THE CRUSTAL STRUCTURE BENEATH THE SHIDAO STATION ON XISHA ISLANDS OF SOUTH CHINA SEA

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Abstract We installed a temporary earthquake station at Shidao on the Xisha Islands in the South China Sea to study the seismicity and lithospheric structure of the region, and carried out the observation experiment for more than one year. Although the seismic data recorded in the reef and island areas have relatively large background noise, especially during the passage of a tropical cyclone, earthquakes above $M_w$ 6 can still be recorded. In this paper, those teleseismic records with clear P waveforms are chosen to carry out receiver function analysis and modeling. A simple crustal structure model beneath the station is obtained, in which the Moho depth is 28 km. On the top of the upper crust is a 2 km-thick low velocity layer with a shear wave velocity of only 2.3 km/s. The shear wave velocity increases gradually with depth to 3.8 km/s in the lower crust. We compare this model with previous results and discover that the crustal models of the Shidao station and Qiongzhong station (QIZ) are the natural extensions of the Xisha Trough section. The crustal structure of the Xisha block consists of thinned continental crust, with a velocity structure that is similar to the normal continental crust of the South China block.

Key words South China Sea, Xisha Islands, Shidao Station, Teleseismic receiver function, Crustal velocity structure

1 INTRODUCTION

The South China Sea (SCS) is one of the largest marginal seas in the western Pacific. It is located at the junction of the Eurasian, Indian-Australian and Pacific plates. Among the continental margins around the SCS, the northern margin is the only extensional continental margin, which possesses the same stress property as the sea floor spreading of the SCS. The northern margin contains important information about the spreading and evolution of the SCS. The crustal structure and tectonic nature of the northern margin are key topics for studying the formation and evolution of the SCS. In the past decade, a number of Ocean Bottom Seismometer (OBS) experiments with active airgun sources have been carried out in the northern SCS. For example, a profile was obtained by Sino-Japanese cooperation in 1993 in the middle of the Pearl River Mouth Basin[1]; three profiles were shot by the Sino-Germany cooperation in 1996 in northwestern SCS[2~4]; and a profile was completed in 2001 in the northeastern SCS by the collaboration between the Mainland and Taiwan[5~7]. These profiles have provided important constraints on the crustal structure and tectonic features of the northern SCS[8~10].

However, because of the limited energy of the active airgun source, the maximum seismic signal propagation distance is only about 250 km[11], which is insufficient to explore the deeper lithospheric structure below the crust. Furthermore, the onboard airgun seismic sources and multi-channel streamer are difficult to operate in shallow water, reef and island areas. Ideally a combination of active sources and earthquakes should be used to provide a comprehensive study of deep water, shallow water, reef, island and land areas. But because of the sparse distribution of earthquakes and seismic stations, previous studies of crust and upper mantle structure
using earthquake data are restricted in the northwestern SCS. For instance, Liu\textsuperscript{[12]} and Xu et al.\textsuperscript{[13]} used the body wave arrival times of earthquakes and 3-D tomography imaging technique to invert the crustal and upper mantle structure of South China and Red River region, including some submarine areas of the northern SCS. The inversion results indicate that good images can be obtained in the areas of Taiwan and Hainan, where earthquakes and stations are relatively densely distributed. In contrast, inversion results could not be obtained in the marine areas where there are neither earthquakes nor seismic stations, so that the extension of the Red River Fault towards the southeast cannot be identified. Using the earthquake surface wave data (e.g. Zheng\textsuperscript{[14]} and Zhu\textsuperscript{[15]}), the structure information of lithosphere and upper mantle in marine areas could be obtained. But both the surface wave frequency and the spatial resolution of the model are low. We therefore decided to install a temporary seismic station on the Xisha Islands in the northwestern SCS to acquire seismic data and to learn about the problems of installing portable seismic stations in the reef and island areas, which has great significance for the study of lithospheric structure in the northwestern SCS and other marine areas.

The receiver function method is currently a well known technique widely used to study the crustal shear velocity structure beneath a seismic station\textsuperscript{[16}–\textsuperscript{18]}. This method retrieves the receiver function, or the station site response, from teleseismic broadband P waveform and constructs a detailed shear velocity structure beneath the receiver station using a forward and inverse waveform fit of synthetic seismograms. This method has many advantages, for example, the receiver functions are not affected by the source time function, focal mechanism, source area structure, mantle path and the instrument response. Good results can be obtained from data from a single station.

In this paper, we first analyze the earthquake data recorded by the Shidao station at the Xisha Islands (Fig. 1) and discuss how the seismic records are affected by the background noise of ocean waves during the passage of a tropical cyclone. Then we process and model the available teleseismic P waveform data using the receiver function method and compare the resulting crustal structure model with those of the QIZ and Xisha Trough Profile. Finally, we infer the causal link between the Xisha block and South China block.

2 EARTHQUAKE OBSERVATION AND DATA PROCESSING OF SHIDAO STATION

The biggest island in the Xisha (Paracel) Islands is the Yongxing Island, which is located 300 km southeast of the Hainan Island. A deep water harbor and an airstrip have been built on the Yongxing Island so that the transportation is relatively convenient. The Shidao Island and the Yongxing Island are situated on the top of same coral reef. They are less than 800 m apart and there is a man-made land bridge connecting the two islands\textsuperscript{[19]}. The Shidao Island, with an area of only 0.08 km\textsuperscript{2}, is a rocky islet of cemented limestone, where the bed rock conditions are good and human disturbances are few. In-situ measurements also indicated that better seismic records can be obtained here than on the Yongxing Island\textsuperscript{[20]}. The Shidao Station was installed and operated from September 2001 to October 2002, using a portable seismometer (Reftek 24-bit digitizer and STS-2 ultra-broadband sensor). 16 GB of raw seismic data were recorded in this period.

The data pre-processing includes format conversion and earthquake identification. The raw data in SUDS format are first converted to the more common SAC format. Then the Centroid Moment Tensor (CMT) catalogue of the Harvard University is used to select the waveform data. The IASPEI model\textsuperscript{[21]} is used to calculate the theoretic arrival times and assist the identification of the P and S phases. Low-pass filters are used to check if surface wave trains exist. Finally, 75 events with relatively clear waveforms were identified. These events are mainly medium and strong earthquakes in the magnitude ($M_w$) ranges 5.5–7.9. There are 35 regional events within the 30° epicentral distance, 37 teleseismic events with an epicentral distance between 30°–90°, and 3 teleseismic events with an epicentral distance larger than 90°. These events are mainly distributed in the circum-Pacific seismic zone and the Himalayan-Indonesian seismic zone (Fig. 2).
The Shidao station was constructed as the first attempt to provide temporary earthquake observations on the reef and island areas in the SCS. Compared with the seismic stations on land, the seismic records here are certainly affected by the background noise of ocean waves. To understand this problem, we collect the hydrologic and meteorological data of the northern SCS during the operation period of the Shidao station. According to the data published by Hong Kong Observatory\textsuperscript{[22,23]}, 39 tropical cyclones formed in the western Pacific from September 2001 to October 2002, but only 13 of them affected the SCS. The tropical cyclone “Vongfong” (No. 0214), which formed in the central part of the SCS and lasted from 15 to 20 August 2002 with maximum winds of 25 m/s, affected the Shidao station most severely. It moved cross the Xisha Islands (Fig. 1), skirted the northeast coast of the Hainan Island, and landed at the Zhanjiang area\textsuperscript{[24]}.

We compare the raw seismic data recorded by the Shidao station before, during and after the passage
of “Vongfong”. Three days before “Vongfong”, the Shidao station recorded a low level of background noise (Fig. 3a). The amplitude of high frequency was about $\pm 300$ counts, superposing on some larger ($\pm 500$ counts) long period disturbances. Because of the low level of the background noise, some small signals, probably from local small seismic events, were clearly recorded.

In the morning of 19 August, the Shidao station recorded the maximum level of background noise (Fig. 3b), which was as high as $\pm 5000$ counts, more than 10 times higher than the normal levels, and obscured all small seismic signals. At this time, “Vongfong” passed just west of the Shidao station. It intensified into a severe tropical storm that afternoon.

![Seismograms of different time periods recorded by Shidao station before, during and after the passage of tropical cyclone “Vongfong”](image.png)

Fig. 3 Seismograms of different time periods recorded by Shidao station before, during and after the passage of tropical cyclone “Vongfong”

(a,b,c) Raw records (vertical component); (d) Long period seismograms obtained from (c) by low-pass filter with corner frequency 0.05 Hz. P and S phases in (c) are the theoretical arrival times from IASPEI model.

P, S and Rayleigh wave in (d) are identified phases according to the waveform characteristics.

The labels on upper-right corner are the beginning time (in GMT) of the seismograms. $A$ is digital amplitude.

An earthquake of magnitude 6.2 ($M_w$) occurred at 10:59 on 20 August with the epicenter south of Japan. Fig. 3c is the one-hour raw record starting at the origin time. By this time, “Vongfong” had landed and ended.
Even though the background noise had reduced to ±1500 counts, it is difficult to identify the P and S phases from the raw record. After a low-pass filter (corner frequency 0.05 Hz), most high frequency noise is removed and a clear long period seismic record is obtained (Fig. 3d). Obvious P and S waves are observed consistent with the calculated arrival times. The Rayleigh wave train arrived between 850~2000 seconds with clear dispersion.

The seismic data recorded in several time periods before and after the passage of “Vongfong” indicates that the background noise of the Shidao station under the influence of a tropical cyclone increases by one order of magnitude. But the noise is mainly at high frequency and if a proper filter parameter is chosen, waveform data of earthquakes larger than magnitude 6 can still be retrieved.

3 TELESEISMIC RECEIVER FUNCTION MODELING AND CRUSTAL STRUCTURE

The receiver function method has been applied to the crustal structure studies in many regions\(^{[25\sim 29]}\). The principle of this technique is that the radial component of teleseismic P waveforms is deconvolved by its vertical component. This procedure removes the common factors of radial and vertical components, including the effects of the earthquake focal mechanism, source region structure, recording instrument response, and P wave reverberations near the receiver site. After the deconvolution, the radial component only contains the P-S converted phase and its multiple reverberations. This record is known as the receiver function, and only depends on the shear wave velocity structure near the station. This method can obtain 1-D shear wave velocity model beneath the station using the three component broadband records of only one station, and is very suitable for analysing the seismic data of the Shidao station.

We selected 7 records from the teleseismic earthquakes with epicentral distances between 30\(^\circ\) ~ 90\(^\circ\) (Table 1). We required that the raw records of P waveforms had relatively high signal-to-noise ratio, i.e. clear P wave first arrivals on both vertical and radial components, and only small signals on the tangential component. We cut the seismic waveform 30 seconds before and after the P first arrival and carried out the deconvolution process. We used the source equalization procedure proposed by Langston\(^{[16]}\) and chose a Guassian parameter of 1.0, similar to applying a low-pass filter of 0.4 Hz, and a deconvolution water-level of 0.001. Fig. 4 shows the vertical and radial components of the P waveforms and the corresponding receiver functions for the 7 selected events. This figure indicates the stable seismic phase in the receiver function waveforms is the direct P wave, which has a time delay of 0.4 second, consistent with the time delay of first P arrivals on the radial component. The Ps phases, with an arrival time of 3.8 second, are obvious only on two events, 20020303 and 20020628. The Ps phases are not clear on other events. No later phases are observed. We have tried various Gaussian parameters and deconvolution water-levels but have not obtained a better result. Finally, we chose two receiver functions of the 20020303 and 20020628 events for further modeling studies.

<table>
<thead>
<tr>
<th>No</th>
<th>Origin date (y-m-d)</th>
<th>GMT time (h-m-s)</th>
<th>Lat. ((^\circ))</th>
<th>Lon. ((^\circ))</th>
<th>Depth(km)</th>
<th>(M_s)</th>
</tr>
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<tr>
<td>1</td>
<td>2001-10-12</td>
<td>15:02:23.2</td>
<td>12.78</td>
<td>145.12</td>
<td>39.9</td>
<td>7.0</td>
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<tr>
<td>2</td>
<td>2001-12-02</td>
<td>13:01:58.2</td>
<td>39.52</td>
<td>141.11</td>
<td>123.4</td>
<td>6.5</td>
</tr>
<tr>
<td>3</td>
<td>2002-01-02</td>
<td>17:23:05.8</td>
<td>–17.80</td>
<td>167.81</td>
<td>36.9</td>
<td>7.3</td>
</tr>
<tr>
<td>4</td>
<td>2002-03-03</td>
<td>12:08:22.4</td>
<td>36.57</td>
<td>70.27</td>
<td>204.1</td>
<td>7.2</td>
</tr>
<tr>
<td>5</td>
<td>2002-04-26</td>
<td>16:06:13.1</td>
<td>13.17</td>
<td>144.49</td>
<td>67.5</td>
<td>7.2</td>
</tr>
<tr>
<td>6</td>
<td>2002-06-28</td>
<td>17:19:39.9</td>
<td>43.83</td>
<td>130.46</td>
<td>566.8</td>
<td>7.2</td>
</tr>
<tr>
<td>7</td>
<td>2002-09-08</td>
<td>18:44:38.3</td>
<td>–3.27</td>
<td>143.38</td>
<td>19.5</td>
<td>7.8</td>
</tr>
</tbody>
</table>

The waveform modeling of receiver functions consists of two steps, the forward and inverse modeling. First, we constructed an initial model according to the regional geology information, and used the reflectivity algorithm of Kennet\(^{[30]}\) to calculate synthetic waveforms. Then we applied the deconvolution process with the
same method and parameters used on the observed data to obtain the synthetic receiver functions. By comparing the synthetic and observed receiver functions and adjusting the initial model to get a better waveform fit, we obtained a reasonable forward model (Fig. 5). This crustal model consists of a 2 km thick low velocity surface layer with a shear velocity of 2.3 km/s above a gradient represented by a 2 km thick 3.2 km/s layer and a 4 km thick 3.6 km/s layer. The lower crust consists of a single 3.8 km/s layer, with the Moho at a depth of 28 km. Although the waveform fits between the observed and synthetic receiver functions of this model are not perfect (Fig. 5), the arrival time and amplitude of direct P wave, and the arrival time of Ps phase agree well. From the forward modeling we know the crustal velocity and the Moho depth determine the arrival time of Ps, and the low velocity layer in the uppermost crust controls the time delay of direct P wave in the receiver function. Owens[31] and Mangino et al.[32], also point out that the direct P time delay is a good constraint on the low velocity layer near the surface. Because of the relatively large noise in the observed data, we tried to use a simple model and not to fit the waveform details, such as the amplitude of the Ps and the waveform after 6 seconds.

![Fig. 4 Telesismic P waveforms and their receiver functions of Shidao station](image)

$A_N$ is normalised amplitude.

We continued to carry out the inversion modeling tests by dividing the forward model into thin layers of 2 km thickness. The fast partial derivative method of Randall[33] and the linear inversion procedure of Ammon[18] were used for automatic fitting and a better fit to the receiver functions could be achieved. However, the result is a complex model, with interlaced low and high velocity layers, and oscillating to the left and right of the starting model. This behavior is probably an artificial result of over-fitting the receiver functions. We therefore abandoned the inversion model and adopted the simple crustal structure from forward modeling.
4 COMPARISON OF CRUSTAL STRUCTURE IN NORTHWESTERN SOUTH CHINA SEA

The Qiongzhong station (QIZ) is a standard station of the China Digital Seismic Network (CDSN), which has accumulated seismic data for many years. We processed the teleseismic P waveform data recorded by the QIZ from events near the Tonga Trench (azimuth 117° and epicentral distance 81°) and chose 8 receiver functions with similar waveforms. The direct P wave of these receiver functions has no time delay and clear Ps phase appears at 4 seconds. The stable peak at about 14 seconds is probably the PpPms phase. The receiver functions from individual events were stacked to obtain a receiver function of higher signal-to-noise ratio, which was automatically fitted by the inversion method. The inversion results produced a good fit to the receiver function. The peaks at 4 seconds, 14 seconds, and the trough at 17 seconds are matched very well. The inversion model indicates that the crustal structure beneath the QIZ consists of two layers, an 8 km thick 3.6 km/s upper crust and a 22 km thick 3.8 km/s lower crust. The Moho is a velocity gradient over the depth interval 30–36 km. Compared with the crustal model beneath the Shidao station, there is no low velocity surface layer and the model of the QIZ has deeper and gradational Moho, but the velocity values within the crust are similar.

The Xisha trough is between the Hainan Island and Xisha Islands (Fig. 1). Previous results of OBS surveys indicate that the shallow structure of the Xisha trough is composed of a 1–4 km thick Cenozoic sedimentary layer. Grabens cause the basement interface to have a complex shape. The compression velocity of crystalline crust increases from 5.5 km/s near the basement interface to 6.8 km/s at the Moho. There is no high velocity layer in the lower crust. The compression velocity has a large contrast at the Moho and jumps from 6.8 km/s near the bottom of crust to 8.0 km/s at the top of upper mantle. The Moho depth is 15 km near the center of the section and increases gradually to more than 25 km on both sides. Correspondingly, the thickness of crystalline crust is 8 km near the center of section and becomes thicker on both sides. The strong uplift of the Moho interface causes the crust to display the characteristics of a rift generated by crustal extension. The thickness of 8 km for the crystalline layer near the center of the trough is close to the thickness of normal oceanic crust. Because continental rifting stopped at a later stage, there is no oceanic crust in this region. The crustal structures on both sides of the trough are similar and are approximately symmetrical.
about an E-W line between north and south, suggesting a homogeneous pre-rift continental setting.

The crustal models of the Shidao station, QIZ and Xisha Trough refraction section are combined in Fig. 6 to obtain a profile which crosses the Xisha trough and links the Xisha block and South China block at both ends. The 2 km thick sedimentary layer on the south end of the Xisha trough section can be traced to the Shidao station, where a 2 km low velocity layer also exists at the top of the crustal model. The Moho depth increases gently from 25 km to 28 km below the Shidao station. The sedimentary layer at the north end of the Xisha trough section is 3 km thick, but this layer does not extend to the QIZ and must pinch out in the shelf area. The Moho depth increases gently from 25 km to 33 km beneath the QIZ. This combination profile suggests that the crustal structures beneath the Shidao station and QIZ are closely related to that beneath the Xisha trough. The crustal structure of the Xisha block is a slightly thinned continental crust, similar to the normal continental crust of the South China block.

5 DISCUSSION AND CONCLUSIONS

Geological drilling has been carried out previously on the Yongxing Island and Shidao Island\[19,36,37\]. There are 3 deeper wells with coring, i.e. “Xiyong 1 Well” with 1385 m penetration, “Xiyong 2 Well” with 600 m penetration and “Xishi 1 Well” with 201 m penetration. Only “Xiyong 1 Well” reaches the granite basement at 1251 m depth. The isotopic ages suggest that the basement probably formed during Proterozoic or Palaeozoic\[38\]. Above the basement is a 28 m thick weathered layer, overlain with a coral reef carbonate sedimentary layer deposited since Miocene. The low velocity near surface layer in the Shidao station crustal model corresponds to the sedimentary layer seen in the drilling data, and the normal crust below the low velocity layer correlates with the granite basement.

Comparison of receiver functions show that the direct P wave at the QIZ lacks the 0.4 second time delay of the Shidao station, so that there is no surficial low velocity layer in the inversion crustal model\[34\], which agrees well with the fact that the QIZ was directly installed on granite basement. Relatively speaking, the QIZ has produced more and better quality of receiver functions. Stacking and inversion can be carried out from similar receiver functions chosen from many teleseismic events of the same region. The resulting crustal model is more detailed, for example, the Moho interface can be resolved as a simple discontinuity or a complex gradient. However, only a few of receiver functions are available for the Shidao station. The only clear phases
are direct P wave and the Ps conversion. These waveform fittings are modeled with the trial-and-error forward modeling method, and only a simple structure model is obtained. There are two reasons for the lower quantity and quality of receiver functions recorded at the Shidao station. One is the short time period of temporary observation, and the other is large background noise caused by sea waves in reef and island regions. This is a drawback for the receiver function method because high quality raw data are necessary for the deconvolution process.

Ruan et al.\[39\] used the seismic data recorded by the Shidao station to obtain the receiver functions from P waveforms of 9 events with epicentral distances between 20° ~ 60°. Although they used different filter parameters and inversion methods from those used here, they obtained similar results. Their direct P wave has 0.4 second time delay and the Ps is also the only clear converted phase. Their inversion model has a 2 km thick low velocity layer at the top, and downwards has oscillating and interlacing behavior, similar to our inverse results. They also abandoned this over-complex model and simplified the model by average. They obtained 3.8 km/s average shear velocity for depths 5~16 km, which is the same as the crustal velocity value of our forward modelling. However, they get a smaller lower crustal velocity (3.6 km/s) and shallower Moho depth (26.5 km). We believe that the differences are caused by non-uniqueness of modeling. Since there is only one converted Ps phase, it is difficult to constrain both lower crustal velocity and Moho depth, a pair of trade-off parameters. If considering the nearby Xisha trough section, where P wave velocity is increasing with depth, and assuming the P wave velocity and S wave velocity have certain relationship (e.g. \(V_P = \sqrt{3}V_S\)), our model is more reasonable.

Data from the temporary Shidao station shows that even though seismic records in reef and island areas are affected by the background noise of ocean waves, earthquakes above magnitude 6 can still be recorded during a tropical cyclone. The ability to acquire seismic waveform data from such stations is very important for studies of the crustal and upper mantle structure of the northwestern South China Sea.

The results of Shidao station receiver functions indicate that the Moho depth is 28 km. The S wave velocity in the crust is 3.8 km/s, and there is a 2 km thick near surface low velocity layer. This model is supported by the drilling data and previous studies, but the low data quality prevents us from obtaining a more detailed crustal model.

The models of the Shidao station and QIZ are the natural extensions of the Xihsa trough section. The Xisha block has the crustal structure of a thinned continental crust. The Xisha trough is a rift where the amount of stretching was almost sufficiently large to generate oceanic crust. The Hainan Island, together with the South China block, has a normal continental crustal structure. The Xisha block is similar but has been slightly stretched.

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