



Review Article

Tectonostratigraphic evolution of the Northeast South China Sea Rifted Margin: From Mesozoic orogeny to Present

Mateus Rodrigues de Vargas^{a,*}, Geoffroy Mohn^a, Julie Tugend^a, Nick Kusznir^b, Andrew Lin^{c,d}, Liang-Fu Lin^e

^a CY Cergy Paris Université, Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre de Paris, ISTEP, F-95000 Cergy

^b Department of Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool, United Kingdom

^c Department of Earth Sciences, National Central University, Taoyuan, Taiwan

^d Carbon Storage and Geothermal Research Center, National Central University, Taoyuan, Taiwan

^e Ocean Center, National Taiwan University, Taipei, Taiwan

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ABSTRACT

We present a new integrated tectonostratigraphic framework for the proximal-to-distal rifted margin of the Northeast South China Sea, based on a review of seismic and borehole observations, as well as crustal thickness variations determined from a gravity inversion scheme. The structural domains of the NE SCS shaped by Cenozoic rifting include the proximal (Northern Rift System and Penghu-Peikang High), necking (Tainan Basin, Central High, and its southern vicinities), and distal domains (Southern Rift System and Southern High). Rifting (Late Paleocene to Early Oligocene) occurred synchronously throughout the margin and was accommodated by large-offset and low-angle normal faults. This resulted in localized rift basins filled by marine/deltaic sedimentary rocks in the proximal domain and a sediment-starved, likely deep-marine setting in the distal domain. During the post-rift period (Early Oligocene to latest Miocene), shelf-dominated deposition prevailed north of the Central High, whereas a deep-marine environment is interpreted to its south. This overall trend persisted during the foreland basin sedimentation linked to the Taiwan orogen (latest Miocene to recent). The comparison of the NE SCS rifted margin with the adjacent Pearl River Mouth rifted margin shows differences in both their crustal structure and sediment infilling history. Their contrasting crustal structures are interpreted as a response to rifting processes that differ due to initially contrasting crustal rheology and the proximity/magnitude of sediment source areas. More generally, this study highlights how the dynamic evolution of marginal sea basins drives rapid changes in rifting styles and sedimentary infill during and after rifting.

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* Corresponding author.

E-mail address: mrvargas1989@gmail.com (M. Rodrigues de Vargas).

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1. Introduction

The South China Sea is one of the most extensively studied marginal sea basins of SE Asia (Fig. 1a). Numerous recent studies have provided critical insights into its mode of rifting (e.g., Ding et al., 2020; Lei et al., 2019; Zhang et al., 2019), continental breakup (e.g., Larsen et al., 2018; Mohn et al., 2022; Zhang et al., 2024), and Cenozoic sedimentary infilling (e.g., Chen et al., 2024; Yao et al., 2012; Zhang et al., 2023). Tectonostratigraphic studies are numerous in the northern Pearl River Mouth margin (e.g., Lei et al., 2019, 2020; Xie et al., 2019; Yang et al., 2018; Zhao et al., 2020) and its southern conjugate (e.g., Dangerous Grounds) (Fig. 1a and b) (e.g., Franke, 2013; Liang et al., 2019). In these regions, thick syn-rift sequences overlie a wide rift zone characterized by the succession of hyper-thinned basins and basement highs (Franke, 2013; Nirrengarten et al., 2020; Xie et al., 2019).

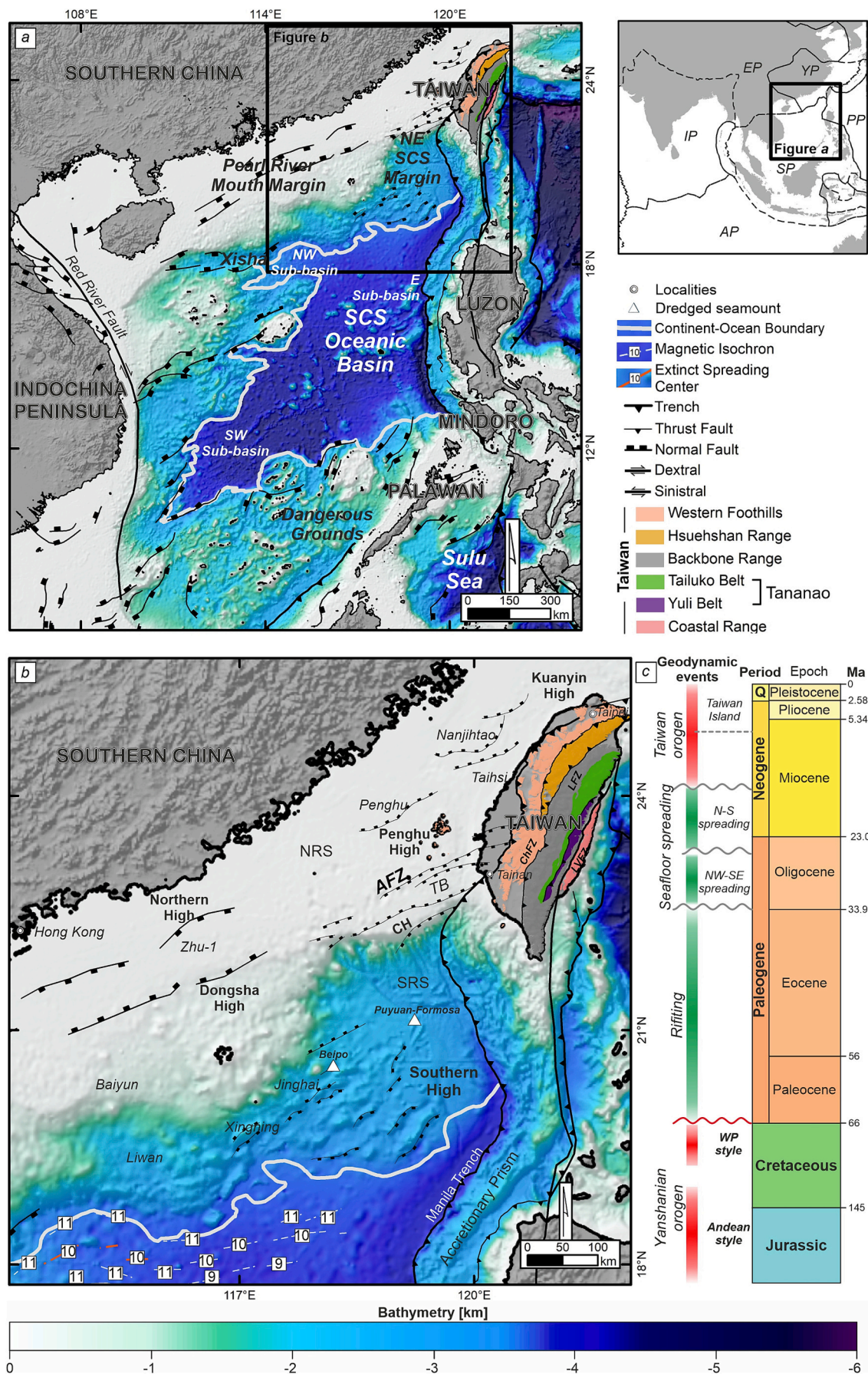
In contrast, less research has been done in the Northeast South China Sea Margin (NE SCS) (Fig. 1a and b). Previous studies suggest that the NE SCS has a contrasting geological evolution that differentiates its Cenozoic evolution from that of its adjacent neighbors (Ding et al., 2008; Lester et al., 2014; Li et al., 2007; Sibuet et al., 2016; Yeh et al., 2010, 2012). However, the factors explaining these differences have yet to be integrated and clarified.

The NE SCS rifted margin is located between the Pearl River Mouth Margin (PRMM, west) and the Taiwan orogen (east) (Fig. 1a and b). This

segment records all the geological events that shaped the SCS during the last Wilson Cycle, consisting of: i) the Mesozoic Yanshanian orogeny resulting from the subduction of the Paleo-Pacific below the South China Block (SCB) and the docking with the Luconia Microcontinent (Hall and Breitfeld, 2017; Pubellier and Sautter, 2022; Sautter and Pubellier, 2022); ii) Paleogene to Neogene rifting culminating in continental breakup during the Early Oligocene (Larsen et al., 2018b; Sibuet et al., 2016); iii) the Middle Miocene cessation of seafloor spreading, subduction of the South China Sea oceanic crust, and the onset of the Taiwan orogen (Sibuet et al., 2016; Lin et al., 2003) and iv) the onset of foreland development in the latest Miocene, due to collision between Eurasia's rifted margin and the Luzon magmatic arc (Fig. 1c) (Ho, 1982).

This study presents a new comprehensive tectonostratigraphic framework, integrating for the first time the proximal to distal domains of the NE SCS rifted margin, relying on analysis and reinterpretation of a wide range of geological and geophysical datasets. Our results on the crustal structure, rifting style, and tectonostratigraphic evolution of the margin enable us to propose:

- (i) a standardized stratigraphic nomenclature of the NE SCS comparable with adjacent segments of the SCS.
- (ii) an identification of the rift domains for the NE SCS rifted margin and limitation of the method.



(caption on next page)

Fig. 1. Location of the NE SCS Margin. Upper right: location of SCS in the SE Asia plate tectonic setting. The black rectangle is the area shown in (a). (a) The South China Sea and its main sedimentary basins and structures. The black rectangle corresponds to the NE SCS and is the area shown in (b). (b) Close-up on the NE SCS and the adjacent PRMM and Taiwan orogen. Cenozoic rift basins and faults are according to [Rodrigues de Vargas et al. \(2024\)](#) and references therein. Updated COB of the NE SCS based on [Mohn et al. \(2022\)](#) and [Zhang et al. \(2024\)](#). Magnetic isochrons are from [Briaies et al. \(1993\)](#) with a revised chron age adjusted according to [Sibuet et al. \(2016\)](#). Taiwan's tectonic domains and main structures are according to [Lin and Chen \(2016\)](#) and [Zhang et al. \(2020\)](#). Abbreviations: AP: Australia Plate; EP: Eurasia Plate; IP: India Plate; PP: Philippine Plate; SP: Sundra Plate; YP: Yangtze Plate; AFZ: A Fault Zone; BFZ: Boundary Fault Zone; ChFZ: Chukou Fault Zone; LFZ: Lishan Fault Zone; LVFZ: Longitudinal Valley Fault Zone. CH: Central High; NRS: Northern Rift System; SRS: Southern Rift System; TB: Tainan Basin.

- (iii) an assessment of the control of Late Cretaceous paleogeographic settings on the subsequent Cenozoic rifting.
- (iv) a synthesis of the pre-, syn-, and post-rift tectonostratigraphic units and their associated structures and interpretation of the infilling processes and depositional environments of the margin since the Late Cretaceous.
- (v) a comparative framework highlighting the first-order similarities and contrasts between the NE SCS and the PRMM.

Our results suggest that first-order tectonic events can be correlated across the SCS and illustrate the role of pre-rift structural inheritance, magnitude of accommodation, and proximity/magnitude of source areas on the evolution of this marginal rifted margin.

2. Review of data

2.1. Seismic reflection data

We combined 87 open-access seismic reflection profiles from eight surveys (covering over 15,000 km-line). The seismic reflection dataset includes surveys RC2006 (three lines) (Hayes, 2011a), RC2612 (23 lines) (Hayes, 2015), V3608 (five lines) (Talwani, 2015), V3613 (eight lines) (Hayes, 2011b), V3614 (nine lines) (Leyden, 2015), EW9509 (seven lines) (Reed, 1995), MGL0905 (22 lines) (Liu et al., 2018a), and MGL0908 (10 lines) (McIntosh et al., 2017) (Fig. 2a). Seismic polarity follows the American system.

2.2. Well log data

Well logs were used for horizon mapping and to guide age calibration

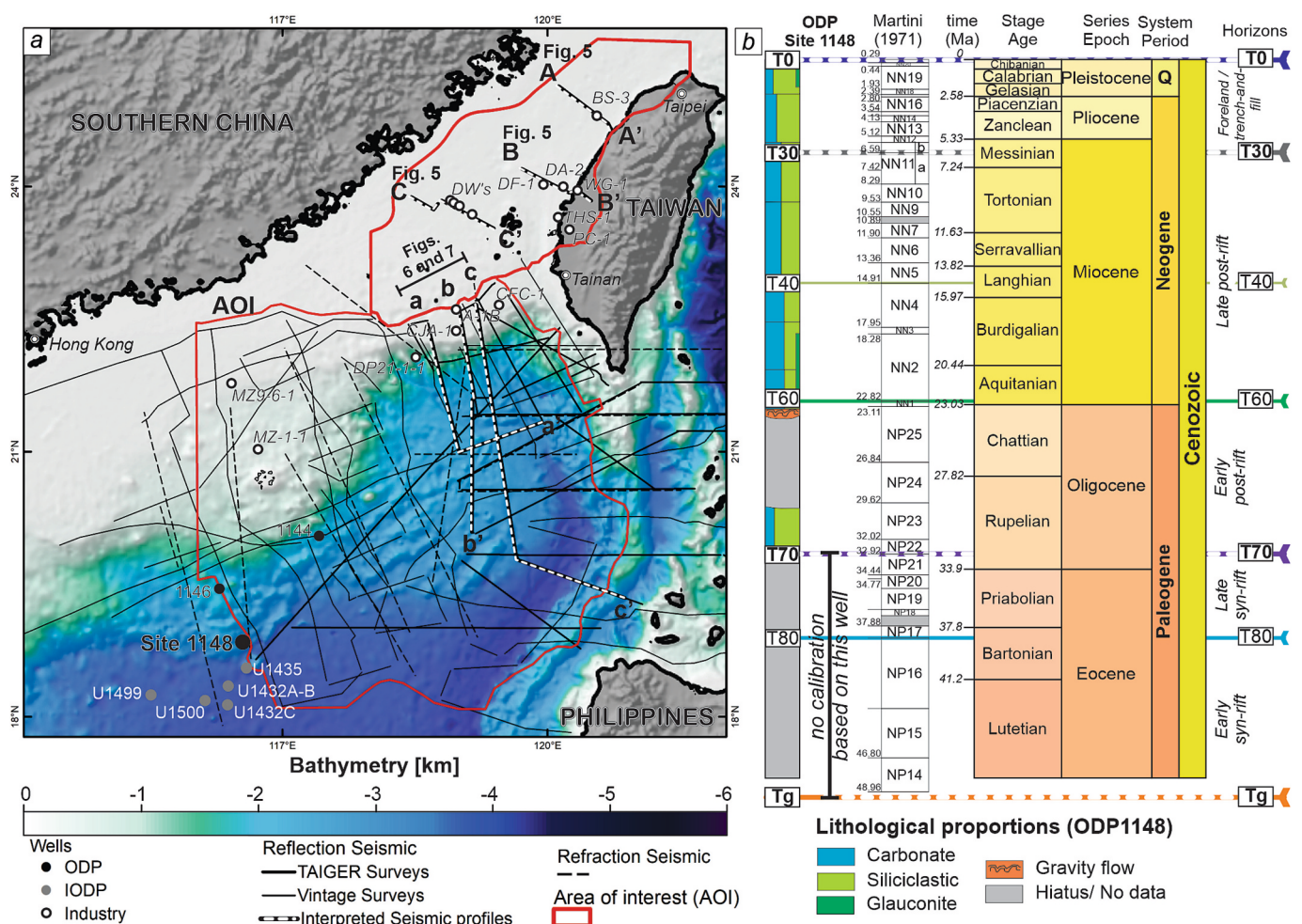


Fig. 2. Dataset used in this study. (a) Location of seismic and well log data used in this study. AOI: Area of interest. Interpreted seismic profiles A-A', B-B', and C-C' are located in Fig. 5. Interpreted seismic profiles a-a', b-b', and c-c' are located in Fig. 6 and Fig. 7. (b) Calibrated biozones and horizons used in this study. Nannofossil biostratigraphy follows [Martini \(1971\)](#). The lithostratigraphy column is from ODP site 1148 (after [Wang et al., 2000](#)) and shows the proportion of carbonate (blue) over siliceous rocks (yellow). Glauconite is present in dark green intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of seismic reflection data, including both open and published industry datasets. Open data well logs correspond to IODP Expedition 349 (i.e., U1432, U1435) (Li et al., 2015a), 367/368 (Larsen et al., 2018b), and ODP Leg 184 (i.e., 1144, 1146, and 1148) (Fig. 2a) (Wang et al., 2000). Industry well data from Penghu, Nanjihtao, and Taihsi basins are DW-1, DW-3, DW-4, DW-5, DF-1, DA-2, WG-1, and BS-3 (Fig. 2a) (Lin et al., 2003). For the Penghu-Peikang basement Highs, wells THS-1, WG-1 (Yang et al., 2006), and PC-1 were used (Fig. 2a) (Huang et al., 2013). In the Tainan Basin, we also included the A-1B and CFC-1 wells (Fig. 2a) (Ding et al., 2008). The Central High stratigraphy is derived from the CJA-1 (Ding et al., 2008) and DP21-1-1 wells (Fig. 2a) (Morley, 2016; Zhang et al., 2019). In the PRMM, information on Mesozoic stratigraphy is derived from wells LF-35-1-1 (Fan et al., 2022), and MZ9-6-1 (Fig. 2a) (Fan et al., 2022, and references therein).

2.3. Horizon mapping

The nomenclature we use to define seismic horizons follows the scheme widely used in the Northern South China Sea (e.g., Dai et al., 2015). These horizons bound key tectonostratigraphic units of the NE SCS rifted margin's geodynamic evolution. First-order horizons, from oldest to youngest, are: Tg (top basement), T70 (top of syn-rift/onset of post-rift), T30 (top of post-rift/onset of foreland), and T0 (top of foreland/trench-and-fill/seabed) (Fig. 2b). Second-order horizons include T80 (top of early syn-rift), T60 (end of early post-rift/onset of late post-rift), T40 (maximum transgressive surface within the post-rift) (Fig. 2b) (e.g., Dai et al., 2015).

These horizons were correlated to Martini's (1971) Paleogene to Neogene nannofossil zonation using available well data (Li et al., 2015b; Su et al., 2006). The biozonation scheme was imported as well tops and calibrated using our seismic reflection data. Seismic horizon T80 (top of early syn-rift) corresponds to the biozone NP16 (Late Eocene); T70 (top of syn-rift) to the base of biozone NP22 (Early Oligocene); T60 (top early post-rift) to the base of biozone NN2 (earliest Miocene); T40 between the boundary of NN4/NN5 (Middle Miocene) and T30 to the base of biozone NN11b (latest Miocene) (Fig. 2b). Well tops were integrated into horizons mapped from seismic reflection data and corresponding to major seismic facies changes. The analysis of seismic sequences in the distal margin relies on seismic facies interpretation (Xu and Haq, 2022) and horizon extrapolation. Elevation maps and sedimentary thickness maps (in depth) are available, respectively, in Supplementary Materials 1 and 2.

2.4. Seismic refraction data and time-to-depth horizon conversion

P-wave velocity information from 12 seismic refraction profiles was compiled to build the velocity volume used to depth-convert the seismic horizons picked in the time domain. The refraction profiles used for this time-depth conversion are the OBS1993 (Yeh et al., 1998), line 29–33 (McIntosh et al., 2005), OBS2001 (Wang et al., 2006), OBS2006–3 (Wei et al., 2011), MGL0905–27 (Lester et al., 2013), OBST1 and OBST2 (Eakin et al., 2014), OBST3 (Lester et al., 2014), OBS2012 (Wan et al., 2017), OBS2015–2 (S. Liu et al., 2018), OBS2016–2 (Wan et al., 2019), OBS2019 (Liu et al., 2021) (Fig. 2a).

The building of the velocity volume uses the seabed and base Cenozoic (Tg) as bounding surfaces. The velocity of seawater is considered constant at 1500 m/s. Below the seabed, the P-wave velocities from refraction profiles were interpolated using the moving average. The depth-converted seismic pick of the seabed was combined with open-source topographic and bathymetric data (Tozer et al., 2019). Depth-converted surfaces of Tg, T70, and T30, as interpreted in this study, were respectively merged with the depth to the base syn-rift, top syn-rift, and onset of foreland surfaces mapped by Lin et al. (2003) for the Northern Rift System. The depth-converted surfaces were quality-controlled by comparison with a series of depth-converted reflection seismic profiles available from the TAIGER survey (C.-S. Liu et al.,

2018).

2.5. Crustal thickness from gravity inversion

Crustal thickness variations have been determined using a gravity inversion scheme at the scale of the whole SCS (Gozzard et al., 2018) and more recently at the scale of the NE SCS rifted margin (Fig. 3a) (Rodrigues de Vargas et al., 2024). These data are available in Supplementary Material 3.

The gravity inversion calculates the mantle residual gravity anomaly using satellite-derived free-air gravity anomaly data (Sandwell et al., 2014), bathymetry (Tozer et al., 2019), sediment thickness, and ocean age (Barckhausen and Roeser, 2004; Barckhausen et al., 2014). Our sediment thickness compilation merges results from depth-converted seismic interpretations (inside AOI) (Lin et al., 2003) and public domain data (outside AOI) (Divins, 2003). The gravity inversion technique includes a correction for the lithospheric thermal gravity anomaly and a parameterization for magmatic additions (Alvey et al., 2008; Chappell and Kusznir, 2008; Gozzard et al., 2019; Greenhalgh and Kusznir, 2007). A rifting/break-up age of 33 Ma is assumed based on the age interpretation of the C11 magnetic anomaly (Briais et al., 1993; Sibuet et al., 2016). A maximum decompression melt thickness of 7 km is also assumed, which is consistent with the observed normal thickness of oceanic crust in the area (Li et al., 2014).

3. Crustal structure of the NE SCS margin

The results of the gravity inversion, as presented in Rodrigues de Vargas et al. (2024), confirm the heterogeneous crustal architecture of the NE SCS rifted margin (Fig. 3a and b), which was previously mostly imaged through 2D seismic refraction profiles (Eakin et al., 2014; Lester et al., 2013, 2014; Liu et al., 2021, 2023; McIntosh et al., 2005; Wan et al., 2017). These different crustal domains reflect varying degrees of crustal thinning that occurred during rifting, with comparable domains identified in other rifted margins worldwide (e.g., Nirrengarten et al., 2020; Nonn et al., 2017; Peron-Pinvidic et al., 2013; Sutra et al., 2013; Tugend et al., 2014). The mapping of structural rift domains generally relies on the identification of characteristic elements such as crustal thickness, structural style, syn- to post-rift accommodation, and the geometry of the sedimentary infilling (Peron-Pinvidic et al., 2013; Tugend et al., 2015). Distinct crustal domains of the NE SCS rifted margin are hereafter defined and include: (i) **proximal domain** (Northern Rift System and bounding structural highs); (ii) **necking zone** (Tainan Basin, Central High, and northernmost part of the Southern Rift System); (iii) **distal domain** encompassing most of the Southern Rift System and the Southern High (including a continent-ocean transition; COT), and (iv) **oceanic domain** (Fig. 3b). The identification of the different rift domains was originally based on observations from the remnants of the Alpine Tethys and Iberia–Newfoundland magma-poor rifted margins (Péron-Pinvidic and Manatschal, 2009). However, this conceptual framework has since been widely applied to other rifted margins with different tectono-magmatic evolutions, including magma-rich and marginal-sea settings (e.g., Nirrengarten et al., 2020; Peron-Pinvidic et al., 2013; Sapin et al., 2021; Tugend et al., 2015). The crustal structure of the NE SCS margin fits well within this classification, exhibiting a distinct variation in crustal thickness between the proximal and distal domains, separated by a well-defined necking zone.

3.1. The Northern Rift System: Proximal Domain

The northern part of the NE SCS rifted margin is characterized by an average crustal thickness exceeding 30 km (Fig. 3a and Fig. 4) (Gozzard et al., 2019; Rodrigues de Vargas et al., 2024). Local crustal thinning coincides with Nanjihtao, Taihsi, and Penghu basins of the Northern Rift System, where syn-rift sequences have been previously identified (Fig. 3a, Fig. 4a and Fig. 5) (e.g., Hsiao et al., 1991). In the Taihsi and

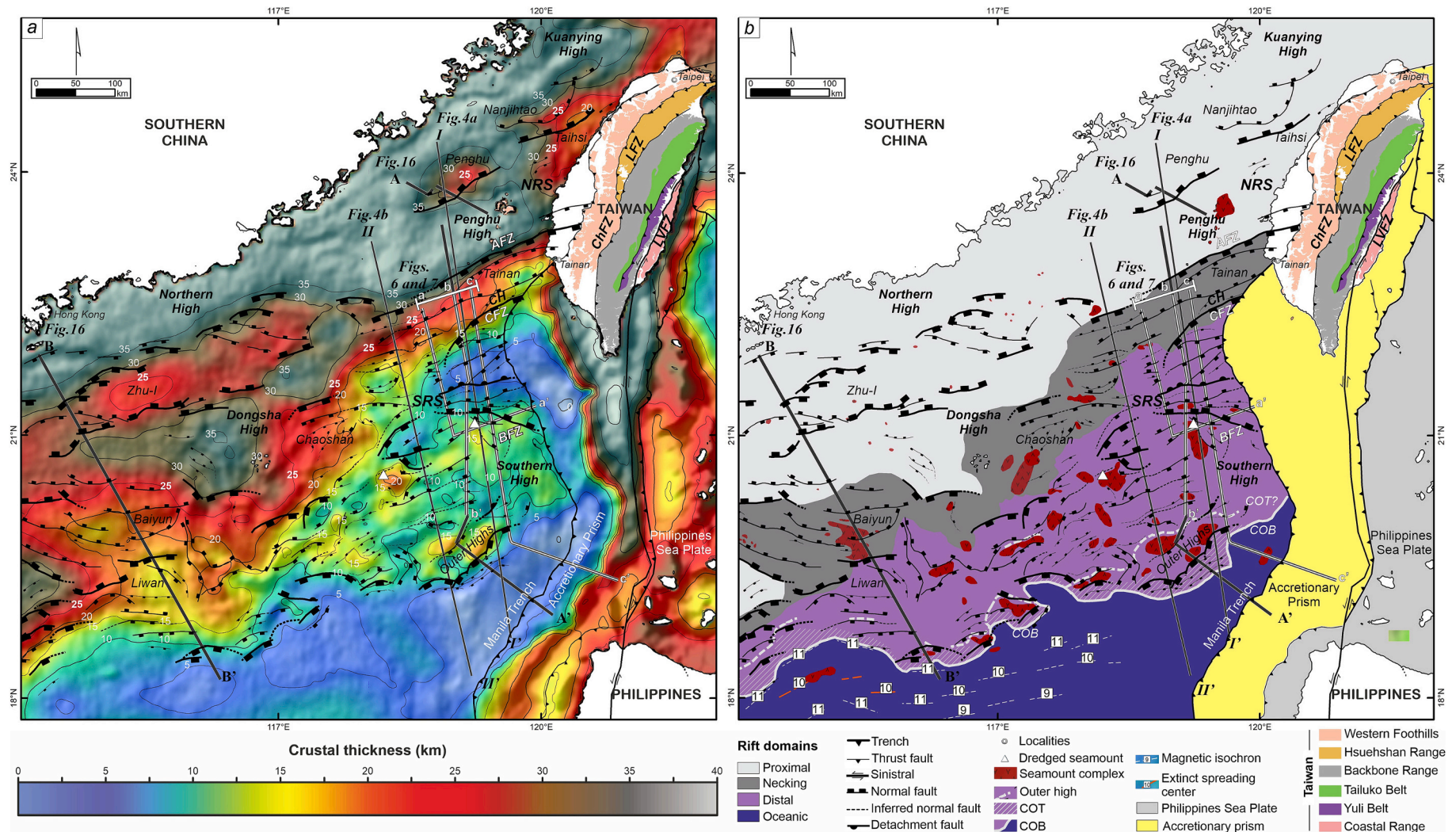


Fig. 3. The crust of the NE SCS. (a) Crustal thickness map from gravity inversion (more information in Rodrigues de Vargas et al., 2024) and its main mapped structures. Structures located in the PRMM are modified from Lei et al. (2018), Mi et al. (2023), and Xie et al. (2019). (b) Map of the rift domains of the NE SCS. Seamounts are revised from Rodrigues de Vargas et al. (2024) and Fan et al. (2017). The Cenozoic accretionary prism is modified from Pubellier et al. (2017). Taiwan's tectonic domains and main structures are according to Lin and Chen (2016) and Zhang et al. (2020). Magnetic isochrons are from Braies et al. (1993) with a revised chron age adjusted according to Sibuet et al. (2016). Updated COB of the NE SCS based on Mohn et al. (2022) and Zhang et al. (2024). NW-SE Crustal transects I-I' and II-II' are shown in Fig. 4. Composite seismic transects are shown in Figs. 6 and 7. NW-SE regional transects A-A' and B-B' are shown in Fig. 16. NRS: Northern Rift System. SRS: Southern Rift System. AFZ: A Fault Zone; BFZ: Boundary Fault Zone; CFZ: Central High Fault Zone; ChFZ: Chuzou Fault Zone. LFZ: Lushan Fault Zone. LVFZ: Longitudinal Valley Fault Zone.

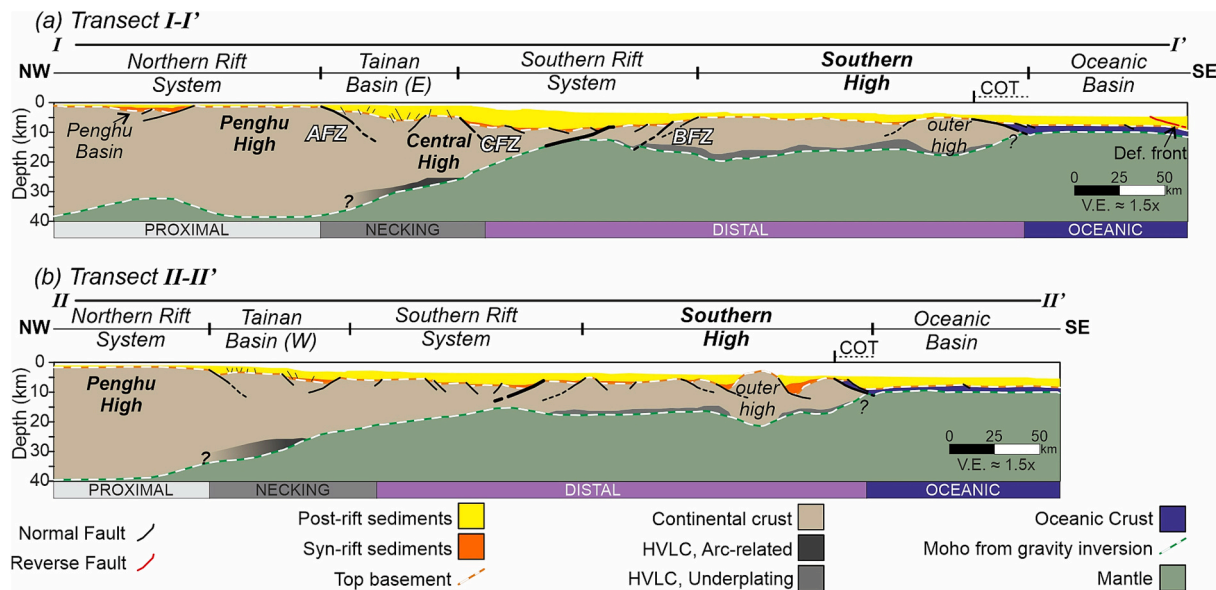


Fig. 4. NW-SE-oriented crustal transects along the NE SCS. (a) Transect I-I' of the central part of the NE SCS. (b) Transect II-II' of the east part of the NE SCS. Bathymetry, basin and basement morphologies, high-velocity lower crust layer, and Moho depth are according to Rodrigues de Vargas et al. (2024) and this work. Vertical exaggeration is 1.5:1. For the location of profiles, please check Fig. 3.

Nanjihtao basins, crustal thicknesses locally drop further to 20 km near Taiwan's onshore region (Fig. 3a, Fig. 4a, and Fig. 5a and b). To the east, some of the Taihsi and Nanjihtao basins are integrated into the northern part of the Western Foothills fold-and-thrust belt, onshore Taiwan (Fig. 3) (Brown et al., 2017; Byrne et al., 2011; Conand et al., 2020; Ho, 1982). In the Penghu Basin, crustal thicknesses can reach 25 km (Fig. 3a) (Gozzard et al., 2019; Rodrigues de Vargas et al., 2024). These isolated rift basins of the Northern Rift System are delimited by the structural highs of Kuanyin to the north and Penghu-Peikang to the south (Fig. 3 and Fig. 4) (Lin et al., 2021).

This crustal domain, with an average thickness exceeding 30 km and localized thinning in isolated rift basins, fits well with the **proximal domain** of a rifted margin (Fig. 3, and Fig. 4) (Peron-Pinvidic et al., 2013; Sapin et al., 2021; Tugend et al., 2015). This domain is bounded to the south by a large-offset normal fault, named the *A fault zone* (AFZ) (also called Yichu Fault) (Sun, 1985), separating the Penghu-Peikang High (north) from the Tainan Basin (south) (Fig. 3, and Fig. 4).

3.2. Tainan Basin and Central High: Necking domain

South of the AFZ, gravity inversion results indicate the onset of an abrupt crustal thinning under the Tainan Basin and Central High (Fig. 3a and Fig. 4) (Gozzard et al., 2019; Rodrigues de Vargas et al., 2024). Crustal thickness derived from gravity inversion ranges from approximately 30 to 35 km north of the AFZ, to 20 to 15 km in the northern part of the Southern Rift System (Fig. 3a and Fig. 4). This tapering of the continental crust occurs over a distance of ca. 80 km from NW to SE and is corroborated by refraction seismic data (Lester et al., 2014; McIntosh et al., 2014; Wan et al., 2017). Refraction seismic data in the western part of Tainan Basin and Central High show the presence of a high-velocity lower crust layer (2 to 10 km thick), interpreted as related to arc-related magmatism generated during the Mesozoic Paleo-Pacific subduction (Wan et al., 2017). The joint analysis of reflection seismic and gravity data additionally suggests the extension of a dense material further east, which is interpreted as corresponding to this high-velocity layer (Rodrigues de Vargas et al., 2024). The easternmost parts of the Tainan Basin and Central High are now incorporated into the southern part of the Western Foothills fold-and-thrust belt (Fig. 3) (Brown et al., 2017, 2022).

The observed abrupt localized crustal thinning is characteristic of the

necking domain (Fig. 3b and Fig. 4) (Peron-Pinvidic, 2022; Peron-Pinvidic et al., 2013; Sapin et al., 2021; Tugend et al., 2015). In the NE SCS rifted margin, the AFZ is interpreted to mark the landward limit of the necking domain (necking line in Nirrengarten et al., 2018; Sapin et al., 2021). The seaward limit of the necking domain has previously been defined as a zone where complete crustal embrittlement is reached so that normal faulting can reach or offset the Moho (Peron-Pinvidic, 2022; Peron-Pinvidic et al., 2013; Sapin et al., 2021). Such a criterion is not applicable in the area due to the resolution of available seismic reflection data (Fig. 6). Instead, the southern boundary of the necking domain is mapped a few kilometers south of the Central High Fault Zone breakaway, where an inflection of the top basement and seismic Moho (in time and depth) coincides (Fig. 3 and Figs. 6,7). This criterion generally coincides with a ca. 15 km thick crust isoline, which is used as a proxy in the absence of direct seismic observations to map the seaward termination of the necking domain (Fig. 3) as previously done in the adjacent PRMM by Nirrengarten et al. (2020) (i.e., seaward termination of their thinned domain).

3.3. Southern Rift System and Southern High: Distal domain

Between the necking and the oceanic domain lies the **distal domain** (Peron-Pinvidic et al., 2013; Tugend et al., 2015) of the NE SCS (Fig. 3b and Fig. 4). The distal domain of the NE SCS rifted margin is wide (ca. 300 km along-dip) and shows contrasted crustal thicknesses, including hyper-thinned (i.e., <10 km thick) to thin crust (i.e., between 15 and 10 km thick) (Fig. 3a), respectively corresponding to the Southern Rift System and the Southern High (Rodrigues de Vargas et al., 2024).

3.3.1. Southern Rift System

The Southern Rift System is located directly south of the necking domain and characterized by highly thinned continental crust (i.e., < 10 km thick crust) (Fig. 3a and Fig. 4). The maximum crustal thinning (<5 km thick crust) defines the NE-SW trend of an aborted rift axis (Fig. 3a and Figs. 6,7). This structural trend is also identified in the Northern Rift System (Fig. 3a) and the adjacent PRMM (Lei et al., 2019, 2020; Lin et al., 2003; Sun et al., 2020; Wu, 1985; Jinmin, 1988). Mantle exhumation is neither confirmed by the analysis of seismic refraction data (Eakin et al., 2014; Lester et al., 2014; Liu et al., 2021, 2023; Wan et al., 2017) nor by the gravity inversion results (Gozzard et al., 2019;

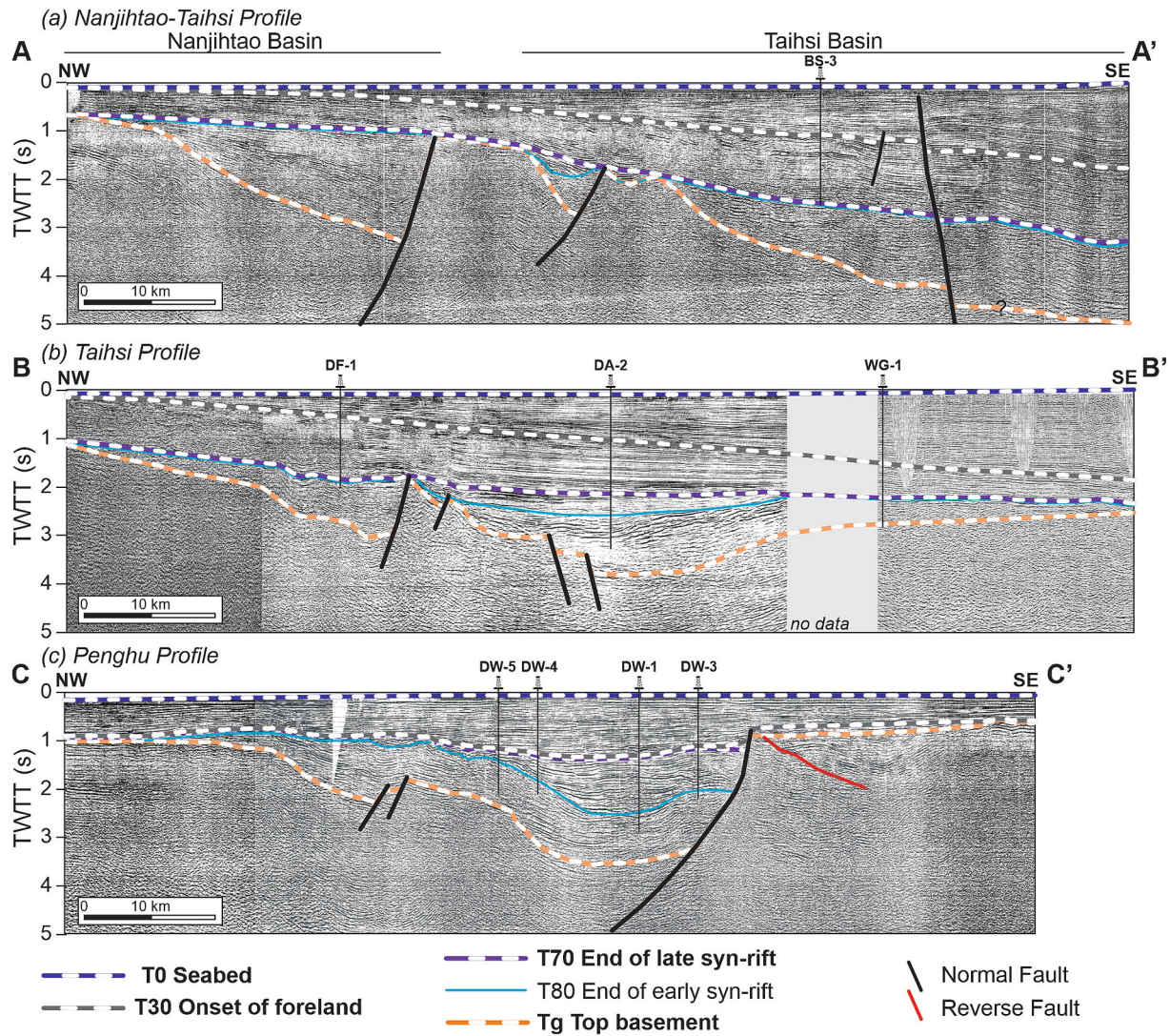


Fig. 5. Reflection seismic examples in the time domain (TWTT) illustrating along-dip variations in crustal architecture, and Cenozoic infilling of the main horizons of the NE South China Sea proximal domain. (a) NW-SE dip-oriented transect along Nanjihtao and Taihsi. (b) NW-SE dip-oriented transect along Taihsi Basin. (c) NW-SE dip-oriented transect along Penghu Basin. The structures and horizons (well-seismic calibrated) are modified from Lin et al. (2003). For the location of profiles, please check Fig. 2.

Rodrigues de Vargas et al., 2024). Nevertheless, given the extreme crustal thinning recorded, local mantle exhumation at the seafloor may have occurred, although not captured within our seismic grid. South of the rift-axis and toward the Boundary Fault Zone (BFZ), the crust thickens again, reaching values from ca. 10 to ca. 15 km thick (Fig. 3a and Fig. 4).

Previous refraction studies (OBS2012, OBS2019-1, and OBS-T3) (Eakin et al., 2014; Lester et al., 2014; Liu et al., 2021, 2023; Wan et al., 2017) show significant velocity variations within the continental basement of the Southern Rift System. North of the rift axis, velocities ranging from 3.5 to 5.5 km/s were interpreted as highly compacted pre-rift sedimentary rocks, probably corresponding to Mesozoic (meta) sedimentary rocks (Eakin et al., 2014; Liu et al., 2021; Wan et al., 2017). In the lower part of the crust, seismic refraction data show the presence of a ca. 3 km thick high-velocity layer (7 to 7.6 km/s) that pinches out toward the rift axis to the south (Fig. 4b, and c, Fig. 6b and c, Fig. 7b, and c) (Wan et al., 2017). At the rift axis, the Moho signal from seismic refraction data is locally absent, which was interpreted as evidence for mantle serpentinization beneath thin crust (Liu et al., 2021). Both the Moho signal and a ca. 3 km thick high-velocity lower crust (7 to 7.5 km/s), extending beneath the Southern High, are identified again in seismic refraction data south of the rift axis (Fig. 4b, and c, Fig. 6b and c, Fig. 7b,

and c).

3.3.2. Southern High

South of the BFZ, crustal thicknesses determined from gravity inversion range between 8 and 15 km (Fig. 3a) (Gozzard et al., 2019; Rodrigues de Vargas et al., 2024). Crustal thickness generally exceeds 10 km and is locally up to 15 km thick, where seamount complexes are observed in reflection seismic data (Fig. 3). Some of these seamounts or basement highs are frequent close to the transition with the oceanic domain and morphologically referred to as *outer highs* (Fig. 3b and Fig. 4). The Southern High is involved in the Manila subduction to the east (Fig. 3); up to 200 km might have been subducted as inferred from tomography and seismological data (Bautista et al., 2001; Fan et al., 2016).

Refraction seismic data over the Southern High show a thin upper layer characterized by velocities of 3.5 to 5 km/s, which is interpreted as fractured/weathered volcanic rocks or syn-rift sedimentary rocks over basement (velocities >5 km/s) (Eakin et al., 2014; Lester et al., 2014). The presence of volcanic rocks over part of the Southern High is also supported by reflection seismic data (Figs. 6, 7) (Eakin et al., 2014; Lester et al., 2014; Rodrigues de Vargas et al., 2024; Sibuet et al., 2016;

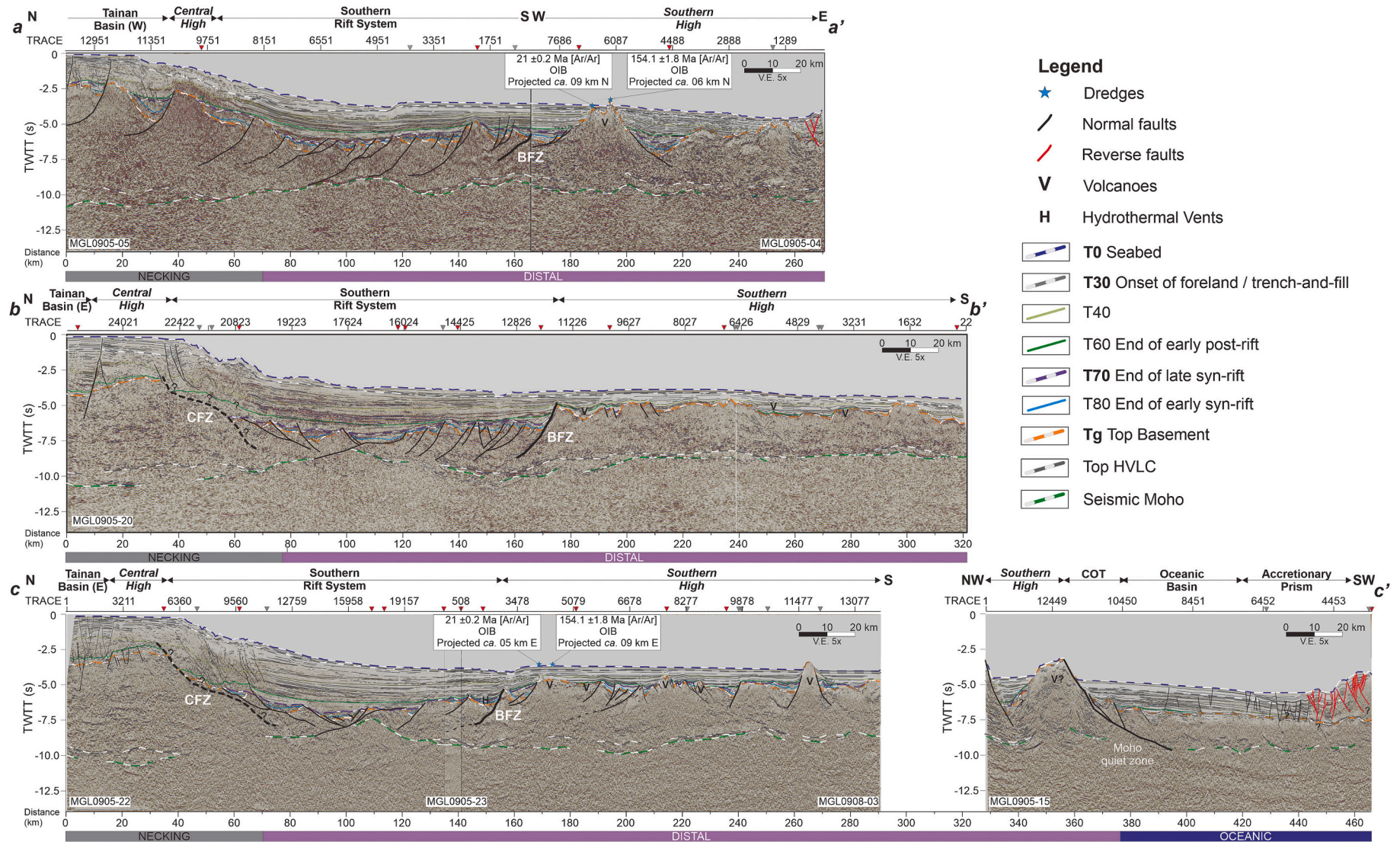


Fig. 6. Reflection seismic examples in the time domain (TWTT) illustrate the crustal architecture and along-dip variations of the main horizons of the NE South China Sea's necking, distal, and oceanic domains. (a-a') Composite section of seismic lines 0905-05 (N-S) and 0905-04 (W-E). (b-b') Along-dip seismic line 0905-20 (N-S). (c-c') Composite section of seismic lines 0905-22 (N-S), 0905-23 (E-W), 0905-03 (W-E), and 0905-15 (NW-SE). For the location of profiles, please check Fig. 2 and Fig. 3. Black rectangles are shown in Fig. 12 and Fig. 13. Images of corresponding uninterpreted seismic profiles are provided in Supplementary Material 4.

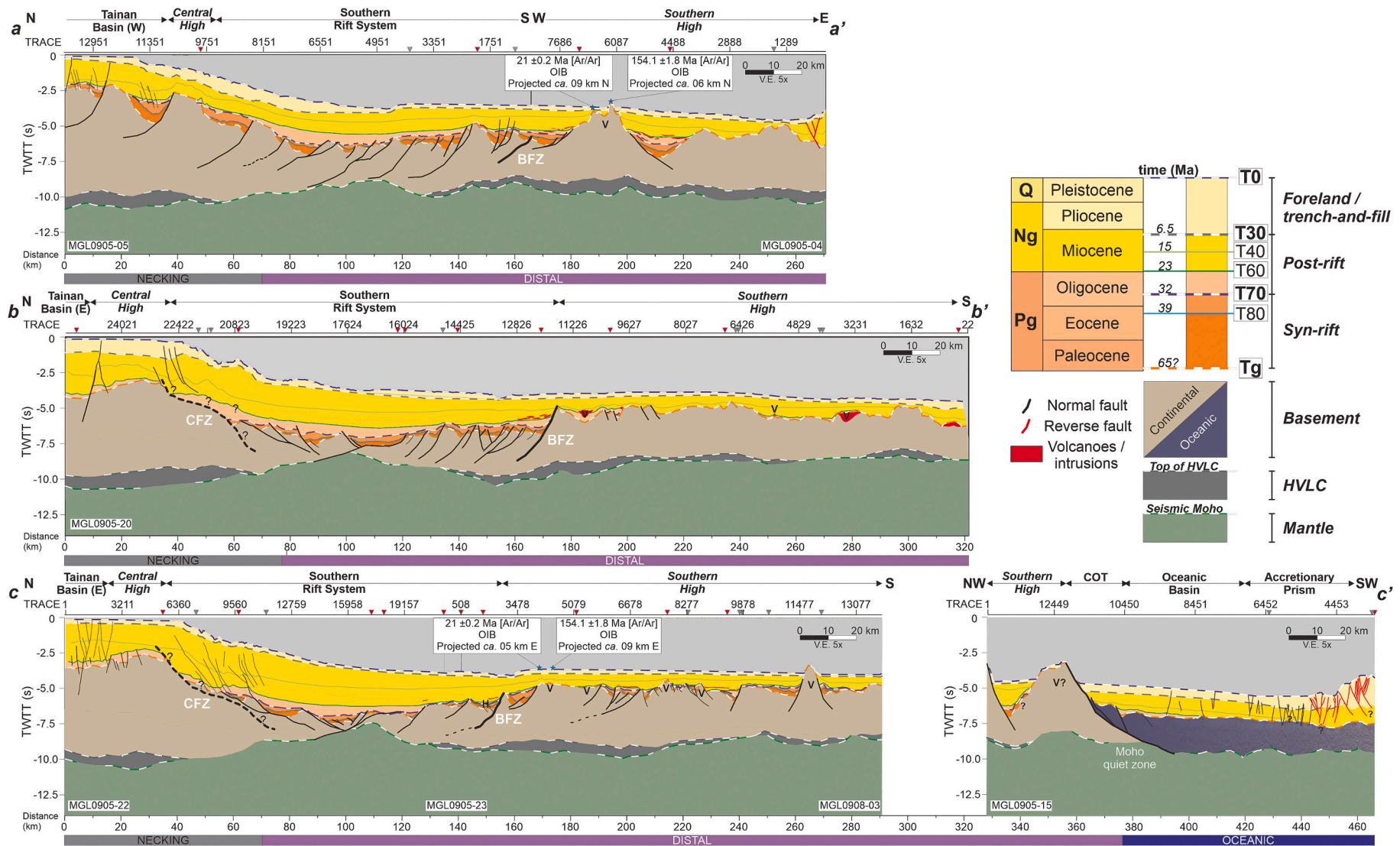


Fig. 7. Interpreted reflection seismic examples in the time domain (TWTT), illustrating the crustal architecture and along-dip variations of the NE SCS. (a-a') Composite section of seismic lines 0905-05 (N-S) and 0905-04 (W-E). (b-b') Along-dip seismic line 0905-20 (N-S). (c-c') Composite section of seismic lines 0905-22 (N-S), 0905-23 (E-W), 0905-03 (W-E), and 0905-15 (NW-SE). For the location of profiles, please check Fig. 2 and Fig. 3. Images of corresponding uninterpreted seismic profiles are provided in Supplementary Material 4.

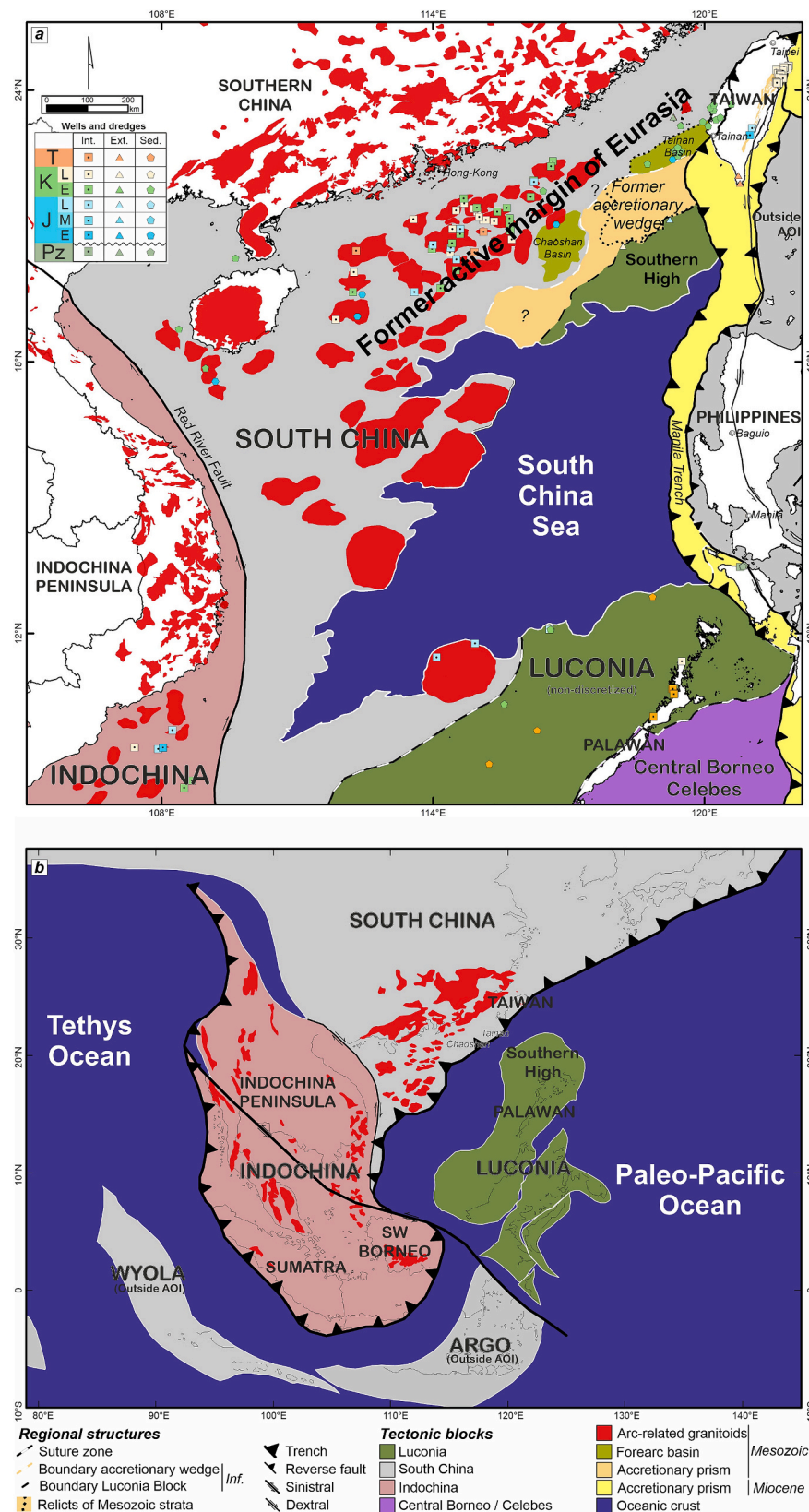


Fig. 8. The pre-Cenozoic (basement) blocks of the NE SCS Margin. (a) The present-day setting, modified from [Sautter and Pubellier \(2022\)](#). (b) Reconstruction model of SW Asia for the early Late Cretaceous, modified from [Pubellier and Sautter \(2022\)](#). Jurassic-Cretaceous rocks from Taiwan in (a) are according to [Lin and Chen \(2016\)](#) and [Chen et al. \(2017\)](#). Magnetic isochrons are from [Briais et al. \(1993\)](#) with a revised chron age adjusted according to [Sibuet et al. \(2016\)](#). Updated COB of the NE SCS based on [Mohn et al. \(2022\)](#) and [Zhang et al. \(2024\)](#). Basement data from wells, dredges, and outcrops are according to [Chen et al. \(2016\)](#), [Suggate et al. \(2014\)](#), [Knittel \(2011\)](#), [Knittel et al. \(2010\)](#), [Yui et al. \(2009\)](#), [Lan et al. \(2008\)](#), [Kudrass et al. \(1986\)](#) and references therein. Granitoid bodies are modified from [Pubellier et al. \(2017\)](#).

Yeh et al., 2010, 2012). The top basement is flat or irregular, rising at the location of seamounts, some of which are unambiguous volcanoes (Figs. 6, 7) (Lester et al., 2014; Liu et al., 2021; Rodrigues de Vargas et al., 2024). Stratiform geometries within the crust, which may correspond to pre- and syn-rift sequences, are punctual (Figs. 6, 7). The lack of pre- and syn-rift sequences could be due to signal obliteration caused by syn- and post-rift magmatic additions (Lester et al., 2014). Refraction seismic data show the presence of a discontinuous 3 to 5 km thick high-velocity lower crust layer (7 to 7.5 km/s) (Eakin et al., 2014; Lester et al., 2013, 2014), which is consistent with the high average crustal densities determined from the joint analysis of seismic and gravity data (Rodrigues de Vargas et al., 2024). This high-velocity lower crust is interpreted as being composed of gabbroic intrusions related to underplating processes during the post-rift stage (Eakin et al., 2014; Lester et al., 2013, 2014; Liu et al., 2018b; Liu et al., 2021, 2023).

3.4. Oceanic Domain

South of the *outer highs*, W-E and NE-SW lineaments are observed in magnetic data and interpreted as magnetochrons from at least ca. 33 Ma (Briaies et al., 1993; Sibuet et al., 2016). In the crust, a sub-horizontal top acoustic basement reflection is interpreted around 6.5 s TWTT, and rare faulting is observed on seismic reflection data (Fig. 6c,7c). At depth (ca. 9 s TWTT), sub-horizontal and discontinuous quasi-parallel strong reflections have been identified as the Seismic Moho (Fig. 6c,7c). This results in a tabular-shaped architecture that is approximately 2 to 2.5 s TWTT thick (Figs. 6c and 7c), which corresponds to an approximately 5 to 7 km thick crust (Fig. 3a) (Gozzard et al., 2019; Rodrigues de Vargas et al., 2024). Such tabular crust and these crustal thickness values are characteristic of the **oceanic domain** (Fig. 3b) (Sapin et al., 2021).

4. The pre-rift setting

The continental basement of the NE SCS rifted margin, below the Tg horizon, shows diverse lithological associations and geophysical characteristics (Fig. 11).

4.1. Relics of a Mesozoic active continental margin

Available public domain data provide limited constraints on the nature of the continental basement beneath the Northern Rift System. Nevertheless, they support a polyphasic history linked to the Yanshanian Mesozoic magmatic arc developed over the Paleozoic basement of the SCB (Fig. 8) (Chen et al., 2010; Fan et al., 2022; Li et al., 2018a; Lin et al., 2003; Lu et al., 2014; Shi et al., 2011; Xu et al., 2016, 2022). In the Kuanyin High (northern offshore Taiwan) (Fig. 3a), drill cores show deformed Jurassic and Early Cretaceous sedimentary rocks unconformably overlying a metamicrodiorite of SCB affinity (71.5 Ma metamorphic recrystallization age; whole-rock Ar—Ar) (Chen et al., 1997; Lin et al., 2003). In the Penghu-Peikang Basement High, subsurface data record Early Cretaceous (Aptian) to Paleogene volcano-siliciclastic rocks unconformably overlying Permian marbles (Fig. 8) (Huang, 1978; Jahn et al., 1992; Lin et al., 2003, 2021; Teng and Lin, 2004; Yuan et al., 1985). Notably, on Huayu Island (Penghu Archipelago), Paleogene bimodal (dacitic-rhyolitic) arc-related volcanic rocks (ca. 65 to 58 Ma; U—Pb in zircon) contain inherited zircons of Silurian age (437 ± 13 Ma; U—Pb in zircon), which may represent part of the continental core of the area (Fig. 8) (Chen et al., 2010). In the Zhu-I and Baiyun sub-basins (PRMM), drilled Mesozoic arc-related granitoids yield ages from 161.6 to 72 ± 2.8 Ma (Fig. 8) (Fan et al., 2022; Li et al., 2018a). These geological data align with the South China Sea Magnetic Anomaly, a major geophysical feature interpreted as the remnant signal of the Yanshanian Mesozoic magmatic arc (Fig. 8 and Supplementary Material 5) (Chen et al., 2010; Doo et al., 2025; Li et al., 2008; Li and Song, 2012; Li et al., 2018a).

4.2. Relics of the Mesozoic forearc basin and accretionary wedge

In the Tainan Basin and Central High, drilling has recorded the uppermost pre-rift interval, consisting of Jurassic to Cretaceous marine sandstones and mudstones (Fan et al., 2022; Lu et al., 2014). These pre-rift sedimentary rocks are usually Late Cretaceous in the Tainan Basin, but Late Jurassic to Early Cretaceous in the Central High (Lee et al., 1993; Lin et al., 2021). These Mesozoic sequences coincide with parallel seismic reflectors and therefore are interpreted to have been deposited in a forearc setting, based on analogies with the nearby and coeval forearc Chaoshan Depression (Fig. 8a) (Fan et al., 2022; Rodrigues de Vargas et al., 2024).

Further south, the Southern Rift System lacks direct constraints on the pre-rift continental basement. However, near the rift axis, folded reflectors below Tg, with velocities between 3.5 and 5.5 km/s, have been interpreted as deformed Jurassic-Cretaceous pre-rift successions (Lester et al., 2014; Liu et al., 2021, 2023; Reed, 1995). These potential (meta) sedimentary rocks are inferred to be remnants of a Mesozoic accretionary wedge (Sibuet et al., 2002), also observed in the basement of Liwan (PRMM), and the Xingning-Jinghai (NE SCS) sub-basins (Fig. 8a) (Deng et al., 2020; Fan et al., 2022; Wang et al., 2018). Collectively, these data suggest that the Southern Rift System was likely developed along the NE-SW trending Mesozoic accretionary wedge of the SCB active continental margin (Chen et al., 2017; Hall and Breitfeld, 2017; Lo and Yui, 1996; Pubellier and Sautter, 2022; Rodrigues de Vargas et al., 2024).

4.3. The Southern High as a remnant of the Luconia Microcontinent?

Only sparse subsurface data are available to interpret the pre-rift setting of the Southern High, located south of the Southern Rift System. Mesozoic volcanic rocks dredged from the Puyuan and Beipo seamount complexes provide the only direct constraints on the area (Figs. 6,7) (Xu et al., 2022). At Puyuan, a Late Jurassic OIB-type pillow basalt (154.1 ± 1.8 Ma; whole-rock Ar—Ar) shows a geochemical signature cogenetic with that of Pacific oceanic plateaus, interpreted as an early-stage extrusion from a (Paleo)-Pacific mantle plume (Fig. 1 and Fig. 3) (Xu et al., 2022). Further southwest, at Beipo, an E-MORB-type pillow basalt yielded a Late Cretaceous cooling age (93.2 ± 5 Ma; whole-rock Ar—Ar), interpreted as the product of remelted mafic cumulates during slab roll-back of the SE-NW subducting Paleo-Pacific oceanic crust (Fig. 1 and Fig. 3) (Xu et al., 2022).

Crustal velocity profiles from seismic refraction indicate that part of this basement may be continental (Eakin et al., 2014; Lester et al., 2014, 2013; Liu et al., 2018b; Liu et al., 2021, 2023; Rodrigues de Vargas et al., 2024). Joint analyses of seismic and gravity data reveal high average crustal densities beneath the Southern High, which, together with dredged volcanic rocks, suggest a largely intruded continental basement (Rodrigues de Vargas et al., 2024). As a result, the Southern High is interpreted as thin continental crust, at least as old as Jurassic, extensively intruded by multiple magmatic phases linked to the Mesozoic orogen and the Miocene post-rift settings (Eakin et al., 2014; Lester et al., 2013, 2014; Liu et al., 2018b; Liu et al., 2021, 2023; Rodrigues de Vargas et al., 2024; Xu et al., 2022).

The determination of the paleogeographic affinity of this highly intruded crust is crucial to understanding the geodynamic evolution of the Paleo-Pacific subduction beneath the Eurasian active margin, as well as the Yanshanian Orogeny. Previous studies have highlighted similarities in lithology and crustal structure between the Southern High and the reconstructed Luconia Microcontinent (Fig. 8) (Rodrigues de Vargas et al., 2024). Fragments of this microcontinent are mainly preserved along the southern margin of the SCS (Pubellier and Sautter, 2022). These fragments suggest an assemblage of Late-Paleozoic to Late-Cretaceous accretionary wedges surrounding older pieces of continental crust and recycled continental crust (Holloway, 1982; Knittel et al., 2010; Kudrass et al., 1986; Tong et al., 2019). Places that potentially

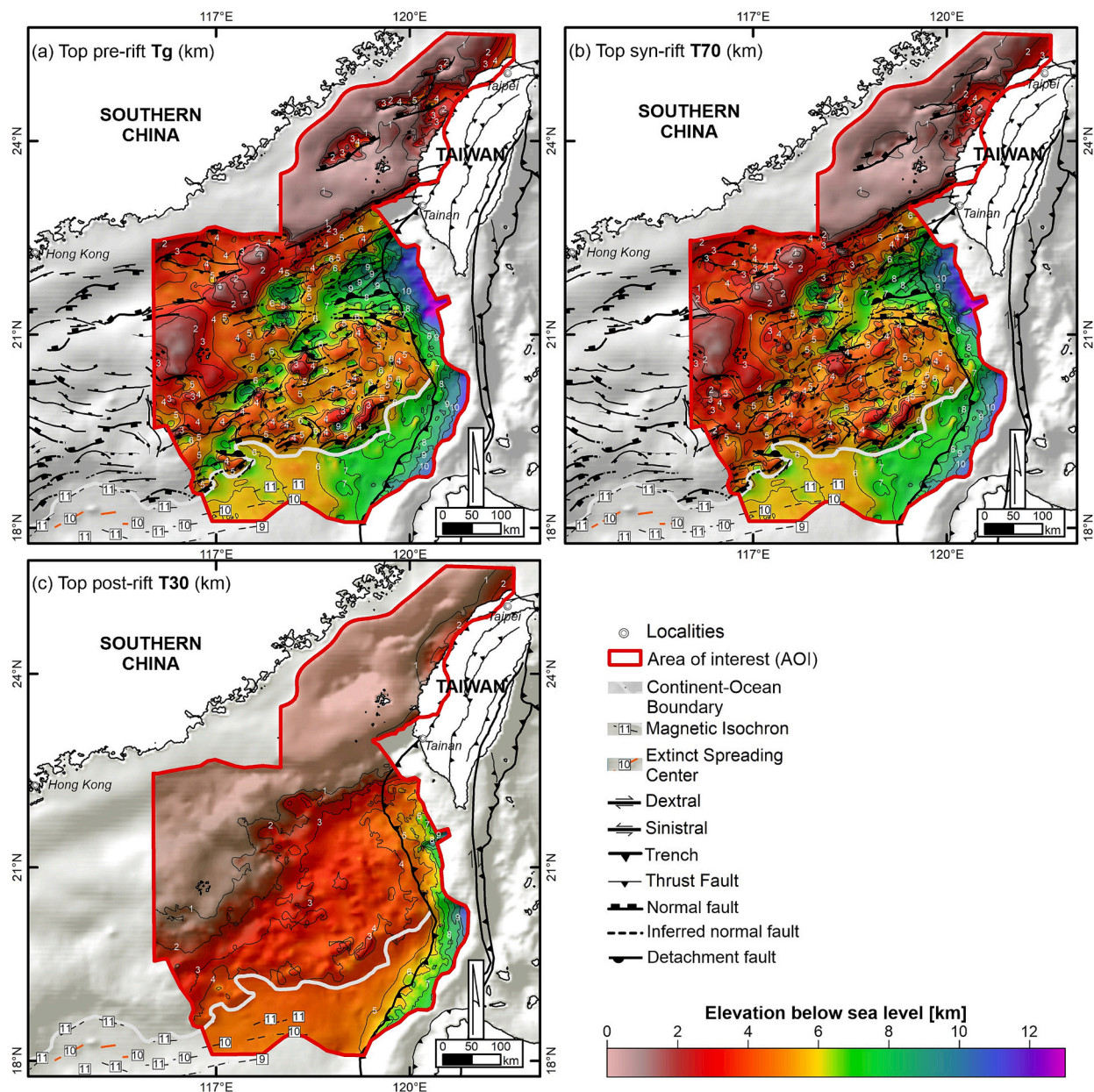


Fig. 9. Elevation (isobaths) maps (km) of the first-order tectonostratigraphic horizons used in this study. (a) Top pre-rift (Tg). (b) Top syn-rift (T70). (c) Top post-rift (T30). Magnetic isochrons are from [Briaes et al. \(1993\)](#) with a revised chron age adjusted according to [Sibuet et al. \(2016\)](#). Updated COB of the NE SCS based on [Mohn et al. \(2022\)](#) and [Zhang et al. \(2024\)](#).

record this block include Java (e.g., [Granath et al., 2011](#)), Natuna (e.g., [Webb et al., 2023](#)), Palawan (e.g., [Dycoco et al., 2021](#)), Dangerous Grounds (e.g., [Taylor and Hayes, 1983](#)), Taiwan (e.g., [Chen et al., 2019](#); [Chou, 1985](#)), and Mindoro (e.g., [Canto et al., 2012](#); [Knittel, 2011](#); [Knittel et al., 2010](#)) (Fig. 8b). The Luconia Microcontinent is thought to have docked with SCB during the Late Cretaceous (ca. 85 Ma) (Fig. 8b) ([Hall and Breitfeld, 2017](#); [Hamilton, 1979](#); [Pubellier and Sautter, 2022](#); [Taylor and Hayes, 1980, 1983](#); [Webb et al., 2023](#)).

5. Syn-rift tectonostratigraphic unit (Tg to T70)

The sedimentary succession between Tg and T70 (Fig. 11) defines the syn-rift record of the NE SCS margin deposited between major fault systems that form half-graben and graben architectures. This tectonostratigraphic unit shows significant thickness variations across the margin (Fig. 10b). It is subdivided into early syn-rift (?Late Paleocene to

Late Eocene, ?NP5 to NP16, ca. 59 to 39 Ma) and late syn-rift sequences (Late Eocene to late Early Oligocene, NP16 to NP22, ca. 39 to 32 Ma), which are separated by the T80 horizon (Fig. 11).

5.1. Isolated rift basins of the proximal domain: The Northern Rift System

Early syn-rift sedimentation in the proximal domain is inferred from well THS-1, which records marine sedimentary rocks potentially younger than the Late Paleocene (zone NP5) filling three isolated half-grabens: the Nanjihtao, Taihsi, and Penghu basins (Fig. 3a, Fig. 4a, Fig. 5) ([Huang and Chi, 1979](#); [Lin et al., 2003](#)). These rift basins are bounded by NE-SW trending continentward-dipping high-angle normal faults with offsets exceeding 3 s (TWTT) (Fig. 4a, Fig. 5) ([Lin and Watts, 2002](#)). Syn-rift deposits are commonly over 2 km thick and locally reach up to 4 km in the main depocenters (Fig. 10b). In the Penghu-Peikang basement high, pre-Tg reflectors (some of them folded and thrust) are

unconformably overlain by post-rift strata (Fig. 5c). The Penghu-Peikang High is bounded to the south by the AFZ, which marks the necking line of the NE SCS. This major seaward-dipping normal fault zone extends over 200 km offshore NE SCS to onshore Taiwan (Fig. 3) (Lin et al., 2003). The AFZ was mainly active during rifting, with offsets exceeding 3 s (TWTT) (Fig. 3) (Lin et al., 2021). This suggests that the

AFZ partly accommodated the crustal thinning documented in the necking zone of the NE SCS (Fig. 3 and Fig. 4).

The early syn-rift sequence (Tg to T80; Late Paleocene to Middle Eocene) consists of marine shales and sandstones, probably deposited under the influence of deltaic systems and expressive along-dip variations of paleodepth (Fig. 5 and Fig. 11) (Hsiao et al., 1991; Huang et al.,

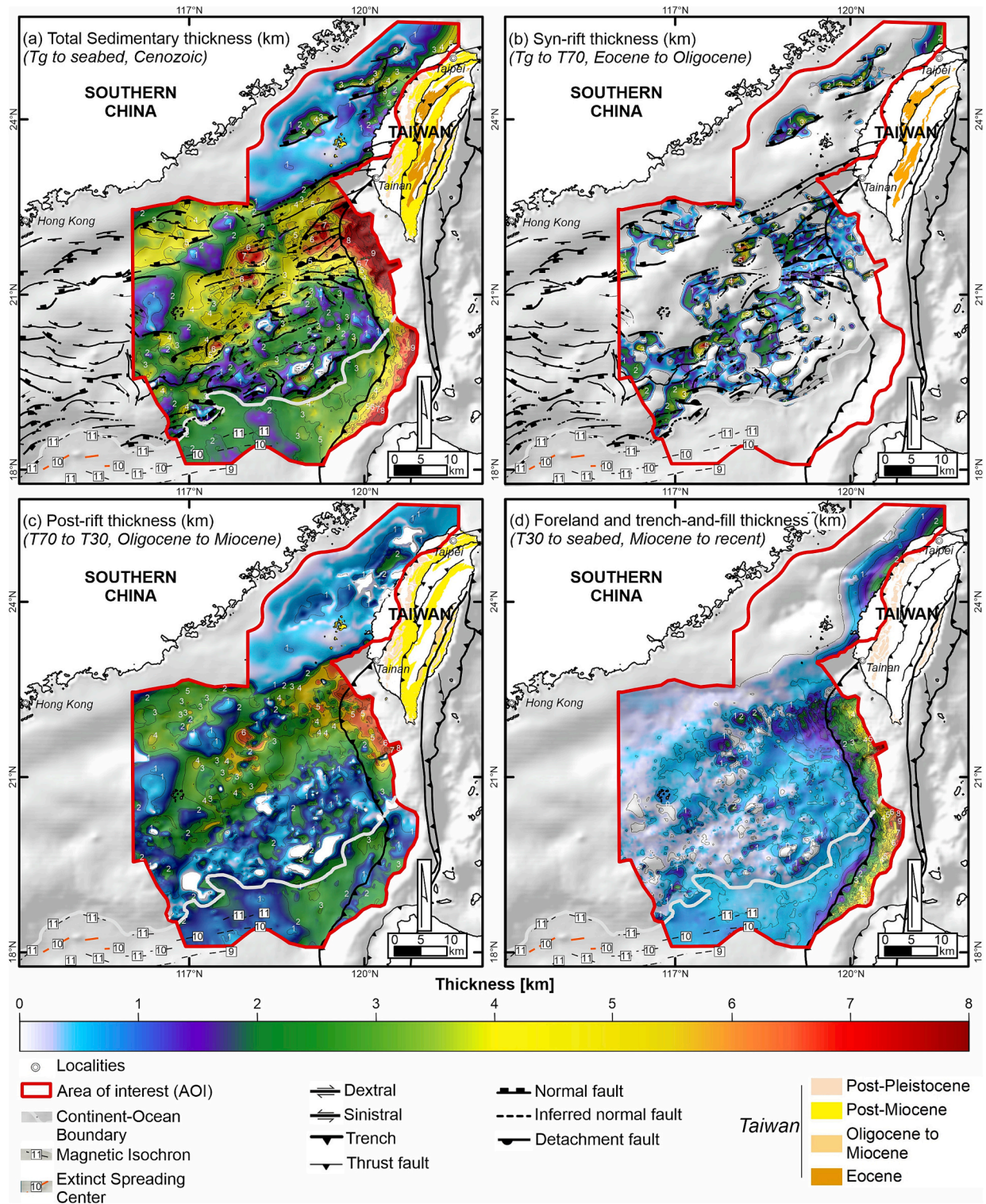


Fig. 10. Thickness maps (km) of each first-order tectonostratigraphic stage of the Northeastern South China margin. (a) Cenozoic total sedimentary thickness (Tg to the seabed). (b) Rift thickness (Tg to T70). (c) Post-rift thickness (T70 to T30). (d) Foreland and trench-and-fill thickness (T30 to the seabed). Geological units from Taiwan are from Lin and Chen (2016). Magnetic isochrons are from Briaies et al. (1993) with a revised chron age adjusted according to Sibuet et al. (2016). Updated COB of the NE SCS based on Mohn et al. (2022) and Zhang et al. (2024).

2017; Sun, 1985; Teng and Lin, 2004). Coeval bimodal volcanism (basalt-dacite) is observed in the vicinity of the Penghu-Peikang High and Taihsi Basin (e.g., well WG-1; 53.5 ± 2.7 Ma; WR Ar—Ar and well PC-1, 44.1 ± 2.2 Ma WR Ar—Ar) (Fig. 11) (Hsiao et al., 1991; Lee et al., 1996; Lin and Watts, 2002; Sun, 1985; Teng and Lin, 2004; Wang et al., 2012a). The early syn-rift sequence is truncated by the regional T80 unconformity (ca. 39 Ma; top NP16) (Fig. 5, Fig. 11). This T80 unconformity is linked to the uplift in the northwestern portions of the proximal rift basins and the Penghu-Peikang High (Lin et al., 2003; Sun, 1985).

The late syn-rift sequence (T80 to T70; Late Eocene to late Early Oligocene) is preserved in the southeastern Penghu and Taihsi basins (Fig. 5b and c) (Lin et al., 2003). Seismic reflectors onlap earlier syn-rift deposits toward the NW and SE paleo-topographic highs, and suggest an overall NE to SW transgression (Fig. 5b and c). No significant changes in depositional environment are observed across the early to late syn-rift transition (Fig. 5b and c) (Lin et al., 2003; Teng and Lin, 2004). The late syn-rift sequence is truncated by the T70 unconformity (late Early Oligocene, base NP22, ca. 32 Ma) (Fig. 5, Fig. 11), which currently lies at ca. 1–2 km below sea level in the west and deepens to ca. 3–4 km toward the deformation front (Fig. 9b).

5.2. Differential erosion over the necking domain: Eastern vs. western Tainan Basin

The syn-rift tectonostratigraphic unit of the Tainan Basin is confined within elongated NE-SW trending sub-basins, bounded by the AFZ to the north and the Central High Fault Zone (CFZ) to the south (Fig. 3a, Fig. 4a, Fig. 9a). The stratigraphic record and structural style vary significantly between the east/central and the west parts of this basin (Figs. 6,7 and Fig. 12a and b).

The easternmost Tainan Basin is exposed onshore in Taiwan, near Tainan town, in the southern part of the Hsuehshan Range (Brown et al., 2022; Sun, 1985). There, deltaic-marine deposits of the Chungliao Formation yield Middle Eocene (NP14/15) and reworked Late Paleocene (NP5/6) nannofossils (Huang et al., 2013). These reworked nannofossils suggest that syn-rift deposition may have begun during the Late Paleocene, coinciding with extensional deformation in the proximal margin. The overlying Middle Eocene Pinglin Tuff (NP16; 38.8 ± 1 Ma U-Pb in zircon; Huang et al., 2013) suggests active volcanism during the early syn-rift of the region, as observed in the proximal margin.

Offshore, the central to eastern Tainan Basin has no diagnostic syn-rift geometries on a seismic scale (Fig. 12b). Although syn-rift architectures are not observed in seismic data, syn-rift sedimentary rocks may be locally present, as suggested by the well C-1, where early post-rift (Late Oligocene) sedimentary rocks overlie a 350 m-thick sterile sandy unit that is possibly equivalent to early syn-rift rocks observed onshore (Huang et al., 2013; Lee et al., 1993; Lin et al., 2003). The apparent absence of preserved syn-rift strata in these offshore areas is attributed to major erosional episodes between the Late Eocene and the latest Oligocene (Fig. 11) (Lin et al., 2003; Sun, 1985). This led to a Tg topography forming the Tainan Basin depocenter, followed by the Central High to the south (Fig. 9b) (Lin et al., 2021). To the south of the Central High, the inferred southward deepening of the top basement is interpreted to be controlled by the CFZ, which is a large-offset oceanward-dipping fault zone (Figs. 3, 6, 7b, and c, and Fig. 9a). This fault zone accommodated extensional deformation in the upper crust and likely contributed to the observed abrupt crustal thinning in the necking zone and the formation of the Southern Rift System (Fig. 3, Fig. 4, and Fig. 6b and c,7b and c).

In contrast, the westernmost Tainan Basin shows a different structural style (Fig. 6,7a and Fig. 12a). The Central High and CFZ are absent (Fig. 3 and Figs. 6, 7). NE-SW trending, continentward-dipping normal faults bound wedge-shaped syn-rift basins (Figs. 6,7a and Fig. 12a) (Ding et al., 2008; Mi et al., 2023). Offsets of these faults exceed 2.5 s (TWTT), forming depocenters that locally record over 2 km of syn-rift

deposits (Fig. 10b). Seismic facies of these wedge-shaped basins (Fig. 12a) resemble those described in the Penghu (NRS) and Panyu (PRMM) (Liang et al., 2023; Lin et al., 2003). Similar seismic facies associations have been interpreted elsewhere as rift basins infilling under the influence of deltaic depositional systems (Hanafi et al., 2022; Li et al., 2018b; Liang et al., 2023; Rapozo et al., 2021; Song et al., 2020). Toward the top of the syn-rift tectonostratigraphic unit, a truncation marks the end of rifting in west Tainan and is interpreted as coeval with the T70 unconformity observed in Penghu and Panyu (Fig. 12a).

5.3. Sediment-starved distal domain: The Southern Rift System and Southern High

5.3.1. The V-shaped Southern Rift System

The syn-rift tectonostratigraphic unit of the Southern Rift System is characterized by thin deposition atop a series of NE-SW short-spaced, fault-controlled wedge-shaped basins (Fig. 9a, Fig. 10b). These basins evolved on a hyper-thinned crust, and were bounded by the CFZ (north) and BFZ (south) (Fig. 3a, Fig. 4, and Figs. 6,7). This rift system also shows, as in the Tainan Basin, significant east-to-west along-strike structural variations (Figs. 6,7 and Fig. 12c and d).

In the west, closely spaced (10–15 km) continentward-dipping normal faults are observed (Fig. 3a, Figs. 6,7a, Fig. 9b). In contrast, the eastern sector shows both continent- and oceanward-dipping normal faults that define a V-shaped rift basin centered on the zone of maximum crustal thinning (Fig. 3a, Fig. 6b and c,7b and c, Fig. 9b) (Eakin et al., 2014; Lester et al., 2014). The rift axis is defined by a large-offset, low-angle detachment fault system dipping toward the continent, with exhumed continental basement in its footwall (Fig. 12d). This fault system likely cuts through the remaining continental crust and soles out at the Moho, suggesting complete or near-complete crustal embrittlement (Figs. 6,7b and c, and Fig. 12d). South of the axis, closely spaced, high-angle normal faults dipping toward the continent control the deposition of wedge-shaped syn-rift sequences. The most prominent of these is the NE-SW trending BFZ (Fig. 3, Fig. 6b and c,7b and c).

Despite extreme crustal thinning and the expected high subsidence, the syn-rift sequence is thin, typically ~1 km thick, and rarely exceeding 2 km near major normal faults (Fig. 10b), suggesting a sediment-starved environment during rifting. The early syn-rift sequence shows chaotic to stratiform seismic facies, which transition abruptly into stratiform and wavy facies interpreted as the late syn-rift sequence (interpreted as bounded by the T80 unconformity) (Fig. 12c and d). These seismic facies suggest syn-rift deposition was dominated by gravity-driven processes (Xu and Haq, 2022). Based on coeval deposits from the proximal margin (e.g., Liang et al., 2023; Lin et al., 2003), a marine, and potentially deeper setting is inferred for the Southern Rift System, considering that the crust was comparatively thinner than in the proximal counterpart (Fig. 11). The top of the late syn-rift is truncated by the T70 unconformity, lying 4–5 km below sea level near the BFZ and CFZ, and over 7 km near the rift axis (Fig. 9b).

5.3.2. Sparse Faulting and the Continent-Ocean Transition in the Southern High

The transition between the Southern Rift System and the Southern High is marked by sharp contrasts in top-basement morphology and crustal thickness, occurring at the BFZ (Fig. 3a, Fig. 4, Fig. 6a,7a, Fig. 9b). In contrast to the fault-controlled, rugged top-basement observed in the Southern Rift System, the Southern High shows a smoother basement morphology (Figs. 6,7). The linear distribution of basement highs can be used as a proxy to map syn-rift faulting in the distal domain throughout the South China Sea. However, the core of the Southern High in particular lacks these pronounced basement highs typically associated with rift-related fault blocks and/or volcanic edifices (Fig. 1 and Fig. 3b). Fault-controlled, wedge-shaped deposits are rare and are mostly found near the northern and southern boundaries of the Southern High (Figs. 6,7). These local syn-rift sequences rarely

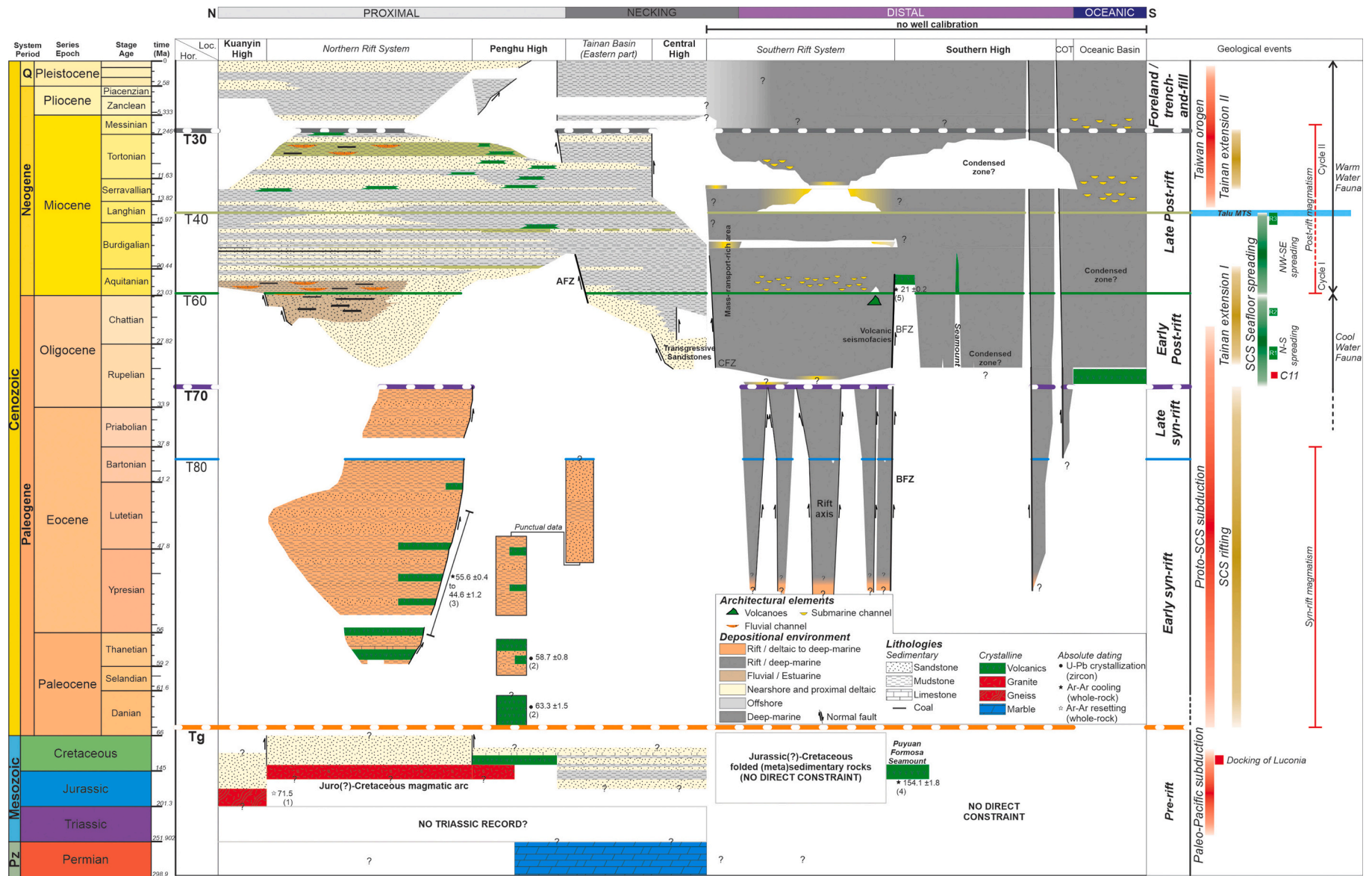


Fig. 11. Tectonostratigraphic chart of the NE South China Sea Margin based on the Composite Section c-c'. The stratigraphic chart is presented as an N-S Wheeler Diagram, which is built based on observations on the eastern part of the NE SCS. Lithologies of the syn-rift stage of the proximal domain are according to Lin et al. (2003). The post-rift stage of the proximal and necking domains is based on Lin et al. (2021). The Foreland and trench-and-fill stage of the proximal and necking domains is based on Lin et al. (2003). Interpretations of the distal domain are based on the sedimentary architecture presented in this manuscript and analogous outcrops in Taiwan. Dating information is taken from (1) Chen et al. (1997), (2) Chen et al. (2010), (3) Wang et al. (2012b), (4) Xu et al. (2022), and (5) Wang et al. (2012a). Faunal changes according to Huang et al. (2012). Tainan extension, according to Lin et al. (2021, 2003). SCS seafloor spreading and ridge jumps according to Briaies et al. (1993) and Sibuet et al. (2016). Docking of Luconia according to Hall (2012).

exceed 1 km in thickness, and their deposition appears to be primarily controlled by low-offset normal faults (Fig. 4b, Figs. 6,7, and Fig. 10b). Seismic facies and sediment thickness may also suggest a starved marine setting during the syn-rift tectonostratigraphic unit (Fig. 6,7) (Xu and Haq, 2022).

Several symmetrical outer basement highs are identified across the southern boundary of the Southern High, preceding the first unambiguous oceanic crust to the south (Fig. 14). The absence of a continuous seismic Moho signal underneath them suggests they are at least partly made of magmatic rocks (Lester et al., 2014; Liu et al., 2021), possibly intruding into and extruding over rotated continental crustal blocks, characterized by stratiform reflections (Fig. 13a, Fig. 14). The age of this volcanism is not directly constrained; however, onlaps of T60 and possibly T70 horizons suggest emplacement during the late syn-rift to early post-rift period (Fig. 13a, Fig. 14). These *outer highs* are bounded on one (Fig. 14a) or both sides (Fig. 14b and c) by a large-offset normal fault.

The continent-ocean transition (COT) of the area is narrow and defined by a major large-offset normal fault system onto which smaller faulted blocks root, marking the transition from ~15 km thick polygenic crust to 5 km thick oceanic crust (Fig. 13a, Fig. 14). This transition zone is characterized by a poorly imaged or absent Moho reflector (the “Moho quiet zone” in Fig. 14). Thin patches of syn-rift and early post-rift deposits are inferred to overlie the acoustic basement (Fig. 13a), similar to sequences drilled in the COT of the PRMM (e.g., U1502; Larsen et al., 2018a). The reappearance of a deeper Moho signal seaward, interpreted as being offset by the COT major normal offset faulting, and the absence of syn-rift sequences further south of it mark the boundary with the oceanic domain (Fig. 14).

6. Post-rift tectonostratigraphic unit (T70 to T30)

The post-rift tectonostratigraphic unit comprises rocks deposited from the Early Oligocene to the latest Late Miocene and is bounded by the horizons T70 and T30 (Fig. 11). It is subdivided into early (Early Oligocene to the earliest Miocene, NP22 to NN1; ca. 32 to 23 Ma) and late (Early to latest Late Miocene, NN2 to NN11b; ca. 23 to 7 Ma) post-rift sequences, which are separated by the T60 horizon (Fig. 11).

6.1. Fluvial to littoral sedimentation in the Northern Rift System (proximal domain)

During the early post-rift, the Penghu-Peikang High was a subaerial structural high, separating the Northern Rift System from more distal parts of the NE SCS rifted margin (Fig. 5c) (Lin et al., 2003). Up to 3500 m of erosion has been estimated over it and its vicinity (Fuh, 2000; Lin et al., 2003). A similar setting is observed in the western part of the Penghu Basin (Lin et al., 2003), which was shaped by fluvial processes that sourced the Taihsi and Nanjihtao depocenters with sediments derived from exposed parts of the SCB. The stacking patterns in these basins indicate a major transgressive event from the Early Oligocene to the earliest Miocene (NP23 to NN1) (Fig. 5) (Hsiao et al., 1991; Lin et al., 2003, 2021). This transgressive event has an overall east-west trending and is associated with a predominant thin littoral deposition that onlaps toward the basin margins, the northern parts of Penghu-Peikang High, and the eastern Penghu Basin (Fig. 5, Fig. 10c, and Fig. 11) (Hsiao et al., 1991; Lin et al., 2003, 2021). The regionally recognized T60 unconformity bounds the top of this early post-rift sequence (Fig. 11).

In the late post-rift, the Northern Rift System recorded shoreline shifts mainly associated with fluvial to shallow marine sedimentation (Fig. 5, Fig. 11) (Lin et al., 2003, 2021; Yu et al., 2013). Notably, the Penghu-Peikang High was submerged during two high-hierarchy transgressive events (Lin et al., 2021). The first occurred during the Early Miocene (NN2, ca. 19 Ma) while the second, which corresponds to the T40 surface, occurred in the Middle Miocene (boundary NN4-NN5) (Fig. 5c, Fig. 11) (Lee et al., 1993; Lin et al., 2003, 2021). These

maximum transgressive events were able to connect sedimentary pathways between the proximal domain, necking and distal domains. Two distinct post-rift magmatic episodes affected the Penghu-Peikang High and NW Taiwan during the Early Miocene (23 to 20 Ma whole-rock Ar–Ar dating) and Late Miocene (13 to 8 Ma, whole-rock Ar–Ar dating) (Chung et al., 1994, 1995; Wang et al., 2012b) (Fig. 11).

6.2. Shelf-dominated sedimentation in the Tainan Basin and Central High (necking domain)

Localized extensional deformation occurred in the Tainan Basin during the early post-rift. This event reactivated some rift structures and formed a dense network of horsts and grabens controlled by low-offset planar normal faults (Fig. 6,7b and c, Fig. 9b, and Fig. 12a and b) (Lee et al., 1991, 1993; Lin et al., 2003, 2021). Seismic facies that correspond to Oligocene shelf sedimentary rocks (Lee et al., 1991, 1993; Lin et al., 2021) characterize the early post-rift sequence of the Tainan Basin (Fig. 12a and b). Basal littoral sandstones (Lin et al., 2003, 2021) grade to a thick shelf mudstone (up to 630 m thick) (Fig. 11) (Lee et al., 1991). This stacking pattern indicates a south-to-north transgression observed on sedimentary rocks from the Central High (Early Oligocene; NP23), which progressively onlaps the AFZ (Late Oligocene; NP25) (Fig. 11; Fig. 16a) (Lee et al., 1991; Yang et al., 2006). This transgression culminated in the Early Miocene (NN1) with the T60 unconformity and the cessation of the first stage of localized extensional deformation for the area (Fig. 11) (Lin et al., 2003, 2021). Cogenetic Late Oligocene (NP25) shallow marine rocks of the Wuchihshan Fm. crop out in Nantou, in the vicinity of Tainan town, and unconformably overlie the early syn-rift Pinglin Tuff (NP16) (Huang et al., 2013).

The late post-rift of the area is characterized by seismic facies that correspond to shelf-related mudstones and minor sandstones, as validated by drilling results (Fig. 6,7, Fig. 12a and b) (Lin et al., 2021). Overall, the basal part of this sequence corresponds to a period of tectonic quiescence where a transgressive trend culminates in a maximum transgression event at T40 (boundary NN4-NN5) (Lin et al., 2021). Overlying clinothems downlap onto this T40 horizon and are affected by low-offset planar faults, suggesting shelf progradation and a superimposition of the second stage of localized extensional deformation (Fig. 12a and b) (Lee et al., 1991, 1993; Lin et al., 2003, 2021). Toward their top, these clinothems are truncated by the Late Miocene T30 unconformity (latest Late Miocene; NN11b), which marks the onset of the foreland and trench-and-fill tectonostratigraphic unit (Fig. 12a and b) (Lin et al., 2003, 2021). The base-level drop tied to this event led to the subaerial exposure and associated erosion of the Central High (Ding et al., 2008; Lee et al., 1993).

6.3. Deep-marine sedimentation in the Southern Rift System and Southern High (distal domain)

The analysis of seismic sequences in the distal margin is integrated within a previously defined depositional framework and relies on seismic facies interpretation (Xu and Haq, 2022) and horizon mapping. The onset of the early post-rift is marked by parallel to semi-parallel high-amplitude reflectors directly overlying the T70 surface in the Southern Rift System (Fig. 12c). These reflectors onlap structural highs to the north and downlap onto the T70 unconformity toward the basin (Fig. 11, Fig. 12c). We interpret these geometries as submarine fan complexes, probably related to a forced regressive systems tract (Fig. 11, Fig. 12c) (Catuneanu, 2006; Van Wagoner et al., 1990). This regressive sequence is overlapped by parallel to semi-parallel reflectors of high-amplitude and moderate frequency interpreted as basin floor fans deposited during the first pulses of the Oligocene transgression that later affected the shelf over the proximal and necking domains (Fig. 11, Fig. 12c). This early post-rift sequence is bounded by our mapped T60 horizon, which characterizes an abrupt change in seismic facies of the late post-rift sequence (Fig. 12c, Fig. 12d, and Fig. 13a). In the late post-

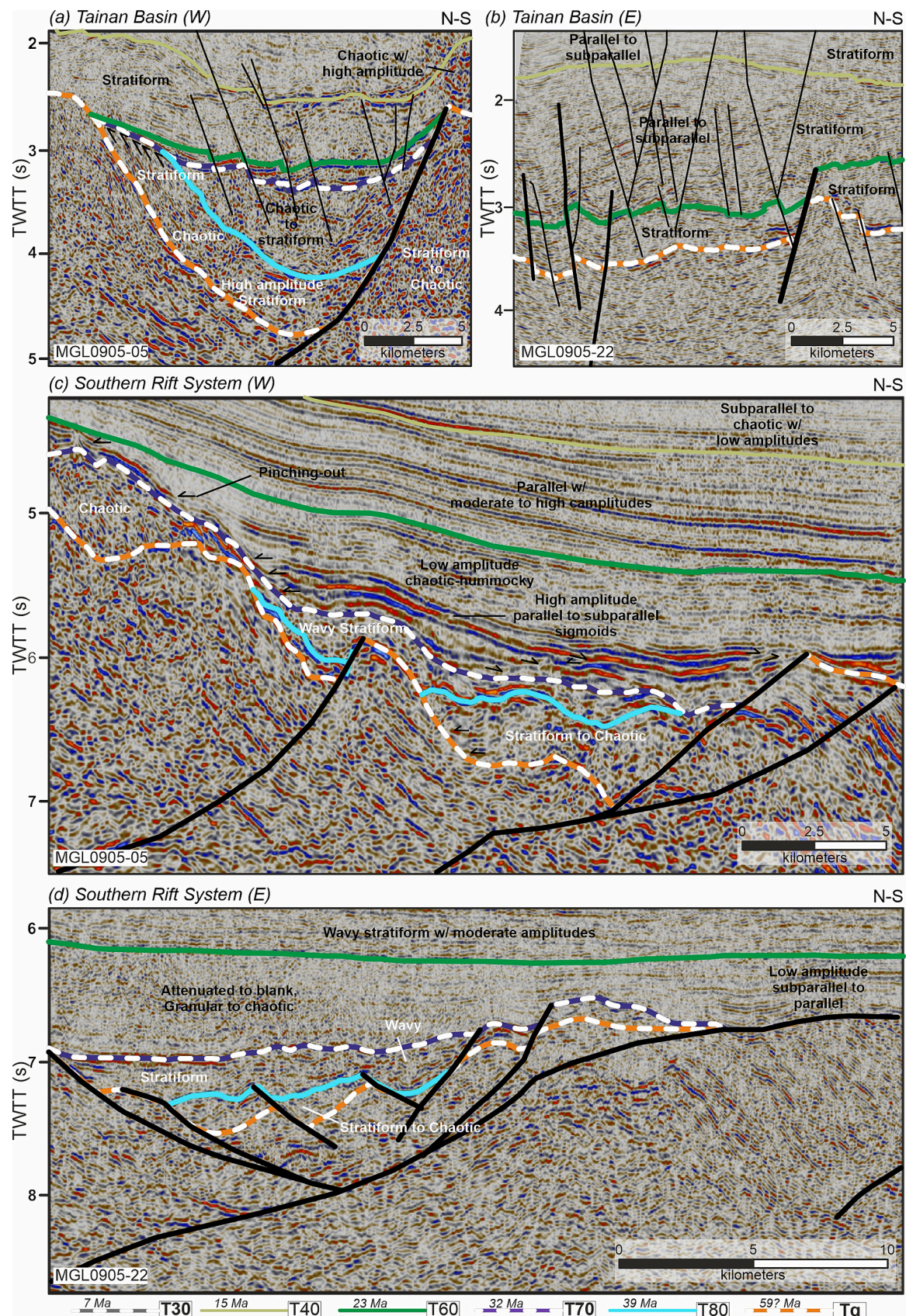


Fig. 12. The reflection seismic character of the pre-, syn-, and early post-rift of the NE SCS. (a) Tainan Basin (West Part); (b) Tainan Basin (East Part); (c) The Southern Rift System (West Part); (d) The Southern Rift System (East Part).

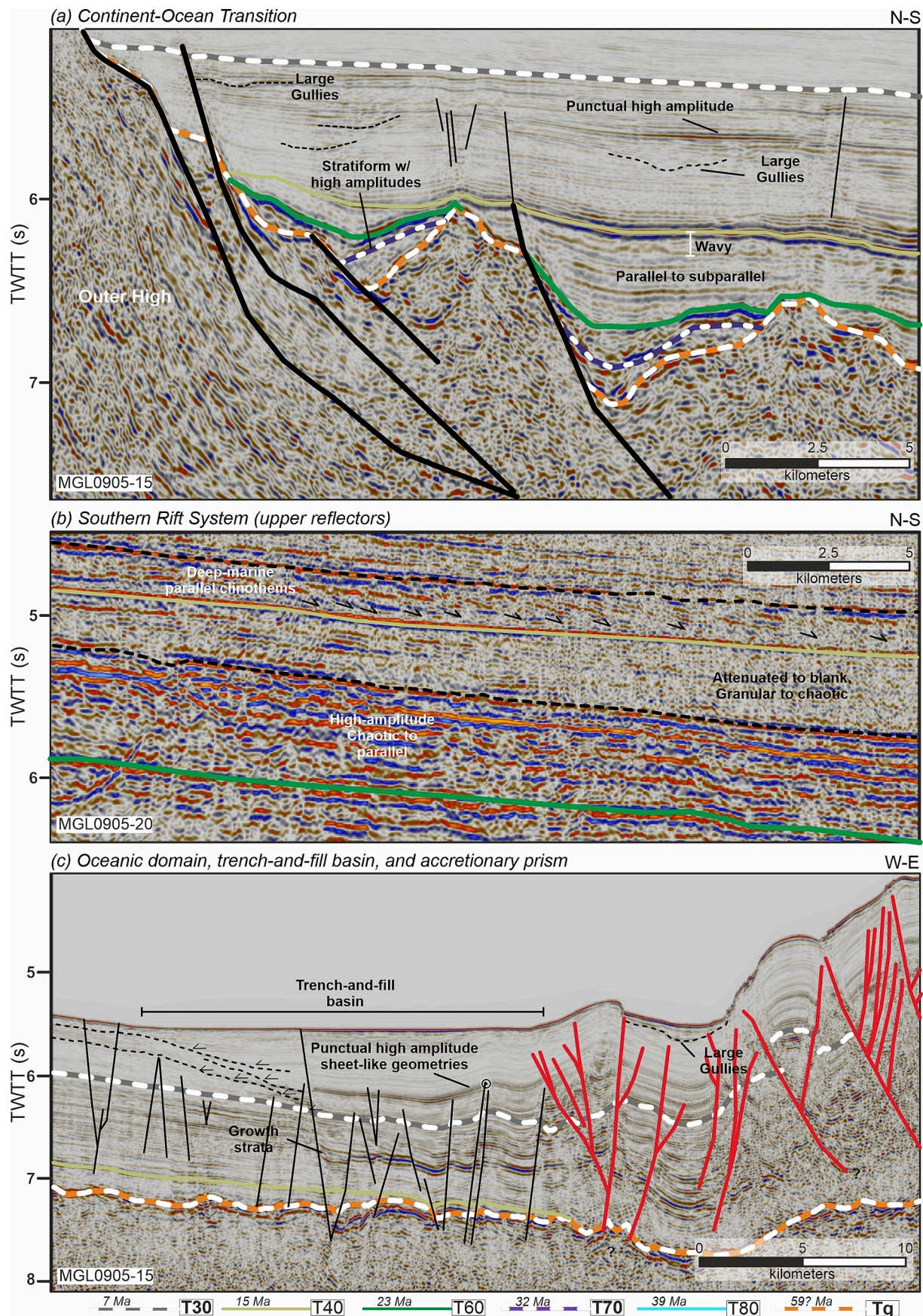


Fig. 13. The reflection seismic character of the NE SCS margin. (a) South of the Outer High (Continent-Ocean Transition); (b) Southern Rift System (post-rift reflectors); (c) Unambiguous oceanic domain, trench-and-fill basin, and accretionary prism.

rift sequence, parallel to semi-parallel low-amplitude reflectors onlap structural highs to the north and south (Fig. 11, Fig. 12c), suggesting continued deep-marine deposition under a high-hierarchy transgressive system tract (Fig. 6 and Fig. 11). Toward the top, clinothems showing parallel and shingled geometries (Fig. 11, Fig. 13b) downlap onto a high-amplitude surface interpreted as the distal continuation of the T40 horizon (Fig. 13b). Late post-rift magmatism in the Southern High is supported by the pillow basalts dredged from the Puyuan-Formosa seamount, which yield an Early Miocene age of 21 ± 0.2 Ma (whole-rock Ar—Ar) (Wang et al., 2012b).

6.4. Deep-marine sedimentation in the oceanic domain

Sedimentation in the oceanic domain initiated in the Early Oligocene, as inferred from mapping of seismic horizons, magnetic anomalies (e.g., Briais et al., 1993; Sibuet et al., 2016), and correlation with IODP drilling results in the adjacent PRMM (sites U1500 and U1502) (Larsen et al., 2018a; Stock et al., 2018). Sedimentation is inferred to have been dominated by deep-marine processes based on the stratiform and parallel geometries of the reflectors (Xu and Haq, 2022) and correlation with the PRMM (Fig. 6,7c and Fig. 13b and c).

7. Foreland and trench-and-fill tectonostratigraphic unit (T30 to T0)

The successions deposited since the latest Miocene (T30 to T0, NN11b onwards, ca. 7 Ma to present-day) are part of a foreland and trench-and-fill tectonostratigraphic unit (Fig. 11) (Lin et al., 2003). In the NE SCS, an overall increase in sediment thickness is observed toward the collisional front and subduction zone to the east (Fig. 10d). These depocenters represent wedge-shaped basins mainly controlled by lithospheric flexure generated by the nappe stacks of the Taiwan orogen and the Manila subduction zone further south (Ernst et al., 1985; Ho, 1982).

7.1. The foreland basin system in the proximal domain

The base of the foreland tectonostratigraphic unit (T30 horizon) is constrained by drilling data (NN11b) in the Nanjihtao and Taihsi basins (Lin et al., 2021). The overlying NW-SE trending wedge-shaped sequence is characterized by parallel reflectors locally truncated by channel-like geometries (Fig. 5c). This tectonostratigraphic unit thickens toward the collisional front, marking the western boundary of the Taiwan fold-and-thrust belt (i.e., Western Foothills) (Fig. 10d).

Depositional environments, constrained by drilling data and correlations with onshore Taiwan, indicate a shallow marine, wave- and tide-influenced setting recording a transgressive phase (latest Miocene to Early Pliocene; NN11b to NN14) (Fig. 11) (Lin et al., 2003; Pan et al., 2015). This was followed by a transition to fluvial environments during regression (Early Pleistocene; NN15 onwards), interpreted as being related to Taiwan's mountain building (Fig. 11) (Lin et al., 2021; Pan et al., 2015; Simoes and Avouac, 2006).

7.2. Shelf-to-slope transition in the necking domain

The base of the foreland tectonostratigraphic unit in Tainan Basin is also calibrated by drilling data at ca. 7 Ma (NN11b) (Lin et al., 2021). An eastward thickening trend is also observed within this region (Fig. 10d). This tectonostratigraphic unit is characterized by parallel to subparallel reflectors (Fig. 6,7, and Fig. 12a and b) that mostly correspond to shelf mudstones (Lin et al., 2003; Xu and Haq, 2022). Concave geometries are also observed and interpreted as submarine canyons, commonly associated with the transition from outer shelf to upper slope settings (Harris and Whiteway, 2011). This implies that the sediments of the foreland and trench-and-fill tectonostratigraphic unit in the Tainan Basin were mostly deposited within this paleoenvironmental range.

7.3. Variable foreland basin system geometries in the distal domain

In the absence of wells and drilling data in the distal domain, interpretations of the foreland tectonostratigraphic unit rely on seismic facies analysis (e.g., Xu and Haq, 2022) and correlations with the adjacent necking and oceanic domains. This tectonostratigraphic unit shows reflectors incised by concave geometries. These concave geometries are interpreted as representing lenses, canyons, and channel-levee complexes (Fig. 6, Fig. 12c) (Xu and Haq, 2022). At the top of this tectonostratigraphic unit, high-amplitude wavy reflectors become common and are interpreted either as scours within submarine canyons or as deep-marine sediment waves (Kuang et al., 2014; Li et al., 2020; Li et al., 2021b; Yin et al., 2016). These two seismic facies associations are also observed, although condensed, over the Southern High (Fig. 6). These observations suggest a predominant deep-marine setting (Ding et al., 2008; Xu and Haq, 2022; Yin et al., 2016).

The thickness of the foreland and trench-and-fill tectonostratigraphic unit increases from ca. 1 km to more than 7 km toward the accretionary prism, to the east (Fig. 10d). The foredeep over the Southern Rift System is large and characterized by large wavelength synclines and anticlines extending over roughly 50 km west of the accretionary prism. No clear foredeep is observed over the Southern High, where a narrow, less-than-20-km-wide thrust system was developed (Fig. 10d).

7.4. Trench-and-fill basin in the Oceanic Domain

The base of the trench-and-fill tectonostratigraphic unit marks the onset of the associated basin architecture (Fig. 13c). The interpreted T30 surface was correlated with equivalent time-converted well tops from IODP drillings in the PRMM oceanic domain (Larsen et al., 2018a; Stock et al., 2018; Sun et al., 2018). Seismic facies associations (parallel, sheet-like, and cotton-like reflectors) suggest deep-marine depositional environments (Fig. 13c), as demonstrated in the IODP drillings U1500 and U1501 located westward (Larsen et al., 2018a; Stock et al., 2018; Sun et al., 2018).

8. The Cenozoic evolution of the NE SCS rifted margin: A synthesis

8.1. Structural and compositional inheritance from the Late Mesozoic tectonic framework

The identification of relics of a Mesozoic terrane assemblage in the present-day SCS (Fig. 8a) clarifies the pre-rift history of its northeastern part and shows how this inherited setting may have influenced Cenozoic rifting processes. Pre-rift events predate the latest Cretaceous to Early Paleogene phase of regional uplift, erosion, and non-deposition, particularly pronounced in the north, which is marked by the *Tg unconformity*, widely recognized throughout the SCS margins (Fig. 11) (Holloway, 1981; Sun, 1985; Xie et al., 2019; Yao et al., 2012).

The proximal margin of the NE SCS formed over the former SCB active continental margin, characterized by the NE-SW Mesozoic Yanshanian Andean-style magmatic arc (Fig. 8a and Fig. 15a) (Chen et al., 2016; Li et al., 2018a). Arc-related processes, due to the SE-NW Paleopacific subduction beneath the SCB, significantly modified the crustal composition of the future proximal domain, with widespread felsic and mafic intrusions into Paleozoic-Mesozoic (meta)sedimentary rocks as inferred from direct and indirect sources, such as seismic, magnetic, and gravity data (Fan et al., 2022; Li et al., 2018a; Rodrigues de Vargas et al., 2024; Wan et al., 2017). The pre-rift crustal thickness of the proximal domain is uncertain, but based on present-day estimates, it was no less than 30 km and may have reached 35–40 km by the end of the Yanshanian orogeny and the docking of the Luconia microcontinent to its south (Fig. 15a).

The distal domain of the NE SCS developed over the Luconia microcontinent (e.g., the Southern High) and its docking zone with the

SCB margin (Fig. 8 and Fig. 15a) (Rodrigues de Vargas et al., 2024). Mesozoic-aged deep-marine sedimentary rocks drilled along the southern SCS margin (Kudrass et al., 1986; Liang et al., 2019), indirectly support pre-existing crustal thinning of the Luconia microcontinent before Cenozoic rifting (Fig. 15a). Although poorly constrained, it suggests that the pre-rift crustal thickness of this part of Luconia was thinner than that of the adjacent SCB, thereby isostatically allowing deep-marine deposition (Fig. 15a). Dredges from the Southern High indicate mafic extrusion in a subaqueous environment (Fig. 11) (Xu et al., 2022), consistent with the high average crustal densities of the block, which suggests variable degrees of pre- and post-rift magmatic additions (Rodrigues de Vargas et al., 2024).

A Mesozoic accretionary wedge developed along the docking zone, as inferred from seismic observations within the Southern Rift System basement (Fig. 8 and Fig. 15a) (Rodrigues de Vargas et al., 2024; Sibuet et al., 2002). Outcrops of this Mesozoic accretionary system are identified in Taiwan's Kenting Mélange (Zhao et al., 2025) and in the Tananao Complex (Chen et al., 2017; Ho, 1986; Jahn, 1988; Yui, 2005; Yui et al., 2012). In the Kenting Mélange (south of Taiwan), some schists record Mesozoic recrystallization age in their matrix, interpreted as related to Paleo-Pacific subduction processes (Zhao et al., 2025). In the Tananao Complex, Jurassic-Cretaceous high-grade meta-sedimentary rocks, thought to represent a Mesozoic accretionary prism, unconformably overlie Permian marbles (Fig. 8a) (Chen et al., 2017; Ho, 1986; Jahn, 1988; Yui, 2005; Yui et al., 2012).

8.2. Syn-rift tectono-magmatic and sedimentary evolution influenced by Mesozoic inheritance

8.2.1. Diffuse deformation during the early rifting stage (?Early Paleocene to late Middle Eocene)

The onset of rift-related deformation in the NE SCS margin is interpreted to have occurred synchronously across a broad region in the Late or possibly Early Paleocene, as documented in the Northern Rift System (Huang and Chi, 1979; Lin et al., 2003) and the conjugate Palawan margin to the south (Fig. 15b) (Franke et al., 2011; Holloway, 1981, 1982; Ru and Pigott, 1986; Yao et al., 2012). Initially, pure shear extension was the dominant mechanism, producing diffuse extension across the future NE SCS and Palawan margins (Fig. 15b) (Ding et al., 2020; Mohn et al., 2022). In the Northern Rift System, extension led to the development of major continentward-dipping normal faults (e.g., Fig. 5c). Some of these faults may have nucleated along contacts with older Yanshanian magmatic intrusions (Fig. 15b) (Sautter and Pubellier, 2022). Likewise, normal faults of the Southern Rift System may have nucleated along contacts with former thrust faults throughout the Mesozoic accretionary prism (Fig. 15b) (Deng et al., 2020; Rodrigues de Vargas et al., 2024; Sautter and Pubellier, 2022). This stage likely represents the main extensional phase in the proximal domain, associated with localized crustal thinning beneath isolated rift basins (Fig. 15b and c).

Sediments likely originated from major fluvial systems draining the SCB, with additional local contributions from basement highs, notably the Penghu-Peikang High. These sources mostly supplied wedge-shaped marine basins dominated by deltaic processes (Huang et al., 2001; Sun, 1985) in the proximal and necking domains (Fig. 15c). A transition from subaerial (Penghu-Peikang and Central highs) to a likely deep-marine setting (Tainan depocenter and Southern Rift System) is recorded along the AFZ and CFZ in the forming necking zone (Fig. 15b and c). Erosion of the Penghu-Peikang High mostly supplied Tainan Basin, while erosion of the Central High supplied both Tainan Basin and the Southern Rift System (Fig. 15b and c). Such conditions could explain the deeper-marine sediment-starved setting in the Southern Rift System deduced from seismic observations. Additional limited volumes of sediment might have sporadically been supplied from the Southern High, representing a relative promontory in a deep-marine setting (Fig. 15b and c). Deep-marine conditions were also observed in the

conjugate Palawan margin from the Late Paleocene to Early Eocene (Franke et al., 2011; Yao et al., 2012). The Backbone Range in Taiwan might represent an analogue of the distal margin (Conand et al., 2020; Zhao et al., 2025). Its basal section comprises highly deformed (meta) sedimentary rocks, generally interpreted as having been deposited in a shallow marine setting (Brown et al., 2012; Chou, 1988; Huang et al., 1997). Deep-marine conditions are already recorded in the Early Eocene (NP12) (Huang, 1980). Early to Middle Eocene (NP14-NP16) sedimentary rocks are unconformably overlain by Early Oligocene shallow marine rocks (Lin and Chen, 2016). Paleocurrents from tabular sandstones, detrital zircons, and monazites support a southward sediment source for the area (Chen et al., 2019; Chou, 1985; Yokoyama et al., 2007; Yui et al., 2012). This source area, likely from a topographic high, may be an eastern prolongation of the Southern High, possibly subducted and no longer exposed in Taiwan (Fig. 15b and c) (Bautista et al., 2001; Fan et al., 2016).

8.2.2. Late rifting and continental breakup (late Middle Eocene to Early Oligocene)

This stage corresponds to the main phase of continental lithosphere thinning along the NE SCS rifted margin. Deformation in the proximal domain decreased while localizing within the evolving necking and distal domains (Fig. 15d). In the western part of the margin, crustal thinning was mainly accommodated by continentward-dipping normal faults (Fig. 6a and Fig. 7a). Eastward, crustal thinning in the necking zone is accommodated along the AFZ and CFZ seaward-dipping large-offset normal faults (Fig. 15d). Isostatic rebound caused by the activity of these large-offset faults may explain the uplift and erosion recorded in the Central High since the early rifting stage (Fig. 15b and c). Extreme crustal thinning in the Southern Rift System was likely partially accommodated by a low-angle normal fault system located near the aborted-rift axis (Fig. 15d).

The limited extensional faulting identified over the Southern High by the end of rifting (i.e., BFZ and faulting associated with the COT) cannot fully explain its crustal thinning to only 10–15 km (Fig. 3a). Several complementary factors may account for the crustal architecture. Post-rift magmatism may have partially obscured rift structures in the upper basement (Eakin et al., 2014) and also locally rethickened the crust. A high-density layer at the base of the Southern High crust (inferred from Vp-Vs data from refraction seismic and reflection seismic data) (Eakin et al., 2014; Lester et al., 2014; Liu et al., 2023; Rodrigues de Vargas et al., 2024) suggests that magmatic underplating may also have played a role in modifying the crustal architecture of this domain. More importantly, perhaps, this portion of the Luconia Block was likely already partially thinned before rifting, although its pre-rift thickness, thinner than SCB, requires further evaluation (Fig. 15a). Despite these hypotheses, the relative contribution of each mechanism responsible for the thinning of the Southern High remains debated. Future studies integrating, for example, higher-resolution geophysical imaging and geodynamic modeling may help further constrain the respective roles of tectonic extension, magmatic processes, and inherited lithospheric structure in the development of this domain. Continental breakup was localized within a narrow COT, accommodated by a large-offset normal fault system, likely accompanied by decompression melting, potentially recorded in the *outer highs* during the late syn-rift stage (Fig. 15d).

No notable change in depositional environments is recorded during the late syn-rift (Fig. 15d). The SCB, further north, potentially represents the main sedimentary source for the proximal domain. The Penghu-Peikang and Central highs continued acting as topographic barriers, trapping most of the sediments from the SCB, which explains the sediment-starved environment observed in the necking and distal domains (Fig. 15d). The limited deposition in the Southern Rift System was mainly supplied by gravity flows along escarpments generated by the CFZ and BFZ large-offset faults (Fig. 15d).

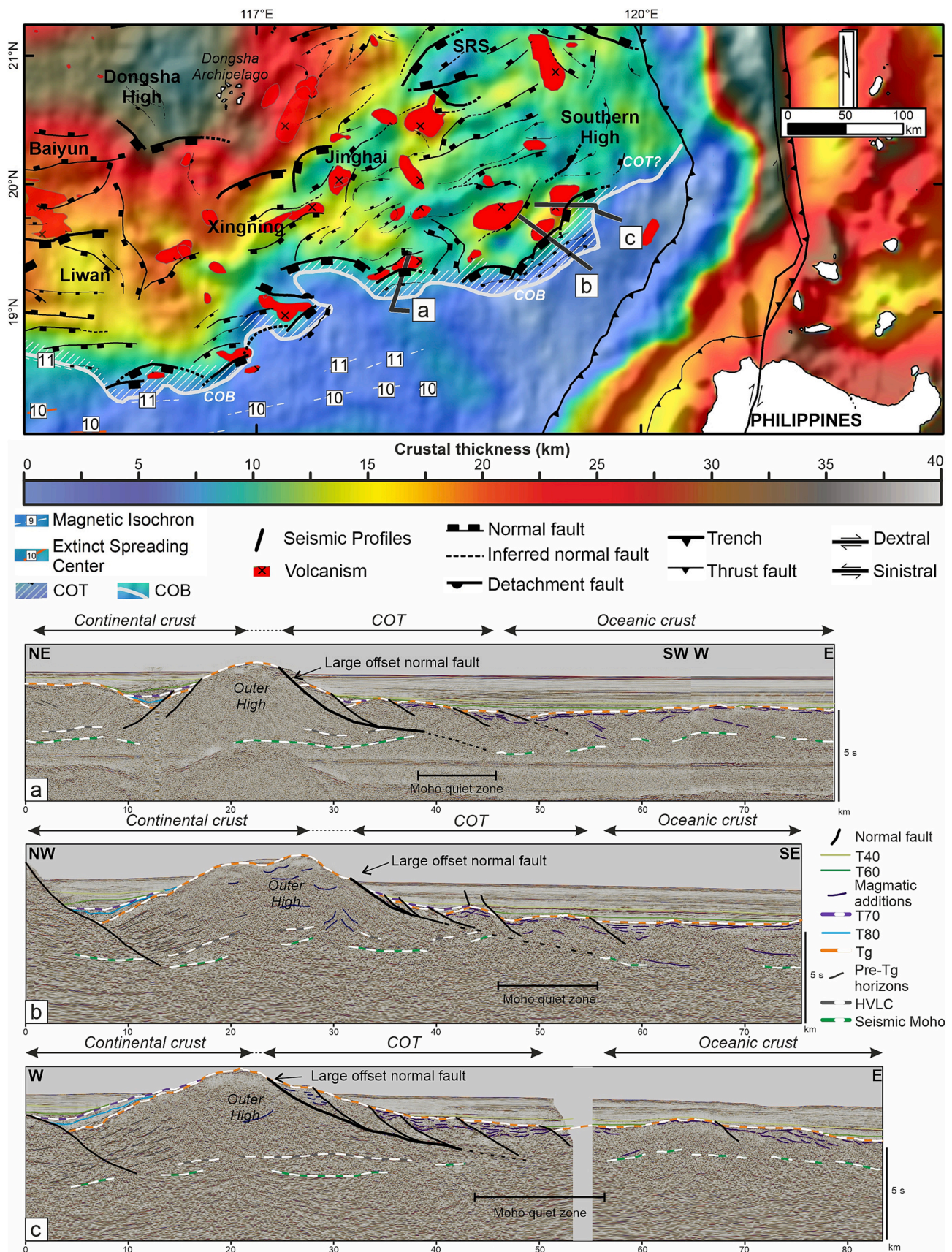


Fig. 14. The Continent-Ocean Transition (COT) of the NE SCS rifted margin. The upper map shows the crustal thickness (33 Ma break-up age; Rodrigues de Vargas et al., 2024), main structures (this work), the continent-ocean boundary (COB; this work), magnetochrons (Briais et al., 1993; Sibuet et al., 2016), and the location of reflection seismic transects a, b, and c (thick black lines). Updated COB of the NE SCS based on Mohn et al. (2022) and Zhang et al. (2024). (a) Composite seismic reflection profile; (b) Seismic reflection profile; (c) Composite seismic reflection profile.

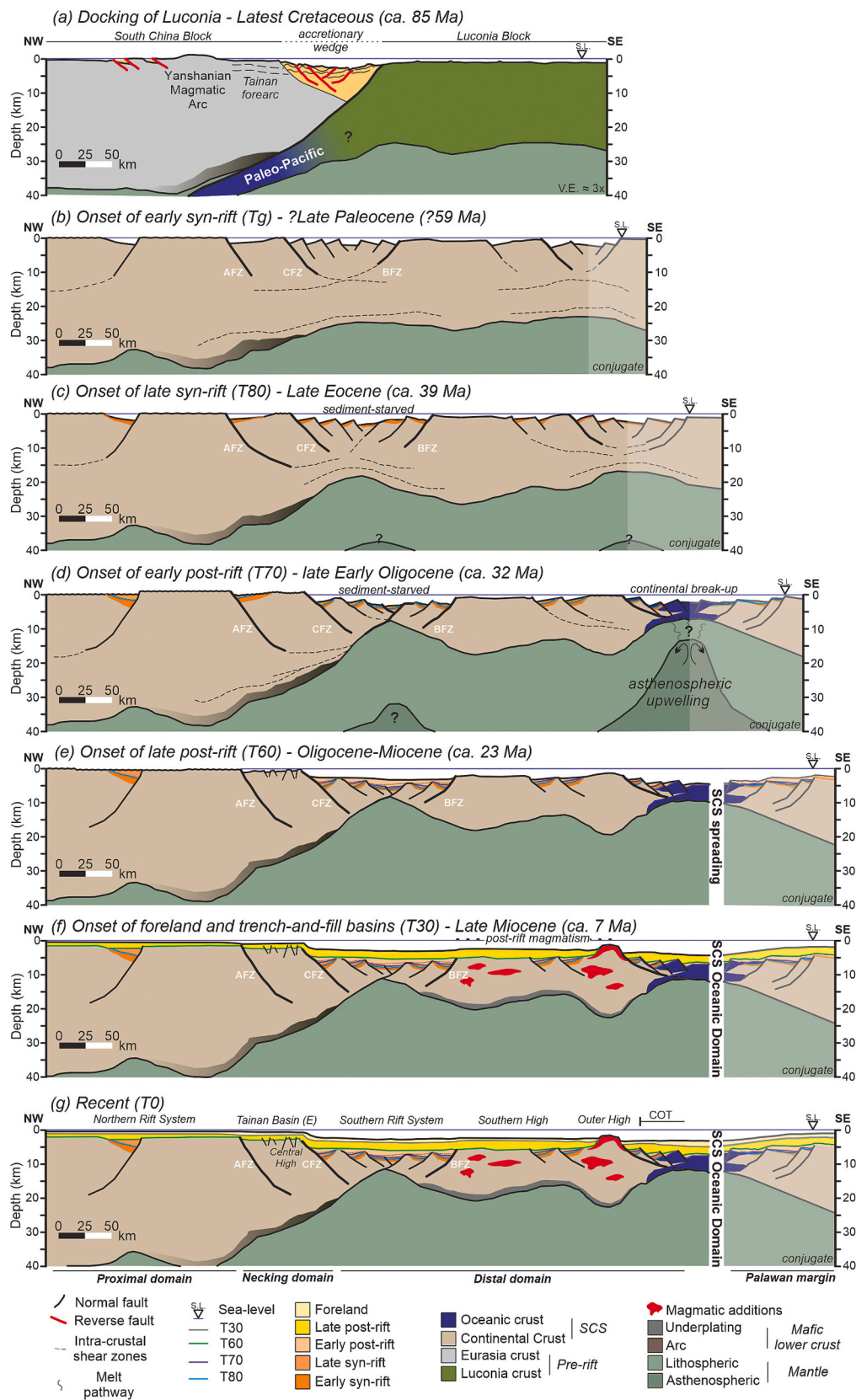


Fig. 15. Simplified scheme for the Cenozoic evolution of the NE SCS rifted margin. (a) The Late Cretaceous (late pre-rift) setting. (b) Onset of early syn-rift (Tg). (c) Onset of late syn-rift (T80). (d) Onset of early post-rift (T70). (e) Onset of late post-rift (T60). (f) Onset of foreland and trench-and-fill stage (T30). (g) Recent. The conjugate margin is based on the eastward-most part of Palawan, as shown in [Franke \(2013\)](#).

8.2.3. Influence of Mesozoic inheritance on tectono-magmatic processes during rifting

We suggest that Mesozoic structural inheritance significantly influenced the style and localization of Cenozoic rifting in the NE SCS rifted margin. The Southern Rift System is interpreted as an aborted hyper-thinned rift basin, partially reactivating structures along the former South China-Luconia docking zone (Fig. 8a) (Rodrigues de Vargas et al., 2024). This optimally oriented NE-SW zone most likely acted as a structural weakness, localizing rift-related deformation (Andrés-Martínez et al., 2019; Sapin et al., 2021) and generating a narrow necking domain, which is atypical for the SCS (Tugend et al., 2024).

Rifting in a heterogeneous setting may also partly explain the distribution of magmatism. Volcanism is recorded in the proximal and necking domains of the NE SCS margin, occurring synchronously or slightly later in the necking zone (Fig. 11). Bimodal basalts and andesites (56 to 38 Ma) show isotopic signatures indicative of asthenospheric upwelling, with contributions from subducted Paleo-Pacific material (Chung et al., 1994, 1995; Smith and Lewis, 2007; Wang et al., 2012a,b). In contrast, evidence for syn-rift magmatism in the Southern Rift System remains scarce, despite extreme continental lithosphere thinning. This absence might suggest that the underlying mantle was too depleted to generate sufficient magma to initiate continental break-up at this location. Indirect evidence for late syn-rift magmatism is observed farther south in the *outer highs* (Fig. 13a, Fig. 14), where continental breakup and oceanic spreading ultimately crosscut the Luconia Microcontinent, leaving their remnants in the Southern High and the southern SCS (e.g., Mindoro Block, Liyue – Reed Bank; Knittel et al., 2010; Tong et al., 2019) (Fig. 8a).

8.3. Post-rift sedimentation: Interplay of thermal subsidence, eustasy, and tectonic reactivation

8.3.1. Early post-rift (Early Oligocene to Earliest Miocene)

Sediment deposition in the early post-rift was not solely influenced by passive margin thermal subsidence and eustatic variations. Extensional deformation in the Tainan Basin during the Oligocene generated localized uplift followed by rapid subsidence (Fig. 15e) (Lin et al., 2003). The origin of this tectonic activity remains unclear. It has been tentatively correlated with post-rift magmatic activity recorded in the proximal and necking domains (Chung et al., 1994, 1995; Wang et al., 2012a, b). The uplift inferred north of the Central High, together with eustatic variations, generated a widespread subaerial region prone to erosion along the proximal and necking domains (Fig. 15e) (Fuh, 2000; Lin et al., 2003). This large erosional event may explain the absence of syn-rift sedimentary rocks in the eastern Tainan Basin and sediment bypass from the exposed margin directly to a deep basin setting (Fig. 15e). The arrival of large volumes of eroded material from the exposed SCB margin likely triggered the progradation toward the south of deep-marine forced-regression fan complexes, as interpreted in the Southern Rift System (Fig. 11, Fig. 12c, and Fig. 15e).

The subsequent Oligocene transgressive event is associated with the deposition of basin-floor submarine fans in the distal domain (Fig. 11), primarily sourced from the exposed SCB shelf. Younger, shallow marine to continental sedimentary rocks directly overlie the basement of the necking domain and parts of the proximal domain (i.e., Taihsi and Nanjihtao), and shift to deep-marine settings toward the distal domain (Fig. 15e). Deep-marine conditions in the distal domain during the early post-rift period, inferred from seismic data, are supported by analogous records from the Backbone Range, onshore Taiwan. There, Oligocene tabular sandstones are interpreted to have been deposited at a paleo-water depth of 300–600 m (Brown et al., 2012; Huang et al., 1997). The end of the early post-rift transgression (marked by the T60 horizon) coincides with a shift from cool to warm fauna, as documented in the Northern Rift System and Tainan Basin (Fig. 11) (Huang et al., 2012), suggesting a role of climatic factors on the transgressive pattern observed in the area.

8.3.2. Late post-rift (earliest Miocene to latest Miocene)

The late post-rift phase was initially dominated by thermal subsidence and eustatic variations, during a phase of tectonic quiescence in the Tainan Basin from ca. 20 to 15 Ma (Lin et al., 2003, 2021). Shallow marine conditions predominated in the proximal and necking domains, while deep-marine environments persisted in the distal counterparts (Fig. 15f). Sediments were probably mostly derived from the emerged parts of SCB and, to a lesser extent, from structural highs (e.g., Kuanyin and Penghu-Peikang) whenever they were subaerially exposed.

A regional regressive event is recorded from the late Middle Miocene to the Late Miocene (Huang, 1989; Lin et al., 2003), which led to the subaerial re-exposure of the Kuanyin, Penghu-Peikang, and Central highs. The erosion of these highs probably provided part of the sediment supply for both the Tainan Basin and the northern Southern Rift System (Fig. 11). This subaerial exposure was probably linked with coeval extensional deformation in the Tainan Basin (Fig. 11, Fig. 15f) (Lin et al., 2003, 2021). This tectonic activity also coincided with renewed post-rift volcanic activity recorded over the Penghu-Peikang and Southern High, as well as onshore Taiwan (Fig. 11) (Chung et al., 1994, 1995; Smith and Lewis, 2007; Wang et al., 2012a,b). This second post-rift magmatic pulse was tentatively interpreted as the interaction of the lithospheric mantle with melts from the asthenosphere mantle during decompression melting (Chung et al., 1994, 1995; Wang et al., 2012a, 2012b). Geochemical modeling also favors this scenario, indicating significant lithospheric attenuation and asthenospheric upwelling to 70–80 km depth (Chung et al., 1994). This tectono-magmatic event probably generated part of the mafic rocks inferred for the Southern High's lower crust, the intense magmatic intrusion through all domains of the NE SCS margin, and onshore Taiwan (Fig. 4, Fig. 5, Fig. 6, Fig. 15f) (Eakin et al., 2014; Lester et al., 2014; Li et al., 2021a; Liu et al., 2021; Smith and Lewis, 2007; Wang et al., 2012b).

The first pulses of this regressive event are marked, in the Southern Rift System deep basin, by the occurrence of parallel to shingled clinothems (Fig. 11, Fig. 13b). These geometries suggest high depositional rates (Xu and Haq, 2022) in a deep-marine setting with source areas from the adjacent exposed shelf and deep-marine Southern High (Fig. 11, Fig. 13b). This regressive event has previously been interpreted as a response to base-level fall, likely controlled by climatic factors such as the growth of the East Antarctic Ice Sheet (Lin et al., 2021). Nonetheless, it may also be explained by several major late Middle Miocene geodynamic events, such as the cessation of seafloor spreading (Briais et al., 1993; Sibuet et al., 2016) and the onset of the South China Sea subduction in the east (Fig. 11) (Sibuet et al., 2016; Lin et al., 2003). Although the timing is similar, the role of these events in driving this base-level drop cannot yet be definitively established.

8.4. Foreland and trench-and-fill stage: Impact of basement morphology

At approximately 7 Ma, a widespread erosional event occurred across the NE SCS shelf, marking a shift in tectonic regime and margin morphology corresponding to the onset of the foreland and trench-and-fill tectonostratigraphic stage. Foredeep infilling occurs exclusively on continental crust, while on the oceanic crust, a trench-and-fill architecture is observed. At the scale of the NE SCS passive margin, the transition from shallow- to deep-marine deposition occurs in the vicinity of the Central High, located within the necking domain (Fig. 15g) (Beyssac et al., 2007; Lin et al., 2003; Pan et al., 2015; Yin et al., 2016).

Deformation and sediment deposition within the foreland basin system of the Taiwan orogen appear to be partly influenced by the crustal structure and the rift-inherited morphology. Notably, significant thickness variations within the foredeep spatially correlate with inherited rift geometry: the foreland and trench-and-fill tectonostratigraphic unit thins over former basement highs and thickens over former rift basins (Fig. 10d), where syn- and post-rift sedimentary sequences are more developed, and the underlying crust is thinner (Fig. 3a, Fig. 10b and c).

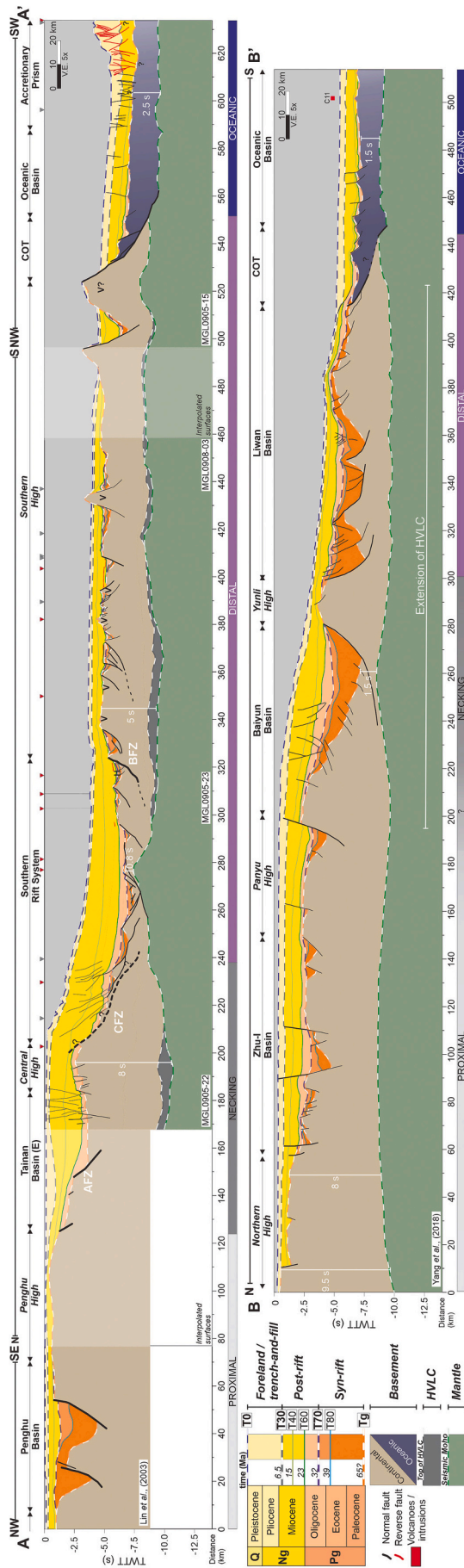


Fig. 16. Comparison between NE SCS (A-A') and PRMM (B-B') interpreted reflection seismic profiles. PRMM interpreted profile is modified from Mohn et al. (2022), Yang et al. (2018), and Zhao et al. (2023). Extension of HVLC in (B-B') is according to Zhao et al. (2023). Abbreviations: AFZ: A Fault Zone; BFZ: Boundary Fault Zone; CFZ: Central High Fault Zone; HVLC: high-velocity lower crust. For the location of profiles, please check Fig. 3.

Former basement highs of the Northern Rift System (e.g., Penghu-Peikang High) have been shown to influence the nappe stack geometry of the Taiwan fold-and-thrust belt, acting as a structural buttress to deformation (Brown et al., 2017, 2022; Lacombe and Mouthereau, 2002). Along the submarine continuation of the collisional front to the south, pronounced lateral variations in foreland basin geometry are also observed. A wider foreland basin system developed above thick sedimentary rocks of the Southern Rift System (Fig. 10b and c), which is underlain by extremely thinned continental crust (Fig. 3a). In contrast, a narrower foreland basin system, with a poorly developed foredeep, formed over the Southern High. In the oceanic domain, a narrow trench-and-fill basin developed at the toe of the accretionary prism (Fig. 13c), suggesting that lithospheric flexure in this setting is strongly controlled by the Manila oceanic subduction zone system.

9. Comparison between the NE SCS and Pearl River Mouth margin

9.1. Source-to-sink variability and rift morphology controls on sediment pathways

Time equivalents of the first- (Tg, T70, T30) and second-order (T80, T60, T40) horizons identified in the NE SCS have long been identified in the PRMM (e.g., Ho-Shing, 1990). These horizons delimit key tectonostratigraphic units in both rifted margins, suggesting synchronous major geodynamic changes across the northern SCS (Fig. 11).

The syn-rift record of the PRMM differs from that of the NE SCS in both thickness and depositional environments (Fig. 16), reflecting variations in depositional rates and source-to-sink dynamics. Thick rift basins in the proximal and necking domains of the PRMM record continental, predominantly lacustrine environments (Dongsheng et al., 2018; Jiang et al., 2012; Tian et al., 2023; Wu et al., 2016), while its distal domain is characterized by marine deltaic influences in thick rift basins (Fig. 16) (Zhang et al., 2019). In contrast, the NE SCS is dominated by shallow marine environments across most of its proximal and necking domains (Lee et al., 1993; Lin et al., 2003; Sun, 1985), whereas the distal domain records deep-marine, sediment-starved deposition (Fig. 11).

The contrasting Cenozoic thicknesses between the thick syn-rift basins of the PRMM and proximal NE SCS, and the sediment-starved distal NE SCS (Fig. 10a) highlight the importance of proximity to sediment sources, the maturity of fluvial systems, and the role of the structural highs as barriers controlling sediment pathways in rifted margins. In the PRMM rift basins, the earliest syn-rift deposits were likely sourced predominantly from nearby structural highs, as shown by the Jurassic and Cretaceous detrital zircon signatures (Zhu-I, Baiyun, Liwan) (Wang et al., 2019). A shift to a multimodal provenance pattern in the late syn-rift sequences suggests increasing sediment contributions from the northern SCB (i.e., South China Block) due to the development of a mature catchment area, rather than primarily local sources (Wang et al., 2019; Zhang et al., 2019). The sediment-starved setting in the distal NE SCS is attributed to the Penghu-Peikang and Central highs, which trapped sediments derived from SCB in basins over the proximal and necking domains, and became the main local sediment source for the distal domain (i.e., Southern Rift System).

The post-rift sequences of the PRMM and NE SCS show remarkable similarities, both recording synchronous first-order shoreline shifts. In both rifted margins, the proximal domain is characterized by fluvial-to-shelf deposition (Lee et al., 1993; Lin et al., 2003), while the distal domain records a predominant deep-marine setting (Fig. 11). During the early post-rift phase, both margins were mainly sourced from the SCB (Shao et al., 2016; Wang et al., 2019, 2022), during a major south-to-north transgression, likely dominantly controlled by climatic factors. The late post-rift stage was primarily influenced by eustatic variations, with a major regressive event after the Middle Miocene. Although not quantitatively constrained, the cessation of seafloor spreading and the

onset of subduction of the SCS during the Middle Miocene may suggest that regional-scale geodynamic factors also contributed to this base-level drop.

The significance of the horizon T30 differs between the two rifted margin segments. In the NE SCS, it marks the base of the foreland and trench-and-fill tectonostratigraphic unit, influenced by flexural subsidence related to Taiwan orogenic processes (Fig. 11). In contrast, in the PRMM, located further away from the orogenic front, it is still part of the post-rift passive margin sequence (Fig. 16).

9.2. Contrasted continental crustal structure but similar COT

The NE SCS and PRMM rifted margins show contrasting crustal structures (Fig. 16). The PRMM is characterized by a distributed and progressive crustal thinning, from a proximal domain with ca. 35–30 km thick crust to a distal domain with <15 km thick crust (Fig. 3a). As observed across most of the SCS rifted margin, the necking domain in the PRMM is diffuse rather than sharply localized (Tugend et al., 2024), in contrast to the NE SCS segment (Fig. 3a and Fig. 16). Consequently, standard criteria commonly used to define crustal domains in rifted margins (Peron-Pinvidic et al., 2013; Sutra et al., 2013; Tugend et al., 2014) are not readily straightforward in the PRMM. Different domain boundaries have been proposed (e.g., Nirrengarten et al., 2020 versus Yang et al., 2018), highlighting the distributed thinning of the continental crust and the absence of sharply defined boundaries between margin crustal domains.

The PRMM is characterized by an array of thinned (e.g., Zhu-I) to hyper-thinned rift basins (e.g., Baiyun and Liwan) separated by comparatively thicker structural highs (e.g., Yunli High) (Fig. 3a and Fig. 16B-B') (Xie et al., 2019; Yang et al., 2018). The crustal structure of the PRMM has been interpreted as the result of crustal boudinage, proposed as the main mechanism of crustal thinning for the area (Pérez-Gussinyé et al., 2023; Pichot et al., 2014). This mechanism involves the formation of upper crustal boudins (structural highs), bounding thinned to hyper-thinned basins where domes of lower crust may develop, analogous to metamorphic core complexes capped by low-angle normal faults (Deng et al., 2020; Legeay et al., 2024; Xu et al., 2024). This style of deformation is characteristic of wide rifting in continental lithosphere with high geothermal gradients, which promotes the development of a thick, weak lower crust (Buck, 1991; Tugend et al., 2024).

Although the NE SCS is adjacent to the PRMM and likely recorded similarly elevated thermal conditions at the time of rifting, it shows a markedly different crustal architecture (Fig. 16). Possible key differences are the initial crust and lithosphere composition and thickness. The PRMM developed over the former SCB, which was extensively affected by Yanshanian arc magmatism and the emplacement of numerous granitic intrusions (Chen et al., 2010; Doo et al., 2025; Fan et al., 2022; Li et al., 2008; Li and Song, 2012; F. Li et al., 2018). Rifting in the PRMM hot lithosphere (and its dominantly felsic crustal composition) may have enhanced the development of a thick ductile lower crust (Brune et al., 2017; Pérez-Gussinyé et al., 2023; Ros et al., 2017). The additional high depositional rates in the PRMM during rifting, in contrast to the sediment-starved setting of the NE SCS, may also have facilitated large fault displacement (Buiter et al., 2008; Burov and Poliakov, 2001; Olive et al., 2014; Theunissen and Huisman, 2019) and amplified the effects of crustal boudinage (Andrés-Martínez et al., 2019; Sapin et al., 2021).

Only the proximal part of the NE SCS formed from the former European margin, while its distal domain formed from the interaction between the South China and Luconia blocks (Rodrigues de Vargas et al., 2024). Although still poorly constrained, Luconia crustal and lithospheric composition and thickness are distinct from those of the SCB. The localized necking domain, rather than a diffuse, wide one, with well-developed crustal boudins, as observed in the PRMM, may reflect deformation localization along a zone of contrasting lithospheric composition and rheology (Pérez-Gussinyé et al., 2023; Sapin et al.,

2021; Tugend et al., 2024). The NE-SW orientation of the lithospheric scale heterogeneous docking zone might be optimal for reactivation during Cenozoic rifting (Fig. 8) (Andrés-Martínez et al., 2019; Sapin et al., 2021). Our interpretation, however, does not exclude that some minor lithospheric thermal heterogeneities between these two blocks may also have played a secondary role in localizing deformation of these contrasting rift margins.

Despite differences in continental crust structure, both the NE SCS and PRMM show a similarly narrow COT, characterized by a low-angle normal fault system and syn-extensional magmatism (Fig. 16) (Ding et al., 2020; Larsen et al., 2018; Mohn et al., 2022; Zhang et al., 2024). Comparable COT structures are observed in several marginal seas, suggesting a common mode of continental breakup (Mohn et al., 2022). Although the overall rifting history of the SCS is associated with several phases of rifting, the final transition from continental breakup to a steady-state oceanic spreading occurs rapidly once extensional deformation and decompression melting are localized. This continental breakup observed in marginal sea basins is interpreted to record a rapid shift in space and time (ca. 1 Ma in less than 20 km), likely controlled by boundary conditions directly or indirectly imposed by nearby subduction zones (Larsen et al., 2018; Mohn et al., 2022).

10. Conclusions

We propose a tectonostratigraphic integration of the NE SCS rifted margin in the geodynamic evolution of the SCS. This study illustrates the role of structural inheritance, sediment source proximity, and major fluvial catchment systems in the tectonostratigraphic evolution of marginal sea basins. The main points are as follows.

- From north to south, the NE SCS rifted margin is characterized by contrasting structural domains corresponding to different magnitudes of crustal thinning: (i) a proximal domain (>30 km thick; the Northern Rift System), (ii) a narrow necking domain (30 to 15 km thick; the Tainan Basin), and (iii) a wide distal domain, including a V-shaped rift basin (<10 km thick; the Southern Rift System) and an adjacent, comparatively thicker and less faulted piece of crust (10 to 15 km thick; the Southern High).
- The regional identification of former Mesozoic crustal blocks clarifies the impact of pre-rift geological inheritance for the subsequent Cenozoic rifting. The docking of the Luconia microcontinent at ca. 85 Ma generated a major tectonic boundary along which extensional deformation preferentially localized, explaining the narrow necking observed in the NE SCS rifted margin.
- Paleocene to Early Oligocene rifting was synchronous across the NE SCS rifted margin, but extensional deformation was distributed. This resulted in: (i) thick, isolated half-grabens filled with marine deltaic sediments in the proximal domain, (ii) a necking domain shaped by large-offset normal faults and recording a transition from subaerial to deep-marine environments, and (iii) the sediment-starved deep-marine distal domain, with most of the syn-rift deformation localized in the Southern Rift System.
- During the post-rift (Early Oligocene to latest Miocene), fluvial-to-shelf sedimentary sequences were deposited north of the Central High, while deep-marine deposition prevailed to its south. Post-rift stratigraphic evolution was controlled by thermal subsidence, eustatic variations, and localized extension, possibly associated with episodes of post-rift volcanism.
- Time-equivalent units of the tectonostratigraphic units mapped in the NE SCS are also identified in the adjacent PRMM. Contrasts between the crustal structure and stratigraphic infill of the NE SCS and PRMM are highlighted. The PRMM formed solely on the SCB, while the NE SCS formed along the South China and Luconia blocks and their docking zone. Rifting in the PRMM was characterized by crustal boudinage and high syn-rift sedimentation rates. In contrast, in the NE SCS, extensional deformation was mostly localized in the

sediment-starved Southern Rift System, while most of their syn-rift sediments were deposited in proximal rift basins.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2026.105501>.

Data availability

Surface data (XYZ point cloud) and uninterpreted seismic sections shown in this study are available in the supplementary materials.

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