Yanagisawa and Goto *Earth, Planets and Space* (2017) 69:136
DOI 10.1186/s40623-017-0713-4

Earth, Planets and Space

**FULL PAPER** **Open Access**

# Source model of the 1703 Genroku Kanto earthquake tsunami based on historical documents and numerical simulations: modeling of an offshore fault along the Sagami Trough

Hideaki Yanagisawa[1*] and Kazuhisa Goto[2]

**Abstract**

The 1703 Genroku Kanto earthquake and the resulting tsunami caused catastrophic damage in the Kanto region of Japan. Previous modeling of the 1703 earthquake applied inversion analyses of the observed terrestrial crustal deformations along the coast of the southern Boso Peninsula and revealed that the tsunami was generated along the Sagami Trough. Although these models readily explained the observed crustal deformation, they were unable to model an offshore fault along the Sagami Trough because of difficulties related to the distance of the offshore fault from the shoreline. In addition, information regarding the terrestrial crustal deformation is insufficient to constrain such inverted models. To model an offshore fault and investigate the triggering of large tsunamis off the Pacific coast of the Boso Peninsula, we studied historical documents related to the 1703 tsunami from Choshi City. Based on these historical documents, we estimated tsunami heights of ≥5.9, 11.4–11.7, ≥7.7, 10.8 and ≥4.8 m for the Choshi City regions of *Isejiga-ura*, *Kobatake-ike*, *Nagasaki*, *Tokawa* and *Na'arai*, respectively. Although previous studies assumed that the tsunami heights ranged from 3.0 to 4.0 m in Choshi City, we revealed that the tsunami reached heights exceeded 11 m in the city. We further studied the fault model of the 1703 Genroku Kanto earthquake numerically using the newly obtained tsunami height data. Consequently, we determined that the source of the 1703 earthquake was a 120-km-long offshore fault along the Sagami Trough, which is in close proximity to the Japan Trench. Our results suggest that earthquake energies resulting in magnitudes greater than Mw 8.32 along the entire length of the Sagami Trough could have been released during the 1703 Genroku Kanto earthquake.

**Keywords:** 1703 Genroku Kanto earthquake, Tsunami, Numerical simulation, Historical documentation, Source model, Sagami Trough

## Background

The Amur, Okhotsk and Philippine tectonic plates adjoin in the vicinity of the Greater Tokyo area, which is the most populated metropolitan area in the world (Sato et al. 2005). The Sagami Trough constitutes one of the convergent boundaries of this triple junction, which extends approximately 250 km from Sagami Bay to offshore of the Boso Peninsula (Fig. 1). Two immense earthquakes have occurred along this trough in Japanese recorded history (e.g., Grunewald and Stein 2006): the 1703 Genroku Kanto earthquake (Mw 8.2) and the 1923 Taisho Kanto earthquake (Mw 7.9). Both events were megathrust earthquakes that initiated along the same plate interface, and they were accompanied by severe ground shaking (Usami 1980) and large tsunamis (Hatori et al. 1973). Compared with the tsunami following the 1923 event, the tsunami that followed the 1703 earthquake reached

---

*Correspondence: h-yanagi@mail.tohoku-gakuin.ac.jp
[1] Department of Regional Management, Tohoku Gakuin University, Tenjinsawa 2-1-1, Izumi-ku, Sendai, Miyagi, Japan
Full list of author information is available at the end of the article

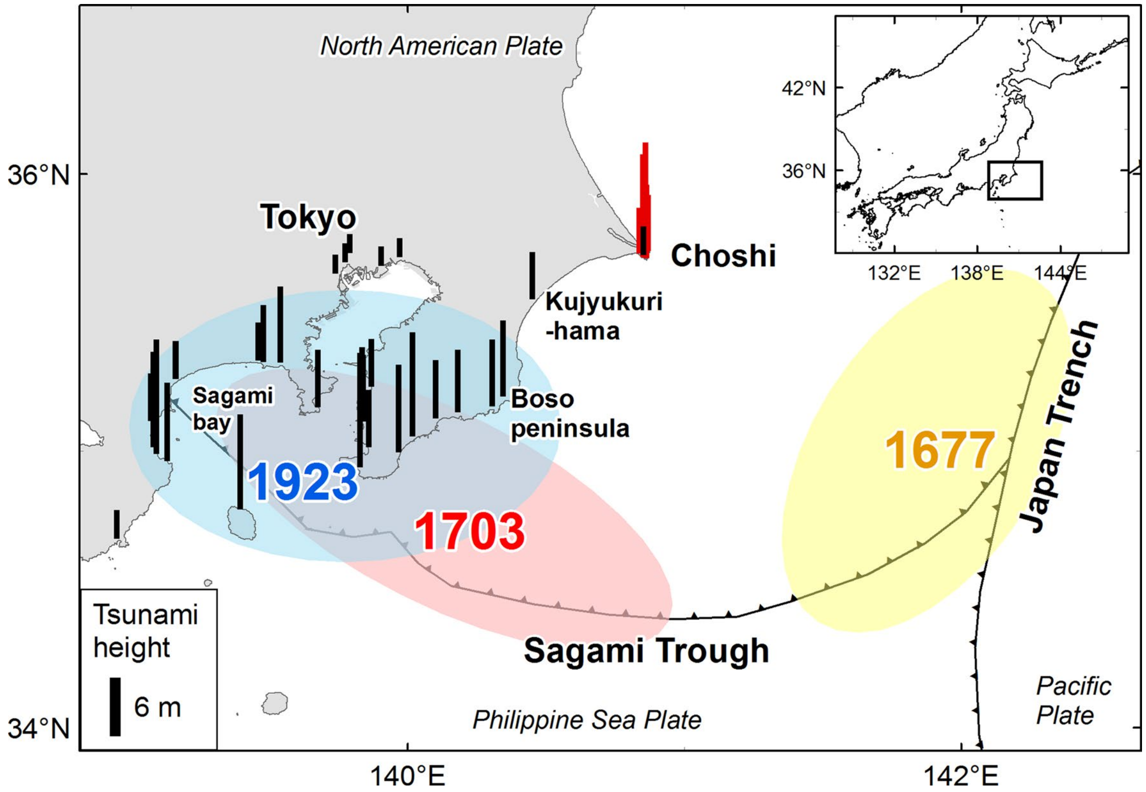

**Fig. 1** Source areas of the 1677, 1703 and 1923 earthquakes and resulting tsunamis (Hatori 1975). Black bars illustrate the historical heights of the 1703 tsunami (after Namegaya et al. 2011). Red bars represent the historical heights of the 1703 tsunami obtained during this study (see Table 2; Fig. 2). The Sagami Trough and Japan Trench are presented as proposed by the Cabinet Office (2013)

significantly greater heights of 11–12 m along the Pacific coast of the Boso Peninsula (Fig. 1) (Hatori et al. 1973; Satake et al. 2008; Namegaya et al. 2011). Thus, the source area of the 1703 earthquake is believed to include both the region between the Sagami Bay and the southern Boso Peninsula as well as the offshore area along the Sagami Trough (e.g., Matsuda et al. 1978; Satake et al. 2008; Namegaya et al. 2011).

During the 1703 and 1923 events, crustal deformations along the coastline of the southern Boso Peninsula appeared as marine terraces or uplifted littoral bio-constructions (Matsuda et al. 1978; Shishikura 2014). Studies have proposed fault models for the 1703 earthquake using inversion analyses of the observed heights of the crustal deformations (e.g., Namegaya et al. 2011; Cabinet Office 2013; Sato et al. 2016). Although these inversion models were able to explain the observed crustal deformations on land, modeling offshore faults along the Sagami Trough is difficult because the offshore faults are located far away from the shoreline and do not significantly contribute to terrestrial crustal deformation; however, offshore faults can still trigger large tsunamis along the Pacific coast of the Boso Peninsula (Namegaya et al. 2011). Therefore, to model offshore faults, it is important to consider historical tsunami data. Recently, the Japanese Cabinet Office (2013) proposed a source model for the 1703 event based on an inversion analysis using the observed terrestrial crustal deformations in conjunction with historical tsunami data. However, limited data are available on the historical tsunami heights in the northern Boso Peninsula, and this lack of information could

**Table 1 Validation criteria for the historical tsunami heights (before the 1960 Chilean earthquake tsunami) (Japan Society of Civil Engineers 2002)**

| | Criteria for historical tsunami data |
|---|---|
| A | Validity is high. Both the tsunami run-up and its location are confirmed by a historical document, and the height has been measured in recent years |
| B | Validity is moderate. Both the tsunami run-up and its location are confirmed by a historical document, although the height has not been measured in recent years |
| C | Validity is low. The tsunami run-up is confirmed by a historical document or tradition, although its location is indicated only by a village name, and a detailed location is unclear |
| D | Validity is doubtful. The tsunami run-up is estimated by conjecture through the extent of damage and its associated phenomena |

**Table 2 Historical descriptions of the 1703 tsunami and its effects**

| Place (current name) | Latitude (deg) | Longitude (deg) | Documents | Present-day height (m above T.P.)[d] | Flow depth (m) | Tsunami height (m above T.P.) | Validity value[f] | Account[g] |
|---|---|---|---|---|---|---|---|---|
| *Isejiga-ura* | 140.86942 | 35.72062 | Genba-Sendaisyu[a] | 3.9 | ≥2.0 | ≥5.9 | C | Five barns for fishing nets were destroyed by the tsunami flow<br>*We measured the ground level near the 1703 location of the harbor of the village* |
| *Kobatake-ike* | 140.85988 | 35.71018 | Homan Temple[b] | 11.3 (10.8)[e] | 0.6–0.9 | 11.4–11.7 | A | The tsunami overran *Kimiga-hama* beach and reached *Kobatake-ike* pond. Seven hundred trees were destroyed by the tsunami flow. Sea algae were caught in a tree at the side of the pond at a height of 2–3 shaku (approximately 0.6–0.9 m) above the ground |
| *Nagasaki* | 140.86236 | 35.69500 | Homan Temple[b]<br>Tokai shrine[c] | 5.7 | ≥2.0 | ≥7.7 | C | A barn[b] and *Nishinomiya* shrine[c] were destroyed by the tsunami flow<br>*We measured the ground level at the possible 1703 location of the destroyed shrine* |
| *Tokawa* | 140.85106 | 35.69893 | Homan Temple[b] | 10.8 | 0.0 | 10.8 | C | Tsunami destroyed barns under the *Ebisu* shrine and reached the mountain pass<br>*According to the Tokai shrine document, Ebisu shrine was located at the western edge of the village. Thus, we measured the ground level at the 1703 location of the mountain pass on the west side of the village* |
| *Na'arai* | 140.83685 | 35.71167 | Homan Temple[b] | 3.8 | ≥1.0 | ≥4.8 | C | A house was destroyed by the tsunami flow |

[a] Editorial Committee for the History of Chiba Prefecture (1958)

[b] Editorial Committee for the History of Kaijyo town (1988)

[c] Committee for local history (1989)

[d] T.P. is Tokyo Peil. Ground levels were measured by GPS (Promark, Ashtech)

[e] A dike was constructed surrounding the pond in recent years. Thus, the present-day ground level is 50 cm higher than that during 1703

[f] See Table 1

[g] Our interpretations are indicated in italicized text

be significant in the effort to model the offshore faults (Fig. 1).

To model the offshore fault that generated the 1703 earthquake and the subsequent tsunami, we study tsunami heights by focusing on historical documents from Choshi City, which is located at the eastern edge of the Greater Tokyo area (Fig. 1). Based on new findings from these historical documents, we have updated the previously generated source model for the 1703 Genroku Kanto earthquake.

## Study area

We conducted field surveys of the region affected by the 1703 earthquake and tsunami, namely Choshi City, Chiba Prefecture, Japan (Fig. 1). The city is located at the tip of the cape and constitutes the easternmost section of the Greater Tokyo Area. Two large tsunamis have struck in the vicinity of the area since the Edo era (i.e., 1603–1867) (Fig. 1). The first tsunami was generated by the 1677 Enpo Boso-oki earthquake and occurred along the Japan Trench, and the second tsunami was induced by the 1703 Genroku Kanto earthquake and occurred along the Sagami Trough (Hatori 2003; Tsuji et al. 2012; Yanagisawa et al. 2016). According to previous studies (e.g., Hatori 1976), a height of approximately 3–4 m was predicted for the Choshi City tsunami from the 1703 event, which would produce only minor damage. However, an investigation of several historical documents and newly unearthed descriptions of severe damage estimates in Choshi City, which indicate a greater degree of destruction than previously assessed, we find that relatively large tsunamis have struck the city over the past several 100 years.

## Historical records of the 1703 Genroku Kanto earthquake tsunami

### Methodologies

The 1923 Taisho Kanto earthquake caused significant crustal deformation around the southern Boso Peninsula. However, the earthquake did not have a significant effect on the terrestrial deformations in the vicinity of Choshi City, which is located far from the event epicenter. Therefore, we proceeded to estimate the height of the tsunami from the 1703 event based on present-day ground elevation measurements without adjusting for the deformation by the earthquake. The validity of the estimated data

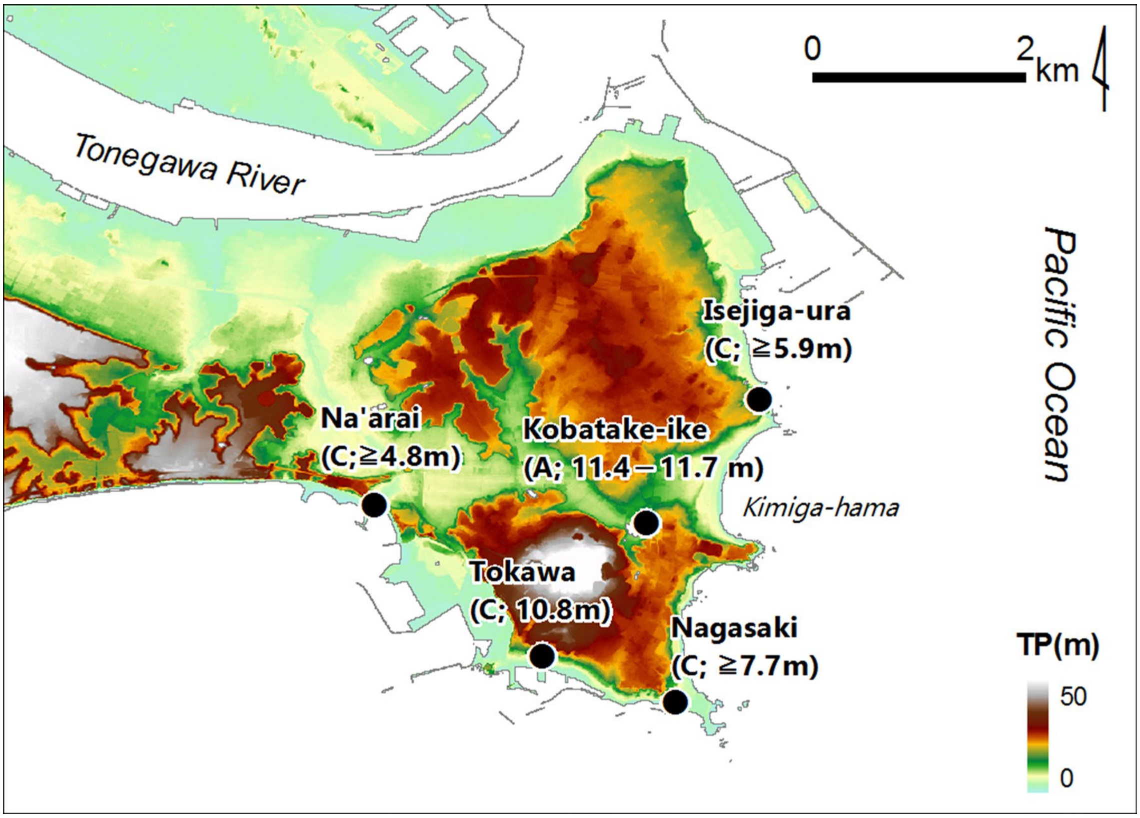

**Fig. 2** Ground level [Tokyo Peil (T.P.)] and historical tsunami heights in Choshi City. The letters A and C in brackets represent the validity criteria for the tsunami heights (see Table 1)

has been classified into four levels (valid values: A, B, C and D) according to the Japan Society of Civil Engineers (2002) (Table 1).

Three historical documents are available that describe the 1703 earthquake and subsequent tsunami in Choshi City: the "*Genba-Sendaisyu*" (Editorial Committee for the History of Chiba Prefecture 1958); a historical document from the *Homan* temple (Editorial Committee for the History of Kaijyo town 1988); and a historical document from the *Tokai* shrine (Committee for local history 1989). The *Genba-Sendaisyu* was written by *Genba Tanaka*, the founder of a famous Japanese soy sauce company established in the Edo era. The descriptions of the tsunami were entered into the document shortly after the disaster. The writers of the *Homan* temple and *Tokai* shrine documents are unknown. However, the *Homan* temple document was likely written shortly after the tsunami because the document includes descriptions of the immediate aftermath of the disaster (Table 2). The *Tokai* shrine document was written in 1723 to note the reconstruction of the *Nishinomiya* shrine at *Nagasaki*, which was destroyed by the tsunami. Using a GPS instrument (Ashtech Promark), we measured the present-day surface elevation of locations that were damaged or flooded as described within the historical documents. We estimated the tsunami height by adding the ground elevation to the flow depth that has been inferred from descriptions within historical documents. However, descriptions within historical documents capable of indicating the flow depth are sparse. When the flow depth is not indicated in the documentation, we interpreted the flow depth from the magnitude of damage to residential structures, which is similar to the method applied in other historical documentary studies. According to previous studies (e.g., Hatori 1984; Tsuji et al. 2012), a

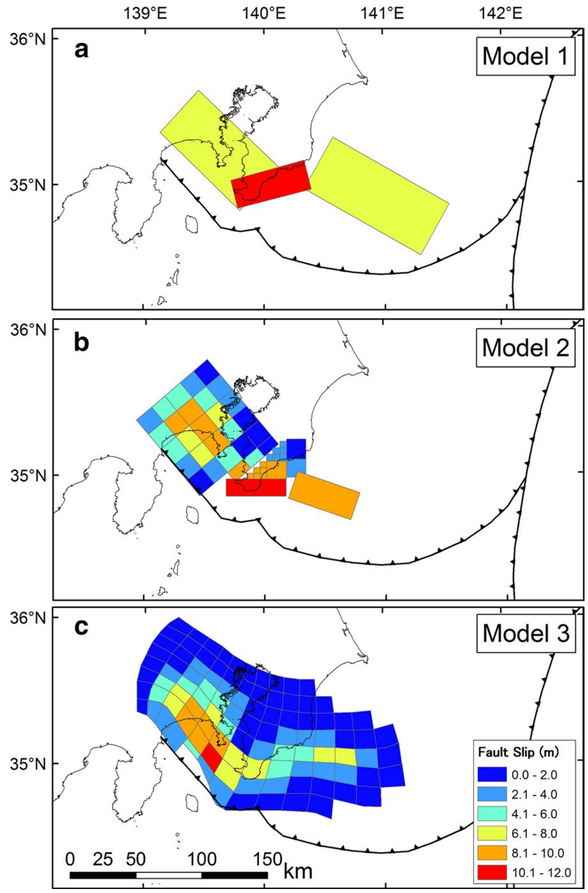

**Fig. 3** Previously proposed source models of the 1703 earthquake and resulting tsunami. **a** Model 1 (Shishikura model in Satake et al. 2008). **b** Model 2 (Namegaya et al. 2011). **c** Model 3 Cabinet Office (2013). The area of Model 3 is divided into 100 segments to determine the fault slip parameter. These segments are further divided into 51,399 nodes to extract the other fault parameters, such as the fault depth, strike and dip angle (also see Table 3)

**Table 3 Models of the 1703 earthquake and tsunami. The parameters are as follows: *d* is focal depth, *θ* is strike, *λ* is slip angle, *U* is dislocation, *L* is fault length, and *W* is fault width**

| Name | Mw[a] | Number of faults | Parameters of the offshore fault | | | | | | | References |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | *d* (km) | *θ* (deg) | *δ* (deg) | *λ* (deg) | *U* (m) | *L* (km) | *W* (km) | |
| Model 1 | 8.33 | 3 | 0.0 | 300 | 30 | 135 | 7.1 | 100 | 50 | Shishikura model in Satake et al. (2008) |
| Model 2 | 8.23 | 45 | 1.3 | 290 | 45 | 125 | 10 | 50 | 30 | Namegaya et al. (2011) |
| Model 3 | 8.51 | 51,399 | – | – | – | – | – | – | – | Cabinet Office (2013) |
| Model 4 | 8.30 | 45 | 1.3 | 290 | 45 | 125 | 20 | 50 | 30 | This study[b] |
| Model 5 | 8.30 | 45 | 1.3 | 290 | 45 | 125 | 10 | 50 | 60 | This study[c] |
| Model 6 | 8.32 | 45 | 1.3 | 274 | 45 | 109 | 10 | 120 | 30 | This study[d] |

[a] The rigidity coefficient is $5 \times 10^{10}$ Nm (Namegaya et al. 2011)

[b] Model 2 × 2.0 fault slip factor (20 m slip)

[c] Model 2 × 2.0 fault width factor (60 km width)

[d] Offshore fault length of Model 2 was extended to 120 km along the Sagami Trough

house during the Edo era was fragile and could thus be destroyed by a flow depth ≥1 m, and a number of houses could be washed away by a flow depth of ≥2 m. Accordingly, we considered the flow depth to be ≥1 m when a house was reported as destroyed and ≥2 m when several houses were reported as washed away.

### Determination of tsunami heights from the 1703 event

Descriptions of the 1703 tsunami in Japan are summarized in Table 2. These descriptions reveal that the tsunami caused considerable damage in the vicinity of Choshi City that was substantially greater than previously predicted. For example, the *Genba-Sendaisyu* mentions that "*five barns for fishing nets were destroyed by the tsunami flow.*" The tsunami flooded several villages, and several houses, and seven hundred trees were damaged from flood heights exceeding 10 m. Figure 2 illustrates the distribution of tsunami-affected locations in the city estimated from historical documents. The affected areas are distributed to the southeast of the city, which indicates that the tsunami struck primarily from the southeast. When comparing the overall trend of the 1703 tsunami heights from the Pacific coast of the Boso Peninsula to Choshi City (Figs. 1, 2), the latter are exceptionally large,

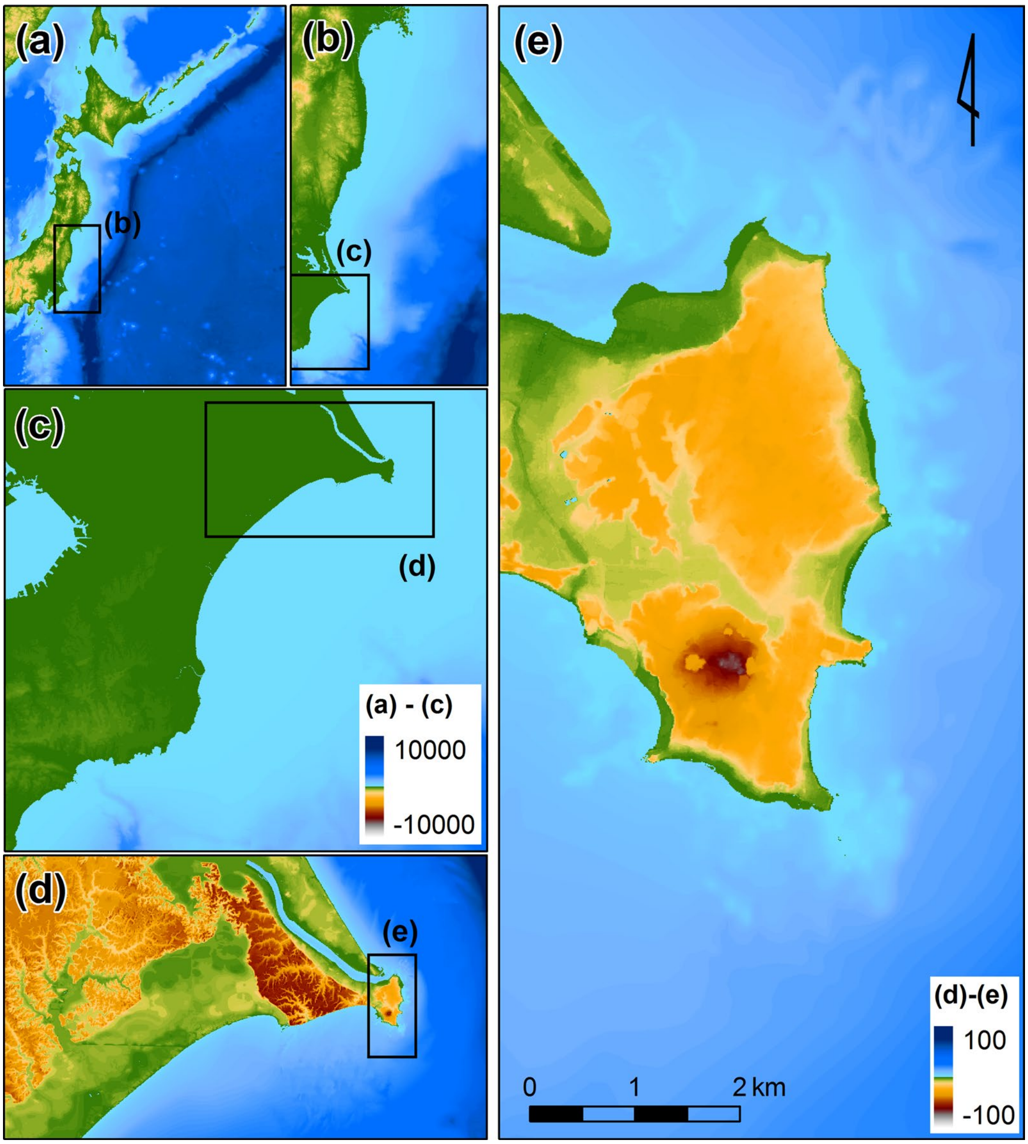

**Fig. 4** Bathymetry and topography data in the nesting grid system for the tsunami simulation with grid sizes of **a** 1350 m, **b** 450 m, **c** 150 m, **d** 50 m and **e** 10 m

despite the geographical distance of Choshi City from the earthquake epicenter.

The locations that were inundated are *Isejiga-ura* village, *Kasagami* village, *Nagasaki* village, *Tokawa* village, *Na'arai* village and *Kobatake-ike* pond. Modern ground elevations (meters above Tokyo Peil, or T.P.) and the estimated tsunami flow depths for each location are presented in Table 2. These results show that the validity values for the estimated tsunami heights are mostly "C" because the exact locations of the damage sites are unclear. However, the *Homan* temple document mentions that "*the tsunami overran Kimiga-hama beach, destroyed seven hundred trees, and reached Oo-ike (modern name: Kobatake-ike) pond,*" where the modern ground level is T.P. 11 m. Thus, the exact site of *Kobatake-ike* pond was located, and we were able to determine the tsunami height at this location (validity value: A). According to Yanagisawa et al. (2016), the tsunami of the 1677 Enpo Boso-oki earthquake also reached this pond. The historical document states that "sea algae were caught in the branches of a tree on the side of the pond at a height of 2–3 shaku (approximately 0.6–0.9 m) above the ground," which indicates that the tsunami carried sea algae at a flow depth between 0.6 and 0.9 m. Thus, the estimated flow depth at the site of *Kobatake-ike* pond was 0.6–0.9 m.

## Numerical simulations

### Tsunami source model

The aforementioned new discoveries of historical tsunami data are extremely important for reconsidering the source of the 1703 Genroku Kanto earthquake, particularly because the tsunami heights around Choshi City were not considered within earlier models. Our results are consequently highly anticipated for use in the modeling of offshore faults capable of triggering a large tsunami along the Pacific coast of the Boso Peninsula.

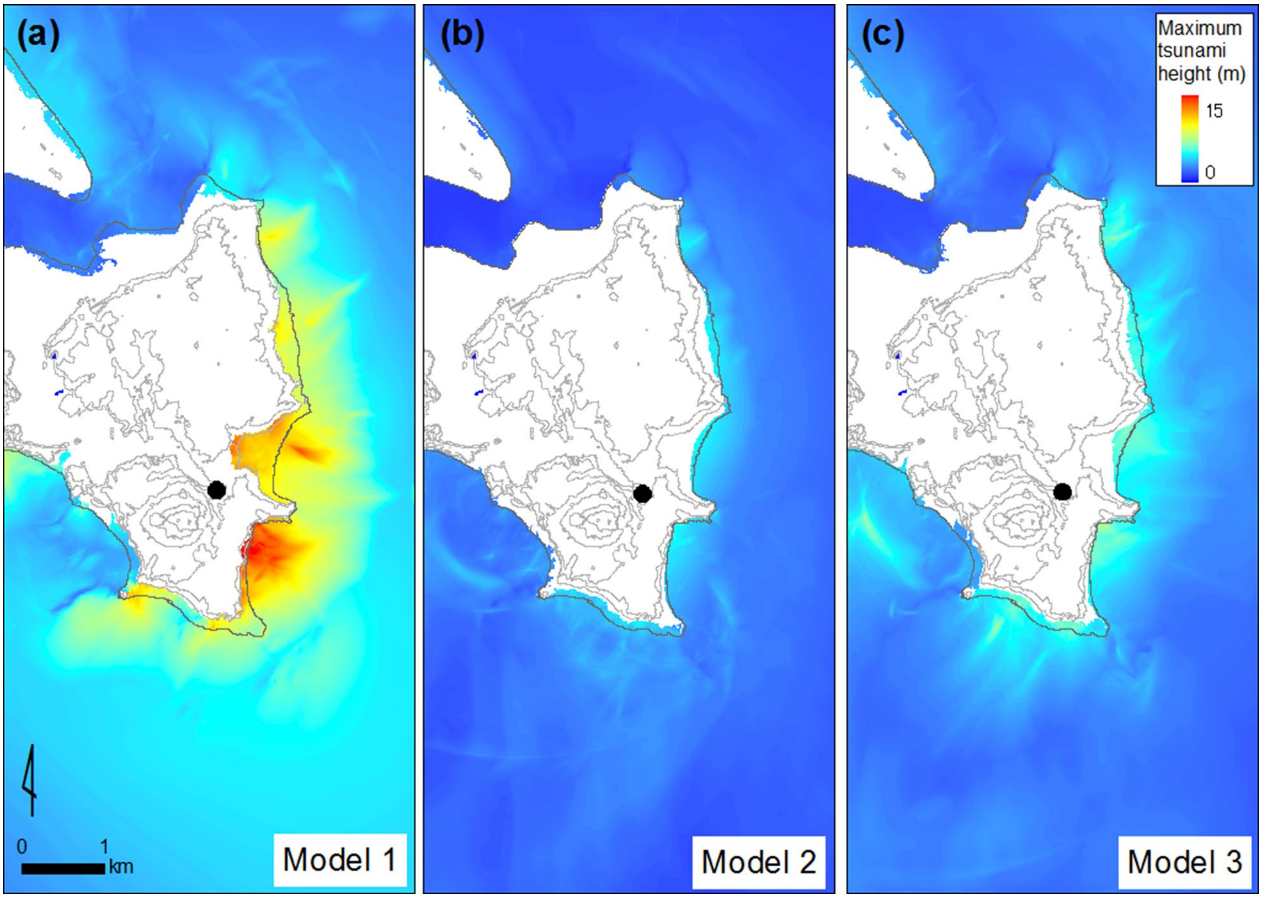

**Fig. 5** Maximum tsunami height derived from previous source models. **a** Model 1 (Shishikura model in Satake et al. 2008), **b** Model 2 (Namegaya et al. 2011) and **c** Model 3 (Cabinet Office 2013). Contour lines show the ground elevation at a 10-m interval. The black dot denotes the location of the *Kobatake-ike*

We first conduct numerical simulations based on previously proposed scenarios to confirm the validity of each model regarding the 1703 event. Here, we adopt three representative models: Model 1 (Shishikura model in Satake et al. 2008), Model 2 (Namegaya et al. 2011) and Model 3 (Cabinet Office 2013) (Table 3).

Model 1 is a three block-triangular model representing a magnitude of Mw 8.3. Models 2 and 3 are multiple block-triangular models that represent magnitudes of Mw 8.2 and Mw 8.5, respectively (Fig. 3). Model 2 is acquired using an inversion analysis of the vertical seismic deformation along the coast of the Boso Peninsula (Namegaya et al. 2011). However, the inversion model does not include an offshore fault because the fault cannot contribute terrestrial crustal deformation. To explain the tsunami inundation along the *Kujukuri-hama* coast, Namegaya et al. (2011) proposed the existence of an offshore fault. Model 3 is also obtained via an inversion analysis but includes both vertical seismic deformation and tsunami height data (Cabinet Office 2013). To confirm the validity of each model, we conduct numerical simulations based on the constraint condition, which is whether the tsunami can reach the *Kobatake-ike* pond, for which the validity value of the tsunami height is "A."

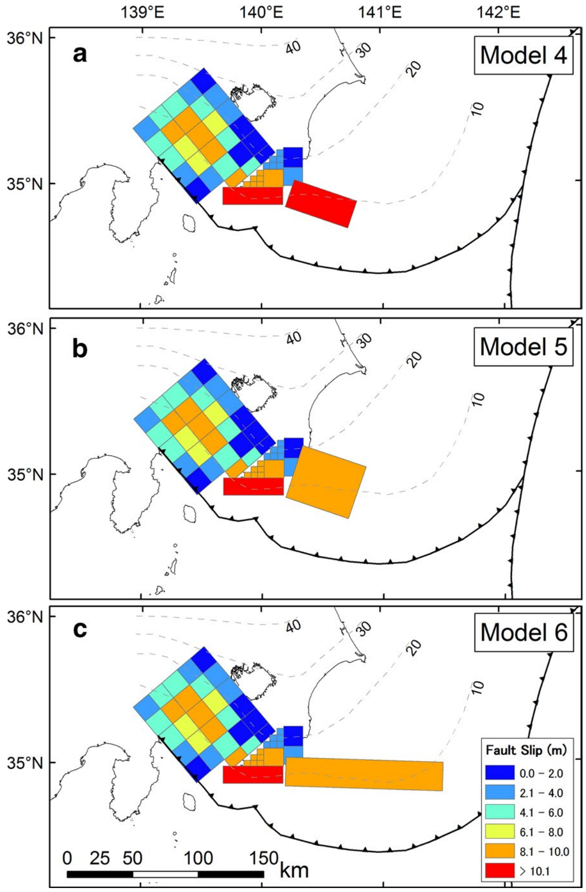

**Fig. 6** Source models for the parametric study of the 1703 earthquake and resulting tsunami. **a** Model 4 (Model 2 × 2.0 fault slip factor for an offshore fault). **b** Model 5 (Model 2 × 2.0 fault width factor for an offshore fault). **c** Model 6 (120-km offshore fault length along the Sagami Trough). Dotted lines show the geometry of the upper plane of the Philippine tectonic plate (Cabinet Office 2013)

### *Methodologies*

Similar to other tsunami computations (e.g., Imamura 1995), we employ nonlinear shallow water wave theory to simulate the tsunami propagation and inundation (TUNAMI-N2 model). The approach incorporates the effects of bottom friction in the form of Manning's formula. For the initial conditions of the propagation model, we estimate the vertical seismic deformation of land and the sea bottom using the theory of Manshinha and Smylie (1971). In the coastal area, we use a nesting grid system with modern digital bathymetry and topography data with grid sizes of 1350, 450, 150 and 50 m provided by the Central Disaster Management Council. For the target area of Choshi City, we use 10-m gridded data resampled from a 5-m digital elevation model (DEM) obtained from the Geospatial Information Authority of Japan (Fig. 4). To remove recent construction objects, such as ports, from the modern topographic data, we use a historical map originating from the early- to middle-Meiji period of the nineteenth century, which was obtained from the National Institute for Agro-Environmental Sciences (http://habs.dc.affrc.go.jp/) (Yanagisawa et al. 2016). For the time grid of the tsunami propagation, we use 0.9, 0.3 and 0.1 s for nesting regions with grid sizes of 1350 m, 450 m and 150–10 m, respectively.

## Results of tsunami simulations using previously proposed models

Our results ultimately reveal that tsunamis generated using Models 1 through 3 are unable to reach and inundate *Kobatake-ike* pond (Fig. 5), which in turn suggests that previous models have underestimated the size and height of the 1703 tsunami, especially Models 2 and 3. The tsunami height obtained using Model 1 is larger than that using Models 2 and 3, which could be related to the larger offshore fault in Model 1 compared with that in Models 2 and 3. Thus, we determined that the previous models were unable to sufficiently estimate the geometry of an offshore fault that served to trigger a larger tsunami that eventually reached Choshi City. Based on these numerical results, we infer that the source model of an offshore fault should be updated.

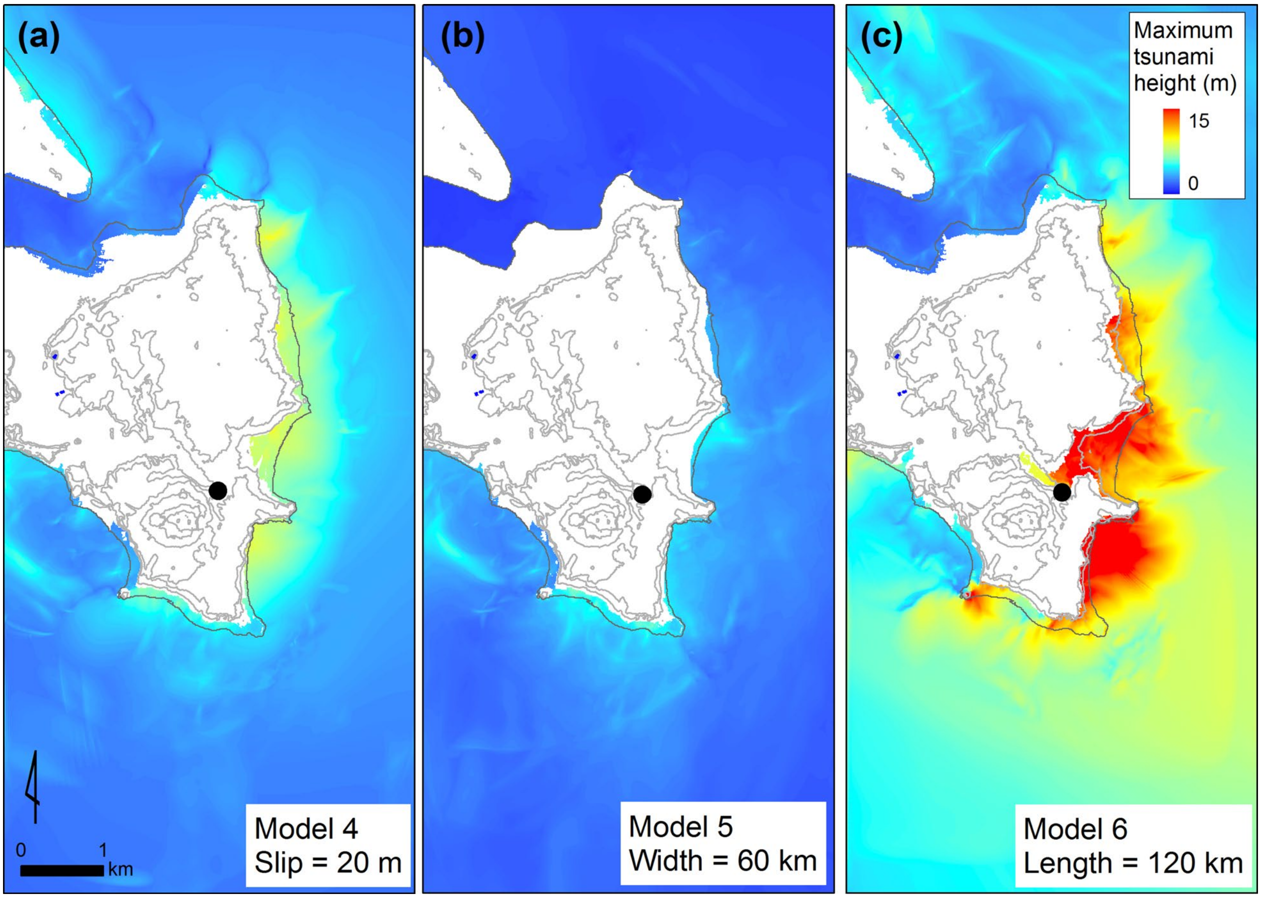

**Fig. 7** Maximum tsunami height derived from the revised models. **a** Model 4, **b** Model 5 and **c** Model 6

## Reevaluation of source models for an offshore fault along the Sagami Trough

For the purpose of modeling the 1703 event, Models 2 and 3 are sufficiently accurate in reproducing the terrestrial crustal deformations along the southern Boso Peninsula. However, modifying the offshore fault in Model 3 is difficult because this model is derived from an inversion analysis of the previous tsunami data set and does not include the newly discovered larger tsunami heights in Choshi City. Therefore, Model 3 is constructed using insufficient information, which leads to smaller predicted tsunamis. Thus, to modify an offshore fault along the Sagami Trough, we selected Model 2, which is derived solely from the terrestrial crustal deformations along the coast of the southern Boso Peninsula. However, to modify Model 2, the parameters of the offshore fault must be altered according to the constraint condition, which indicates that fault deformations have an insignificant effect on land along the coast of the southern Boso Peninsula. To reevaluate the offshore fault within Model 2, we selected the three most important parameters of the offshore fault that contribute to the generation of a sufficiently large tsunami, namely the fault slip, width and length, which have original values of 10 m, 30 km and 50 km, respectively (Table 3). To modify the fault length, we extended the fault along the boundary between the subducting Philippine sea plate and the overriding plate as proposed by Cabinet Office (2013) (Fig. 6c). The slip angle is determined by the direction of slip deficit at the Boso Peninsula (Namegaya et al. 2011).

Figure 7a, b illustrates the inundation area simulated using a fault slip and width multiplied by 2.0 (i.e., a 20-m fault slip (Model 4) and 60-km fault width (Model 5), respectively). The resulting tsunamis generated by either model cannot reach *Kobatake-ike* pond. Furthermore, fault slip and width parameters are not modified further because additional modifications may produce effects on the terrestrial crustal deformation patterns for the southern Boso Peninsula. Therefore, Fig. 7c presents the inundation area simulated using a 120-km fault length, and

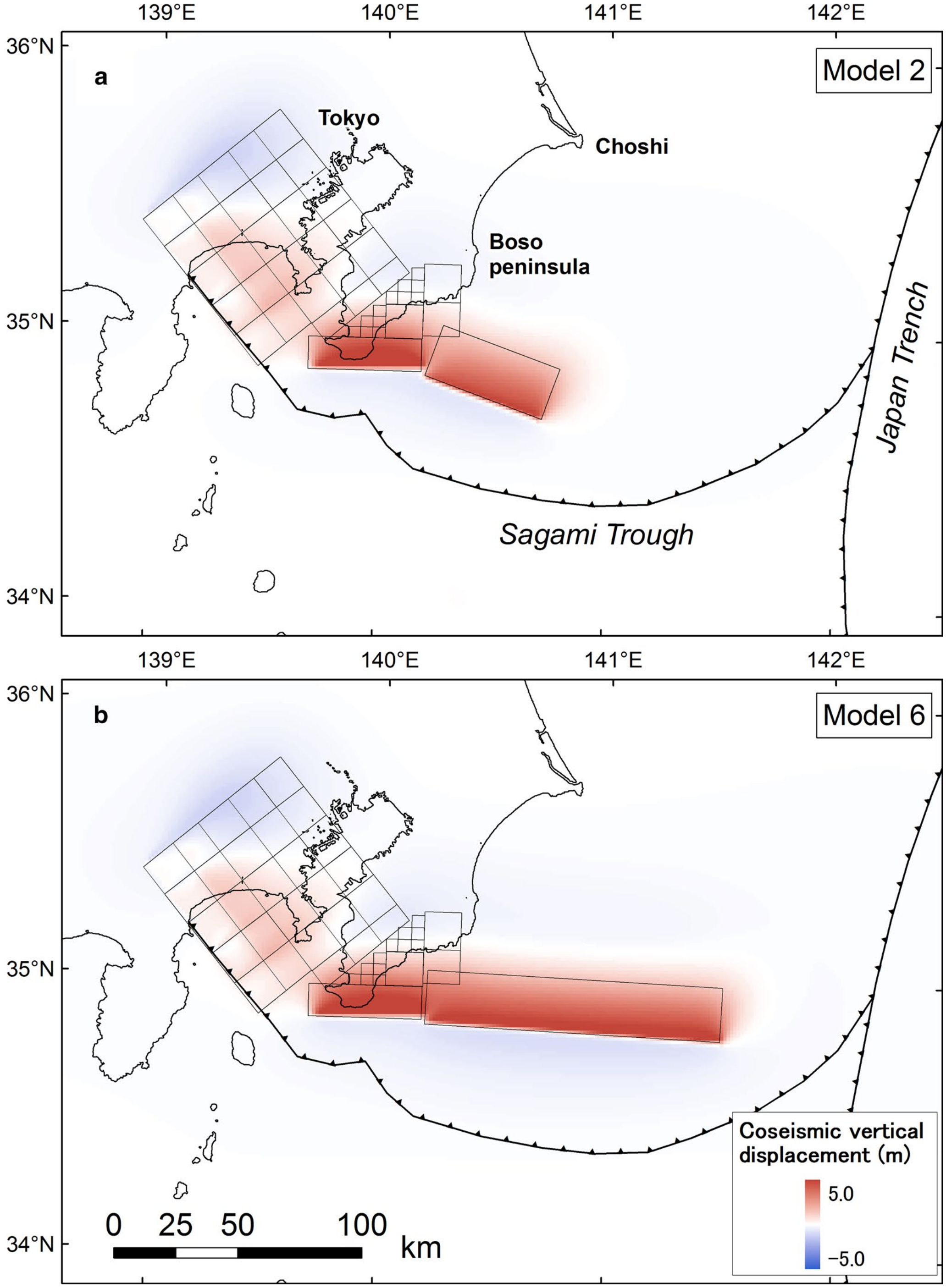

**Fig. 8** Coseismic vertical displacement of the 1703 earthquake calculated by **a** Model 2 (Namegaya et al. 2011) and **b** Model 6

the resulting tsunami is capable of reaching *Kobatake-ike* pond. Because the fault length alone is extended away from the shore along the Sagami Trough, the deformation of the fault exerts an insignificant influence on the Boso Peninsula (Fig. 8). A parametric study indicates that the tsunami heights in Choshi City become substantially large when the fault length is extended in the offshore direction along the Sagami Trough (Fig. 9a).

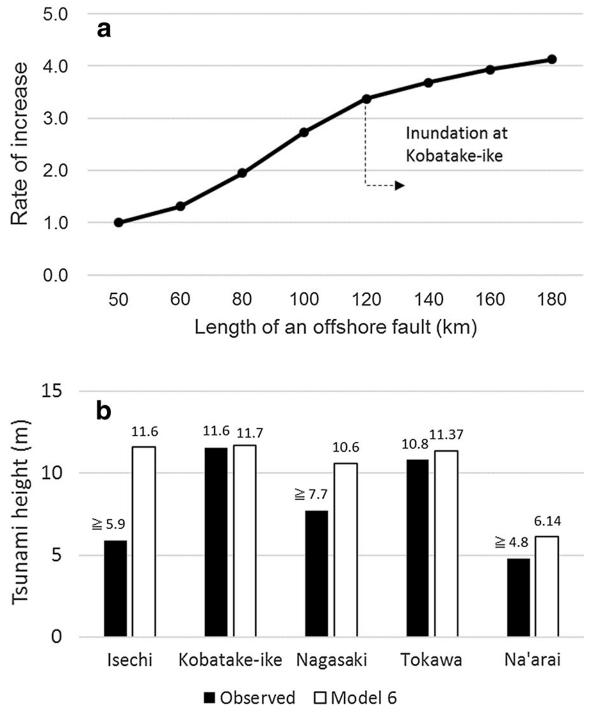

**Fig. 9** **a** Rate of increase in the tsunami height by extending the offshore fault length. The data were acquired at *Kimiga-hama* beach, which is located in front of *Kobatake-ike* (see Fig. 2). The rate of increase is defined as the tsunami height divided by that of the offshore fault with a length of 50 km. The tsunami reaches *Kobatake-ike* for offshore fault lengths exceeding 120 km. **b** Comparison between the observed tsunami heights and the calculated results according to Model 6

To verify our reevaluated model, we compared the calculated results with the observed tsunami heights (Fig. 9b). Model 6 matches the conditions at *Isejiga-ura* (≥5.9 m), *Nagasaki* (≥7.7 m) and *Na'arai* (≥4.8 m) and approximately reproduced the tsunami heights at *Kobatake-ike* and *Tokawa*.

### *Why are the local tsunami heights in Choshi City greater?*

The local tsunami heights in Choshi City are large, despite the geographical distance from the earthquake epicenter (Figs. 1, 2). To examine the bathymetric effects along the tsunami propagation path, we apply a wave ray tracing analysis (e.g., Satake 1988). Figure 10a illustrates the ray tracing results for tsunami propagation routes sourced from an offshore fault along the Sagami Trough. Most of the wave rays up to 80 km offshore from the edge of the fault converge upon the Boso Peninsula. However, the wave rays from 80 km to 160 km converge onto Choshi City, which is located at the tip of the cape. The energy of the tsunami hydrodynamically tends to concentrate around the tip of the cape because of wave refraction. Similarly, the wave ray tracing analysis reveals that the tsunami energy preferentially concentrated on Choshi City from the offshore routes. The calculated maximum tsunami heights also indicate that tsunami waves originating from offshore faults concentrate around Choshi City (Fig. 10b). Consequently, we conclude that the locally large tsunami heights in Choshi City are sufficiently reasonable because the offshore fault is extended by approximately 80–160 km; thus, it is relatively close to the Japan Trench. This finding indicates that the entire breadth of the Sagami Trough might have ruptured with an energy release of more than Mw 8.32 during the 1703 Genroku Kanto earthquake.

## Concluding remarks

We investigated the characteristics of the offshore fault that generated the 1703 Genroku Kanto earthquake and subsequent tsunami based on analyses of historical documents as well as numerical modeling. The historical data demonstrate that the tsunami reached heights in excess of 11 m in the vicinity of Choshi City, despite the geographical distance from the earthquake epicenter.

Furthermore, we conducted numerical simulations based on scenarios inferred from historical documents to represent the inundation area. Scenarios of the sources for the 1703 earthquake and the subsequent tsunami provide a 120-km fault length for an offshore fault along the Sagami Trough, which is close to the Japan Trench. Our results suggest that earthquake energy along nearly the entire Sagami Trough could have been released during the 1703 Genroku Kanto earthquake. Accordingly, a future study will be performed to provide a more detailed fault model with evidence spanning regions other than Choshi City.

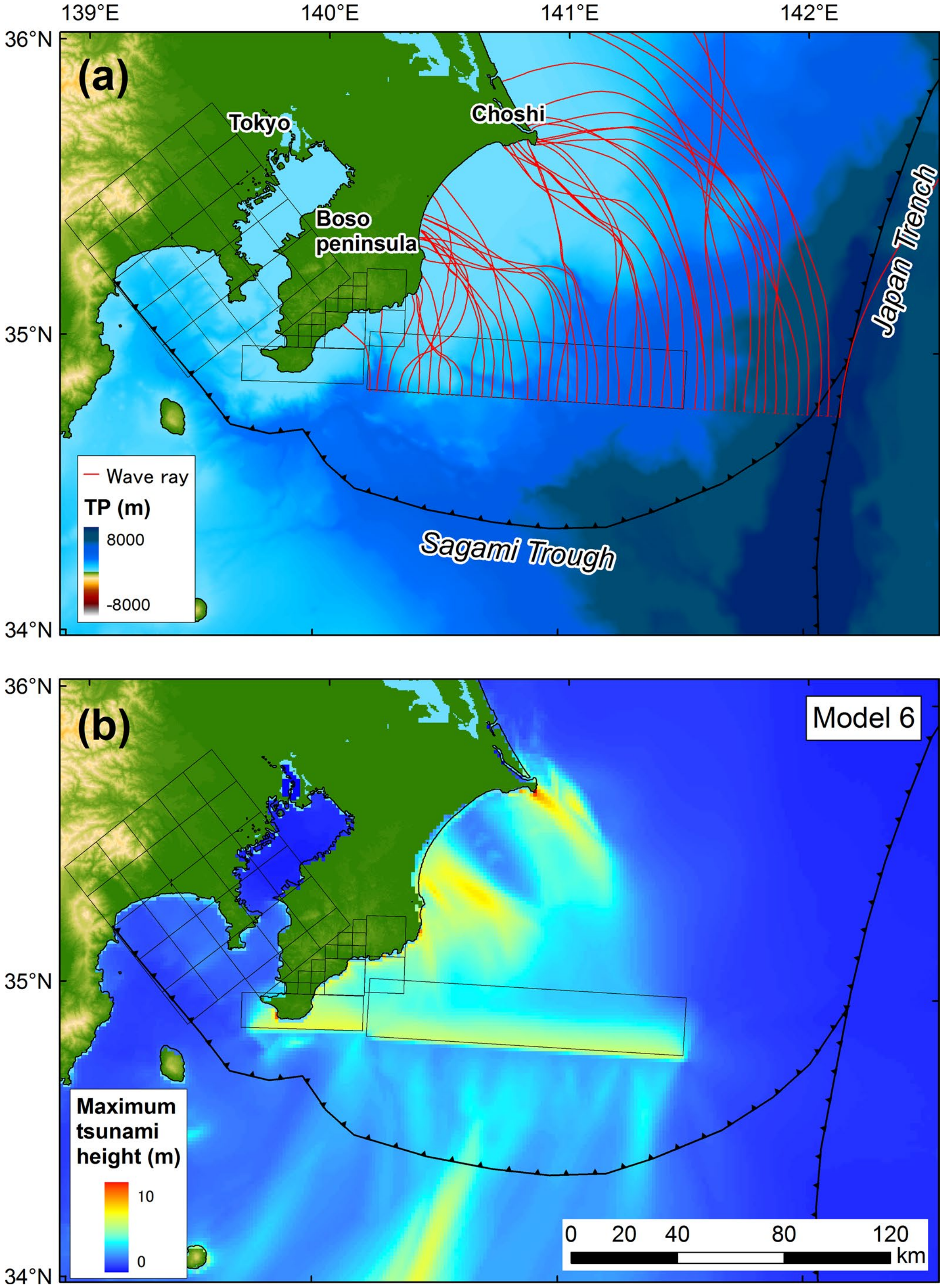

**Fig. 10** **a** Wave ray tracing analysis along an offshore fault in the Sagami Trough. The black rectangle shows the fault area of Model 6 (120 km length of the offshore fault). **b** Maximum tsunami height of Model 6

## Authors' contributions

HY conducted the simulation and field surveys and prepared the manuscript. KG conceived this study, managed the grant awarded by IRIDeS and conducted the field surveys. Both authors read and approved the final manuscript.

## Author details

[1] Department of Regional Management, Tohoku Gakuin University, Tenjinsawa 2-1-1, Izumi-ku, Sendai, Miyagi, Japan. [2] International Research Institute of Disaster Science, Tohoku University, Aramaki Aza-Aoba 468-1, Aoba-ku, Sendai, Miyagi, Japan.

**Acknowledgements**

We especially thank Yoshifumi Takamori, Kaito Suzuki, Takashi Sato and Koyomi Imaizumi for the support they provided during the historical document studies and field surveys. Certain documentation was provided by the Choshi City Kosei library. The anonymous reviewers provide valuable comments on improving our manuscript.

**Competing interests**

The authors declare that they have no competing interests.

**Funding**

This study was financially supported by the International Research Institute of Disaster Science, Tohoku University (Tokutei Project) and the Environment Research and Technology Development Fund (2-1712) of Environmental Restoration and Conservation Agency.

## Publisher's Note

Received: 31 May 2017 Accepted: 4 September 2017

**References**

Cabinet Office (2013) The Committee of the model for Tokyo Metropolitan Earthquake (in Japanese). http://www.bousai.go.jp/kaigirep/chuobou/senmon/shutochokkajishinmodel/

Committee for Local History (1989) Visit historic sites of Nagasaki and Tokawa (in Japanese). Cultural Foundation for Youth of Choshi City

Editorial Committee for the History of Chiba prefecture (1958) History of Chiba prefecture the early modern period (in Japanese). Shimousa-koku (the first volume)

Editorial Committee for the History of Kaijyo town (1988) History of Kaijyo town, Chiba prefecture (in Japanese). vol 2

Grunewald ED, Stein RS (2006) A new 1649–1884 catalog of destructive earthquakes near Tokyo and implications for the long-term seismic process. J Geophys Res 111:B12306. doi:10.1029/2005JB004059

Hatori T (1975) Tsunami source off Boso peninsula -estimation of tsunami source area and magnitude of Enpo (1677), Genroku (1703) and 1953 Boso-oki tsunami- (in Japanese). Bull Earthq Res Inst 50:83–91

Hatori T (1976) Monuments of the 1703 Genroku Tsunami along the South Boso Peninsula: wave Height of the 1703 Tsunami and its comparison with the 1923 Kanto Tsunami (in Japanese). Earthq Res Inst Univ Tokyo 51:63–81

Hatori T (1984) On the damage to houses due to Tsunamis (in Japanese). Bull Earthq Res Inst Univ Tokyo 59:433–439

Hatori T (2003) Irregular height deviation of the 1677 Enpo Boso-Oki Tsunami, Eastern Japan (in Japanese). Hist Earthq 19:1–7

Hatori T, Aida I, Kajiura K (1973) Tsunamis in the south Kanto district (In Japanese). In: Publications for the 50th anniversary of the Great Kanto Earthquake, 1923. Earthquake Res Inst, Univ Tokyo, pp 57–66

Imamura F (1995) Review of tsunami simulation with a finite difference method. In: Yeh H, Liu P, Synolakis C (eds) Long-wave run-up models. World Science, Singapore, pp 25–42

Japan Society of Civil Engineers (JSCE) (2002) Tsunami assessment method for nuclear power plants in Japan (in Japanese). Tsunami Eval Subcomme Nucl Civil Eng. Comm

Manshinha L, Smylie DE (1971) The displacement field of inclined faults. Bull Seismol Soc Am 61:1433–1440

Matsuda T, Ota Y, Ando M, Yonekura N (1978) Fault mechanism and recurrence time of major earthquakes in southern Kanto district, Japan, as deduced from coastal terrace data. Geol Soc Am Bull 89:1610–1618

Namegaya Y, Satake K, Shishimura M (2011) Fault models of the 1703 Genroku and 1923 Taisho Kanto earthquakes inferred from coastal movements in the southern Kanto area (in Japanese with English abstract). Annu Rep Act Fault Paleoearthq Res 11:107–120

Satake (1988) Effects of bathymetry on tsunami propagation: application of ray tracing to tsunamis. Pure Appl. Geophys. 126:27. doi:10.1007/BF00876912

Satake K, Shishikura M, Namegaya Y, Fuji R, Takeuchi H (2008) Fault models of the Genroku (1703) Kanto earthquake and tsunamis along the eastern coast of Boso peninsula (in Japanese with English abstract). Hist Earthq 23:81–90

Sato H, Hirata N, Koketsu K, Okaya D, Abe S, Kobayashi R, Matsubara M, Iwasaki T, Ito T, Ikawa T, Kawanaka T, Kasahara K, Harder S (2005) Earthquake source fault beneath Tokyo. Science 309:462–464

Sato T, Higuchi H, Miyauchi T, Endo K, Tsumura N, Ito T, Noda A, Matsu'ura M (2016) The source model and recurrence interval of Genroku-type Kanto earthquakes estimated from paleo-shoreline data. Earth Planets Space 68:17. doi:10.1186/s40623-016-0395-3

Shishikura M (2014) History of the paleo-earthquakes along the Sagami Trough, central Japan -review of coastal paleoseismological studies in the Kanto region-. Episodes 37:246–257

Tsuji T, Yanuma T, Hirahata T, Imamura F (2012) Field survey of inundation height of Eno Boso earthquake tsunami (1677) in Boso Peninsula, Chiba prefecture (in Japanese). Rep Tsunami Eng Res 29:209–223

Usami T (1980) Intensity distribution of the Genroku earthquake of Dec. 3, 1703 (in Japanese). Report of the Coordinating Committee for Earthquake Prediction, vol 24(7–2), pp 248–250

Yanagisawa H, Goto K, Sugawara D, Kanamaru K, Iwamoto N, Takamori Y (2016) Tsunami earthquake can occur elsewhere along the Japan Trench—historical and geological evidence for the 1677 earthquake and tsunami. J Geophys Res Solid Earth. doi:10.1002/2015JB012617