Kitamura *et al. Earth, Planets and Space* (2015) 67:197
DOI 10.1186/s40623-015-0367-z

Earth, Planets and Space
a SpringerOpen Journal

FULL PAPER Open Access

# Examination of an active submarine fault off the southeast Izu Peninsula, central Japan, using field evidence for coseismic uplift and a characteristic earthquake model

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**Abstract**

Detailed mapping and radiocarbon dating of emergent marine sessile assemblages show that coseismic uplift occurred at 1256–950 BC, AD 1000–1270, AD 1430–1660, and AD 1506–1815 in the southern Izu Peninsula, central Japan. Employing a characteristic earthquake model, this study reconstructed the source fault for the uplift events from the spatial distribution of coseismic vertical displacements and historical documents. The source is inferred to be a reversal fault located about 3 km off the southern Izu Peninsula that is 25 km long and 13 km wide (strike = 250°, dip = 52° to the north) and slip of 2.7 m and has generated a Mw 7 class earthquake.

**Keywords:** Coseismic uplift, Late Holocene, Izu Peninsula, Emergent marine sessile assemblages, Fault model, Characteristic earthquake model

## Findings

### Introduction

The Izu Peninsula in central Japan, which is located between the Sagami and the Suruga troughs and lies at the northern tip of the Philippine Sea (PHS) plate, is currently colliding with central Japan (Sugimura 1972; Somervill 1978; Nakamura and Shimazaki 1981; Arai and Iwasaki 2014, 2015) (Fig. 1). GPS and leveling data have indicated that the Izu microplate, which includes the Izu Peninsula, is moving independently of the PHS plate (Sagiya 1999; Heki and Miyazaki 2001; Nishimura et al. 2007) and is a region of concentrated deformation between the Izu Peninsula and the PHS plate (Fig. 1). Thus, many earthquakes have occurred along the active faults in this area (Sagiya 1999), including the AD 1930 North Izu earthquake (M 7.3; Tanna Fault) and the AD 1974 Off-Izu Peninsula earthquake (M 6.9; Irozaki Fault).

Emergent sessile marine invertebrates and raised coastal landforms, up to 3 m above mean sea level (amsl), occur at Shimoda in the southeast Izu Peninsula and appear to have been uplifted during seismic events (Fukutomi 1935; Ota et al. 1986; Taguchi 1993; Kitamura et al. 2014, 2015). Kitamura et al. (2015) examined the faunal compositions and $^{14}$C ages of emergent sessile assemblages at four sites in the southern Izu Peninsula (Fig. 2) and concluded that coseismic uplift occurred at 1256–950 BC, AD 1000–1270, AD 1430–1660, and AD 1506–1815. The authors also noted that the most recent event coincided with a large historical earthquake in the southern Izu Peninsula in AD 1729 (Usami 1975) and that the fault appeared to be located offshore, because onshore reversal faults are not known to occur in that region.

In this paper, we examine emerged marine sessile assemblages at three sites in the southern Izu Peninsula. Then we estimate coseismic vertical displacement based on a combination of previous work and new data. We

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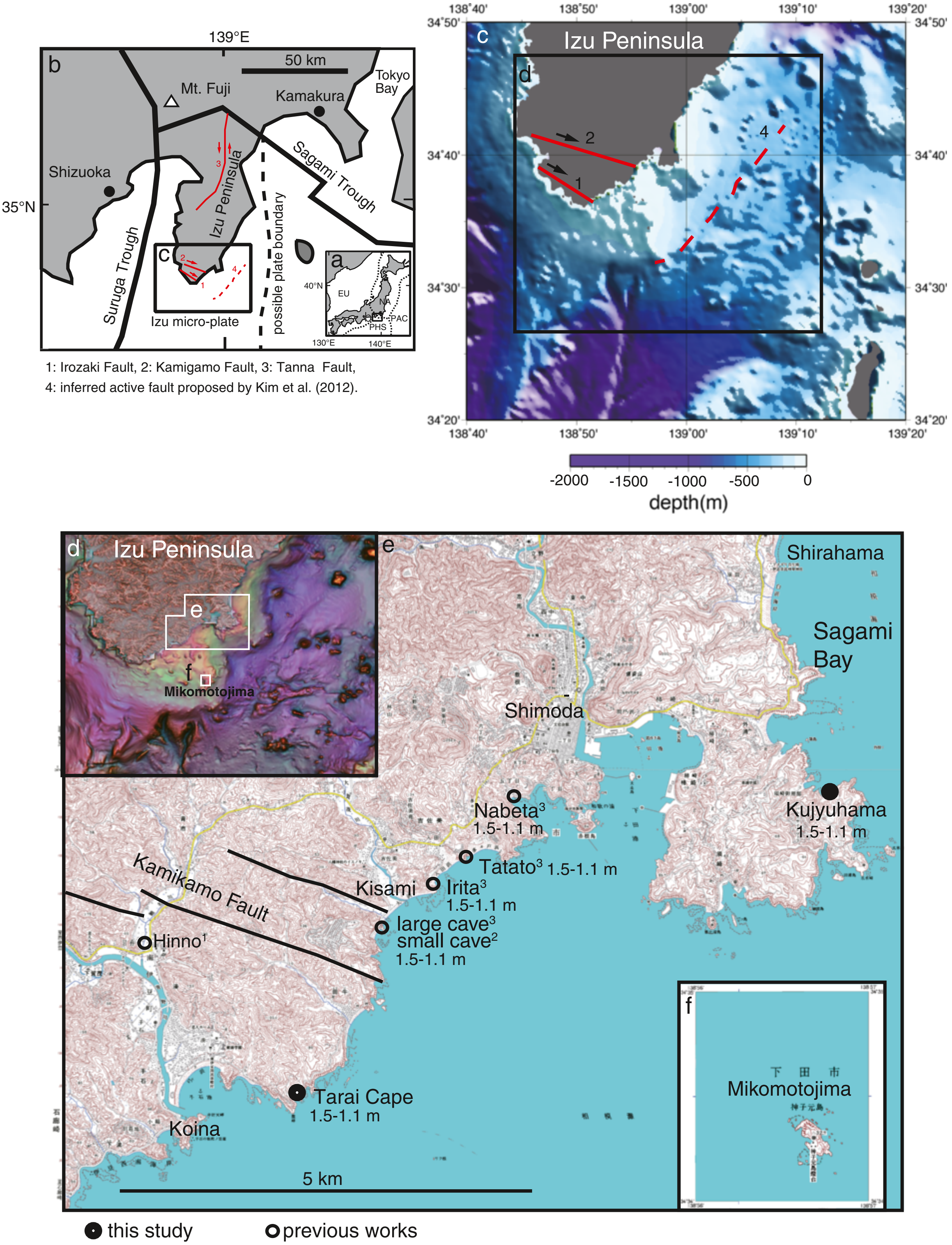

**Fig. 1** (See legend on next page.)

(See figure on previous page.)

**Fig. 1** Locality maps. **a** Japan Islands, showing plate boundaries and the location of the Izu Peninsula. *EU*, Eurasia Plate; *NA*, North American Plate; *PAC*, Pacific Plate; *PHS*, Philippine Sea plate. **b** Locations of key active faults on the Izu Peninsula. The postulated plate boundary is after Nishimura et al. (2007). **c** Bathymetric map off the southern end of the Izu Peninsula. **d** Locations of the study areas on a 1:25,000 scale topographic map of the Shimoda and Mikomotojima districts (published by the Geospatial Information Authority of Japan). *1*, Kitamura et al. (2013); *2*, Kitamura et al. (2014); *3*, Kitamura et al. (2015). *Inset* shows a red-relief image map off the southern end of the Izu Peninsula (from Asia Air Survey, Japan)

propose that coseismic uplift events were caused by characteristic earthquakes, and we predict the location and geometry of the source fault using a fault model.

### Study area

The coastline along the southern Izu Peninsula is characterized by a wave-dominated and microtidal regime, with a maximum tidal range of 1.6 m during spring tide. Based on geodetical records from 1896 to 1968 (Danbara and Tsuchi 1975), the study area has been subsiding at a rate of ca. 0.6 mm/year.

Ota et al. (1986) examined cored sediments from coastal lowlands and emergent sessile marine invertebrates in sea caves (large and small caves) at Kisami (Fig. 1). The authors reported that millennial-scale vertical land movements in the area changed from subsidence to uplift at ca. 3000 year BP. The uplift trend was caused by at least three coseismic uplift events (Ota et al. 1986). Taguchi (1993) reported raised benches and notches from Shirahama to Koina (Fig. 1). The elevations of the upper and lower notches are 2.5–3.0 and 1.5–2.0 m amsl, respectively. Taguchi (1993) reported no significant difference in the elevations of notches from Shirahama to Koina; coastal landforms were not observed west of Koina (Fig. 1).

Kitamura et al. (2014, 2015) investigated the faunal compositions and $^{14}$C ages of emergent sessile assemblages at five sites between the Nabeta and Kisami coasts (Fig. 1). Of these sites, the assemblages at the "large cave" on the Kisami coast, west of Shimoda, provided a complete history of coseismic uplift. The assemblages occur continuously between 0.14 and 3.40 m amsl and consist of intertidal barnacles, bivalves, and worm tubes (Fig. 2). Based on the faunal compositions and $^{14}$C ages of the assemblages in this cave, Kitamura et al. (2015) identified four coseismic uplift events at 1256–950 BC (uplift 1), AD 1000–1270 (uplift 2), AD 1430–1660 (uplift 3), and AD 1506–1815 (uplift 4). Based on a mean inter-seismic subsidence rate of 0.6 mm/year and uplift of 0.1 m resulting from the AD 1974 Off-Izu Peninsula earthquake, the estimated amounts of vertical uplift during uplifts 1–4 are 1.67–2.97, 0.01–0.67, 0.72–1.04, and 0.76–0.94 m, respectively. Emergent sessile assemblages are incomplete at the other four sites, but Kitamura et al. (2015) detected no significant difference in total uplift across the five sites.

## Methods

Emerged benches and notches are observed from Shirahama to Koina (Taguchi 1993), and the $^{14}$C ages of emergent sessile assemblages have been reported from five sites between the Nabeta and Kisami coasts (Kitamura et al. 2014, 2015) (Fig. 1). Thus, we searched for emergent sessile assemblages along the coast between Shirahama and Nabeta and between Kisami and Koina. We also investigated uplifted Holocene landforms and sessile assemblages at Mikomotojima, a small (ca. 0.1 km$^2$) previously unstudied island located 10 km off the coast of Shimoda (Fig. 1).

We found emergent sessile assemblages at the previously unstudied Kujyuhama coast and Tarai Cape (Fig. 1) and determined their faunal compositions and $^{14}$C ages. Specimens were cleaned with a micro-knife, identified, and checked for secondary crystallization within shell cavities using a binocular microscope. We determined the $^{14}$C ages of two specimens by accelerator mass spectrometry (Beta Analytic, USA) (Table 1). Ages were calibrated to a calendar timescale using the program OxCal4.1 (Bronk Ramsey 2009), on the basis of IntCal13 data (Reimer et al. 2013) and after applying a local correction for the Shimoda area of $\Delta R = 109 \pm 60$ (Yoneda et al. 2000).

We combined new and previous data to reconstruct the deformation caused by coseismic uplift. We analyzed the geometry and deformation of the inferred source fault using the boundary element method with a Green's function in a homogeneous elastic half-space (Okada 1992). To model the source fault, we made assumptions: (1) the fault is a reverse fault with pure dip-slip movement, to account for the large coseismic uplift; (2) the upper edge of the fault is located along the cliff near the coast; and (3) the lower limit of the fault is at 10-km depth, which roughly corresponds to the lower limit of seismogenic layer in this region (Tanaka 2004).

## Results

Many individuals of the barnacle *Fistulobalanus albicostatus* and worm tubes were found within a crevice at 1.5 m amsl in Plio-Miocene tuffaceous breccia of the Shirahama Group at the Kujyuhama coast (Fig. 3). The $^{14}$C age of *F. albicostatus* shows AD 1135–1340 (2σ) (Fig. 2, Table 1). At Tarai Cape, many individuals of *F. albicostatus* and the bivalve *Hormomya mutabilis* occur

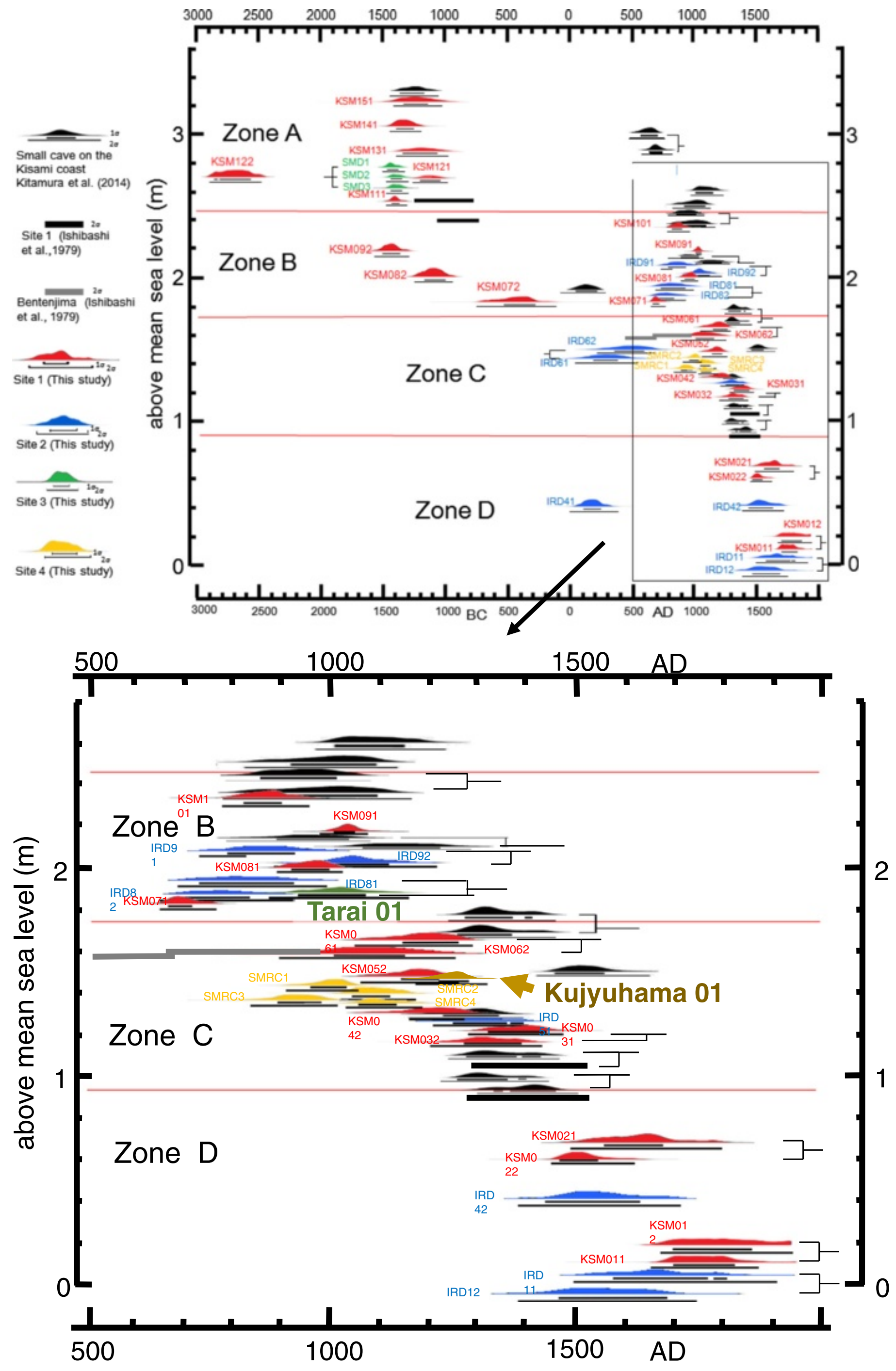

**Fig. 2** Elevation distributions and ages of emergent sessile assemblages at two sites of this study and five additional sites of Kitamura et al. (2015) in the southern Izu Peninsula

at 1.9 m amsl in the wall of a sea cave developed in Plio-Miocene tuffaceous breccia (Fig. 4). The cave is 22 m long, 4 m high, and 8 m wide. The $^{14}$C age of specimen shows AD 880–1165 (2σ) (Fig. 2, Table 1).

Taguchi (1993) reported barnacle fossils at 1.8–2.2 m amsl in the coastal area of Koina, located 1.2 km west of Tarai Cape (Fig. 1); however, we were unable to locate the fossils at this site. We did observe living sessile assemblages that included barnacles and oysters at the coast of Mikomotojima (Fig. 5), but we did not find uplifted Holocene morphologies or sessile assemblages in this area.

**Table 1** Results of $^{14}$C dating

| Sample no. | Site | Altitude (m above msl) | Materials | $\delta^{13}$C (‰) | Conventional $^{14}$C age (year BP) | Calibrated age (2σ) (calendar year) (95.4 %) | Calibrated age (2σ) (calendar year BP) (95.4 %) | Lab number (Beta) |
|---|---|---|---|---|---|---|---|---|
| 1 | Kujyuhama | 1.5 | *Fistulobalanus albicostatus* | +1.3 | 1250 ± 30 | AD 1135–1340 | 815–610 | 399105 |
| 2 | Tarai Cape | 1.9 | *Fistulobalanus albicostatus* | +1.6 | 1500 ± 30 | AD 880–1165 | 1070–785 | 399108 |

# Discussion

## Distribution of coseismic vertical displacement

Global sea level during the past 5000 years has remained within 0.25 m of the present-day level (Woodroff et al. 2012). This study assumes that sea level has been stable over the past 5000 years.

Both *F. albicostatus* and *H. mutabilis* inhabit in intertidal zone from −0.8 to 0.8 m amsl (Okutani 2000; Yamaguchi and Hisatsune 2006). Their fossils occur at 1.5 m amsl at the Kujyuhama coast and at 1.9 m amsl at Tarai Cape, indicating that 1.5 and 1.9 m of relative sea level fall has occurred at the Kujyuhama coast and Tarai Cape, respectively. Figure 2 compares our $^{14}$C data with

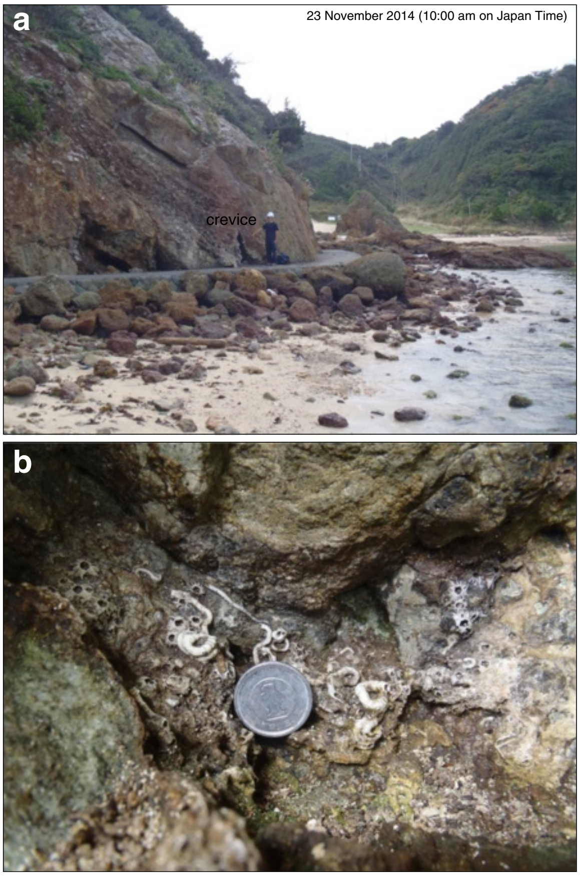

**Fig. 3** **a** Photograph of the crevice on the Kujyuhama coast. **b** The barnacle *Fistulobalanus albicostatus* and worm tubes

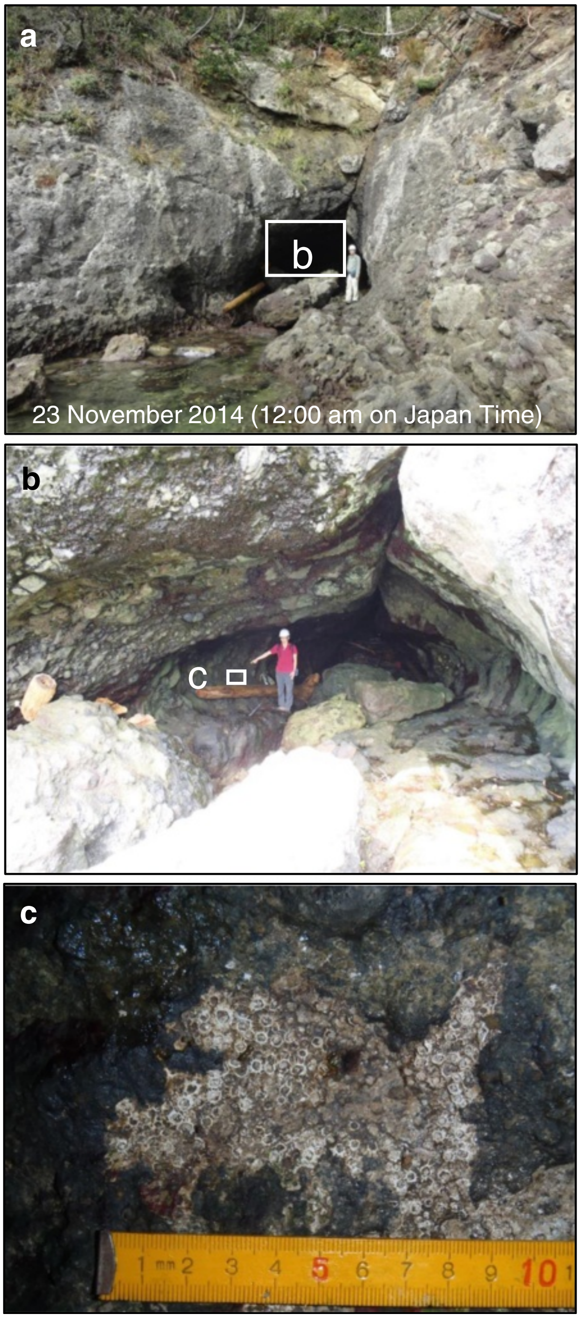

**Fig. 4** **a** Photograph of the coastal cave at Tarai Cape. **b** Close-up of the entrance of the cave. **c** The barnacle *Fistulobalanus albicostatus*

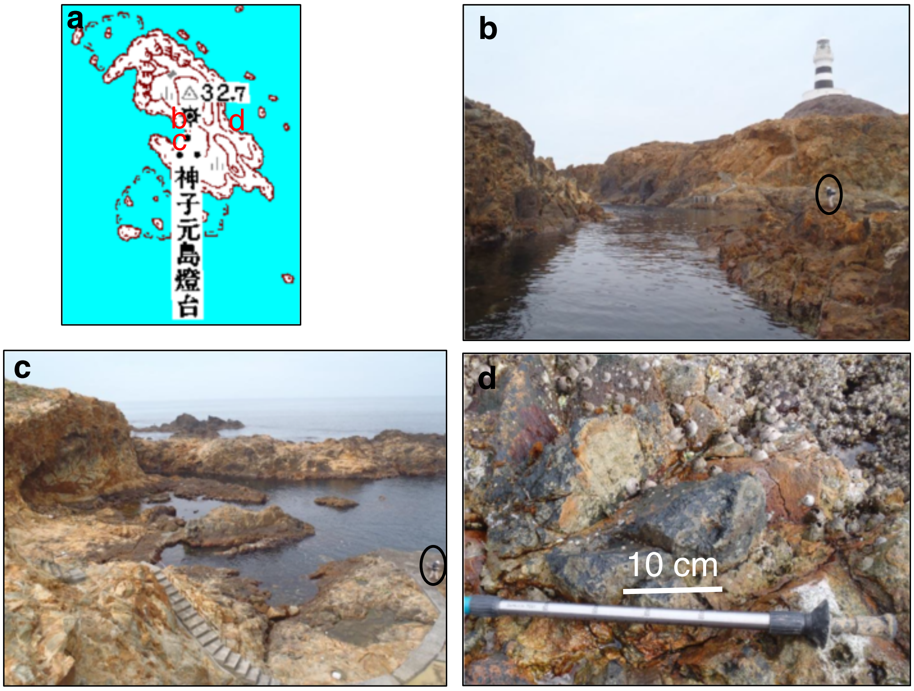

**Fig. 5** **a** Location of Mikomotojima on a 1:25,000 scale topographic map. **b** Photograph of the coastal area at site b. **c** Photograph of the coastal area at site c. **d** Living sessile assemblage at site d

those of Kitamura et al. (2015). The ages and elevations of the specimens at Tarai Cape and the Kujyuhama coast match those of zones B and C at Kisami, respectively. This indicates that their emergence was related to uplifts 2 and 3, respectively, and that there is no significant spatial difference in total uplift in the coastal area between Tarai Cape and Kujyuhama.

As noted above, barnacle individuals have been reported at 1.8–2.2 m amsl along the Koina coast (Fig. 1) (Taguchi 1993), and their elevation corresponds to that of zone B at Kisami. We therefore used the values of total coseismic uplift deduced from the large cave at Kisami to infer the total coseismic uplift in the coastal area between Koina and Kujyuhama.

At the large cave at Kisami, the highest emergent sessile assemblages, dated at 1256–950 BC, occur at 3.40 m amsl and consist of the barnacle *Tetraclitella chinensis*. Given that this species inhabits the intertidal zone from −0.8 to 0.8 m amsl (Yamaguchi and Hisatsune 2006), we estimate the total uplift at Kisami to be 2.6–4.2 m. The AD 1974 Off-Izu Peninsula earthquake on the Irozaki Fault caused 0.1 m of uplift in the study area (Danbara and Tsuchi 1975). Given that the rate of subsidence during the past 3000 years has been the same as that between 1896 and 1968 (0.6 mm/year; Danbara and Tsuchi 1975), the net uplift is calculated to be 4.3–6.1 m. In each of the four uplift events, the mean coseismic uplift is estimated to have been 1.1–1.5 m (Fig. 6).

Based on previous studies of the sedimentary facies in cored coastal plain deposits of the southeastern Izu Peninsula, reliable constraints on the age and amount of coseismic uplift were obtained at site 7 near Minami Izu (Fig. 1). Here, Kitamura et al. (2013) determined that the uppermost tidal deposits were deposited at 4530–4430 calendar year BP, at −0.7 m amsl. Using the above constraints, the mean coseismic uplift at site 7 is estimated to be 0.3–0.7 m (Fig. 6).

Taguchi (1993) reported that the elevations of emerged notches, which form in the intertidal zone (from −0.8 to 0.8 m amsl), are up to 3.0 m amsl at Shirahama. Given that the rate of subsidence during the past 3000 years has been the same as that between 1896 and 1968 (0 mm/year; Danbara and Tsuchi 1975), the net uplift is calculated to be 2.2–3.8 m. At Shirahama, the mean coseismic uplift is estimated to be 0.6–1.0 m (Fig. 6).

## Fault source model

As noted above, there is no significant spatial difference in total uplift in the coastal area between Tarai Cape and Kujyuhama, indicating that the fault is a west-dipping reverse fault and strikes NNE–SSW, parallel to the coastline of the Izu Peninsula. Since emerged coastal

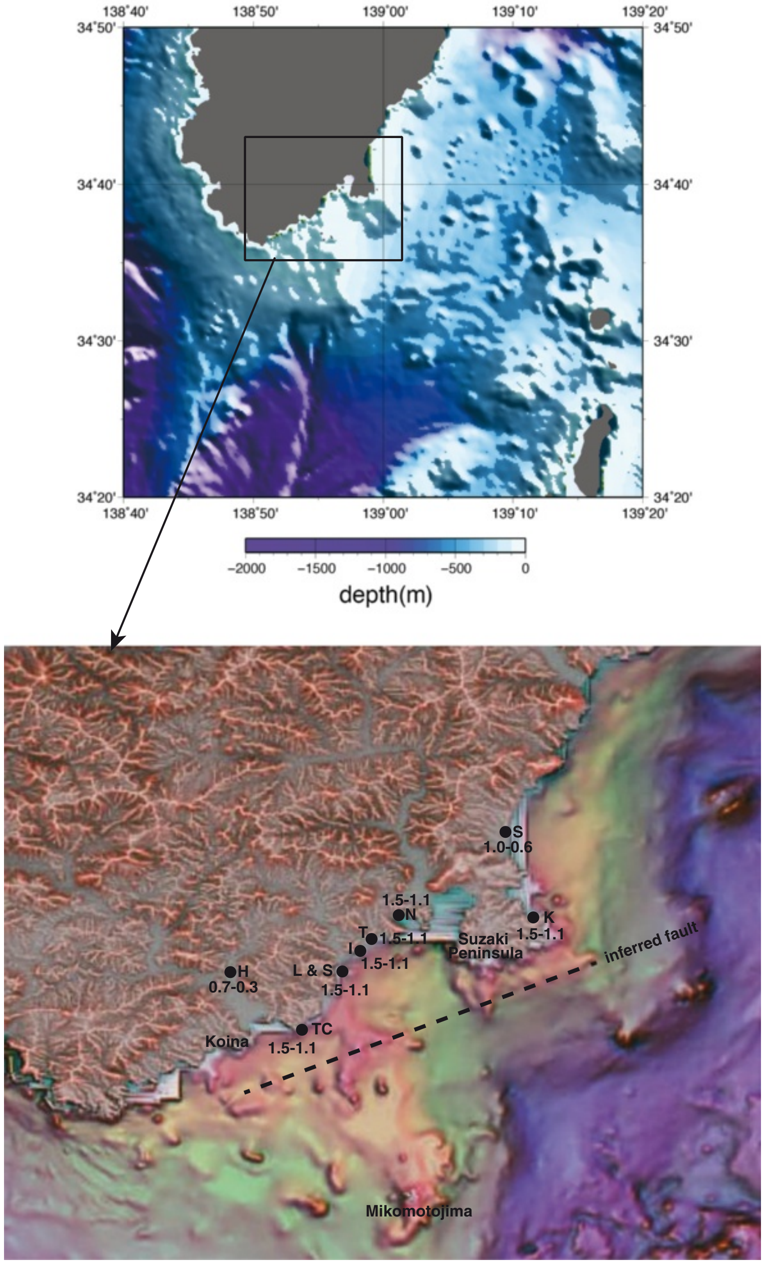

**Fig. 6** Distribution of inferred mean coseismic uplift and the offshore fault at the southern end of the Izu Peninsula. **a** Bathymetric map. **b** Red-relief image map off Shimoda area (Asia Air Survey, Japan). *Deep red* indicates steep slope and *light red* indicates flat surface (Chiba et al. 2008)

landforms are not observed west of Koina (Fig. 6), the western edge of the fault seems to be located off Koina.

We applied a characteristic earthquake model to reconstruct the source fault for the four uplift-inducing earthquakes. Kitamura et al. (2015) suggested that the most recent coseismic uplift event (uplift 4) was caused by a historical earthquake near the southern Izu Peninsula at 1200–1300 hours (local time) on 8 March 1729 (Usami 1975). This earthquake was recorded at Edo (present-day Tokyo), Nikko, Sunpu (present-day Shizuoka), Kyoto, and Nara (Fig. 7) (Usami 1975). This distribution of shaking closely matches that of intensity map for the AD 1974 Off-Izu Peninsula earthquake (M 6.9) (Murai and Kaneko 1974), meaning that the reverse fault located offshore of the southern Izu Peninsula has caused a Mw 7 equivalent earthquake.

Kanamori and Anderson (1975) proposed a typical stress drop value of 10 MPa for intraplate earthquakes.

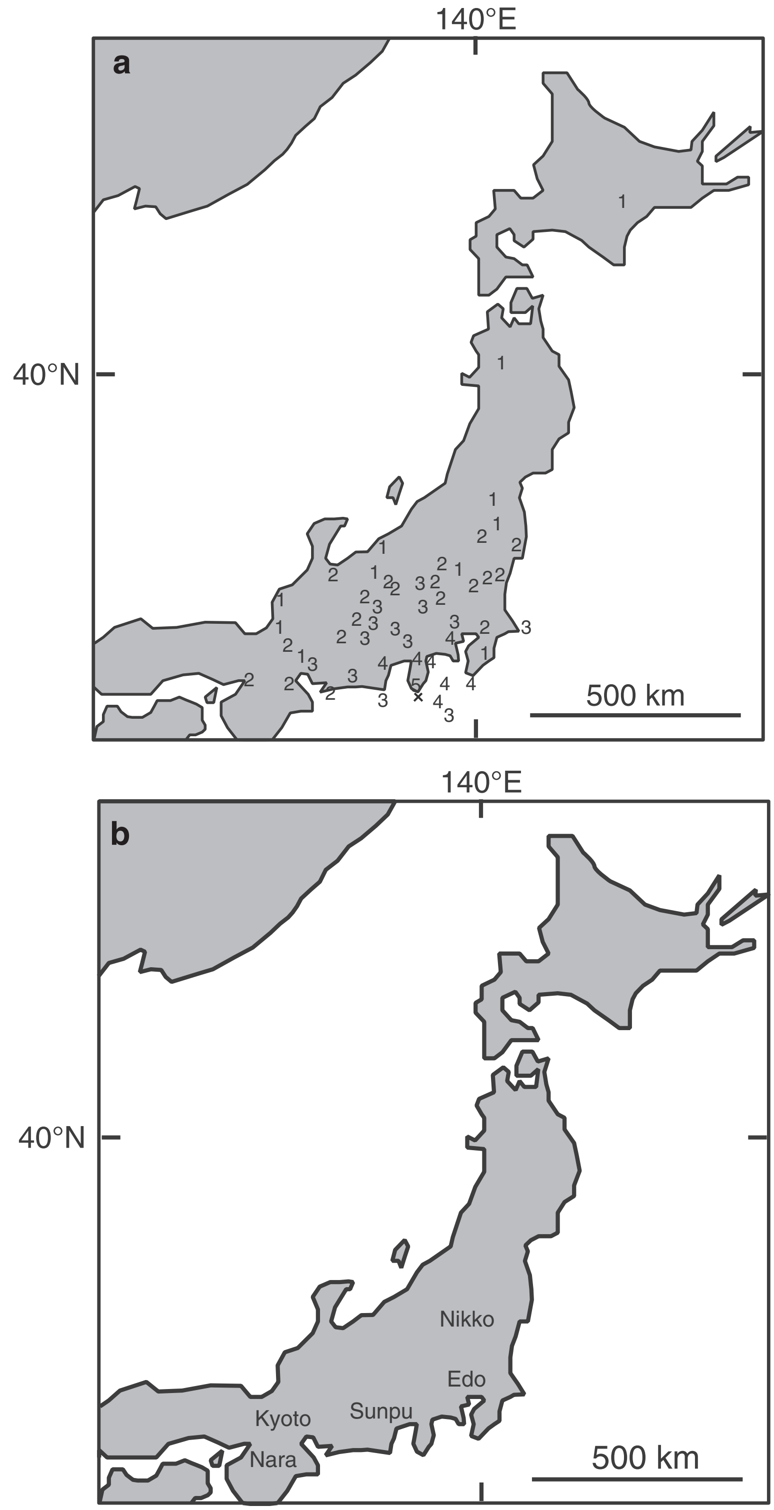

**Fig. 7** Seismic intensity distribution for two earthquakes that occurred around the southern Izu Peninsula. **a** The AD 1974 Off-Izu Peninsula earthquake (M 6.9). *Numerals* depict seismic intensities of the Japan Meteorological Agency scale. The symbol *X* denotes the epicenter. **b** The AD 1729 earthquake. *Location names* show where shaking was recorded in historical documents

Using this value and a scaling relation between stress drop and fault area (Kanamori and Anderson 1975), we estimate that the fault area of the targeted Mw 7 class earthquake was several hundred square kilometers.

Given these constraints on the fault, and the assumptions described in the methods, we constructed two models for estimating the average coseismic uplift. A submarine fault in model 1 is located 15 km off the coast of Shimoda, based on topographic analysis of the seabed inferred by Kim et al. (2012) (Fig. 1), and is located 5 km south of Mikomotojima. Although there is absence of emergent marine sessile assemblages and landforms at the island, the area is very erosional all around, so that emerged evidences might disappear. A submarine fault in model 2 is located at the base of a steep slope at 1 km off the Suzaki Peninsula (Fig. 6b).

First, we set a rectangular fault for model 1. The eastern corner of the top edge (0 km depth) is located at 34.6979° N, 139.1468° E, and the western corner is at 34.5336° N, 138.9415° E. The fault strike is about 226°. Figure 8a presents the results of a grid search performed by varying the dip angle and the slip amount of the fault. The best-fit case (i.e., that with the minimum sum of squared residuals) indicates a dip angle of 31° and a slip amount of 4.4 m. Based on our assumption that the lower limit of the fault occurs at 10-km depth, the fault width is calculated to be 19 km. The moment magnitude is 7.2 with a rigidity of 30 GPa. The stress drop estimated from the scaling relation (Kanamori and Anderson 1975) is about 13 MPa.

Second, we set another fault for model 2. The eastern corner of the top edge (0 km depth) is at 34.6882° N, 139.1364° E, and the western corner is at 34.6165° N, 138.8905° E. The fault strike is approximately 250°. Figure 8b shows the grid search result. The best-fit case is a dip angle of 52° and a slip amount of 2.7 m. The fault is 25 km long and 13 km wide. The moment magnitude is 6.9 with a rigidity of 30 GPa. The stress drop is approximately 11 MPa.

Then we reconstructed the coseismic vertical deformation at each observation point using the boundary element method with Green's function (Okada 1992). Figure 9 compares the observed vertical deformation with the calculated deformation from the best-fit cases. In both models (models 1 and 2), the maximum seafloor uplift around the top edge of the fault is below 1.9 m. This value is almost as large as the observed coseismic uplift at the coastal area. This fact implied that the tsunami height at the coastal area was small and explained that there is no document about tsunami associated with the 1729 earthquake.

When comparing two models, model 2 is more realistic than model 1 in the following respects: (1) the sum of squared residuals between the observed and calculated values for model 2 is far smaller than the sum of squared residuals for model 1 (see Fig. 8). (2) The vertical deformation at Mikomotojima (34.5754° N, 138.9416° E) for model 2 is nearly zero, but that for model 1 is over 1.8 m. The slight vertical deformation for model 2 may correspond to the absence of emergent marine sessile assemblages and landforms at Mikomotojima.

In contrast, the dip angle for model 2, 52° (>45°), seems peculiar as a reverse fault in terms of Anderson's theory. One can consider that the high-angle reverse fault was a reactivated one (Jackson 1980). Or we confirmed that the dip angle for model 2 can be <45° when the eastern corner of the top edge is near the coastline, although this setting leads to a smaller fault and higher stress drop deviating from the scaling relation.

## Conclusions

On the basis of the distribution and radiocarbon dating of emergent marine sessile assemblages, we determined that coseismic uplift occurred at 1256–950 BC, AD 1000–

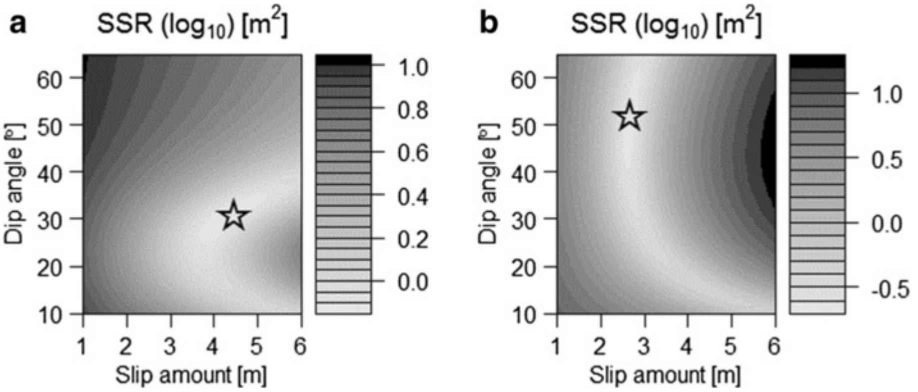

**Fig. 8** Sum of squared residuals between the observed and calculated values when varying the dip angle of the fault plane and amount of fault slip. **a** For model 1. The best-fit case (represented by the *star*) indicates a fault dip of 31° and a slip amount of 4.4 m. **b** For model 2. The best-fit case (represented by the *star*) indicates a fault dip of 52° and a slip amount of 2.7 m

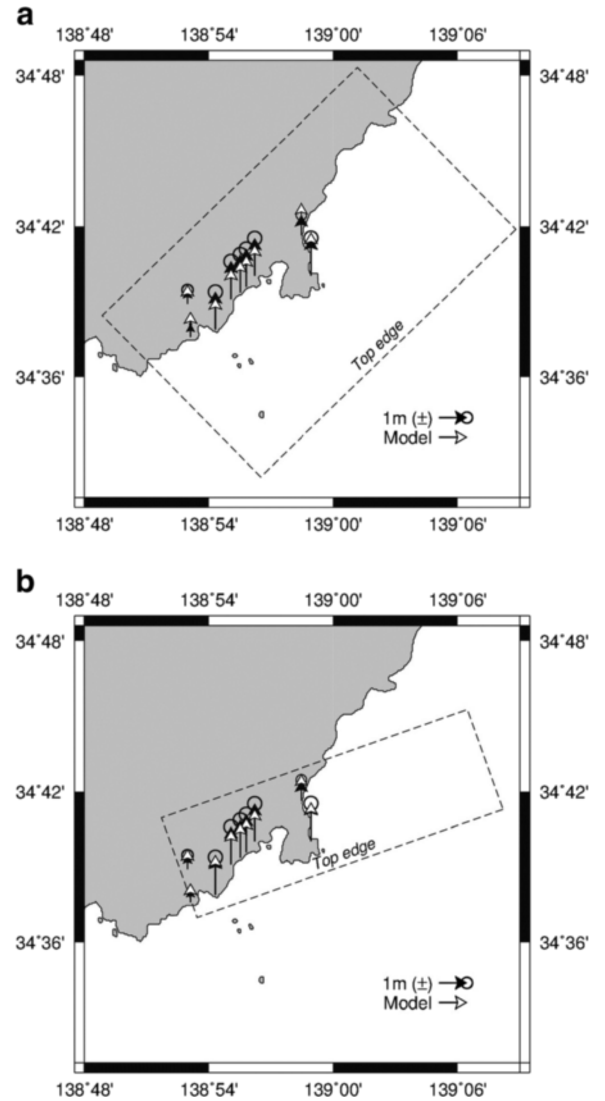

**Fig. 9** Comparison of the observed and calculated coseismic uplifts. The observed values are represented by the *black vectors*, and the calculated values in the best-fit cases are illustrated by the *white vectors*. **a** For model 1. **b** For model 2

1270, AD 1430–1660, and AD 1506–1815 in the southern Izu Peninsula, central Japan. We constructed source fault models from the spatial distribution of coseismic vertical displacement and from historical documents. The results indicate that a reverse fault (strike = 250°, dip = 52° to the north) is located about 3 km off the southern Izu Peninsula and is 25 km long and 13 km wide, records a total slip of 2.7 m, and has caused a Mw 7 class earthquake.

### Competing interests

The authors declare that they have no competing interests.

### Authors' contributions

AK, YM, and HYK participated in the design of this study and drafted the manuscript. AK and SK conducted the field work and identified fossils. All the authors have read and approved the final manuscript.

### Acknowledgements

We thank Takafumi Imai and Youki Takikawa for the help in field work. We also thank A. Stallard for improving the English of the manuscript. This study was funded by Grants-in-Aid (26287126) awarded by the Japan Society for Promotion of Science. This study was conducted under the permit from the Agency for Cultural Affairs, Kanto Regional Ministry of the Environment.

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Received: 2 September 2015 Accepted: 28 November 2015

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