate the age of the Japan Sea on the basis of three independent methods; stratigraphic consideration of the basin sediments, age-depth correlation, and age-heat flow correlation.

2. Age Estimation Based on Sediment Stratigraphy

There are four major sedimentary basins in the Japan Sea. They are the Japan Basin, the Yamato Basin, the Tartary Trough, and the Tsushima Basin (Fig. 1). The previous seismic refraction surveys document or suggest that these basins are underlain by oceanic or sub-oceanic crusts (e.g., LUDWIG *et al.*, 1975). These basins are buried by the sediments with a maximum thickness of 1.5 to 3.0 sec in two-way acoustic travel time (ISHIWADA *et al.*, 1984). Abundant geological and geophysical data, including deep sea drilling data by DSDP, are available in the Yamato and the Japan Basins (Fig. 2). The sediment stratigraphy is deducible from these abundant data.

Two major stratigraphic units are observed in the Yamato Basin (Fig. 3), a stratified layer in the upper part and a transparent layer in the lower part. Another

Fig. 2. Survey track lines of Geological Survey of Japan research cruises GH77-2, GH77-3, GH78-2, and GH78-3. Solid lines show localities of seismic profiles of Figs. 3, 4, 6, and 12.

Fig. 3. Seismic profile of the Yamato Basin. Line L39 on Fig. 2.

stratified layer underlies the transparent layer in the marginal area of the basin (Fig. 4). This stratified layer is also underlain by another transparent layer on the flanks of the rise (Fig. 4). Thus, the stratigraphic units on the seismic profiles of the Yamato Basin are divided into four units in descending order; the upper stratified layer, the upper transparent layer, the lower stratified layer, and the lower transparent layer. The lower stratified layer and the lower transparent layer are only observed in the marginal part of the basin and on the flank of the rise.

There are two deep sea drilling sites in the Yamato Basin and its vicinity; Site 299 in the central part of the basin and Site 302 on the northeastern flank of the Yamato Rise (KARIG and INGLE, Jr., 1975). Outcrops of the lower sedimentary units of the Yamato Basin are commonly observed along the surrounding rises and ridges such as the Yamato Rise and the Sado Ridge (TAMAKI *et al.*, 1981). The results of two deep sea drilling sites together with the bottom sampling data from the surrounding outcrops present constraints that are effective for estimating the age of the acoustic basement of the Yamato Basin, even though the hole of Site 299 in the basin did not reach the basement. The principle of the age estimation of the Yamato Basin based on such data is summarized in a schematic drawing as shown in Fig. 5.

Fig. 4. Seismic profile of the northwestern margin of the Yamato Basin. Line L38 on Fig. 2.

Fig. 5. Summary cartoon of stratigraphy of the Yamato Basin.

The hole of the Site 299 stopped at the bottom of the upper stratified layer and the age of the hole bottom was estimated to be 3.5 Ma by diatom analysis (KOIZUMI, 1979). The upper transparent layer, which was not penetrated by the drilling, crops out on the southern slope of the Yamato Rise. Piston and gravity cores from the southern slope of the Yamato Rise such as sites RC24 and St. 65-6 recovered older sediments with an age of 4 to 5 Ma (HONZA, 1979; KOIZUMI, 1979). Site 302 penetrated the transparent layer and the lower stratified layer on the flank of the Yamato Rise and almost touched the basement. Diatom analysis on this site shows that the age of the lower stratified layer and the lower transparent layer is from 5 to 9 Ma (KOIZUMI, 1979). The value of 9 Ma is based on the assumption that sedimentation rate is constant. A chip of supposed basement rock was sampled from the bottom of site 302. Although the age was not determined, it is probably correlated with the Oligocene-Miocene volcanic rocks (so-called "Green Tuff" horizon on the Japanese islands) (SHIMAZU, 1979). According to these results, the age of the lower stratified layer is older than 5 Ma, presumably extending to 10 Ma.

The lower stratified layer of Late Miocene age (5 Ma to 10 Ma) is not distributed in the central part of the basin, but is distributed only in the marginal area of the Yamato Basin. There is a problem about tracing the lower stratified layer into the central basin area. This layer appears to become transparent towards the central part of the basin. The age of the bottom of the transparent layer at the central part of the basin is estimated to have almost the same age as that of the lower stratified layer at the margin. Consequently, it is estimated that the age of the acoustic basement or the age of the bottom of the sedimentary sequence of the Yamato Basin is around 10 Ma (Middle-Late Miocene time). The acoustic basement of the Yamato Basin, however, may not be correlated to oceanic basement or oceanic basalts as discussed later. The age for the Yamato Basin needs more discussion.

In the case of the Japan Basin, there are no outcrops of the lower sedimentary units in the margin area of the basin. DSDP Site 301 in the Japan Basin presents a unique stratigraphic constraint for the sedimentary sequence of the basin. The sedimentary sequence of the Japan Basin is divided into two units; the stratified layer in the upper part and the transparent layer in its lower part (Fig. 6). The penetration of Site 302 was 497 m, nearly reaching the bottom of the upper stratified layer. The age of the bottom of the hole is estimated to be 4 Ma on the basis of the diatom analysis

(KOIZUMI, 1979). The maximum thickness of the sediments of the Japan Basin is 2.5 seconds in two-way travel time which is considerably thicker than that of the Yamato Basin of 1.5 seconds (ISHIWADA *et al.*, 1984). This difference of the sediment thickness is due to the difference of the thickness of the transparent layer, while the upper stratified layer shows the same thickness and age. The difference of the sediment thickness in both basins indicates that the age of the basement in the Japan Basin is older than that in the Yamato Basin.

3. Age Estimation Based on Basement Depth

Table 1 shows the correlation of lithospheric thickness, depth, and terrestrial heat flow of the oceanic lithosphere according to its age. This correlation was established in the major oceans, the Pacific, the Indian, and the Atlantic oceans as a function of square root of the age. The basement depth of the oceanic crusts in the marginal sea does not follow this age-depth correlation (SCLATER *et al.*, 1976). KOBAYASHI (1984) compiled the age-depth correlation in the marginal seas and suggested that a similar correlation is observed in the marginal sea but that the depth of the basement in the marginal seas is generally 1000 m deeper than the calculated depth from the equation for major oceans. The comparison of basement depth of the basins of the Japan Sea with those of the other marginal seas in the Western Pacific whose ages are well identified will present a constraint for the age estimation of the Japan Sea.

A sediment loading correction is necessary in the discussion of the basement depth of the marginal seas which have thick accumulations of sediments. If the sedimentary cover is removed from the basin, the basement of the basin will rebound isostatically. The basement depth of isostatic compensation after removal of the sediments should be used for the discussion of the age. CROUGH (1983) presented a simple formula for the sediment loading correction of an oceanic basin. The correction formula is:

$$\begin{aligned} &\text{basement depth after sediment loading correction (m)} \\ &= (\text{water depth (m)}) + 600 * (\text{two-way sediment thickness (sec)}). \end{aligned}$$

In the case of the Japan Basin on Fig. 6, the water depth is 3690 m and the two-way sediment thickness is 2.1 seconds. Then the basement depth after the sediment loading correction is 4950 m and was obtained as follows.

$$3690 + 600 * 2.1 = 4950 \text{ (m)}.$$

According to Table 1 the basement depth of 4950 m corresponds to an age greater than 48 Ma. Depth 1 and Depth 2 on the table, however, are only valid for major oceans such as the Pacific and the Atlantic oceans but not for those of marginal seas.

Figure 7 shows a comparison of the age basement depth after sediment loading correction of marginal seas in the Western Pacific. The basement here is identical with the acoustic basement on the seismic profile. The Shikoku Basin, which is documented to have been active from 30 Ma to 15 Ma from the deep sea drilling results and the identification of magnetic anomaly lineations (KLEIN and KOBAYASHI,

Table 1. Basement depth (Depth 1 and Depth 2), heatflow (Heatflow 1 and Heatflow 2), and lithospheric thickness according to the age of the oceanic crusts.

Age (Ma)	Basement Depth1 (m)	Basement Depth2 (m)	Heatflow1 (mW/m ²)	Heatflow2 (mW/m ²)	Lithosphere Thickness (km)
5	3504	3283	211	224	16.75
6	3561	3357	193	205	18.35
7	3614	3426	179	190	19.82
8	3664	3490	167	177	21.18
9	3710	3550	157	167	22.47
10	3754	3607	149	159	23.69
11	3795	3661	142	151	24.84
12	3835	3712	136	145	25.95
13	3873	3762	131	139	27.01
14	3910	3810	126	134	28.03
15	3946	3856	122	130	29.01
16	3980	3900	118	125	29.96
17	4013	3943	115	122	30.88
18	4046	3985	111	118	31.78
19	4077	4026	108	115	32.65
20	4107	4065	106	112	33.50
21	4137	4104	103	109	34.32
22	4166	4142	101	107	35.13
23	4195	4179	98	105	35.92
24	4223	4215	96	102	36.69
25	4250	4250	94	100	37.45
26	4277	4285	93	98	38.19
27	4303	4319	91	97	38.92
28	4329	4352	89	95	39.63
29	4354	4385	88	93	40.33
30	4379	4417	86	92	41.02
31	4403	4449	85	90	41.70
32	4427	4480	83	89	42.37
33	4451	4511	82	87	43.03
34	4474	4541	81	86	43.67
35	4497	4571	80	85	44.31
36	4520	4600	79	84	44.94
37	4542	4629	78	82	45.56
38	4564	4658	77	81	46.17
39	4586	4686	76	80	46.78
40	4608	4714	75	79	47.37
41	4629	4741	74	78	47.96

The equations for the calculation are as follows; Depth 1=2900+270*(Age)^{1/2} (HAYES, 1983), Depth 2=2500+350*(Age)^{1/2} (PARSONS and SCLATER, 1977), Heatflow 1=4.18*11.3/(Age)^{1/2} (PARSONS and SCLATER, 1977), Heatflow 2=4.18*12/(Age)^{1/2} (DAVIS and LISTER, 1977), and Thickness=7.49*(Age)^{1/2} (YOSHII *et al.* 1976).

1980), has a basement depth of 4500 to 5000 m after sediment loading correction. The South China Basin in the South China Sea with an age of 30 to 17 Ma also shows the same basement depth range of 4500 to 5000 m. The South China Basin is overlain by thicker sediments, 2.0 seconds, than the Shikoku Basin which has a sediment thickness of less than 0.5 second. The age range and basement depth range after sediment loading correction of the Shikoku Basin and the South China Basin coincide

Fig. 7. Basement depths and ages of marginal basins of the Western Pacific. The basement depths are depths of acoustic basements on seismic profiles after sediment loading correction by CROUGH's method (1983). Question marks show marginal shallow basements in the basin and may not be correlated to oceanic crusts. The identified ages of the basins are based on KLEIN and KOBAYASHI (1980) for the Shikoku Basin, TAYLOR and HAYES (1983) for the South China Sea, and HUSSONG and UYEDA (1982) for the Mariana Trough.

with each other. This means that the comparison method of basement depth after sediment loading correction is valid for the age estimation of the marginal sea basins. Figure 7 also suggests that the basement depth after sediment loading correction is 600 to 700 m deeper than the calculated depth from the age-depth equation for major oceans. The difference, 600 to 700 m, is less than the previously suggested difference, 1000 m, by KOBAYASHI (1984).

Figure 7 shows that the basement depth of the Japan Basin is almost the same as those of the Shikoku Basin and the South China Basin. The Shikoku Basin has an age range of 30 to 15 Ma and the South China Basin has an age range of 32 to 17 Ma. It is probable that the Japan Basin has an age range of about 30 to 15 Ma. The basement of the Japan Basin becomes shallower at some margins of the basin and reaches to 3600 m after sediment loading correction. The depth of 3600 m is correlated to the age of 0 Ma on the basis of comparison with the Mariana Trough. The acoustic basement of the Japan Sea, however, commonly has a sonic velocity of 3.5 km/sec which is slower than the normal oceanic layer (4.5–5.5 km/sec layer) (LUDWIG *et al.*, 1975). The presence of the 3.5 km/sec layer is critical for the discussion of the basement depth. This problem is discussed later.

ABE and KANAMORI (1970a) measured group velocities of surface waves of earthquakes across the Japan Basin and concluded that lithospheric thickness of the Japan Basin is about 30 km. The thickness of 30 km for the lithosphere corresponds to the age of 17 Ma according to YOSHII *et al.* (1976) (Table 1). This estimation is not

greatly different from the above estimation, if we take account of the rough resolution of the measurements of lithospheric thickness by surface wave. ABE and KANAMORI (1970b) observed the same value, 30 km, for the lithospheric thickness of the eastern half of the Philippine Sea (Shikoku-Parece Vela Basin) whose age is 32 Ma to 15 Ma. The same thickness of the lithosphere of the Japan Basin and the Shikoku Basin supports that the Japan Basin has the comparable age with Shikoku Basin.

The basement depth of the Yamato Basin is shallower than that of the Japan Basin (Fig. 8). The basement depth after sediment loading correction is almost the same as that of the Mariana Trough and the suggested age is 6 to 0 Ma. The sonic velocity of the acoustic basement of the Yamato Basin does not show normal oceanic layer either. This problem is also discussed later.

4. Age Estimation Based on Heat Flow Value

There have been several discussions about age-heat flow correlation of the marginal sea basins. SCLATER *et al.* (1976) studied the heat flow value of the

Fig. 8. Typical profiles of the Japan Basin and the Yamato Basin. Both profiles represent the area of the thickest sediments of each basin.

Philippine Sea and suggested that the age-heat flow equation for the major oceans is applicable to the marginal seas. WATANABE *et al.* (1977) compiled the heat flow data in the Western Pacific and concluded that the heat flow value of the marginal seas is appreciably higher than the value calculated from age-heat flow equation of the major oceans. KONO and AMANO (1977) examined the age-heat flow correlation of the Japan Sea and presented an opposing conclusion. They evaluated the influence of sedimentation ratio to the heat flow value on the basis of VON HERZEN and UYEDA's (1963) model which takes account of cooling effects by turbidite sedimentation and concluded that the heat flow value of the Japan Sea is lower than the value based on age-heat flow equation when the sedimentation ratio is large with the range from 10^{-3} cm/yr to 10^{-1} cm/yr. These divergent observations were caused by the uncertainty of the age of some marginal seas at that time. ANDERSON (1980) later examined the age-heat flow correlation in marginal seas of well identified ages and suggested that the age-heat flow correlation similar to major oceans exists in the marginal seas. TAYLOR and HAYES (1983) measured the heat flow value of the South China Basin and confirmed that the age-heat flow correlation of the major oceans are applicable to the marginal seas (Fig. 9). The South China Basin has a sedimentary cover with the thickness of about 2.0 seconds, which resembles the Japan Sea. Here I examine the heat flow value of the Japan Sea according to the results by ANDERSON (1980) and TAYLOR and HAYES (1983) to show that the age-heat flow correlation of the major oceans is valid even in marginal sea basins.

Table 2 shows selected heat flow values from the digital heat flow data of the Japan Sea (YOSHII and YAMANO, 1983) which include heat flow data from over 100

Fig. 9. Age-heat flow correlation of the South China Basin (TAYLOR and HAYES, 1983). Upper curve is based on DAVIS and LISTER (1977) and lower one is from PARSONS and SCLATER (1977).

Table 2. Average heat flow values of the basins in the Japan Sea.

Japan Basin	120	117	116	113	112	Average heat flow	
67 sites	112	111	111	110	110	of Japan Basin =	95 ± 12
	110	109	109	108	107		
	106	105	105	104	102		
	102	102	101	100	99		
	99	97	97	97	95		
	95	94	94	93	92		
	92	92	91	90	89		
	89	89	89	89	89		
	89	88	87	87	87		
	87	87	86	86	85		
	84	84	84	84	83		
	83	82	80	79	78		
	71	59					
Yamato Basin	145	111	108	107	107	Average heat flow	
26 sites	102	102	100	99	98	of Yamato Basin =	97 ± 12
	98	97	97	97	92		
	91	90	90	90	89		
	89	89	87	86	84		
	82						
Tsushima Basin	103	100	99	94	90	Average heat flow	
6 sites	89					of Tsushima Basin =	96 ± 6
Tartary Trough	137	100	97	96	91	Average heat flow	
6 sites	83					of Tartary Trough =	101 ± 19
Mogami Trough	67	59	58	54		Average heat flow	
4 sites						of Mogami Trough =	59 ± 6
Oki Trough	87	83	79	72		Average heat flow	
4 sites						of Oki Trough =	80 ± 6
Kita-Yamato Trough	75	75				Average heat flow	
2 sites						of Kita-Yamato T. =	75 ± 0

The heat flow values are selected from YOSHII and YAMANO's (1983) heat flow digital data file according to the manner that the sites of the sediment thickness less than 300 m are rejected as well as sites less than 10 km from topographic highs.

sites in the Japan Sea. The sites were selected where the sediment thickness is greater than 300 m and where there are no seamounts within 10 km, to eliminate the thermal disturbance by water circulation through porous basement rocks (Fig. 10). Values too low, less than 40 mW/m², were also eliminated in the Japan Basin. Seismic profiles on the ship's tracks of Fig. 2 and the sediment isopach map by ISHIWADA *et al.* (1984) were used to evaluate sediment thickness at the sites.

KOBAYASHI and NOMURA (1972) suggested that the heat flow value of the Japan Sea appears to be higher with an extent of 1.0 HFU (41.8 mW/m²) as a result of iron sulfide oxidation. However, careful heat flow measurements in the Japan Basin and a heat flow measurement in a DSDP hole at Site 301 in the Japan Basin did not detect

Fig. 10. Distribution of heat flow values in the basins of the Japan Sea. Plotted data are listed in Table 2. Dotted lines show boundaries of the basins for the averaging the heat flow value for each basin.

heat generation effect in the sedimentary layer (WATANABE *et al.*, 1977). In this discussion, I disregard the secondary heat generation in the sediments, although there still remains the possibility of a little heat generation effect in the sediments of the Japan Sea as suggested by WATANABE *et al.* (1977).

The average heat flow value of the Japan Basin is 95 mW/m^2 corresponding to an age of 25 to 28 Ma. That of the Yamato Basin is 97 mW/m^2 , corresponding to an age of 23 to 27 Ma. The average heat flow value of the Japan and Yamato Basins are very close. The average heat flow value, however, may not represent the average age of the basin. The data in Table 2 show a broad distribution as shown in Fig. 11. The broad distribution may depend on the variation of the age of the crusts in each basin, some

Fig. 11. Distribution of heat flow values in the Japan Basin and the Yamato Basin. The heat flow data are after YOSHII and YAMANO's (1983) digital heat flow data file.

observational error, or local thermal disturbance by turbidites. However, it should be noted that 94% of the heat flow values of the Japan Basin and 96% of those of the Yamato Basin are included in the range between 80 and 120 mW/m². If we can adopt the range of 80 and 120 mW/m² as representative of the age range of the Japan Sea, the age of the Japan Sea is correlated to 39 to 15 Ma.

The sea bottom heat flow data generally appear less than the true terrestrial heat flow value because of the mass heat transfer by water circulation in the sediments and the basement rocks and rarely appear larger than the true terrestrial heat flow value. Therefore the discussion of the highest heat flow value may be valid. The highest heat flow value in the Japan Basin is 120 mW/m² which corresponds to an age from 15 to 18 Ma. The highest heat flow value in the Yamato Basin is 145 mW/m² which corresponds to an age from 10 to 12 Ma. An age from 10 to 12 Ma for the Yamato Basin is concordant with the stratigraphic age estimation. The comparison of the highest heat flow values in the Japan and Yamato Basins reflects the younger age of the Yamato Basin. The sites of the highest heat flow for each basin are located in the central part of the Japan Basin and in the marginal part of the Yamato Basin (Fig. 10). The highest heat flow value may not correspond to the youngest age of the basin, but it is probable that the highest heat flow value suggests the youngest limit of the possible age of the basin if there are abundant measurements in the basin.

5. Discussion

Figure 12 summarizes the above discussion on the age of the Japan and Yamato Basins. Although the stratigraphic evaluation of the age of the Japan Basin is difficult to determine from the available data, the results of the age estimation based on basement depth and heat flow of the Japan Basin show good coincidence.

Fig. 12. Summary of the age estimation of the Japan Basin and the Yamato Basin on the basis of the three methods.

On the contrary, the results from the Yamato Basin show a large discrepancy among the three age estimation methods of stratigraphy, basement depth, and heat flow. Heat flow values suggest the age range from 30 or more to 10 Ma, the stratigraphy shows the age to be around 10 Ma, and the basement depth shows the age to be less than 6 Ma through to 0 Ma. Earthquake and heat flow data, however, do not present any evidence which infers that the Yamato Basin is actively spreading. DSDP drilling results show the basement age to be older than 9 Ma. These observations indicate that the basement depth of the Yamato Basin is anomalously shallow. There are the following two possible causes for such a shallow basement.

(1) The acoustic basement is not identical with oceanic basaltic layer.

(2) The thickness of the crust is thicker than the normal oceanic crust and the depth becomes isostatically shallow.

Results of seismic refraction survey by LUDWIG *et al.* (1975) suggest that both of these causes are probable for the shallow basement of the Yamato Basin. According to their results, the acoustic basement of the Yamato Basin has a slower sonic velocity of 3.5 km/sec compared to the normal oceanic basaltic layer which generally shows a velocity range from 4.5 km/sec to 5.5 km/sec. The 3.5 km/sec layer has a thickness of about 1 km and overlies a normal oceanic basaltic layer. The thickness of the crust is also thicker than that of the Japan Basin which is similar to normal oceanic crust. The crust of the Japan Basin is 6 to 7 km thick and that of the Yamato Basin is 11 to 12 km. LUDWIG *et al.* (1975) explained that the 3.5 km/sec layer is correlated to Oligo-Miocene volcanoclastics which are abundantly distributed on the Japan Sea side of the Japanese islands and are correlated as the "Green Tuff" horizon. The Yamato Basin with a thicker crust overlain by volcanoclastic layers may be formed under conditions different from the case of the Japan Basin (TAMAKI, 1985).

If a deeper true basement is the case of the Yamato Basin, the heat flow value of the basin is probably comparable with the true basement. The stratigraphic consideration of the age of the Yamato Basin is based only on the sedimentary layer. The 3.5 km/sec layer intervenes between the sedimentary layer and the true basement. The rather young age from the stratigraphic consideration is reasonable if the 3.5

km/sec layer is underlying the sedimentary layer. As a preliminary conclusion of an estimated age of the Yamato Basin, I present an age range of 30 Ma or older to 15 Ma which was deduced mainly from the distribution of heat flow values in Fig. 11. However, as a high heat value of 145 mW/m^2 is observed, there is a possibility that the younger age is extended to 10 Ma.

In the case of the Japan Basin, the age estimated from the basement depth shows rather good coincidence with the age estimated from heat flow values. The maximum basement depth observed is 5000 m after sediment loading correction in the Japan Basin. As the 3.5 km/sec layer is also observed in the Japan Basin but not so commonly as in the Yamato Basin, the true basement depth may be a little deeper. I present an estimated age of 30 Ma or older to 15 Ma for the Japan Basin which is the same as that of the Yamato Basin. The Japan Basin also has a high heat flow value of 120 mW/m^2 , suggesting that the age may be a few Ma younger.

The above estimated ages of the Japan Basin and the Yamato Basin have the same age range of 30 Ma or older to 15 Ma. The results are inconsistent with two stage opening models of the Japan Sea (HILDE and WAGEMAN, 1973; KOBAYASHI, 1983) which insist that the Japan Basin is older than the Yamato Basin. If the opening ages of the both basins are different, a fracture zone structure is expected along the boundary between the both basins. Figure 13 shows a transition profile from the Japan Basin to the Yamato Basin. The basement gradually becomes shallower from the Japan Basin to the Yamato Basin without any fracture zone boundary. This feature suggests that the 3.5 km/sec layer becomes thicker in the Yamato Basin. The conclusion of this paper is that the both basins opened concurrently with some time lags at the beginning and the ending stages.

6. Conclusions

Age estimation on the basis of three independent sets of data, sediment stratigraphy, basement depth, and heat flow value, suggests same age ranges of 30 Ma or older to 15 Ma for the Japan and the Yamato Basins. However, the estimated age range is not so confident as to constrain tectonic evolution of the Western Pacific. Further deep sea drillings and studies of magnetic anomaly lineations are necessary to fix the exact age of the Japan Sea. We expect the new Ocean Drilling Project and also new technology such as the three component magnetometer and deep-tow magnetometer for the identification of magnetic anomaly lineations.

Recent studies of paleomagnetism from the Southwest Japan arc (HAYASHIDA and ITO, 1984; OTOFUJI and MATSUDA, 1984) strongly suggest that the Southwest Japan arc rotated clockwise with an extent of 47° and that the Japan Sea opened at 15 Ma with a duration of less than 1 million years (OTOFUJI *et al.*, 1985b). The suggested age of 15 Ma conflicts with the age estimated in this paper. The maximum basement depth of the Japan Sea, 5000 m, suggests the age to be around 30 Ma and the average heat flow value of the Japan Sea, 95 to 97 mW/m^2 , is much less than the expected heat flow value, 122 to 130 mW/m^2 for the age of 15 Ma. This is a serious contradiction for the study of the Japan Sea. However, this contradiction may be substantially related to a unique tectonic evolution of the Japan Sea.

Fig. 13. Continuous seismic reflection profile from the Japan Basin to the Yamato Basin on Line J104 on Fig. 2.

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