



# Preliminary evidence for a 1 000-year-old tsunami in the South China Sea

SUBJECT AREAS:  
PALAEOCEANOGRAPHY  
PALAEOCLIMATE  
HYDROGEOLOGY  
OCEAN SCIENCES

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Received  
15 January 2013

Accepted  
15 March 2013

Published  
11 April 2013

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The risk of large, devastating tsunamis in the South China Sea and its surrounding coastal region is commonly underestimated or unrecognized due to the difficulty of differentiating tsunami from storm deposits. As a consequence, few convincing records have documented tsunami deposits in this region. Here we report preliminary evidence from Xisha Islands in the South China Sea for a large tsunami around AD 1024. Sand layers in lake sediment cores and their geochemical characteristics indicate a sudden deposition event around AD 1024, temporally consistent with a written record of a disastrous event characterized by high waves in AD 1076. Heavy coral and shell fossils, which are older than AD 1024, deposited more than 200 meters into the island, further support the occurrence of a high-energy event such as a tsunami or an unusually large storm. Our results underscore the importance of acknowledging and understanding the tsunami hazard in this area.

Despite being close to the highly tsunamigenic Manila subduction zone, no tsunami warning system has been implemented in the South China Sea and its surrounding coastal region, one of the most populated areas in the world<sup>1</sup>. Indeed, few written records have documented devastating tsunamis in the coastal region of the South China Sea<sup>2</sup>. Neither of the two recent largest tsunamis, the 2004 Indian Ocean Tsunami and the 2011 Tohoku Tsunami, has had significant impact in this area. Because the South China Sea lies between two volcano arcs, the risk of large tsunamis is often underestimated and not recognized until recently<sup>1</sup>. However, East Asia is a region where large earthquakes take place frequently, making the South China Sea vulnerable to devastating tsunamis. Knowledge of the existence and extent of past tsunamis is critical in developing warning mechanisms. This makes the identification of past tsunamis, and their frequency and severity particularly important in the implementation of warning mechanisms.

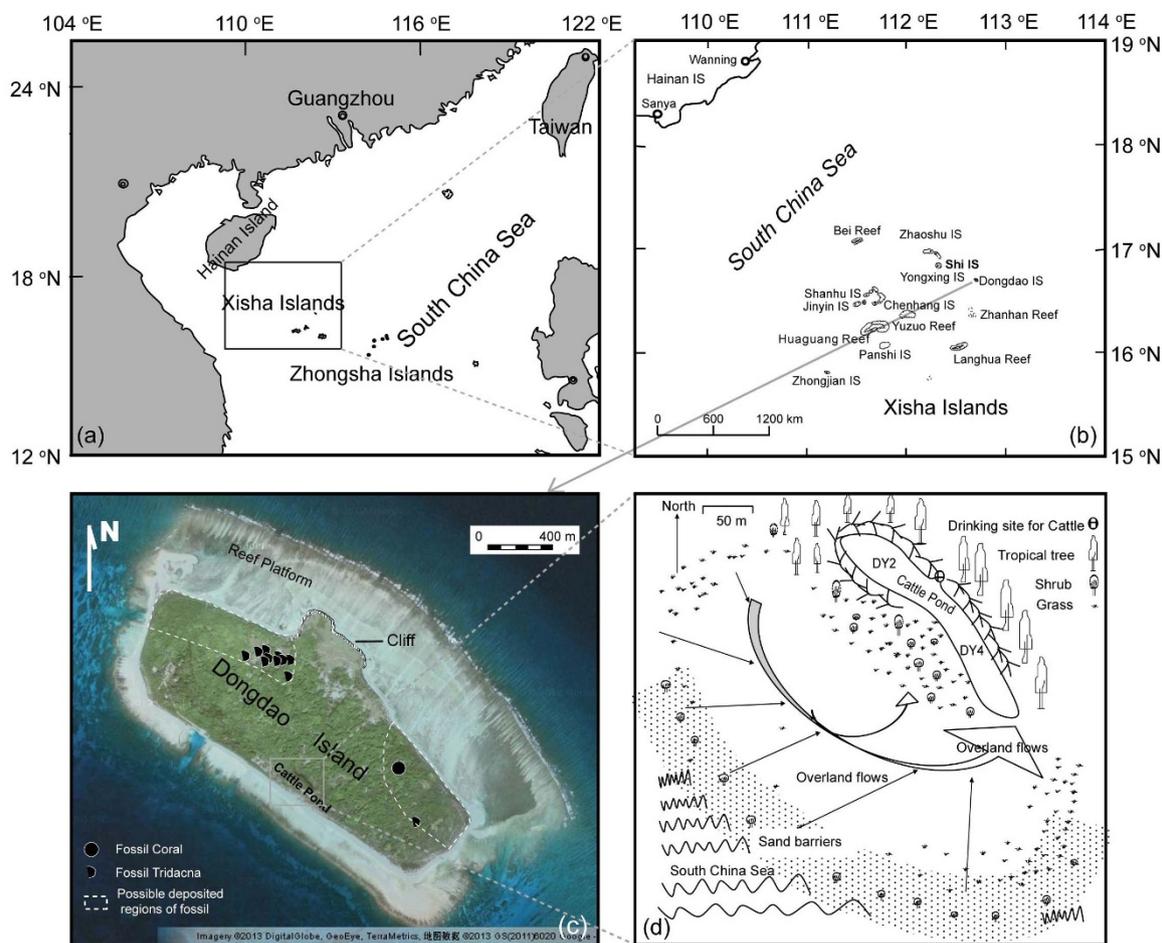
A fundamental problem in identifying past evidence of tsunami impact is the difficulty of differentiating their deposits from those of storms and tropical cyclones<sup>3–5</sup>. This problem is particularly acute in the South China Sea, given that it is one of the three main centers for tropical cyclones. Yu *et al.*<sup>6</sup> reconstructed a 4000-year long record of storm/tsunami using continuous lagoon sediments. Six of these events were temporally correlated with dated coral blocks during the past millennia<sup>7</sup>. Because coarse fractions of sediments and large coral blocks can be transported by both tsunamis and large storms to lagoons below sea level, Yu *et al.*<sup>3,4</sup> could not differentiate between causes.

Multiple sources of physical, chemical, paleontological evidence are clearly needed to separate storm from tsunami deposits. For example, Pilarczyk *et al.*<sup>4,8</sup> searched for indicators such as foraminiferal taphonomy to discriminate storms from tsunamis. They found that abundance of foraminifer species, combined with other proxies such as particle size distribution, can be used to identify tsunami deposits. In the present study, we first show geological and ecological records of an event on an island in the South China Sea. Then we discuss the evidence and report the possibility of a large tsunami in the South China Sea around AD 1024.

## Results

Dongdao Island (16°39'~16°41'N, 112°43'~112°45'E), one of the Xisha Islands in the South China Sea (Figure 1), is a tropical reef island with a land area of 1.55 km<sup>2</sup> and an elevation of 3–6 m. The island has only small military outposts and no civilian residents (Figure 1).

During field investigation in 2003, we collected two sediment cores (DY2 and DY4) from a small fresh-water lake, called the “Cattle Pond”<sup>9,10</sup>. The lake is located on the southwest of Dongdao Island with a length of 150 m, a



**Figure 1 | Study areas.** Maps showing the locations of the Xisha Islands (a), our sampling sites on Dongdao Island (b), the distribution of the fresh water lake, *Tridacna sp.* and coral fossils collected on Dongdao Island (c), and geographical features of the “Cattle Pond”. Base map used in (c) is from Google Earth software.

maximum width of 15 m and an altitude of 6 m above sea level. The lake is hydrologically closed, and the main inorganic sediments are coral sand originating from a sand barrier<sup>11</sup> (Figure 1d). As shown by an early study<sup>9</sup>, the lake has been closed since being an open lagoon around 1300 years ago.

The two sediment cores exhibit similar lithological profiles, both of which can be characteristically separated into three distinct sediment units based on their color, grain size and the presence of lamination (Figure 2). The bottom unit (unit 1 in Figure 2) consists mainly of fragments of grey-white coral, shells and sandy gravels, and no ostracodes or plant remains are identified. This unit likely represents deposition in a lagoon environment. Unit 2, on top of unit 1 with sharp stratigraphic contact, is an ornithogenic sediment unit (unit 2 in Figure 2). It consists of primarily medium- to fine-grained coral sandy mud with a brown-red color, and contains abundant ostracodes and plant caryopses. Unit 2 is interrupted by a well-sorted coral sand unit (unit 3) between 84 and 88 cm in core DY2 and 58 and 69 cm in core DY4 (Figure 2). Sediments in all three units contain foraminifer shells.

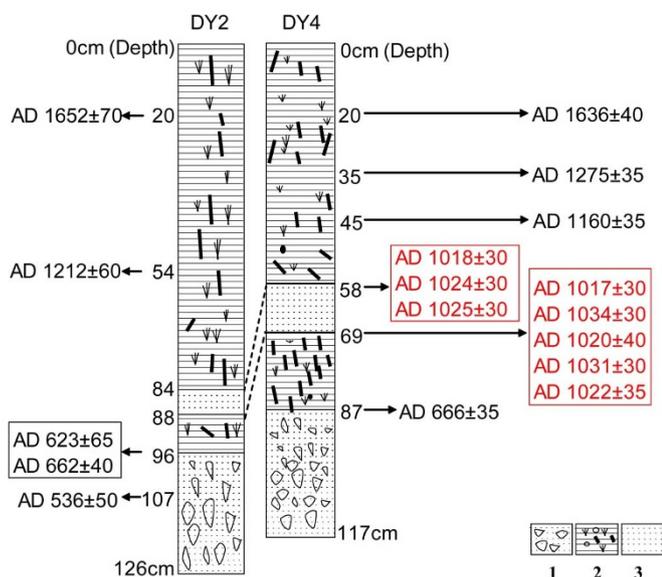
We dated selected depths of the DY2 and DY4 cores by AMS radiocarbon dating of terrestrial plant caryopsis and total organic carbon (Figure 2 and Table S1). Surprisingly, the ages of plant caryopsis samples at the depths of 57–58 cm and 70–71 cm in DY4, immediately encompassing the 11-cm coral sand unit 3 are within the analytical error (Figure 2 and Table S1), indicating that deposition occurred in a short time interval around AD 1024 (the mean of eight AMS <sup>14</sup>C intercept ages are between AD 978 and AD 1160; Table S1).

To further characterize the sediment units, we analyzed particle sizes along the DY4 core. Particle sizes in the coral sand unit 3 are homogeneous, suggesting a uniform origin of materials and the absence of resizing after deposition (Figure 3). Furthermore, particles in unit 3 are coarser than those in units 1 and 2 (Figure 3), implying that materials in unit 3 were likely transported by higher-energy processes than those of unit 2<sup>11</sup>.

Geochemical profiles of unit 3 in the DY4 core (Figure S1) show stable LOI<sub>950</sub><sup>°C</sup>, CaO, LOI<sub>550</sub><sup>°C</sup>, TOC and TN, which are distinctive from other parts of the cores. The high LOI<sub>950</sub><sup>°C</sup> and CaO levels are consistent with the coral sand composition of unit 3; elements derived mainly from seabird droppings (Se, P, Zn, As and Cd)<sup>12,13</sup> are also reduced (Figure S1). In addition, unit 3 shows depletion in caryopses of *Urochloa paspaloides* and shells from the ostracodes *Cyprinotus cingalensis*, which are abundant in other parts of the core (Figure 4). Furthermore the  $\delta^{13}\text{C}$  of the ostracode valves in unit 3 is close to that of the sea water, indicating a marine sediment source<sup>9</sup>.

Taken together, these data imply that the deposition of unit 3 was the result of a short-lived, high-energy event around AD 1024. To infer the nature and magnitude of that event, we sought additional marine-derived sediment on other parts of the island. We found several large *Tridacna sp.* shell fossils of length 40–80 cm and weight 20–60 kg, as well as a large fossil coral 120 cm in diameter, on the north and east of Dongdao Island at around 4 meters above sea level (Figure 1 and Figure S3). Furthermore, the *Tridacna sp.* shells are single valves with the dorsal side facing upward.

Although the presence of large coral and shell clasts are also consistent with deposition during a high-energy marine event, their ages



**Figure 2** | Lithological profiles of lake sediment cores DY2 and DY4 on Dongdao Island in the South China Sea. The lithological profiles of the DY2 and DY4 cores can be separated into three sediment units. Unit 1 consists of grey-white coral, shells, and sandy gravels; Unit 2 is brown-red colored and consists of medium to fine grained coral sandy mud, containing abundant plant remains and sea bird droppings; Unit 3 interrupts unit 2 and is composed of well sorted coral sand. AMS  $^{14}\text{C}$  ages are shown next to selected depths of the sediment cores.

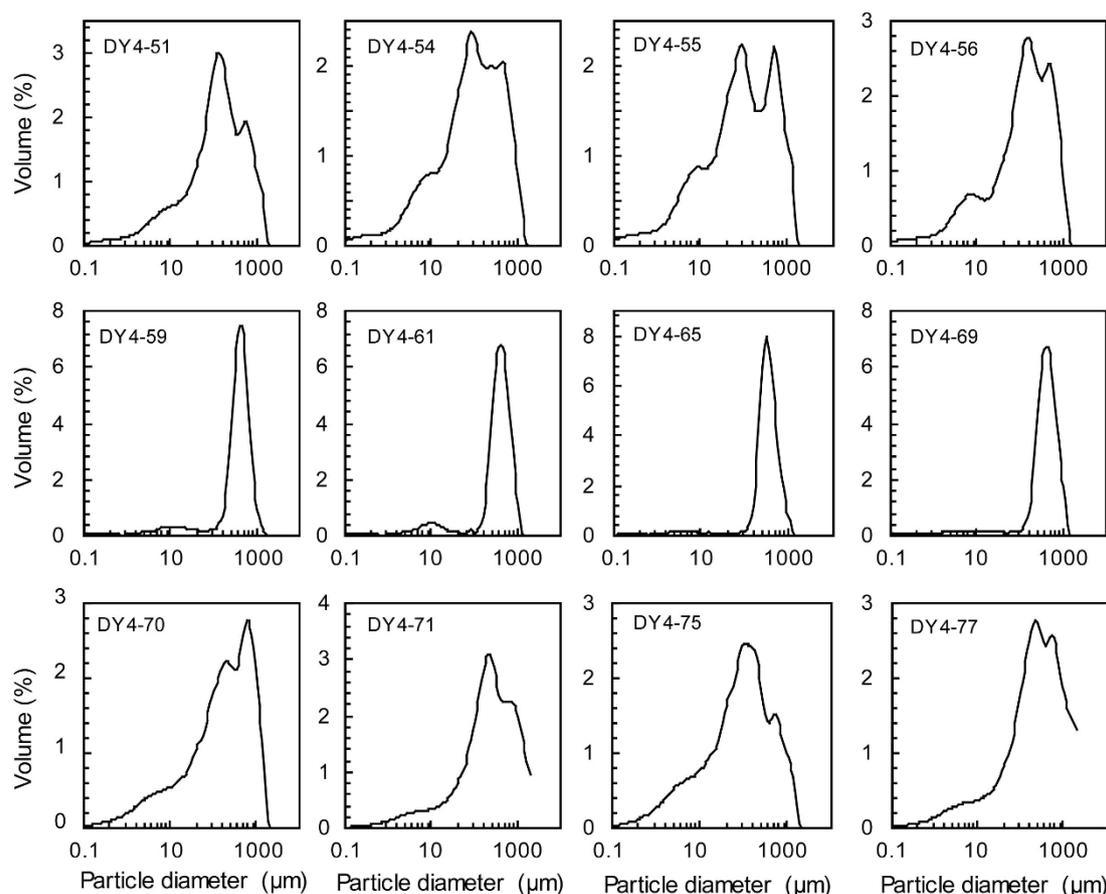
should not be younger than those measured from unit 3 in order to show they were coeval. Indeed, AMS  $^{14}\text{C}$  ages of the 13 fossils fall between BC 1980 and AD 720 (Table S2). In particular, one of the *Tridacna sp.* shell fossils and the coral fossil are younger than AD 666, the time at which the lithological and geochemical profiles of the lake sediment cores transitioned from unit 1 to unit 2 and stabilized (possibly because the lake became a relatively closed environment; Figure 2). Given the large sizes and heavy weights of the fossils, the most likely event that could have transported these two fossils after AD 666 and left a trace in the sediment cores was the presumptive high-energy event around AD 1024. No fossil is younger than AD 1024, indicating that no other event had happened with comparable size in the last 1,000 years.

## Discussion

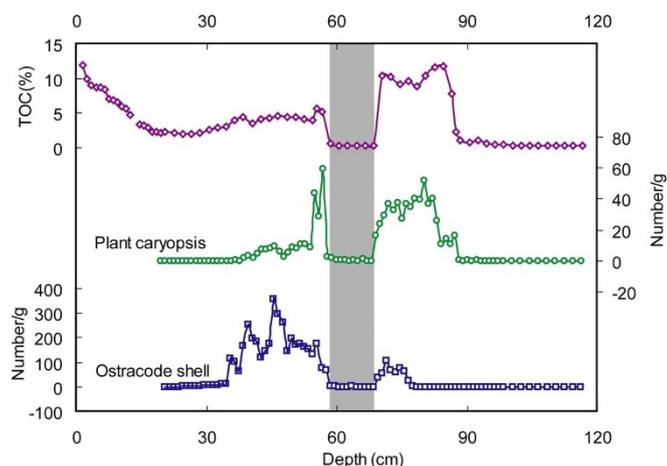
Possible explanations for the high-energy deposition event around AD 1024 include temporary opening of the lake to form a part of the lagoon, a direct strike on the island by an intense tropical cyclone, or overwash of the island during a tsunami. We ruled out lake re-opening and closing due to the sharp upper and lower contacts of unit 3, which imply a rapid event of limited duration. An upper sharp contact is therefore inconsistent with a gradual lake closure event.

Differentiating between tropical cyclone and tsunami, however, is more difficult<sup>3-5</sup>. This is because large storms, particularly tropical cyclones, are common in the South China Sea and generate high waves which deposit coral sands near the coast. Indeed, more than ten tropical cyclones affect the South China Sea annually<sup>14,15</sup>.

Some studies have used taphonomic or taxonomic criteria to differentiate storm from tsunami deposits<sup>4,8</sup>. In our case, the taxa of



**Figure 3** | Comparison of grain size distributions of sediments between unit 3 (DY4-59, 61, 65 and 69) and unit 2.



**Figure 4 | Biological remains.** Down-core variation profiles of contents of caryopses of *Urochloa paspaloides* origin and ostracodes *Cyprinotus cingalensis* in the sediment core DY4.

shallow benthic foraminifera that are common in all the three units of the lake sediment core (Figure S2), were likely reworked from the sand barrier. The composition of the foraminifera, while a useful indicator for distinguishing storms and tsunamis in other regions<sup>4,8</sup>, was less informative on this particular island. However, lithological and geochemical profiles above unit 3 in the cores are stable implying that no storm since AD 666 had generated sufficient force to affect the lake inland at a comparable magnitude to the high-energy event that produced unit 3 (Figure 4, Figure S1).

A similar argument can be used for the large clasts: if storms commonly deposit large coral and tridacnid shells, then similar fossils younger than AD 1024 should be present on the island. Earlier studies have found large coral blocks on reef flats in the southern South China Sea<sup>6</sup>, which might be transported by tropical cyclones. However, these coral fossils were found only in lagoons below the sea level. Our *Tridacna sp.* fossils were transported for more than 200 meters into Dongdao Island, which is above sea level. However, the possibility exists that a particularly intense tropical cyclone made landfall on the island and caused inundation that deposited unit 3 in the sediment cores and the large fossils on the island.

However, we consider that a large tsunami appears to be most likely cause for the sudden deposition event around AD 1024. Tsunamis often generate high waves through wave shoaling on sea shores and inundate extensive areas. For example, the 2004 Indian Ocean Tsunami generated a 35 m high wave in Sumatra<sup>16</sup>, and a 10 m high wave in the south coast of Sri Lanka<sup>17</sup>, ~1,500 kilometers away from the quake epicenter. In our case such high waves generated by tsunamis could easily inundate the sand barrier between the inland lake and the sea. Indeed, sand sheets, similar to the interbedded sand layer in the sediment cores in this study, had been identified by previous studies as results of tsunamis in other areas<sup>18–22</sup>. The energies of tsunamis would also be able to carry large and heavy fossils onto the islands<sup>23</sup>. Interestingly, the age of the putative tsunami recorded in the sediment cores coincides with a written record of disastrous event characterized by a high wave in AD 1076<sup>24</sup>.

Indeed, the Manila Subduction Zone, about 1000 km to the east of Dongdao Island, has been and is a highly active region of earthquakes (Figure S4). Earthquakes originating in the Manila Subduction Zone could generate devastating tsunamis in the coastal region of the South China Sea<sup>2</sup>, including Dongdao Island. The large and heavy fossils are exclusively distributed along the north and east coasts of the islands (Figure 1) while no heavy *Tridacna sp.* and coral and fossils could be found behind the cliff of the islands, suggesting that

they were brought onto the islands from the northwest of the Xisha Islands (Figure S5) – most probably the Bashi Channel.

Although our evidence is most consistent with a historic tsunami, the possibility of an extremely large storm cannot be completely ruled out. Furthermore, the unique island environment of our study site has made the distinction particularly challenging. As tsunamis generally have wider impacts than storms, the cause of this sudden deposition event can not be definitively determined until similar deposits of the same age are identified on other islands in this region. Nevertheless, several risk assessment studies of tsunami hazard in the South China Sea have indicated that this region is under high risk for devastating tsunamis due to its geographical proximity to the Manila Subduction Zone<sup>1,25–27</sup>. Yet no tsunami warning system is in place in this area. Our study, presenting sediment evidence for a possible tsunami in this area, calls for awareness and attention to the potential risk of tsunamis in the South China Sea.

## Methods

We collected two lake sediment cores named DY2 (126 cm length) and DY4 (117 cm length) from the fresh water lake on Dongdao Island using PVC plastic gravity pipes of 12 cm diameter during the field investigations in 2003. We also collected 12 large *Tridacna sp.* shell fossils of length 40–80 cm and weight 20–60 kg and a large coral fossil of 120 cm in diameter on the Dongdao Island. One *Tridacna sp.* fossil, DD-1, was collected in 2008, and other 11 ones were collected in 2012.

In the laboratory, the DY2 and DY4 cores were photographed and sectioned at 1 cm intervals. The caryopses of *Urochloa paspaloides* origin, foraminifera and *Cyprinotus cingalensis* in the DY4 core were selected and identified under the microscope. For grain size analysis, all the subsamples were first sieved through a 2000  $\mu\text{m}$  sieve and then approximately 0.5 g was taken for analysis at the Institute of Geology and Geophysics, Chinese Academy of Sciences, using a SALD-3001 laser particle analyzer. The detailed description for geochemical analysis (percentage of loss on ignition at 550°C and 950°C, the contents of calcium oxide (CaO), total organic carbon (TOC), total nitrogen (TN), Se, P, As, Zn and Cd) were presented in our previous studies<sup>9,10,13</sup>.

Radiocarbon analyses for DY2 and DY4 cores were performed on terrestrial organic matter (plant caryopsis) and TOC (Table S1), and calibrated into calendar years before present using the Intercal 04<sup>28</sup>. Radiocarbon analyses for *Tridacna sp.* and coral fossils were performed on carbonate (Table S2), and calibrated by Marine Intercal 04<sup>29</sup>. A total of 16 samples from the sediment cores were analyzed using the Accelerator Mass Spectrometer facility at Institute of Heavy Ion Physics in Beijing University (Table S1). The *Tridacna sp.* fossil DD1 was analyzed at Earth System Science Department, UC Irvine, and the other 12 fossils samples were analyzed at the Center for Applied Isotope Studies at the University of Georgia (Table S2).

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## Acknowledgements

This study was jointly supported by the NSFC (41176042), the National Basic Research Program of China (2010CB428902) and the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA05080302). We also thank Wenbo Wu and Shican Qiu for their help in preparing Figure S1.

## Author contributions

L.S. designed the study. L.S., X.Z. and W.H. wrote the paper. All authors contributed to the collection and analyses of samples, discussion of results and manuscript refinement.

## Additional information

**Supplementary information** accompanies this paper at <http://www.nature.com/scientificreports>

**Competing financial interests:** The authors declare no competing financial interests.

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**How to cite this article:** Sun, L. *et al.* Preliminary evidence for a 1000-year-old tsunami in the South China Sea. *Sci. Rep.* **3**, 1655; DOI:10.1038/srep01655 (2013).