

## Holocene ostracod palaeobiogeography of the Seto Inland Sea, Japan: impact of opening of the strait

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**ABSTRACT** – In this study, published Holocene ostracod data for Osaka, Hiroshima, and Iyo-nada Bays within the Seto Inland Sea (SIS), Japan, are re-examined. Five major faunal changes are recognized at different stratigraphic horizons (Horizons 1–5) in the Holocene sedimentary record. Horizons 1 and 5 (faunal changes) were most likely triggered by the respective openings of the Bisan-seto (and resulting formation of the SIS) and Akashi Straits. Three other major faunal changes, at Horizons 2–4, may also be linked to the opening of straits and resulting formation of bays, although the exact nature of these events is less certain. This re-examination indicates that the opening of straits extensively affected the benthic inner-bay community during the Holocene transgression in the SIS. Further high-resolution studies are needed for confirmation of faunal changes triggered by opening of straits. *J. Micropalaeontol.* 27(2): 111–116, November 2008.

**KEYWORDS:** *Ostracoda, Holocene, palaeobiogeography, sea-level change, Japan*

### INTRODUCTION

The impact of opening and closing of coastal straits on organisms has been recognized over relatively long time-scales (e.g. Isthmus of Panama, Collins *et al.*, 1996; Bering Strait, Marinovich & Gladenkov, 1999) and includes ostracod speciation (Cronin & Ikeya, 1990). Despite this, the impact of opening of straits due to Holocene sea-level rise on organisms is not well known (Irizuki *et al.*, 2001; Yasuhara *et al.*, 2004). Irizuki *et al.* (2001) and Yasuhara *et al.* (2004) described a major ostracod faunal change in Osaka Bay at the eastern end of the Seto Inland Sea (SIS), Japan, which was probably triggered by the opening of the strait. The triggered faunal change was confirmed in Osaka Bay during the Holocene, whilst this change in other areas of the SIS has yet to be determined. Two factors have enabled the reconstruction of Holocene high-resolution records of inner-bay ostracods: the recent development of Accelerator Mass Spectrometry (AMS) radiocarbon dating, and the relatively high sedimentation rate within inner-bay areas.

The aim of this study is to reconstruct the Holocene ostracod palaeobiogeography of the SIS. The resultant high-resolution ostracod record assembled in this study is then tested to reveal whether the opening of straits and resulting formation of bays had a major impact on the inner-bay ostracod benthos.

### LOCALITY AND METHODS

The following overview of the SIS is based mainly on published work of the Coastal Oceanography Division of the Oceanographic Society of Japan (1985), Okaichi *et al.* (1996) and Yanagi (1998). The SIS is the largest enclosed sea in Japan, with an area of about 20 000 km<sup>2</sup>, and is surrounded by Honshu, Shikoku and Kyushu Islands (Fig. 1). The SIS contains >700 small islands and has an average depth of about 40 m. The SIS is linked to the open ocean via the Kitan and Naruto Straits in the east and the Hoyo and Kanmon Straits in the west. The SIS comprises of multiple enclosed bays joined by narrow straits.

The principal bays, from east to west, are Osaka, Harima-nada, Hiuchi-nada, Hiroshima, Iyo-nada and Suo-nada Bays, and these are connected by the Akashi, Bisan-seto, Kurushima and Tsurushima Straits. For the purposes of this study, the Bisan-seto Strait marks the boundary between the eastern and western SIS.

In this study, published data of temporal changes in Holocene ostracods of the SIS are re-examined to reconstruct the Holocene palaeobiogeography. To detect major faunal change, attention is focused on temporal changes in the relative abundance (%) of five dominant ostracod species (Fig. 2): *Spinileberis quadriculeata* (Brady), *Pistocythereis bradyi* (Ishizaki), *Trachyleberis scabrocuneata* (Brady), *Bicornucythere* sp. (= *Bicornucythere* sp. of Yasuhara *et al.*, 2005) and *Bicornucythere bisanensis* (Okubo) [=form A (Abe & Choe, 1988) of *B. bisanensis*]. In the SIS, such ostracod data are available for the Osaka Bay area (Irizuki *et al.*, 2001; Masuda *et al.*, 2002; Yasuhara *et al.*, 2002a, b, 2004), Hiroshima Bay (Yasuhara & Seto, 2006) and Iyo-nada Bay (Yasuhara *et al.*, 2005). In Osaka and Iyo-nada Bays, ostracod data are available from several cores. Cores OB2 (Irizuki *et al.*, 2001) and S1 (Yasuhara *et al.*, 2005) (see Fig. 1) are selected as representative cores for Osaka and Iyo-nada Bays, respectively, because the cores have more continuous and longer ostracod records and better age control (Yasuhara *et al.*, 2004, 2005). The discussion is based mainly on these two cores because changing trends in the relative abundances of the dominant species are similar in most cores from each bay area (Yasuhara *et al.*, 2004, 2005). In Hiroshima Bay, ostracod data are available only from core HIR94-3, which has ages based on high-density AMS radiocarbon dating (Fig. 1; Yasuhara & Seto, 2006). Ostracods from these cores are considered to be generally *in situ* because the mud prevalent throughout these cores indicates sedimentation within a low-energy (serene) environment (Fig. 2). Detailed discussions on ostracod taphonomy in each core are found in Yasuhara *et al.* (2004, 2005) and Yasuhara & Seto (2006).

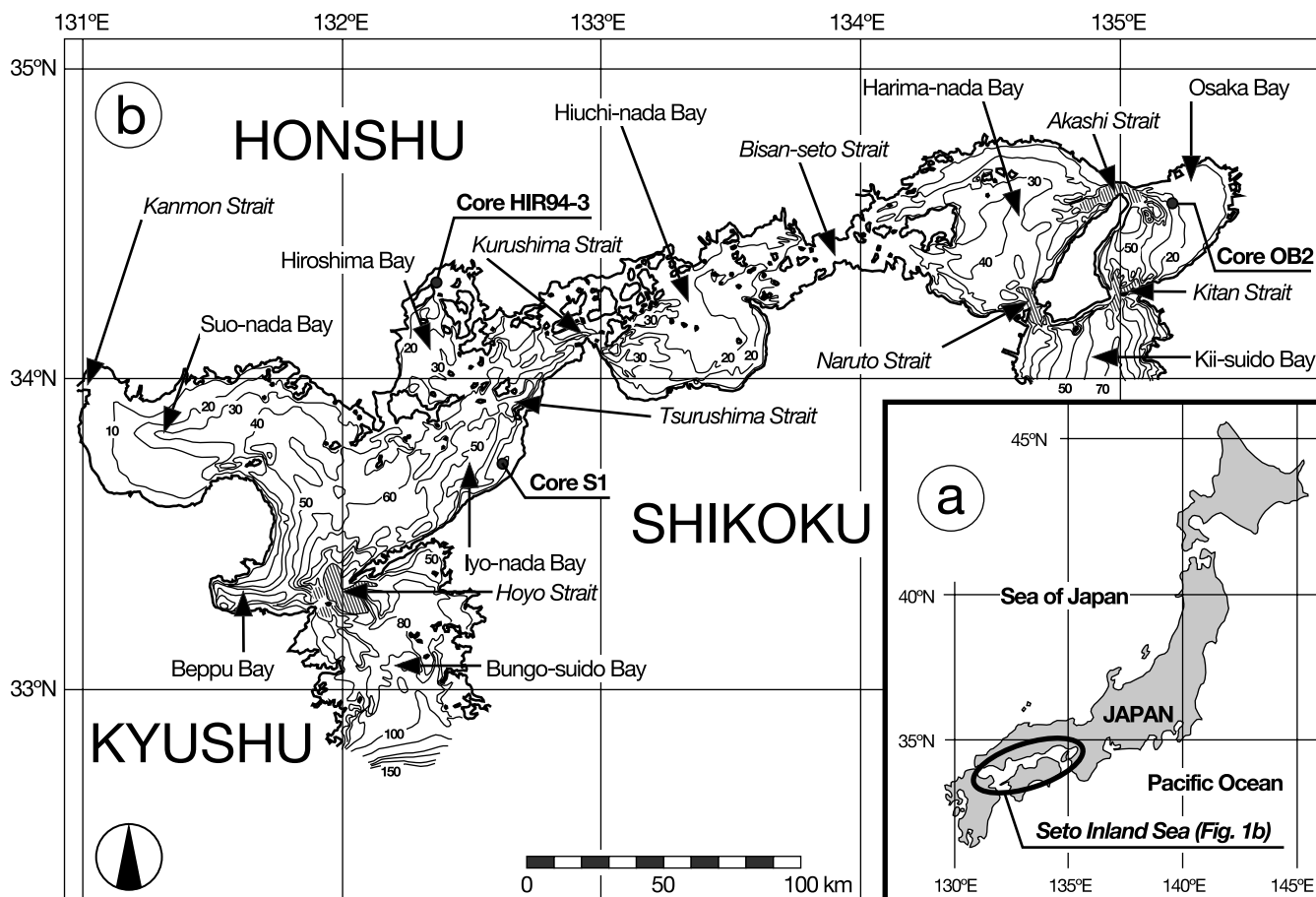


Fig. 1. Index and location maps. Coastal line and bathymetric data (contour interval 10 m) from Inouchi (1982). Shaded areas show deeply eroded straits that have tightly spaced bathymetric contours.

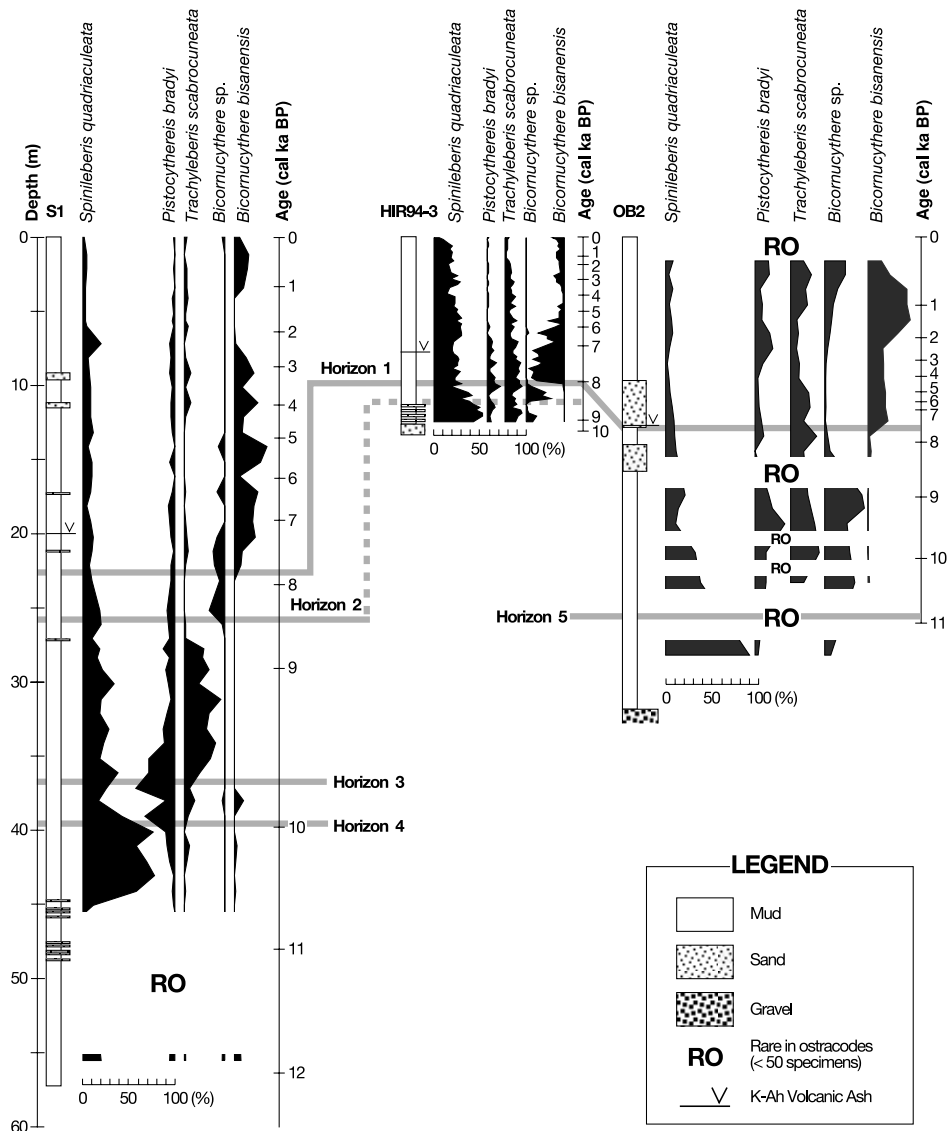
Standard methods of sample processing and ostracod picking and counting were used for these published studies (Irizuki *et al.*, 2001; Masuda *et al.*, 2002; Yasuhara *et al.*, 2002a, b, 2004, 2005; Yasuhara & Seto, 2006) and they are generally similar to each other and thus major ostracod faunal trends are comparable to each other as summarized and discussed below. Sediment samples were disaggregated by boiling or using 10% hydrogen peroxide solution prior to wet-sieving in most cases. Irizuki *et al.* (2001) lack description on their disaggregation method. Ostracods were well preserved regardless of disaggregation methods (i.e. many specimens are translucent; Yasuhara *et al.*, 2005; Yasuhara & Seto, 2006). Then the samples were washed through a 63  $\mu\text{m}$  or 75  $\mu\text{m}$  sieve, oven-dried and dry-sieved through a 125  $\mu\text{m}$  sieve, except in one study in which the samples were washed through three piled sieves of 25  $\mu\text{m}$ , 63  $\mu\text{m}$  and 250  $\mu\text{m}$  size openings (Irizuki *et al.*, 2001). Ostracods were picked from the >125  $\mu\text{m}$  size fraction, except for Irizuki *et al.* (2001) who studied the >250  $\mu\text{m}$  fraction. The number of specimens refers to the sum of the number of left and right valves and carapaces or the estimated minimum number of carapaces (i.e. total number of left or right valves, whichever was the greater). In summary, changing trends of the dominant species' relative abundance are similar in most cores from each bay area regardless of differences in sieve size or counting method. Notably, a particular

ostracod faunal change (Horizon 1: see below) was recognized in all cores throughout the SIS (see below), suggesting only minor impact due to methodology differences on this study.

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Analysis of temporal changes in the abundance of the dominant ostracod species within the Osaka (Irizuki *et al.*, 2001; Masuda *et al.*, 2002; Yasuhara *et al.*, 2002a, 2004), Hiroshima (Yasuhara & Seto, 2006) and Iyo-nada Bays (Yasuhara *et al.*, 2005) reveals five ostracod faunal-change horizons (Horizons 1–5; Fig. 2). These horizons are characterized by rapid increases in the relative abundance of *Bicornucythere bisanensis* in Horizon 1, *Bicornucythere* sp. in Horizon 2, *Trachyleberis scabrocuneata* in Horizon 3, *Pistocythereis bradyi* in Horizon 4, and *Bicornucythere* sp., *T. scabrocuneata*, and *P. bradyi* in Horizon 5. The ages of Horizons 1–5 are approximately 8000, 8500, 9500, 10 000 and 10 500–11 500 cal years BP, respectively (Fig. 2).

Figure 3 contains five palaeogeographical maps constructed mainly from the relative sea-level curve of Masuda *et al.* (2000) and Inouchi's (2002) contour map of the base of the Holocene and latest Pleistocene marine sediments. Onodera & Ohshima (1983), Fujiwara (1986), Ohira *et al.* (2003) and Chujo *et al.*

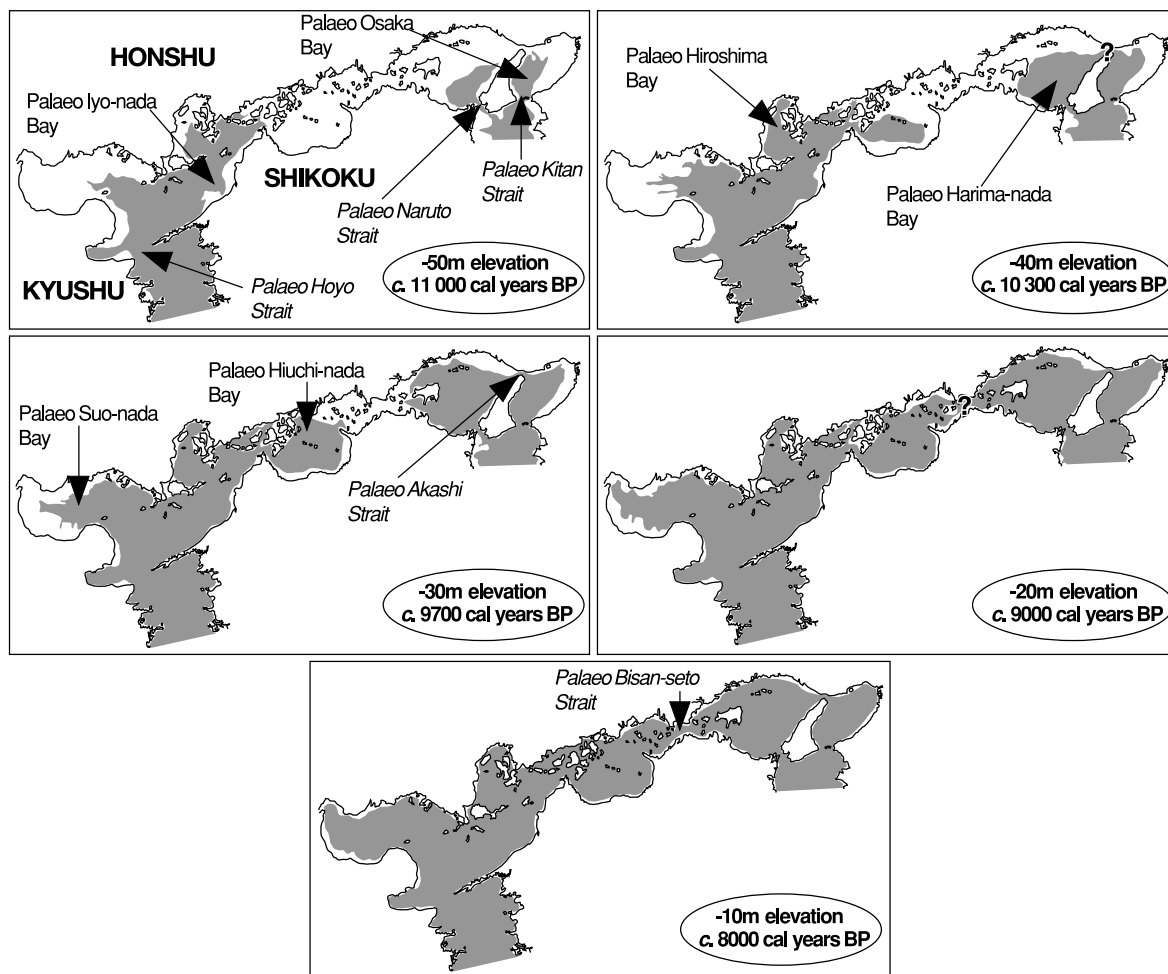


**Fig. 2.** Temporal changes in the relative frequencies (%) of *Spinileberis quadriaculeata*, *Pistocythereis bradyi*, *Trachyleberis scabrocuneata*, *Bicornucythere* sp. and *Bicornucythere bisanensis* at Osaka, Hiroshima and Iyo-nada Bays for samples that contain >50 ostracod specimens. The relative frequency of each species, Kikai–Akahoya (K–Ah) volcanic ash (c. 7300 cal years BP; Fukusawa, 1995), and lithofacies of cores S1, HIR94-3 and OB2 are from Yasuhara *et al.* (2005), Otsuka *et al.* (2002), Yasuhara & Seto (2006), Commission on Subsurface Investigation of Hiroshima Bay (1995), Irizuki *et al.* (2001), and Nanayama *et al.* (2000). Time-scales for cores S1, HIR94-3 and OB2 are based on the age models of Yasuhara *et al.* (2005), Yasuhara & Seto (2006) and Yasuhara *et al.* (2004), respectively.

(2004) were also consulted for palaeogeographical map reconstruction.

Faunal changes recorded within Horizons 1–4 are independent from changes in palaeo-water depth. Present-day water depths and palaeo-water depths differ both within and between bays (Yasuhara *et al.*, 2004, 2005; Yasuhara & Seto, 2006, for details). Present water depths of six core sites in Osaka Bay range from 21.9 m to –3.5 m (i.e. drilling core on land) (Yasuhara *et al.*, 2004), and are 14.0 m for one site in Hiroshima Bay (Yasuhara & Seto, 2006), and from 33.3 m to 26.0 m for four sites in Iyo-nada Bay (Yasuhara *et al.*, 2005). Palaeo-water depths at each faunal change horizon (Horizons 1–4) are different between sites and between bays. The palaeo-water depth of Horizon 1 is about 5–25 m within Osaka Bay (six sites), about

20 m within Hiroshima Bay (one site) and 20–25 m within Iyo-nada Bay (four sites). The depth of Horizon 2 is about 10 m within Hiroshima Bay and about 20 m within Iyo-nada Bay, while Horizon 3 is at about 10–15 m depth in Iyo-nada Bay, and Horizon 4 is at about 5–15 m depth in Iyo-nada Bay. These palaeo-water depths are estimated from relative sea-level curves (Masuda *et al.*, 2000, Osaka Bay; Yasuhara & Seto, 2006, Hiroshima Bay; Yasuhara *et al.*, 2005, Iyo-nada Bay) and depositional curves (Yasuhara *et al.*, 2004, Osaka Bay; Yasuhara & Seto, 2006, Hiroshima Bay; Yasuhara *et al.*, 2005, Iyo-nada Bay), i.e. the age–depth model (Yasuhara *et al.*, 2004, 2005; Yasuhara & Seto, 2006). If increasing water depth was the agent of faunal change, one might expect to observe a progressive variation in the timing of faunal change at each site related



**Fig. 3.** Palaeogeographical maps of the SIS. Palaeo-shoreline reconstruction is based on Onodera & Ohshima (1983), Fujiwara (1986), Masuda *et al.* (2000), Inouchi (2002), Ohira *et al.* (2003) and Chujo *et al.* (2004) (see text for details). Solid line represents the current-day shoreline. Grey area represents the area of the SIS at each time period.

to progressive changes in palaeo-water depth. However, each period of faunal change occurred almost simultaneously at multiple sites of contrasting present-day and palaeo-water depth. Therefore, these faunal changes are interpreted as not being directly caused by changes in water depth.

The faunal changes recorded in Horizon 1 indicate that the rapid increase in the relative abundance of *Bicornucythere bisanensis* reported widely in Osaka Bay (Irizuki *et al.*, 2001; Yasuhara *et al.*, 2004), thought to be triggered by the opening of the Bisan-seto Strait and resulting formation of the SIS (Yasuhara *et al.*, 2004), can now be traced to the western SIS. Environmental conditions such as sea-water circulation, salinity, strength of tidal currents, food supply and dissolved oxygen should change abruptly following formation of the SIS (Yasuhara *et al.*, 2004). The timing of the opening of the Bisan-seto Strait is estimated to be c. 9000–8000 cal years BP (Masuda *et al.*, 2000; Ohira *et al.*, 2003; Fig. 3).

Irizuki *et al.* (2001) documented faunal changes triggered by the opening of the Akashi Strait and formation of Harima-nada Bay at about 10 000 cal years BP (see Yasuhara *et al.*, 2004); these changes are equivalent to the faunal changes recorded in Horizon 5 of this study. The timing of the opening of Akashi

Strait has been dated at c. 9700 cal years BP (Masuda *et al.*, 2000; Fig. 3).

As discussed above, it is plausible that the openings of these straits had major impacts on the inner-bay benthic community. Other faunal changes, such as those recorded in Horizons 2–4, may also reflect the opening of straits (e.g. Kurushima Strait) and resulting formation of bays (e.g. Hiroshima Bay), although the available data are still limited and further research is needed to confirm this hypothesis.

Although the rapid expansion of the SIS described above might have caused abrupt changes in sea-water circulation, salinity, strength of tidal current, food supply and dissolved oxygen, and these abrupt changes might have triggered changes in the ostracod fauna at Horizons 1–5, the specific causes of the ostracod events are unknown. One plausible explanation is that changes occurred in bottom-water oxygen content, at least for Horizon 1, because *Bicornucythere bisanensis* is well known to have resistance to lowered oxygen levels (Irizuki *et al.*, 2003). Living specimens (i.e. specimens with well-preserved soft parts) of this species were found from the bottom samples of the sites where dissolved oxygen is lower than  $1 \text{ mg l}^{-1}$ , in fact (Irizuki *et al.*, 2003). The strait opening might cause changes in ocean

circulation and tidal current, and these changes may cause surface primary productivity change, which possibly influences oxygen condition at the bottom.

There are differences in the timing of faunal changes between the western and eastern SIS, although the Horizon 1 event occurred throughout the entire SIS. The principal differences are the timing of rapid increases in the relative abundance of *Bicornucythere* sp., *Trachyleberis scabrocuneata* and *Pistocythereis bradyi*. The relative abundances of these three species increased synchronously in the eastern SIS (Horizon 5), but increased independently of each other in the western SIS (Horizons 2–4). These differences may be due to simpler coastal shape of the eastern area than that of the western area, with fewer bays and straits. It is suggested, therefore, that faunal changes did not occur between Horizons 1 and 5 in the eastern area because of the absence of events such as strait opening and the formation of bays. The Kitan and Naruto Straits had already connected the eastern SIS to the open ocean at around 10 000 cal years BP. Thus, sea-water circulation in eastern areas should be better established than in western areas, which had only one strait connecting the open ocean at that time. The synchronous increase in the relative abundance of *Bicornucythere* sp., *T. scabrocuneata* and *P. bradyi* (Horizon 5) in eastern areas at this time may reflect the better circulation compared with western areas, although ostracod migration from the south and west to Osaka Bay may also have been important.

## CONCLUSIONS

There is no clear relationship between the present-day distribution of the five dominant ostracod species considered in this study and water depth (see Yasuhara & Seto, 2006, for a summary of the contemporary water-depth distribution of Japanese shallow-marine ostracods). In addition, a variation in distribution from *Spinileberis quadriculeata* to *Bicornucythere bisanensis*, corresponding to Horizons 1–4 (see Fig. 2), is not recognized in modern ostracod data of Japan. This is despite the existence of abundant ostracod data for Japanese inner-bay areas (Ishizaki, 1968 – Uranouchi Bay; Ishizaki, 1969 – Lakes Nakaumi and Shinji; Ishizaki, 1971 – Aomori Bay; Ikeya & Hanai, 1982 – Lake Hamana; Frydl, 1982 – Tateyama Bay; Bodergat & Ikeya, 1988 – Ise and Mikawa Bays; Takayasu *et al.*, 1990 – Lakes Nakaumi and Shinji; Ikeya & Itoh, 1991 – Sendai Bay; Ikeya *et al.*, 1992 – Otsuchi Bay; Iwasaki, 1992 – Ariake-kai Bay; Itoh, 1998 – Lake Hamana; Tanaka *et al.*, 1998 – Miho Bay to Lake Shinji; Yamane, 1998 – Hiuchi-nada Bay; Yasuhara & Irizuki, 2001 – Osaka Bay; Irizuki *et al.*, 2003 – Lake Nakaumi; Irizuki *et al.*, 2006 – Urauchi Bay). The absence of such regular variations in ostracod distribution within modern Japanese inner bays may reflect the complex environment of each bay in terms of sea-floor topography, anthropogenic impacts, nature of inflowing rivers, etc. Notably, anthropogenic impacts, such as eutrophication, bottom-water hypoxia, pollution and land reclamation, have intensively and extensively altered inner-bay environments and ecosystems including ostracod benthos during the past *c.* 100 years worldwide as well as the SIS (e.g. Yasuhara *et al.*, 2003, 2007; Ruiz *et al.*, 2005; Yasuhara & Yamazaki, 2005; Tsujimoto *et al.*, 2006). Thus, it is likely that such intensive anthropogenic effects mask the regular variations in ostracod distribution to a greater

or lesser degree. None the less, the above observations support the hypothesis that the faunal changes documented in this study were triggered by strait opening and cannot be explained by environmental parameters, such as water depth and temperature, which have a modern-day spatial gradient.

Re-examination of published data indicated that opening of straits affected the benthic inner-bay community during the Holocene transgression in the SIS. Further high-resolution studies are needed for confirmation of faunal changes triggered by opening of straits, because the early Holocene sea-level rise was very rapid.

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