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Temporal and Spatial Variations of Accommodation and Sediment Accumulation during Transgressive to Highstand Stages as Reconstructed from a Latest Pleistocene to Holocene Sequence in the Intra-Arc Osaka Basin, Japan

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Abstract

Temporal and spatial variations in accommodation (*i.e.*, paleo-water depth) and sediment accumulation (amount of deposition) in the intra-arc Osaka Basin, Japan, were reconstructed from the post-glacial transgression through the sea-level highstand, a total of 9000 years. At the beginning of the marine transgressive stage (about 11,000 cal y BP), paleo-water depths were shallow and the sediment accumulation was large. The area occupied by Osaka Bay gradually extended and sediment deposition decreased from 11,000 to 6000 cal y BP. During the period of maximum transgression (6000 - 5000 cal y BP), an inner bay, Kawachi Bay with a water depth of 5 - 10 m, was expanded in the inland eastern Osaka area, and paleo-water depths reached a maximum and depositional rates reached a minimum. During the subsequent highstand and small regression (about 5000 cal y BP to the present), however, deposition increased rapidly as a result of river delta and shoreline progradations. Regional differences were observed in accommodation and accumulation between the outer bay area and the inner bay area. During both the transgressive and regressive stages, deposition decreased in the inner bay area. In contrast, in the outer bay area and in the basin overall, deposition was high during the first part of the transgressive stage but it decreased during the maximum transgression, before reaching a maximum during the subsequent highstand and regression. During the regressive stage, fluvial delta progradation led to the forma-

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tion of a thick sequence of delta body sediments. Sediment accumulation was 30% - 40% higher during the regressive stage than that during the transgressive stage.

Keywords

Accommodation, Holocene, Osaka Plain, Paleo-Depths, Sediment Accumulation, Sequence Stratigraphy

1. Introduction

Sequence stratigraphy is a relatively new geological paradigm that is used to classify sedimentary strata and clarify their formation history [1] [2]. Sequence stratigraphic methods have gained worldwide acceptance and have had a great impact on stratigraphic and sedimentological studies, including in Japan [3]. Sequence stratigraphy, however, was originally applied to long-buried strata for which a detailed chronology could not be established. Because of the lack of detailed chronological information, it has been difficult to discuss dynamically the formation of strata.

The uppermost Pleistocene to Holocene succession in Japanese coastal areas is the youngest depositional sequence for which ^{14}C ages have been determined with measurement error of less than 100 years [4]-[6]. Deposition of this sequence began at about 30 - 18 ka above the sequence boundary. During the long marine transgressive stage started from 11 ka, relative sea level rose about 50 m. Maximum transgression was reached at about 6000 - 5000 cal y BP. During the regression that followed the sea-level highstand (about 5000 cal y BP to the present), relative sea level decreased by about 3 m [7]-[9].

In this report, we propose a new method for analyzing sequence formation based on borehole data densely dated with many ^{14}C ages from the Osaka intra-arc basin. We examine temporal and spatial changes in paleo-water depth, representing accommodation, and depositional amounts, representing sediment accumulation during these 9000 years, to clarify the youngest depositional sequence in this region.

2. Analytical Methods and Results

2.1. Borehole Sites and Areas

The Osaka Plain lies in an intra-arc basin in western Japan (**Figure 1**). In this study we used well-dated borehole

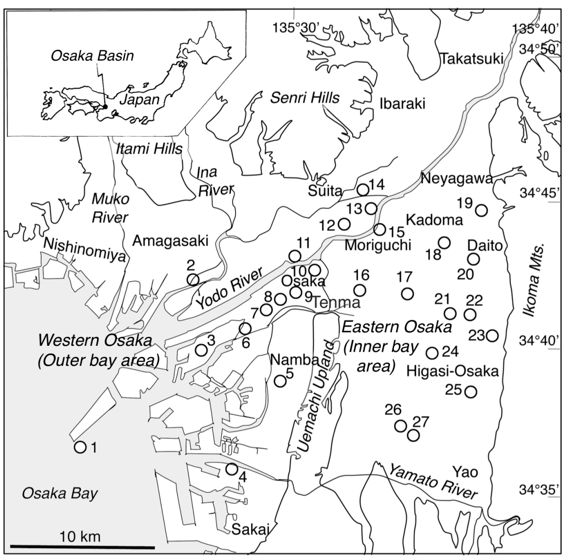

Figure 1. Locations of the studied borehole core sites (1 to 27) on the Osaka Plain.

cores with many calibrated ^{14}C dates obtained by academic research studies [10]-[18]. We also used supplemental data from other boreholes containing the Kikai-Akahoya tephra layer (erupted 7300 cal y BP [19]) [20]-[23] and made accessorily use of uncalibrated ^{14}C dates [21] [24]. These borehole sites are 1: Off Yumeshima [14], 2: Tatsumibashi [24], 3: Shimaya [22], 4: Suminoe [11], 5: Kitatsumori [12] [25] [26], 6: Yoshino [15], 7: Fukushima [22], 8: Umeda [21], 9: Daisanbilu [27], 10: Nagara-Hachiman [17], 11: Shin-Yodogawa [13], 12: Houshin [16], 13: Ousumi [16], 14: Kitaeguchi [22], 15: Moriguchi [18], 16: Gamou, [15] 17: Mattamoroguchi [20], 18: Kadoma [22], 19: Neyagawa [22], 20: Daito [22], 21: Kawachino [15], 22: Kitamiya [15], 23: Kitoragawa [20], 24: Uryudou [20], 25: Ikeshima-Fukumanji [20], 26: Kami [20], and 27: Kyuhouji [20]; as shown in **Figure 1**.

The modern Osaka Plain can be divided into two areas of western and eastern areas by paleo-environmental characteristics. The western Osaka, as describe the outer bay area in this paper, includes the modern western Osaka Plain and Osaka Bay area, and the eastern Osaka, the inner bay area, includes the modern eastern Osaka Plain and/or Paleo-Kawachi Bay. The Uemachi Upland distributed in the central part of the studied area (**Figure 1**) and paleo-spit, called the Tenma Spit, extended northward from the upland, is a boundary between the inner bay and the outer bay areas.

2.2. Determination of Depositional Age

We used a method described previously [4] [28] to construct a depositional curve for each borehole core from the elevations of dated strata (calendar years) (**Figure 2**). The depositional curves were plotted as smoothed curves on an age versus elevation diagram. By referring to these curves, we could determine the depositional age of each horizon, and from the slope of the curve we could determine the depositional rate during each period. The paleo-water depth of the deposits was determined as previously described [4] [25] by comparing the depositional curves with the relative sea-level curve after 11,000 cal y BP in the Osaka Bay area [12] [26]. The paleo-water depth of each horizon was obtained by calculating the elevation difference between the position of the horizon on the depositional curve and sea level at the time of deposition (see **Figure 2**). In this study, paleo-water depth is considered to represent accommodation [29].

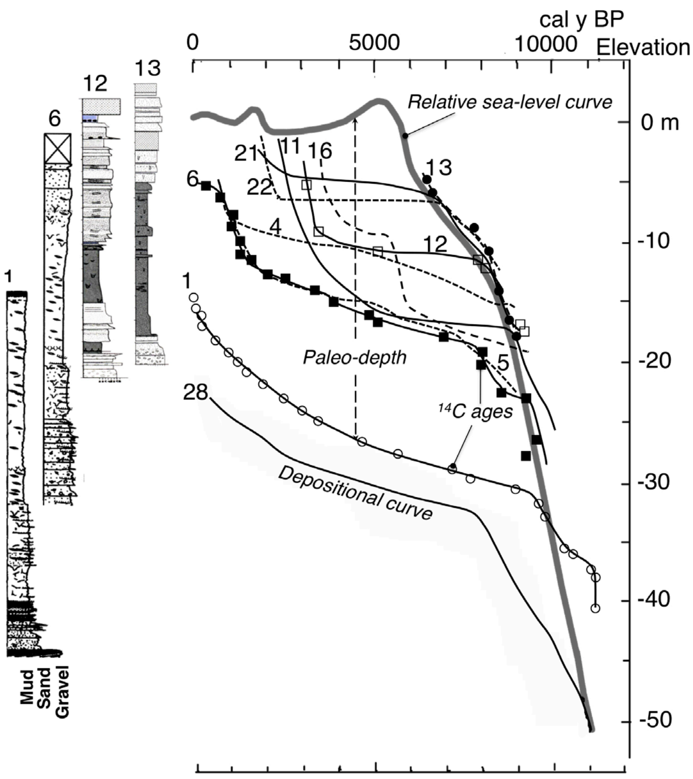

Figure 2. Relative sea-level curve for the Osaka Basin [12] and depositional curves on a elevation-age diagram and columnar sections at some borehole sites on the studied area. Curve of 28 is the Off-Kobe [10].

2.3. Construction of Paleo-Water Depth Maps

Paleo-water depth maps (**Figure 3**) were constructed for the following four time points, selected in part because abundant paleo-water depth data were available and the horizons were decided on easier: 1) 9000 cal y BP, when the marine transgression reached what is today the inland part of the modern Osaka Plain; 2) 7300 cal y BP, when the Kikai-Akahoya tephra was deposited (during the transgressive stage); 3) 5300 cal y BP, the age of the maximum flooding surface; and 4) 3500 cal y BP, the highstand and/or regressive stage, characterized by progradation of the river delta and costal line. At these four time points, sea level, obtained from the relative sea-level curve for Osaka Bay [12], was –20, –8, +3, and –1 m, respectively (**Figure 2**).

We used paleo-geomorphic data for the seafloor to construct the paleo-water depth (bathymetric) maps, in addition to the paleo-water depth data from the cores. For the map of 9000 cal y BP, we used the basement surface proposed sequence boundary between the latest Pleistocene and Holocene [24]. As the sequence boundary reflects erosion due to transgressive wave and tidal effects [23], we have to consider the topographies of pre-transgression, steeper slopes of drowned valley and coastal cliff. To draw the map for 7300 cal y BP, we referred to the map for 9000 cal y BP. We used the coastline at the maximum transgression [30] to draw the map for 5300 cal y BP. To construct the map of 3500 cal y BP, we drew the depth contours between those of the 5300 cal y BP bathymetry and the modern bay floor bathymetry of Osaka Bay. We also referred to the published geologic cross sections [23] [27] [31] [32] in constructing the paleo-water depth maps.

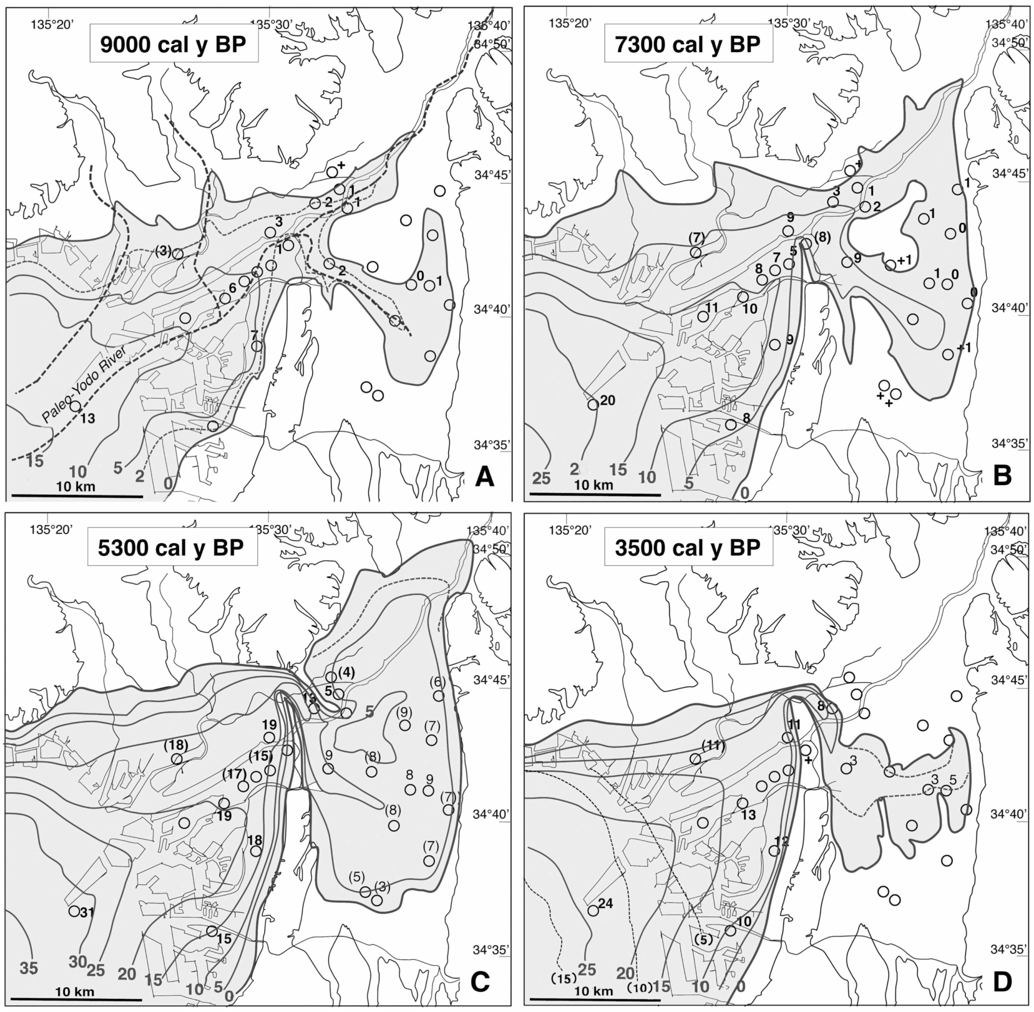

Figure 3. Maps of paleo-water depth (contours) at 9000, 7300, 5300, and 3500 cal y BP. Circles indicate borehole sites, and the adjacent numbers indicate the paleobathymetry (m) at the corresponding site. The paleo-Yodo River and other paleo-river channels are also shown in panel A.

2.4. Construction of Sediment Accumulation Maps

The sediment accumulation on the seafloor between each pair of time points (**Figure 4**) was determined by using the corresponding paleo-water depth maps, constructed as described before. The sediment accumulation between 3500 cal y BP and the present was obtained by using the paleo-water depth map for 3500 cal y BP and modern plain elevations and bay bathymetry of modern Osaka Bay. Temporal variations in the depositional rates and paleo-water depths at representative localities are shown in **Figure 5**. We also calculated the depositional rates (mm/y) per unit area between each pair of time points for the outer bay area (western Osaka), the inner bay area (eastern Osaka), and the whole study area (**Figure 6**).

3. Variations in Paleo-Water Depth and Sediment Accumulation

In the Osaka Basin, the post-glacial marine transgression began after 10,000 cal y BP and was followed by a period of maximum transgression from 6000 to 5000 cal y BP. The subsequent sea-level highstand and slight regression lasted until the present (**Figure 2**) [12]. In this section we describe temporal variations in paleo-water

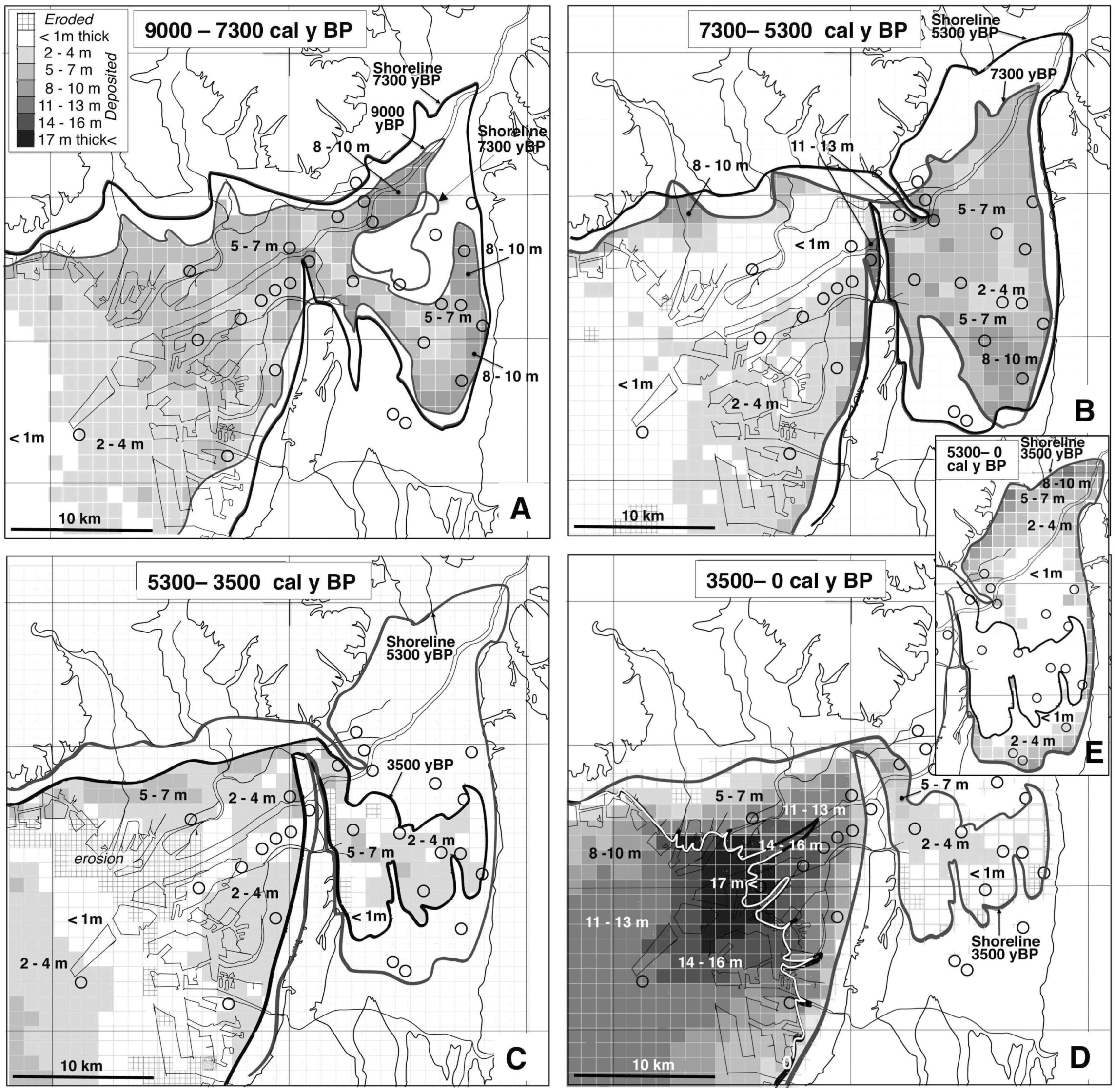

Figure 4. Maps showing the sediment accumulation during 9000 to 7300, 7300 to 5300, 5300 to 3500, 3500 cal y BP to the present, and 5300 cal y BP to the present. The gray scale shows the accumulated thickness (m) per 100 years during the ages.

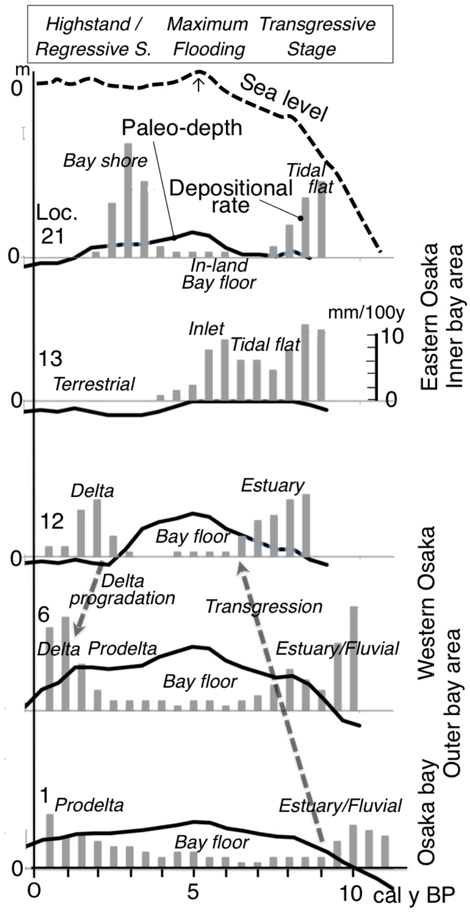

Figure 5. Temporal variations in paleo-water depth (m; bold black lines), depositional rate (mm/100y; gray bars) at some borehole sites and relative sea level curves (bold dashed line) in the Osaka Basin.

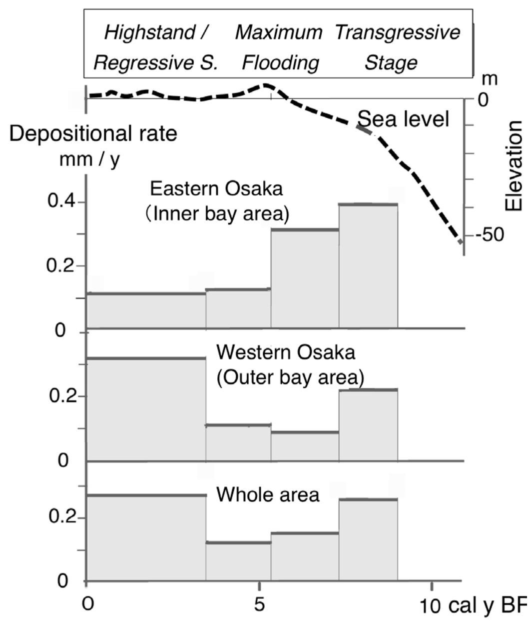

Figure 6. Temporal variations of depositional rates during these 9000 years in the eastern Osaka (inner bay area), western Osaka (outer bay area) and the whole Osaka basin.

depth and sediment accumulation during each of these stages (**Figures 3-6**).

3.1. Transgressive Period

From 9000 to 7300 cal y BP, sea level rose rapidly at a rate of 0.7 cm/y (**Figure 2**). The marine transgression in coastal areas is represented by a flat transgressive surface on the basement [23]. This surface, which was cut by wave and tidal erosion, is easily recognized in the stratigraphic sequence [27].

In the outer bay area of the western Osaka, the transgressive surface is found off Kobe at –51 m (relative to mean sea level) and its age is 11,000 cal y BP [10]; Off Yumeshima, it is at –37.2 m (10,800 cal y BP) [14]; in Shin-Yodogawa, it is at –22.5 m (9500 cal y BP) [13]; in Yoshino, at the mouth of the Yodo River, it is at –20.0 m (9200 cal y BP) [14]; and in Kitatsumori, Nishinari, it is at –22.0 m (9200 cal y BP) [12].

In the inner bay area of the eastern Osaka, transgression occurred later and the transgressive surface is at higher elevations compared with the outer bay area. About 9000 cal y BP, the ocean invaded the narrow, steep-walled incised valleys that had formed in the paleo-Osaka Plain during the glacial period (**Figure 3(A)**), and these valleys began to fill with sediment. From 9000 to 7300 cal y BP, sediment accumulation was highest in the shallow waters in the area of the paleo-Yodo River mouth and in the estuary of inner bay area (**Figure 4(A)**). In the small inner bay, muddy deposits 5 - 10 m thick accumulated in tidal flats, where the water was less than 2 m deep (**Figure 3(A)** and **Figure 4(A)**). As transgression progressed, the area of deep water expanded and sediment accumulation decreased (**Figure 5**).

At about 7300 cal y BP, water depths in the outer bay exceeded 5 m (**Figure 3(B)**), and in these calm, deeper waters, the amount and rate of deposition decreased (**Figure 4(B)** and **Figure 5**). In contrast, in the inner bay (eastern Osaka) area, the accumulated deposits are twice as thick (2 to 10 m; **Figure 4(B)**) as in the outer bay (**Figure 5**). Rapid deposition continued in muddy tidal flats in coastal areas of the inner bay.

From 7300 to 5300 cal y BP, the rate of sea-level rise increased to 1 cm/y (**Figure 2**). Around 5300 cal y BP, at water depths of 25 to 35 m in the outer bay area (**Figure 3(C)**), the sediment accumulation rate was slow, about 40% of that during the early transgression (**Figures 4(B)-(C)**, and **Figure 5**. In the small and shallow inner bay, the tidal flats were replaced by expanded Kawachi Bay with a water depth of 5 to 10 m (**Figure 3(C)**). During this period, thick (5 to 10 m) mud was deposited in the inner bay, and the deposition rate was about four times that in the outer bay (**Figure 4(B)**, **Figure 5** and **Figure 6**). Thus, most suspended sediments from the major rivers (the Yodo and Yamato rivers) were deposited in inner Kawachi Bay during this time interval [26].

3.2. Maximum Transgression

Maximum flooding occurred from 6000 to 5000 cal y BP in the modern Osaka Plain area [12]. Maps showing the coastline during this period have been published previously [21] [30]. At this time, in the shallow waters north of the Uemachi Upland a spit, called the Tenma Spit, formed between the inner bay and the outer bay. This spit, which was 7 to 8 km long and less than 100 m wide, extended northward from the northern end of the upland [27]. A shoal was in the Moriguchi and Kadoma area of the northwestern part of the inner bay area (**Figure 3(B)**) and the northern edge of the shoal had been eroded to a steep cliff by the Yodo River during the glacial period, as shown on a paleogeographic map [21].

At 5300 cal y BP, the age of the maximum flooding period, the water depth was 10 to 35 m in the outer paleo-Osaka Bay and 5 to 10 m in inner bay (**Figure 3(C)**), and both the depositional rate and sediment accumulation were low (**Figure 5** and **Figure 6**).

3.3. Highstand and Regression

After 5300 cal y BP, the area occupied by the inner bay (Kawachi Bay) gradually decreased. By 3500 cal y BP, sea level had decreased to 3 to 4 m below the highstand (**Figure 2**), and the inner bay had become the brackish Kawachi Lagoon [30]. This lagoon was only about 3 m deep (**Figure 3(D)**), and tidal flats were widely distributed along its shores [16]. In Kawachi Lagoon, 1 to 5 m of sand and mud was deposited between 5300 and 3500 cal y BP (**Figure 4(C)**). This amount of deposition was only one-third to one-fourth the amount deposited during the transgressive stage (**Figure 5** and **Figure 6**). In the whole Osaka area, the sediment accumulation decreased; in many areas less than 5 m of sediment was deposited (**Figure 6**).

From 3500 cal y BP to the present, the Yodo River delta has prograded into Osaka Bay [23]. Sandy delta body deposits, 10 to 20 m thick, formed the modern Osaka Plain (**Figure 4(D)**). The sediment accumulation after 3500 cal y BP exceeded that during the transgressive stage by 30% - 40% (**Figure 6**), primarily because of the progradation of the river delta. In the inner bay area, the Kawachi Lagoon became the freshwater Kawachi Lake as regression progressed, and eventually the modern Kawachi Plain emerged. The sediment accumulation also decreased (**Figures 4(D)-(E)**). The prograding sediments and coastal system deposits during this period were composed primarily of sand and gravel. The Tenma Spit and the shallow shoreface of west of the Uemachi Upland became a strand plain under the regressive coastal regime [27].

3.4. Regional Differences of Accommodation and Sediment Accumulation

The variations in paleo-water depth and amounts of deposition in the Osaka basin differ regionally. In particular, the pattern of variation in accommodation and sediment accumulation differs between the outer bay area, western Osaka, and the inner bay area, eastern Osaka (**Figures 4-6**). The depositional rare in the outer bay area reached a maximum during the period of regression during the subsequent highstand and regression (**Figure 6**). By contrast, the depositional rate in the inner bay area was large in the early transgressive period, small during the period of maximum transgression, and reached a minimum during the subsequent highstand (**Figure 6**). The pattern of the variations in the basin overall was similar to that observed in the outer bay area (**Figure 6**). Moreover, the pattern of variation in depositional amounts during the latest Pleistocene to Holocene in the intra-arc Osaka basin is similar to the pattern predicted by depositional sequence models [1] [2].

4. Conclusions

This study presents temporal and spatial variations in paleo-water depth and sediment accumulation during the transgressive, highstand, and regressive stages of the latest Pleistocene to Holocene in the intra-arc Osaka basin. Paleo-water depths were smaller and sediment accumulations were greater in the early transgressive period, but later during the transgression, the outer bay expanded inland and became deeper. Sediment deposition decreased during transgression. The maximum paleo-water depth and minimum depositional rate were reached during the period of maximum transgression. During the subsequent sea-level highstand and regression, deposition increased rapidly as a result of river delta and coastal progradations.

Accommodation and sediment accumulations differed regionally between the outer bay area and the inner bay area. From the transgressive to the regressive stage, the sediment accumulation decreased in the inner bay area; in contrast, in the outer bay area and in the basin overall, deposition was high during the first part of the transgressive stage, decreased during the period of maximum transgression, and increased again during the following highstand and regression. Moreover, during the regressive stage, thick deposits were formed by fluvial delta progradation. As a result, sediment accumulation during this stage was 30% - 40% more than the accumulation during the transgressive stage.

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