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Reconstruction of Holocene relative sea-level change and residual uplift in the Lake Inba area, Japan

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ABSTRACT

We collected and analyzed fossil diatoms and volcanic ash and determined ^{14}C ages in core samples from the lowlands around Lake Inba in the eastern Kanto Plain, central Japan, an area where late Quaternary sea-level change, fluvial erosion, and tectonic uplift have affected a region of archeological interest. We inferred Holocene paleoenvironmental changes and relative sea levels on the basis of indicators, such as high tide levels, derived from fossil diatom assemblages as well as the stratigraphic positions of ^{14}C-dated samples and the K–Ah tephra. Our results lead to estimates of the upper half tidal range during 6800–7000 cal yr BP of 1.7 m. The Holocene highstand took place at approximately 6400–6500 cal yr BP, and mean sea level reached an elevation of 1.9 m. However, the timing of this sea-level rise is earlier in the Lake Inba area than documented in previous studies, and it is suggested that the timing of the Holocene highstand may appear at least 1000 years earlier as a result of Holocene residual uplift. After this, sea-level fell abruptly around 4000 cal yr BP. We also recognized a sea-level fall corresponding to the Yayoi regression at about 2600 cal yr BP, during which the mean relative sea level may have been as low as −2.5 m after compensating for uplift, subsidence or geomorphologic effects in this area.

1. Introduction

Research on paleo sea-level changes due to glacial isostatic adjustment from the last glacial period to the Holocene has been carried out around the world (Woodroffe and Horton, 2005; Yokoyama and Esat, 2011; Lambeck et al., 2014). An important aspect of paleo sea-level change is whether the study site has a near-field, intermediate-field or far-field location with respect to glacial ice sheets. Relative sea level (RSL) change in the far field has been studied through coastal deposits or coral geochemistry (Yokoyama and Esat, 2011), because the effects of glacial isostasy can be ignored in the far field, leaving eustatic, local tectonic, and hydro-isostatic sea-level changes to be accounted for (Nakada et al., 1998; Sato et al., 2001; Yokoyama and Esat, 2011; Okuno et al., 2014).

In Japan, which is located both in the far field and along subduction zones, researchers have been faced with the separation of tectonics and eustasy in making comparisons between relative and predicted sea-level change, as constrained by analyses of coastal sediment (Fig. 1a) (Sato et al., 2001; Tanabe et al., 2010; Yokoyama et al., 2012). In pursuing this question, there are areas of Japan where RSL records are not yet accurately known. For example, the Kanto Plain area has a complicated tectonic setting at the triple junction of the Eurasian, Pacific, and Philippine Sea plates (Fig. 1a) (e.g. Shishikura, 2003). Actively uplifting geologic structures are recognized here (Kaizuka, 1974; Sugiyama et al., 1997), although the cause of their uplift is not known in detail.

Evidence of Holocene sea-level change is abundant in the eastern Kanto Plain. Masubuchi and Sugihara (2010) reconstructed changes of paleo sea-level and the paleoshoreline during the Holocene transgression and estimated a maximum sea-level elevation of 2.54 m from fossil diatom analysis in the Kinosaki area (Fig. 1b). The Editorial Committee of History in Noda-shi (2010) reported that the maximum sea level was higher than 2.0 m in Sekiyado on the basis of fossil diatoms (Fig. 1b). These sea-level changes are consistent with a sea-level maximum of 3.`0 m based on evidence from multiple sea-level proxies at Nagareyama in the central Kanto Plain (Fig. 1b) (Endo et al., 1982, 1983, 1989, 2013; Tanabe et al., 2008). In the Takagami lowland, in the lowest reach of the Tone River, Ota et al. (1985) and Kashima (1985) suggested that the maximum sea level was higher than 4.0 m from diatom assemblages. In the Kujukuri area, Masuda et al. (2001) used sediment analysis to suggest that the maximum sea-level was 4.0–6.0 m. In sum, the inferred maximum sea levels are higher in the eastern Kanto Plain than in the area to its west (Fig. 1b).

The geological evidence of the sea-level maximum known as the Holocene highstand (HHS) are recognized such that the southern part

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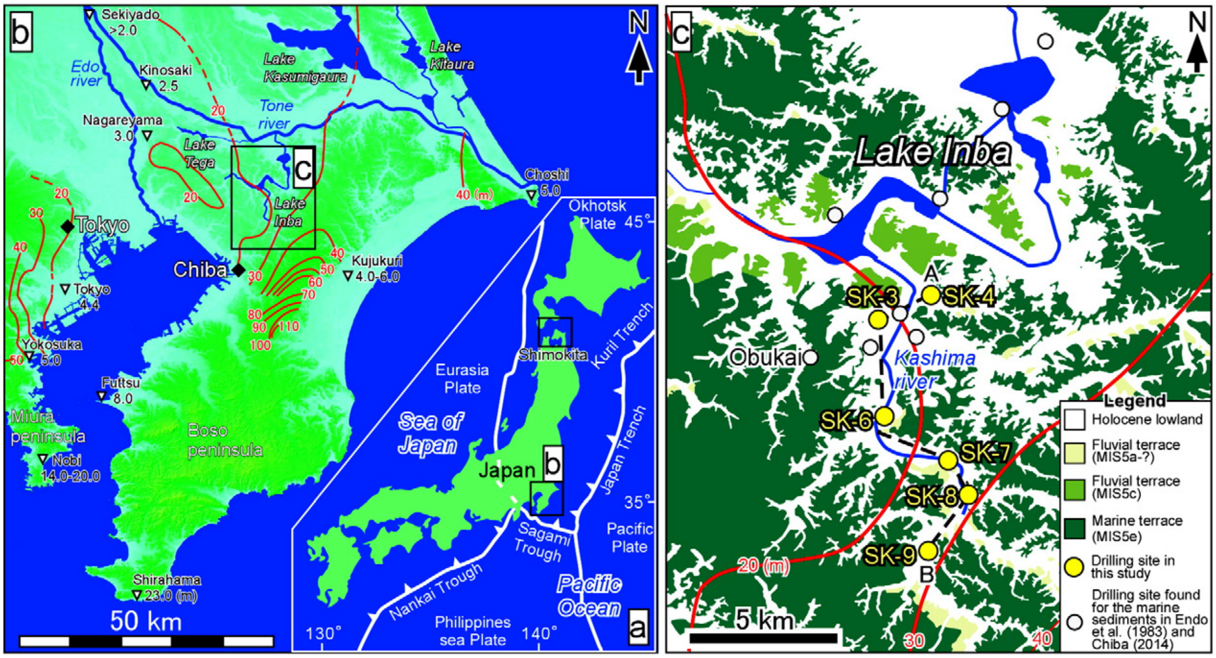

Fig. 1. Maps showing (a) location of the study area in Japan, (b) the Kanto Plain, and (c) drilling sites and geographic setting of the study area (modified from Sugihara, 1970; Sugihara et al., 2011). Sea levels during the Holocene highstand are shown for Tokyo (Matsushima, 1988), Sekiyado (Editorial Committee of the History in Noda-shi, 2010), Kinosaki (Masubuchi and Sugihara, 2010), Nagareyama (Endo et al., 1989, 2013; Tanabe et al., 2008), Choshi (Ota et al., 1985), Kujukuri (Masuda et al., 2001), Futtsu (Kayane, 1991), and Yokosuka (Matsushima, 1996) in (b). Marine terraces formed in the Holocene highstand for Shirahama (Nakata et al., 1980) and Nobi (Kumaki, 1999) are shown in (b). Maps b and c also show contours representing the height of marine terraces formed during MIS5e (Koike and Machida, 2001).

is higher in distribution of the elevation than the northern part of Kanto (Fig. 1b), and tectonic activity clearly differs between the northern and southern parts of the Kanto Plain, an effect of variations in the plate subduction regime. Data for Tokyo Bay indicate HHS sea levels of 4.4 m (Matsushima, 1988). The sea-level maximum was around 8.0 m in the Futtsu area in southern Chiba Prefecture (Kayane, 1991), 14–20 m in Nobi on the Miura Peninsula (Kumaki, 1985, 1999), and about 23 m as indicated by marine terraces at Shirahama at the southern tip of the Boso Peninsula (Nakata et al., 1980). The topography of the southern Kanto Plain is also strongly influenced by Quaternary tectonics and seismicity (Sugimura and Naruse, 1954; Yonekura et al., 1968; Matsuda et al., 1978; Nakata et al., 1980; Kaizuka, 1987; Horiguchi, 1997; Kumaki, 1999; Shishikura, 2003; Takahashi, 2006; Shimazaki et al., 2011). On the other hand, the distribution of marine and fluvial terraces at 20–30 m elevation, dating from marine isotope stages MIS5a–e, attests to gradual uplift during late Pleistocene and Holocene time in the lower reach of the Tone River including the Lake Inba area in central Japan (Fig. 1b,c) (e.g. Sugihara, 1970; Machida, 1973; Kaizuka, 1987). From the elevation of the MIS5e marine terrace, the vertical uplift rate is estimated to be about 0.1–0.3 mm/yr during the late Pleistocene (Kaizuka et al., 2000).

The RSL curve for the Kanto area is poorly known in detail; HHS heights are known only for a few localities. On the other hand, recently, new insight into the timing of the HHS in far-field localities have come from reexamination of ice models (Nunn and Peltier, 2001), geophysical models (Okuno et al., 2014), as well as geomorphologic, micropaleontological and geochemical data (Yokoyama et al., 2012), on the basis of glacial isostatic adjustment considerations. Holocene sea-level changes have been studied using many methods and records from many localities (e.g. Yokoyama and Esat, 2011; Horton and Sawai, 2010). In earlier studies, for example, Shennan (1982) and Tooley (1982) used the boundary between terrestrial and marine sediments as a proxy of sea level, the "sea-level index point," and used it for reconstruction of sea-level during the Holocene. Since then, various ways to obtain the sea-level index point have been devised (Maeda et al., 1982; Sato et al., 1983, 2001; Eronen et al., 1987; Denys and Baeteman, 1995; Yokoyama et al., 1996; Shennan and Horton, 2002; Tanabe et al., 2010; Stattegger et al., 2013; Tanigawa et al., 2013; Reynolds and Simms, 2015). To investigate the details of RSL changes in central Japan during the Holocene and reexamine the timing of the HHS, we obtained six drill core samples from the Lake Inba area including the Kashima river area of the eastern Kanto Plain, for which the residual uplift during MIS5e is known, and analyzed them using fossil diatom assemblages as a sea-level proxy as well as ^{14}C dates from the cores.

2. Materials and methods

2.1. Core samples and ^{14}C dating

In 2006–2009, six cores designated SK-3 (elevation 2.6 m), SK-4 (elevation 3.7 m), SK-6 (elevation 4.7 m), SK-7 (elevation 6.3 m), SK-8 (elevation 8.5 m) and SK-9 (elevation 11.6 m) were obtained from the lowland south of Lake Inba at localities considered to be at the upper limit of the coastline during the HHS (Fig. 1c; Sugihara et al., 2011). These cores penetrated the entire succession of valley-fill deposits laid down during the Holocene transgression. Sedimentary facies in these cores were described and their radiocarbon ages were reported by Sugihara et al. (2011); however, we found it necessary to reexamine the lower limits of the postglacial deposits and these facies (Fig. 2). In this paper, we report new ^{14}C dates from core samples and tephra ages, along with lithostratigraphic data, from the six cores of Sugihara et al. (2011). We selected shell materials from sediments that represented as much as possible the main habitat of that species.

New radiocarbon ages were obtained using accelerator mass spectrometry by Paleo Labo Co., Ltd., and all ages, including previously reported age data (Sugihara et al., 2011), were calibrated by the program Calib 6.0 (Stuiver and Reimer, 2010). The reservoir effect ΔR (the difference between regional and global marine ^{14}C ages; Stuiver and Braziunas, 1993) was taken as 0 for marine samples such as shell