Chapter 4

Seismic Stratigraphic Features of the Late Miocene-Present Unconformities and Related Seismic Units, Northern Offshore Taiwan

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Abstract

We investigate the seismic stratigraphic features offshore northern Taiwan by using newly collected multichannel seismic data. Two significant regional unconformities U1 and U2 have been identified, which further subdivide the sedimentary sequence into three seismic units as SU I, SU II, and SU III. The lowermost seismic unit SU I is a pre-late Miocene sequence, while the middle and upper seismic unit SU II and SU III result from the interactions between the rapid fault-controlled subsidence and the stable thermal-controlled subsidence. We consider that the present-day offshore northern Taiwan is under a post-collisional state and the unconformities U1 and U2 represent a response to the mountain collapse and to the cessation of the regional volcano-tectonic activities. It is not until 1.5 Ma that northern offshore Taiwan became a post-collisional basin and started to receive sediments, with a rapid fault-controlled subsidence. Afterward, the basin became dominated by a stable thermal-controlled subsidence at 0.2 Ma. Although the main volcano-tectonic activities in the northern offshore Taiwan are ceased, modern geophysical and geochemical investigations have suggested that the tectonism and the volcanism are still active and represent potential threatening geohazard.

Keywords: seismic reflection, orogeny, mountain collapse, northern offshore Taiwan

1. Introduction

In addition to gravimetric and magnetic data, the reflection seismic data are powerful tools to understand the subsurface geological features and to determine the nature of the sedimentary basins. In terms of regional stratigraphy, they provide not only the thickness and the distribution of the sedimentary sequences but also the contact relationships between the sedimentary sequences, representing stratigraphic lap-out and geological unconformities. In addition to sea level change, tectonic events are generally accepted as a general cause for these seismic unconformities, indicating the basin formation mechanisms directly. In this study, we aim at analyzing the dominant tectonic events and the present-day tectonic setting of northern offshore Taiwan based on newly collected marine reflection seismic data, which reveal the subsurface stratigraphic features.

The northern offshore Taiwan is located at the junction among the southernmost part of the East China Sea, the south-western extension of Okinawa Trough and the northern tip of the Taiwan orogenic belt (**Figure 1**). The northern offshore area of Taiwan is surrounded by different geological units highlighting that several basins have influenced its tectono-sedimentary evolution. It could be the part of the post-rift stage of the Paleogene rift basin in the East China Sea [1, 2]. It may also be proposed that it is dominated by relict back-arc basins, which were controlled by a progressive eastward migrating subduction of the Pacific plate and ended up in the present Okinawa Trough [3–5]. The progressive southward migration of the Taiwan orogenic belt could be a practical mechanism for basin formation as well [6–9]. Recently, strike-slip motion along the East Asia continental margin is considered to play a role on the basin evolution of the East China Sea [10]. A re-appraisal of which basin formation mechanism is more dominant for the Neogene basin development in the northern offshore Taiwan is thus required.

This chapter provides new seismic stratigraphic information on the Neogene tectonic setting in the northern offshore Taiwan through seismic interpretation. The stratigraphic architecture of the Neogene sedimentary sequences in the northern offshore Taiwan has been reconstructed through the geological interpretation of high-resolution seismic profiles. Here, we examine two high-resolution reflection seismic profiles of different orientations northern offshore Taiwan (**Figure 2**). One of the profiles runs in NE-SW direction, showing a northward dipping sequence. The other one, on the other hand, runs in NW-SE direction, showing a series of tilted fault blocks. Most significantly, both profiles feature obvious, angular unconformities. The geological and tectonic significance of these unconformities is discussed in this study.

2. Geological backgrounds

Connecting Japan to the north and Taiwan to the south, the East China Sea is a marginal sea over a broad continental shelf (**Figure 1a**). The basin of the East China Sea shelf, also known as East China Sea Shelf Basin, is the largest Cenozoic sedimentary basin of the East Asia continental margin [2]. There are several sub-basins at the southern end of the East China Sea Shelf Basin (**Figure 1b**) [11]. These sub-basins were formed in Paleogene, filled with the syn-rift sedimentary sequence and covered by Neogene post-rift sedimentary sequence [1, 12].

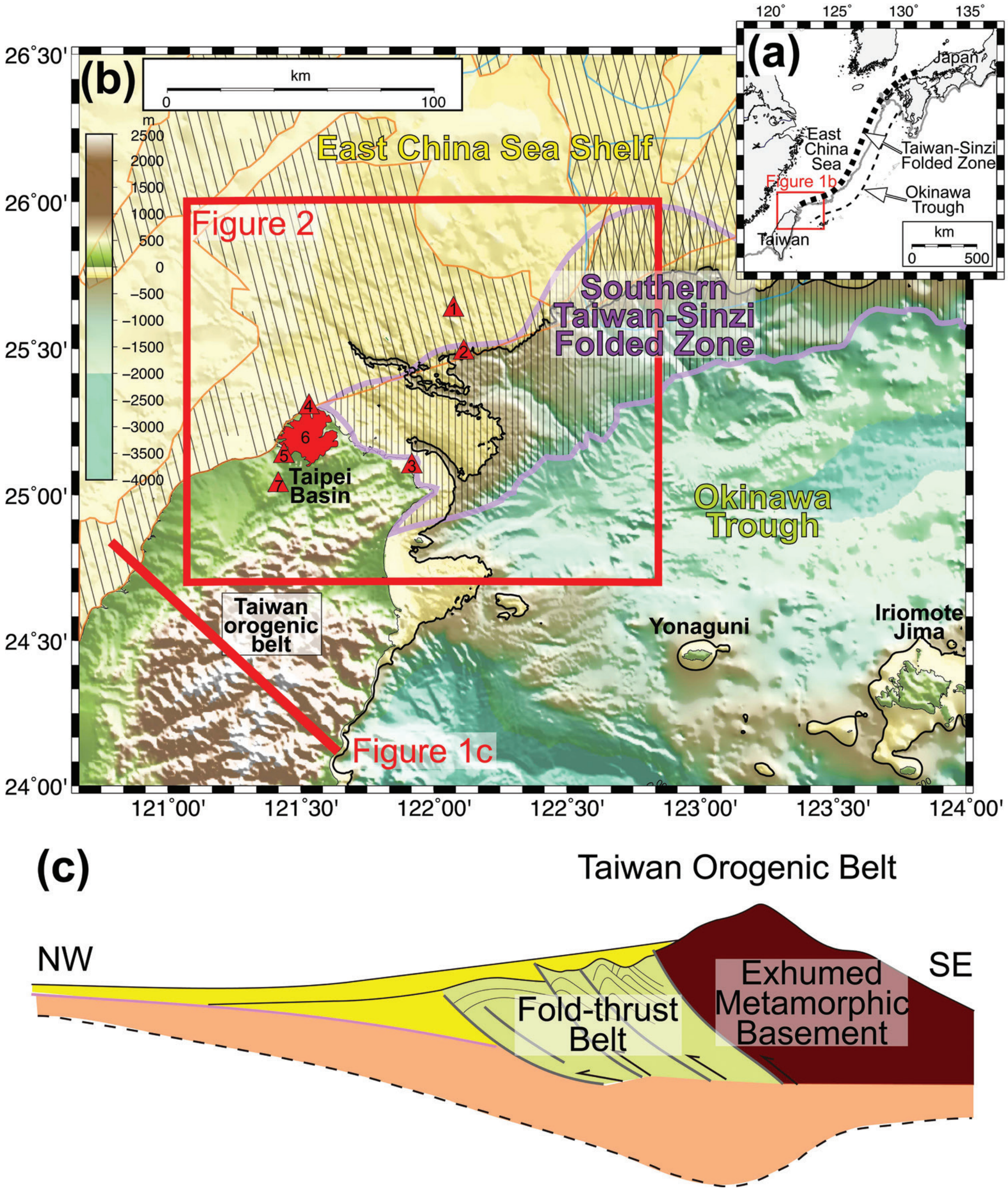

Figure 1. Geological settings and basin location in the study area. (a) Regional setting map showing the approximate location of the East China Sea, of the Okinawa Trough (thin dashed line) and of the Taiwan-Sinzi Folded Zone (thick dashed line). (b) Bathymetric map showing the location of the Paleogene rift basins identified by seismic data (backslash area) and back-arc basin identified by magnetic data (slash area), southern Taiwan-Sinzi Folded Zone (vertical bar line), and Northern Taiwan Volcanic Zone (red area and triangles. (1) Pengjia Islet, (2) Mianhua Islet, (3) Keelung Volcanic Group, (4) and (5) Kuanyinshan, (6) Tatun Volcanic Group, and (7) Tsaolingshan). The black thin lines indicate 200 m contour, and the Red thick line indicates the location of the schematic profile shown in **Figure 1c**. (c) Sketch profile across the Taiwan orogenic belt at its culminating stage The green and yellow area indicate the deformed Tertiary-present sequence, respectively.

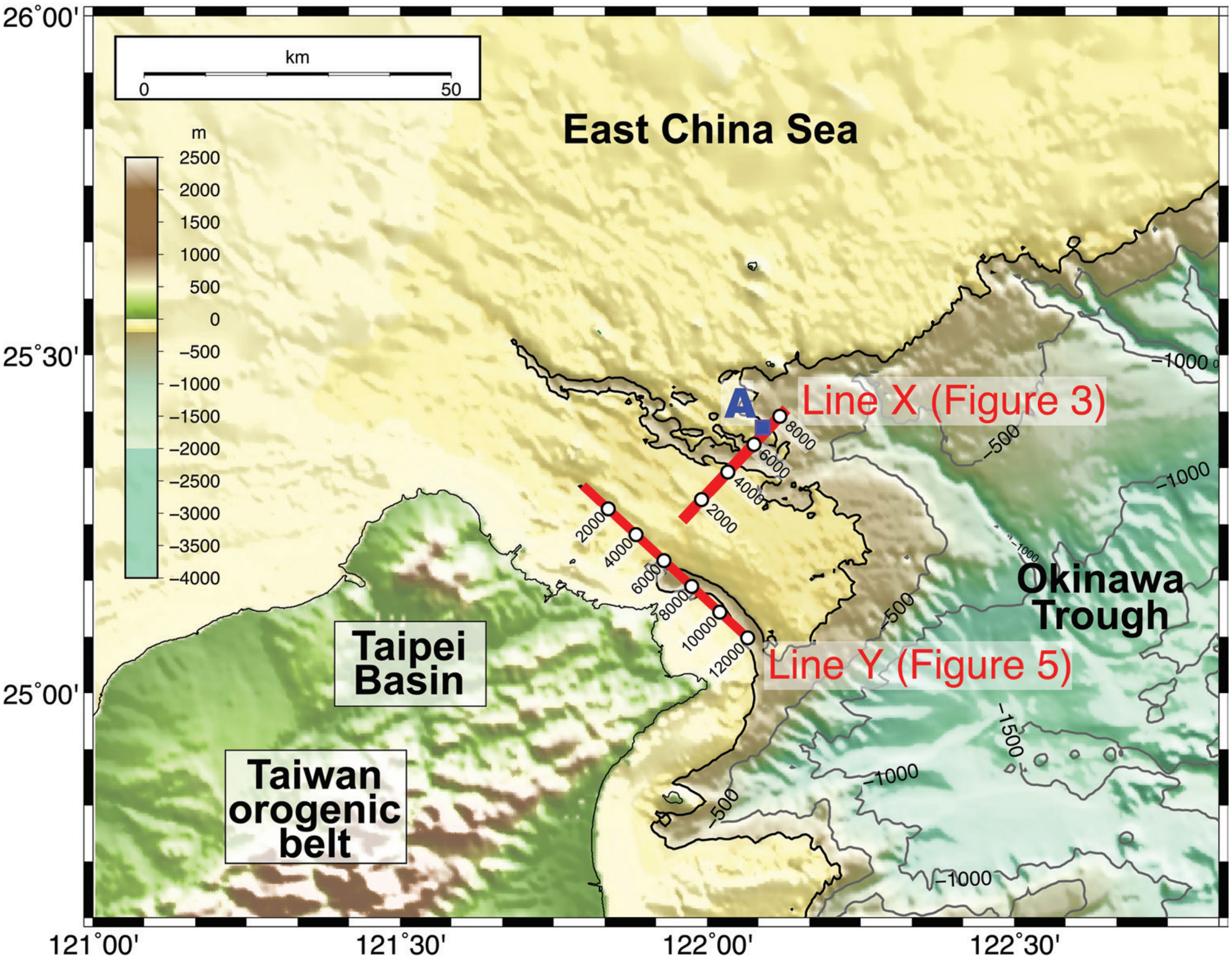

Figure 2. Bathymetric map with location of seismic lines. Red lines indicate the locations of the selected seismic profiles. White circles along the red lines indicate the locations of the shot points. Blue square A indicates the location of the exploration wells.

The Okinawa Trough is a long, N-S trending that connects Japan and Taiwan (**Figure 1**). It is a back-arc basin formed by extension within the continental lithosphere landwards of the Ryukyu trench-arc system [13, 14]. The initial opening of the northern and middle part of the current Okinawa Trough occurred during the Miocene, while it delayed until the Pleistocene in the southern part of the Trough [15, 16]. It is also believed that this back-arc basin may be suited even westwards before Miocene, controlling the emplacement and the tectonic setting of the East China Sea Shelf Basins [3, 5].

The Taiwan is located between the large marginal seas of the East China Sea and the South China Sea and includes a young orogenic belt, formed by Late Miocene collisional events in the SE Eurasian continent (**Figure 1b** and **c**) [17, 18]. In addition to metamorphic basement rocks, the body of the Taiwan orogenic belt is mainly composed of metamorphic basement rocks and deformed Tertiary rift basins, including Paleogene syn-rift and Neogene post-rift sedimentary sequences [19]. Since the Taiwan orogenic belt is moving southward, different evolutionary stages of the orogenic belt features along the trending of Taiwan have been distinguished [20, 21]. The central part of the Taiwan, which is characterized by high mountain peaks of Taiwan mountain ranges, is bearing the culmination of the collisional activity (**Figure 1b**) [22, 23]. Accordingly, the northward descending topography of the mountain range represents the northward decline of the collision [6].

The Taiwan-Sinzi Fold Zone is another significant geological unit in this area (thick dashed line in **Figure 1a**; purple area in **Figure 1b**) [8, 9, 24–28]. It runs approximately along the shelf break, trending parallel to the Okinawa Trough and representing a structural high separating the East China Sea Basin to the west and the Okinawa Trough to the east. In the northern and middle part, the Taiwan-Sinzi Folded zone is characterized by structural highs of the acoustic basement, while it shows folded structures and tilted blocks in the southern part, interpreted as the earliest Taiwan orogenic belt [7, 8, 29].

Northern Taiwan area is also characterized by the Quaternary-present magmatic activities, which is also known as Northern Taiwan Volcanic Zone (NTVZ). The NTVZ is composed of several groups of the volcanic fields, including the earliest (before 2.6 Ma) Tatun Volcanic Group, Mianhua Islet, and Sekibisho; later (2~1 Ma) Tatun Volcanic Group, Pengjia Islet and Keelung Volcanic Group; and the latest (after 1Ma) Tsaolingshan, Kuanyinshan, and Kobisho (**Figure 1b**). They occur probably in association with the westernmost part of the Ryukyu Arc or in response to the extensional magmatism of the northern Taiwan mountain range [6, 30, 31].

3. Data acquisition and processing

In this study, we used the multichannel reflection seismic data collected by the Taiwanese research vessel *Ocean Researcher II*. The source energy was shot via a 210-cubic inch GI gun with shot interval of 37.5 m. The reflection seismic data were acquired through a 24-channel, 150-meter long streamer, with a 1-ms sampling rate. The reflection seismic data were processed by the ProMAX and KINGDOM software at the Institute of Oceanography, National Taiwan University. The data-processing procedures include trace editing, geometry set-up, band-pass filtering, amplitude compensation, predictive deconvolution, velocity analysis, normal move-out correction, stacking, water velocity F-K time migration, and water column mute. Bathymetric dataset is a 500-m gridded data, produced by compiling shipboard and global dataset [32]. The bathymetric charts are prepared by the GMT [33].

4. Results

4.1. Line X

We interpret the seismic data and depict stratigraphic boundaries, mainly on the basis of the concepts carried out by Vail and Mitchum [34] and Mitchum et al. [35]. Line X runs NE-SW, extending approximately 30 km and perpendicularly to the coastline of Taiwan (**Figure 2**).

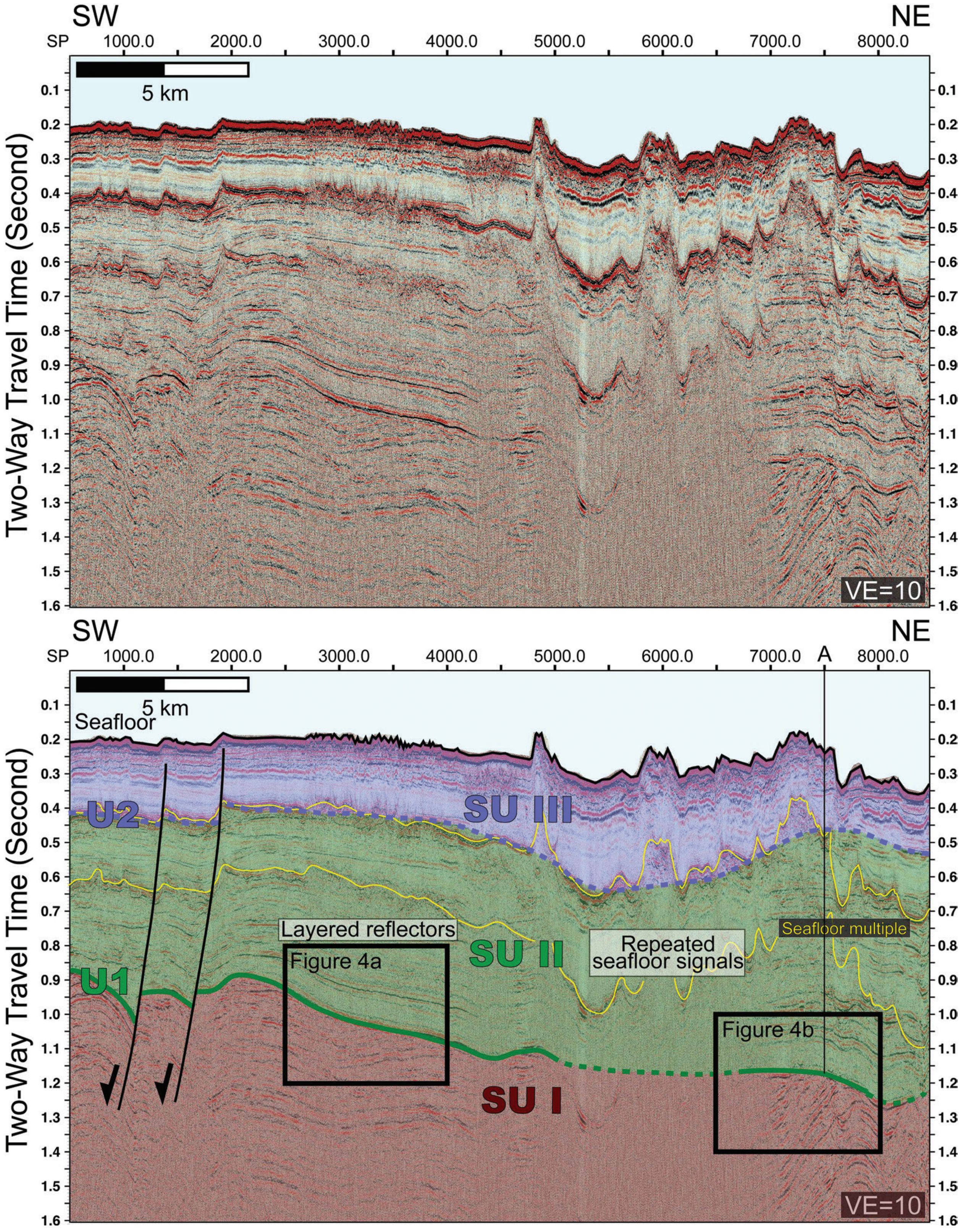

Figure 3. Selected reflection seismic profile along Line X. See **Figure 2** for the location.

The most of line X is located on the continental shelf, and the central and northeastern part of the Line X have the bathymetry deeper than 200 m (**Figures 2** and **3**). A drilling site at the NE part of the survey line X, providing geological information and chronostratigraphic controls in study area [8, 9].

A seismic boundary namely U1 at about 1 second Two-Way Travel Times (twt) has been observed (**Figure 3**, marked as a green line), extending in the whole profile. In the middle-south part of the profile X (SP 2500-4000; **Figure 4a**), the reflectors beneath the U1 show very apparent termination against the U1, of which we interpreted as erosional truncation. In the northeastern part of the profile (SP 6500-8000; **Figure 4b**), the termination relationship between the U1 and the underlying reflectors shows erosional truncation as well. Collectively, we suggest that U1 is an unconformable surface. At the southwestern part of the profile, the unconformity U1 is located around 0.85 s (twt) (**Figure 3**), while the unconformity U1 becomes deeper to around 1.2 s (twt) at the north-eastern end of the profile, showing a gently descending trend toward north-east.

The characteristics of the seismic reflectors above the unconformity U1 are not always consistent along the Line X. In the central-south and northernmost part of the profile (**Figure 3**,

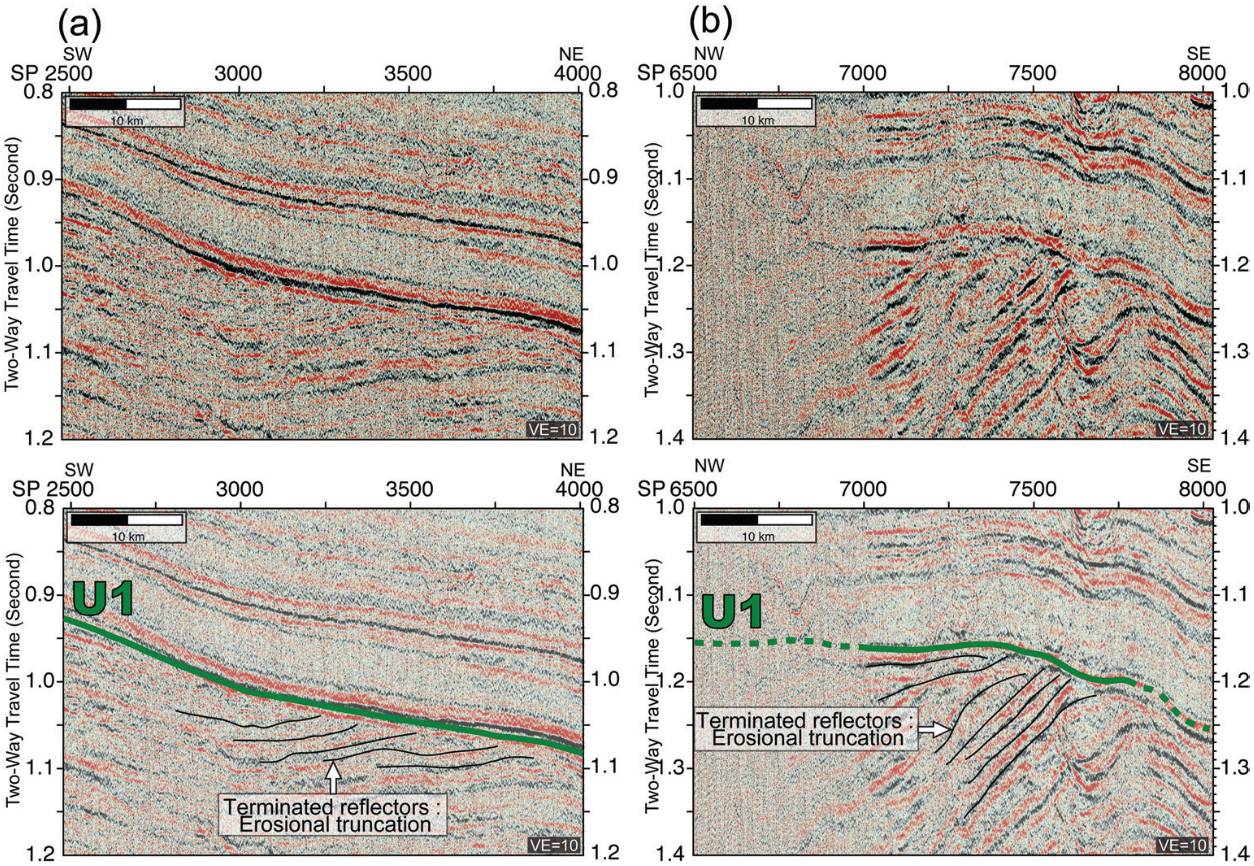

Figure 4. Selected seismic sections showing the termination feature of the U1. See **Figure 3** for locations.

SP 500-5000; 7000-8500), it is dominated by layered reflectors. However, in the middle-north part of the profile (**Figure 3**, SP 5000-7000), it shows strong seafloor reverberation above 1 s (twt) and an area of reflection-free below 1 s (twt). It seems that the strong seafloor reverberation has intervened between layered reflectors to both southern and northern ends of the seismic profile. We interpret that this reflection feature is plausible to be the seismic response of very hard and solid seafloor material, probably crystallization or extrusive rocks.

4.2. Line Y

Line Y is located near offshore northern Taiwan, and runs NW-SE, parallel to the coastline of the Taiwan (**Figure 2**). It extends around 40 km along dip of the continental shelf, showing even no drastic change in bathymetry (**Figures 2** and **4**). There are some gentle bathymetric reliefs associated with dominant fault structures (indicated by write triangles in **Figure 5**; SP 4300-4500, 5900-6100, 8300-8600).

In the north-western part of the seismic profile Y (SP 400-1700; **Figure 6a**), the truncated reflectors are tilted, suggesting the occurrence of tectonic and/or erosional events. In addition, the

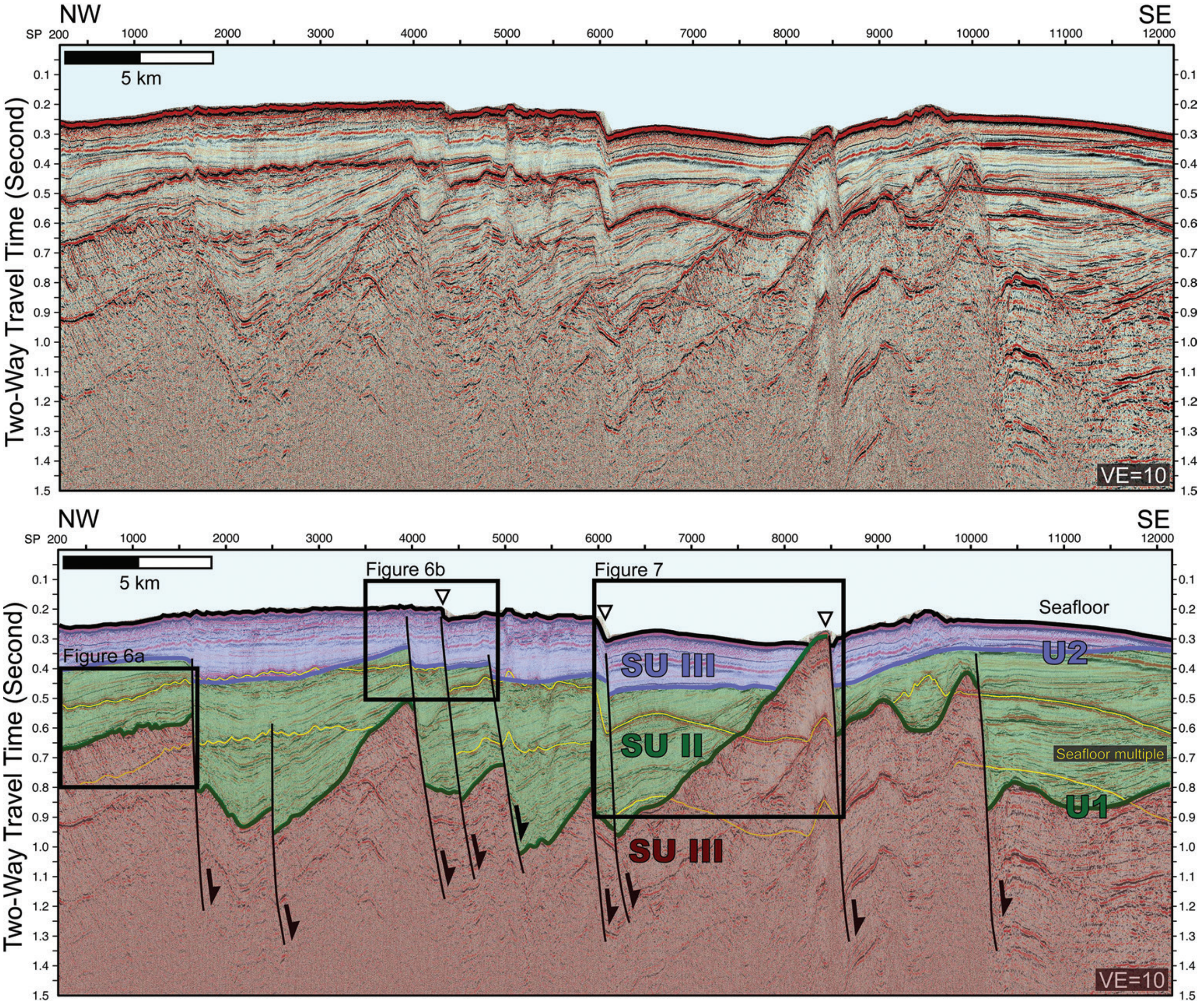

Figure 5. Selected reflection seismic profile along Line Y. See **Figure 2** for the location.

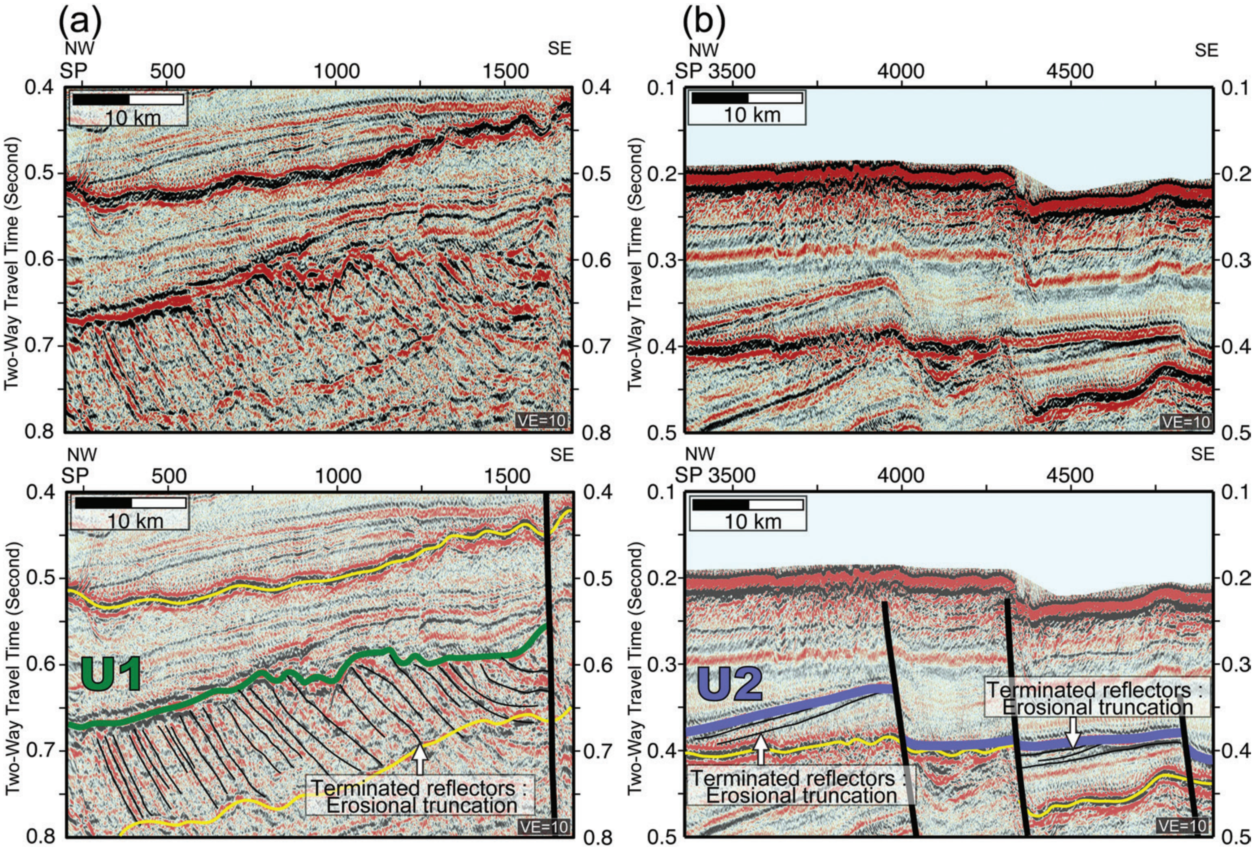

Figure 6. Selected seismic sections showing the termination feature of the U1 and U2. See **Figure 5** for locations.

U1 in the seismic profile Y also serves as a top surface of the dominating tilted fault blocks. In this way, the U1 is of regional importance, and the distribution of the U1 reflects the local tilting of the fault blocks.

We also identified another seismic boundary U2 in the seismic profile Y (**Figure 5**, marked as purple lines), although it often coexists with seafloor multiple signals (**Figure 5**, SP 1700-3000 and 5000-6000). In the middle-south part of the profile (SP 3500-5000; **Figure 6b**), the U2 is identified at around 0.3-0.4 s (twt), serving as a termination surface of underlying updipping reflectors. On the basis of on the parallelism of terminated reflectors [35], we interpret an erosional truncation relationship between the U2 and terminated reflectors. In the middle-north part of the profile (SP 6000-8700; **Figure 7**), the parallelism of terminated reflectors and the feature of erosional truncation become much obvious. We interpret the U2 as an unconformity that may mark a tectonic event as the unconformity U1.

We note that both the unconformities U1 and U2 do crop out at seafloor in the seismic profile Y (**Figure 6**). The unconformity U1 crops out at the crest of a local structural high, along with a fault-block bounding fault (**Figure 7**, SP 8200-8500). The U2 crops out at southeasternmost of the profile (**Figure 7**, SP 12000). These may be the result of the interaction between the degree of fault block rotation and local sediment discharge. In addition to the U1 and U2 in the seismic profile Y, we observe a strong and continuous reflector shown between the clear features of the U1 and U2 (dashed line in **Figure 7**). Such reflector may also indicate the existence of the minor and local events, probably the halts of the fault block rotations.

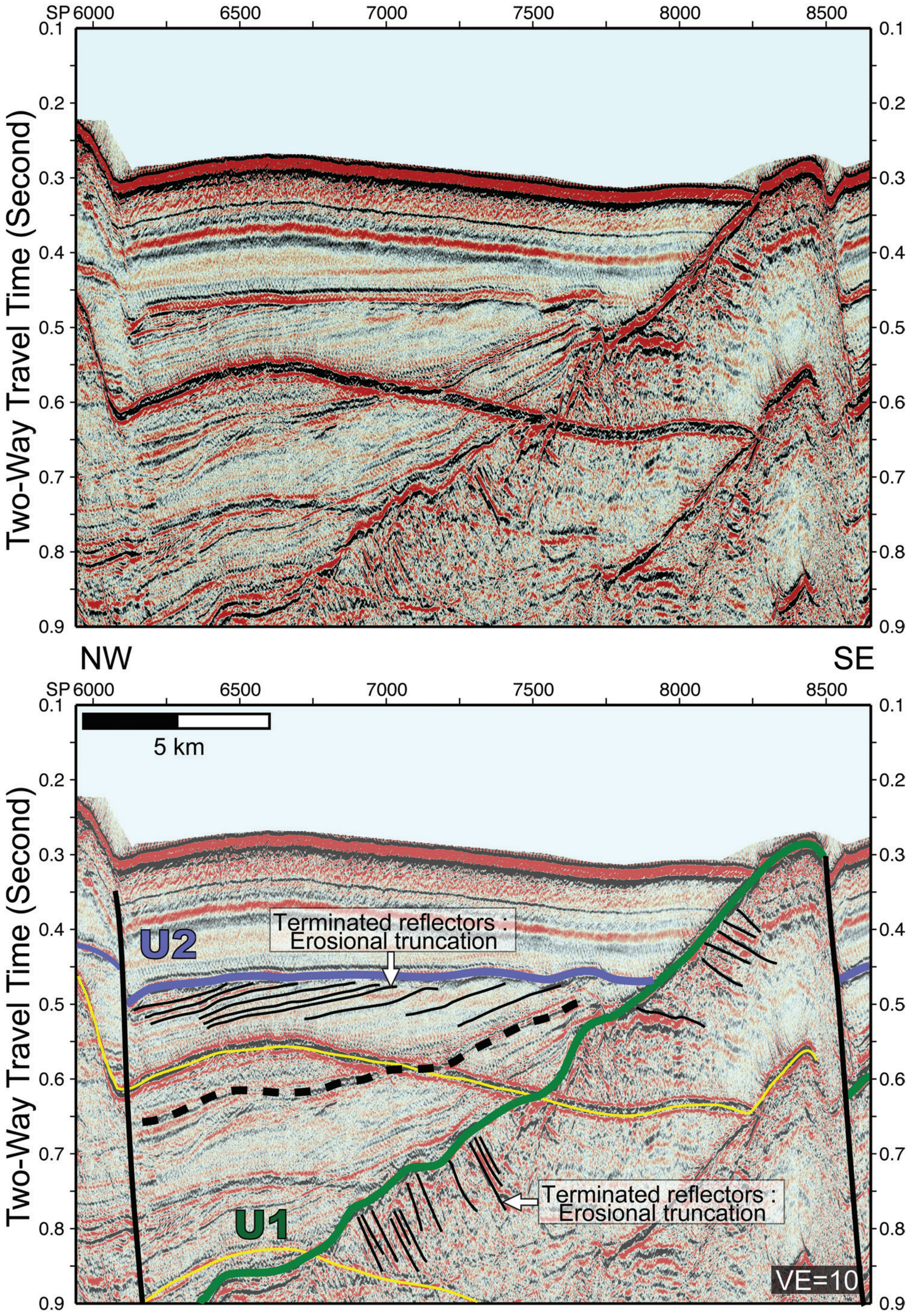

Figure 7. Selected seismic sections showing the termination feature of the U1 and U2. See **Figure 5** for locations.

4.3. Seismic units

On the basis of the U1 and U2, three seismic units are determined accordingly: the SU I, SU II, and SU III, which indicate the sedimentary sequence beneath the U1, the sedimentary sequence between the U1 and U2, and the sedimentary sequence above U2, respectively (**Figures 3** and **5**). In the seismic profile Y, we note that the thickness of the SU II varies along the profile, mainly depending on the relief of the underlying fault structures (**Figure 5**), while the thickness of the SU III change slightly and diminish toward the southeast end of the seismic profile Y (**Figure 5**, SP 10000-12000). The thickness variation of the SU II and SU III may indicate the change in subsidence patterns and rates, probably reflecting the change in controlling factor of subsidence [36, 37, 38].

5. Discussion and conclusion

5.1. Age of U1 and U2

In our seismic data, the seismic boundaries U1 and U2 are remarkable unconformities, which show similarity in the truncation relationship with underlying strata. The ages of the unconformities U1 and U2 formation are thus significant, revealing more information on regional tectonic events. Based on drilling results [8], the strata overlying the unconformity U1 were dated back to approximately Pleistocene and the strata beneath the same unconformity were dated back to Late Miocene [8]. Accordingly, the unconformity U1 bears a hiatus of Late Miocene-Quaternary age, while there is still no available drilling information reporting the existence of the unconformity U2 up-to-date. In this way, the age of the unconformities U2 may be alternatively proposed by additional local Late Miocene-present tectonic events.

The Quaternary magmatism is also a significant feature in post-collisional environment in northern Taiwan, resulting in the NTVZ [30]. The ages of the NTVZ have been dated, mainly distributing from 2.8 to 0.2 Ma. During this period, three age groups of before 2.6 Ma, 2~1 Ma, and after 1 Ma have been identified [30]. We note that the first age group may represent the earliest signals of the post-collisional state [30]. Among the three groups, the second age group is mainly composed of the volcanic edifice formed at the Pengjia Islet (2.1 Ma), the Tatun Volcanic Group (1.5 Ma), and the Keelung Volcanic Group (1.4 Ma). We consider that, the formation of the unconformity U2 and deposition of the SU II are likely simultaneous to the second age group of the NTVZ [8]. Another point we note is that most of the NTVZ events may cease no later than 0.2 Ma [30], suggesting that 0.2 Ma may be a critical timing of tectonic environment change in the NTVZ area. Collectively, we suggest the unconformities U1 and U2 may represent the age of 1.5 Ma and 0.2 Ma, respectively.

5.2. Late Neogene basin of north offshore Taiwan

The formations of the unconformities U1 and U2 shall be related to the tectonic development of the Late Miocene-present sedimentary basin of northern offshore Taiwan, which has been considered as post-rift basin [1, 2], back-arc basin [3–5], post-collisional basin [6–8], and strike-slip basin [10]. Among the four competing models, the strike-slip motion has been proposed for long time, as it may be caused by the formation of the East China Sea Shelf Basin or the opening southern Okinawa Trough [9, 10]. However, the shape of the Late Neogene basin does not present as a rhombic shape reflecting strike-slip pull apart basins. In addition, the strike-slip structures have not been fully supported by mapping result from marine reflection seismic survey. The post-rift basin model is proposed as northern offshore Taiwan being considered as an extension of the East China Sea Shelf Basin. While in our study area, the post-rift shall have been ceased since the activities of both Taiwan orogenic belt to the south and the back-arc extension of the Okinawa Trough to the southeast are more immediate and are more likely to dominate. On the basis of the geographical connection of our study area with the Okinawa Trough and the Taiwan mountain range, the rest back-arc basin and post-collisional basin models are better candidates for the Late Neogene basin formation.

Our reflection seismic data show that U1 is an unconformity that truncated the underlying fault blocks and the tilting strata. We consider that those tilting strata may indicate a drastic uplift event prior to the formation of the unconformity U1. As a result, the back-arc basin model may be less likely to ascribe for strong tectonic uplift, once the back-arc basin is more dominated by crustal extension. In this way, we tend to agree with the post-collisional basin model. We suggest that the unconformity U1 represents an age mark of the post-collisional stage that started to receive sediments; the SU I were the strata deposited before the mountain collapse, and the SU II were deposited probably after the post-collisional basin had formed. The thickness variation of the SU II depends on the distribution of faults, indicating that SU II may be formed in association with fault-controlled subsidence [36, 37, 38]. The unconformity U2 shall be a regional tectonic event later in the Quaternary. Based on its erosional and relatively flattening feature upon tilting fault blocks, we propose that the unconformity U2 may be related to the cessation of the fault blocks rotation and change of regional subsidence rate. The thickness of the SU III does not vary greatly, indicating that the fault-controlled subsidence was followed by a relatively stable, probably a thermal-controlled subsidence [36, 37, 38].

5.3. Tectonic evolution and implication of post-collisional basin

Figure 8 is a sketch cartoon showing the development of the unconformity U1 and U2 and of the related seismic units in the post-collisional tectonic setting in northern offshore Taiwan. After reaching the culmination of orogenic activities in northern offshore Taiwan (~2.6 Ma; **Figure 8A**), the post-collisional magmatism was also about to begin. Afterward, the mountain range began to collapse, leaving the unconformity U1 at 1.6 Ma and SU II (**Figure 8B**). The initial subsidence was fault-controlled and was likely to be dominated by the rotation of the fault blocks, reflecting a mechanical stretching typical of early stages of rifting basin development [36, 37, 38]. The fault-controlled subsidence and volcanic activities may cease at late Quaternary (~0.2 Mal **Figure 8C**), resulting in a change in regional subsidence rate, a horizontally distributed unconformity U2, and a relatively even-thick SU III. In this model, the lowermost seismic unit SU I is a pre-Late Miocene sequence, representing the main body of collapsed imbricated thrusts. The middle seismic unit SU II caused by probably more rapid, fault-controlled subsidence indicates the depositional sequence of early stage mountain collapse. The uppermost seismic unit SU III, on the other hand, resulted from slower, probably thermal-control subsidence and indicates the depositional sequence of late stage of mountain collapse.

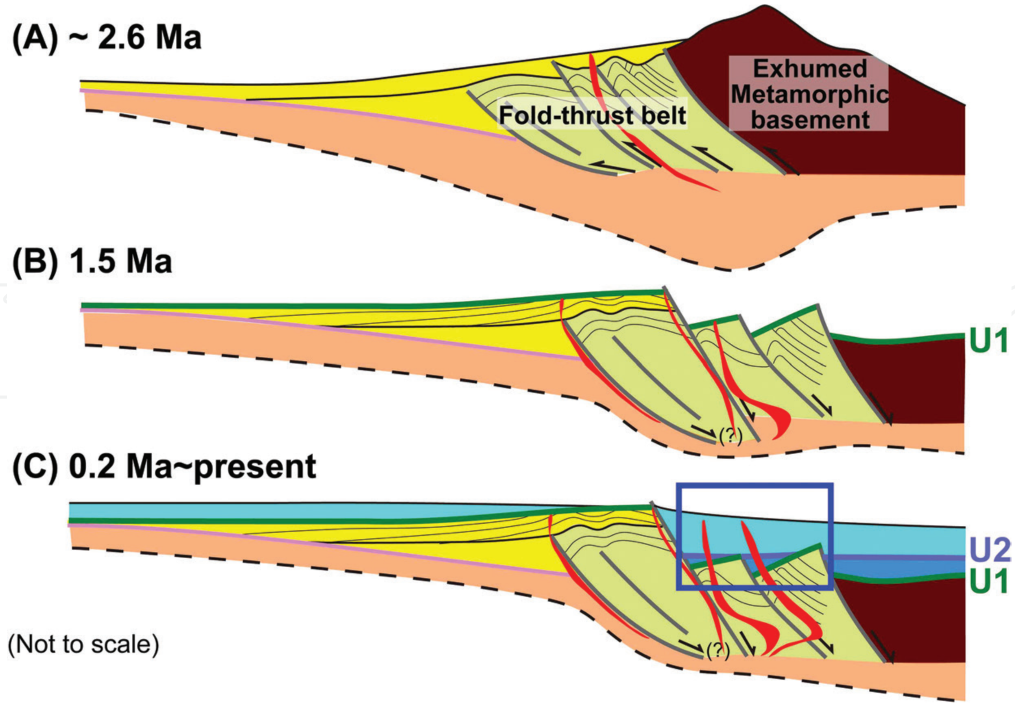

Figure 8. A schematic cartoon showing the development of the U1 and U2, with the tectonic scenario of post-collisional in northern Taiwan. Blue rectangle indicates the sites referring to our study area. We interpret the U1 and U2 indicate the onset and cessation of fault-controlled subsidence at 1.5 Ma and 0.2 Ma, respectively.

Also in this model, the volcanic magmatism of the NTVZ may be reducing since unconformity U2 appears to indicate the cessation of active extension. However, previous geophysical observations have shown that in addition to siliciclastic sediments, andesitic intrusions were also found at several places offshore northern Taiwan [39]. Recent observations about volcanic activities suggest that there are even younger, Holocene volcanic events in the NTVZ area, and hydrothermal activities in the Tatun Volcanic Group area are still very common at present [40, 41]. New seismological evidence clearly indicates that a deep magma reservoir is beneath Taipei [42]. Also, increasing active submarine volcano, gas plumes, and topography lineaments have been identified in the offshore area [43–45]. To sum up, investigation on whether the volcanic activities are still potential threatening geohazards, along with the geophysical and geochemical monitoring on present-day activities, remains important. We wish that the better understanding of the unconformities formation and relevant stratigraphic architectures will provide a good insight into Late Pleistocene-Holocene volcano-tectonic evolution of the NTVZ.

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