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Key Points:
- Unravel source of the deadliest historic tsunami event in the South China Sea
- Examined possible tsunami sources based on their geological setting
- Submarine mass failure can best explain this mysterious event

Supporting Information:
- Texts S1–S6, Figures S1–S4, and Tables S1 and S2

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What caused the mysterious eighteenth century tsunami that struck the southwest Taiwan coast?

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Abstract Several different historical records allude to a disastrous tsunami on the southwestern Taiwan coast sometime between 1781 and 1782, with a reported death toll of more than 40,000. Despite consistent reports from southwest Taiwan, no corroborative information exists for neighboring shorelines in southeast China or northwest Luzon, Philippines, and a plausible source of this tsunami has never been identified. Neither a large earthquake from the Manila trench and active thrust faults nor a submarine volcanic eruption from the northern Luzon Arc can explain the very localized area affected and the physical phenomena described in the historical records. Comparing the results of 13 numerical models of tsunamis generated from different sources (earthquake, volcano, and submarine mass failure), we therefore suggest that a seismically triggered, submarine mass failure on the upper portion of the continental slope offshore from southwestern Taiwan is the most likely source of the eighteenth century event.

1. Introduction

The offshore region of southwest Taiwan has distinctive morphotectonic features controlled by the subduction and collision processes between the Eurasian and the Philippine Sea plates and sequentially draped by sediment during submarine erosional and depositional processes [*Liu et al.*, 2004; *Shyu et al.*, 2005]. The complicated tectonic features present, include the Manila megathrust, a N-S running accretionary prism (Hengchun Ridge; Figure 1), and a series of east dipping active upper plate out-of-sequence thrust (OOST) faults above the megathrust (Figure 1) [*Lin et al.*, 2009] and reflect the northward transition from subduction to collision. Numerous submarine canyons cut into the Chinese continental slope and the Kaoping slope, offshore from SW Taiwan, are characterized by steep slope with rapid sedimentation and strong erosion [*Chiang and Yu*, 2006; *Liu et al.*, 1993, 2004; *Yu and Chang*, 2002]. The region is best described as a seismically active, heavily sediment laden collision zone with numerous submarine canyons and characteristic steep slopes.

Within this tectonic setting, a Chinese historical document [*Chen*, 1830] reported a disastrous flooding event that occurred at Jiateng Bay (now called Dapeng Bay, located in Donggang, Figure 1) in southwestern Taiwan in May 1781. According to the report, large waves suddenly struck under clear skies and submerged all the villages nearby: this description eliminates a storm as the causative event. Instead, the phenomena described in this report (e.g., *the sea suddenly roared like thunder*, and *sea retreat quickly, exposing leaping fishes and shrimps*) are comparable to the classic features found in descriptions of tsunami events. It is believed that two other historical accounts in English [*Mallet*, 1854] and French [*Perrey*, 1862] also refer to the same event, although listing different years of occurrence (mostly 1782) and levels of destruction (supporting information Text S1). The French record [*Perrey*, 1862] provides a vivid description of a tsunami that inundated 3 cities and 20 villages in Formosa (Taiwan), reportedly killing >40,000 (supporting information Figure S1). Notably, two forts in Tainan (Figure 1) were specifically mentioned as having *disappeared with the hills they were built on*. Remarkably, although the literature describes considerable damage in southwest Taiwan and an impact in Fujian, China [*Perrey*, 1862], records in neighboring Guangdong China, including Macau and northwest Luzon do not include a contemporaneous destructive tsunami [*Bautista et al.*, 2013; *Hsu*, 1983; *Hsu and Li*, 1995; *Lu*, 1984; *National Geophysical Data Center of National Oceanic and Atmospheric Administration*, 2014]. For example, the coastal city of Laoag (northern Luzon, Figure 1), which had a population of ~100,000 in the late eighteenth century, provides no report of any significant tsunami in that time period [*Bautista et al.*, 2013] and *Lau et al.* [2010] report no records of the event from Macau, then a Portuguese colony which would have had a heightened awareness of tsunami following the 1755 Lisbon tsunami. These historical

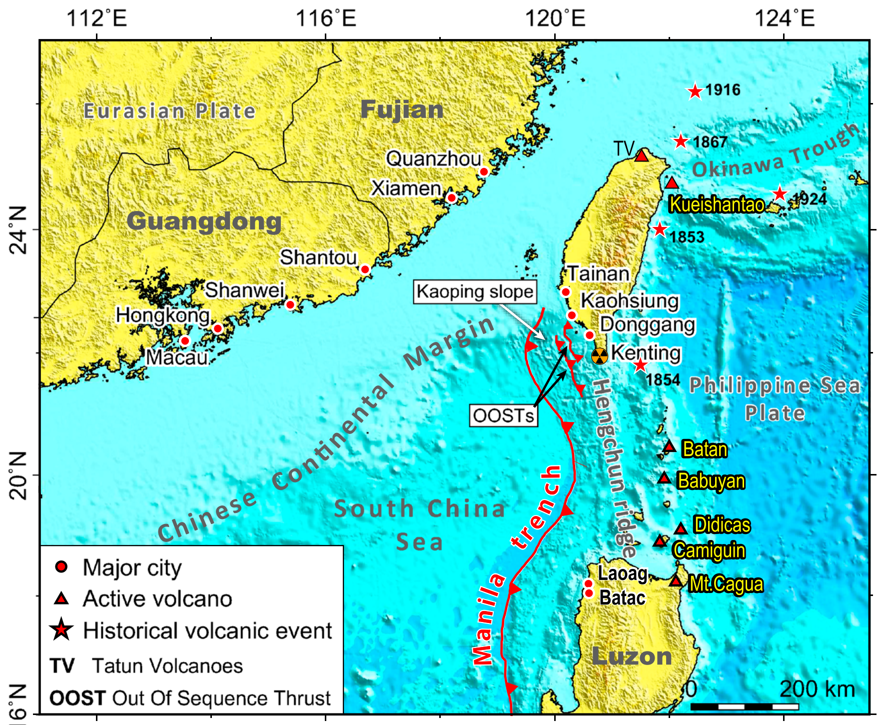


Figure 1. Elevation map of the northeast South China Sea and surrounding regions. Historical volcanic eruption events are marked with red stars. Active volcanoes are marked with red triangles. (The locations of historical volcanic events are derived from *Chen and Shen* [2005]; the locations of active volcanoes in Luzon strait are derived from *Yang et al.* [1996]).

accounts suggest that a damaging tsunami wave of ~5–10 m or higher struck only the coastline of southwest Taiwan (Figure S1) with minor damage in Fujian, while no appreciable tsunami wave (>2 m) was observed along the Guangdong coast of China or in northwest Luzon [*Li et al.,* 2006]. We are aware that historically, small and nondestructive tsunami waves might not be noticed or reported, whereas similar waves occurring in the present period are recorded on monitoring instruments [*Ambraseys and Synolakis*, 2010]. However, we have high confidence in the claim that no damaging tsunami struck Guangdong and Fujian around 1781/1782 as many other types of natural disaster (e.g., earthquakes, flooding, and typhoons) were described and reported along this part of the Chinese coastline during this time, even those with very minor damage and losses [*Hsu*, 1983; *Hsu and Li*, 1995; *Lu*, 1984].

While this event could be considered the most fatal tsunami reported in the South China Sea, its source is yet unknown [*Okal et al.,* 2011]. It should be noted that two of the three available original records make no mention of the probable cause [*Chen*, 1830; *Mallet*, 1854], while the third refers to a volcanic eruption near Taiwan [*Perrey*, 1862]. At that time a volcanic eruption was considered as all seismicity was generally attributed to volcanic activity back then. The hypothesis that a volcano is responsible for the reported tsunami inundation can be rejected purely based on the geographical location of active or recently active volcanoes in or near Taiwan and their potential efficiency as tsunami generators (Figure 1 and supporting information Text S2).

Despite this reference to volcanic source in a key historical account of the event, a widely cited tsunami catalogue ascribes this tsunami to a large earthquake that shook the whole Taiwan island [*Soloviev and Go*, 1974], and a recent study suggested that a megathrust earthquake with magnitude larger than M_w 8.8 was the cause on the basis of tsunami simulations [*Tsai*, 2012].

We point out that while megathrust earthquake scenarios are able to explain the tsunami record from Taiwan, these scenarios fail in that they produce appreciable tsunami waves along the southern China coast, where historical records indicate a lack of significant tsunami waves during that time [*Hsu*, 1983; *Hsu and Li*, 1995; *Lu*, 1984; *Lau et al.*, 2010]. In cases where exceptionally large and localized tsunami waves cannot be explained by pure tectonic source, submarine mass failures are often implicated. Examples

Table 1. Key Parameters for Submarine Landslide

Parameters	Landslide 1	Landslide 2	Landslide 3
Width (km)	5	7	12
Length (km)	16	10.5	11
Thickness (m)	250	150	150
Mean local slope angle (°)	3	5	6
Latitude (°)	22.45	22.31	22.56
Longitude (°)	119.7	120.26	121.25
Azimuth of motion (° East)	−60	−135	−20
Initial acceleration (m/s^2)	1.54	1.54	1.54
Terminal velocity (m/s)	83.1	83.1	83.1

include the 1956 tsunami in Amorgos, Greece [*Okal et al.,* 2009], the 1998 Papua New Guinea tsunami [*Synolakis et al.,* 2002], and most recently the 2011 Tohoku tsunami [*Tappin et al.,* 2014].

Here we test the hypothesis that a submarine mass failure is the most likely source of the 1781/1782 century Taiwan tsunami. We first numerically simulate the tsunami wave height in the northeast South China Sea region from a series of synthetic fault-rupture models, and then compare the simulated tsunami wave height with the criterion set by the historical accounts to investigate and eliminate the possibility of a seismic source. By process of elimination, our simulation results indicate that it would be very difficult to find a megathrust source, which could generate 5–10 m tsunami waves in the southwest Taiwan coast without affecting the southeast Chinese coast or northern Luzon. We then simulate the tsunami waves generated by three previously identified submarine landslides [*Liu et al.,* 2004; *Wu*, 2008] near southern Taiwan and compare their results to the criteria used above. We find that a submarine landslide offshore from southwest Taiwan best explains the historical records, with the best fit provided by a slide body moving in a southeastward direction from the northern end of the SW Taiwan accretionary prism.

2. Modeling Approaches

For earthquake-generated tsunamis, we use COMCOT (Cornell Multigrid Coupled Tsunami Model) [*Liu et al.,* 1995] to simulate the tsunami generation and propagation. COMCOT adopts an explicit leapfrog finite difference method to solve shallow water equations on nested grids. In this study, the seafloor displacement is calculated using the Okada's model [*Okada*, 1985]. Three layers of nested grids are used for all the earthquake scenarios with grid size of 2000/500/100 m (see supporting information Figure S2 for the domain boundaries).

For tsunamis generated by submarine mass failure, we use the NHWAVE (Nonhydrostatic Wave Model) by *Ma et al.* [2012] to simulate the tsunami generation process and use FUNWAVE-TVD (Fully Nonlinear Boussinesq Wave Model with TVD solver) by *Shi et al.* [2012] to simulate wave propagation. For landslide tsunami generation in this study, NHWAVE solves the Euler equations for incompressible flow in a surface and terrain following form using a σ coordinate system. The geometry of landslides is defined using truncated hyperbolic secant functions

$$\delta = \frac{T}{1-\epsilon}\left[\operatorname{sech}(k_b x)\operatorname{sech}(k_w y) - \epsilon\right] \tag{1}$$

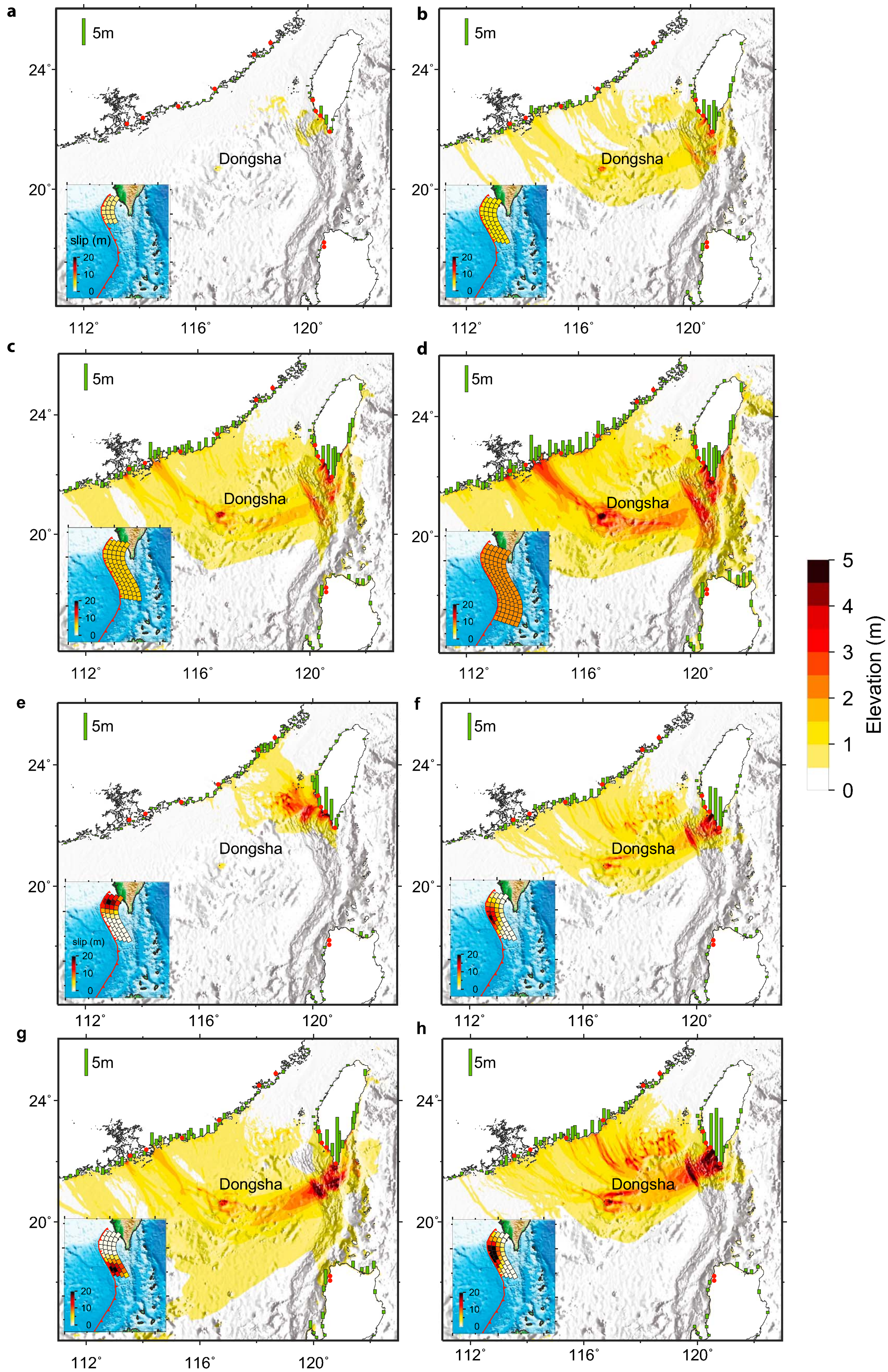
in which $k_b = \frac{2}{b}\text{acosh}(1/\epsilon)$, $k_w = \frac{2}{w}\text{acosh}(1/\epsilon)$. The length b, width w, and maximum thickness T of landslide mass are listed in Table 1, which is primarily derived from previous studies [*Liu et al.,* 2004; *Wu*, 2008]. The truncation parameter is $\epsilon = 0.717$, and the kinematics of submarine landside is prescribed based on a set of semiempirical formulas described by *Enet and Grilli* [2007] (also see the details in *Tehranirad et al.* [2012]). NHWAVE specifies the submarine mass failure (SMF) sliding path over the actual seafloor bathymetry rather than using the simple planar slopes as an imposed path in earlier numerical models which is more realistic. Given that no precise field data are available, although there are indications from marine geophysical data that cohesive slumps are present in the source area of the tsunami (section 4, below), we use a rigid slide body in our simulations since scenarios generated by a rigid body could provide the first-order estimate of tsunami wave magnitude [*Grilli et al.,* 2015]. After a certain time (6–10 min), the wave elevation and flow velocity are interpolated into FUNWAVE-TVD as the initial condition. FUNWAVE-TVD simulates wave propagation from the source region to coastlines. The tsunami simulation capacity of both NHWAVE and FUNWAVE-TVD was validated against a series of tsunami benchmarks [*Tehranirad et al.,* 2011, 2012]. This dual modeling approach (NHWAVE/FUNWAVE-TVD) insured the accuracy and efficiency of the simulation process at the same time. The NHWAVE/FUNWAVE-TVD coupling approach has been applied to quantify the contribution of a submarine landslide to the 2011 Tohoku tsunami and has been validated by modeling the SMF tsunami hazard along the upper U.S. East Coast [*Grilli et al.,* 2015].

3. Numerical Simulation for Earthquake Sources

To investigate whether megathrust earthquakes could be a possible source, we simulate tsunamis generated by a series of synthetic faults, in the northern Manila Trench offshore southwestern Taiwan, an area capable of generating earthquakes with $M_w \geq 7.7$ [*Shyu et al.,* 2005]. We ran a series of tsunami simulations with the prerequisite that they are likely to generate 5 to 10 m high-tsunami waves in southwestern Taiwan (Figure 2). Initially, the earthquake magnitudes ranged from M_w 7.8 to 8.6 (Figures 2a–2d), with the rupture patch positioned at the northern portion of the Manila Trench with a fault slip model constrained to hypocenters along the subduction zone. The fault-rupture length and width are constrained by the empirical fault-scaling relationship for subduction zone earthquakes [*Blaser et al.,* 2010], and uniform slip distribution is assumed for each earthquake (see supporting information Text S3). The fault geometry is informed by the instrumentally recorded seismicity during 1973–2014 from National Earthquake Information Center (the U.S. Geological Survey) (supporting information Figure S3) Unsurprisingly, the wave height along southwestern Taiwan and southeast China increases with increasing earthquake magnitude (Figures 2a–2d), although the rate of increase in wave height with earthquake magnitude along the southeastern China coast is significantly larger than in southwest Taiwan. Notably, it is only when the earthquake magnitude reaches M_w 8.6, which the maximum tsunami height exceeds 5 m in the southwest Taiwan. However, such an event would also significantly affect much of the southeast China coast (Figure 2d) including Guangdong, due to refraction near Dongsha Island, and source directivity effects (see supporting information Text S4), a scenario clearly not supported by the distribution of historical accounts of the tsunami.

The common assumption of uniform slip used in tsunami modeling can underestimate local tsunami runup as large slip may concentrate on a small portion of the rupture area [*Hill et al.,* 2012]. To investigate if spatially varied slip effects could generate anomalously large tsunamis, we considered three additional scenarios with slip distribution patterns similar to the 2005 Nias-Simeulue [*Briggs et al.,* 2006] and 2010 Mentawai earthquakes (Figures 2e–2g) [*Hill et al.,* 2012] where we maintained a moment magnitude of M_w 8.2 and applied Gaussian smoothing functions to distribute the slip. Aiming to achieve the prerequisite wave characteristics, we placed the largest slip on the northern, shallower (west) and southern patches, respectively (Figures 2e–2g). Our results highlight the dramatic influence of nonuniform slip distribution on local tsunami runup, and one scenario with very large slip (~20 m) concentrated in the extreme north segment of the trench (Figure 2g) gave modeled tsunami heights in Tainan and Kaohsiung coast of 2–4 m, with coincident modeled tsunami of < 1 m on the southeastern Chinese coast. However, as the rupture patch is very close to Taiwan and M_w 8.2 is relatively large, this scenario would likely coincide with extremely strong ground shaking similar to that described for an event in Tainan in 1661 [*Hsu*, 1983] and would generate notable seismic intensity in southeast China similar to the M_w 7.1 Pingtung earthquake in 2006.˙ Notably, only one of the three historic records of the tsunami [*Perrey*, 1862] includes any mention of coincident ground shaking for the 1781/1782 event and states that tremors and waves lasted for 8 h, a statement that may imply a tsunami with an associated main shock and aftershocks. Although reports of shaking support the inference that there was significant seismicity associated with the 1781/1782 event, no scenario can fulfill the wave requirements of >5 m in Tainan to the north (Figures 2a–2g). In contrast, ramping up the magnitude to >8 creates a disproportionally large tsunami in Guangdong. Finally, we applied a scenario for a tsunami earthquake that suggests such an event would likely affect the southeast China coast more severely as it would have bigger slip compared with an ordinary earthquake given the same magnitude (Figure 2h) (supporting information Text S5). In summary, our result suggests it is unlikely that a conventional megathrust source generated the 1781/1782 tsunami.

Recent submarine seismic reflection studies and high-resolution bathymetry reveal several active splay faults in the incipient arc-continent collision zone offshore of southwest Taiwan [*Lin et al.,* 2009], similar to the tsunamigenic faults observed along the Nankai prism of Japan [*Park et al.,* 2002]. These potentially seismogenic structures (out-of-sequence thrusts (OOSTs) in Figure 1) are closer to the southwest Taiwan coast making them potential sources for localized tsunamis. We consider scenarios for (M_w 7.7 and M_w 7.6) earthquakes rupture on each of these OOSTs with average slip of 7 m, similar to the fault slip (maximum value 9.8 m) of the 1999 Chi-Chi earthquake (M_w 7.6) in central Taiwan [*Ma et al.,* 1999]. The results show that near coast splay faults would be capable of generating very localized and damaging tsunami along the southwesternmost Taiwan coast (~3 m) without affecting the southeast Chinese coast (Figure S4). However, the location and orientation of these splay faults together with directivity effects limit the extent of the tsunami affected region and most notably fail to explain the high-tsunami waves reported in Tainan.


a
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Dongsha
24°
20°
112°
116°
120°
slip (m)
20
10
0
Elevation (m)
5
4
3
2
1
0

Figure 2

To conclude, there are two primary reasons that indicate thrust faulting earthquakes are unlikely to be the sole cause of the 1781/1782 event:

1. Any earthquake from the Manila Trench capable of generating 5–10 m tsunami waves on the southwest Taiwan coast would likely generate waves exceeding 2 m on the populated southeast Chinese coast (Guangdong) as megathrust earthquakes normally generate tsunami waves with considerably longer wavelength that lose little energy in the deep ocean and would likely cause damage in the far field. This is not in keeping with the description related to the 1781/1782 event.
2. The northern termination and the orientation of the Manila Trench limit the tsunami affected area to only the southernmost part of Taiwan as the trench and associated OOST all veer from northwest to northeast at the Kaoping slope to connect with structures onshore [*Lin et al.,* 2009]. All modeling here suggests that this geometry spares cities in the northern stretch of coastline, including Tainan, from a direct impact of tsunami waves, again in direct contrast with the historic record, where inferred wave heights were larger than 5 m at Tainan city in the 1781/1782 event.

4. Numerical Simulation for Submarine Mass Failure

The inability of any purely earthquake-based scenario to match the historical evidence demands the consideration of other tsunami sources, such as seismically triggered submarine mass failures (SMFs). In contrast to the regional effects caused by the long wavelength characteristics of earthquake-generated tsunamis, SMFs can generate locally devastating tsunamis without affecting the far field [*Lynett et al.,* 2003; *Ward*, 2001]. The geophysical conditions offshore from southwest Taiwan are characterized by overpressured sediment layers [*Su et al.,* 2012], steep and dissected continental slope [*Lin et al.,* 2009], wide spread mud diapiric intrusions and mud volcanoes [*Chen et al.,* 2014; *Su et al.,* 2012], and frequent seismicity [*Shyu et al.,* 2005], all of which create a favorable environment for SMFs. Detailed bathymetric data and seismic profiles clearly show evidences that SMFs are present in the upper reach or middle reach of major submarine canyons, e.g., Kaoping canyon and Penghu canyon [*Chiang and Yu*, 2006; *Liu et al.,* 1993; *Yu and Chang*, 2002]. These observed SMFs involve slumping and sliding on the canyon walls which could occur during the downward excavation by downslope sediment flows or could be easily triggered by strong ground shaking. Although it is difficult to confirm whether these SMFs are truly responsible for the 1781/1782 event due to lacking of dating information, the features of these SMFs [*Chiang and Yu*, 2006; *Liu et al.,* 1993; *Yu and Chang*, 2002] have a striking similarity with the coherent slump identified by *Tappin et al.* [2001] as being responsible for the 1998 Papua New Guinea tsunami.

To investigate whether or not a SMF is capable of generating the 1781/1782-type tsunami, we run three example cases to quantitatively demonstrate their tsunami generation capacity in the region (Figure 3a). We chose three of the largest mapped SMFs identified by *Wu* [2008] for numerical simulations (Table 1). These mapped SMFs are identified from high-resolution (~100 m) seafloor morphology by searching the typical geomorphologic features of a SMF (e.g., an arcuate head scarp two subparallel sidewalls and commonly with slumped material at the base of the landslide scar) [*Wu*, 2008]. Figure 3b shows that a southeastward sliding SMF could generate a very large local tsunami ($>$10 m) with waves spanning the southwest coast of Taiwan, from Tainan to Kenting. Due to its close proximity to the coastline, southwestward directed slide (landslide 2) could also generate ~5 m tsunami waves on the Donggang and Kenting coasts (Figure 3c) in contrast to an east coast slide (Figure 3d) that would only be capable of generating submeter waves on the southwest Taiwan coast. All SMF models show that tsunami wave energy dissipates rapidly with increasing distance from the source, and in all scenarios the Guangdong coast experiences tsunami waves $<$1 m. The SMF scenarios here are only a few examples, and tsunamis would vary considerably with the volume of the sliding body, the depth that the body slides originates and ends, and the speed at which the slide moves. Our model results indicate that a southeastward sliding SMF in the Kaoping slope region could be the most important contributor to the 1781/1782 tsunami described in the historical records. Considering the geomorphic characteristics in offshore SW Taiwan, we think it is very likely that multiple SMFs with different scales were triggered during this event. The accompanied phenomena may also include mud volcanic

Figure 2. Fault geometries of synthetic fault model and maximum tsunami wave height. Fault geometries and slip distributions are shown in the subfigures. Red dots are city locations (see the city's name in Figure 1). Green vertical bars show the tsunami wave height at selected coastal locations. Four scenarios have magnitude (a) 7.8, (b) 8.2, (c) 8.4, and (d) 8.6, while four scenarios show results from nonuniform slip distribution with largest slip localized on (e) northern portion, (f) shallow and middle portion, (g) southern portion of the rupture area, and (h) a scenario for tsunami earthquake.

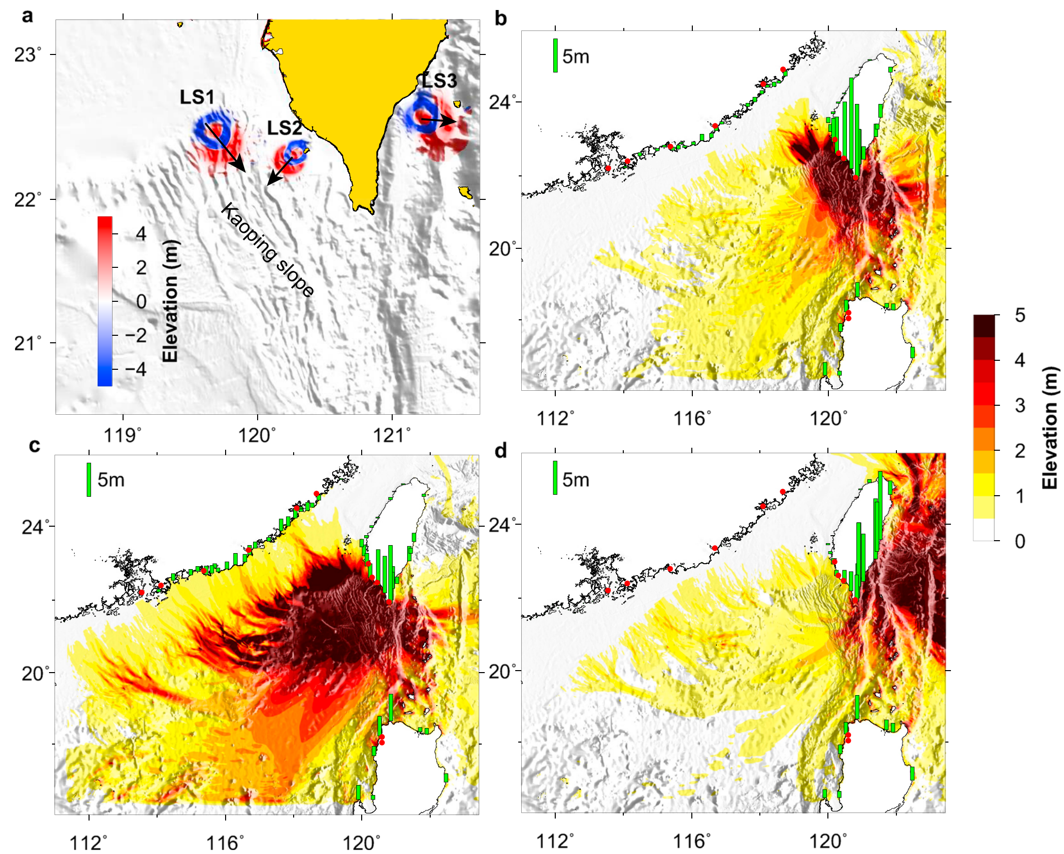

Figure 3. The locations of selected submarine landslides and maximum surface elevation. (a) Instantaneous wave surface elevation generated by NHWAVE at 150 s after landslide triggering, computed using 500 m horizontal grid with 3σ layers. The black arrows show the sliding directions. The figure also indicates the simulation domain of NHWAVE. Maximum surface elevation generated by (b) landslide 1, (c) landslide 2, and (d) landslide 3.

eruptions although the eruptions themselves could not be the main tsunami generators in terms of their relatively small scale (65 m to 345 m in height) and shallow locations (365 m–760 m water depth) [*Chen et al.,* 2014]. The disappearance of two ancient forts reported in *Perrey* [1862] might be related to the diapiric intrusion in the Tainan basin and coseismic liquefaction and subsidence [*Chen and Liu*, 2000; *Huang et al.,* 2006] (a detailed discussion in supporting information Text S2). This multiple sources would be similar to the source of the 1998 Papua New Guinea tsunami for which three slumps were identified from 3-D images and seismic profiles [*Tappin et al.,* 2001].

5. Conclusions and Implications

In summary, the available historical records, numerical modeling results, and the SMFs-prone environment in the offshore SW Taiwan together indicate that SMFs in the Kaoping slope region could have been the main contributor to the 1781/1782 southwest Taiwan tsunami event. We therefore provide the most plausible source for the largest known historic tsunami event in the South China Sea. However, confirming such a source would require further investigations, such as marine geophysical surveys, coring, and dating the mass failure sediment. Nevertheless, the key message we emphasize here is that future landslides in this region present a clear tsunami hazard. Under the geomorphic characteristics in offshore SW Taiwan, such hazard could be easily triggered by moderate seismicity (~M_w7), degassing of gas hydrates, instability of the steep continental slope, or increases in pressure on the sediments of the continental shelf induced by sea level change [*Lin et al.,* 2010; *Smith et al.,* 2013]. We raise the question of what would happen if a similar event were to occur today. The area affected by the 1781/1782 event now has a population in excess of 3 million, a major deep water port, and Maanshan Nuclear Power Plant on the coast: a repeat event today could be truly catastrophic. Similar events like this serve as a reminder of the potential tsunami risk posed by SMFs during seismic activity, a risk with unpredictable nature that poses additional tsunami threats to the coastlines worldwide, including those considered tsunami immune [*Ambraseys and Synolakis*, 2010; *Hasegawa and Kanamori*, 1987; *Lynett et al.,* 2003].

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