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Holocene beach deposits for assessing coastal uplift of the northeastern Boso Peninsula, Pacific coast of Japan

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ABSTRACT

This paper presents a case study that assessed spatial variations in the tectonic uplift rates of beach deposits in the relict Kujukuri strand plain, situated on the northeastern coast of the Boso Peninsula, eastern Japan. The southern Boso Peninsula is tilted downward to the northeast due to plate subduction along the Sagami Trough. However, the cause of the northeastern coast uplift creating the relict strand plain is unclear, due to the absence of a Holocene raised marine terrace sequence. Elevations and ages of beach deposits were collected from drilled cores and ground-penetrating radar profiles along three shore-normal sections in the southern Kujukuri strand plain. From this, alongshore variations in the relative sea level since the mid-Holocene could be seen. These corresponded to north-to-northeast downward tilting at a rate of 0.4 m/ka for an interval 10 km and are concordant with the longer term tilting of the last interglacial marine terrace surrounding the plain. Although it is difficult to assess shore-normal variations of uplift based on the present dataset, the recognized tilting apparently continues to the tilting of the southern Boso Peninsula, implying the Sagami Trough probably affects the uplift of the Kujukuri coast.

Introduction

In tectonically active margins, past relative sea-level changes provide important information on tectonic activity. Coastal uplift/subsidence is an expression of crustal deformation and is often recorded as a relative sea-level fall/rise observed in sediments and landforms. The rate, frequency, and spatial distribution of the vertical motion of the coast have been regarded as criteria for tectonic activity (e.g., Chappell et al., 1996; Ota and Yamaguchi, 2004). Observed sea-level changes reflect both glacio-isostatic and tectonic components of vertical crustal movements as well as eustatic sea level. Thus, the accurate assessment of the tectonic component requires exclusion of glacio-isostatic component and eustatic sea level from the observed sea level (Nakada et al., 1991), which are more predictable than the spatially irregular tectonic component (e.g., Lambeck et al., 2004).

Several studies have numerically estimated these predictable components to extract the tectonic component (e.g., Sato et al., 2003, 2006). The predicted sea-level changes inherently have uncertainty, depending on the model used (e.g., Nakada et al., 1991; Lambeck et al., 2004). Thus, calibration of the model results needs to be practiced by referring observed sea-level history in a tectonically stable point where the mean sea level recorded by the last interglacial terrace is supposed to be several meters above the present sea level (e.g., Rohling et al., 2008). Such a locality is not easy to find in a tectonically active area. In this paper, we propose an effective method for assessing spatial variations in tectonic uplift/subsidence rate that can be applied to the coastal barrier and strand plain characterized by a sequence of beach ridges, showing a case study in a raised strand plain in the Boso Peninsula, central Japan.

The Boso Peninsula on the Pacific coast of central Japan is a tectonically uplifted region close to the convergent boundaries between the Philippine Sea, Okhotsk, and Pacific plates (Fig. 1A). This peninsula is tilted northeast downward, and the mid-Holocene marine terrace at its southern tip is over 25 m higher relative to the present sea level (Fig. 2; e.g., Nakata et al., 1980). The spatial distribution of the Holocene marine terraces is accountable by net uplift caused by two different types of historical great earthquakes that occurred in AD 1703 and AD 1923, both due to the subduction of the Philippine Sea plate below the Okhotsk plate along the Sagami Trough (Sugimura and Naruse, 1954, 1955; Matsuda et al., 1974, 1978; Shishikura, 2000, 2001; Shishikura and Miyauchi, 2001). Shishikura and Miyauchi (2001) suggested that the 1703- and 1923-type earthquakes have occurred 4 and 11 times since the mid-Holocene, respectively, based on coastal landforms and the sediment record of uplifts. Ota and Yamaguchi (2004) compared the Holocene and last interglacial marine terraces to assess the difference between short- and long-term rates of crustal deformation rates along the Pacific Rim, but not for the southern edge of

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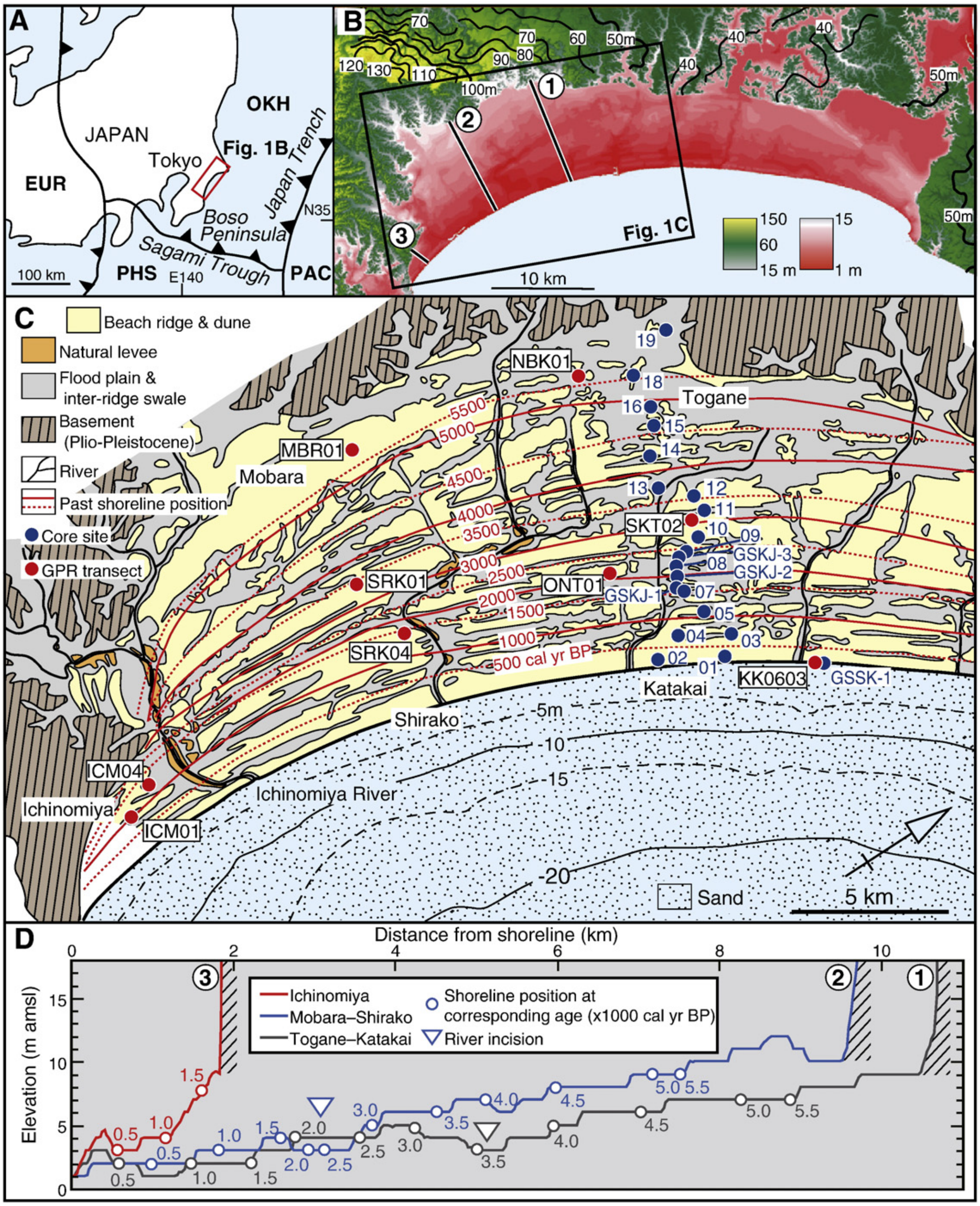

Figure 1. A: Location map of the Kujukuri strand plain. EUR, Eurasia plate; OKH, Okhotsk plate; PAC, Pacific plate; PHS, Philippine Sea plate. B: Digital elevation map of the Kujukuri strand plain and the surrounding area, based on the 50-m grid digital map of the Japanese Geographical Survey Institute. Contours show the elevation (m above mean sea level) of the marine terrace surface associated with Marine Isotope Stage 5e. C: Map showing the geomorphology of the Kujukuri strand plain (simplified from Moriwaki, 1979), the past shoreline positions at 500-yr intervals, and drill core (Masuda et al, 2001; Tamura et al., 2007) and GPR transect (Tamura et al., 2008) locations. All ages are expressed in cal yr BP. D: Elevation profiles in the Togane–Katakai, Mobara–Shirako, and Ichinomiya sections of the Kujukuri strand plain based on the digital elevation map. The locations of elevation profiles are shown in Fig. 1B.

the Boso Peninsula, where the last interglacial marine terrace is not preserved. The nearest marine terrace of MIS 5e is developed at the northeastern edge of the tilting zone, where the terrace lowers from +130 m to +30–40 m northeastward (Figs. 1B and 2; Kaizuka, 1987). The terrace surrounds the Kujukuri strand plain, in the central part of which there has been a 5-m relative sea-level fall since the mid-Holocene (Masuda et al., 2001).

The Kujukuri strand plain and its surrounding last interglacial marine terrace are located in the Kashima–Boso uplift zone (Kaizuka, 1974, 1987) with an inferred neighboring uplift axis trending NE–SW (Yachimata uplift in Fig. 2). This uplift zone shows a different trend from the southern Boso Peninsula, and contrasts with the subsidence of the Tokyo Bay to the west. Kaizuka (1974) proposed that the Kashima–Boso uplift is related to the subduction of the Japan Trench, over 200 km southeast from the coast (Fig. 1A). Shishikura (2001) compared the maximum mid-Holocene sea level to conclude that the uplift rate increases eastward in the northeastern Boso peninsula, which is consistent with the view of Kaizuka (1974). However, he pointed out that the Japan Trench is too far away to be a causal factor in the observed uplift. Uplift from faulting can also be rejected as there is no known effective fault in the area. Thus, the causes of the Kashima–Boso uplift zone still remain unclear.

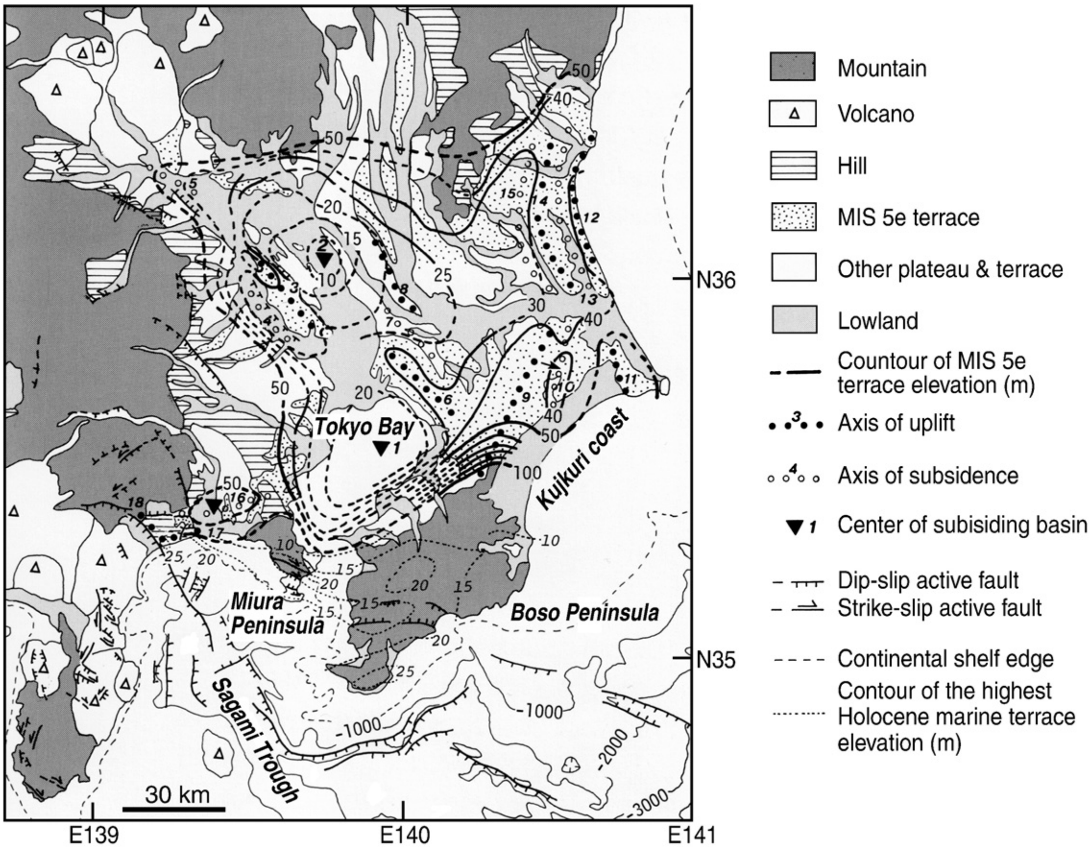

Figure 2. Late Quaternary vertical crust motion around the Tokyo Bay and Boso Peninsula (Kaizuka, 1987). 1, Tokyo Bay subsiding basin; 2, Koga subsiding basin; 3, Konosu–Hatogaya uplift; 4, Arakawa subsidence; 5, Takasaki–Kumagaya subsidence; 6, Narashino uplift; 7, Kashiwa subsidence; 8, Moriya–Toride uplift; 9, Yachimata uplift; 10, Kuriyamagawa subsidence; 11, Iioka uplift; 12, Kashima uplift; 13, Kitaura subsidence; 14, Namekata uplift; 15, East Kasumigaura subsidence; 16, Hadano–Yokohama subsidence; 17, Oiso uplift; 18, Sogayama uplift.

We assessed uplift patterns of the Kujukuri strand plain since the mid-Holocene based on the date and spatial distribution of Holocene beach deposits. Alongshore variations of the Holocene relative sea-level changes in the Kujukuri strand plain were investigated by compiling the radiocarbon ages and elevations of the beach deposits in published drill cores and ground-penetrating radar (GPR) profiles (Masuda et al., 2001; Tamura et al., 2003, 2008) and in newly collected GPR profiles. We consider the tectonic and glacio-isostatic components in detected alongshore variations of the relative sea level, and assess uplift rate and pattern in the northeastern Boso Peninsula.

Regional setting

The Kujukuri strand plain faces the northeastern Pacific coast of the Boso Peninsula, eastern Japan (Fig. 1A). This strand plain has a straight to slightly arcuate 60-km-long shoreline extending in a NE–SW direction, along which a sandy beach with multiple subtidal longshore bars has developed (Fig. 1C). The coast is microtidal, with a mean tide range of 107 cm; during the spring tide, high- and low-tide water levels are +70 cm and −100 cm, respectively, relative to mean sea level. The beach face is divided into foreshore and backshore, which generally dip seaward at angles of 1/10–1/50 and 1/50–1/100, respectively (Tamura et al., 2008).

The landward margin of the Kujukuri strand plain, which corresponds to the shoreline at 6 ka (Moriwaki, 1979), is defined by a plateau and hills (Fig. 1B). After 6000 cal yr BP, the shoreline prograded a maximum of 10 km to form an extensive strand plain composed of sediments supplied by erosion of the neighboring headlands (Sunamura and Horikawa, 1977; Uda, 1989). The landforms on the strand plain include beach ridge, sandy dune, inter-ridge swale, and flood plain (Moriwaki, 1979; Fig. 1C). Beach ridges are arranged parallel or subparallel to the shoreline. The elevation of the beach ridge generally descends seaward from ca. +10 m to +2–3 m. Comparison of strand plain profiles (Fig. 1D) indicates that the elevation of the strand plain surface generally rises southward.

The Kujukuri strand plain is surrounded by a raised marine terrace of Marine Isotope Stage (MIS) 5e age (Fig. 1C). The terrace surface varies its elevation in the alongshore direction from +50 m on the NE edge of the plain, to +30–40 m in its central part, and increasing southeastward to +130 m (Fig. 1B). Along a shore-normal cross section in the central Kujukuri strand plain, Masuda et al. (2001) recognized five downsteps of the foreshore facies and, therefore, five corresponding relative falls in sea level since 6000 cal yr BP (Figs. 3 and 4A). They recognized some of these falls to episodes of coastal uplift which are approximately synchronous to those detected in marine terraces of the southern Boso and Miura peninsulas (Nakata et al., 1980; Kumaki, 1985). The foreshore facies shows well-defined parallel lamination in core sections, which can be clearly distinguished from the trough cross-bedded shoreface facies (Fig. 3). Among these relative sea-level falls, Tamura et al. (2007) further obtained drill cores (GSKJ-1 to GSKJ-3; Fig. 1C) to focus those at 2300–2600 cal yr BP and 1800–2000 cal yr BP, and confirmed the stepped lowering of relative sea level. The total estimated relative sea-level fall since 5700 cal yr BP is 5.1 m in the central part of the strand plain (Masuda et al., 2001). This was supported by Tamura et al. (2008), who identified the boundary between the foreshore and upper shoreface facies in ground-penetrating radar profiles of beach ridges.

Methods

We compiled radiocarbon ages and distribution of the beach deposits in published drill cores (Masuda et al., 2001; Tamura et al.,

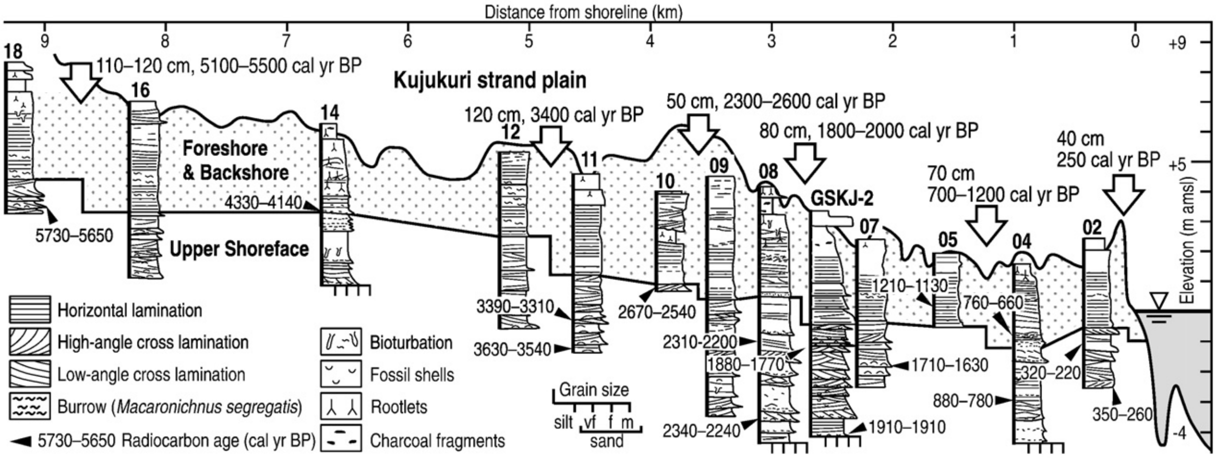

Figure 3. Shore-normal cross section of the subsurface beach deposits in the central strand plain (Togane–Katakai section). Simplified after Masuda et al. (2001) and Tamura et al. (2007). Core locations are shown in Fig. 1C.

2003; 2007) and ground-penetrating radar (GPR) profiles (Tamura et al., 2008), and also collected GPR profiles in order to detect the spatial variation in the relative sea-level changes in the Kujukuri strand plain. The relative sea-level changes were investigated in three shore-normal sections in the central, southern, and southernmost parts, which are referred to here as Togane–Katakai, Mobara–Shirako, and Ichinomiya sections, respectively (Fig. 1C). Newly collected GPR profiles from the Mobara–Shirako and Ichinomiya sections determined the relative sea level recorded in the beach deposits based on a criterion of Tamura et al. (2008). Chronology of the surveyed beach deposits relies on radiocarbon ages reported from the Togane–Katakai section (Figs. 1C and 3; Masuda et al., 2001; Tamura et al., 2007). The radiocarbon dates and orientation of beach ridges define the position of the past shoreline for every 500 yr (Fig. 1C). Depositional age of the surveyed beach deposits is then interpolated from ages of the nearest two past shorelines assuming a linear progradation rate in each interval. Radiocarbon dates of marine shells from cores 05, 07, and 18 were used. These dates were reported by Masuda et al. (2001) and were converted into calendar ages using the program CALIB rev. 4.0 (Stuiver and Reimer, 1993) with data set C and delta R set to zero. This procedure thus enabled detection of the alongshore variations of the relative sea-level changes in the strand plain without additional drilling cores and radiocarbon dates.

GPR profiles were collected along three transects (MBR01, SRK01, and SRK04) for the Mobara–Shirako section and two transects (ICM04 and ICM01) for the Ichinomiya section. We employed a PulseEkko 100 GPR system (Sensors & Software Inc., Ontario, Canada) with bistatic, unshielded 100-MHz antennae and a 1000-V transmitter. The 100-MHz antennae were arranged normal to the direction of travel with a separation of 1 m and a step size of 0.25 m. Transects were arranged normal to the beach ridges, which formed parallel to past shorelines. We processed the GPR data with Reflexw software (Sandmeier Scientific Software, Karlsruhe, Germany). Data processing included dewow filtering, zero-time correction, bandpass filtering, gain control, time–depth conversion, and static correction. We calculated the radar wave velocity from common-mid-point surveys and used it for time–depth conversion. The calculated velocity was consistently ca. 0.06 m/ns, leading to an electromagnetic wavelength of ca. 60 cm and an estimated vertical radar resolution of ca. 15 cm, 1/4 of the wavelength (Reynolds, 1997).

Results and interpretation

We recognized two distinct facies units in the GPR profiles (Fig. 5). The ca. 1-m-thick surface layer was possibly modified during road construction and thus is not considered here. The radar facies defined in the profiles are equivalent to the foreshore and backshore facies and the underlying upper shoreface facies recognized in drill cores from the Togane–Katakai section (Fig. 3). Masuda et al. (2001) distinguished the foreshore facies from the overlying backshore in drill cores basically based on the continuity of parallel lamination. However, we combine these two facies as the distinction is not evident in the GPR profiles, and the boundary between the foreshore and upper shoreface is focused for the purpose of sea-level reconstruction.

The foreshore and backshore radar facies is characterized by a sequence of continuous and well-defined reflections dipping seaward at an angle of 1/10 to 1/100, gradients consistent with those of the modern foreshore and backshore. The sequence thus reveals the progradation of the flat beach face, which is also confirmed in the GPR profile of the modern beach (Tamura et al., 2008). A similar pattern is commonly reported for other prograding beach deposits (Jol et al., 1996; Smith et al., 1999; Bristow and Pucillo, 2006; Rodriguez and Meyer, 2006). The continuous reflections terminate at the boundary with the underlying shoreface unit; this boundary is not marked by a reflection but is revealed by the discontinuity of the reflections. The foreshore and backshore facies is 2–3 m thick, which is comparable to the thickness range of the modern foreshore and backshore (Tamura et al., 2008).

The shoreface radar facies is distinguished from the foreshore and backshore facies by the absence or lower abundance of continuous reflections. Sedimentation in the upper shoreface, which is immediately seaward of the beach face, is typically characterized by longshore bars and troughs and by dune migration (Clifton, 2006); thus, its strata are more likely to be complicated and laterally discontinuous than those of the foreshore and backshore facies.

The GPR profiles contain some hyperbolic reflections (e.g., those centered on 0 m, 50 m, and 95 m in profile MBR01; Fig. 5A). These reflections occur because we used an unshielded antenna, which thus inevitably received signals from nearby structures. The responsible structures were carefully checked in the field after we had processed the GPR profiles. Reflections of buried pipes (e.g., at 10 m along profile MBR01) and manholes (e.g., at 35–40 m along profile ICM04; Fig. 5B) also disturb the GPR profiles.

The elevations of the boundary between the foreshore and backshore facies and the shoreface facies in the GPR profiles and the estimated depositional ages are summarized in Table 1. In the Mobara–Shirako section, the elevation of the boundary lowers seaward, and the depositional age becomes younger. As for the Ichinomiya section, which is narrower, the difference between ICM04 and ICM01 is small or negligible both in the depositional age and elevation of the foreshore base.

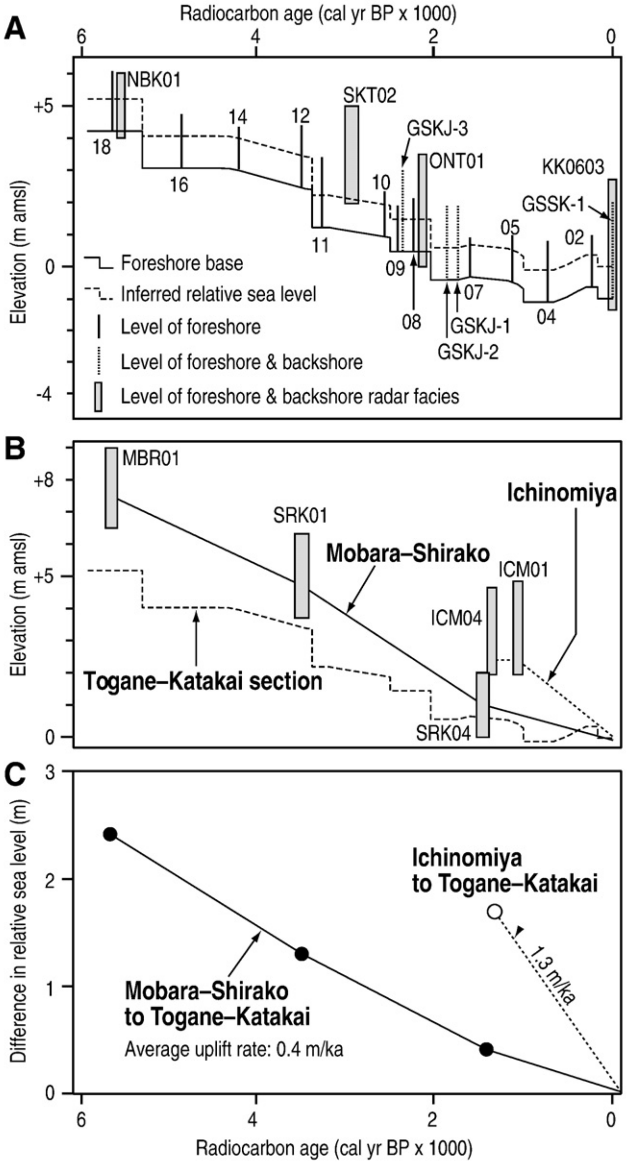

Figure 4. A: Temporal changes in the base of the foreshore facies along the Togane–Katakai section based on drill core data (Masuda et al., 2001; Tamura et al., 2007) and GPR profiles (Tamura et al., 2008). B: Relative sea-level curves for the Togane–Shirako and Ichinomiya sections in relation to that for the Togane–Katakai section, as determined from GPR profiles. C: Differences in relative sea level among the three sections and calculated rates of relative uplift.

Discussion

We reconstructed relative sea-level fluctuations in the Mobara–Shirako and Ichinomiya sections of the Kujukuri strand plain (Fig. 4B) on the basis of distribution and ages of beach deposits (Table 1). The boundary between the foreshore and backshore facies and the shoreface facies is known to occur at the low-tide level during the spring tide, 1 m below the mean sea level (Tamura et al., 2008) in the Kujukuri coast. This criterion was also confirmed in the modern beach on the sea of Kattegat by Nielsen and Clemmensen (2009). The level 1 m above the facies boundary in the GPR profiles thus corresponds to the mean sea level at the time of deposition. The sea-level curve drawn for the Mobara–Shirako section by using profiles MBR01, SRK01, and SRK04 suggests that the relative sea level has lowered 7.5 m since 5700 cal yr BP, 2.4 m more than the lowering in the Togane–Katakai section (Fig. 4B). In the Ichinomiya section, we recognized a relative sea-level fall of 2.3 m since 1300 cal yr BP, which is 1.7 m and 1.3 m more than the fall in the Togane–Katakai and Mobara–Shirako sections, respectively.

The detected spatial variations of the relative sea-level history cannot be attributed to glacio-isostasy, as this is thought to be negligible in this area in the mid- to late Holocene as shown by Nakada et al. (1991), who provided several results of relative sea level at 6 ka using different ice and viscosity models. Alongshore variation is also not the result of differing offshore coastal platform topography, as all results showed isobaths parallel to the Kujukuri coast. Thus, the longshore variation recognized here is considered mainly due to the tectonic component. The differences in relative sea level in the Mobara–Shirako and Ichinomiya sections relative to the Togane–Katakai section are plotted in Fig. 4C. The difference between the Mobara–Shirako and Togane–Katakai sections decreases over time from 2.4 m at 5700 cal yr BP, to 1.3 m at 3500 cal yr BP, to 0.4 m at 1400 cal yr BP, and finally to the present 0 m. This trend suggests that the Mobara–Shirako section has been uplifted relative to the Togane–Katakai section since the mid-Holocene. The slope of the line connecting data points in Fig. 4C gives the rate of relative uplift during each time interval, which gradually decreased toward the present. However, because the sea-level fall in the Togane–Katakai section was episodic (Masuda et al., 2001) the estimate strongly depends on the time points used in the comparison, and is sensitive to the uncertainty due to the radar resolution of ca. 15 cm. Thus, in the present data set, only the average value since 5700 cal yr BP, 0.4 m/ka, reasonably describes the rate of relative uplift between the Togane–Katakai and Mobara–Shirako sections.

Spatial variation in the beach deposit elevation suggest non-linear tilting of the Kujukuri strand plain. The Ichinomiya section reveals an uplift rate of 1.3 m/ka relative to the Togane–Katakai section and 1.0 m/ka to the Mobara–Shirako section since 1300 cal yr BP (Figs. 4C and 6B). The trend implies north-to-northeast downward tilting, and that its spatial gradient is not linear: the rate between the Ichinomiya and Mobara–Shirako is three times larger than that between the Mobara–Shirako and Togane–Katakai even though both intervals between these sections are 10 km. The Ichinomiya River divides the narrow Ichinomiya section from the main body of the strand plain (Fig. 1C), across which the strand plain surface, despite the continuity of beach ridge and inter-ridge swale, rises abruptly southward (Fig. 1B, D). This, in addition to the nonlinear increase in uplift rate, implies that the Ichinomiya River follows a tectonic line that separates a rapidly uplifting block, which includes the Ichinomiya section, from the rest of the plain.

The inferred north-to-northeast downward tilting of the Kujukuri strand plain apparently follows the overall trend of the Boso Peninsula. Shishikura (2001), based on the maximum relative sea level recorded at the mid-Holocene, estimated spatial trends of uplift rate and concluded that the uplift rate increased seaward in the northeastern Boso Peninsula (Fig. 6A). This view is consistent with Kaizuka's (1974, 1987) that the area forms an NE–SW extending zone, which has been uplifted relative to the Tokyo Bay, and shows a different trend from the southern Boso Peninsula, which is tilted north-to-northeast downward. The estimation of Shishikura (2001), however, does not reflect late Holocene relative sea-level records from nearshore of the Kujukuri coast, and depends on extrapolation of data from lowlands at Ohara and Onjuku which are located to the south (Fig. 6A). These lowlands are close to the Ichinomiya section, which is possibly separated by a tectonic line outlined by the Ichinomiya River from the main body of the strand plain (Fig. 6B). Thus data from these lowlands should not be extrapolated to define a contour for the Kujukuri strand plain.

Unfortunately, further consideration of the younger sea-level records from nearshore and comparison with older landward sea-level records are needed in order to assess the shore-normal variations of uplift. These would also need a precise determination of a time-series of the glacio-isostatic component of sea level. It is thus

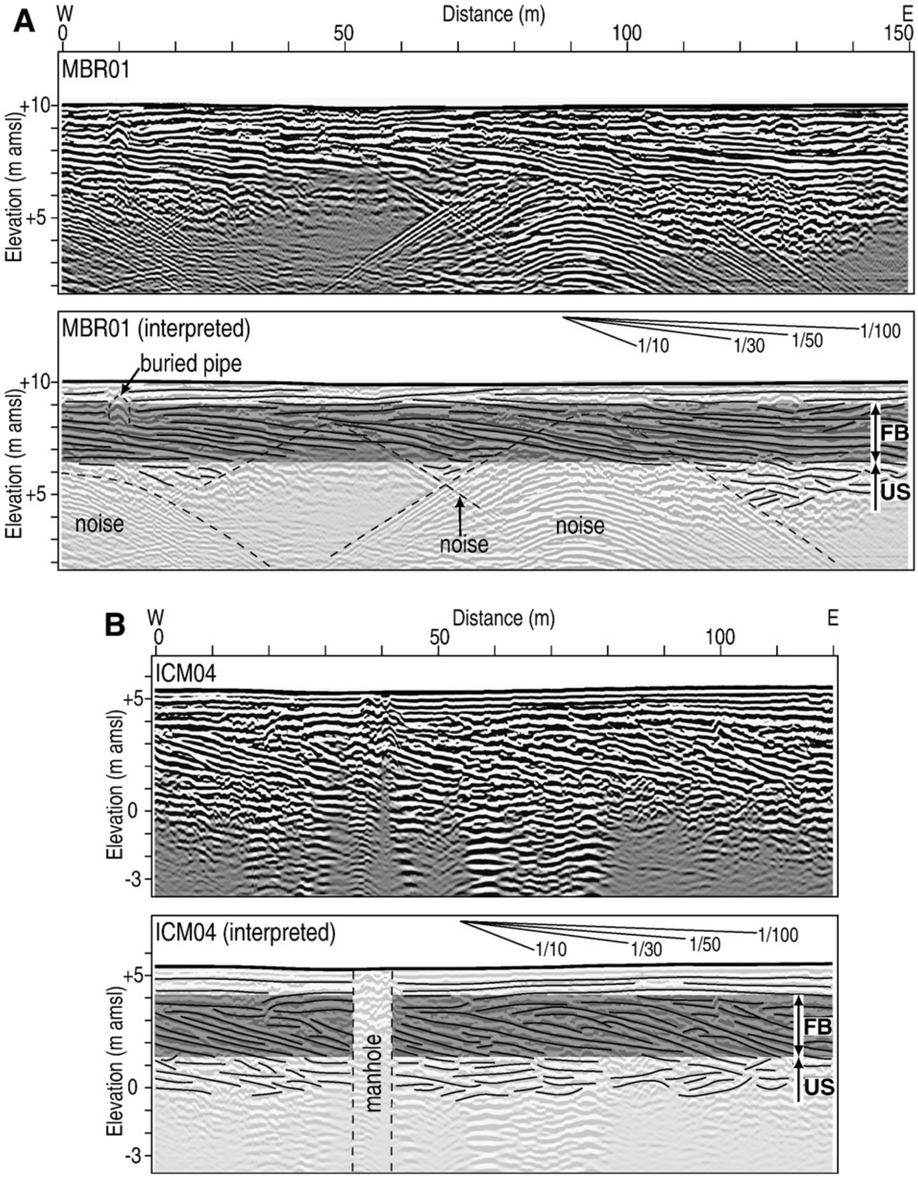

Figure 5. Ground-penetrating radar profiles and line drawings along transects (A) MBR01 and (B) ICM04. These transects were established normal to the past shorelines. The sea is to the right. FB, foreshore and backshore facies; US, upper shoreface facies. Transect locations are shown in Fig. 1C.

not possible at the present to deny that the uplift rate increases offshore as Shishikura (2001) suggested. However, the obvious alongshore gradient of the uplift rate suggests a possibility that the southern part of the Kujukuri strand plain is a continuum of the southern Boso Peninsula, which has been tilted northeast downward due to the subduction of the Sagami Trough (Fig. 6B).

Table 1

Summary of the results of the GPR survey and comparison with reference cores along the Togane–Katakai section. amsl, above mean sea level.

GPR Transect	Foreshore base elevation (m amsl)	Relative sea level (m amsl)	Reference core in Togane–Katakai	Foreshore base elevation in reference core (m amsl)	Relative sea level in Togane–Katakai (m amsl)	Difference in relative sea level (m)	Conventional ^{14}C age (yr BP)	Radiocarbon age (1 σ) (cal yr BP)	Laboratory code
MBR01	+6.5	+7.5	18	+4.1	+5.1	2.4	5340±40	5730-5650	JNC-1630
SRK01	+3.7	+4.7	12	+2.4	+3.4	1.3		3500 (interpolated)	
SRK04	0	+1	Interpolation (07, 05)	−0.4	+0.6	0.4		1400	
			07	−0.3	+0.7		2100±30	1710-1630	JNC-1620
			05	−0.5	+0.5		1600±40	1210-1130	JNC-1072
ICM01	+1.3	+2.3	05	−0.5	+0.5	1.8	1600±40	1210-1130	JNC-1072
ICM04	+1.3	+2.3	Interpolation (07, 05)	−0.4	+0.6	1.7		1300	
			07	−0.3	+0.7		2100±30	1710-1630	JNC-1620
			05	−0.5	+0.5		1600±40	1210-1130	JNC-1072

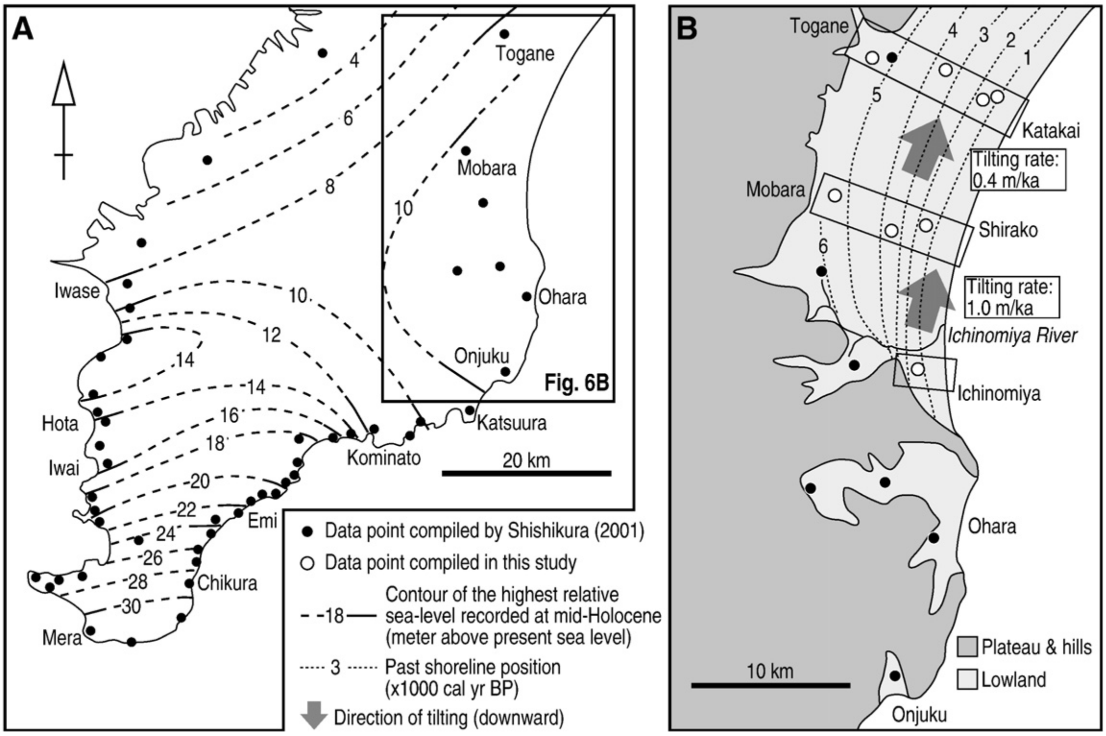

Figure 6. A: Trends of vertical crustal motion revealed by the maximum mid-Holocene relative sea level recorded in coastal sediment and marine terrace of the Boso Peninsula (Shishikura, 2001). B: Distribution of data points for the relative sea-level reconstruction compiled in this study, and spatial trend of the tilting in the Kujukuri strand plain.

Geodetic data obtained for a historical earthquake also suggest that the uplift of the Kujukuri coast is related to the Sagami Trough. Two earthquakes that greatly affected the Boso Peninsula occurred in AD 1703 and AD 1923 due to the subduction of the Philippine Sea plate below the Okhotsk plate along the Sagami Trough. These earthquakes resulted in different uplift patterns: the 1703-type has a longer recurrence interval and larger magnitude. Shishikura and Miyauchi (2001) suggested that 4 and 11 times of the 1703- and 1923-type uplifts roughly account for the spatial distribution of the Holocene marine terraces of the Boso Peninsula. Although the influence of the 1703 earthquake is unclear, it is known that the 1923 earthquake caused coseismic uplift 0.2 and 0.15 m at Ichinomiya and Mobara, respectively (Land Survey Department, 1926). Thus even the accumulation of 1923-type uplifts since the mid-Holocene may result in a visible amount of uplift. Masuda et al. (2001) pointed out that the 1703 earthquake might be responsible for the most recent relative sea-level fall recognized nearby the shoreline in the Togane–Katakai section. They also recognized sea-level falls at 5100–5500 cal yr BP and 3400 cal yr BP (Fig. 3) that occurred around the time of uplifts revealed by the marine terrace in the southern Boso and Miura peninsula (Nakata et al., 1980; Kumaki, 1985), which are directly affected by the subduction of the Sagami Trough (Fig. 2). These facts suggest that the Sagami Trough at least partly affects the uplift of the Kujukuri coast.

The rate of the Holocene tilting between the Togane–Katakai and Mobara–Shirako sections is comparable to that estimated from the MIS 5e marine terrace. By assuming that the relative uplift rate of the Mobara–Shirako section has been sustained over the last 125 ka, the cumulative uplift can be estimated as ca. 50 m. This value is concordant with the elevation difference of the last interglacial marine terrace surface, + 70–80 m and + 120–130 m above present sea level near the Togane–Shirako and Mobara–Katakai sections, respectively (Fig. 1B), suggesting the consistent rate of north-to-northeast downward tilting of this region. To the west, the last interglacial marine terrace inclines northwestward, continuing to the subsiding basin of the Tokyo Bay (Fig. 2). However, the eastern edge of the MIS 5e terrace and southern Kujukuri strand plain seemingly form a tilting zone that continues to the Boso Peninsula, of which tilting rate since the mid-Holocene is not much different from that over the last 125 ka.

The results obtained here suggest that beach deposits in the strand plain provide important information on the vertical tectonic displacement and its spatial variation. In the prograding strand plain, beach deposits become younger seaward, and the reconstruction of the relative sea-level history is inevitably practiced along a shore-normal transect. Comparison between the younger seaward site and older landward site needs an accurate extraction of the tectonic component from the relative sea level. Thus, the basic approach of this study is useful to for detecting the alongshore variations of the tectonic uplift/subsidence, while there is a restriction in its application to the shore-normal variations.

Conclusions

We confirm the tilting of the Kujukuri strand plain, which has been periodically uplifted on the northeastern coast of the Boso Peninsula, by comparing the relative sea-level histories recorded in beach deposits along three shore-normal transects. Elevations and dates of the beach deposits reveal that the total fall of the relative sea level since the mid-Holocene highstand increases southwestward. The alongshore variations of the relative sea level is mostly due to differing rate of tectonic uplift. The trend thus suggests that a north-to-northeast downward tilting has occurred in the strand plain with a rate equivalent to that inferred from the tilting MIS 5e marine terrace surrounding the plain. The tilting of the strand plain continues to the tilting of the southern Boso Peninsula, which is driven by great earthquakes related to the subduction of the Philippine Sea plate along the Sagami Trough. Although the northeastern coast of the Boso Peninsula was previously thought to be affected mainly by the Japan Trench over 200 km offshore, our results suggest that at least a part of uplifts of the area has been related to the activity of the Sagami Trough. The approach used in this study is useful for detecting alongshore variations of the relative sea-level history of barriers and strand plains, and it is effective for assessing tectonic displacement of these area when combined with appropriate consideration of glacio-isostaticy.

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