

Observations of Earthquake-Generated T-Waves in the South China Sea: Possible Applications for Regional Seismic Monitoring

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ABSTRACT

We present a detailed study of T-waves originating from earthquakes in the South China Sea region, near the Indochina Peninsula and Luzon islands which were recorded by a broadband seismic station at Nansha Island. Most of these T-waves appear to have been the source originating from earthquakes with epicentral distances greater than 600 km from this station. The T-waves in this region were identified via their apparent stable measured velocities of about 1.45 km s⁻¹, and represent the first reported T-waves and the first T-waves observed from an island station in the South China Sea. However, during the period of analysis (November 2004 to December 2005) additional earthquakes also occurred beyond the South China Sea region, but in these instances, any associated T-waves were not picked up by the station at Nansha Island. An analysis of T-wave travel times reveals the possible locations of the P-wave to T-wave transitions at the ocean to crust interface were presumably situated near the earthquake source side. Our results indicate that the Sound Fixing and Ranging (SOFAR) channel is well developed in the South China Sea region. Ultimately, developing a solid understanding of the effective transmission of T-waves through the ocean may provide new opportunities for detecting and locating small earthquakes which would be useful for both seismic monitoring and in helping to predict and reduce the damaging effects of earthquakes and tsunamis in the South China Sea region.

Key words: T-wave, Earthquake, SOFAR channel, Nansha Island, South China Sea, Seismic monitoring

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1. INTRODUCTION

The acoustic phase related to earthquake energy propagating through seawater is called the T-phase (or T-wave), which was first analyzed by Linehan (1940) for Caribbean earthquakes recorded at Harvard Observatory. In early studies, T-waves were regarded as acoustic water waves that propagated over large distances (several thousand kilometers) in seawater along the Sound Fixing and Ranging (SOFAR) channel of minimum sound velocity (Ewing et al. 1950, 1952). The 'T' in T-phase (and T-wave) denotes 'tertiary' because these waves are the third type to arrive, after P- (primary) and S- (secondary) waves which

propagate instead through the Earth's crust; as a rule, T-phases are recorded at sea using hydrophones. However, the seismic conversion wave generated by a T-phase that strikes an island or continental shore can also be recorded by a seismometer on land (Shurbet 1955; Galanopoulos and Drakopoulos 1974; Lin 2001; Huang et al. 2011).

Over the last decade, several investigations of earthquake-generated T-waves have been carried out - most of which have benefited, incidentally, from the enforcement of the Comprehensive Nuclear - Test Ban Treaty (CTBT), which requires the constant monitoring of acoustic disturbances in the world's oceans in order to detect and guard against possible nuclear testing. Consequently, these new studies have recorded important data regarding natural earthquake-generated T-waves, which has led to a wide variety of novel

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seismic applications for these acoustic phases propagating through seawater. For example, T-phases have been used to locate remote earthquake epicenters that are situated far out in the deep ocean with a high degree of accuracy (Yang and Forsyth 2003). In another study, T-phases recorded using a small hydroacoustic array were used to study the pattern of rupture propagation and the geographic extent of the source rupture for the $M_w = 9.0$, 2004 Sumatra earthquake (Guilbert et al. 2005). Furthermore, recently T-waves have been shown to provide important information in detecting and monitoring a range of physical disturbances in global ocean environments, including earthquakes, submarine landslides, and volcanic activity, as well as providing clues to global climate change and aiding in the development of tsunami warning systems (Okal 2001; Graeber and Piserchia 2004).

The Manila Trench, located in the northeastern part of the South China Sea (SCS), is an area that is considered to have one of the highest risks of potential natural disaster occurrence in the entire western Pacific Ocean with regards to earthquake and tsunami generation (Huang et al. 2009; Liu et al. 2009). However, the necessary levels of seismic monitoring and related tectonic investigations in this region required to develop a complete understanding and an adequate ability to evaluate, predict, and reduce the impact of such natural hazards have been somewhat limited. In order to monitor seismic activity accurately in this region, it is essential to have a number of seismic and hydroacoustic stations located directly in the SCS and close to the western side of the Manila Trench, which will allow for proper observations of both seismic waves and T-waves. In principle, such an array of seismic/hydroacoustic stations would provide a more complete network of coverage required to detect earthquakes in the Manila Trench both for tectonic investigation and to try and reduce the impact of seismic hazards in the area. Prior to deployment as noted in this study, such hydrophones or seismic stations were not available in the northeastern SCS.

Consequently, in this paper we document the installation of the first broadband station in this region in order to carry out the present research study focused on the observation and analysis of earthquake-generated T-waves in the SCS and their propagation characteristics. Our study represents the first T-wave study conducted in the SCS and provides important new data that we use to evaluate possible tectonic interpretations for the origin and propagation of T-waves in this region. The installation of a new seismic station and our investigation of earthquake-generated T-waves propagation in the SCS is presented here and will facilitate the construction of a more complete seismic network across the SCS, which could be used to monitor seismic activity in the area, to understand regional tectonic evolution, and to reduce the impact of natural hazards related to earthquakes and tsunamis in this region.

2. OBSERVATIONS

Over November 2004 to December 2005, a portable seismic station was installed at Nansha Island (Fig. 1) by the Institute of Earth Sciences, Academia Sinica (IESAS), in order to monitor earthquake activity within the SCS region, and also to observe teleseismic events as part of a regional seismic structure investigation. This station was equipped with a Nanometrics Trillium 40 broadband sensor and a Quanterra/Kinometrics Q330 recorder with 24-bit analogue-to-digital conversion. The seismometer measured ground motion over a wide frequency range with a flat response to velocity from at least 0.025, to 50 Hz. The ground motion signal was recorded continuously and digitized at a rate of 100 samples per second, which allowed for the recording of nearly 6 months of continuous data on a 20-Gbyte high-capacity recording system (Quanterra PB14F Packet Baler). Timekeeping was provided by a built-in Global Positioning System (GPS) clock that resets the internal clock each hour to keep timing errors below 1 millisecond. Power was supplied by a 12-V automotive battery that could be recharged either with AC power or solar panels. All equipment was installed at the meteorological station on Nansha Island (latitude, 10.377°N; longitude, 114.365°E; elevation, 2 m). An overview photograph of this station, along with a photograph showing an inside look at the appearance of the equipment are displayed in Fig. 2 including all of the aforementioned specifications. This instrumental set-up was considered to be suitable for making reliable seismic observations from this remote island station.

In fact, the location of this seismic station is ideal for recording T-phases from earthquakes in and around the surrounding coastal and continental slope areas of this region (Fig. 1). Typical vertical-component seismograms and related spectra are shown in Fig. 3a, for an event located in the Manila Trench characterized by large T-phase amplitudes. It was found in this study that P- and S-waves have a similar high frequency content with regard to comparatively late-arriving T-waves. In another recorded example of a different seismic event, only T-waves were observed; whereby no P- or S-waves were detected (Fig. 3b). It can be the reason that the relatively lower attenuation of the T-waves than seismic P- and S-waves, has presented, in some case, the T-waves alone. Consequently, this observation indicates that T-waves show great promise for providing valuable information about relatively small or remote earthquakes in the SCS, whose P- and S- waves may go undetected.

According to the earthquake catalog of the United States Geological Survey (USGS) Preliminary Determination of Epicenters (PDE), throughout the time period in which our seismic station was deployed at Nansha Island (from November 2004 to December 2005), a total of 95 earthquakes spanning a range of magnitudes from 4.0 to 5.8 took place at locations inside or nearby to the SCS region

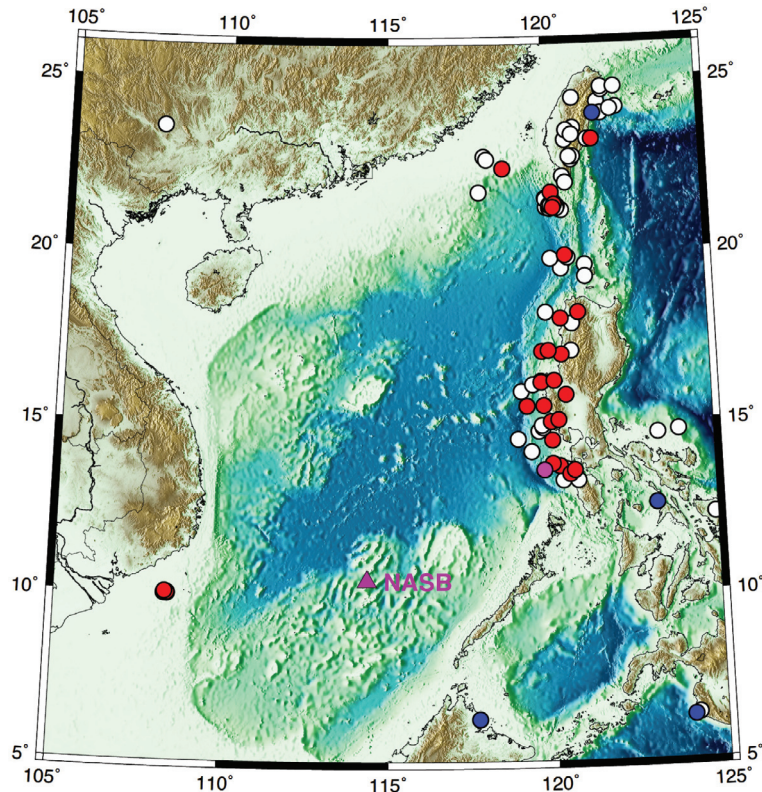


Fig. 1. Bathymetric map of the northeastern South China Sea, highlighting the seismic station (NANB) located at Nansha Island (pink triangle) and regional earthquakes that occurred within the observation period of November 2004 to December 2005. The circles indicate the epicenters of earthquakes. The red circles and blue circles indicate seismic events for which T-waves have and have not been recorded, respectively. More information about those particular events is listed in Table 1. The white circles indicate low S/N events for which no visible T-waves were identified (in comparison, the blue circles represent events that also did not record T-waves, but for a different reason: they were blocked by the presence of land in between the source and the Nansha Island station). The pink circle corresponds to one particular event that is specifically discussed in the text.

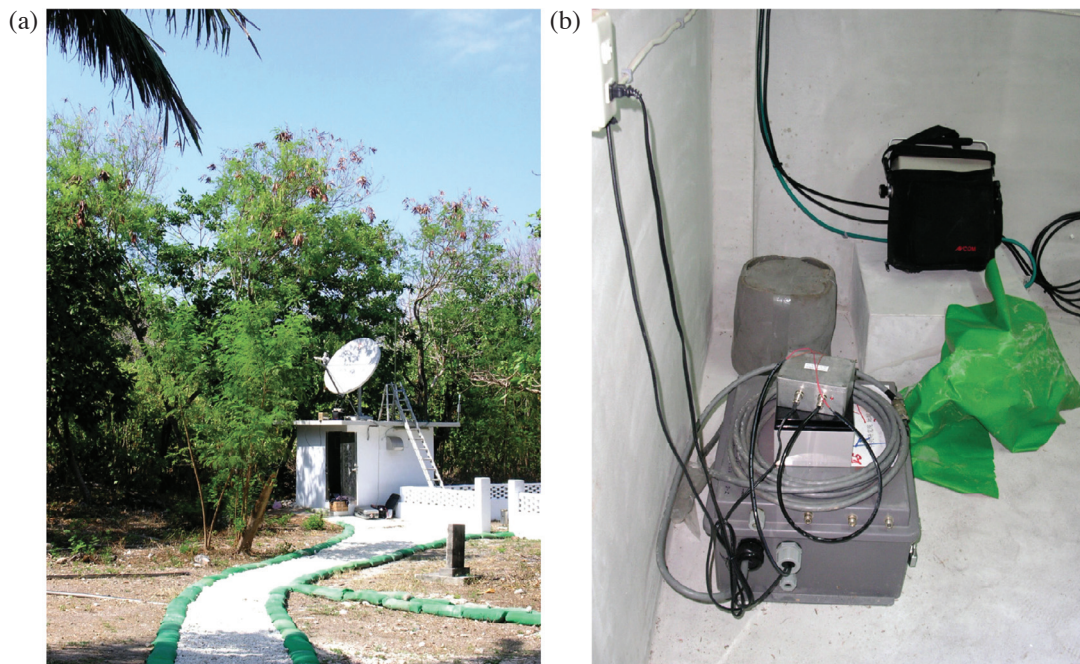


Fig. 2. Photographs showing the exterior of the seismic station house and the instrumental set-up inside. (a) An external view of the Nansha Island seismic station house. This station is located beside the meteorological observation garden. (b) This photo shows the seismometer (covered by the temperature isolator) and recorder box inside the station house.

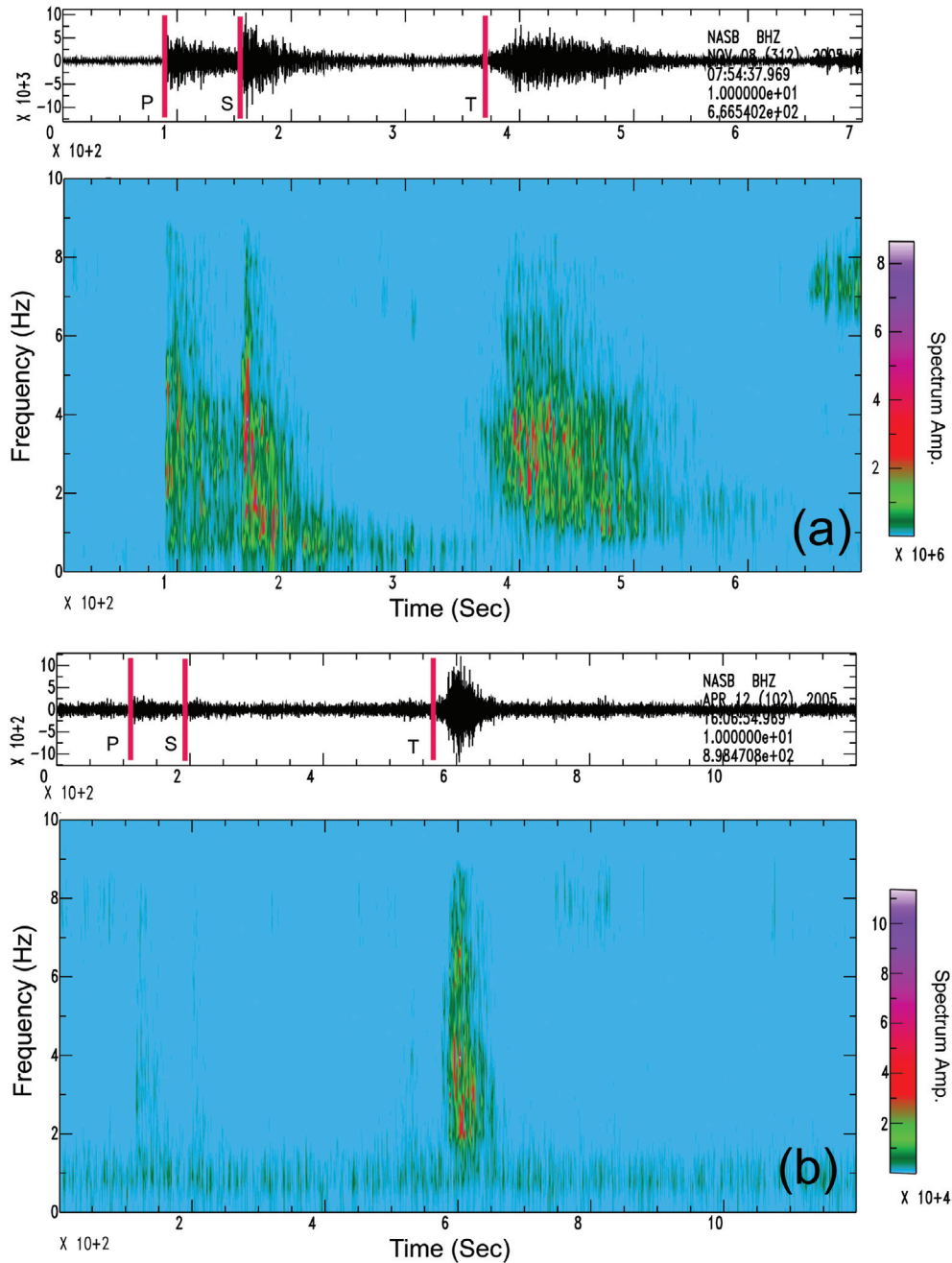


Fig. 3. Two vertical component seismograms (black and white, with red lines) with relevant spectrograms (full color diagrams) for seismic events observed at Nansha Island. (a) A representative example of a T-wave seismogram recorded in this study (upper plot), high-pass filtered at 0.5 Hz, and generated by an event having an epicentral distance of 667 km. The red vertical bars indicate the picked arrival times of P-, S- and T-phases, respectively. Note the similar frequency contents of all three phases, and that all three phases are clearly visible in both the seismogram (top) and spectrogram (bottom). (b) A representative example of a T-wave seismogram recorded in this study (upper plot), high-pass filtered at 0.5 Hz, generated by an event having an epicentral distance of 898 km. Note that only the T-phase is clearly visible in both the seismogram (top) and spectrogram (below).

(Fig. 1). All those events are far away from the SCS seismic station and with epicentral distances greater than 600 km, thus more than half of those data have a low signal to noise (S/N) ratio. Therefore, in this study, selected seismograms were examined and categorized as separate from the others if it was high S/N ratio. Events with clear T-phases were re-

corded by the Nansha Island station, which then allowed for valuable systematic searches and follow-up analyses using available observations on the generation and characteristics of the T-waves in this region. The hypocenter parameters of those events categorized separately in this fashion for the existence of T-phases are listed in Table 1.

Table 1. Hypocenter parameters for the events used in this study*.

Date			Time (UT)			Lat.	Lon.	Depth	Mag	Notes
y	m	d	h	m	s	(°N)	(°E)	(km)		
2004	11	30	17	49	14.93	17.06	119.79	81	4.2 m_b	A
2004	12	10	19	38	31.25	15.79	120.51	59	4.1 m_b	A
2004	12	26	20	8	34.60	14.47	120.05	58	4.8 m_b	A
2004	12	28	7	47	9.46	18.02	120.40	17	4.7 m_b	A
2005	1	27	6	13	3.90	15.48	119.81	68	4.9 m_b	A
2005	2	11	7	43	55.63	16.17	119.74	62	4.9 M_w	A
2005	2	18	20	18	17.90	23.21	121.56	16	5.4 M_w	B
2005	2	22	3	20	7.31	12.58	123.18	17	5.8 M_w	C
2005	3	2	9	11	29.40	19.85	120.60	44	4.4 m_b	A
2005	4	3	16	25	19.88	22.39	118.67	10	4.5 m_b	B
2005	4	8	6	9	49.36	15.48	119.29	31	5.3 M_w	A
2005	4	12	16	6	55.28	16.21	120.15	10	4.2 m_b	A
2005	4	14	16	25	16.31	13.72	120.27	24	5.1 M_w	B
2005	4	24	12	17	40.52	21.68	120.21	42	4.8 m_b	B
2005	4	30	14	48	16.08	23.96	121.64	7	5.3 M_w	C
2005	5	12	8	37	10.99	16.97	120.39	46	4.7 m_b	A
2005	5	23	19	58	9.66	6.26	117.71	19	5.3 M_w	C
2005	5	30	10	56	52.05	13.61	119.79	42	4.3 m_b	C
2005	6	4	14	28	37.49	13.48	120.58	61	4.8 M_w	B
2005	6	20	11	0	41.08	21.24	120.25	17	4.3 m_b	B
2005	8	5	13	35	15.93	9.99	108.37	16	4.4 m_b	B
2005	8	5	18	7	13.87	9.98	108.38	10	4.5 m_b	B
2005	8	31	21	26	59.33	15.01	120.03	10	4.5 m_b	B
2005	9	6	22	24	31.95	15.06	120.26	35	4.5 m_b	A
2005	9	26	10	40	3.22	13.79	120.05	10	4.7 m_b	B
2005	10	13	23	31	56.95	21.33	120.30	35	5.0 M_w	B
2005	10	23	8	42	1.17	17.08	119.99	59	4.9 M_w	A
2005	10	27	15	19	10.52	13.59	120.72	29	4.8 M_w	B
2005	11	7	11	9	24.24	18.19	120.96	60	4.3 m_b	A
2005	11	7	17	8	22.50	10.02	108.31	10	4.0 m_b	B
2005	11	7	17	15	50.77	9.96	108.39	10	5.2 M_w	A
2005	11	8	7	54	38.95	9.97	108.29	10	5.3 M_w	A
2005	11	30	16	53	42.47	6.27	124.03	13	6.4 M_w	C

* The data originate from the PDE catalog of the USGS. Notes: Classification of the presence of a T-phase in each dataset: A (clear), B (unclear), and C (no). Abbreviations: Mag. - earthquake magnitude; m_b - body wave magnitude; M_w - moment magnitude scale; UT - Universal Time.

3. ANALYSIS AND RESULTS

Amongst 33 selected seismic events documented in the SCS by the USGS between November 2004 and December 2005 (Table 1), T-phases were positively identified in the data for 28 events that had epicentral distances (from the Nansha Island station) ranging from 667 to 1404 km. Each of these 33 events occurred along or nearby the Manila Trench

with the exception of three earthquakes that took place near the Indochina Peninsula (westernmost red circles in Fig. 1). A number of selected vertical component recordings, for 18 earthquakes with large T-phase amplitudes, are plotted in Fig. 4. In contrast, in the recordings of 62 other selected events, T-phases could not be positively identified because of low S/N ratios. Furthermore, T-waves from events outside of the SCS are rarely observed, amongst 33 selected seismic

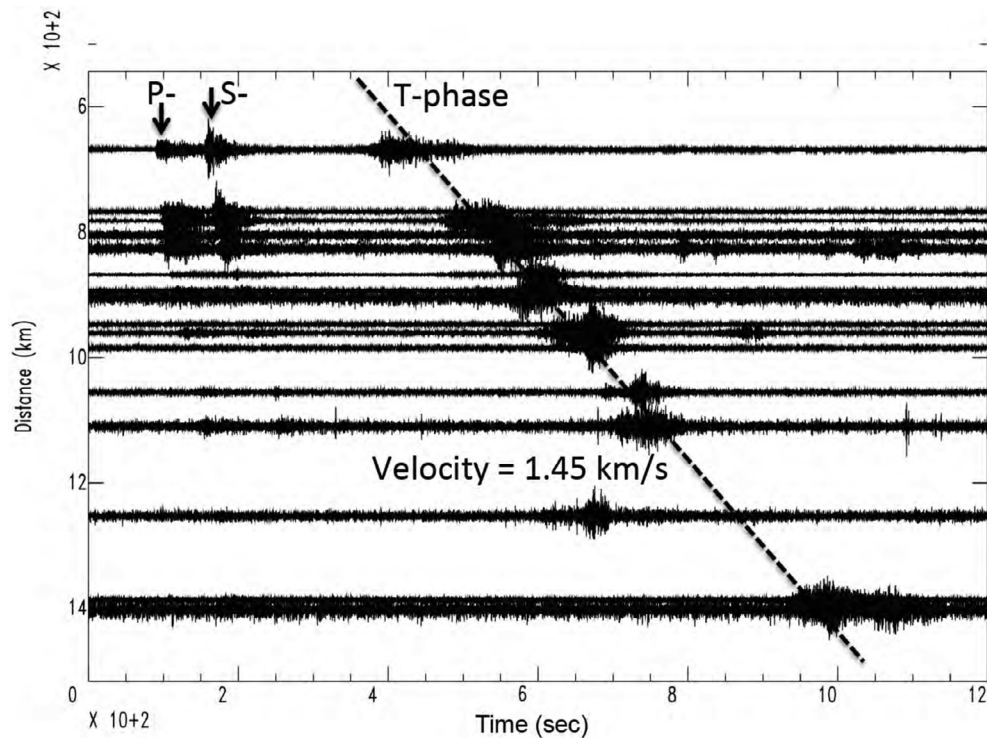


Fig. 4. Time-plot versus distance for several seismic events recorded at the Nansha Island station, showing the profiles of individual events that took place in the SCS region (during deployment of the station) along with their epicentral distances. The vertical arrows indicate the identified phases of P- and S-waves. The dashed line represents a linear regression through the mean duration of T-phases with the slope indicating an apparent velocity of 1.45 km s^{-1} for T-waves propagating through the SCS. All seismograms were normalized individually.

events, the recordings of four additional earthquakes that took place nearby the Manila Trench (epicenters shown as solid blue circles in Fig. 1) with a magnitude larger than 5 are selected as examples that show clear evidence of seismic waves (but without T-phases) in this study for comparison with the other datasets. The hypocenter parameters of these four events are also listed in Table 1. The data for one of these events in particular (which occurred on 23 May 2005) is also shown in Fig. 5 as a representative example of a three component seismograms. One feature that all four of these events have in common, is that their sources were located outside of the SCS where linear paths between each one of them and our seismic station were actually blocked by the occurrence of land (Fig. 1) thereby resulting in a lack of water layers directly connecting each source to the Nansha Island station. As a direct consequence of this, any associated T-waves generated near the sources of each of these four events (i.e., on the other side of the obstructing land) would have been blocked from reaching our seismic station in all four cases. However, one exceptional event located near the eastern shore of Taiwan (northernmost red circle in Fig. 1, which occurred on 18 February 2005, Table 1) actually showed a T-wave signature on seismograms that we classified as ‘unclear.’ In this particular case, the T-waves may have been converted from the southwestern shore of Taiwan

or scattered from some border region of the SCS. During the time period that our seismic station was deployed, we recorded only one of 33 events located near the western shore of southern Luzon (solid pink circle in Fig. 1, which occurred on 30 May 2005, Table 1) that cannot reasonably be explained in terms of its lack of any T-wave signature using the above arguments (i.e., for the aforementioned four T-wave absent datasets). Nevertheless, some events nearby this one actually did show significant T-waves in their time traces. A detailed examination of these particular ‘nearby’ events reveals that the events which occurred at shallow depths (less than 30 km) tended to show some evidence of T-waves, whereas one of these events which had a relatively deep source depth of 61 km showed a more indistinct T-wave signature, even though P- and S-waves were clearly observed. Therefore, in comparison to these ‘nearby’ events, this anomalous T-wave absent event (pink circle in Fig. 1) may have been caused by an earthquake that had both a deeper source depth and a smaller magnitude, such that as a result, the T-waves generated during this event might have been below background noise thresholds, so a low S/N ratio may be the reason that no T-waves were detected for this particular event.

In Fig. 4, the vertical component seismic records for several events (18 events that displayed strong T-wave sig-

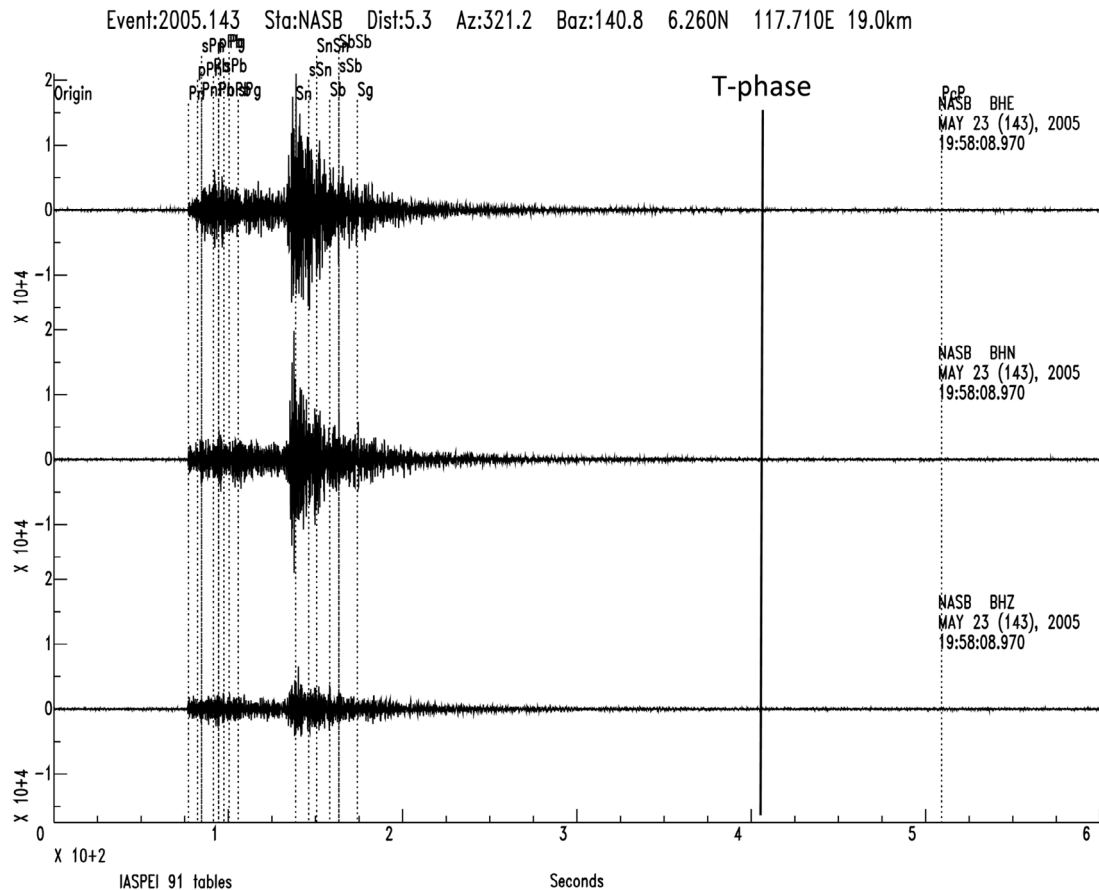


Fig. 5. Representative example of a three component seismograms recorded in this study at the Nansha Island station, for a seismic event that occurred in northern Borneo, nearby to the SCS region (blue circle at bottom-center in Fig. 1). No T-phase was observed in each component waveform, because the T-waves were blocked by land occurring directly between the event source and the Nansha Island station. The predicted T-wave arrival time was plotted as a solid vertical line passing through all three seismograms.

natures) located in the SCS on the eastern side of an imaginary N-S line drawn through the Nansha Island station, were plotted on a graph showing arrival time (in s) versus distance (in km). The strong late-arriving phases on each plot (i.e., T-waves) collectively define a linear trend that passes through all of them, and which can be reliably separated from P- and S-wave coda over the entire time-distance plot. This late-arriving phase exhibits quite a variable time of initial onset between individual events and also a relatively long duration time especially when compared to the P- and S-wave signatures. Nevertheless, the aforementioned well-defined linear trend with a slope of 1.45 km s^{-1} can be regressed with a reasonable degree of fit through the mean duration of the late-arriving phase for most of the events (dashed line in Fig. 4); we interpret this value to indicate the mean velocity of T-wave propagation through seawater of the SCS.

During the above-mentioned observation period, three nearby events located offshore of southern Vietnam (the southern- and westernmost red circles in Fig. 1) were documented, all of which recorded significant T-waves arriving

at the Nansha Island station (these three events are also listed in Table 1 in the 4th, 3rd, and 2nd rows from the bottom). All three of these events have similar waveforms (as recorded at this station), and the largest event was characterized by a magnitude of 5.3 (M_w). For direct comparison to one of these three nearby events (which occurred on 8 November 2005), we selected one event from the Manila Trench region (which occurred on 8 April 2005) that has a similar epicentral distance from the Nansha Island station (see this comparison in Fig. 6). Notably, these events were located distally in directions approximately due W and approximately due NE from Nansha Island, respectively (Fig. 1). From this observation, we can deduce that there may have been contrasting (i.e., different) bathymetries (e.g., variations in depth and slope) from one source to the Nansha Island station than from the other, or alternatively, lateral variations of solid Earth structure along these two propagation pathways.

Discounting the short land paths within Nansha Island, we assumed in this study that the T-waves we recorded for each event had passed only through seawater (i.e., purely

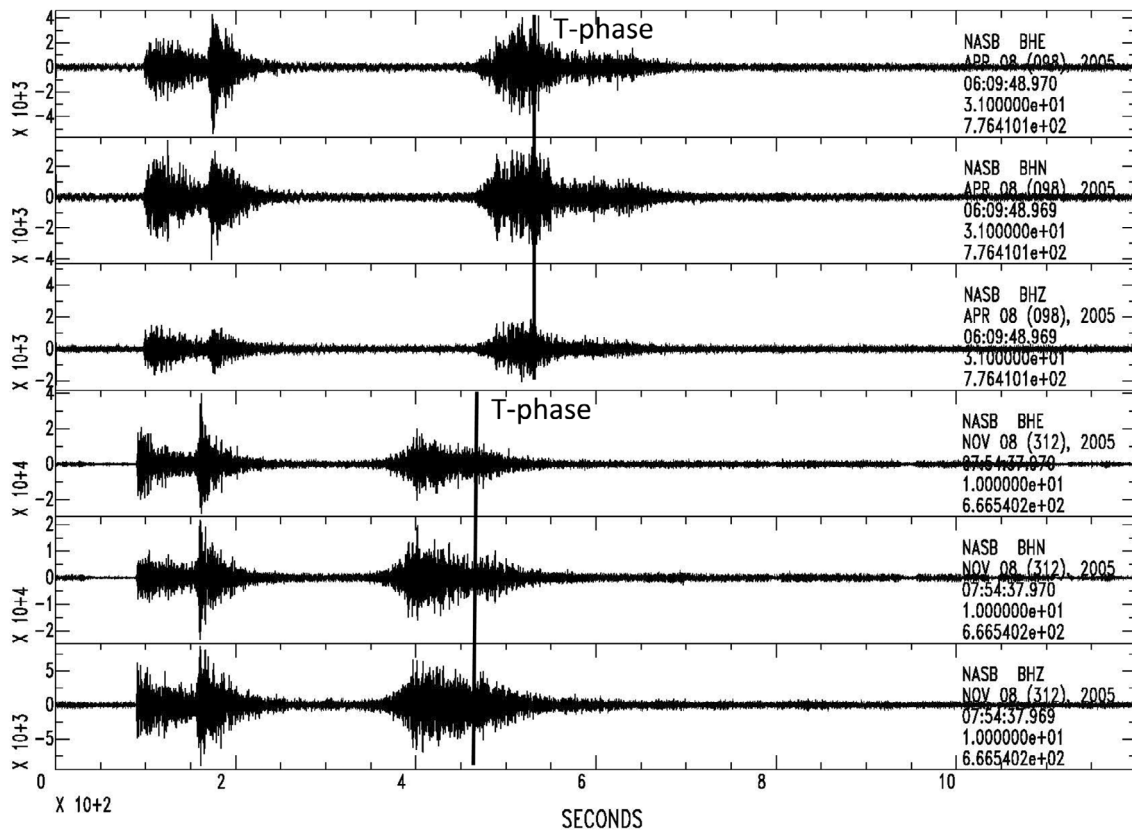


Fig. 6. Two representative examples of three component seismograms recorded for one seismic event (upper three time traces) that took place at a location distal to the Nansha Island station on an azimuthal direction of \sim due NE and another seismic event that took place more or less equally distal to this station but far to the west instead. The vertical bars indicate the predicted arrival times of T-phases using an estimated velocity of 1.45 km s^{-1} , after travelling from their epicenters. Note the relatively early arrivals of the predicted T-waves can be considered as part of T-wave segments are propagating inside solid earth and the seismic wave propagation in faster velocity than acoustic wave at sea.

oceanic propagation) when travelling from the epicenter to our station, and accordingly, we computed the theoretical T-phase travel times from all of the individual epicenters to Nansha Island using the T-wave propagation velocity in the SCS that we estimated above to be 1.45 km s^{-1} . These calculated T-wave arrival times were also plotted (as vertical lines) directly on the seismograms shown in Fig. 6, and from this combined information it was found that the actual T-wave energy packets seem to have arrived at both stations earlier than our predictions (i.e., from the aforementioned calculations). This indicates in turn, that at least some regions of relatively faster solid (crustal) pathways may also have been traversed by these T-waves along their propagation paths by two-way, two-step seismic conversion (Talandier and Okal 1998). Furthermore, the T-wave propagation from the western side of the SCS to the Nansha Island station was faster than from the northeastern side (Fig. 6).

4. DISCUSSION

Earthquake-generated T-waves can be excited by fault ruptures in the solid Earth through conversion of crustal

seismic energy into oceanic acoustic waves which takes place at the solid-liquid (crust-ocean) interface. Such T-waves propagate across the ocean by travelling within the minimum sound velocity SOFAR channel, which acts as a waveguide for acoustic energy in the ocean. By adding the collective contributions of the various seismic and acoustic segments along its ray path, successful modeling of T-wave propagation times can be carried out for many seismic events. It is well-established that seismic stations situated on land can also record accurate information about T-phase activity in instances when a hydroacoustic wave strikes an island or continental margin thus generating (i.e., converting to) seismic waves which are picked-up by the on land station. Investigations of this type of conversion are helpful in understanding T-wave propagation across land (as seismic waves), in order to help evaluate the capability of such on-land seismic stations to monitor hydroacoustic activity in the oceans (Wei 2010; Huang et al. 2011). In contrast, however, the opposite process of conversion of seismic energy into acoustic waves at the earthquake source region is significantly more complex invoking several different possible conversion mechanisms. Although the role of sloping

bathymetry (the ocean-water interface) in trapping acoustic energy inside the low-velocity waveguide (SOFAR channel) is a fundamental aspect of the conversion of seismic energy into acoustic waves at the event source location, the T-waves themselves, however, are considered to represent acoustic energy that was converted from the P- or Lg-phases originating from shallow seismic events (Koyanagi et al. 1995; Talandier and Okal 1998), or alternatively, from the S-waves originating from deep earthquakes (Okal and Talandier 1997; Lin 2001). Early named this model as the downslope conversion model, it was originally proposed to explain many attributes of the observed T-waves, and this model proved to be quite adequate in doing so (Officer 1958; Johnson et al. 1963). More recently, Talandier and Okal (1998) documented contrasting T-waves received from various types of earthquakes, which could be identified according to the various corresponding characteristic shapes of the recorded T-wave profiles. These studies indicated that shallow seismic events having a simple conversion process to acoustic waves, generated impulse-shaped T-wave profiles whereas deep events occurring under a gentle sloped bathymetry induced an emergent, spindle-shaped T-wave. Furthermore, a small intra-plate earthquake occurring beneath a flat abyssal plain far away from any documented shallow slope can also generate strong T-waves (Johnson et al. 1968).

In the present study, these various possible mechanisms of seismic-to-acoustic conversion were examined as potential T-wave generating mechanisms within the SCS region. In light of these considerations we refer to these mechanisms as they are described in the aforementioned studies of T-wave characteristics and their relationships to different types of earthquake and starting environmental conditions. Figure 6 shows two selected 3-component seismic recordings (as chosen above in section 3), displaying theoretical T-wave arrival times (vertical lines) from sources located more or less due northeast (top three time traces) and more or less due west (bottom three time traces) of the Nansha Island station (Fig. 1). From these data, we observe that the events originating to the west of Nansha Island (lower three time traces in Fig. 6) generated a short duration T-wave trace with an arrival time significantly earlier than that predicted by the above purely oceanic propagation pathway calculation made in section 3. Considering the observed 'shallow' source depth of only 10 km for this (western) event, we assumed that the corresponding T-waves originated from the direct conversion of P waves. At this point, we assume a 'simple' P-wave to T-wave conversion scenario for computing travel times and consider the P-wave velocity in the solid crust to be 5.5 km s^{-1} (Bullen and Bolt 1985). In addition, we estimate that the portion of solid crust through which the original P-waves must have travelled during this western event is about 27.2 km. For the other (northeastern) seismic event (upper three time traces in Fig. 6), we also in-

voke a similar 'simple' scenario for the T-wave generation mechanism (as we did for the western event). However, the estimated distance from the earthquake source to the seismic-to-acoustic conversion point is significantly shorter for the northeastern event than for the western one, resulting in an initial propagation of P-waves through an 18.5-km-long pathway through the solid crust. In addition, by examining the bathymetry of the SCS near these two events (Fig. 1), it is found that the P-wave to T-wave conversion mechanism is suitable to explain both cases with a continental slope environment surrounding the Nansha Island. Furthermore, we also highlight that the nature of the bathymetry between these two continental slope sites and our Nansha Island station strongly favors (in both cases) the downslope propagation mechanism of T-wave travel to the Nansha Island station through a well-developed SOFAR channel in the SCS.

Figure 1 shows the locations of the epicenters of earthquakes that generated T-waves (red circles) recorded by the Nansha Island station which originated from a wide array of azimuthal directions with respect to the location of the station including the both the entire western Manila Trench and also parts of the eastern coast of the Indochina Peninsula. Collectively, these seismic events and T-wave data indicate that the SOFAR channel in the SCS region is well developed. However, the Nansha Island station did not record any T-waves originating from seismic events outside the SCS. This observation can be explained as a result of the SOFAR channel being highly obstructed in shallow water regions and land paths; consequently, the propagation direction of the T-waves originating from these areas may be affected by water depth as observed along the eastern shore of Taiwan (Huang et al. 2011).

In this study, we have shown that T-waves can transmit energy from small seismic events over large distances through seawater of the SCS (Figs. 3 and 4) providing new opportunities for detecting and locating small earthquakes in the SCS region that would otherwise have gone undetected. Within this context, we highlight the fact that T-waves can be used to enhance seismic monitoring in the SCS, and ultimately reduce hazards from earthquakes and tsunamis in coastal areas surrounding the SCS region. The installation of seismic stations at Nansha Island and hopefully on other islands of the SCS in the near future represent significant steps towards improving seismic monitoring and tectonic investigations in this region which can be used for hazard evaluation and reduction. Furthermore, seismic studies focused on natural resource development and oceanic environmental change in the SCS area, although very interesting and potentially quite beneficial, have so far seen only very limited activity by countries surrounding the SCS. The observation and documentation of T-waves that have propagated across vast distances in the ocean have the potential to carry important information pertaining to oceanic environmental monitoring studies. Therefore, we suggest that in

order to begin addressing some of these broader scientific issues, it will be crucial to advance and continue to carry out further investigations focused on studying the nature of T-wave excitation and propagation in the SCS.

5. CONCLUSIONS

Earthquake-generated T-waves have been recorded by a broadband seismic station installed at Nansha Island in the SCS. This study represents the first research effort aimed at investigating the origin and propagation of T-waves across the SCS region, and as a result of this study we have determined a stable T-wave propagation velocity of about 1.45 km s^{-1} for seawater (i.e., pure oceanic propagation) in this region. In addition, this scientific investigation of T-waves in the SCS has shown that the SOFAR channel in the SCS region is well developed and has enabled us to suggest likely scenarios and mechanisms for the excitation and propagation of T-waves in this region. Developing an understanding of and carrying out monitoring studies of T-wave generation and propagation over large distances in the SCS provides new opportunities for detecting and locating small earthquakes in the SCS region. Ultimately, this scientific knowledge will prove useful for seismic monitoring studies aimed at reducing hazards posed by earthquakes and tsunamis in populated areas surrounding the SCS region.

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