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Likelihood of Tsunamis Affecting the Coast of Southeastern China

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Abstract

Tsunami is a high-impact low-probability maritime hazard that poses a threat to the coastal communities worldwide. The coast of southeastern China is vulnerable to tsunamis generated by earthquakes in the northern part of the South China Sea. In this study, the likelihood of local and distant tsunamis affecting the coast of southeastern China is assessed taking into account historical records of tsunamigenic earthquakes, seismicity, and focal mechanism of earthquakes in the various potential source areas. The results show that the chance of tsunamis generated by earthquakes near the Pearl River Estuary is small. Coastal regions from Fujian to eastern Guangdong and around Hainan may be affected by local tsunamis with a return period of about 210 years. Strong earthquakes over the seas and near the coast west of Taiwan and Luzon and in the Luzon Strait may generate regional tsunamis to affect the coast of southeastern China. The return periods for tsunamis to be generated by earthquakes of magnitude exceeding 7.5 in the Taiwan and Luzon regions that may affect the coast of southeastern China are about 110 and 120 years respectively.

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1. Introduction

A tsunami is a series of travelling water waves generated by an impulsive excitation to a large volume of water. They are usually caused by submarine earthquakes which account for more than 90 percent of all tsunamis. Coastal and submarine landslides and volcanic eruptions are less common causes of tsunamis. Tsunami generation by meteor impacts is very rare. Tsunami can be generated in any large volume of water including oceans, seas and lakes.

The Pacific Ocean, covering more than one-third of the Earth's surface, is lined with series of volcanoes, deep-ocean trenches and island arcs at the junctions of major tectonic plates where many major earthquakes occur. High seismicity in the circum-Pacific seismic belt renders the Pacific a favourable place for tsunami generation. Over 85 percent of all tsunamis are generated in the Pacific.

The land masses of Taiwan and Luzon prevent tsunamis generated in the Pacific from entering the South China Sea. Only a small portion of the wave energy could leak through the Luzon Strait. The continental shelf in the South China Sea further damps the waves and rapidly dissipates the energy. Hence tsunamis originating from the Pacific hardly have severe impact on the coast of southeastern China.

Taiwan and Luzon are located on the circum-Pacific seismic belt with high seismicity (Figures 1 and 2). Earthquakes that occur to the west of Taiwan, west of Luzon or in the Luzon Strait may generate tsunamis to affect the coast of southeastern China. Historically, some earthquakes over the coastal areas of southeastern China might have generated tsunamis to affect regions near the epicentres (Figure 3). This paper assesses the likelihood of tsunamis affecting the coast of southeastern China, taking into account historical records of tsunamigenic earthquakes, seismicity, and focal mechanism of earthquakes in the various potential source areas in the South China Sea.

2. Tsunamigenic earthquakes

Not all earthquakes generate tsunamis. Only those that occur in the fault zone near or underneath the seafloor causing a large area of the seafloor to displace vertically can trigger tsunamis. Most destructive tsunamis are generated by shallow earthquakes in the subduction zone with reverse faulting. The size of tsunami generated depends on the extent of horizontal and vertical movements of the seafloor, total area of the seafloor moved, any slumping of underwater sediments due to the quake, and the efficiency with which energy is transferred from the earth's crust to the water volume. Seismic moment analysis can give the orientation of the fault rupture and its extent of displacement but takes time. In tsunami warning operation, earthquake magnitude is used for assessing the likelihood of tsunami generation.

In order to calculate the probability of tsunami generation for different earthquake magnitudes, tsunami records for 1981-2005 from the National Geophysical Data Center (NGDC) of the US National Oceanic and Atmospheric Administration (NOAA) and the integrated tsunami database of Novosibirsk Tsunami Laboratory are examined. After removing cases not caused by earthquakes and those with unknown earthquake magnitudes, a total of 180 cases of tsunamis generated by earthquakes are used in the analysis. The earthquake magnitudes of these tsunami cases are matched to those determined by the National Earthquake Information Center (NEIC) of the United States Geological Survey (USGS) for analysis.

Among the 180 tsunami cases, 12 events were caused by earthquakes of magnitude 6 or below. These included one earthquake of magnitude 3.7, one of magnitude 4.4, and 10 of magnitude 5.1 to 6.0. Some of these earthquakes might have caused submarine landslides. The tsunami heights were below 0.5 metre with no damage reported. They were local events that affect areas within about 100 kilometres from the epicentres. With over 28,000 earthquakes of magnitude 5.1 to 6.0 in 1981-2005 worldwide, the probability of tsunami generation by this range of earthquake magnitudes is less than 0.04 percent.

A plot of tsunami generation probabilities against earthquake magnitudes is given in Figure 4. It can be seen that about 0.9 percent of earthquakes of magnitude 6.1 to 6.5 have generated a tsunami. The probabilities for tsunami generation by earthquakes of magnitude above 6.5, 7.0, 7.5 and 8.0 are 16, 33, 60 and 73 percents respectively. For an earthquake of magnitude above 8.0, the probability would exceed 80 percent if only earthquakes in or near the sea are considered. It can be seen that an earthquake of magnitude greater than 7.0 has a certain chance of generating a tsunami. The probability gets much higher if the earthquake magnitude is above 7.5. For an earthquake of magnitude exceeding 8.0, it is very likely that a tsunami will be generated.

Although earthquakes of magnitude exceeding 6.5 may generate local tsunamis to affect places up to about 100 kilometres from the epicentres, large tsunamis are more likely if the earthquake magnitude exceeds 7.0. Earthquakes of magnitude exceeding 7.5 can produce destructive regional tsunamis that affect areas several hundred to a thousand kilometres away from the epicentres. For example, a magnitude 7.7 earthquake in the Japan Sea in 1983 generated a regional tsunami that claimed more than 100 lives in Japan and the Republic of Korea. In general, earthquake magnitude 7.5 can be used as a threshold above which a destructive regional tsunami is probable.

Most ocean-wide tsunamis are generated by earthquakes of magnitude above 8.0. During the period 1981 to 2005, one destructive ocean-wide tsunami was generated by a magnitude 9.0 earthquake in the Indian Ocean west of northern Sumatra in 2004. The tsunami travelled across the Indian Ocean, Pacific Ocean and Atlantic Ocean. With the intervening landmasses, the tsunami went through a number of oceans and seas before reaching the South China Sea. The tide

gauge at Xisha Islands was the only one in the South China Sea that recorded the tsunami with a height of several centimetres. Around the middle of the twentieth century, five ocean-wide tsunamis occurred in the Pacific Ocean, generated respectively by a magnitude 8.6 earthquake near the Aleutian Islands in 1946, a magnitude 9.0 earthquake in Kamchatka in 1952, a magnitude 8.3 earthquake near the Aleutian Islands in 1957, a magnitude 9.5 Chilean earthquake in 1960 and a magnitude 9.3 earthquake in Alaska in 1964. Only the events in 1952 and 1960 caused measurable tsunami heights in Hong Kong which were 0.15 metre and 0.3 metre respectively. The earthquake magnitude was 9.0 or above in these two cases.

3. Source areas in southeastern China

Seismicity studies show that the coastal faults from Quanzhou to Nan'ao and over Hainan (the outer zone) are more active while inland Guangdong and the Pearl River Delta (the inner zone) have much lower seismicity (Figure 5). All historical earthquakes of magnitude 7 or above occurred in the outer zone and few earthquakes exceeded magnitude 6 in the inner zone (Lee et al., 1996). While the coastal fault extends east-northeast from Hainan to Quanzhou, it is crossed and overlapped by northwest orientated faults in the east near Quanzhou to Nan'ao and in the west over Hainan (Ren et al. (1998), Liang et al. (1998), Liu (1994), Wei et al. (1996), Liu et al. (2002) and Zhao et al. (2003)).

Since 1600, 5 earthquakes of magnitude 7 or above have occurred in the outer zone, namely a magnitude 7 earthquake in Nan'ao in 1600, a magnitude 7½ earthquake in Quanzhou in 1604, a magnitude 7½ earthquake in Qiongzhan in 1605, a magnitude 7.3 earthquake in Nan'ao in 1918 and a magnitude 7.3 earthquake in Taiwan Strait in 1994. All these earthquakes were probably tsunamigenic except the one at Nan'ao in 1600 (Table 1).

Based on Harvard University's Centroid Moment Tensor (CMT) catalogue, the focal mechanisms of 8 recent earthquakes in the Taiwan Strait and Beibu Wan were analysed. It was found that the magnitude 7.3 earthquake and its three aftershocks in the Taiwan Strait in 1994 were of normal fault type while two other earthquakes in the Taiwan Strait and two earthquakes in Beibu Wan were of strike-slip fault type (Figure 6). According to a study by Wei et al. (1996) on tectonic stress field of earthquakes near Yangjiang, Haifeng and Nan'ao, the fault motion of earthquakes in the above regions were mostly strike-slip type. As there are no subduction zones and ocean trenches in the coastal waters of southeastern China, earthquakes in this region are mostly of strike-slip type with some normal fault type.

Lee et al. (1998) studied the seismic activity in the inner and outer zones of southeastern China and found that the return periods of earthquakes of magnitude above 6.0 and 6.5 in the inner zone were 33 and 81 years respectively. It was perceived that the chance for an earthquake of magnitude above 7.0 to occur in the inner zone would be very low. From the 1978-2005

earthquake records from the China Earthquake Administration, the return period of earthquakes within 200 kilometres of Hong Kong were computed using the Gutenberg-Richter relation between earthquake magnitude and frequency ($\log N = a - bM$). It is estimated that the return periods of earthquakes of magnitude above 6.0 and 6.5 are 33 and 71 years respectively, which are similar to the results of Lee et al. (1998). Since half of the areas within the 200 kilometre radius of Hong Kong are over land, the number of earthquakes that can generate tsunamis will be halved. If only earthquakes of magnitude above 6.5 are considered, and using the tsunami generation probabilities obtained in section 2 above, the return period of tsunamis generated by earthquakes of magnitude above 6.5 near Hong Kong is around 890 years. As the earthquake is probably strike-slip or normal fault type (Ding et al., 1998) with a magnitude unlikely to exceed 7.0, the size of the tsunami generated by the earthquake will be relatively small and it is unlikely to propagate to other sea areas.

For earthquakes in the regions of Quanzhou to Nan'ao and Hainan, the formula obtained by Lee et al. (1998) can be used to calculate the return periods. It is estimated that the return periods of earthquakes of magnitude above 6.5, 7.0 and 7.5 are 33, 71 and 150 years respectively. Using the tsunami generation probabilities in section 2 above, the return period of tsunamis to be generated by earthquakes of magnitude above 6.5 in these regions is around 210 years. Although the earthquake magnitude may reach 7.0 or above, earthquakes in these regions are mostly strike-slip type so the size of the tsunami will be limited. It is probable that the tsunami may cause severe damages to areas near the epicentre but propagation to affect coastal areas further away is less likely.

4. Seismic source zones in the Taiwan region

Taiwan is located at the boundary of the Philippine Sea plate and the Eurasian plate, and also the intersection of the Manila trench and the Ryukyu trench (Figure 7). The crustal structure near Taiwan is very complicated. In the south, the Eurasian plate subducts to the east beneath the Philippine Sea plate. In the north, the Philippine Sea plate subducts to northwest underneath the Eurasian plate. The two plates move towards each other at a rate of 8 centimetres per year causing frequent seismic activity near the plate boundaries (Yu et al., 1997).

Applying the method of Hauksson (1990) to fault plane solutions of the Harvard University's CMT catalogue, the focal mechanisms of 215 earthquakes in the sea areas near Taiwan were analysed. 60 percent of the earthquakes are found to be of the reverse fault type while the percentage of normal fault type and strike slip fault type are 21 and 19 respectively (Figure 8). This shows that earthquakes in the Taiwan region are more likely to generate a large tsunami.

Taiwan was affected by tsunamis a number of times in the past four centuries. Earthquakes in and near western Taiwan which might have been tsunamigenic are given in Table 1 and Figure 3.

In the twentieth century, 23 earthquakes of magnitude above 7 occurred in and near Taiwan, i.e. there was an earthquake of magnitude above 7 every 4 to 5 years on average. The largest earthquakes occurred over the seas east of Keelung in 1910 and over the seas east of Hualien in 1920 with the magnitude reaching 8.3 in both cases. Using NEIC's earthquake records from 1973 to 2005 and the Gutenberg-Richter relation, it is estimated that the return periods of earthquakes of magnitude above 7.0, 7.5 and 8.0 in Taiwan are 5, 16 and 50 years respectively.

Tsunamis generated by earthquakes in eastern Taiwan or the seas east of Taiwan are blocked by the Taiwan landmass and unlikely to affect the coast of southeastern China significantly. If only seismic source zones over western Taiwan and the seas west of Taiwan are considered, the area of the seismic source zones is about one quarter of the entire Taiwan seismic source zone. For potential regional tsunamis that may propagate to the coast of southeastern China, earthquakes of magnitude above 7.5 are considered and the probability of tsunami generation by earthquakes of such magnitude as given in section 2 is used. The return period of tsunami generation by earthquakes of magnitude exceeding 7.5 in western Taiwan or over the seas west of Taiwan that may propagate to affect the coast of southeastern China is estimated to be around 110 years.

5. Source areas in the Luzon region

Similar to Taiwan, the Philippines is also located at the boundary of the Eurasian plate and the Philippine Sea plate. In northeastern Luzon, the Philippine Sea plate collides with the Eurasian plate at a rate of 7 centimetres per year. In the southeast near the Philippine trench, the Philippine Sea plate collides with the Eurasian plate at a rate of 9 centimetres per year (Bautista et al., 2001). Seismic moment tensors analysis of 116 earthquakes in Luzon Strait and 72 earthquakes in the sea area to the west of Luzon shows that 64 and 49 percent of the earthquakes in these two areas are of reverse fault type respectively (Figure 8). This indicates that earthquakes in these areas are more likely to generate larger tsunamis. In the past four centuries, a number of tsunamis have been reported along the west coast of Luzon (Table 1).

Using NEIC's earthquake records from 1973 to 2005 and the Gutenberg-Richter relation, it is estimated that the return periods of earthquakes of magnitude above 7.0, 7.5 and 8.0 in the Luzon region are 7, 23 and 74 years respectively.

Tsunamis generated by earthquakes in eastern Luzon or the seas east of Luzon are blocked by the Luzon landmass and unlikely to affect the coast of southeastern China significantly. If the seismic source zones in the Luzon region are divided into one facing the South China Sea

which includes the seas west of Luzon and the Luzon Strait, and another one not facing the South China Sea, the area of the seismic source zones facing the South China Sea is about one-third of the entire Luzon seismic source zone. For potential regional tsunamis, earthquakes of magnitude above 7.5 are considered and the probability of tsunami generation by earthquakes of such magnitude as given in section 2 is used. The return period of tsunamis generated by earthquakes of magnitude exceeding 7.5 in the seas west of Luzon and the Luzon Strait that may propagate to affect the coast of southeastern China is estimated to be around 120 years.

6. Conclusion and discussion

Seismicity near the Pearl River Delta is relatively inactive. There were no earthquakes of magnitude 7 or above and few earthquakes of magnitude 6 in history. The probability of a tsunami to be generated by a local earthquake is very low. Historically, tsunamis may have occurred in areas from Quanzhou to Nan'ao and over Hainan. Seismicity studies and tsunami generation probability analysis suggest that local tsunamis may be generated to affect these regions with a return period of around 210 years. Seismicity in the Taiwan and Luzon regions is rather high. Strong earthquakes over the seas and near the coast west of Taiwan and Luzon and in the Luzon Strait may generate regional tsunamis to affect the coast of southeastern China. The return period for tsunamis to be generated by earthquakes of magnitude exceeding 7.5 in western Taiwan or over the seas west of Taiwan is about 110 years while the return period for tsunamis to be generated by earthquakes of magnitude exceeding 7.5 in the seas west of Luzon and the Luzon Strait is estimated to be about 120 years.

Table 1 : Earthquakes in the northern part of the South China Sea that were probably tsunamigenic

	Year	Mth	Day	Lat.	Long.	Mag	Epicentre	Tsunami report
1.	1604	12	29	25.0	119.5	7½	Quanzhou, Fujian	Quanzhou : mountains and sea in motion, many boats sunk; Shaxian : streams and rivers spilled over
2.	1605	7	13	19.9	110.5	7½	Northern Hainan	Wenchang : flooding and soil collapses
3.	1661	2	15	23.0	120.2	6	Tainan, Taiwan	Anping : boats sunk in harbour, seawater swirled up in the air
4.	1677	12	7				West of Luzon	Sea waves in some places, reports of boats at sea almost submerged by waves
5.	1744						Northern Luzon	Earthquakes accompanied by waves which entered the river mouth
6.	1792	8	9	23.6	120.5	6¾	Chiayi, Taiwan	Zhanghua : Nantou and Beitou flooded with seismic water ; Chiayi : water shoot up tens of feet, waves bombarding the coast
7.	1867	12	18	25.5	121.7		Keelung, Taiwan	Near Danshui : sea flooding, hundreds of people drown
8.	1872	1	26				Manila Bay, Luzon	Town of Agno invaded by a moderate sea wave
9.	1918	2	13	23.5	117.0	7.3	Nan'ao, Guangdong	Shantou : roaring of seawater; Fengshun : tides turning white colour like rice soup
10.	1924	5	6	16.0	119.0	6.9	Seas west of Luzon	Shock felt in western Luzon, 4 waves came in at Agno
11.	1934	2	14	17.6	119.0	7.6	Seas west of Luzon	A wave was reported at San Esteban where some people narrowly escaped drowning, surges were noted at sea south of Vigan
12.	1983	8	17	18.23	120.86	6.5	Northwestern Luzon	Small tsunamis near the coast of Ilocos Norte province
13.	1988	6	24	18.61	121.01	5.4	Luzon Strait	Hong Kong: Tsunami height of 28 cm ^[1] recorded at Quarry Bay
14.	1992	1	5	18.5	108.5	3.7	Beibu Wan	Tsunami amplitudes of 80 and 78 cm ^[2] recorded at Sanya and Yulin respectively
15.	1994	9	16	22.53	118.71	7.3	Taiwan Strait	Tsunami amplitudes of 38 · 26 and 47 cm ^[2] recorded at Penghu, Dongshan, Shantou respectively

^[1] Tsunami height above the normal tide level.

^[2] Wave height from crest to trough, about two times the tsunami height above the normal tide level.

^[3] Tsunamigenic earthquakes over the eastern sides of Taiwan and Luzon are not included.

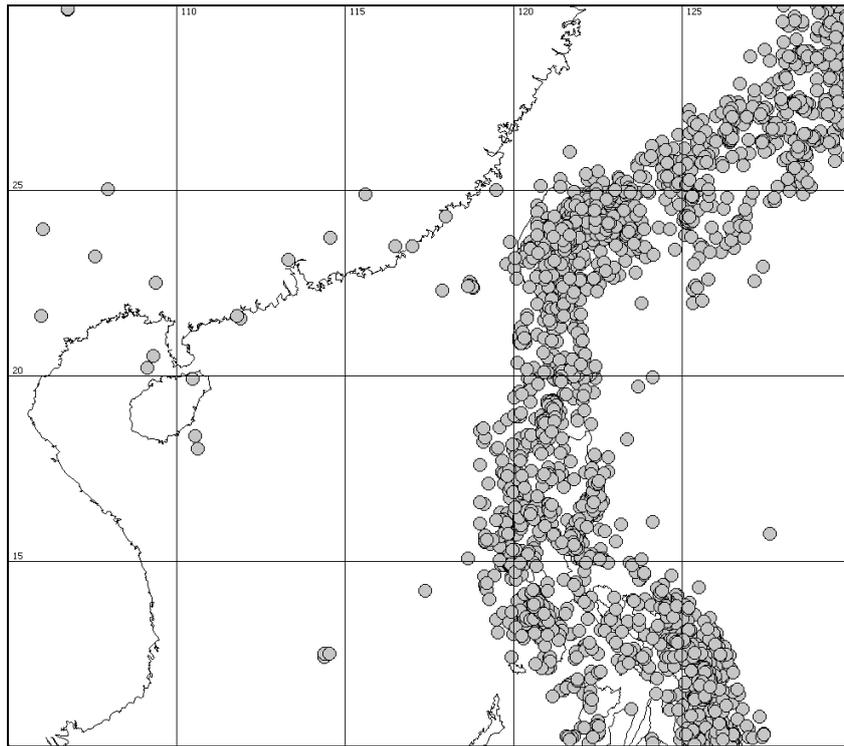


Figure 1 : Locations of earthquakes (magnitudes above 5) in the northern part of the South China Sea and adjacent areas (1604-2001).

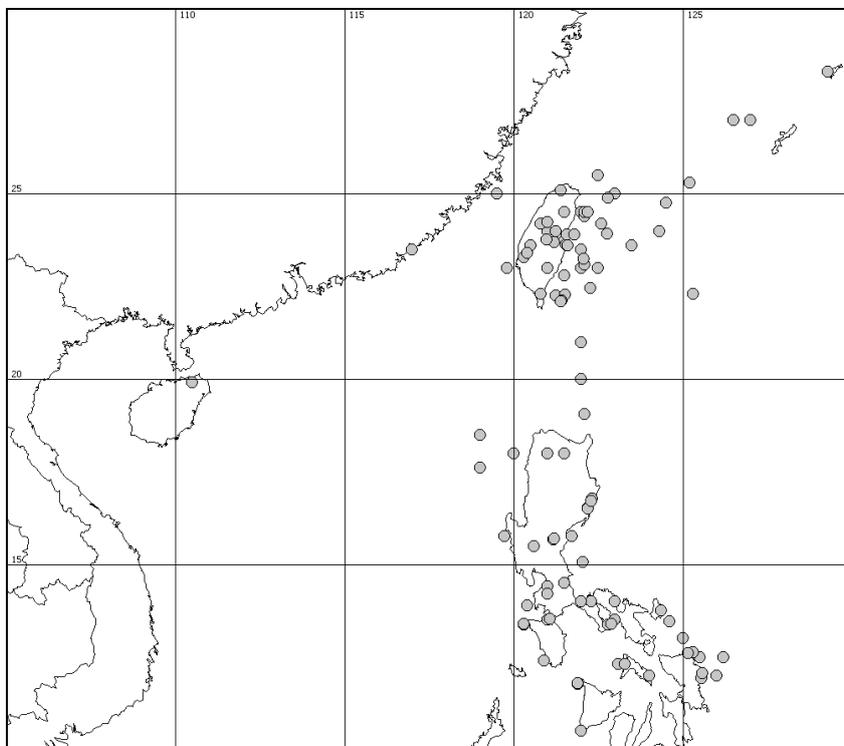


Figure 2 : Locations of earthquakes (magnitudes above 7) in the northern part of the South China Sea and adjacent areas (1604-2001).

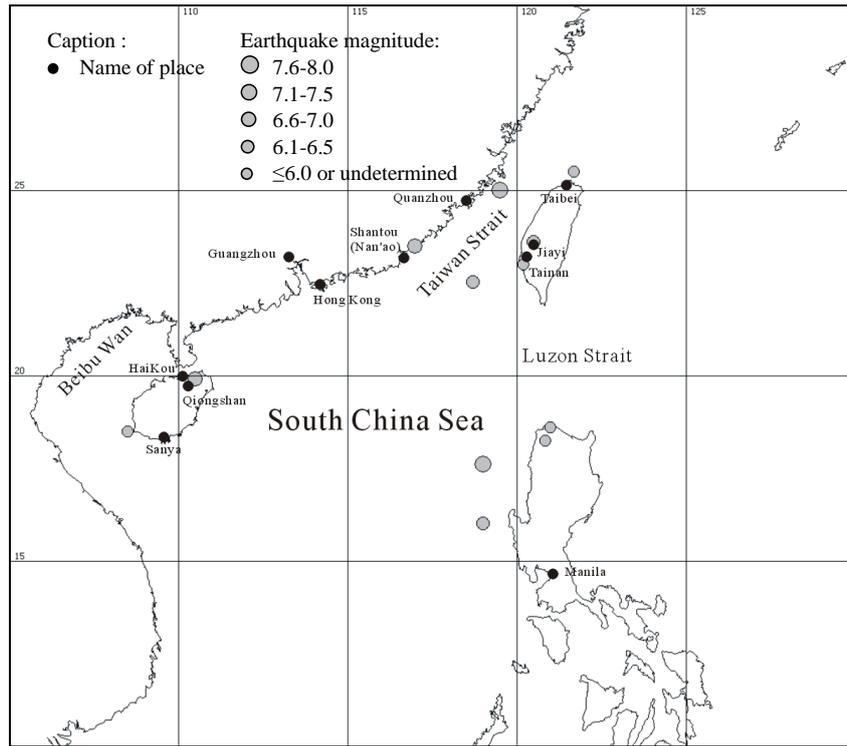


Figure 3 : Earthquakes in the northern part of the South China Sea that might have been tsunamigenic (1600-2005).

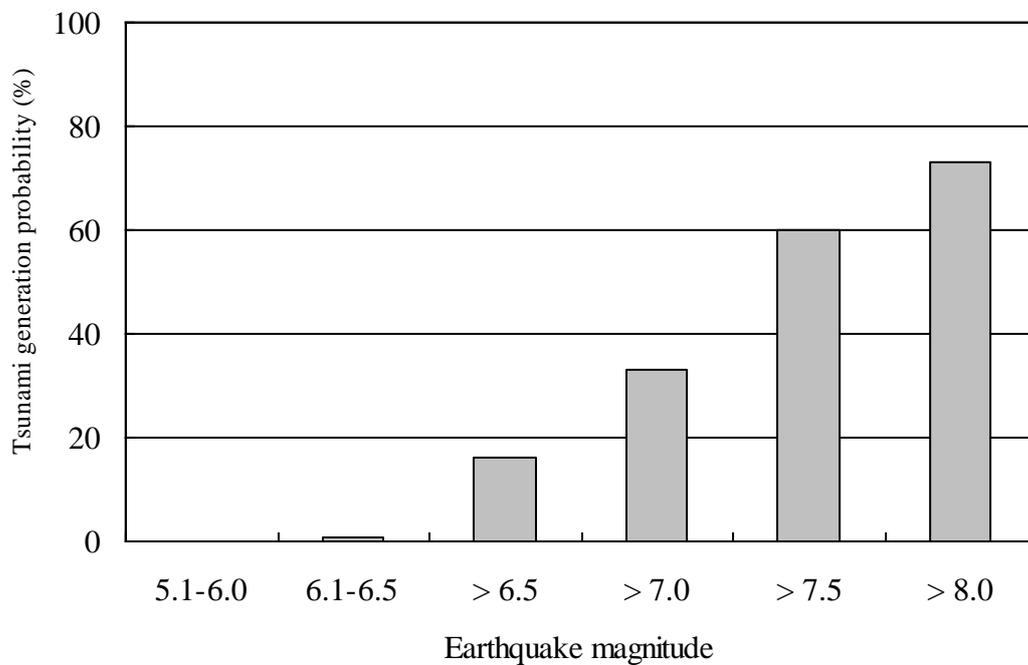


Figure 4 : Tsunami generation probability for various earthquake magnitudes based on tsunami records 1981-2005.

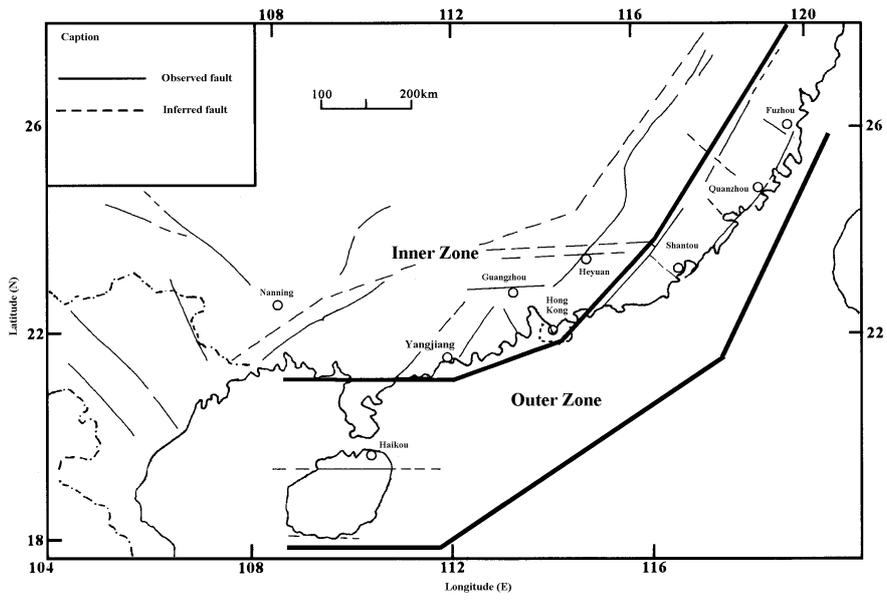


Figure 5 : Coastal seismic faults in southeastern China.

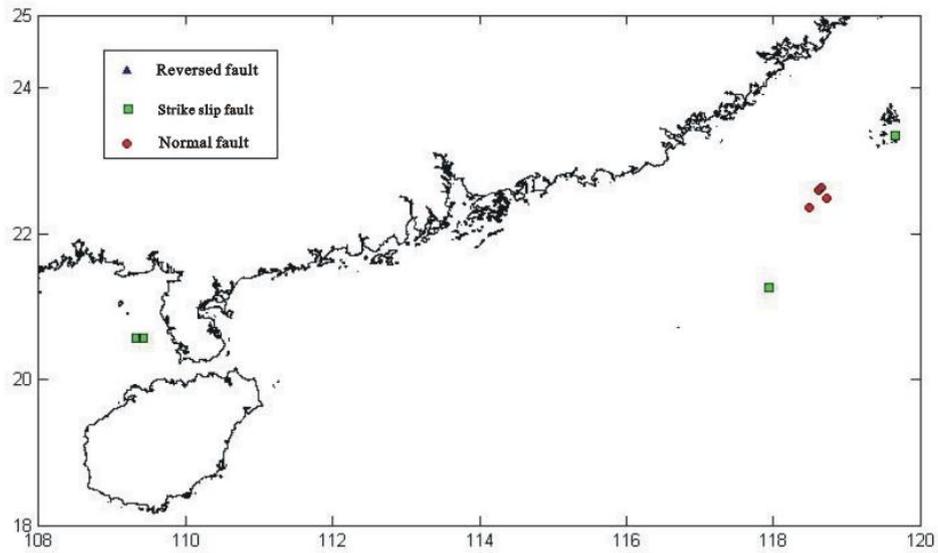


Figure 6 : Focal mechanisms of earthquakes in the coastal waters of southeastern China in recent years.

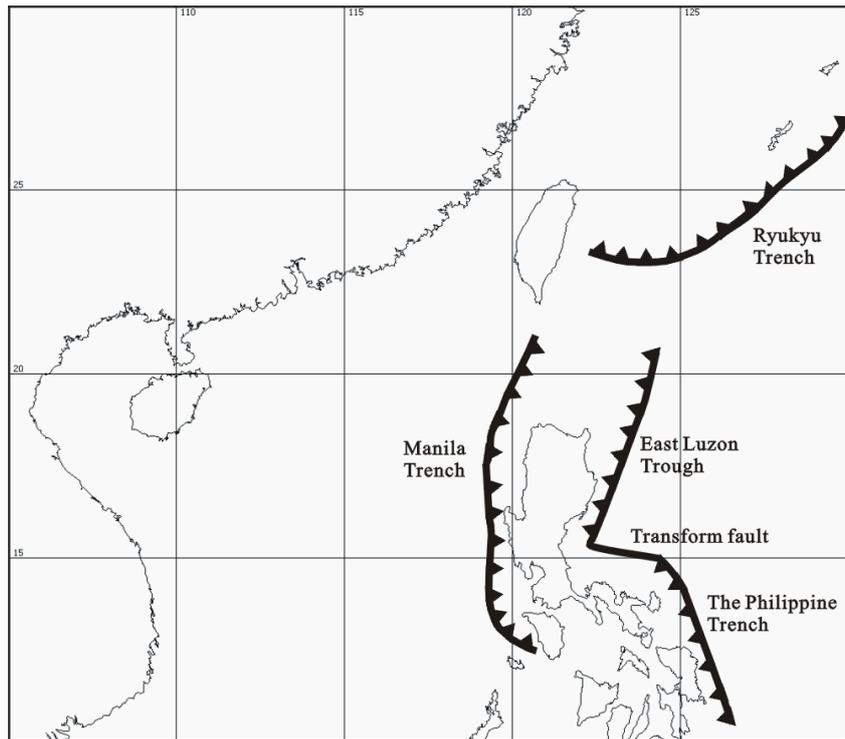


Figure 7 : Ocean trenches and subduction zones near Taiwan and Luzon

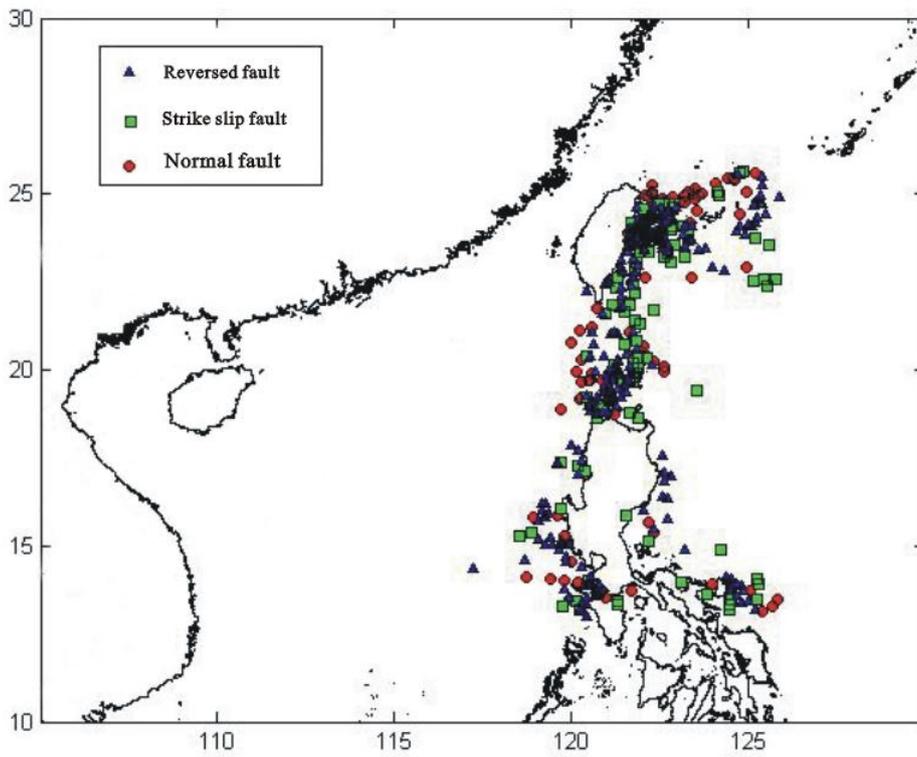


Figure 8 : Focal mechanisms of earthquakes in the Taiwan and Luzon regions

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