Enlightenment of the Mariana Fore-arc Sedimentary Basin Evolution to the Subduction Process

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Abstract: The Mariana subduction structure is a hot topic in ocean-ocean subduction zone research, and its subduction mechanism has attracted wide attention from experts and scholars in China and abroad. Based on the multi-channel seismic data of survey line MGL1204 in the Mariana fore-arc and DSDP ocean drilling data, this paper studies the development and evolution characteristics of the structure and strata in the Cenozoic Mariana fore-arc sedimentary basin. The Cenozoic strata are divided into six seismic sequences, with the possible era of each seismic sequence discerned, and the relationship between fault development and earthquakes analyzed. The episodic activity of the volcanic chain of the Mariana island arc is thought to control the tectonic and stratigraphic development pattern of the Cenozoic sedimentary basin in the fore-arc. Between 16°N–19°N and 146°E–151°E, the maximum thickness of the sedimentary center of the Cenozoic fore-arc sedimentary basin in Mariana is about 2360 m. Normal faults are developed in the area and some broke to the seabed, indicating that the Mariana island arc is still in the post-arc expansion stage. The application of multi-channel seismic sections in structural and stratigraphic evolution study is an important means to elucidating the Mariana subduction mechanism.

Key words: subduction system, fore-arc basin, sedimentary evolution, subduction mechanism, Mariana

1 Introduction

As a typical trench type developed in the western Pacific Ocean basin, the Mariana trench has always been a hot topic in the study of the regional structure of a subduction zone. The fore-arc region of Mariana is an important part of the 'trench-arc-basin' system in the western Pacific. At present, geologists mainly determine the nature and development characteristics of oceanic crust by deep-sea drilling and bottom tow sampling (Wu and Yu, 2006), but the sampling amount, potential depth and coverage are relatively limited. The Mariana subduction system is relatively uncomplicated for an ocean-ocean subduction zone structure, which makes researchers take much interest in the study of its subduction mechanism. The SEA-TAR plan, Deep Sea Drilling Project (e.g., DSDP: 1968–1983) to International Ocean Discovery programs (e.g., IODP: 1985–2013) have done a great deal of work near 18°N, and accumulated much drilling and seismic data (e.g. National Research Council, 2011), making it possible to study the structural and stratigraphic development characteristics in the Mariana fore-arc basin. Sedimentary evolution characteristics of the fore-arc basin truly record the past tectonic and volcanic activity information of a subduction system, which is of great significance to the study of the sedimentary mechanism and sedimentary process of the Mariana subduction system.

Based on multi-channel seismic and DSDP ocean drilling data, this paper analyzes the Cenozoic strata in the fore-arc basin, and discusses the possible era of seismic stratigraphic unit development. Constrained by earthquake epicenters, fault development is analyzed to glean important evidence regarding the subduction process of the Mariana island arc.

2 Geologic Settings

The Mariana subduction system is composed of the Mariana island arc, the Western Mariana Ridge and the Mariana Trough (Fig. 1; Wu et al., 2013). The study of the
Mariana arc system is mostly based on the geological evolution model proposed by Karig (1971). His model purports to show that the formation of the Mariana arc system is caused by the active volcanic activity area of the subduction zone that splits longitudinally, with new submarine crust then developed in the extensional basin formed by the rift. The inactive part then forms the residual arc with the development of an extensional basin. The present Palau–Kyushu Ridge and the West Mariana Ridge are the residual arcs formed in the development and evolution of the Mariana arc.

In recent years, studies on submarine hydrothermal activities have shown that the Mariana Trough slowly expands symmetrically to the east and west along a lunular curve almost parallel to the Mariana trench (Fig. 1), with an expansion rate of about 3–4 cm/yr in the latest 5 Myr, with the expansion center located near 18°N (Hukssong and Li, 1982).

Dating of volcanic samples from the Palau–Kyushu Ridge and Izu–Bonin Arc suggest that the Izu–Bonin–Mariana (IBM) subduction began by 50 Myr (Taylor, 1992). Subduction along the IBM trench led to trench rollback, arc rupture and back-arc rifting in the Parece Vela and Shikoku basins at ~30 Myr, and seabed spreading in the Parece Vela basin developed at ~28 Myr (Sdrolias et al., 2004; Taylor and Goodliffe, 2004). DSDP drilling cores show that Oligocene volcanoes in the fore-arc area were active until 29–31 Myr (Scott et al., 1980). From 29 Myr to 15 Myr, this rifting and subsequent spreading created the characteristic bow shape of the Mariana subduction zone (Chapp et al., 2008). Persistent volcanic activity in Miocene (20–9 Myr) saw the expansion of the Mariana Trough and resulted in the withdrawal of the West Mariana Ridge from the main arc of Mariana, forming a residual arc (Wu et al., 2013). Volcanic accumulation slowed at 9 Myr and most volcanic activity ended (Scott and Kroenke, 1981). At the present, due to the subduction of the Pacific plate towards the Mariana island arc, the Mariana Trough is still expanding, and the long-lasting rifting is still ongoing.

The DSDP Leg 60 drill sites 460 and 461 are located on the inner wall of the Mariana trench. Few sediments were penetrated, with only a small amount of Quaternary soft mud and Eocene–Oligocene limestone deposits. Late Jurassic and Late Cretaceous fossils are found in the lower metamorphic rocks, revealing that the formation age of the primary oceanic bedrock of the Mariana island arc is probably Late Mesozoic (Shipboard Scientific Party, 1978c, 1978d; Lin and Wang, 1992), which further confirmed that the Mariana island arc began to form in the Cenozoic.

### 3 Data Source and Processing

This study is based on the multi-channel seismic reflection data (Lizarralde and Wiens, 2015) of the subduction zone of the Mariana trench collected in 2012 by Dr. Dan Lizarralde. The survey lines are MGL1204.002 and MGL1204.004, which are located between 16°N–19°N and 146°E–151°E in the middle of the Mariana island arc. The acquisition parameters are as follows: there were 636 receiving channels of the multi-channel digital seismic cable with a channel spacing of 12.5 m; the air gun source capacity is 1500 in\(^3\); the working pressure is 2000 psi; the sinking depth is 9 m; the gun spacing is 50 m; the maximum and minimum offsets are 8106.3 m and 156.3 m; the sampling interval is 2 ms; and the recording length is 15 s.

The seabed topography in the multi-channel seismic acquisition area of Mariana island arc is fluctuating, and the water depth and temperature-salt characteristics change greatly. In addition, frequent volcanic activities lead to strong anisotropy of the strata, which makes the seismic wave-velocity changes intense laterally and causes a multiple wave anomaly to develop. In this study, according to the characteristics of the seismic data, amplitude compensation, bubble suppression, LIFT noise suppression, multi-domain combined multiple attenuation, and common offset domain suppression of residual noise are used to improve the signal to noise ratio. The Kirchhoff integral method was used for pre-stack time-migration imaging, which provided the basic data of the study.
4 Structure and Stratigraphic Development Characteristics

4.1 Stratigraphic development characteristics derived from drill holes

There were two drill sites located along 18°N in the Mariana fore-arc in DSDP Leg 60, as shown in Fig. 1: drill site 458 at 17°51.85′N, 146°56.06′E, at a water depth of 3449 m (Shipboard Scientific Party, 1978a); and drill site 459 at 17°51.75′N, 147°18.09′E, at a water depth of 4116 m (Shipboard Scientific Party, 1978b). The penetrated lithology from core analysis shows that the sedimentary basement of the fore-arc basin is Mesozoic igneous rock, and there are obvious sedimentary discontinuities in the overlying Cenozoic sedimentary rock that sits with an angular unconformity on the underlying igneous rock, all of which are related to the intermittent activity of island arc volcanic chain at different periods.

Based on the dates of the sedimentary hiatuses sedimentary shown at site 458 and site 459 and their correlation relationship, the Cenozoic sediments are divided into six stratigraphic sequences: middle Eocene, middle Eocene–late Oligocene, late Oligocene–early Miocene, early–middle Miocene, middle Miocene–late Pliocene, and late Pliocene–Quaternary, respectively from bottom to top.

4.1.1 Site 458

Drill site 458 is located in the middle of seismic survey line MGL1204.002 and to the north and west of the MGL1204.004 seismic survey line. A local fore-arc sedimentary depression was drilled, which is located on the slope belt of a large sedimentary basin. The total thickness of Cenozoic sediments penetrated in the borehole is 256.5 m. Core observation shows that volcanic ash exists in all core samples of Cenozoic beds, which indicates that volcanic activity did not stop during the whole sedimentary evolutionary process of Mariana fore-arc basin. The DSDP Shipboard Scientific Party identified four hiatuses in the Cenozoic sediments according to lithological assemblage characteristics, and dates obtained from nannofossils and radiolarians (Fig. 2). There is only a small gap in Oligocene deposition that lasted from 26.5 Myr to 25 Myr. The second hiatus occurs in middle Miocene lasting from 22 Myr to 17.5 Myr. The third hiatus occurs in middle Miocene that lasted from 13.2 Myr to 12 Myr. The last hiatus occurs from late Miocene to late Pliocene lasting from 7 Myr to 3 Myr, during which the volcanic ash content was at its highest. The Cenozoic sediments are divided into five stratigraphic sequences by these four sedimentary hiatuses, with thicknesses of 38 m, 83.5 m, 87.5 m, 25.5 m, and 38.5 m, respectively from bottom to top. Below that are the Mesozoic high MgO bronzite andesite and basalt basement rocks (Fig. 2).

4.1.2 Site 459

Drill site 459 is located to the east of seismic survey line MGL1204.002 and west of the MGL1204.004 seismic survey line. A small fore-arc sedimentary basin was penetrated. The Cenozoic sediment thickness of site 459 is much larger than that of borehole 458, with a total thickness of 559 m. The DSDP Shipboard Scientific Party also identified four sedimentary hiatuses in Cenozoic sediments based on lithological assemblage characteristics, nannofossil and radiolarian dates (Fig. 3). The first sedimentary hiatus occurs in middle Eocene with a duration from 42–40 Myr. The underlying sediments are claystone and silicified claystone and cherts, deposited in the early stage of the rift. This constitutes the first seismic sequence of the Mariana fore-arc; contemporaneously, there are no sediments at site 458, indicating that seismic sequence 1 is only developed in the deep sag of the basin, and there was no deposition at the basin edge and uplift area. The second sedimentary hiatus occurs from late Eocene to early Oligocene lasting from 34.5–30 Myr. At this time, the rift had just begun at the other location (site 458) and this hiatus is not shown. When the first and second sedimentary hiatuses occur at site 458, the strata are in concordance and the deposition continued at the
The third and fourth hiatuses at site 459 occur in middle Miocene and late Miocene to late Pliocene, lasting from 14–13.4 Myr and 10–3 Myr, respectively. These two sedimentary hiatuses can be correlated with those of site 458, indicating that regional unconformity developed during these timespans. Using the first hiatus at site 459 and the four hiatuses at site 458, the Cenozoic sediments are divided into six stratigraphic sequences with thicknesses of 10 m, 40 m, 149 m, 177 m, 133 m and 50 m from bottom to top. Below the Cenozoic sediments are Mesozoic fine- to medium-grained clinopyroxene-plagioclase pillow basalts and flows.

4.2 Seismic sequence development characteristics

As mentioned above, the study results of the DSDP Leg 60 drill sites 458 and 459 show that the fore-arc sedimentary basin of Mariana was formed in the Late Mesozoic, with a basement of Mesozoic igneous rock. The Cenozoic strata lies with angular unconformity on the underlying Mesozoic strata. Due to the influence of the island arc volcanic chain episodic activities, multi-stage sedimentary discontinuities are developed in the Cenozoic sediments. According to the lithological assemblage characteristics, the volcanic ash content is the highest in early Oligocene and Pliocene–Pleistocene (Figs. 2, 3), and the volcanic activity the strongest at this time, which controls the formation of the regional unconformity. Based on the dates of the recorded unconformities at sites 458 and 459, the hiatuses that occur in the middle and late Miocene are basically the same, which determines the two regional sedimentary hiatuses age in the Cenozoic sediments across the fore-arc basin. The western volcanic chain of the Mariana island arc fore-arc basin had been active during the whole Cenozoic sedimentary process, which resulted in multiple local unconformity surfaces developing in the basin.

Fault interpretation of the multi-channel seismic reflection section was carried out according to the break and distortion characteristics of the seismic events and the contact relationship between seismic reflections of the different layers. This analysis discovered that many high-angle normal faults are developed in the Mariana fore-arc sedimentary basins.

4.2.1 Seismic sequence boundary reflection characteristics

According to the stratigraphic contact relationship, pinch-out of seismic events and superposition style, combined with the stratigraphic development characteristics at sites 458 and 459, six unconformity surfaces have been identified on the multi-channel seismic reflection sections, and thus the Cenozoic strata were divided into six seismic sequences, with sequence boundaries named SB1, SB2, SB3, SB4, SB5 and SB6 from bottom to top. The seismic sequence reflection characteristics and identification marks are as follows:

SB1: the boundary between the Mesozoic igneous rocks and Cenozoic sedimentary rocks. This hiatus is the bottom of a set of sedimentary rocks with low frequency and disorder reflection in the deep-depression area, which was rapidly deposited at the beginning of the basement rift of
the basin. Then the sedimentary environment gradually became more stable and the disorder reflection evolves into a subparallel reflection (Fig. 4a). The reflection shows low frequency and good continuity at the slope, and onlap reflection can be seen in local areas (Fig. 4b).

SB2: at the top of middle Eocene, corresponding to the first hiatus at site 459 (42–40 Myr). This local unconformity surface has medium-strong amplitude and medium continuity on seismic sections. A clear truncation phenomenon can be seen in local areas under this interface, and downlap reflection can be seen in local areas above this interface (Fig. 5a). The reflection energy of the upper strata in some areas is significantly stronger than that of the lower strata. Strata were continuously deposited in the deep-depression area of the basin, which shows subparallel-parallel reflection on seismic sections (Fig. 5b).

SB3: the sedimentary hiatus within late Oligocene, corresponding to the first hiatus at site 458 (26.5–25 Myr). This local unconformity surface has medium-strong amplitude and medium-good continuity on seismic sections, and is easy to identify. A clear truncation phenomenon can be seen in local areas under this interface, and downlap and onlap reflection can be seen in local areas above this interface (Fig. 6a). The strata were deposited continuously in the deep-depression area of the basin, which shows parallel reflection on seismic sections (Fig. 6b).

SB4: the sedimentary hiatus within early Miocene, corresponding to the second hiatus at site 458 (22–17.5 Myr). This is a local unconformity surface with weak-medium amplitude and medium continuity on seismic sections.
Downlap reflection can be seen in local areas above this interface (Fig. 7a). The strata were deposited continuously in the deep-depression area of the basin, which shows subparallel-subparallel reflection on the seismic sections. The reflection energy of the upper strata is significantly stronger than that of the lower strata (Fig. 7b).

SB5: the sedimentary hiatus within middle Miocene, corresponding to the third hiatus at sites 458 and 459 (14–12 Myr). This is a regional unconformity surface with strong amplitude and good continuity on the seismic sections, which is easy to identify. A clear downlap reflection can be seen above this interface, and a truncation phenomenon can be seen in local areas above this interface (Fig. 8a).

SB6: the sedimentary hiatus within late Pliocene, corresponding to fourth hiatus at sites 458 and 459 (10–3 Myr). This is also a regional unconformity surface that shows a medium-good continuity on seismic sections with subparallel reflection below this interface (Fig. 8b). The strata above this interface are volcanic ash and ooze sediments deposited after the last extensive volcanic activity during late Pliocene–Pleistocene, which are all penetrated at sites 458 and 459, as well as at sites 460 and 461; and below at the latter two sites are Mesozoic igneous rocks (Shipboard Scientific Party, 1978c, 1978d). Therefore, it is inferred that SB6 is most probably parallel to the seabed.

4.2.2 Fault and stratigraphic development characteristics

Multi-channel seismic survey line MGL1204.004 is located near 18°N in the middle of the Mariana island arc, and it passes through the Mariana trench from the Mariana fore-arc basin to the East Mariana basin. Here, we only take the Mariana fore-arc basin as the study objective. As can be seen on the multi-channel seismic reflection section and mentioned above, the Cenozoic strata are divided into six seismic sequences, SQ1–SQ6 from bottom to top, with the six unconformity surfaces (Fig. 9).

Affected by the development of the Eocene oceanic basement rift, the Mariana fore-arc basin basement experienced overall subsidence, and the seismic events of the six Cenozoic stratigraphic sequences are superimposed on the Mesozoic crystalline basement by downlap and onlap reflections. SQ1 is developed at the beginning of the basement rift of the basin, so it only can be seen in the deep-depression area. After middle Eocene, the fore-arc basin gradually expanded, and SQ2–SQ6 were widely developed. Influenced by volcanic activity and the basement uplift due to the subduction of the Pacific lithospheric plate at different geological times, the strata at the top of SQ1 to SQ5 suffered different degrees of erosion, and seismic event truncation phenomena can be seen at the top of each seismic sequence. SQ4 to SQ6 are regionally developed in the whole fore-arc basin. Multi-channel seismic survey line MGL1204.004 reveals that near 18°N in the middle of the Mariana island arc, a large Cenozoic sedimentary basin and two small sedimentary basins developed in the Mariana fore-arc, affected by the differential uplift of the oceanic basement of the Philippine Sea plate and the subduction angle of the Pacific plate. The stratigraphic thickness of the
sedimentary center is calculated by measured sonic velocities (Figs. 2, 3) and the two-way time of seismic reflected wave. The stratigraphic thickness of the sedimentary center in the three Cenozoic sedimentary basins is about 2360 m, 770 m and 880 m, respectively. Normal faults are developed in the fore-arc area, and some faults broke to or through Quaternary strata, indicating that the Mariana island arc is still in the post-arc expansion stage. The western seabed near 18° N in front of the Mariana Arc is relatively flat, and the seabed in the central and eastern parts is rugged. From the seismic section, it can be seen that many serpentine mud volcanoes are developed (Shipboard Scientific Party, 1978a), and some of them break through the seabed and become seamounts.

The multi-channel seismic survey line MGL1204.002 is located between 146° E and 151° E in the Mariana fore-arc, and the seismic reflection waveform characteristics of each sedimentary unit are similar to those of the MGL1204.004 section (Fig. 10).

Three Cenozoic sedimentary basins are developed at 146°E–151°E in the Mariana fore-arc, bounded by oceanic basement uplift and rift. According to the measured sonic velocities (Figs. 2, 3) and the two-way time of the seismic reflected wave, we calculate that the thickness of the sedimentary center is about 1370 m, 2030 m and 1810 m, respectively. From the perspective of the seismic facies, there are great differences in structural sedimentary development characteristics between the different sedimentary basins. The seismic reflection amplitude of the southern sedimentary basin is weak, the lateral continuity of the seismic event is poor, and the reflection is chaotic. The Cenozoic sedimentary strata in the central uplift belt are thin, and the seabed topography is dominated by serpentine mud volcanoes. The central and the northern basins merged into a single sedimentary basin in the Miocene, with a large extension span. The bottom of the basin developed chaotic seismic reflection facies. The upper part of the basin had strong seismic reflection
amplitude, good lateral continuity of the seismic event and flat seabed topography. Many high and steep normal faults can be seen on the seismic section, and the faults in the northern sedimentary basin are more well-developed than those in the southern sedimentary basin.

5 Discussion

5.1 Sedimentary age of the six seismic sequences

In the course of this study, we hoped to calibrate the geological age of each seismic reflection layer deposition through the geological dating information from DSDP Leg 60 drilling sites 458 and 459. Unfortunately, sites 458 and 459 were drilled into the basement uplift of the fore-arc sedimentary basin, and affected by the expansion of the Mariana trough and the retreating subduction zone of the Western Mariana Ridge, and so it was not easy to determine the development age of the sedimentary hiatuses within the Cenozoic strata penetrated by the wells. Therefore, through seismic sequence development characteristics and the geological dating information brought by the wells, the sedimentary age of the six seismic sequences has been roughly inferred.

SQ1: was deposited in the early stage of the rift. The IBM subduction began at 50 Myr, and the age of first sedimentary hiatus shown from site 459 is 42–40 Myr. Nannofossil and radiolarian dates show that the deposits are middle Eocene in age. We speculate that the sedimentary period of SQ1 is middle Eocene, from 50–40 Myr.

SQ2: the top interface SB3 is the first hiatus shown in site 458 lasting from 26.5 Myr to 25 Myr, when the strata was continuously deposited at site 459. Accordingly, SB3 is isochronally calibrated from site 458 to site 459. Nannofossil and radiolarian dates show that SQ2 was deposited in middle Eocene–late Oligocene. There is a small gap at site 459 within SQ2 with gap from 34.5–30 Myr, which is taken to be a local sedimentary hiatus and not used as a maker for calibration. We speculate that the sedimentary period of SQ2 is middle Eocene–late Oligocene, with the sedimentary age of 40–25 Myr.

SQ3: the top interface SB4 is the second hiatus shown in sites 458 and 459 lasting from 22 Myr to 17.5 Myr, which is a regionally developed unconformity surface where the strata of the top part have suffered different degrees of erosion. Nannofossil and radiolarian dates show that SQ3 was deposited in late Oligocene–early Miocene, with the sedimentary age of 25–17.5 Myr.

SQ4: its top interface SB5 is the third hiatus shown in sites 458 and 459 lasting from 14 Myr to 12 Myr, which is a regionally developed unconformity surface where the strata of the top part have suffered different degrees of erosion. Nannofossil and radiolarian dates show that SQ4
was deposited in early–middle Miocene, with the sedimentary age of 17.5–12 Myr.

SQ5: its top interface SB6 is the fourth hiatus shown in sites 458 and 459 lasting from 10 Myr to 3 Myr, which is also a regionally developed unconformity surface where the strata of the top part suffered different degrees of erosion. Nannofossils and Radiolarian dates show that SQ5 is deposited in middle Miocene–late Pliocene, with the sedimentary age of 12–3 Myr.

SQ6: these were sediments deposited after the last large-scale volcanic activity within the sedimentary period of late Pliocene–Quaternary and with the sedimentary age of 3–0 Myr.

5.2 Relationship between earthquake activity and fault and volcanic activity
Fault and volcanic activity are important inducing factors of earthquakes. According to the fault lateral development seen on multi-channel seismic section MGL1204.002, faults are well developed in the Mariana fore-arc Cenozoic sedimentary basin, and some of the faults extend up to the seabed, which indicates that some faults are still active. At the same time, compared with the southern sedimentary basin, the faults in the northern sedimentary basin are basically broken to the seabed, and inherited development from the basement to the seabed. It can be inferred that the faults are basically continuously active during the whole sedimentary period of the Cenozoic basin. Three-stage faults have been mainly developed in the southern sedimentary basin. Some of the faults stop at the late stages of SQ3 and SQ5 sedimentary periods, and some of the faults have been active until now.

The epicenters of the earthquakes in the Mariana island arc with magnitudes greater than 5 and focal depth greater than 50 km were counted from 1962 to 2012 (Figs. 1, 11).

The comparison between fault development and earthquake epicenter number shows that the latter is positively correlated with the fault number in the 146°E–151°E Mariana fore-arc area. The earthquake epicenter density in the northern sedimentary basin is much higher than that in the southern sedimentary basin. At the same time, severe crustal movement will further generate faults. Therefore, earthquake activity at different periods and in different subduction areas of the Mariana subduction system can be inferred from the fault development characteristics in the Cenozoic sedimentary basin. The application of the multi-channel seismic section to study the fault development and evolution characteristics has been an important means for the study of the Mariana subduction process. Fault development and evolutionary characteristics revealed from the multi-channel seismic sections have helped to study of the Mariana subduction mechanism.

From the seabed topography revealed by the multi-channel seismic section, serpentine mud volcanoes in the northern sedimentary basin are more developed than those in the southern sedimentary basin, and some of them break through the seabed to become seamounts (Fig. 11). The activity of serpentine mud volcanoes is also an important inducing factor for earthquakes. Because of the lack of specific data on dates of serpentine mud volcanic activity, the correlation between volcano and natural seismic activity is still difficult to judge.

6 Conclusions
(1) Six seismic sequences are developed in the fore-arc Cenozoic sedimentary basin of Mariana. The sedimentary ages from bottom to top are middle Eocene (50–40 Myr), middle Eocene–late Oligocene (40–25 Myr), late

![Fig. 11. The relationship between the number of earthquake epicenters (recorded in 1962–2012, M > 5, and depth > 50 km) and the number of faults extending up to the seabed.](image)
Oligocene–early Miocene (25–17.5 Myr), early–middle Miocene (17.5–12 Myr), middle Miocene–late Pliocene (12–3 Myr) and late Pliocene–Quaternary (3–0 Myr), respectively.

(2) In the middle part of the Mariana arc of 16°N–19°N, 146°E–151°E, the maximum thickness of the sedimentary center of the Cenozoic sedimentary basin developed within the visible range of the seismic reflection section in the Mariana fore-arc is 2360 m. Influenced by volcanic activity and the basement uplift due to the subduction of the Pacific lithosphere plate, the strata at the top each seismic sequence suffered different degrees of erosion.

(3) Many high-angle normal faults are developed in Mariana fore-arc sedimentary basin, and the last rifting of the Mariana subduction system is still ongoing. The fault number is positively correlated with the earthquake epicenter number. Fault development and evolution characteristics revealed from multi-channel seismic sections show that this method can be used feasibly to the study of Mariana subduction mechanism.

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References


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