

Velocity structure in the South Yellow Sea basin based on first-arrival tomography of wide-angle seismic data and its geological implications

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Abstract

The South Yellow Sea basin is filled with Mesozoic–Cenozoic continental sediments overlying pre-Palaeozoic and Mesozoic–Palaeozoic marine sediments. Conventional multi-channel seismic data cannot describe the velocity structure of the marine residual basin in detail, leading to the lack of a deeper understanding of the distribution and lithology owing to strong energy shielding on the top interface of marine sediments. In this study, we present seismic tomography data from ocean bottom seismographs that describe the NEE-trending velocity distributions of the basin. The results indicate that strong velocity variations occur at shallow crustal levels. Horizontal velocity bodies show good correlation with surface geological features, and multi-layer features exist in the vertical velocity framework (depth: 0–10 km). The analyses of the velocity model, gravity data, magnetic data, multi-channel seismic profiles, and drilling data showed that high-velocity anomalies (>6.5 km/s) of small (thickness: 1–2 km) and large (thickness: >5 km) scales were caused by igneous complexes in the multi-layer structure, which were active during the Palaeogene. Possible locations of good Mesozoic and Palaeozoic marine strata are limited to the Central Uplift and the western part of the Northern Depression along the wide-angle ocean bottom seismograph array. Following the Indosinian movement, a strong compression existed in the Northern Depression during the extensional phase that caused the formation of folds in the middle of the survey line. This study is useful for reconstructing the regional tectonic evolution and delineating the distribution of the marine residual basin in the South Yellow Sea basin.

Key words: ocean bottom seismograph, South Yellow Sea basin, strata velocity structure, wide-angle seismic data, CSDP-2

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1 Introduction

The South Yellow Sea basin, situated between the Shandong Peninsula and Korean Peninsula, is a component of the Yangtze Block (Fig. 1a). It is adjacent to the Southern China Orogen and is separated from the North China Block by the Sulu Orogen in the

north. The sedimentary basin is filled with Mesozoic–Cenozoic continental sediments overlying the pre-Palaeozoic and Mesozoic–Palaeozoic marine sediments (Yao et al., 2008; Zhang et al., 2013; Li et al., 2016; Yuan et al., 2018). Multi-stage tectonic activities and sedimentary events have resulted in the formation of

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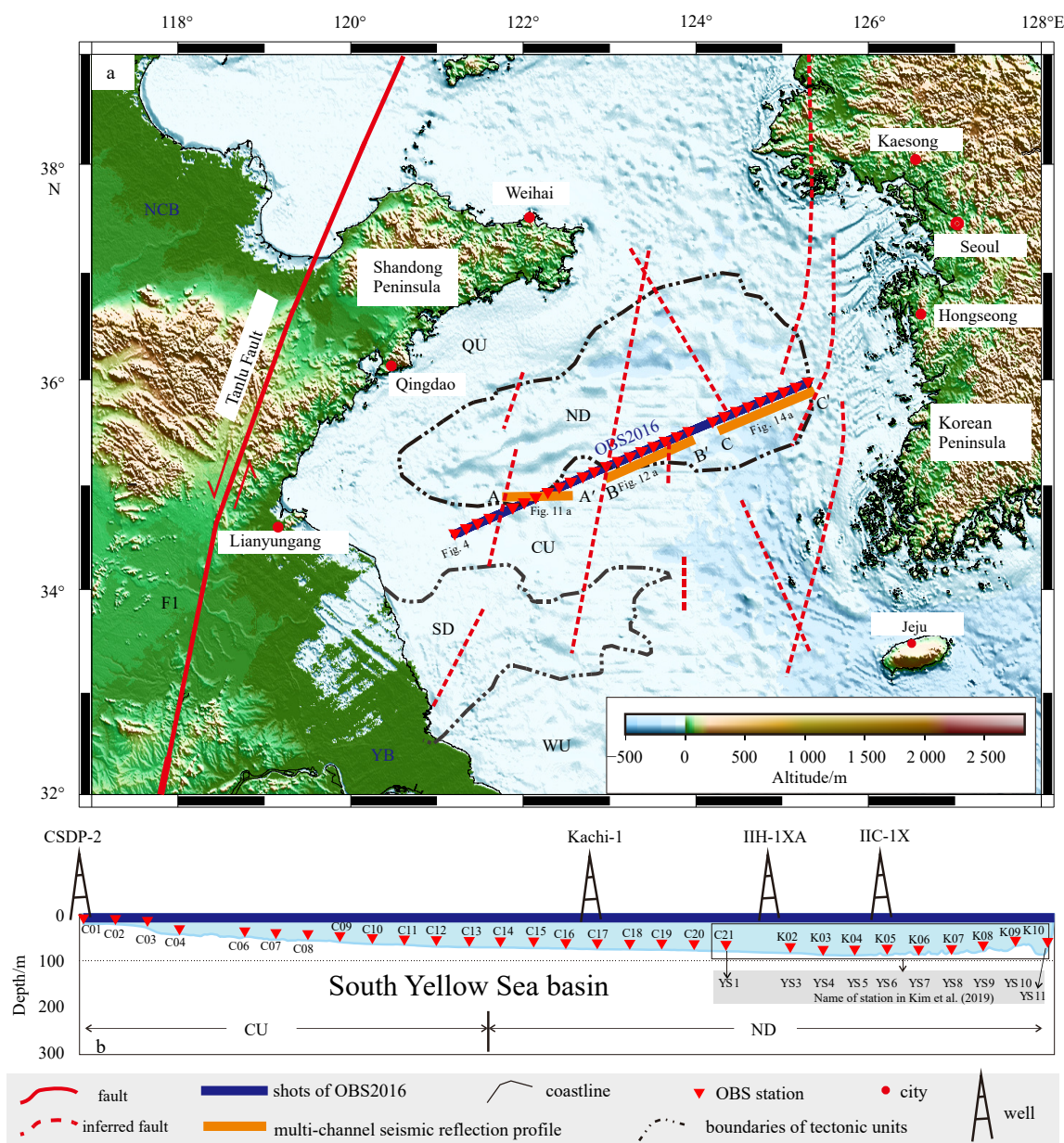


Fig. 1. An overview of the study area and data. a. Location of the South Yellow Sea and the survey lines; b. layout of the effective ocean bottom seismograph (OBS) stations and wells in the tectonic units. Well locations are from [Shinn et al. \(2010\)](#) and [Wu et al. \(2019\)](#); inferred faults are from [Hao et al. \(2002\)](#); QU, Qianliyan Uplift; ND, Northern Depression; CU, Central Uplift; SD, Southern Depression; WU, Wunansha Uplift; NCB, North China Block; YB, Yangtze Block.

complex structures in the South Yellow Sea basin ([Hao et al., 2002, 2010](#); [Huang et al., 2010](#); [Zhang et al., 2013](#); [Li et al., 2017](#); [Tao et al., 2018](#); [Pang et al., 2019](#)). Geophysical surveys have been conducted to uncover the structure of the basin.

The structure of the sedimentary basin is essential for the study of its tectonic background and evolutionary history. However, the detailed tectonic features and stratigraphic distribution of the South Yellow Sea basin could not be fully and accurately evaluated from the west to the east owing to the low resolution of gravity and magnetic data of the upper crustal structures ([Hao et al., 2002](#); [Zhang et al., 2014](#)), the lack of high-resolution seismic data, and unilateral studies on the South Yellow Sea basin between China and South Korea ([Wang et al., 1999](#); [Shinn et al., 2010](#); [Hong and Choi, 2012](#); [Wu et al., 2015](#); [Cai et al., 2019](#); [Qi et al., 2019](#)). On the other hand, due to the large thickness and

the strong basement reflection interface in the continental basin, the marine residual basin images are vaguely based on multi-channel seismic data, and there are uncertainties regarding the existence and age properties of marine residual strata in the South Yellow Sea basin ([Hao et al., 2002](#); [Zhang et al., 2007](#)) that urgently require the support of seismic data.

The use of seismic velocity provides a better understanding of the internal geotectonic setting and evolution of the sedimentary basin ([He et al., 2016](#); [Zou et al., 2016](#); [Zhao et al., 2018](#); [Kim et al., 2019](#)). In the South Yellow Sea basin, pre-existing seismic velocity values are provided by drilled wells, vertical seismic profiles (VSPs), and the stacking velocity spectrum of multi-channel seismic data ([Wu, 2009](#); [Liu et al., 2016](#); [Zhang et al., 2018](#); [Wu et al., 2019](#)). However, a widespread variation between the velocity and depth can result in significant errors during the layer velocity cal-

ulation using the super-gather velocity spectrum (Yang et al., 2015). Additionally, the depth and sparse distributions of wells (Shinn et al., 2010; Wu et al., 2019; Gao et al., 2020) also limit the velocity applications in the entire South Yellow Sea basin. For regions with sea water, the use of velocity anomalies from tomography of seismic data (Weekly et al., 2014) can accurately interpret the geometry of the sedimentary basins. Based on the seismic signals obtained by the low-frequency air gun combined with ocean bottom seismographs (OBSs), previous studies have reported the velocity structure of the western part of the South Yellow Sea basin (Zhao et al., 2019a). The velocity field of the sedimentary basin also refers to the seismic velocity values in the Subei Basin (Wu, 2009), which has a similar tectonic evolution and residual sediments. A fine velocity structure can provide a better basis for the time-depth conversion and migration imaging for the exploration of sedimentary formation. Additionally, the fine velocity structure enables the accurate velocity imaging of the deeper structure, which is of great significance for studying the tectonic evolution and deciphering the relationship of the geological units between the surrounding areas.

This study describes a continuous NEE-trending P-wave-velocity model of the South Yellow Sea basin by using first-arrival-time tomography from a wide-angle OBS array (OBS2016, location is shown in Fig. 1). Based on the geological background, formation assemblage, and velocity structure measurements of well CSDP-2, we also discuss the structural velocity arrangement related to the sedimentary basin, identify the assemblage relationships of continental and marine sedimentary strata distribution along the survey line, and determine velocity indications for the local tectonic evolution of the upper crustal framework in the South Yellow Sea basin.

2 Geological setting

The South Yellow Sea basin spans an area between 121°–126°E, with a structural pattern of E–W zonation and S–N blocking located along the main body of the Lower Yangtze Block. The tectonic evolution (Zhang et al., 2013; Li et al., 2017; Lei et al., 2018a; Kim et al., 2019) of the South Yellow Sea basin is as follows: (1) from the Sinian to the middle and late Triassic, the South Yellow Sea basin assumed a sedimentary platform forming the marine Mesozoic–Palaeozoic basin. (2) Collision between the North China and the Yangtze blocks resulted in the uplift of the entire South Yellow Sea basin. The marine Mesozoic–Palaeozoic structure was folded, uplifted, and denuded, forming the basement of the later continental basins. (3) Since the late Cretaceous, the South Yellow Sea showed the characteristics of an extensional fault depression, thereby developing a continental fault depression basin. (4) During the Neogene and Quaternary, the tectonic movements tended to be calm and the basin experienced subsidence.

Various geophysical characteristics were formed as a result of multiple tectonic movements from the basement to the cover layer, and from the north to the south. Based on the distribution of the Cretaceous–Palaeogene strata, the South Yellow Sea basin comprises the Qianliyan Uplift (QU), Northern Depression (ND), Central Uplift (CU), Southern Depression (SD), and Wunansha Uplift (WU). The ND is a fault-controlled depression originating from the late Cretaceous period with an NEE orientation underlain by the Mesozoic–Palaeozoic residual basin (Huang et al., 2010; Zhang et al., 2014). The CU is a nearly EW-trending structure where the Mesozoic–Palaeozoic marine strata are directly covered by the Neogene strata (Zhang et al., 2009). Regional geological surveys and drilled wells revealed that continental depos-

its (Zhang et al., 2013) in the South Yellow Sea basin mainly comprised sandstones, mudstones (P-wave velocity: 1.7–4.8 km/s), and conglomerate, wherein the thickness of the continental sedimentary formation was over 6 km (Zhao et al., 2019b). Carbonate rocks (5–6.6 km/s), sandstones (4.5–5.2 km/s), mudstones (3.6–4.7 km/s), and metamorphic rocks (>6.3 km/s) are widely distributed in the marine residual strata (Lei et al., 2018b; Wu et al., 2019). Overall, the Bouguer gravity anomaly (Hao et al., 2002) showed that the South Yellow Sea basin represents a positive anomaly with obvious zoning and belting characteristics. Moreover, the gravity values were larger in the uplift than those in the depression. The magnetic anomaly (Hao et al., 2002) of the South Yellow Sea is characterised by a wide and gentle block-shaped positive value on a calm negative field background. Additionally, the dense and disorderly positive anomalies extend over hundreds of kilometres in the NE direction, north and south of the basin.

3 Seismic data and methods

3.1 Wide-angle seismic data

Wide-angle seismic data from ocean bottom seismographs (OBS2016) were acquired across the South Yellow Sea basin along an NEE-trending transect by the Qingdao Institute of Marine Geology, the Institute of Geology and Geophysics of the Chinese Academy of Sciences, and the Korea Institute of Ocean Science and Technology in 2016. In the survey, air gun arrays were combined with OBSs to acquire data over 405 km. A total of 4 502 air-gun shots, with 90-m spacing, were used with an inspiring volume of 6 640 in³ (1 in³=0.000 016 387 m³). The receivers consisted of 31 OBSs spaced at 13.5-km intervals that recorded signals at a sampling rate of 250 Hz or 100 Hz. Continuous and clear first-arrival waves were observed in 29 common receiver gathers (Zhao et al., 2020) after data processing and signal enhancement at a resampling rate of 250 Hz. OBSs YS1 to YS11 in Kim et al. (2019) are represented as OBSs C21 and K02 to K10 in this study. Based on the phase consistency of seismic waves and the maximisation of accuracy from the far offsets, the starting positions of the first-arrival waves were obtained from near to far offsets (parts are shown in Figs 2–6 and all positions are shown in Fig. 7; coloured lines). Notably, the time from far (>150 km) offsets with low signal-to-noise ratio were discarded in the inversion.

3.2 Multi-channel seismic data

To constrain the sedimentary structure, we collected multi-channel seismic (MCS) data (Fig. 1a, AA', BB', and CC') acquired in 2007, 2019, and 2016 near the OBS2016 survey line.

Section AA' was acquired by the Qingdao Institute of Marine Geology, and was recorded near the western portion of the OBS2016 (the intersection is at C09). Air-gun sources spaced at 37.5 m intervals were used with an inspiring volume of 2 940 in³ and a working pressure of 2 000 psi (1 psi=6 894.757 Pa). The cable receivers comprised a 456-channel streamer that provided a 76-fold coverage at 12.5 m intervals with a sampling time of 2 ms.

Section BB' was acquired by the Qingdao Institute of Marine Geology, and was recorded along the middle of the OBS2016 survey line using a 600-channel streamer with a group interval of 12.5 m that provided a 150-fold coverage with a sampling time of 2 ms. Air-gun sources spaced at 25-m intervals were used with an inspiring volume of 5 110 in³ and a working pressure of 2 000 psi.

Section CC' was recorded along the eastern portion of the OBS2016 (Shinn et al., 2010; Kim et al., 2019). Air-gun sources

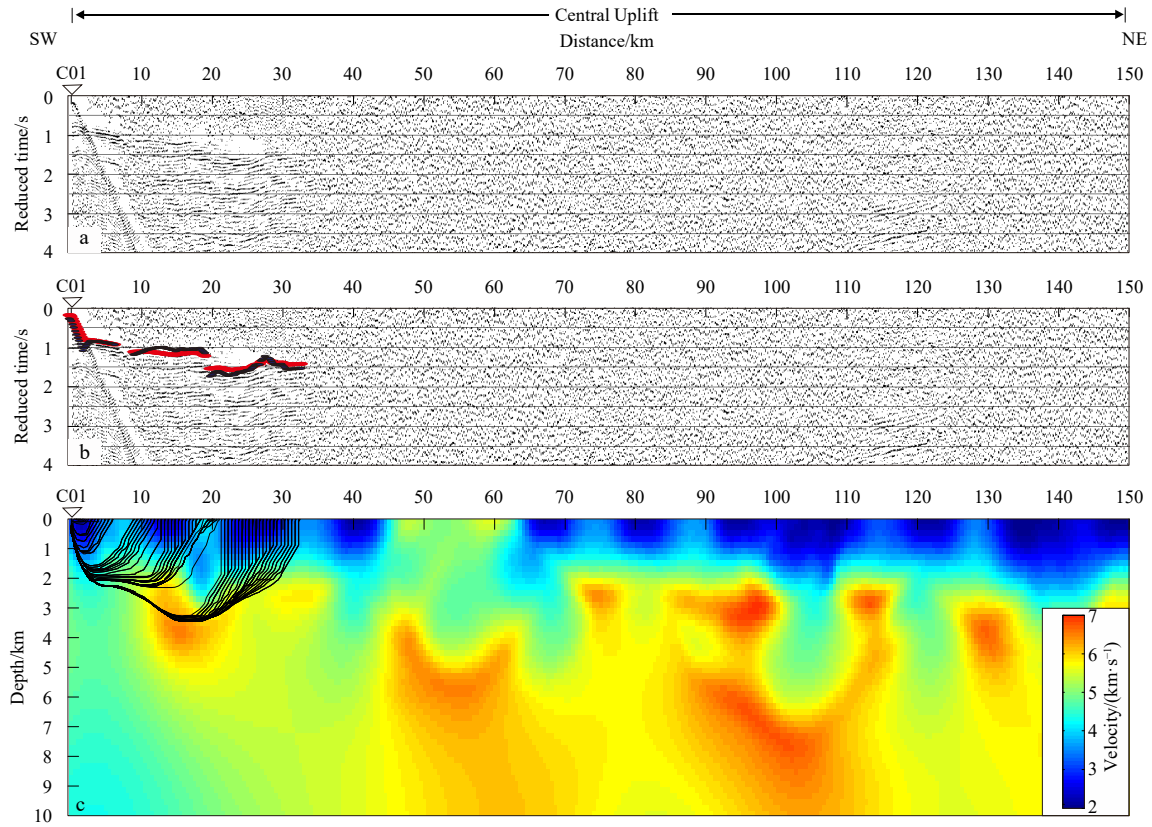


Fig. 2. Profile and time fitting of OBS C01. a. OBS C01 profile; the reduced velocity is 6 km/s; b. picking first-arrival time (red lines) and theoretical calculation travel time (black lines) based on the final velocity model; c. raypaths used in the inversion.

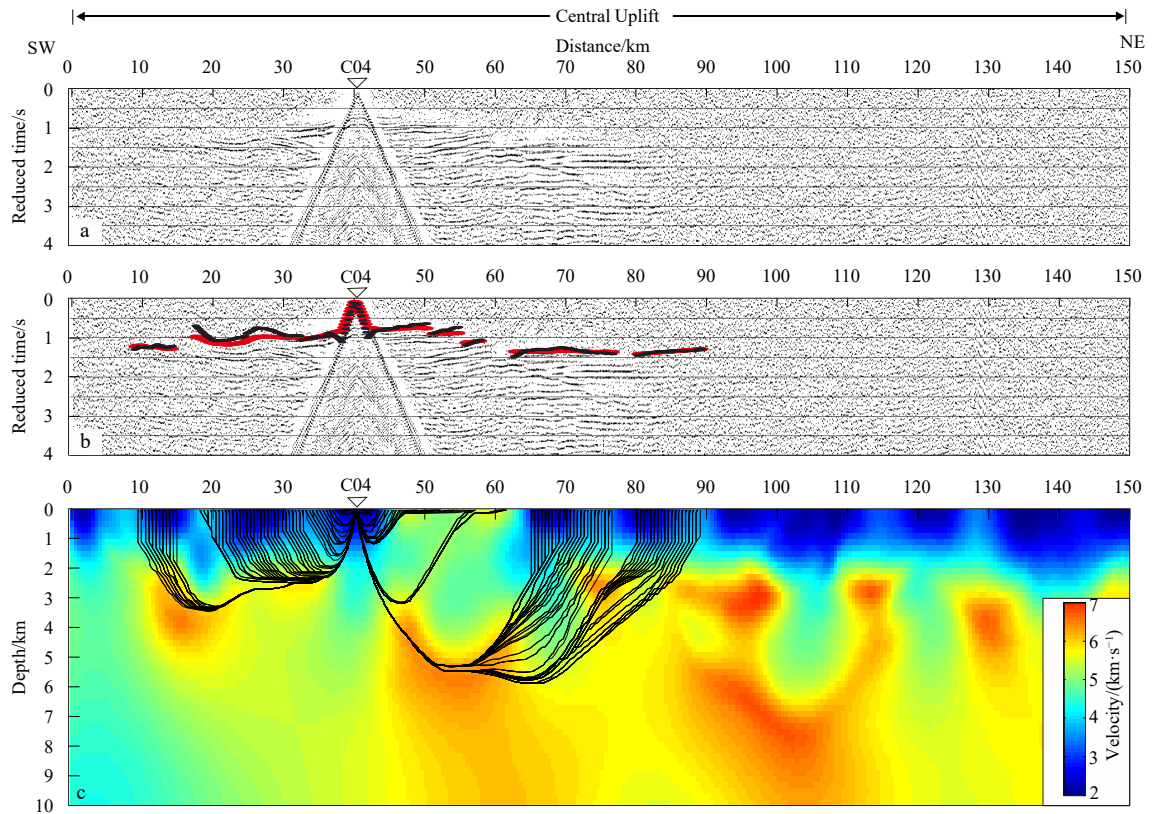


Fig. 3. Profile and time fitting of OBS C04. a. OBS C04 profile; the reduced velocity is 6 km/s; b. picking first-arrival time (red lines) and theoretical calculation travel time (black lines) based on the final velocity model; c. raypaths used in the inversion.

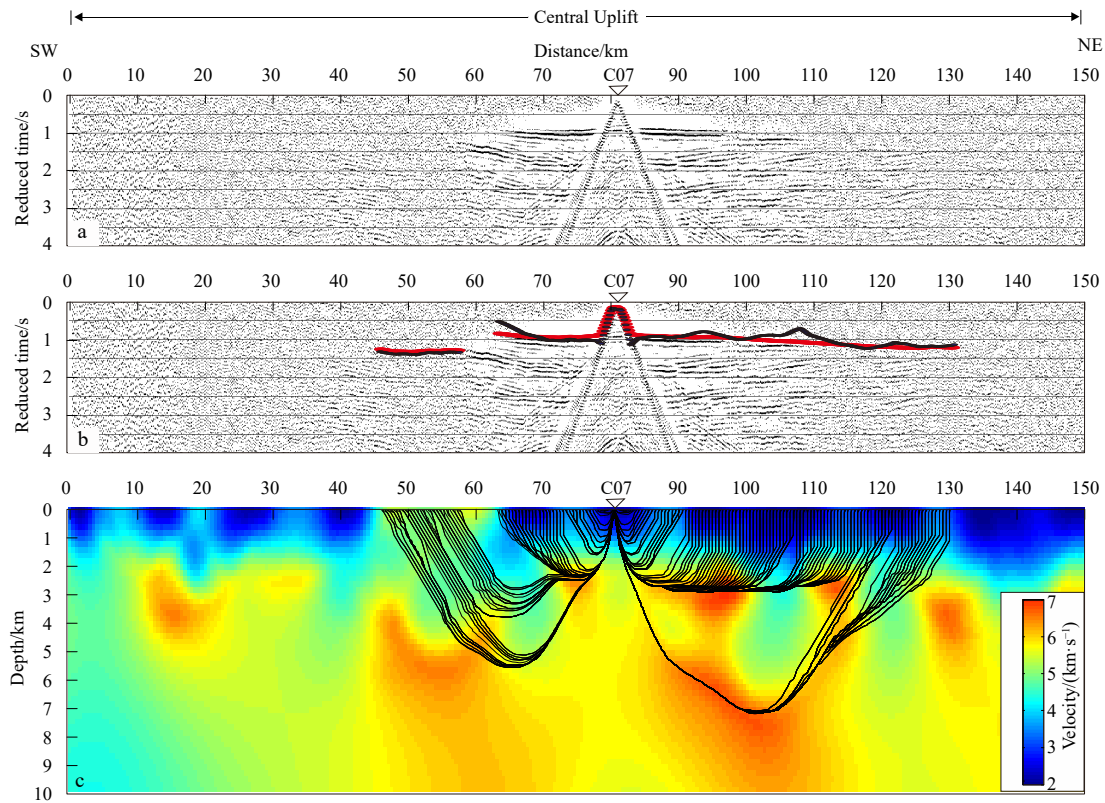


Fig. 4. Profile and time fitting of OBS C07. a. OBS C07 profile; the reduced velocity is 6 km/s; b. picking first-arrival time (red lines) and theoretical calculation travel time (black lines) based on the final velocity model; c. raypaths used in the inversion.

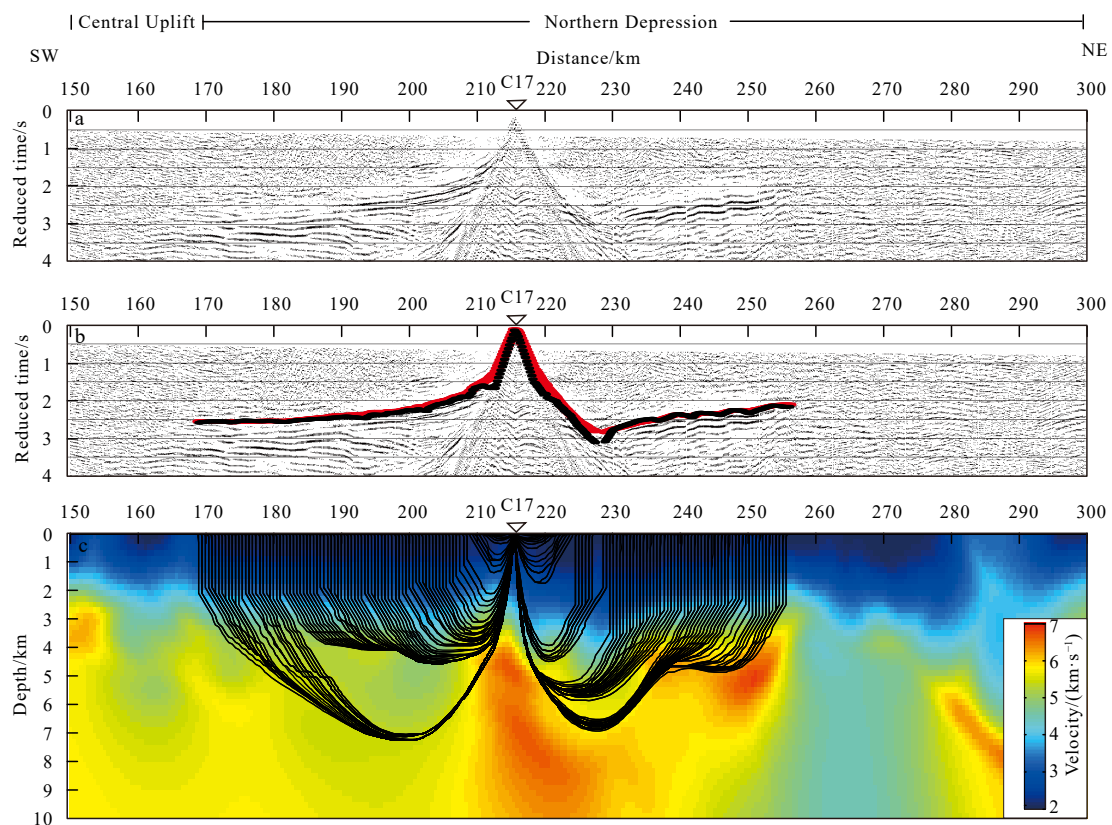


Fig. 5. Profile and time fitting of OBS C17. a. OBS C17 profile; the reduced velocity is 6 km/s; b. picking first-arrival time (red lines) and theoretical calculation travel time (black lines) based on the final velocity model; c. raypaths used in the inversion.

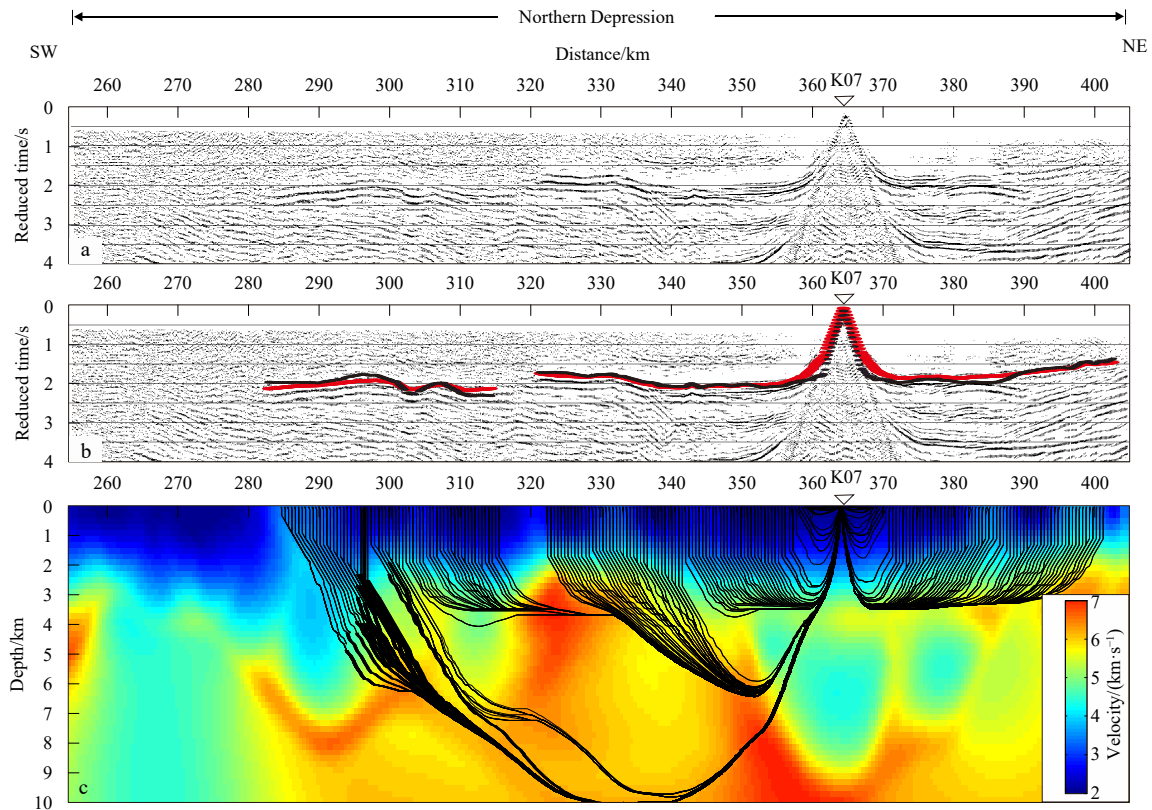


Fig. 6. Profile and time fitting of OBS K07. a. OBS K07 profile; the reduced velocity is 6 km/s; b. picking first-arrival time (red lines) and theoretical calculation travel time (black lines) based on the final velocity model; c. raypaths used in the inversion.

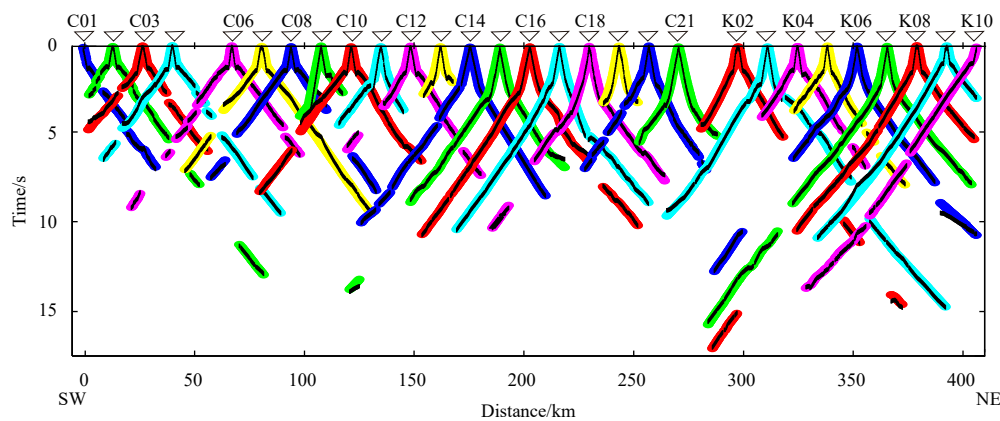


Fig. 7. Picking first-arrival time (color lines) on the OBS gathers and theoretical calculation travel time (black lines) based on the final velocity model (Fig. 8c). Triangles, OBS stations of OBS2016.

spaced at 6 s intervals were used with an inspiring volume of 750 m^3 . The cable receivers comprised a 32-channel streamer that provided a 13-fold coverage at intervals of 6.25 m.

The processing of the MCS data included the geometry assignment, band-pass filtering, deconvolution, velocity analysis, common- and mid-point stacking, and migration. AA' and BB' were processed by Qingdao Institute of Marine Geology and CC' was processed by Kim et al. (2019).

3.3 Methods

Since computerised tomography (CT) was introduced into geoscience, it has been widely used in earthquake and seismic data imaging and improved the study of complex tectonic areas

(Aki and Lee, 1976; Zelt and Barton, 1998). The P-wave-velocity model in this study was obtained using first-arrival seismic tomography (FAST, Zelt and Barton, 1998). The method is adapted to areas with interface fluctuations and large horizontal and vertical velocity variations as well as to those in the presence of high-velocity interlayers (Hou et al., 2009; Wang et al., 2014; Zou et al., 2016). To obtain the velocity using the first-arrival travel-time from the wide-angle seismic data, the underground region was divided into grids and the velocity distributions in the grid cells were used to simulate the complex underground structure. Furthermore, ray paths were calculated according to the travel-time field. Seismic velocity values in each cell were obtained by solving travel-time equations to achieve the underground structure.

4 Results

4.1 Velocity model

In this study, velocity values of the initial model linearly increased from 2 km/s on the ocean floor to 7 km/s at a depth of 30 km (depths of 0–10 km are shown in Fig. 8b). The parameterised cells were 500 m and 200 m in the horizontal and vertical directions, respectively. After 20 iterations in the inversion, travel-time residuals converged quickly and tended to be stable at 0.13 s. Moreover, the travel-time residuals converge between −0.3 s and 0.2 s after the last iteration (Fig. 9).

P-wave velocity structures of the sedimentary basin were inferred by first-arrival tomography beneath the OBS2016, and are shown in Fig. 8c. In the image, the ray's coverage (Fig. 8d) deteriorates at a depth of greater than 5 km owing to a decrease in the velocity gradient at depth and less travel-time picks for far offsets. Beneath the eastern part of the survey line, the ray's depth is over 10 km. The dense distributions of the ray paths at depths shallower than 5 km provide inversion results with high reliability. Uneven rays in the horizontal and vertical directions reveal the

complexity of the velocity structure. The velocity structures of the inversion model (Fig. 8c) within a depth of 5 km (local is within a depth of 10 km) are discussed considering the thickness of the superposed sedimentary basin and ray-paths.

4.2 Resolution of the tomography

To test the resolution, we conducted a checkerboard test using the same parameters as those in the real-data tomographic inversion. The checkerboard velocity model spaced high- and low-velocity perturbations (from −5% to 5%) shown in Fig. 10a was added regularly to the final seismic velocity model shown in Fig. 8c. The checkerboard sizes are 25 km and 2 km in the horizontal and vertical directions, respectively. The reconstructed checkerboard velocity model from the inversion shows that the locations of the velocity anomalies at depths shallower than 5 km were recovered reasonably well (Fig. 10b).

4.3 Multi-channel seismic interpretation

The sedimentary units are separated by two reflectors (T2 and T8) with moderate-to-high amplitudes in the migration time pro-

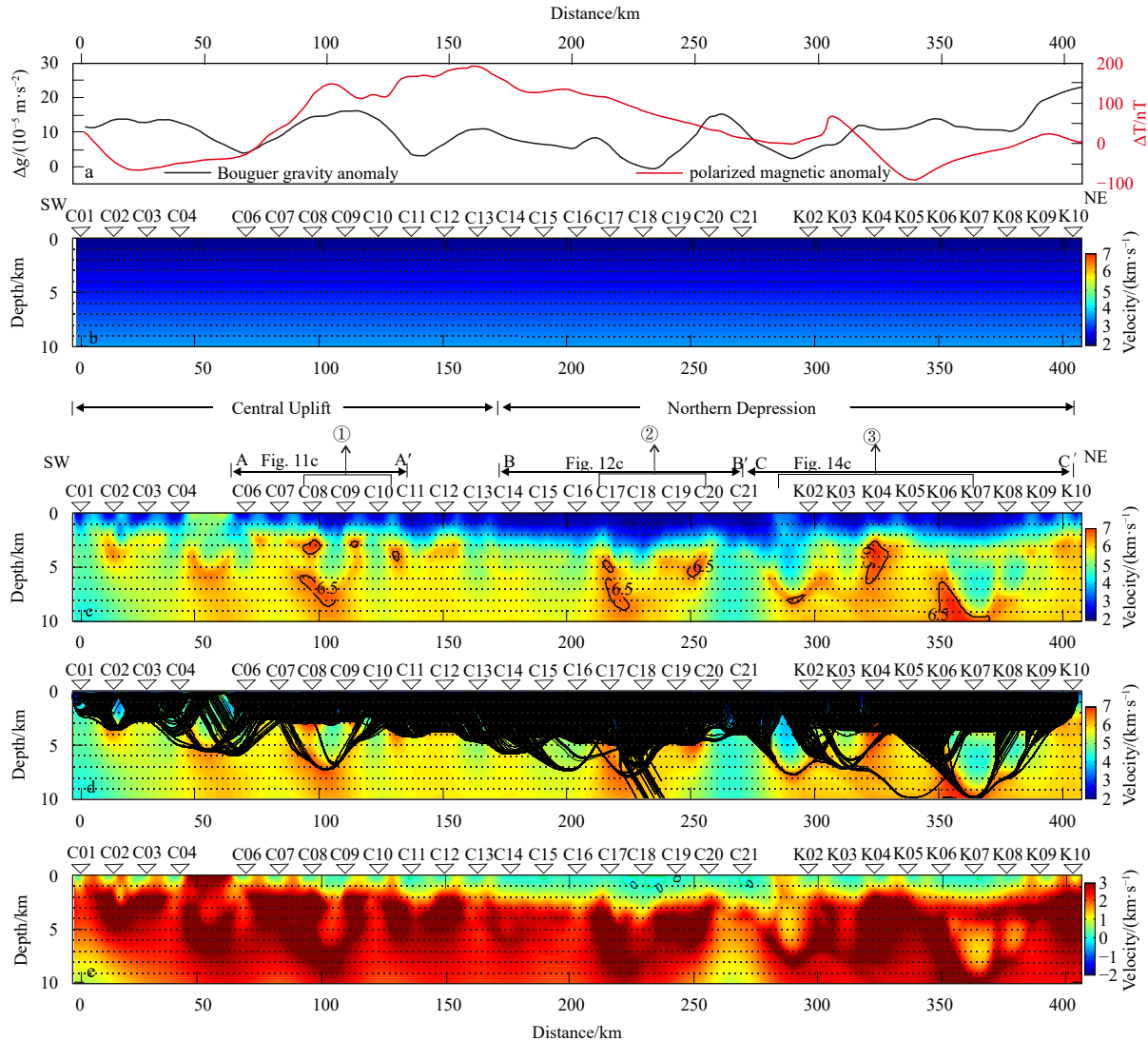


Fig. 8. Magnetic and gravity anomaly and tomographic velocity model beneath OBS2016. a. Magnetic and gravity anomaly (Zhang et al., 2022); b. initial velocity model; c. inverted seismic velocity with contours showing the velocity values (6.5 km/s, black lines); d. ray-paths (black lines) in the inverted velocity; e. differential velocity calculated by the inverted velocity from the initial velocity model with contours showing the velocity values (0 km/s, green lines). Triangles, OBS stations of OBS2016.

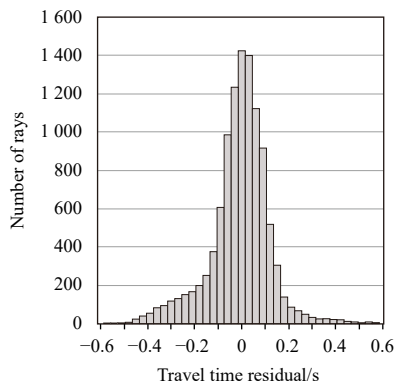


Fig. 9. Travel-time residuals of the final model. Bin are 30-ms wide; picks refer to the number of observations.

files. T2 is the bottom interface reflection of the Quaternary and Neogene (N+Q; constrained by the CSDP-2 well; [Table 1](#)) and it is relatively flat. T8, with dramatic crests and troughs, is the bottom interface reflection of the Mesozoic–Cenozoic continental sediments (constrained by the Kachi-1 well; [Yi et al., 2003](#)), which is a regional unconformity formed during the Indosinian movement in the South Yellow Sea basin. The marine strata before the Indosinian period are clearly imaged in the BB' profile (location is shown in [Fig. 1a](#)), but are not clearly distinguished in the AA' and CC' profiles (location is shown in [Fig. 1a](#)) owing to the small capacity of the air gun source and the small active section of the streamer. Disordered thrusting nappes appear between 1 s and 3 s in the AA' profile ([Fig. 11b](#)). According to the events, the shape characteristics of the material upwelling on the AA', BB', and CC'

profiles are noteworthy with the destruction of T8. All upwellings are discussed in detail in Section 4.4.

4.4 Joint interpretation

The OBS2016 passes through the CU and ND in the South Yellow Sea basin ([Fig. 1b](#)). Strong velocity variations are easily identified at depths of 3–10 km. The velocity model shows characteristics of a multi-layer structure ([Fig. 8c](#)). The structure is characterised by low-velocity strata (<4.5 km/s), high-velocity anomalies (>6 km/s), and sub-high velocity strata (5–6 km/s) varying from shallow to deep. Subsequently, we discussed the velocity section in three parts in conjunction with other geophysical data.

4.4.1 Features and nature in the Central Uplift

In the west (0–165 km and C01–C13; [Fig. 8c](#)), along the survey line OBS2016, strata with a P-wave velocity lower than 4.5 km/s are relatively thin, reaching 5 km/s at a depth of 1–2 km. The thicknesses of these low-velocity anomalies slightly increase to the east, while the high-velocity interlayers (>6 km/s) with low thicknesses of approximately 1–2 km occur at depths of 2–5 km. The CSDP-2 well in CU indicates that the Mesozoic marine strata are distributed underneath the extremely thin Neogene and Quaternary (depth: 863 m, without seawater). Additionally, relatively low-velocity Palaeozoic sandstones and mudstones (3.6–5.2 km/s) underlie the Palaeozoic high-velocity carbonate rocks (5–6.6 km/s; [Wu et al., 2019](#)). Velocity in CU from the tomography inversion is consistent with the VSP velocity of the CSDP-2 well ([Table 1](#)). Special consideration was given to partial high-velocity anomalies (>6.5 km/s; ①, [Figs 8c and 11](#)). We compared our tomographic velocity model (between C06 and C11) with the seismic reflection data (Line AA'). The time-based seismic-reflection pro-

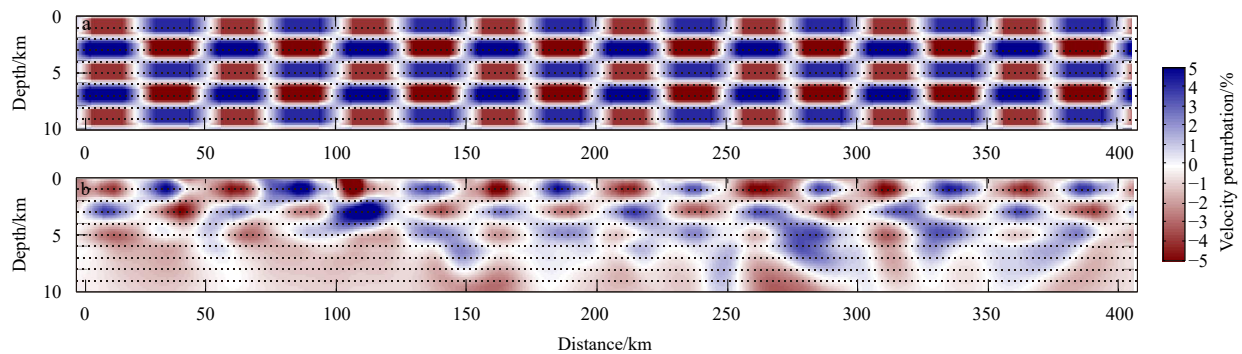


Fig. 10. The checkerboard test for the tomography. a. High- and low-velocity perturbations; b. the reconstructed checker-board velocity model. The checker-board sizes: 25 km×2 km.

Table 1. Strata velocity parameters calculated by vertical seismic profile data (after [Wu et al. \(2019\)](#))

Depth/m (from the seafloor)	System	Formation	$V_p/(m \cdot s^{-1})$ (max–min/average)
629	Cenozoic	N+Q	1 600–2 332/1 803
863	Triassic	T ₁ q	4 341–6 157/5 387
915	Upper Paleozoic	P ₃ d	4 770–5 543/4 889
1 636		P ₃ l	3 605–4 815/4 212
1 649		P ₂ g	4 108–4 239/4 174
1 735		P ₂ q	4 108–5 038/4 308
1 818		C ₃ c	5 678–6 475/5 837
1 960	Lower Paleozoic	C ₂ h	5 170–6 676/5 715
2 020		C ₁ g	4 411–5 262/4 636
2 350		D ₃ w	4 542–5 903/4 812
2 843.4		S ₁	4 586–5 820/4 922

Note: V_p represents P-wave velocity.

file (Fig. 11a) was converted into depth using the root mean-square (RMS) velocity. For better comparison, we overlaid our velocity model (Fig. 11c) onto the multi-channel depth seismic-reflection profile shown in Fig. 11d. These are well preserved marine (N+Q, bottom interface: T2) strata. Beneath ①, the events of the low-velocity Neogene bottom interface (T2) are arching but not disconnected, and the bottom interface reflection events of the Mesozoic–Cenozoic continental sediments (T8) are broken (Fig. 11b). The strata below T2 are unconformable and not completely denuded. The observed anomalies (①) correspond to the location of material upwelling. The buried depth of anomalies is 2–4 km with a short-wavelength magnetic anomaly, which is not caused by the basement of the metamorphic fold (Yang, 2009). In the South Yellow Sea basin, the compaction of the sedimentary

rock was not the main factor for the large velocity values at relatively shallow depths, and the dominant factor was the change of lithology. High gravity and magnetic anomalies occur in this position. The above geophysical data show that the igneous rocks intruded into the original strata together, forming high-velocity anomalies. After partial denudation, the high-velocity anomalies remained in the palaeo-geomorphic mountain, especially below C08, and had been buried since the Neogene. We suggest that these igneous activities predate the Neogene and intruded into the continental strata during the Palaeogene.

4.4.2 Features and nature in the west of the Northern Depression

Low-velocity anomalies (<4.5 km/s) are clearly observed in the middle, that is, at depths of 165–270 km and between

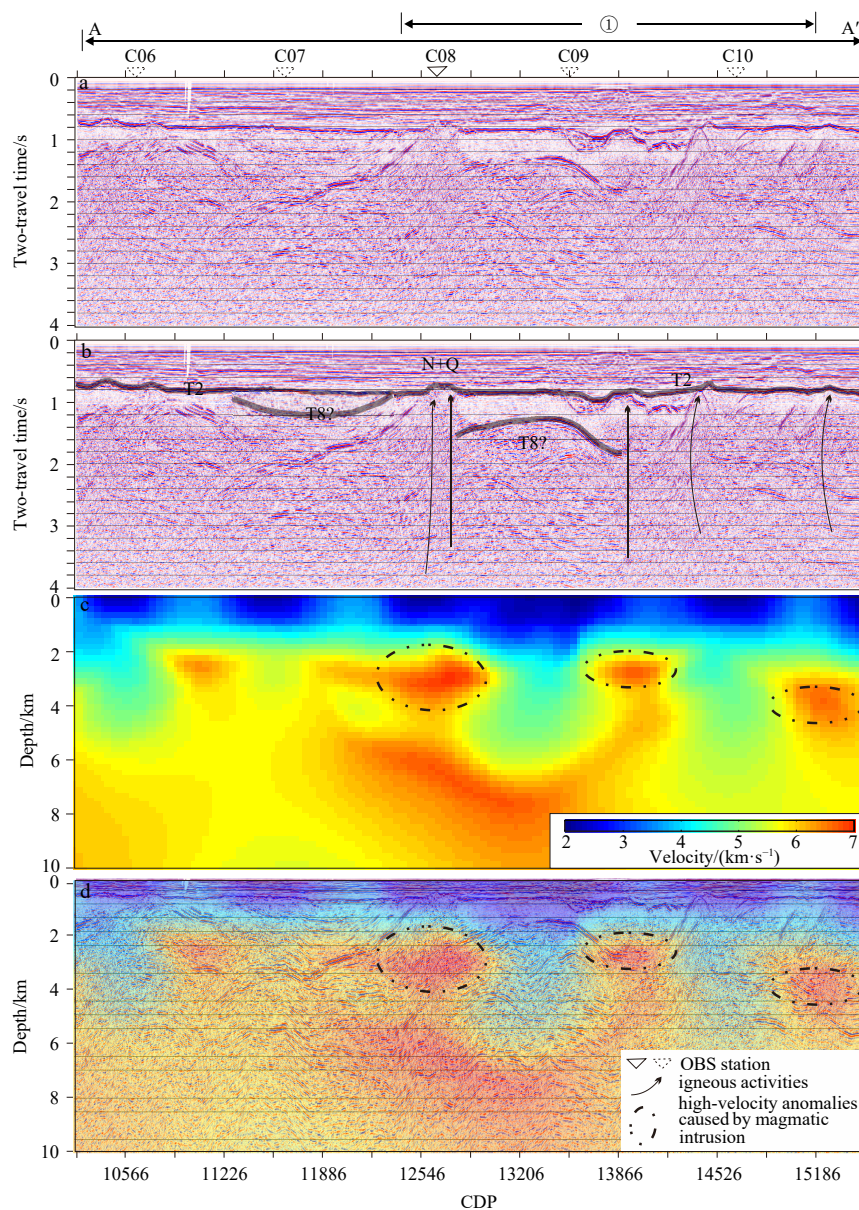
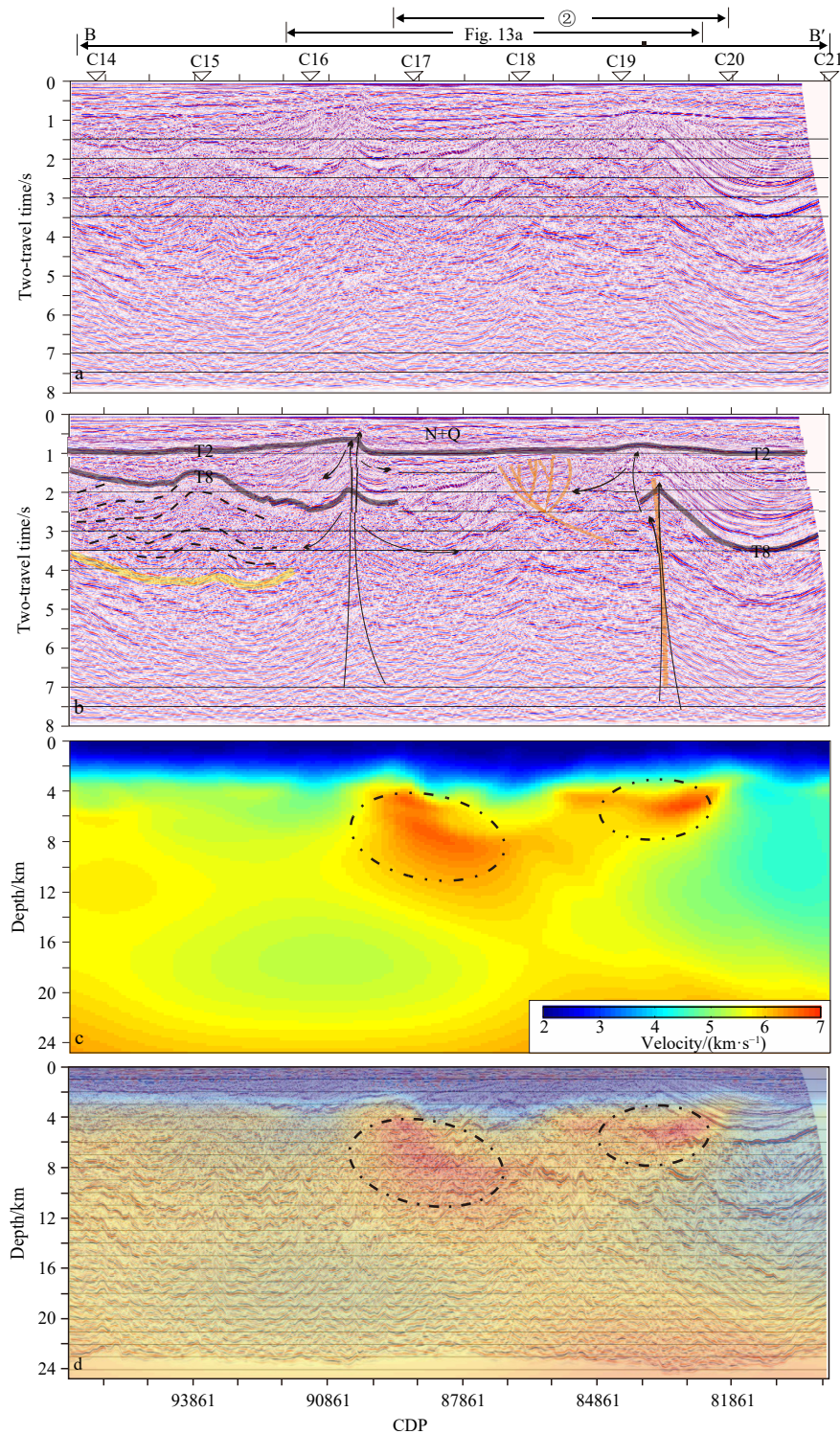


Fig. 11. Joint interpretation of the velocity model and multi-channel seismic reflection. a. AA' multi-channel time seismic-reflection profile across the OBS2016; b. AA' multi-channel time seismic-reflection profile with geological interpretation; c. inversion velocity model; d. overlapped profiles of seismic velocity beneath parts of the OBS2016 and depth seismic-reflection profile. Q: Quaternary; N: Neogene; the gray transparent lines T2 and T8 is the bottom interface of the Neogene and continental basin, respectively; CDP: common depth point.

C14–C21, and along the survey line. The low velocity zone with a thickness of 3 km (local thickness is approximately 6 km) represents the Neogene–Quaternary marine and Mesozoic–Cenozoic continental deposits. Under low-velocity anomalies, some parts of the strata show high (>6 km/s) and sub-high (4–6 km/s) velocities in the horizontal direction. Large-scale block and high-velocity anomalies >6.5 km/s (②, Figs 8c and 12) exist with a thickness of over 5 km.

We compared our tomographic velocity model to seismic reflection data beneath line BB' (location is shown in Fig. 1a). The

time-based seismic-reflection profile (Fig. 12a) was converted into depth using the RMS velocity. The location of the reflectors matched well with the drilling strata from Kachi-1 well (Figs 13b–d). For a better comparison, we overlaid our velocity model (Fig. 12c) onto the multi-channel depth seismic-reflection profile shown in Fig. 12d. The results indicate that the interfaces of high- and low-velocity anomalies (4.5 km/s) coincide with the location of strong reflection, which was interpreted as the basement (T8) of the Mesozoic–Cenozoic continental sediments in ND along line BB'.



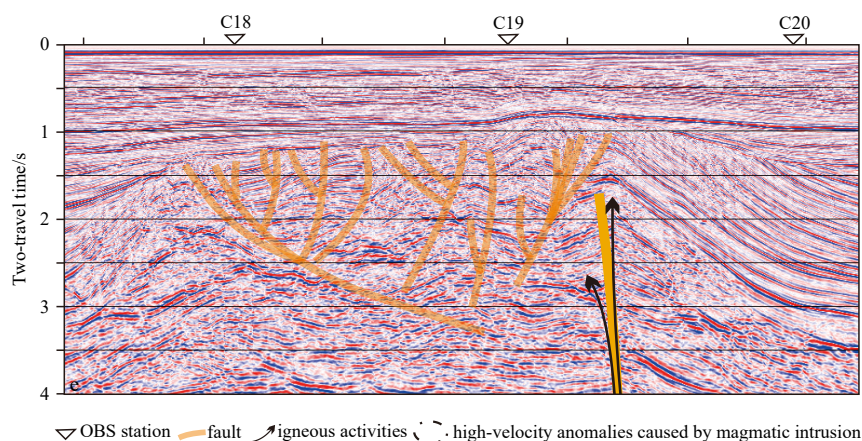


Fig. 12. Joint interpretation of the velocity model and multi-channel seismic reflection. a. BB' multi-channel time seismic-reflection profile alongside the OBS2016; b. BB' multi-channel time seismic-reflection profile with geological interpretation; c. inversion velocity model; d. overlapped profiles of seismic velocity beneath parts of the OBS2016 and depth seismic-reflection profile; e. faults in part of BB' multi-channel time seismic-reflection profile. Q: Quaternary; N: Neogene; the gray transparent line T2 and T8 is the bottom interface of the Neogene and continental basin, respectively; CDP: common depth point.

In the low-velocity syncline (time: >5 s; depth: >10 km; Figs 12b, d; between C19 and C21), the events show good continuity and traceability. These are well preserved marine (N+Q, bottom interfaces: T2), continental (after the Indosinian; bottom interface: T8), and marine (before the Indosinian) strata. To the west (between C16 and C19), the events of low-velocity Neogene bottom interfaces (T2) are arching but not disconnected (Fig. 12b). Conversely, neither events in the high-velocity areas are characterized by disorder and poor continuity (Fig. 13a, blue line). Notably, they appear as though the continuous strata were destroyed. Further down, the events remained discontinuous, although they became relatively better ordered (Fig. 13a, red line). We suggest that a strong compression occurred during the evolution of the South Yellow Sea basin that caused the formation of folds in the middle of the OBS2016 after the Indosinian movement. Subsequently, the possible anticline (between C17 and C19) was denuded, and the strata were destroyed (Figs 12e and 13a). Additionally, faults existed between the syncline and anticline (Fig. 12b). As mentioned in Section 4.2, material upwellings (Fig. 12b; black lines with arrows) occur around this location. Kachi-1 well (Fig. 13c) is located near C17. Late Jurassic or early Cretaceous volcanic activities (aphanitic andesite and basalt) and rhyolite tuff were found at depths of 2 500 m and 2 362 m (Yi et al., 2003), which were destroyed by the nearby material upwellings (Fig. 12b; black lines with arrows). The arching T2, the broken T8, and the overlapped strata reveal that T2 is a flexural phenomenon resulting from formation compression, rather than an arch of material upwelling. Based on the high-velocity anomalies (>6.5 km/s, ②, Fig. 8c), damaged events, well data, larger positive gravity anomaly, and positive magnetic anomaly (Fig. 8a, Zhang et al., 2022), we suggest that the upwelling material was magma. From above, during the Palaeogene, igneous rocks intruded into the continental and marine strata over a wide range in this possible anticline and caused positive gravity and magnetic anomalies.

The high velocity to the right side (between C17 and C19) of the material upwelling position (between C16 and C17) is affected by igneous activities, which is not obvious to the left side (between C14 and C16; Fig. 12c). In the inversion model, the left area presents relatively lower velocities (4.5–5.3 km/s, Fig. 12c)

compared with the surrounding structure. T2 and T8 are preserved in the time profile, but many other events have disappeared (Fig. 12b) between C15 and C16. The underlying formation is unconformable by T8. We suggest that the Mesozoic–Palaeozoic marine strata were compressed in the Indo-Chinese period and formed a broad and gentle anticline (black broken line; Fig. 12b) in this area. The anticline slipped along the reflector near 4 s in the time profile (yellow line; Fig. 12b), and the upper part of the marine strata was weathered, denuded, and finally buried by T2 and T8. Events between C14 and C15 become continuous and near parallel beneath T8 with a sub-high velocity (4.5–6 km/s, Fig. 12b). We speculate that they comprised the marine residual strata during the Mesozoic–Palaeozoic.

4.4.3 Features and nature in the eastern part of the Northern Depression

The thickness of the low-velocity anomalies (<4.5 km/s) is approximately 3 km in the east (270–400 km, C21–K10) along the survey line OBS2016 (Fig. 8c). These strata gradually thin from the west to east with a flat bottom interface and reach 1 km at the eastern end of OBS2016. The velocity is consistent with the information from the wells (IIH-1XA and IIC-1X, locations are shown in Fig. 1b) in the ND. The low-velocity bodies with a depth of more than 5 km in the east (beneath K06–K08) and west (beneath C20–K02) correspond to the syncline in the multi-channel seismic profile (Fig. 14a), which are the Mesozoic–Cenozoic continental deposits (depth is within 6 km). The high-velocity bodies are discontinuous with a maximum thickness of over 3 km and they become blurred in the east. Moreover, considering the parts of the high-velocity anomalies (>6.5 km/s, ③ (Figs 8c and 14) shows sudden events (T8), interruptions, and a blank reflection in the multi-channel seismic profile (Fig. 14b), with a disordered reflection around 1 s (beneath K04, Fig. 14d). The horizontal continuous events (above 2 s, Fig. 14b) and stable velocity (above 3 km, Fig. 14c) on the left (beneath K03) and right (beneath K05) sides reveal that the continental strata (after the Indosinian movement) on both sides were preserved. Based on the almost complete bottom interface of the Neogene, the pull-down events near 1 s, and damaged T8, we suggest that igneous activities probably occurred during the Palaeogene. Compared with those

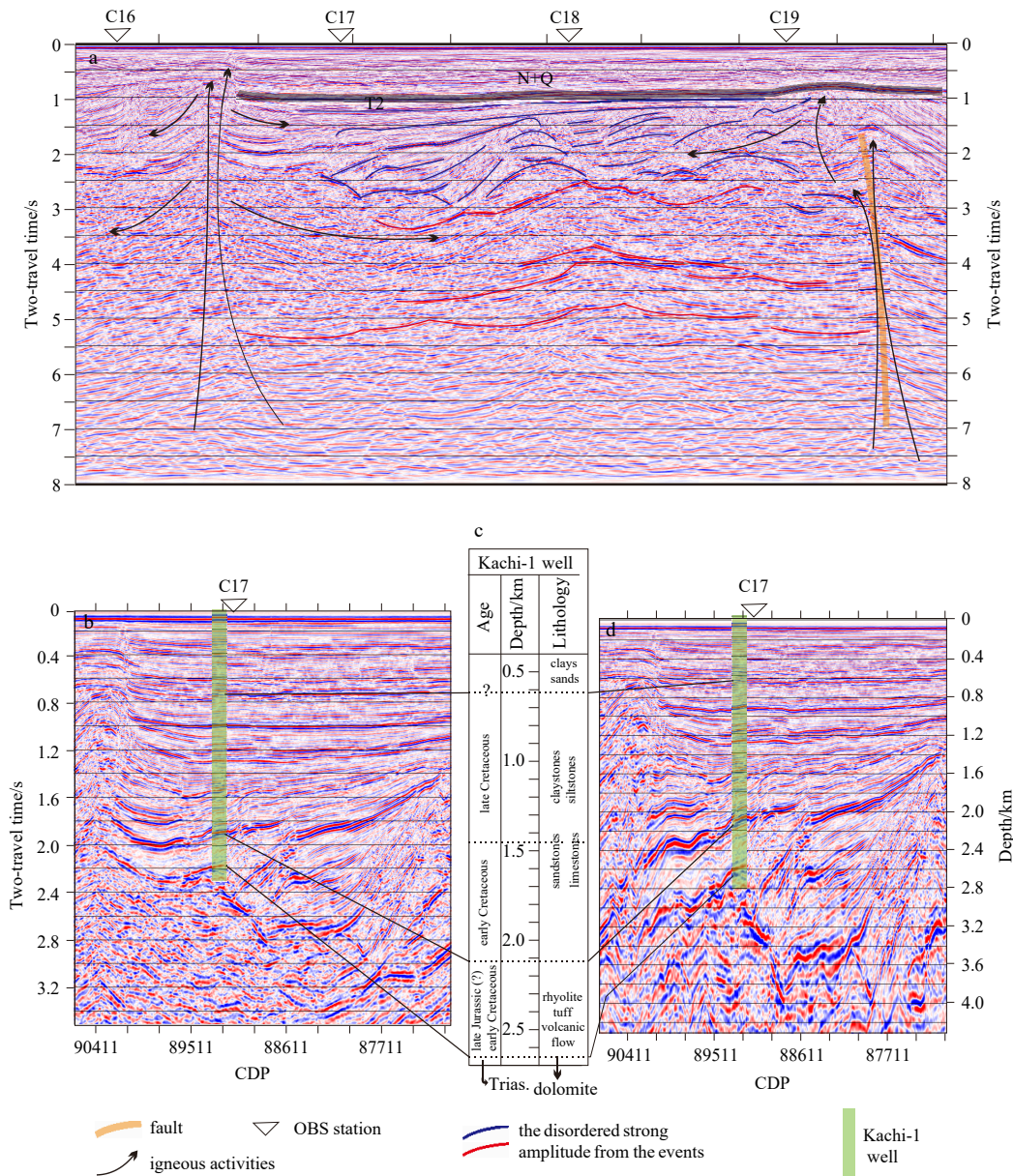


Fig. 13. Joint interpretation of the well and the multi-channel seismic reflection data. a. Disordered events in BB' multi-channel time seismic-reflection profile; b. time seismic-reflection profile from the BB'; c. Kachi-1 well information; d. depth seismic-reflection profile from the BB'. Q: Quaternary; N: Neogene; the gray transparent line T2 in a is the bottom interface of the Neogene; Trias.: Triassic; CDP: common depth point.

of the strata below C08, the gravity anomaly below K04 is similar, but the magnetic anomaly reduces (Fig. 4a). We infer that the igneous rocks below K04 are intermediate or/and acidic. Tomography of the OBS data in Kim et al. (2019) (Fig. 7) also shows the presence of a high-velocity body in eastern ND, which is consistent with Fig. 14c in this manuscript (K04 in this manuscript is YS5 in Kim et al. (2019)).

5 Discussion

The South Yellow Sea basin has been sectionally surveyed and studied. In this study, the wide-angle and multi-channel seismic lines across the previously poorly-documented South Yellow Sea basin in the east-west direction further illustrate the pattern of the continental basin, the preservation of the marine residual strata, and the presence of upwelling igneous activities.

Our interpretations of the geological and structural models enable the tectonic reconstruction of the South Yellow Sea basin.

5.1 Different structure of the South Yellow Sea basin

The structures of CU show a recognisable difference with those of ND in the inversion model. The multi-layer structure within a depth of 5 km in CU is clearly observable, while it is locally distributed in ND. The high velocity bodies, both in the CU and ND, also have different properties. In CU, igneous and carbonate rocks coexist in the high velocity interlayers. We inferred that the Mesozoic and Upper Palaeozoic strata in CU were distributed above the high-velocity (>6 km/s) interlayers, and their depth of burial was approximately 1–2.5 km in the inversion model. Additionally, more complete preservation of the Mesozoic–Palaeozoic strata in ND are distributed below C14–C16 with a

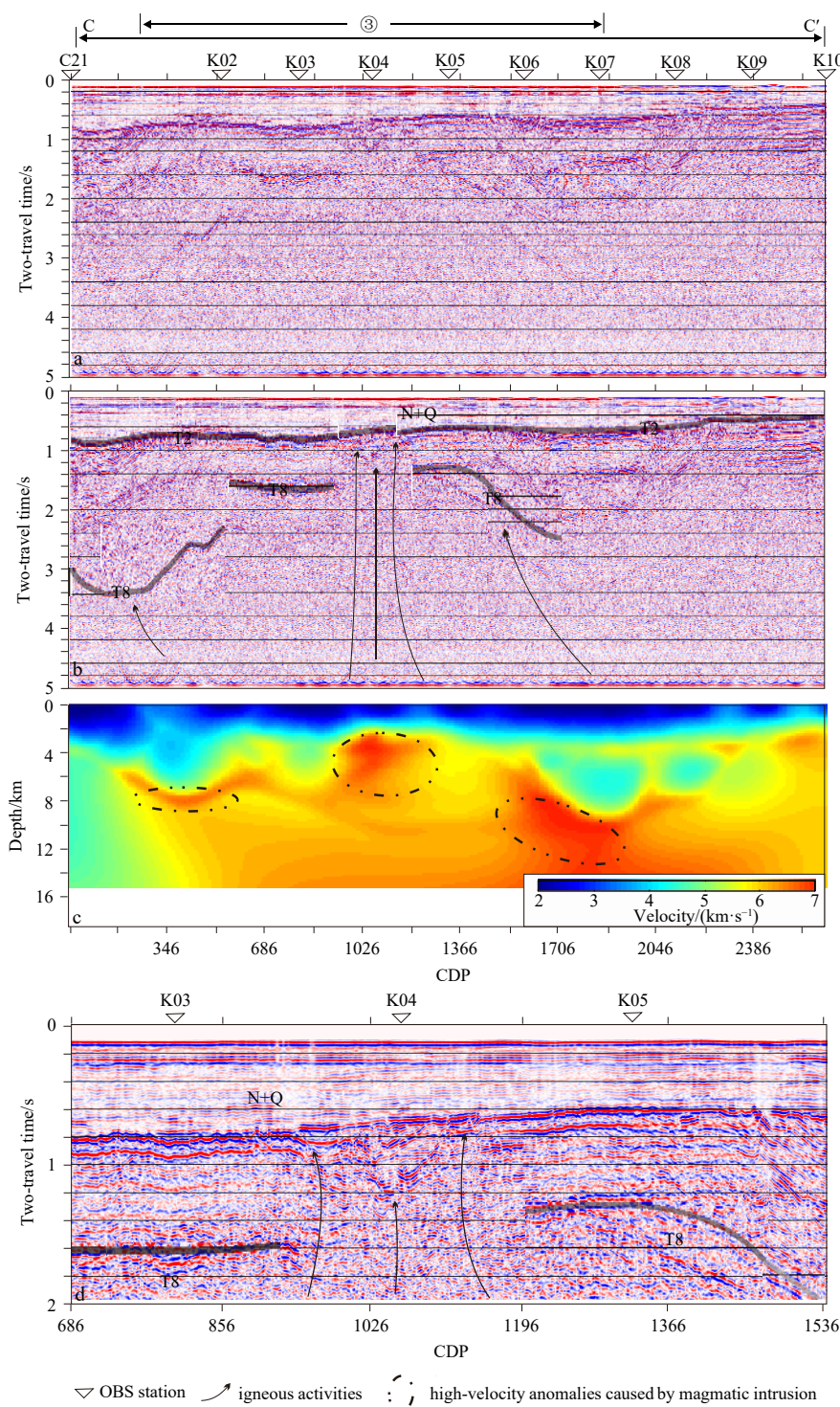


Fig. 14. Joint interpretation of the velocity model and multi-channel seismic reflection. a. CC' multi-channel seismic reflection profile alongside the OBS2016; b. CC' multi-channel seismic reflection profile with geological interpretation; c. the local of the inversion velocity model; d. the local of the multi-channel seismic reflection profile (CC'). Q: Quaternary; N: Neogene; the gray transparent line T2 and T8 in b and d is the bottom interface of the Neogene and continental basin, respectively; CDP: common depth point.

depth of 2.5–5 km and C19–C21 with a depth of 6–12 km. Igneous complexes identified from the high-velocity (>6.5 km/s) anomalies in the ND and CU, which were formed earlier than the Neogene and later than the Cretaceous, had destroyed the pre-Indosinian strata, resulting in poor preservation of the Mesozoic–Palaeozoic strata locally.

In addition, there are significant differences in the velocity models between the east and west in ND, and the average velocity in the east is higher within a depth of 10 km. Preservation of the residual marine strata before the Indosinian period was better in western ND than that in the east beneath the OBS2016 line.

In this study, the structures of the basin in the west are char-

acterised by faults (Figs 12b, e) that are similar to the ones in the western South Yellow Sea basin (Zhao et al., 2019b). On the eastern side, the ND is not obviously controlled by faults, and the area affected by igneous activities is relatively large. According to previous research results (Zou et al., 2016), the strata in western ND are, as an analogy, characterised by a flower structure with broken events in the multi-channel seismic profile and relatively low-velocity anomalies in the velocity model that are indicative of strike-slip faults. In this study, the faults (orange lines beneath C18; Figs 12b, e) with similar characteristics are easily recognised in the basin, and do not cross T2. This provides evidence for the existence of the strike-slip fault in N–S–trending fault systems between the early Cretaceous and the Neogene.

Zhang et al. (2014) computed the buried depth of the crystal basement in the western part of the South Yellow Sea basin ranging from 4–12 km (average depth, 8 km) using magnetic inversion. The comprehensive interpretation profile of the VSP survey, regional stratigraphic distribution, and lithologic characteristics suggest that the buried depth of the crystalline basement was 8.3 km around the CSDP-2 well (Wu et al., 2019). However, the crystalline basement was not distinguished effectively using the velocity model derived from the wide-angle data presented in this study.

5.2 Some igneous activities in the Northern Depression

A simple igneous activity model and its related geological processes beneath the Northern Depression of the South Yellow Sea basin are shown in Fig. 15.

The South Yellow Sea basin is considered to have entered the extension stage that was followed by the overall subsidence after the Indosinian period. Shinn (2015) identified that the half-graben formed by the Cretaceous to Eocene extension subsequently underwent contraction in the western Gunsan basin. Our results support a similar contraction. Based on the interpretations in Section 4.4, we suggest that a strong compression occurred in ND during the evolution of the South Yellow Sea basin that caused the formation of folds in the middle of the OBS2016 after the Indosinian movement (Fig. 15b). Subsequently, the anti-

cline was denuded, strata were destroyed, and the syncline underwent continuous sedimentation (Fig. 15c). Additionally, faults existed between the syncline and anticline, and the strata continued to undergo sedimentation (Fig. 15d) with scattered and multi-point igneous activities in the later stage (Fig. 15e). Finally, strata in the anticline showed discontinuity and disorder (Fig. 13a).

In terms of the geological processes, we suggest that the magmas had originated from the deep crust, while the faults formed a possible igneous migration pathway between the anticline and syncline.

After the Indosinian period, the structure beneath the eastern survey line was relatively simple, allowing igneous intrusion events in the horizontal layered strata, thereby forming igneous rocks (Fig. 15f).

5.3 Possible geological processes in the South Yellow Sea basin

Based on the velocity model proposed in this and previous studies, it is possible to support a tectonic evolution model for the South Yellow Sea basin.

(1) Marine craton basin evolution phase: from the Sinian to the Middle and Late Triassic, the South Yellow Sea basin assumed a sedimentary platform forming the marine Mesozoic–Palaeozoic basin above the metamorphic basement.

(2) Collision uplift and denudation phase: collision between the North China and the Yangtze blocks resulted in the uplift of the entire South Yellow Sea basin. The marine Mesozoic–Palaeozoic structure was folded, uplifted, and denuded, forming the basement of the subsequent continental basins. We observed strong Indosinian unconformity from the collision throughout the South Yellow Sea basin along the OBS2016 line. The extrusion anticline appeared in CU (Fig. 11b), with large scale thrust nappes, and in ND (Fig. 12b). Additionally, marine Mesozoic–Palaeozoic residual strata exist locally after the denudation.

(3) Extensional phase: since the Late Cretaceous, the South Yellow Sea showed activities of an extensional fault depression, thereby developing a continental fault depression basin. However, the presence of inversion stress was identified. A strong compres-

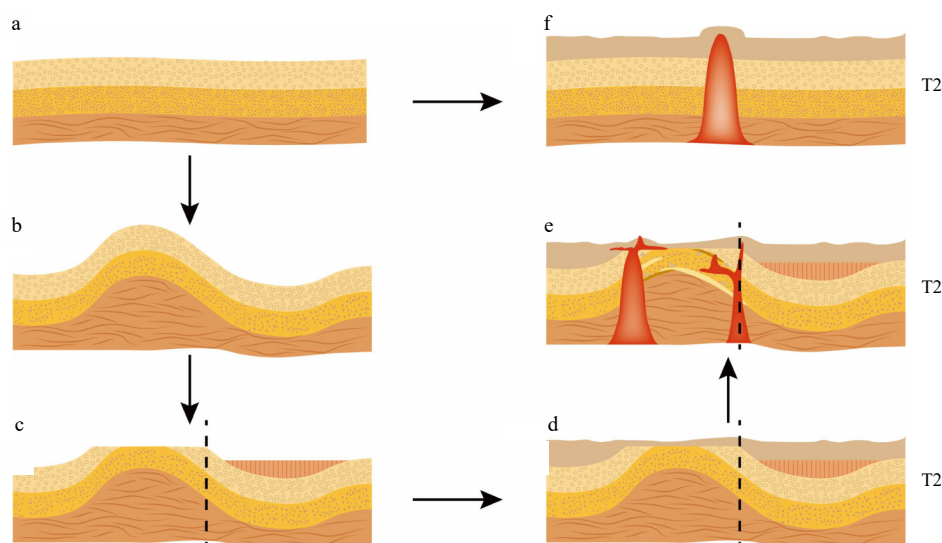


Fig. 15. Simplified graph of igneous activities and related geological processes in the Northern Depression of the South Yellow Sea basin. a. Pre-existing strata structure; b. forming folds in the strata; c. Strata denudation; d. restoring to accept sedimentation; e. igneous activities to the west; f. igneous activities model to the east. Red trees are the igneous activities; the black dashed lines indicate the fault.

sion existed in ND during the evolution of the South Yellow Sea basin that caused the formation of folds (Figs 12a and 13a) in the middle of the OBS2016 line after the Indosinian movement. Subsequently, the anticline was denuded, strata were destroyed, and the syncline underwent continuous sedimentation. During this period, igneous activities existed in the ND and CU (Figs 11, 12 and 14).

(4) Subsidence phase: during the Neogene and Quaternary, the tectonic movements tended to be calm and the basin experienced the subsidence stage.

6 Conclusions

Based on the wide-angle seismic data obtained in 2016, we used the first-arrival tomography method to establish a P-wave velocity model of the South Yellow Sea basin for its interpretation from the west to the east. We conducted comprehensive analysis of the multi-layer velocity structure, gravity data, magnetic data, multi-channel seismic profiles, and drilled well data, and discussed the distributions of the sedimentary strata in the basin.

(1) The velocity model was heterogeneous in both the vertical and horizontal directions, and correlated well with known geological units. The transition from low velocity ~2–4.5 km/s (typical of continental sedimentary fill) to the high (~5–6 km/s) velocity of marine strata was used to assign the depth to the Mesozoic–Cenozoic bottom surface that was ~1 km beneath the Central Uplift, and ~3 km beneath the Northern Depression (local area, ~6 km).

(2) Multi-layer velocity characteristics with high-velocity bodies (>6 km/s) were clearly observed in the Central Uplift within a depth of 5 km, and were locally distributed in the Northern Depression. The igneous complexes formed the high-velocity anomalies (>6.5 km/s) and resulted in the poor preservation of Mesozoic and Palaeozoic marine strata. The possible locations of undamaged Mesozoic and Palaeozoic residual strata by igneous activities are distributed in the Central Uplift and in the western part of the Northern Depression beneath OBS2016.

(3) After the Indosinian movement, the strong compression that existed during the extensional phase caused the folds in the Northern Depression.

This study will be useful for the reconstruction of the regional tectonic evolution and the exploration of the Mesozoic and Palaeozoic marine residual strata in the South Yellow Sea basin.

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