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Evaluation of Holocene crustal movement in the Ako Plain, western Japan

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Abstract: Holocene sea-level observations have been obtained from the Ako Plain in western Japan. In this coastal area, the Holocene crustal movements have been evaluated, except the crustal response due to the last deglaciation, by comparing observations and theoretical predictions of relative sea-level (RSL) variations. Analyses of diatom assemblages and sedimentary sulphur in core sediments were used along with radiocarbon dates to derive the RSL variations. A crustal movement rate between +0.2 mm and −0.2 mm per year, corrected for the prediction, fits well with the observed RSL index points. Owing to the constraint of the reconstructed palaeo-mean sea level (PMSL) at 7300 cal. BP, the coast of the Ako Plain may have the best estimate of a tectonic subsidence rate of 0–0.2 mm/yr. The tectonic uplift rates along the tectonically active coast of western Kobe were derived to be 0.3–0.7 mm/yr and 0.11–0.45 mm/yr for Tarumi and Tamatsu, respectively, relative to Ako over the period concerned. The relative uplift along the traverse from Ako to western Kobe is primarily the result of the crustal movement resulting from the active faulting of the Rokko-Awaji fault system (RFS).

Key words: Holocene relative sea-level, sedimentary sulphur, diatom analysis, crustal movement, active faults, Ako Plain, Japan.

Introduction

The separation of hydro-isostatic crustal movements from local tectonics is important in order to assess the Holocene coastal evolution in Japan (Maeda *et al.*, 1994; Nakada *et al.*, 1994; Yokoyama *et al.*, 1996). To achieve this, comparisons have been made between observations and theoretically based predictions of Holocene relative sea-level (RSL) variations in the tectonically active coast of western Kobe, Japan, in order to estimate the Holocene local tectonics (Sato *et al.*, 2001, 2003). This study also assesses the rates of Late Quaternary local crustal movements in the tectonically uplifted Kobe area (Sato *et al.*, 2001).

RSL variations during the past 6000 yr for tectonically stable areas are typically attributed to the crustal response associated with deglaciation, and these variations are very sensitive to mantle viscosity (Farrell and Clark, 1976; Clark *et al.*, 1978; Nakada and Lambeck, 1989; James *et al.*, 2000). In Japan, systematic observations of Holocene RSL variations have been carried out at sites along the west coast area of Kyushu (Yokoyama *et al.*, 1996), where coastal terraces of the last interglacial maximum with an altitude greater than 10 m have not been reported, although those with an altitude higher than 50 m have been observed at sites facing the Pacific Ocean (Ota and Omura, 1991). The west coast area of Kyushu is also seismically inactive (National Astronomical Observatory, Japan, 1992) and there is little active fault in this area (The Research Group for Active Tectonics in Kyushu, 1989). Thus, this region was considered to have been tectonically inactive for at least the past 125 kyr (Nakada *et al.*, 1998). The mid- to late-Holocene RSL variations for each site and the observed tilting in west Kyushu have been explained as the result of hydro-isostatic adjustment (Yokoyama *et al.*, 1996), which was quantitatively modelled for this coastal area (Nakada *et al.*, 1998).

By comparing the observed RSL variations and the predictions derived from the geophysical model of Nakada *et al.* (1998), the Holocene tectonic uplift rates along the tectonically active coast of western Kobe were estimated to be 0.3–0.5 mm/yr for Tarumi and 0.11–0.25 mm/yr for Tamatsu (Sato *et al.*, 2001) (Figure 1B). These uplift rates primarily reflect the cumulated crustal movement resulting from the active faulting during the Holocene. These sites are located near the epicentre of the 1995 Hyogoken-Nanbu (Kobe) earthquake (*Mj* 7.3),

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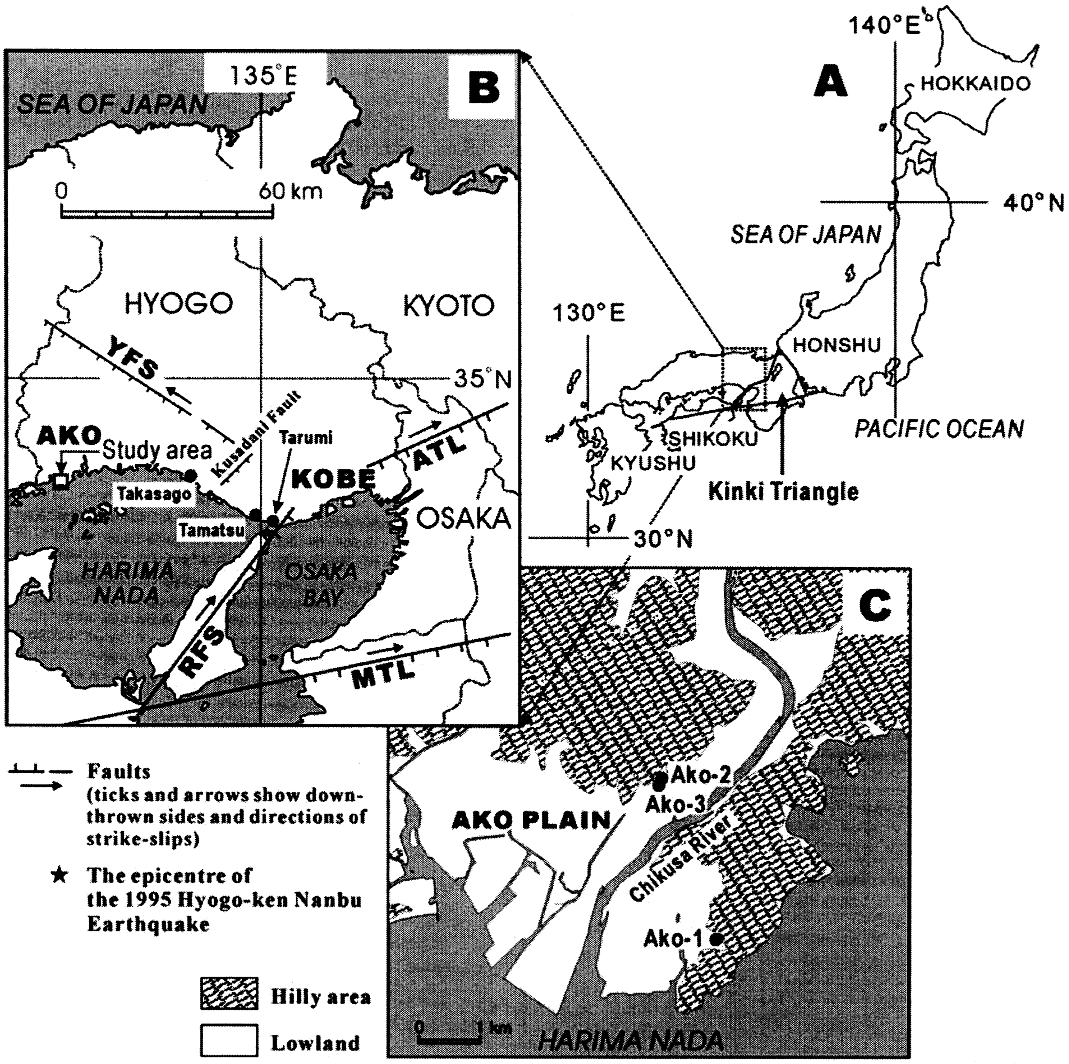

Figure 1 Location maps of the Kinki Triangle and the three coring sites in the Ako Plain. MTL, Median Tectonic Line; ATL, Arima-Takatsuki Tectonic Line; RFS, Rokko-Awaji fault system; YFS, Yamasaki fault system

which resulted in vertical uplifts of 0.07 m at Tamatsu and 0.19 m at Tarumi (Ishihara *et al.*, 1995). A tectonic subsidence rate of 0.08–0.23 mm/yr has also been determined for Takasago (Sato *et al.*, 2003) (Figure 1B), a temporary fixed point for geodetic measurements for the Kobe earthquake (Ishihara *et al.*, 1995).

In this study, the rate of crustal movement is evaluated, excluding the hydro-isostatic contribution, for the Ako Plain as a reference for the tectonically uplifted Kobe area. For this evaluation, Holocene RSL records were determined at three sites in the Ako Plain. Sato and Katoh (1998) obtained the RSL records for the past 7000 yr based on the diatom and sulphur analyses of core sediments at the two Ako sites (Ako 1 and 2). In this study, another core extending to the basement rock was collected at Ako 3, and its diatom and sulphur content were analysed in order to obtain more detailed Holocene RSL records. The records from the three Ako sites were then compared with the prediction derived from the geophysical model of Nakada *et al.* (1998).

Tectonic background

The Kinki Triangle (Huzita, 1962) (Figure 1A) contains one of the largest concentrations of active faults in Japan (The Research Group for Active Faults of Japan, 1991). This region is bounded by active strike-slip fault systems on its three sides and its interior is characterized by north–south trending active reverse faults (Toda *et al.*, 1998; Figure 1A). These active faults have been formed under the east–west compressive stress state in this region since the Middle Pleistocene (Huzita and Kasama, 1982). The northwest side is bounded by active fault systems such as the Arima-Takatsuki Tectonic Line (ATL) and the Rokko-Awaji fault system (RFS) (Figure 1B). The Kobe area lies within the Kinki Triangle and it is located just south of the RFS that is composed of several right-lateral strike-slip faults (The Research Group for Active Faults of Japan, 1991; Okada *et al.*, 2000). The RFS includes the Nojima fault that ruptured during the 1995 Kobe earthquake. To the west, outside the Kinki Triangle, lies the Yamasaki fault system (YFS) where left-lateral strike-slip faults extends towards the southeast and the Kusadani reverse fault extend towards the southwest (Figure 1B). Some large submarine active reverse faults are present in Osaka Bay, whereas no submarine active faults are present in Harima-nada Bay (Okada *et al.*, 2000).

The Ako Plain borders Harima-nada Bay; it lies approximately 60 km from the RFS and is located in the divergence zone of two major fault systems, namely, the YFS and RFS, while Tarumi and Tamatsu on the tectonically active coast of western Kobe are in the convergence zone (Figure 1B). No active faults have been observed in this plain (Okada *et al.*, 2000). Although a sequence of coastal terraces has developed along the coast west of Kobe, each terrace decreases in elevation towards the west (Tanaka, 1989). This trend is also indicated by the geodetic data from the 1995 Kobe earthquake (Ishihara *et al.*, 1995) and the rates of the Holocene crustal movement at Tarumi, Tamatsu and Takasago (Sato *et al.*, 2001, 2003). Middle to late Pleistocene coastal terraces have not developed in the Ako Plain (Okada *et al.*, 2000), suggesting that this plain was either subsiding or stable during the Late Quaternary.

Methods

The Holocene RSL records were investigated at three sites (Ako 1, 2 and 3) in the Ako Plain. Holocene sediments were obtained from the cores (Figure 1C) and the altitude at each site was determined relative to the mean sea level in Tokyo Bay (TP) by instrumental levelling from permanent benchmarks (Sato *et al.*, 2001, 2003). The RSL variations for each site were evaluated using the depositional environment of the sediments, which is derived from the diatom assemblages, sulphur content and derived ages of the sediments.

Diatom assemblages and sedimentary sulphur analyses

For each sedimentary profile, samples were analysed for diatom assemblages and sulphur content at intervals of 4 to 80 cm. Subsamples of 1 g were leached subsequently with 1N HCl and 30% H_2O_2. The residue, consisting almost entirely of clay and other silicate minerals, was used for the diatom analysis (1991, 1995). Sulphate in the 1N HCl soluble and 30% H_2O_2 soluble fractions was determined by a turbidimetric method (American Public Health Association, American Water Works Association and American Pollution Control Federation, 1985; Sato, 1989). In this study, the sum of HCl-soluble and H_2O_2-soluble sulphur in sediments is referred to as sedimentary sulphur (Sato *et al.*, 1998).

The relative abundance of diatoms was determined by counting more than 300 valves: these were expressed as a percentage of the total count. Diatom identification was primarily based on Cleve-Euler (1951–1955) and Krammer and Lange-Bertalot (1986, 1988, 1991). Ecological interpretations were based on Kashima (1986), Kosugi (1988) and Tanimura and Sato (1997). Although new names have been proposed for some species, the nomenclature provided in Round *et al.* (1990) was followed. Most taxa were grouped into one of three ecological categories: marine, brackish or freshwater. For each sedimentary profile, compositional changes in the diatom assemblages based on habitat preference, and the relative abundance of each dominant or common taxon are shown.

Dating

The age of the sediment is based on AMS-^{14}C dates and Kikai-Akahoya tephra (K-Ah), which is a widespread marker tephra in Japan (eg, Machida, 1999). Taking account of the horizon of sea-level index point identified by the diatom analysis as explained below, 16 samples of marine shell or terrestrial wood fragments were obtained from cores at the three sites, and the ^{14}C ages were analysed by AMS-^{14}C age determinations (Table 1). These ^{14}C ages shown in Table 1 were corrected for δ^{13}C isotopic fractionation, and reservoir effect with in 400 years (Stuiver *et al.*, 1986; Bard, 1988) was incorporated for marine shells (sample no. 2, 4 and 6). Radiocarbon ages were calibrated in cal. BP using the program developed by Stuiver and Reimer (1993) and the data set presented in Stuiver *et al.* (1998). The calibrated age of 7300 cal. BP was adopted as the eruption age of K-Ah (Fukusawa, 1995; Kitagawa *et al.*, 1995; Okuno, 2002).

Although it is difficult to assess possible dating errors by re-deposition or contamination of shell and terrestrial wood fragments in core sediments, cross-checking with the age of K-Ah at the two Ako sites (Ako 2 and 3) revealed the expected results of the ^{14}C dating of these samples above and below K-Ah horizons (see Figures 3 and 4). Thus, the 16 ^{14}C dates were considered to provide a chronology of depositional ages of the sediments.

Evaluation of the palaeo-sea level

The sea-level tendency method has been improved by analysing transgressive and regressive overlaps in saltmarsh deposits (eg, Shennan *et al.*, 1983, 2000; Dawson and Smith, 1997; Gehrels, 1999). A similar method has been used to obtain RSL index points (Sato *et al.*, 2001, 2003). In most coastal regions of the Japanese Islands, the Holocene marine transgression termed the 'Jomon transgression', culminated during the mid-Holocene. A subsequent regression led to a transition in sedimentary facies from marine to freshwater. The altitude of the upper limit of marine facies is recognized by the horizon at which diatom assemblages in the sediments change from marine or brackish-water diatoms to freshwater ones (Maeda *et al.*, 1992). In this paper, the upper limit of Holocene marine facies is referred to as the 'Holocene marine limit (HML)'. The HML can provide a sea-level index point approximating the height of the high water level (Sato *et al.*, 1983; Eronin *et al.*, 1987; Yokoyama *et al.*, 1996).

In intertidal conditions, a reasonable index point can be obtained. Among the diatom assemblages, brackish-water diatoms such as *Terpsinoë americana* and *Pseudopodosira kosugii* that live in the mid- and upper intertidal zones are useful indicators of the former sea level during the Holocene (Maeda *et al.*, 1982; Sato *et al.*, 1983, 1996; Tanimura and Sato, 1997), and they have been used to identify the RSL position (Sato and Katoh, 1998). The RSL identified by these intertidal diatoms is an approximate index for the palaeo-mean sea level (PMSL) and is referred to as the RSL index point (Sato *et al.*, 2001, 2003). Considering the situations in which selected species of diatom live, the present spring tidal range is given for the probable vertical range of the RSL index point in which the PMSL occurs, since there is no information on the palaeo-tidal range. At present, the spring tidal range at Ako is 1.00 m (Japan Meteorological Agency, 2000).

When estimating the RSL position, errors affecting the height of the RSL index points must be considered. The most important vertical errors may be caused by autocompaction, which is the process whereby a growing sequence of sediments collapses through self weight (Allen, 1999). Siliceous gravels and sands are almost incompressible, muds compact to a moderate degree and peat and related sediments rapidly become highly compressed (Allen, 1999). These effects are not incorporated in this study because there is no transgressive peaty intercalation in the core sediments. For surveying errors and uncertainties associated with sampling procedures, an estimate of ±0.10 m (Gehrels, 1999) is incorporated into the overall error figure. Consequently, the vertical range of the RSL index point (±0.60 m) includes the sum of the tidal range (±0.50 m) and the surveying errors (±0.10 m). Although the sedimentary sulphur content of sediments is very sensitive to the content of the available organic matter metabolized by sulphate-reducing bacteria (Berner, 1970, 1984), it is generally recognized that a sulphur content of 0.3% or more in muddy

Table 1 ^{14}C dates and depositional environments of dated horizons at Ako

Sample no.	Site name	Laboratory no.	Altitude[a] (m TP)	Material dated	^{14}C age [b] (BP)	δ^{13}C (‰)	Calibrated age (cal. BP) intercept ($\pm 2\sigma$)	Depositional environment	Interpretation[c]
1	Ako 1	I-17991	+0.04	wood fragment	2320±80	−27.3	2344 (2709–2131)	Intertidal	±0.60
2	Ako 1	I-17990	−0.90	shell fragment	3850±80	+1.2	4244 (4508–3989)	Marine	+
3	Ako 1	Beta-90172	−3.50	wood fragment	4120±60	−30.4	4611 (4832–4425)	Marine	+
4	Ako 1	Beta-106427	−3.60	shell fragment	4460±110	+0.3	5046 (5451–4831)	Marine	+
5	Ako 2	Beta-90174	+0.50	wood fragment	3390±60	−28.4	3636 (3828–3471)	Intertidal	±0.60
6	Ako 2	Beta-93838	−1.50	shell fragment	6750±50	−0.1	7600 (7679–7509)	Intertidal	±0.60
7	Ako 2	Beta-90173	−1.50	wood fragment	6780±60	−27.0	7613 (7720–7511)	Intertidal	±0.60
8	Ako 3	Beta-145152	+0.47	wood fragment	2130±40	−27.0	2120 (2170–2000)	Brackish/Fresh	−/+
9	Ako 3	Beta-161277	+0.25	wood fragment	2950±40	−27.3	3090 (3240–2970)	Intertidal	± 0.60
10	Ako 3	Beta-161278	−0.35	wood fragment	3910±70	−28.2	4400 (4520–4150)	Marine/Brackish	+/−
11	Ako 3	PLD-2560	−1.17	wood fragment	5790±35	−25.7	6585 (6665–6500)	Marine	+
12	Ako 3	PLD-2561	−1.46	wood fragment	5900±35	−25.1	6700 (6760–6660)	Marine	+
13	Ako 3	PLD-2562	−2.02	wood fragment	6005±35	−28.1	6830 (6910–6730)	Marine	+
14	Ako 3	Beta-161279	−2.33	wood fragment	6250±40	−28.9	7200 (7260–7020)	Marine	+
15	Ako 3	Beta-161280	−2.98	wood fragment	6730±40	−28.3	7590 (7660–7560)	Marine	+
16	Ako 3	Beta-145153	−3.30	wood fragment	7030±50	−24.6	7845 (7950–7740)	Marine	+

[a] In metres above mean sea level (TP).

[b] All dates are calculated using the Libby half-life 5568 years, and AD 1950 reference. The error is one standard deviation of counting.

[c] Positive (+), slightly positive (+/−) and slightly negative (−/+) tendencies, and probable range of the palaeo-mean sea level are shown.

sediments is indicative of a marine influence (Koma, 1992; Sato, 1995).

Results

Lithology, depositional age and environment of the sediment

The results at the Ako 1 and 2 sites (Sato and Katoh, 1998) are summarized as follows. In order to obtain further details on the RSL position of Ako during the mid- to late Holocene, the sediments from another core (Ako 3) were analysed for diatom and sulphur content.

Ako 1

The lithology, ^{14}C ages and succession of diatom assemblages are summarized in Figure 2 (Sato and Katoh, 1998). Four AMS-^{14}C dates are used as reported (Table 1).

The sediments are silty clay between −4.12 m and −3.21 m, containing shell fragments below −3.51 m, and silt between −3.21 m and −2.00 m. The sediments between −2.00 m and +1.29 m are composed of fine sand and medium sand. The sandy sediments between 0 m and +0.29 m contain plant remains. The ages of wood or shell fragments at −3.60 m, −3.50 m, −0.90 m and +0.04 m are 5451–4831 cal. BP, 4832–4425 cal. BP, 4508–3989 cal. BP and 2709–2131 cal. BP, respectively (Table 1). Sedimentary sulphur content greater than 0.3% and the occurrence of marine diatoms indicate a marine influence below +0.34 m. Although the diatoms are scarce in the sediments, freshwater diatoms increase between −0.71 m and −0.21 m, suggesting freshwater dominance and a rapid sedimentation at these horizons.

Intertidal diatoms such as *Pseudopodosira kosugii* and *Terpsinoë americana* exhibit the highest peak abundance at 0 m, indicating intertidal conditions for Ako 1 at 2709–2131 cal. BP. Although the increase in marine diatoms suggests marine conditions in sedimentary environments between +0.34 m and +1.00 m, a sedimentary sulphur content of less than 0.3% indicates no marine influence at these horizons. This discrepancy was also observed at the Tarumi site in Sato *et al.* (2001) and is interpreted as the reworking of marine diatoms between +0.34 m and +1.00 m. Thus, the HML is regarded to be +0.34 m at Ako 1.

Ako 2

The lithology, ^{14}C ages and succession of diatom assemblages are summarized in Figure 3 (Sato and Katoh, 1998). Three AMS-^{14}C dates are used as reported (Table 1).

The sediments are composed of fine to medium sand between −1.50 m and −1.05 m, containing wood and shell fragments. The sediments consist of silt between −1.05 m and −0.05 m, silty clay between −0.05 m and +0.70 m, clay and silty clay between +0.70 m and +2.95 m, fine to medium sand between +2.95 m and +3.25 m and silty clay between +3.25 m and +3.94 m. The ages of the wood fragments at −1.50 m, shell fragment at −1.50 m and wood fragment at +0.50 m are 7720–7511 cal. BP, 7679–7509 cal. BP and 3828–3471 cal. BP, respectively (Table 1). Based on the vertical variations of glass shard content and the AMS-^{14}C dates at −1.50 m, the K-Ah horizon is determined to be located at −1.30 m (Sato and Katoh, 1998). Sedimentary sulphur content greater than 0.3% and the occurrence of marine diatoms indicate a marine influence below +0.70 m. Intertidal diatoms exhibit their peak abundance near a K-Ah horizon of −1.25 m and at +0.50 m in the dated samples, indicating intertidal conditions of depositional environments for Ako 2. The HML is regarded to be +0.70 m at Ako 2.

Ako 3

This section provides nine AMS-^{14}C dates and detailed evidence for transitions between marine, brackish and freshwater environments (Figure 4). The facies below −3.90 m exhibit granite as the basement rock. The sediments consist of sand and gravel between −3.90 m and −3.70 m, and medium sand between −3.70 m and −3.40 m; this is followed by silty clay intercalation containing plant remains between −3.40 m and +0.33 m. Shell fragments are present between −3.30 m and −0.70 m, and they exist in great abundance between −1.00 m and −0.70 m. Fine sand and brownish silty clay occur between +0.33 m and +0.56 m and between +0.56 m and +2.94 m, respectively. The uppermost horizon is cultivated soil from +2.94 m to +3.20 m. The ages of wood fragments at −3.30m, −2.98 m, −2.33 m, −2.02 m,

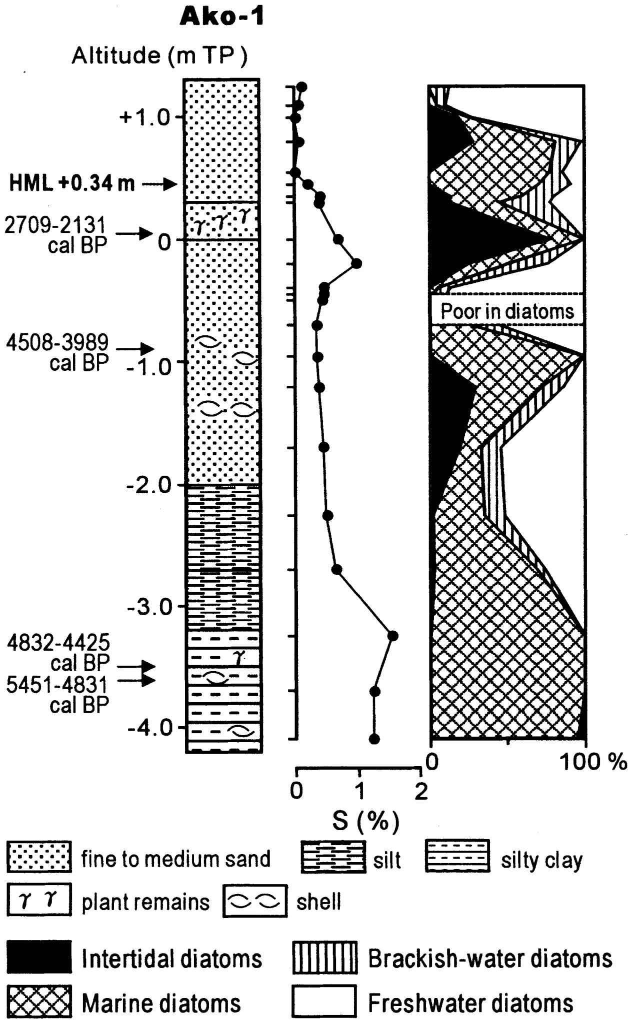

Figure 2 Diatom summary diagrams, columnar sections and AMS-^{14}C ages for the Ako 1 site (after Sato and Katoh, 1998)

−1.46 m, −1.17 m, −0.35 m, +0.25 m and +0.47 m are 7950–7740 cal. BP, 7660–7560 cal. BP, 7260–7020 cal. BP, 6910–6730 cal. BP, 6760–6660 cal. BP, 6665–6500 cal. BP, 4520–4150 cal. BP, 3240–2970 cal. BP and 2170–2000 cal. BP, respectively. K-Ah is located at −2.60 m, yielding the calibrated age of 7300 cal. BP.

Sedimentary sulphur content ranges from 0.61% to 1.41% between −3.74 m and +0.30 m, and decreases to 0.20% in the fine sand at +0.40 m. Sulphur is absent above +0.50 m. No diatom record represents the lowest sand and gravel bed. The diatom assemblages are dominated by marine and brackish-water diatoms at the horizons between −3.70 m and +0.75 m. The presence of marine diatoms such as *Cyclotella stylorum*, *Paralia sulcata*, *Cocconeis scutellum* and *Grammatophora oceanica* increases by more than 50% at the horizons between −3.70 m and −0.20 m, where sedimentary sulphur is abundant. At the K-Ah horizon between −2.70 m and −2.50 m, the brackish-water diatom *Pseudopodosira kosugii* exhibits relative abundances of 11.1% and 50%. *P. kosugii* increases between −1.17 m and +0.75 m and exhibits the peak abundance at +0.60 m. The brackish-water diatom *Diploneis pseudovalis* also occurs between −1.17 m and +0.40 m. Diatom assemblages in the samples above +0.75 m are entirely freshwater diatoms, including *Aulacoseira* spp., *Craticula cuspidata*, *Cymbella* spp., *Epithemia turgida*, *Eunotia* spp., *Gomphonema* spp., *Pinnularia* spp. and *Synedra ulna*.

Although the horizon at +0.75 m may represent the HML based on the diatom record of the sediments, there is a difference in the height of the marine influence derived from diatom assemblage and sulphur content. The sediments exhibit a sedimentary sulphur content that is less than 0.3% above the boundary between silty clay and fine sand at +0.33 m, suggesting the reworking of the diatoms between +0.33 m and +0.75 m. As in the case of Ako 1, the HML is regarded to be +0.33 m at Ako 3.

Discussion

Diatom-inferred palaeo-mean sea level

The observed age and height relationships for the RSL variations are shown in Figure 5. The depositional environments of dated horizons (Table 1) provide the dominant RSL tendency for Ako during the past 8000 yr. The RSL has a positive tendency above the sampled horizon in marine conditions. Marine and brackish conditions show slightly positive tendencies, whereas brackish and freshwater conditions show slightly negative tendencies. Intertidal sediments provide good RSL index points. The chronology is based on the calibrated ages (cal. BP) of AMS-^{14}C dates and the eruption age for K-Ah (7300 cal. BP). Interception ages with a 2σ range of the dates used to define age and altitude relationships are shown in Table 1. Considering the possible errors in both chronological and altitudinal information, error boxes have been drawn around the RSL index points in constructing Figure 5.

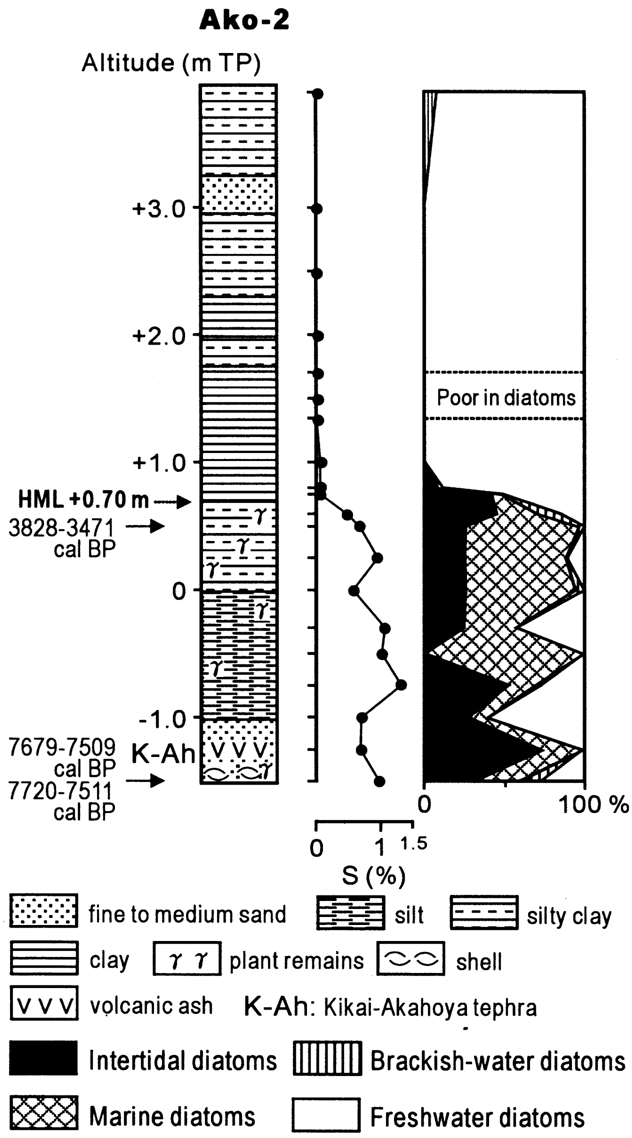

Figure 3 Diatom summary diagrams, columnar sections and AMS-^{14}C ages for the Ako 2 site (after Sato and Katoh, 1998)

The heights of the HML are regarded to be +0.34 m at Ako 1, +0.70 m at Ako 2 and +0.33 m at Ako 3, reflecting a high water level for sea-level variations. Although the ages for these HMLs could not be obtained, the sediment for the HML at Ako 2, for example, is considered to have been deposited after 3828–3471 cal. BP; this is derived from its age at +0.50 m (sample no. 5 in Table 1). For sites where no tidal changes occurred during the past 6000 yr, we can evaluate the PMSL by subtracting half of the present tidal range from the height of the marine limit showing a mean high water level (Yokoyama *et al.*, 1996). The height of the PMSL, which is determined by considering the observed height of the HML and the half of the present tidal range (= 1.00 m) is obtained as +0.20 m at Ako 2. This value is consistent with the height of the PMSL derived from the RSL index points after 3828–3471 cal. BP, as explained below.

For the Ako Plain, the intertidal deposition at +0.04 m at Ako 1 provides the RSL index point at 2709–2131 cal. BP. At Ako 2, the intertidal sediments at +0.50 m (3828–3471 cal. BP) and − 1.50 m (7720–7511 cal. BP and 7679–7509 cal. BP) also provide RSL information. The intertidal deposition at + 0.25 m at Ako 3 provides the RSL index point at 3240–2970 cal. BP. The intertidal diatom *Pseudopodosira kosugii* occurs at the K-Ah horizons of − 1.30 m at Ako 2 and − 2.60 m at Ako 3 (Figures 3 and 4), providing important RSL information at 7300 cal. BP. The diatom assemblage along with the increase in intertidal diatoms at − 1.30 m represents the RSL index point with the vertical range of ±0.60 m, whereas the assemblage that includes more than 50% marine diatoms at − 2.60 m indicates a low water level in the tidal range. Thus, the PMSL at 7300 cal. BP derived from the K-Ah horizon is interpreted to be between − 2.60 m and − 0.70 m.

Holocene subsidence rate in the Ako Plain

The solid line in Figure 5 shows a predicted sea-level curve associated with the glacio-hydro-isostatic adjustment resulting from the last deglaciation. This prediction is obtained by the rheological model with a lithospheric thickness of 30 km, an asthenosphere (200 km) with a low viscosity of 10^{20} Pa s, an upper mantle viscosity of 2×10^{20} Pa s and a lower mantle viscosity of 10^{22} Pa s. This model was derived from observations at sites along the west coast area of Kyushu, Japan, which has been tectonically inactive for at least the past 125 kyr (Nakada *et al.*, 1998). The parameters providing the best overall agreement with the RSL observations in such a tectonically inactive area are used for the purpose of this study, because these parameters have been used in a similar type of study and have provided a good approximation for rates of crustal movements along the coast of western Kobe (Sato *et al.*, 2001, 2003). The ice model after the last glacial

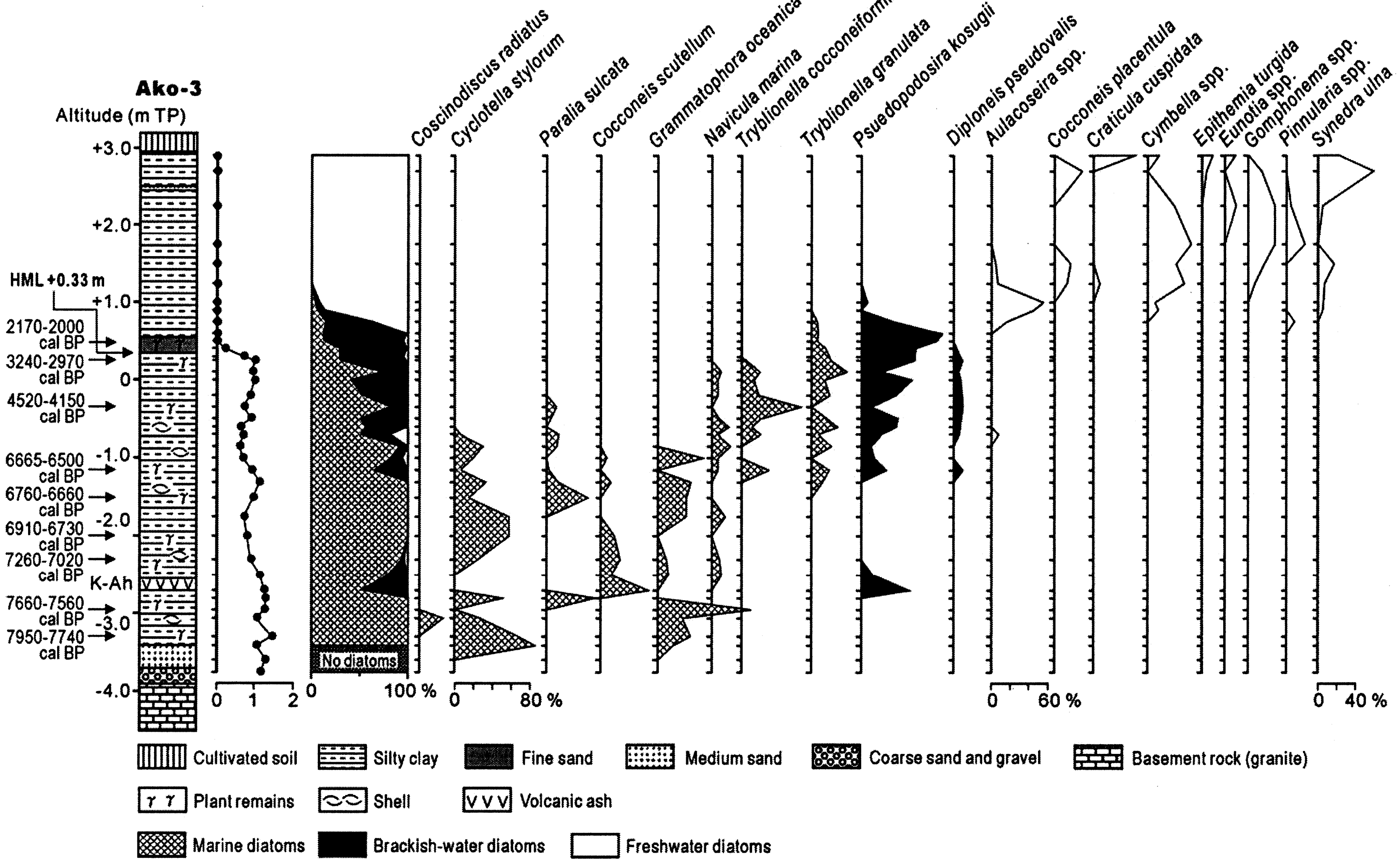

Figure 4 The columnar section, AMS-^{14}C ages, vertical profiles of the sedimentary sulphur (S%) and a diatom diagram for the occurrence of the significant freshwater, brackish-water and marine taxa at the Ako 3 site

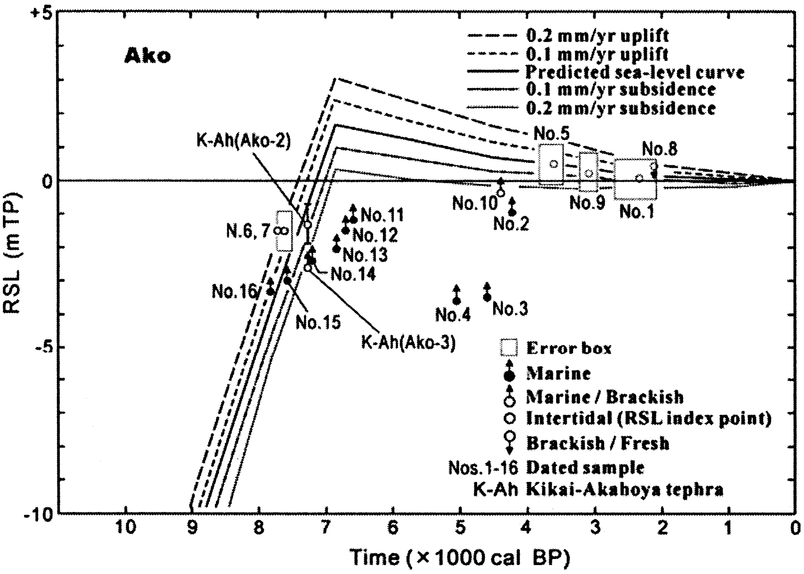

Figure 5 The observed altitude and calibrated ages of the Holocene relative sea-level (RSL) records and predictions at Ako. The ice model after the last glacial maximum is ARC3+ANT4b. Predictions are based on the Earth model with a lithospheric thickness of 30 km, an asthenosphere (200 km) with a viscosity of 10^{20} Pa/s, an upper mantle viscosity of 2×10^{20} Pa/s and a lower mantle viscosity of 10^{22} Pa/s. For sample numbers and RSL tendencies, refer to Table 1. The RSL index point at 7300 cal. BP may indicate the most probable range of the palaeo-mean sea level

maximum is ARC3+ANT4b (Nakada and Lambeck, 1989; Nakada *et al.*, 1991; Okuno and Nakada, 1998). Since the mean sea level (MSL) in the Tokyo Bay is used as the reference sea level in Japan, no attempts to correct the local MSL were made to reconstruct the RSL variation for each site.

In Figure 5, the predicted sea-level curve indicates that the Holocene high stand should be reached around 6900 cal. BP. Although the RSL index point around 6900 cal. BP could not be determined in the field observations, RSL tendencies were indicated and consistent with the predicted curve. By comparing the field observations with the predictions, an estimation of the degree of the crustal movement in the Ako Plain was made. As shown in Figure 5, the dotted lines indicate the predicted RSL variations for the Ako Plain when corrections for tectonic uplift and subsidence are included. A crustal movement rate between +0.2 mm and −0.2 mm per year, corrected for the prediction, fits well with the RSL index points at 7720–7511 cal. BP, 7679–7509 cal. BP, 3828–3471 cal. BP, 3240–2970 cal BP and 2709–2131 cal. BP.

Although changes in the tidal range and possible chronological errors make it difficult to evaluate the exact PMSL, the coast of the Ako Plain may have the best estimate of a tectonic subsidence rate of 0–0.2 mm/yr, depending on the constraint by the PMSL between −2.60 m and −0.70 m derived from K-Ah horizons of Ako 2 and 3 with an age of 7300 cal. BP (Figure 5). This rate appears to explain the absence of middle to late Pleistocene coastal terraces in this plain (Okada *et al.*, 2000).

Holocene relative uplift along the coast from Ako to western Kobe

Along the tectonically active coast of western Kobe, the 1995 Kobe earthquake resulted in vertical uplifts of 0.19 m at Tarumi and 0.07 m at Tamatsu, relative to Takasago (Ishihara *et al.*, 1995). These measurements provide useful information regarding crustal movements in this coastal region. By comparing the observed RSL variations with those derived from model, the Holocene tectonic uplift rates were estimated to be 0.3–0.5 mm/yr for Tarumi and 0.11–0.25 mm/yr for Tamatsu (Sato *et al.*, 2001) (Figure 1B). By considering the results obtained by Sato *et al.* (2001) and the best estimate of the tectonic subsidence of 0–0.2 mm/yr at Ako, uplift rates of 0.3–0.7 mm/yr and 0.11–0.45 mm/yr for Tarumi and Tamatsu, respectively, relative to Ako were derived (Table 2). Meanwhile, the tectonic subsidence rate was estimated to be 0.08–0.23 mm/yr for Takasago (Sato *et al.*, 2003). The Ako Plain exhibits almost the same rate of tectonic subsidence rate as Takasago; thus, the relative uplift rate between Ako and Takasago is estimated to be −0.23 to 0.12 mm/yr (Table 2)

The Ako Plain is located in the divergence zone of two major fault systems, the YFS and RFS, on the west side of the Kinki Triangle, while Tarumi and Tamatsu are located in the

Table 2 Holocene relative uplift rates along the west coast of Kobe.

Site	Crustal uplift rate (mm/yr)	Traverse	Relative uplift rate (mm/yr)
Ako	0 to −0.20	Ako-Tarumi	0.30–0.70
		Ako-Akashi	0.11–0.45
		Ako-Takasago	−0.23 to 0.12
Takasago	−0.08 to −0.23	Takasago-Taumi	0.38–0.73
Akashi	0.11–0.25	Takasago-Akashi	0.19–0.48
Tarumi	0.30–0.50	Akashi-Tarumi	0.05–0.39 (0.15–0.25?)

Crustal uplift rates at Tarumi and Akashi, and at Takasago, and relative uplift rates at these sites are obtained from Sato *et al.* (2001) and Sato *et al.* (2003), respectively.

convergence zone (Figure 1B). The relative uplift along the traverse from Ako to western Kobe is largely the result of the crustal movement. The main seismic sources for the crustal movement along the coast from Ako to Tarumi are the active faults such as the RFS, YFS and Kusadani fault (Figure 1B). Since the Kusadani fault produces relative subsidence to the Kobe area at a rate of less than 0.02 mm/yr based on the displacements and ages of the coastal terraces (Okada *et al.*, 2000), the RFS should induce a relative uplift along the coast, as indicated by the geodetic data in the 1995 earthquake (Ishihara *et al.*, 1995).

The YFS exhibits a left-lateral slip rate of 0.3–0.8 mm/yr and a vertical uplift rate of 0.03–0.075 mm/yr in the north-eastern side of the fault (The Research Group for Active Faults of Japan, 1991). Although the tectonic subsidence at Ako and Takasago may be associated with large strike-slip faulting during earthquakes caused by the YFS, a tectonically stable state is indicated for the coast between Ako and Takasago (Table 2). This indicates that the relative uplift along the traverse from Ako to western Kobe is largely the result of the active faulting of the RFS as the major seismic source during the Holocene.

Conclusions

Holocene sediments were obtained from three sites of the Ako Plain, western Japan, which have not been subjected to significant tectonic activities. Intertidal diatoms are well represented in the sediment assemblages, making it possible to infer Holocene RSL positions. The crustal movement during the Holocene is estimated by comparing sea-level observations with the geophysical model prediction for this area. A crustal movement rate between +0.2 mm and −0.2 mm/yr fits well with the relative sea-level index points for Ako. Based on the constraint of the reconstructed palaeo-mean sea level at 7300 cal. BP, the best estimate of tectonic subsidence of 0–0.2 mm/yr is suggested for the coast of the Ako Plain. The tectonic uplift rates along the tectonically active coast of western Kobe were derived to be 0.3–0.7 mm/yr and 0.11–0.45 mm/yr for Tarumi and Tamatsu, respectively, relative to Ako over the concerned period. The relative uplift along the traverse from Ako to western Kobe is largely the result of the crustal movement resulting from the active faulting of the Rokko-Awaji fault system.

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