Upper crustal structure beneath the northern South Yellow Sea revealed by wide-angle seismic tomography and joint interpretation of geophysical data

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Mapping the crustal structure beneath the South Yellow Sea (SYS), which includes the collision zone between the North China Block and the South China Block, will help to reveal the geologic history and relationship between these geologic blocks. Previous interpretations of the crustal structure of the SYS did not use detailed seismic velocity structure as a constraint. We produced an upper crustal velocity model of the northern SYS using a new wide-angle seismic dataset. Velocity anomalies resolved by our models correlate well with known features such as sedimentary basins and the tectonic uplifts in the SYS as low- and high-velocity anomalies, respectively. As might be expected, not only major faults and/or lithologic boundaries were found to be associated with large velocity gradients, but also our models exhibited resolvable deeply penetrating vertical low-velocity anomalies associated with the locations of strike-slip faults that were poorly resolved in an older seismic reflection profile. Our interpretations of the locations of major faults were based on the stacked seismic reflection profile and velocity modelling of wide-angle seismic array data and were extended to neighbouring regions by following trends in gravity, magnetic and earthquake location data. Faults traversing the North Basin of the SYS converged with the onshore Jia-Xiang Fault (JXF), suggesting that the branching of the JXF fault system controlled the formation of the North Basin. The distribution of the strike-slip faults resolved by our modelling of the JXF leads us to propose a model for the North Basin as a strike-slip stress regime that is consistent with the known tectonic framework. These models will be useful for future analysis of the regional tectonic evolution of the SYS region. Copyright © 2016 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The South Yellow Sea (SYS) is a continental shelf region between the Chinese mainland and the Korea Peninsula. Previous geophysical surveys found strong lateral variations in the structure of the upper crust of the SYS in response to deep geologic processes (Li et al., 2012; Zhang et al., 2014; Choi et al., 2015). Most of the previous geophysical investigations of this region were 2-D reflection profiles conducted by oil companies to assess the sedimentary basins (Zhang et al., 2007; Zhang et al., 2014; Choi et al., 2015) and satellite-based magnetic and gravity surveys to evaluate large-scale tectonic framework (Zhang et al., 2007; Hao et al., 2010; Li et al., 2012; Choi et al., 2015). As a result of these modelling efforts, major geologic units of the shallow crust and the evolution history of the SYS region are relatively well understood. However, to better understand the tectonics of the SYS region, a high-resolution velocity model of upper crustal structure such as the one presented here is needed.

In this study, we mapped the upper crustal structure of the SYS using seismic, gravity, magnetic, earthquake locations and geologic data. We first constructed a seismic velocity model using first-arrival data from a 228-km long wide-angle seismic survey conducted in 2013 across major
geologic units of the SYS (Line A-A’, Fig. 1). We adopted
the multiscale parameterization in seismic tomography,
which helps to reduce the nonuniqueness in tomographic in-
version (Zhou, 2003). We carefully picked first-arrival times
and designed inversion strategies to insure the accuracy of
the velocity profile. The new seismic dataset and multiscale
tomographic method allowed us to construct a reliable
crustal velocity model, which revealed detailed velocity
anomalies that could be used to infer crustal structure.

By combining the seismic velocity model, seismic reflec-
tion profile and local geologic data, we were able to identify
major faults and map them at depth. By further integrating
interpretation of gravity, magnetic, and seismicity data, we
mapped the fault structure from known major fault structure
discovered by our modelling of first-arrival data to adjacent
regions, thereby producing a 3-D model of the upper crust of
the northern SYS. The resulting crustal model will be useful
for tectonic studies of the SYS and surrounding regions.

2. GEOLOGICAL SETTING

The SYS is in the northeast edge of the South China Block
(SCB). There are five main geologic units in the SYS. These
provinces, listed from north to south, are as follows: the
Qianliyan Uplift, the North Basin, the Central Uplift, the
South Basin, and the Wunansha Uplift (Yao et al., 2008;
Zhang et al., 2014; Choi et al., 2015). Our wide-angle seis-
mic array traversed the Qianliyan Uplift, the North Basin,
and the northern part of the Central Uplift.

The Qianliyan Uplift is the part of the Sulu orogen of the
SYS. The onshore portion of the Sulu orogen is divided into

Figure 1. The topographic map showing major faults (red solid lines). The red dashed line marks the boundary between the ultrahigh-pressure metamorphic
belt to the north and the high-pressure metamorphic belt to the south (Li et al., 2012). The distribution of OBS and airguns of the refraction survey line (A-
A’) are represented by the blue dotted line and the pink line, respectively. The yellow line shows the location of the reflection survey Line B-B’. The grey
dashed contours represent the boundaries of the North Basin (Xie et al., 2012). SYS: the South Yellow Sea; BHB: Bohai Bay; QU: Qianliyan Uplift; NB: North
Basin; CU: Central Uplift. The location of working area is shown in the tectonic map (after Yan et al. 2014) at upper-left corner. NCB: North China Block;
SCB: South China Block; QL-DB: Qinling-Dabie orogen; SL: Sulu orogen; TLF: Tanlu Fault.
two parts: the ultrahigh-pressure and the high-pressure metamorphic belts (Xu et al., 2009). The boundary of those two belts is believed to cross the SYS and extend eastward to the Korean Peninsula (Oh, 2006; Li et al., 2014a, b).

The southern boundary of the Sulu orogen is defined by the Jia-Xiang Fault (JXF) (Xu et al., 2009; Li et al., 2012). The onshore JXF is one of the most significant branches of the Tanlu Fault system, which is a tectonically significant, deep strike-slip fault with over 1000-km offset (Xu et al., 1987) and is believed to be the boundary between the NCB and the SCB (Yin and Nie, 1993; Li et al., 2012). The JXF is the boundary between the Qianliyan Uplift and the North Basin (Li et al., 2012).

The SYS region experienced marine and terrestrial sedimentation throughout the Palaeozoic, Mesozoic, and Cenozoic (Li, 1995). The evolution of the SYS region can be divided into four major stages (Li, 1995; Li et al., 2014a, b; Zhang et al., 2014):

1. During the Proterozoic, the basement of the SCB was formed during the Jinning Movement (~800 Ma), when the SYS area was located in the northeastern portion of the Yangtze Block.

2. From early Palaeozoic to Triassic, the SYS area experienced continuous marine carbonate sedimentation. This region experienced uplift and erosion during the Indosinian Movement (~205 Ma), when the SCB and the NCB collided along the Qinling-Dabie–Sulu orogenic belt and the Tanlu Fault (Ames et al., 1993; Hou et al., 2006; Li et al., 2010; Li et al., 2011; Li et al., 2014a, b). At this time, the Tanlu Fault became a left-lateral strike-slip fault (Zhu et al., 2005).

3. From the late Mesozoic to early Cenozoic, the SYS experienced extensional stress resulting in the generation of half-grabens that were subsequently filled with terrestrial sediments. During the late part of the Yanshan Movement (~66 Ma), the SYS area experienced a strong magmatic event (Li et al., 2014a, b), and the Sulu ultrahigh-pressure metamorphic belt was generated by the collision of the SCB and the NCB (Hong and Choi, 2012).

4. After the Neogene, the SYS basin experienced subsidence and terrestrial sedimentation. During this time, there was a small amount of faulting and folding in the SYS, while the Tanlu Fault reversed motion direction and became a right-lateral strike-slip fault (Hou et al., 2006).

As a result of the multi-stage tectonic history and varied sedimentary styles, the SYS area is characterized by a complicated system with laterally heterogeneous basement, sediments, and structural features in the upper crust.

The collision between the NCB and the SCB is among the most important tectonic events to have occurred in Eastern Asia (Yin and Nie, 1993; Oh, 2006; Choi et al., 2015), and it has significantly impacted the formation of sedimentary basins in the SYS. Different tectonic models of the collision between the NCB and the SCB have been proposed to explain the tectonic evolution of the region (Xu et al., 1987; Okay et al., 1993; Yin and Nie, 1993; Zhang, 1997; Li and Yang, 2003; Zhang et al., 2006; Li et al., 2011). Some models suggest that eastern China is tectonically connected with the ultrahigh-pressure belt in the Korea Peninsula (Kim et al., 2006; Oh, 2006; Jung et al., 2011; Li et al., 2014a, b). However, the connection of those tectonic blocks is still unclear due to the lack of detailed geologic and geophysical data in the SYS. Most of the Sulu orogen is covered by the sea in the SYS area. As a result, most studies of the high-pressure and ultrahigh-pressure belts of Sulu orogen have been conducted using the limited onshore data in the east coast of Chinese mainland and the Korea Peninsula (Li et al., 2014a, b; Kim et al., 2015). In this study, we intend to construct a model of the upper crustal structure of the SYS that will fill the gap between these regional onshore tectonic studies.

3. DATA & METHOD

3.1. Seismic data

The wide-angle seismic data used in this study were acquired offshore of the Shandong Province along the east coast of China, in 2013. The receivers of this 2-D Ocean Bottom Seismometer (OBS) array were deployed along a NW–SE direction (Line A–A’ in Fig. 1) in the SYS. The 222-km long seismic profile included 38 stations at 6-km spacing; however, only 31 OBS recorded usable seismic data. The shot line was longer (312.5 km) than the receiver line and consisted of 2501 airgun sources at 125-m spacing (A-A’ in Fig. 1). To reduce the model size and increase the computation efficiency of tomography, we only used shots that were within 250 km of the northernmost receiver.

A multichannel seismic reflection profile (B-B’ in Fig. 1) was produced by an oil company along a profile that was semi-parallel to the wide-angle seismic array used in our work. This seismic reflection image was used to assist in the interpretation of faults identified in velocity models that were produced from the wide-angle data.

3.2. Picking and selection of first arrivals

First-arrival times were picked from the hydrophone component of the OBS data because the hydrophone data had the highest signal-to-noise ratio in the first-arrival waveforms. We first sort the seismic data into the common-receiver gathers and then applied a three-station moving average to the first-arrival waveforms to enhance the signal-to-noise ratio of the first break (a method also used to smooth the seismic reflection profiles by Zou et al., 2014). The three-station moving average method was performed by averaging the
two neighbouring traces with the central ‘target’ trace after aligning the two neighbour traces to the central trace using time shifts found by cross-correlating them with the central trace. In Figure 2, we see that the first-arrival waveforms after application of the three-station moving average have much higher signal-to-noise ratio and are better for picking first-arrival times.

The selection criteria to determine which of the first-arrival picks to include in the inversion were based on the following two criteria:

1. Only first-arrival waveforms with high signal-to-noise ratio (S/N) were selected during first-arrival picking. Data from areas where the sea is shallow proved to be particularly noisy as a result of noise generated by water waves. As would be expected, low S/N and complex seismic waves occur in long offset data and data with raypaths adjacent to boundaries with strong lateral velocity contrasts. To minimize outliers in arrival times, which would significantly bias the least-square inversion results (Menke, 1989), we excluded picks from data with low signal-to-noise ratio. Examples of the picks from selected stations are shown in Figure 3.

2. We excluded picks where the orientation of the line between the shots and the receivers significantly deviated from that of the wide-angle profile. In field acquisition, the airgun shot points can drift from the intended straight survey line. Accuracy in 2-D seismic tomography is best when the line connecting shot-receiver pair is parallel to the receiver line. Therefore, picks from data with shot–receiver pairs that deviated in azimuth from the main profile by less than two degrees were accepted in the inversion.

The application of those two criteria resulted in 10,364 travel time picks being included in the tomographic inversion.

3.3. Multiscale travel time tomography

In general, Earth’s subsurface is composed of geologic units with different seismic velocities and sizes. Therefore, it is suitable to digitize the working area in a multiscale manner, which decomposes the model space into several sub-models with different cell sizes. Following a method by Zhou (2003), we decomposed the velocity model into ten sub-models. The cell size of the first-order velocity model is 0.5 km vertically and 2 km horizontally.

In our multiscale seismic tomography, we use a 1-D initial velocity model to produce a starting 2-D velocity model with a constant velocity and uniform cell sizes for cells across each depth. Theoretical travel times and raypaths for

Figure 2. First-arrival waveforms before (a) and after (b) the application of a three-station moving average. The red crosses represent the first-arrival picks.
Figure 3. Examples of OBS sections with arrival times (Panels a & c) and raypaths (Panels b & d) used in the inversion for the velocity model. Panels (a) and (c) correspond to the hydrophones installed on OBS 28 and 19. The red and blue lines in Panels (a) & (c) are the travel time picked by hand and those estimated using the inverted seismic velocity model, respectively. The seismic data are filtered by a bandpass filter with pass band of 2 Hz to 20 Hz.
each shot–receiver pair are estimated using the shortest-path ray tracing algorithm (Moser, 1991). Each raypath is broken into segments crossing each cell. The length of the segment in each cell is divided by the velocity for that cell to form a linear equation (in slowness) for the theoretical travel time for the given raypath. By subtracting the theoretical travel time from the observed, for each shot–receiver pair, we produce a set of linear equations expressing travel time misfits as a function of model velocities (Shearer, 2009). A similar process is performed to generate a set of the linear equations for different sub-models that can be used to build a matrix for a linear multiscale inversion (Zhou, 2003). We employ a damped least-square inversion that minimizes structure (Shearer, 2009) to solve the overdetermined linear inversion. After each iteration of this inversion, we update the seismic raypaths and repeat the least-square inversion.

To stabilize the inversion, a smoothing strategy is employed throughout the tomographic inversion. In early iterations, two-dimensional smoothing is used to stabilize early models. In later iterations, after the inversion converges to a certain level, smoothing is no longer used. The final velocity model is interpolated and smoothed for interpretation, as shown in Figure 4b and 4c. The perturbation of velocities is more clearly visible in the differential velocity profile (Fig. 4d), which was produced by subtracting the mean velocity at each depth (Fig. 4a) from the inverted velocity model (Fig. 4c).

3.4. Initial velocity model

The stability of the linear inversion relies on the accuracy of the initial model. The initial velocity model for tomographic inversion was built in two steps. We first used large cell sizes and a starting model with a velocity of 2 km/s at the sea floor, increasing the velocity linearly with depth to a velocity of 7 km/s at the 20-km depth. The velocity model after several iterations of the tomographic inversion was averaged at each depth to produce a one-dimensional velocity model (Fig. 4a) that was used as the initial model by multiscale tomography to produce the final velocity model (Fig. 4c).

4. RESOLUTION OF MULTISCALE SEISMIC TOMOGRAPHY

To test the resolution of our multiscale seismic tomography algorithm, we conducted a checker-board test using the same parameters as in the real-data tomographic inversion (e.g. initial velocity model, cell size, number of sub-models, iteration number, acquisition geometry, etc.). The checker-board velocity model in Figure 5a was produced by adding regularly spaced high- and low-velocity anomalies to the averaged final seismic velocity model in Figure 4a. The magnitude of seismic velocity perturbation in the checker-board model decreases with depth to mimic the magnitude of the anomalies in our final 2-D tomographic velocity model (Fig. 4c).

Travel times for the locations of the observed shot–receiver pairs were computed and then used as an input data for the test of tomographic inversion described above. The reconstructed checker-board velocity model from the inversion shows that the locations of the velocity anomalies at depths shallower than 10 km were recovered reasonably well (Fig. 5b). At a depth of ~5 km, the values of the recovered, by inversion, checker-board seismic velocity model have the best match to the “true” checker-board model. At depths greater than 10 km, the velocity anomalies are smeared out in depth showing poor vertical resolution, but they are well resolved horizontally. The resolution found in the checker-board test can be explained by investigating the coverage of seismic raypaths (Fig. 5c).

As shown in Figure 5c, the raypath coverage at shallow depths (i.e. <~5 km) is the most dense, and most of the raypaths at these depths have small incidence angles in the shallow, low-velocity bodies, which are similar to the raypath distributions observed to the tomographic model produced from real data (Fig. 3b). The densest distribution of crossing raypaths occurs at depths of ~5 km, which is why the inverted seismic velocity was best recovered at around 5 km. At depths between 5 and 10 km, the raypaths are still reasonably dense but show an uneven pattern in their turning depths. A closer investigation found that the uneven distribution in turning rays in the 5- to 10-km depth interval is the result of rays turning in the high-velocity anomalies as would be expected. Raypaths at depths greater than 10 km are very sparse and pass through the 10- to 15-km depth interval vertically, turning at depth greater than 15 km. The steep, parallel raypaths at deep regions cause along-raypath smearing of velocity anomalies (Zhou, 2011) but explain why horizontal resolution is better than vertical resolution at depths greater than 10 km.

Overall, the results of the checker-board resolution test show that the multiscale tomography is capable of resolving the velocity anomalies at depths shallower than 10 km for our data distribution. At depths greater than 10 km, velocity anomalies are resolved horizontally to a greater degree than they are resolved vertically, but resolution at these depths may not be sufficient for detailed interpretation.

5. RESULTS

5.1. Raypath coverage

The dense distribution of raypaths at depths shallower than 3 km for the example of common-receiver gathers in Figure 3b and 3d is similar to the distribution of raypaths...
Figure 4. Tomographic velocity profile beneath Line A-A’. (a) Initial velocity model. (b) Raypaths on top of the inverted velocity model. The triangles on top of the profile represent the location of OBS. (c) Inverted seismic velocity with contours showing the velocity values. The velocity models in Panels (a)–(c) have the same colour scale. (d) Differential velocity calculated by subtracting the mean velocity from the inverted velocity model. The region with no ray coverage is masked. Arrows (labelled F1 to F5) on top of the image in Panel (c) show the surface locations of the five major faults.
for all the selected shots and receivers pairs illustrated in Figure 4b. The ray coverage deteriorates at depth greater than 5 km due to a decrease in the velocity gradient at depth and a smaller number of travel time picks for large offsets.

In our later interpretation, we will only consider areas with sufficient raypath coverage. We, therefore, mask the regions in Figure 4b–4d with poor ray coverage so as not to distract from the velocity anomalies that we consider well resolved.
5.2. Travel time residuals

Travel time residuals are defined as misfit between the observed and the calculated (from the tomographic model) arrival times and can be evaluated by investigating the distributions of travel time residuals (Watremez et al., 2015). The initial travel time residuals are between $-2$ s and $1$ s (Fig. 6). The strong asymmetry of travel time residuals is mainly caused by the deviation of the 1-D initial velocity model from the real 2-D velocity model. After three iterations of the tomographic inversion, the travel time residuals fall between $-1$ s and $0.5$ s, and, finally, the travel time residuals converge to between $-0.25$ s and 0.25 s after the last iteration (Fig. 6). The fit between the observed arrival times and the arrival times calculated using the final velocity model is illustrated in Figure 3a and 3c.

5.3. Velocity model

The final inverted velocity model shows strong velocity variations in the horizontal and vertical directions (Fig. 4c). At depths shallower than 3 km, we observe a broad low-velocity anomaly from about 75 km in the model (labelled F2) to about 195 km (labelled F5). F2 and F5 mark the locations of sharp gradients in the velocity model that separate this low-velocity anomaly from high-velocity bodies to north and south, respectively. The locations of these shallow velocity bodies in our model correlate well with surface geological features described in the literature (Fig. 4c) (Xie et al., 2012; Zhang et al., 2014). The low-velocity body between F2 and F5 corresponds to the North Basin of the SYS. The adjacent high-velocity bodies to the north and south correspond to the Qianliyan Uplift and the Central Uplift, respectively. The boundaries between the low-velocity anomaly associated with the North Basin and the adjacent high-velocity anomalies associated with the Qianliyan Uplift (F2) and the Central Uplift (F5) are sharp in both the absolute velocity model (Fig. 4c) and the differential velocity model (Fig. 4d). Another small, low-velocity anomaly in the Northern part of the Qianliyan Uplift is labelled as F1. Two significant but narrow low-velocity anomalies that penetrate to depths of more than 6 km are centred at ~105 km and 145 km (labelled F3 and F5 in Fig. 4c), respectively.

Beneath the Qianliyan Uplift and the Central Uplift, there is a gradual increase in seismic velocity from between 3 km/s and 4 km/s to a velocity of ~6 km/s at a depth of ~1 km, which we assume to be the depth to crystalline basement. The near surface velocity beneath the North Basin is about 2 km/s and has a strong increase in velocity with depth. This strong velocity gradient in the shallow depths beneath the North Basin is likely the result of compaction of sedimentary rocks and/or changes of lithology. The depth at which we observe the strongest velocity gradient beneath the North Basin is consistent with the interpreted boundary between the Mesozoic and the Palaeozoic rocks (Zhang et al., 2014). Our interpreted depth to crystalline basement of ~7 km beneath the North Basin is similar to the basement depth of ~8 km inferred by previous gravity and magnetic surveys (Hao et al., 2010; Zhang et al., 2014).

5.4. Interpretation of depth section

To better understand the geological significance of seismic velocity anomalies observed in our models, we compare

![Figure 6. Histograms of the distributions of the travel time residuals for the initial model (black), third iteration (green), and the 15th iteration. Bins are 30-ms wide; N obs. refers to the number of observations.](image-url)
our tomographic velocity model with the seismic reflection profile beneath Line B-B’ in Figure 1. The seismic reflection profile, which is a time section, was converted into depth using our 2-D seismic velocity model (Fig. 7a). For better comparison, we overlay our velocity model onto the seismic reflection profile in Figure 7b. Our interpretation of the locations of major faults and layered structures is illustrated on top of the seismic reflection profile and our velocity model in Figure 7c.

The geometry of the low-velocity anomaly in our tomographic model matches the locations of strong reflections interpreted to be the base of the sediments beneath the North Basin in the seismic reflection profile. There appear to be no coherent reflectors in the high-velocity regions of our model.

Figure 7. The seismic reflection profile with the final tomography model plotted on top. (a) Stacked seismic profile. (b) The seismic reflection profile with the final tomography model plotted on top. (c) Interpretation of faults on the overlapped profile. Major geological units are labelled on top of Panel (c). The meanings of QU, NB and CU are the same as in Figure 1. Thick dashed and the solid lines mark the top and bottom of the Mesozoic (Mz), respectively. The thin dotted line is the 4.5-km/s velocity contour. N: Neogene; Q: Quaternary.
beneath the Qianliyan Uplift and the Central Uplift. This lack of seismic reflections in a high-velocity region is typical of a metamorphic craton. The abrupt change from low to high velocities (discussed above) beneath F2 and F5 is interpreted as the northern and southern boundary faults of the North Basin, respectively.

In the North Basin, several major faults interpreted on the reflection profile cut through the sediments and correlate with the deep extension of the seismic low-velocity anomalies at F3 and F4. The fault beneath F3 on the seismic reflection profile separates the North Basin into two half-grabens. The faults beneath F4 in the North Basin are in the same location as the strongest and deepest low-velocity anomaly in our velocity model and interrupt interfaces in the reflection profile (Figs. 4d and 7c). We interpret these two nearly vertical faults beneath F4 as strike-slip faults because there is no significant offset of sedimentary layers crossing these faults in the reflection profile. The low velocities and lack of significant offset in reflections on either side of the faults are analogous to observations related to strike-slip faults in other regions (Stern and McBride, 1998; Barnes and Audru, 1999; Hsiao et al., 2004). Significant low-velocity anomalies in association with faulting similar to what we find beneath F4 have been interpreted in other studies as a highly fractured zone caused by strike-slip faults (Hole et al., 2006; Rempe et al., 2013; Jeppson and Tobin, 2015).

The timing of the offset in faults can be estimated by analysing the ages of sedimentary layers cut by the faults. There is very little offset in the horizons, on the reflection profile, that we interpret as the unconformity at the bottom of the Neogene (thick dashed line in Fig. 7c) where these horizons are cut by faults at F2, F3 and F5. However, there is significant offset in Mesozoic strata associated with all three of these faults. This would indicate that most of the displacement on these faults (F2, F3 and F5) occurred during the Mesozoic with little activity during and after the Neogene. The timing of major displacement on these faults appears to be associated with significant uplift and extensional tectonic activity known to have occurred during the Mesozoic and the relatively weak tectonic activity after the Neogene (Li et al., 2012; Zhang et al., 2014). The fault plane of F4 clearly appears to cut the shallow Quaternary sediments and propagate upward to the sea floor. This indicates that the fault beneath F4 may still be active. The shallow faults between F4 and F5 cut sediment of the Neogene and younger and appear to come near the surface and may also still be active; a hypothesis that is supported by the analysis of the distribution of recent seismicity discussed below.

6. UPPER CRUSTAL STRUCTURE AND DISCUSSION

To investigate the 3-D structure of the SYS, we integrate the interpretation of the seismic data with observation from the gravity and magnetic maps of the region (Fig. 8a and 8b). We first projected the locations of the interpreted faults (F1–F5 in the seismic profile in Fig. 4) onto the gravity and magnetic anomaly maps of SYS (modified from Li et al., 2012). The solid and dashed red lines represent the locations of faults. The solid black line shows the location of the station in the wide-angle array. (c) and (d) show schematic sketch of how gravity and magnetic anomalies (modified from Anderson et al., 2004) were respectively used as geologic indicators to interpret a strike-slip fault. JXF: Jia-Xiang Fault; TLF: Tanlu Fault; LYF: Lian-Yan Fault. The stars show the location of Qianliyan Island.
and magnetic maps (red lines on Fig. 8a and 8b), and then, based on the interpretation of patterns of gravity and magnetic anomalies (i.e., offset in observed anomalies; Fig. 8c and 8d), we extended the faults across the maps. The location of the seismic profile is given by the black line on Figure 8a and 8b.

6.1. Division of Sulu orogen in SYS

Our profile images the northern part of the SYS, where the ultrahigh-pressure belt is adjacent to the high-pressure metamorphic belt associated with Sulu orogen. As revealed by a previous geological study, this boundary is near Qianliyan Island (Li et al., 2014a, b), which is near F1 on our seismic profile (Fig. 8).

F1 is located on a ridge of a high-gravity anomaly, possibly indicative of the presence of a high-density, cooled, magmatic belt (Fig. 8a). F1 also lies along the boundary between low magnetic values to its south and high magnetic value to its north, which is hypothesized to be the results of the post-orogenic magmatic activity (Li et al., 2012). We extended F1 to the west by tracing it along the gravity and the magnetic anomalies, described above. By doing so, we find that F1 is located at the boundary between the ultrahigh-pressure and the high-pressure metamorphic belts of the Sulu orogen (Xu et al., 2009; Li et al., 2012).

6.2. Jia-Xiang Fault system

As shown in Figure 8, the trace of faults F2–F5 (based on gravity and magnetic anomalies) converges into the JXF and diverges in the North Basin, forming a flower pattern. In other words, F2 to F5 are the seaward branches of the JXF system.

The geometry of F2 and F3, on the maps in Figure 8, was extended from the seismic interpretation by tracing along the sharp slopes in the gravity values. The converging point of F2 and F3 was constrained using another seismic reflection profile that crosses the North Basin along the longitude of 121°E (Zhang et al., 2014). Only one half-graben basin was found in that seismic reflection profile, instead of the two half-grabens bounded by F2 and F3 in our profile. The disappearance of the northernmost half-graben of the North Basin indicates the convergence of F2 and F3 near the reflection profile at 121°E. F4 is interpreted to propagate along the linear trends of a slope in the gravity map and the boundary between high and low magnetic anomalies in the magnetic map. To be more sensitive to deep anomalies, the magnetic anomaly was smoothed through upward continuation to an elevation of 5 km above Earth’s surface. Therefore, strong anomalies in the magnetic map can be associated with deep structure (Li et al., 2012). The association of F4 with a strong magnetic boundary implies that it is likely a deep feature, which reinforces our interpretation of F4 as a deep-penetrating fault associated with the low-velocity anomaly beneath F4 in the velocity profile (Fig. 4).

The location of F5 matches the southern boundary of the North Basin (Xie et al., 2012; Zhang et al., 2014). We extended F5 to the west from our velocity model by tracing it between distortions of the magnetic features (Fig. 8d). The distortion pattern in the magnetic anomalies along our interpreted trace of F5 is consistent with being caused by a left-lateral strike-slip fault. Since the strong positive magnetic anomalies used to trace F5 are believed to be the result of magmatic activity during Cenozoic extension (Li et al., 2012), F5 should have been active after the Cenozoic, although it may not be active recently.

Overall, our interpretation of the fault distribution of the JXF system fits well with the geometric boundaries and internal structure of the North Basin. Faults interpreted as being associated with the Sulu orogen can be naturally connected with the metamorphic belts in the Korea Peninsula by associating the Precambrian rocks and the metamorphic phases in eastern China and southwestern Korea (Kim et al., 2006; Oh, 2006). The lithosphere beneath the JXF system thickens from about 65 km within the Sulu orogen to about 90 km in the lower Yangtze (Li et al., 2012). These observations support a hypothesis that the JXF has faulted the whole lithosphere beneath this region.

6.3. Activity and mechanism of the JXF system

The geometry of active faults can be revealed by analysing the spatial distribution of earthquakes. In the northeastern SCB, the locations of the onshore earthquakes are mainly concentrated along the Tanlu Fault zone (Fig. 9). The offshore earthquakes are also not evenly distributed. The distribution of earthquake epicentres is denser to the south of F2 than to its north. This suggests that the F2 may be the boundary between two different stress regimes.

In the North Basin, the region between F4 and F5 experiences a greater number of earthquakes than the surrounding areas. This correlates with the large number of shallow faults between F4 and F5 that were inferred from the depth section in Figure 7c. It is also worth noting that three earthquake clusters along the JXF are found near the locations where we interpret F3, F4 and F5 to branch off the JXF system (Fig. 9). The correlation between the earthquake clusters on the JXF system and the hypothesized branching points for F3, F4 and F5 supports our interpretation of fault geometry and indicates that earthquakes in the North Basin are concentrated at branching points of faults. The fact that three large earthquakes, with magnitudes over M5.0, occurred along the traces that we inferred for the faults of the JSF system

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Figure 9. Earthquake distribution and the interpreted faults. The red dots show the epicentre of small earthquakes with magnitude larger than 3.0 (data from China Earthquake Data Center: http://data.earthquake.cn/data/). The red stars show the locations of three big earthquakes with magnitude larger than 5.0 in the South Yellow Sea (Xie et al., 2012; Choi et al., 2015). Other symbols have the same meaning as those in Figure 8.

Figure 10. Block diagram showing the geometry of faults in the South Yellow Sea (SYS). Top map shows the magnetic anomaly. The coloured vertical cross-section in the middle is the velocity profile. The red solid and dashed lines represent the faults.
system crosses the North Basin. The interpretation of shallow active faults between F4 and F5 in the North Basin is supported by the large number of earthquakes in that region. We suggest that a 3-D system of faults related to the strike-slip JXF system controls the regional tectonic framework of the SYS. Future studies using focal mechanisms and better locations of regional earthquakes are needed to further constrain properties (such as displacement direction orientation) of faults identified in this work, and more detailed 3-D velocity models of the SYS are also required to test our hypothesis of the JXF system.

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