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Article

Reflection Seismology in the Southern Ayu Trough, a Slow-spreading Divergent Boundary

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Abstract : A multichannel seismic survey was conducted in the southern Ayu Trough which is the only spreading boundary between the Philippine Sea and Caroline plates. The seismic system used in this study comprises of 2.46-*l* sleeve gun and a 12-channel streamer with a group interval of 6.25 m. Migration technique was used to analyze seismic velocity, and poststack depth migration was applied to the stacked data. The sediment thickness obtained from the depth section tends to increase with distance from the spreading axis. Sedimentation rates are poorly constrainted in the study area. The apparent half-spreading rates estimated from the sediment thickness and sedimentation rate from DSDP hole on the caroline plate are 4.7 mm/yr and 7.9 mm/yr at 1°24'N and 0°42'N, respectively, which are faster than previously suggested. On the basis of new oblique spreading geometry, the recalculated spreading rates are 5.4 mm/yr and 9.1 mm/yr at 1°24'N and 0°42'N, respectively. Seismic sections show that the topography is asymmetric across the Ayu Trough and the acoustic basement is rough. These features are consistent with the earlier suggestion that the Ayu Trough is a slow-spreading divergent boundary. A detailed examination of seismic profiles away from the axis shows that sediments can be divided into two layers which implies a possible change in the spreading rate and/or sedimentation condition during the formation of the trough.

Key words : Ayu Trough, seismic survey, poststack depth migration, divergent plate boundary.

1. Introduction

The Ayu Trough is located in the western equatorial Pacific at the boundary between the Philippine Sea and Caroline plates. It lies just south of the Palau Islands and stretches from 5°30'N to all the way down to the equator. The Ayu Trough is unique in that it is the only part of the Philippine Sea plate margin that is not a subduction zone (Jung and Lee this issue). Because of such characteristics and the possibility that it may provide important constraints on the past relative motion of the Philippine Sea plate (Ranken *et al.* 1984; Seno *et al.* 1993), The Ayu Trough has been at the attention of scientific community for a long time, but so far only a small fraction of the trough has been mapped and surveyed by modern marine geophysical methods.

One of the early bathymetric and seismic investigations of the Ayu Trough was conducted by Weissel and Anderson (1978) who recognized the axial rift valley, the increase in sediment thickness, and subsidence of the seafloor away from the rift valley, thereby resembling a slow-spreading mid-ocean ridge. These findings are consistent with the recovery of fresh pillow lavas near the trough axis and weathered ones away from the axis in the dredged rock samples and the result of their geochemical analyses (Fornari *et al.* 1979). Despite the initial success, many important aspects regarding the evolution of the Ayu Trough remain unclear. For example, there is great uncertainty associated with the spreading rate and direction of the trough. This is because the Ayu Trough lies near the magnetic equator and is spreading in the almost E-W direction. A simple geometric consideration

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shows that the seafloor produced by a such spreading center will have almost zero total field anomaly when measured by standard proton precession magnetometer. Furthermore, if the spreading rate was very low, the anomalies may not be discernable by measurements at the sea surface. According to Weissel and Anderson (1978) who used sedimentation rates at nearby DSDP site 62 (Winterer *et al.* 1971), the trough is thought to have formed during mid-Miocene (10-12 Ma). The interpretation of seismic profile south of 2°N suggests that spreading rate has reduced from approximately 20 mm/yr from about 6-12 Ma to 4 mm/yr in the last 6 Ma. However, it is also possible that the spreading has stopped altogether in the last 5-6 Ma.

Recently, Japanese scientists surveyed the Ayu Trough north of 3°30'N onboard R/V *Hakuho-maru* (Segawa 1993). The survey included multibeam bathymetric mapping, gravity, magnetic, heat flow measurements, piston coring and dredge rock sampling. Single channel seismic reflection profile data were collected from 132°E to 135°E along 3°30'N using a 120 cubic inch airgun as the source. Using this profile and the same sedimentation rate as Weissel and Anderson (1978), Fujiwara *et al.* (1995) estimated the average spreading of the Ayu Trough as 4.1 mm/yr.

In May of 2000 and 2001, the Korea Ocean Research and Development Institute (KORDI) carried out a comprehensive survey on the Ayu Trough from 3°30'N to the equator onboard R/V *Onnuri*. The survey included all the items that were done by the Japanese survey in 1992 to the north of 3°30'N (Segawa 1993) except for heat flow measurements. However, compared to the previous survey, the Korean survey covered much of the off-axial regions as well (Jung and Lee this issue). One of the important discovery as a result of off-axis mapping was that the opening of the Ayu Trough occurred in an oblique manner from NNW to SSE. Also on the basis of bathymetric and geophysical measurements taken in this area, the trough can be divided generally into three sections: the southern (0-1°30'N), middle (1°30'N-4°N) and northern (4°N-6°30'N) ones. The northern section has substantially shallow axial flanks, and therefore thought to be magmatically the most robust among the three sections. The boundary between the northern and middle sections coincides with a sharp break in the trend of the trough axis at 4°N. The middle section is where there is the strongest evidence for asymmetry across the axis and oblique spreading. Between the middle and southern sections, there is a slight but systematic lateral offset in seafloor topography which extends across the trough (Jung *et al.* 2001).

During the Korean survey, three multichannel seismic profiles were taken across the Ayu Trough (Fig. 1). The profiles were obtained in areas that have not been imaged before or some distance from existing seismic lines. For example, line 7 crosses a basin at the outer edges of the trough whose origin is not well known, and line 13 transects the southern section of the trough. Part of line 7 crosses the border between middle and southern sections. Therefore, in addition to being higher quality than previous ones, the profiles may provide new insights on the characteristics of different sections and tectonic elements. This paper describes the processing and interpretation of these multichannel data and discusses the geological structure of the southern Ayu Trough in conjunction with previous geological and geophysical observations.

2. Seismic data

Data acquisition

Although three profiles were taken during our experiment, the first profile was incomplete by a technical problem. This profile is very short and will not be considered in the study. The two remaining multichannel

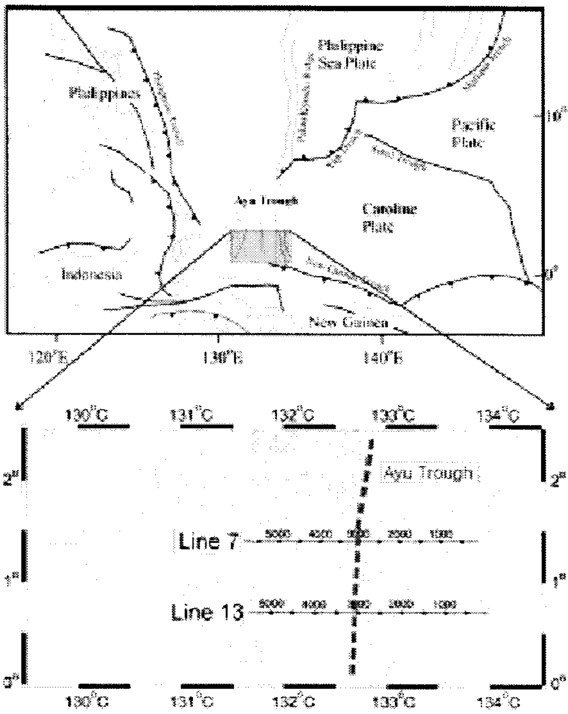


Fig. 1. A track chart showing seismic survey lines. Lines cross the southern Ayu Trough.

Table 1. Acquisition parameters for the reflection survey.

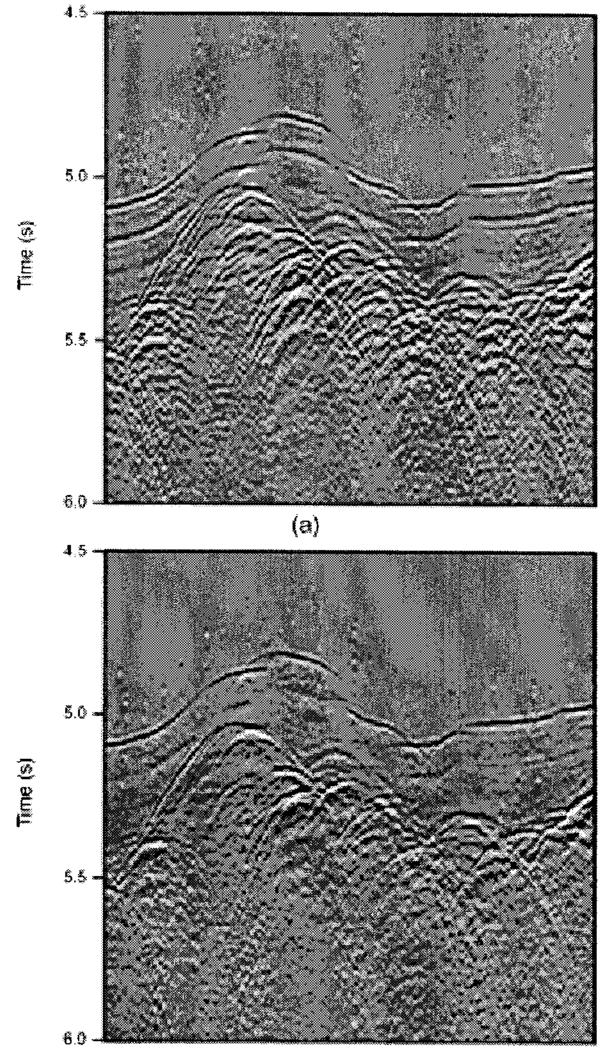
Sampling rate	2 ms
Recording length	10 s
Group interval	6.25 m
Number of groups	12
Total length of streamer	75 m
Near trace offset	132 m
Gun pressure	1600 psi
Shot interval	48 m on average
Gun depth	≅2 m
Streamer depth	≈2 – 5 m
Gun volume	2.46 *l*

reflection profiles, lines 7 and 13, cross the southern trough axis at latitude 1°24'N and 0°49'N, respectively (Fig. 1).

During the experiment, a 2.46-*l* sleeve gun was utilized to generate seismic energy which discharged at 1600 psi. The average shot interval is 48 m, and a 12-channel streamer with a group interval of 6.25 m was used. Seismic data were recorded on the StrataVisor NX recorder manufactured by Geometrics. The offset between the airgun and the nearest trace was set to 132 m. A record length of 10 s and a sampling interval of 2 ms were chosen. Table 1 summarizes the main acquisition parameters during the seismic survey.

Data processing

Data processing was primarily conducted using the Seismic Unix (SU) software package installed on a LINUX machine. For special processing such as spike deconvolution, the GEOVECTEUR package developed by CGG was used. Seismic data processing began by converting the data format from standard SEG-Y to SU SEG-Y. Trace editing was applied to the converted data. The streamer length of only 75 m compared to the average shot interval of 48 m did not produce common depth point (CDP) traces. Therefore, CDP numbers were replaced by shot point numbers. Because the water depth exceeds 2 km, it is impossible to perform velocity analysis. Instead, we fixed stacking velocity to 1500 m/s for NMO correction. Fig. 2a shows part of a stacked section. In the section, noisy bubbles can be seen at 100 ms below the seafloor. To remove the bubbles, predictive deconvolution was applied to stacked data. Fig. 2b is the section after predictive deconvolution in which most of the bubbles were effectively suppressed. Fig. 3 illustrates the flow chart for data processing adopted in this study.



(a)

(b)

Fig. 2. (a) A part of stacked section showing bubbles and (b) the section after predictive deconvolution. Note that bubble energy at 100 ms below the sea floor has reduced after deconvolution.

Migration velocity analysis

In order to estimate the sediment velocity, we applied a time migration method to stacked data. On a stacked section, a single-point diffractor appears as a hyperbolic event. Migration collapses such diffraction energy to the original position. The velocity that is used in migration is determined by checking the degree of imaging. Velocities lower than the true velocity will generate under-migrated images, while higher velocities will give rise to over-migrated images (Yilmaz 1987). A perfectly collapsed image can be obtained only by using the correct velocities.

To determine migration velocities, we chose stacked data showing hyperbolic events and then migrated the data with velocities ranging from 1420 m/s to 1800 m/s at 20

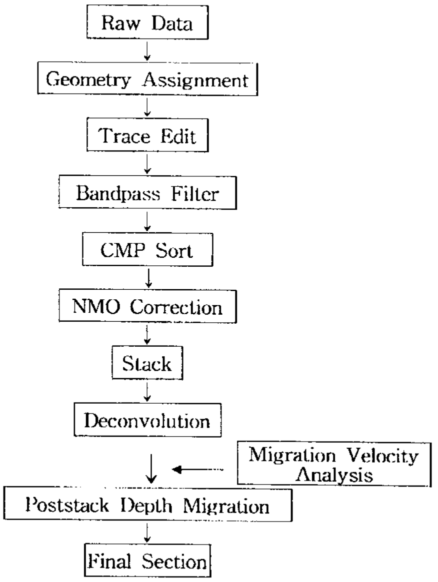


Fig. 3. The seismic data processing sequence for this study.

m/s interval. Migration velocities for hyperbolic events were determined on the basis of best migrated results. Using this approach, the velocity of the sediment is estimated was 1560 m/s. The migrated section shows no significant diffractions beneath acoustic basement. Finite difference poststack depth migration was applied to stacked data. To perform poststack depth migration, we built velocity profiles with determined velocities. Fig. 4 illustrates a part of stacked section and its depth migration.

3. Estimates for spreading rate

If the sedimentation rate has remained the same, the sediment thickness across the trough axis would be inversely proportional to the spreading rate. We determined the half-spreading rate for Lines 7 and 13 on the basis of sediment thickness and sedimentation rate. Variations of sediment thickness are obtained from depth migrated data (Fig. 5). In general, the overall trend shows that sediment is thin around the axis, although it tends to thicken as a function of distance from the axis. There are, however, significant deviations from this overall trend. A least square method was applied to get ratios of sediment thickness to horizontal distance from the axis. The ratios were calculated on both western and eastern sides from the center of the spreading axis.

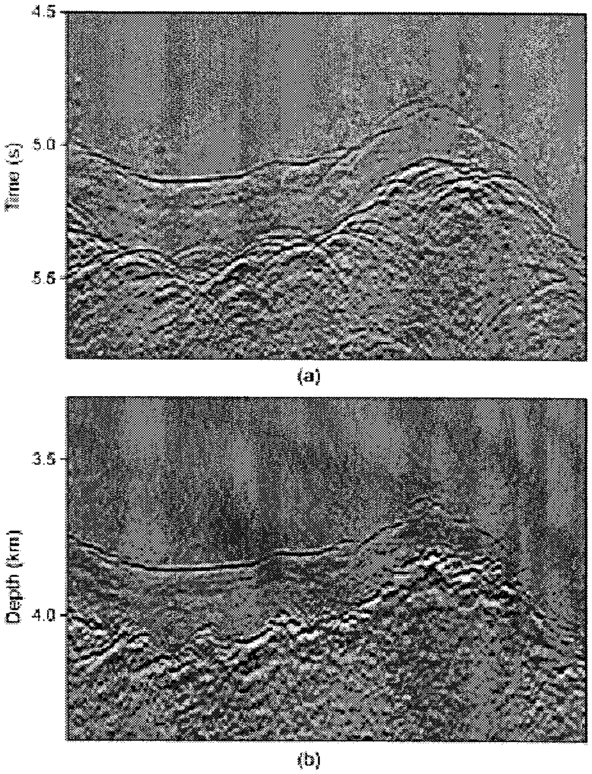


Fig. 4. (a) A part of stacked section and (b) its poststack depth migrated one. The velocity for the sediment is 1560 m/s. After migration, a rough and irregular acoustic basement is well imaged.

Along Line 7, a zone of shallow sediments extends about 40 km from the axis. Here the sediment is less than 50 m thick. The ratios of western and eastern sides are 4.1 m/km and 4.5 m/km, respectively. On Line 13, the ratios of western and eastern sides are determined as 2.7 m/km and 2.4 m/km, respectively. Applying the sedimentation rate of 20 m/m.y. derived from nearby DSDP site 62 (Winterer *et al.* 1971), we estimate the average half-spreading rate to be 4.7 mm/yr and 7.9 mm/yr for Lines 7 and 13, respectively.

4. Seismic structure

Morphology

The topographic characteristics near the spreading axis is closely related to the spreading rate (Macdonald 1982). At fast-spreading centers (>50 mm/yr) such as the East Pacific Rise, topography is smooth and is marked by an axial high. At slow-spreading centers (<35 mm/yr) such as the Mid-Atlantic Ridge, on the other hand, topography is asymmetric and an axial depression typically more than 1 km deep and up to 40 km wide occurs (Mutter and

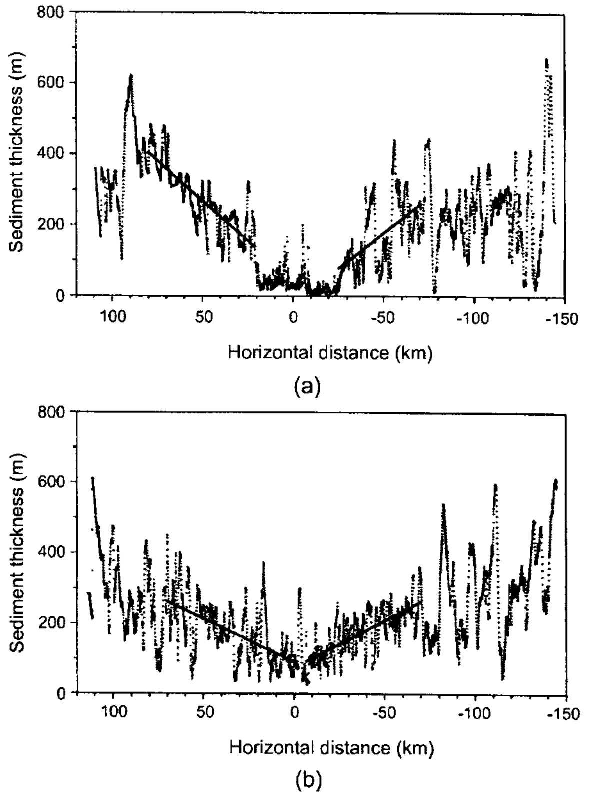


Fig. 5. Sediment thickness versus horizontal distance on (a) Line 7 and (b) Line 13. Straight lines are determined from the least squares method.

Karson 1992).

According to the bathymetric map of the Ayu Trough, a significant contrast exists between the middle and southern sections. In the southern Ayu Trough, the axial depth makes a stepwise decrease to the south. The trough is less prominent in the south than in the middle and northern (Jung *et al.* 2001; Jung and Lee this issue). However, on the seismic sections shown in Figs. 6 and 7, one can clearly identify the center of the spreading axis by sediment thickness and topography.

According to the seismic sections, the centers of the trough on Lines 7 and 13 are surrounded by uplifted flanks with a maximum height of 1.7 km. Topography is asymmetric and the western side of the valley has very steep slopes, which are typical of the slow-spreading ridge. The morphology near the axis revealed on the seismic section is rough and irregular. Near the axis, reflectivity is relatively strong (Fig. 8).

Some distance from the trough, reflectivity becomes small and topography shows a relatively smooth feature. In some area, such as the western part of Line 7 (shot number 4900-5400), the seafloor is almost flat.

Sediment structure

Relatively thick sediments (>200 m) found along the trough axis (Figs. 6 and 7) were probably deposited as a result of downward movement along the steep slopes formed by extension. The high reflectivity in the sediment column suggests that clastic sediments were deposited during extension rather than pelagic origin. There is also a significant variation in sediment thickness which is presumably due to rough topography and subsequent

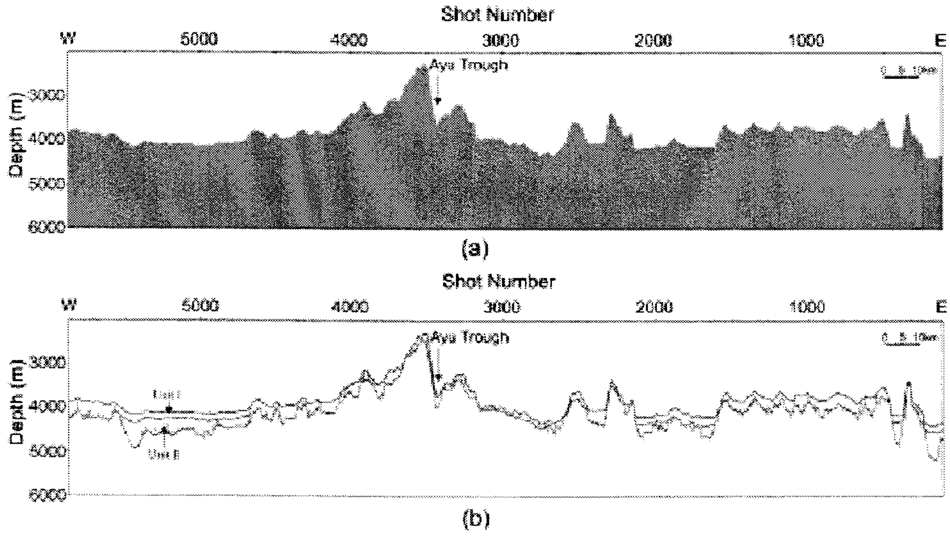


Fig. 6. (a) Seismic profile of Line 7 and (b) its interpretation. Topography shows an asymmetric feature and numerous normal faults. See Fig. 1 for location of the profile.

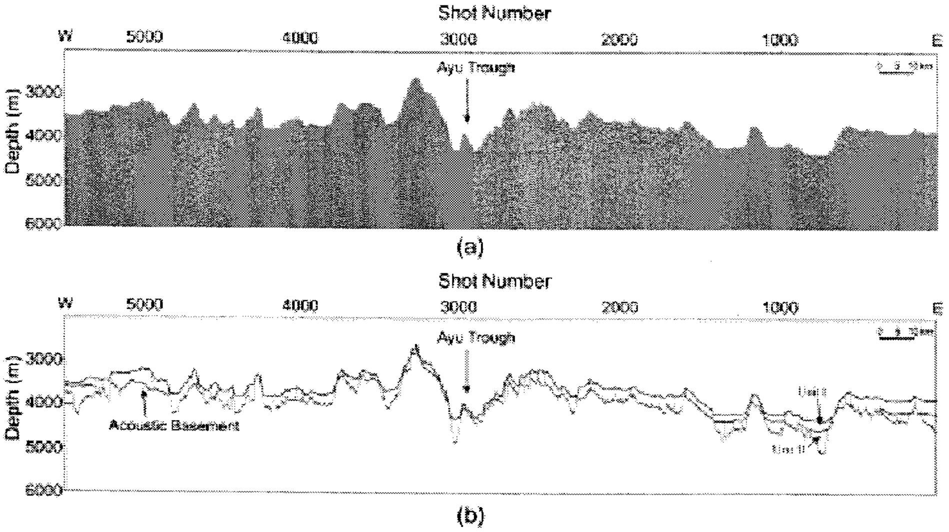


Fig. 7. (a) Seismic profile of Line 13 and (b) its interpretation. At the center, sea floor shows a W-shaped topography. On the eastern side of the profile, normal faults occur more abundantly. See Fig. 1 for location of the profile.

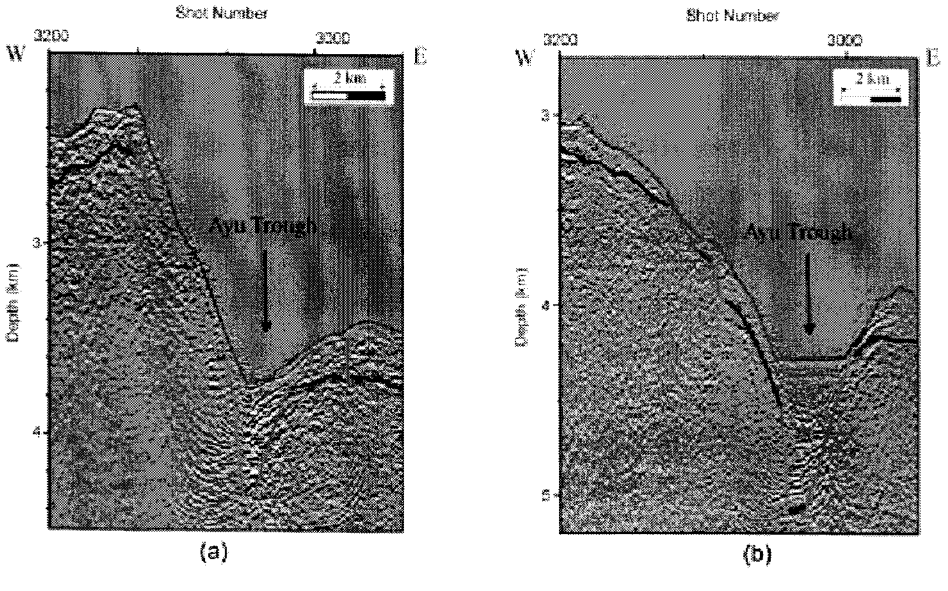


Fig. 8. Seismic sections near the trough axis of Lines 7 (a) and 13 (b). At the center of the trough, thick sediments are found. On the Line 7, reflections from seafloor are not clearly shown.

downward transportation of sediments.

Fig. 8a shows part of the seismic section of Line 7 near the trough axis. Because of the steep slope of the western wall, the quality of seismic image is poor, and the sediment layer above the acoustic basement is not seen clearly. On the western wall of the trough axis, there are faults and here the sediment appears to have transported downward. The eastern flank from the axis has a gentle slope and is covered with thin sediment. On Line 13 shown in Fig. 8b, the sedimentary layer is clearly defined on the wall and is thicker than that of Line 7. Noticeably, the trough is that it is covered with a substantial amount of sediment, which implies that the extension has been ceased or the spreading rate may have been extremely slow.

Some distance away from the axis center (>60 km), the sediment can be divided into two layers (Units I and II). The two units are thought to have emplaced under

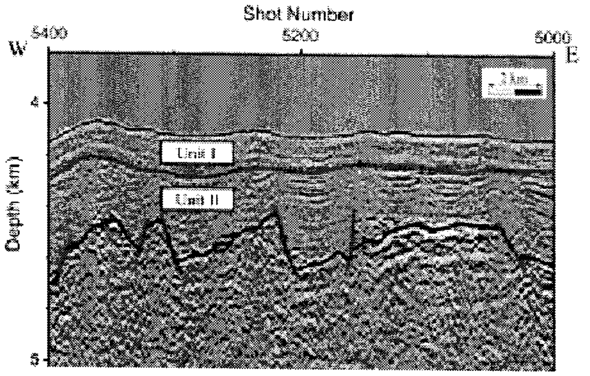


Fig. 9. A part of seismic section of Line 7 between shot numbers 5000 and 5400. The boundary between Units I and II is sub-parallel to the seafloor.

different depositional conditions. A good example of the two units and a boundary is shown in Fig. 8, between shot numbers 5000 and 5500, on Line 7 (Fig. 8). The upper layer (Unit I) has the thickness of up to 160 m. It has a relatively uniform thickness and no internal layering, which implies that the unit has experienced relatively little structural movement during deposition. The lower layer (Unit II) lies on top of the acoustic basement. Its thickness ranges from 100 to 200 m and is quite variable depending on the crustal morphology and proximity to geologic structures such as normal fault. This unit is thought to have been formed during the early stage of the spreading where the depositional environment was not settled. The boundary appears to have been originated from an abrupt slowdown in spreading rates.

Acoustic basement

The acoustic basement exhibits considerable roughness marked by numerous discontinuities. It has strong reflectivity and is interpreted as the top of the crust. Below the acoustic basement, it is difficult to identify significant reflection signals. One reason for it may be that the basement has a very strong reflectivity.

5. Discussion and conclusions

Estimating the spreading rate based on sediment thickness appears to be the only means possible for the Ayu Trough at this stage. However, this method can only provide a rough estimate because sedimentation rate and the effect of bottom current in the Ayu Trough are not well known. In this study, we used the sedimentation rate from DSDP site 62 which is the nearest drilling site but quite far from the survey area as much as 10 degrees in longitude. Also the proximity to the terrestrial region, especially to the south, may pose a problem. During the cruise, piston core samples were acquired, but unfortunately, their analysis has not been performed to date.

The half-spreading rate for Line 7 is consistent with previous results (Weissel and Anderson 1978; Fujiwara *et al.* 1995). The rate for Line 13, on the other hand, is substantially larger than that for Line 7. The difference can not be explained by a difference in sedimentation rate because Line 13 is closer to land which is a potential source of sediment. The higher rate implies that the spreading may have been faster to the south and this argument is consistent with the fan-shaped general morphology of the Ayu Trough.

The direction of major structural strikes on the bathymetric map is not perpendicular to the trough axis but in NNW-SSE direction, which is an evidence for an oblique spreading (Jung and Lee this issue). The direction of the oblique spreading is about N60°W. Therefore, the spreading rate needs to be adjusted. Considering oblique spreding, the spreading rates are recalculated as 5.4 mm/yr and 9.1 mm/yr at 1°24'N and 0°42'N, respectively.

In summary, our study shows that sediment thickness obtained from depth sections increases with distance from the spreading axis. The topography of the Ayu Trough and the morphology of the crust have typical features of a slow-spreading ridge (Macdonald 1982). The sedimentary boundary found in at a distance from the axis implies a possible change in spreading rate during extension and seafloor spreading. However, it is also possible that the two units represent different sedimentary conditions.

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