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Late Quaternary depositional sequences and landforms in relation to sea-level changes in the Osaka intra-arc basin, Japan: A borehole database analysis

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Development of Late Quaternary depositional sequences in the Osaka intra-arc basin was reconstructed, based on the analysis of sequence stratigraphy and new "Shazam stratigraphy", using numerous and high-density borehole data. The latest Pleistocene to Holocene sequence (I) and the lower late Pleistocene sequence (II) underwent several significant phases: 1) formation of alluvial fans and terraces during regression from marine isotope stage (MIS) 5 to MIS 2; 2) formation of a boundary between the two sequences during rapid sea-level fall of ca. 30–20 ka; 3) development of ravinement surfaces by wave and tidal erosion during the transgression from MIS 2 to MIS 1; 4) development of barrier systems and coastal cliffs during the transgression to the maximum high-stand of 6–5 ka; and 5) progradation of alluvial fans, deltas and strand plains during the high-stand since 5 ka. Depositional facies and systems of the two sequences are different among the western study area around Kobe, the central area with the Nishinomiya-Amagasaki lowland, and the eastern area with the Osaka plain, due to differences in sediment flux, wave, tide, shore current, basement and landforms distribution such as plateau and hills. Development of the sequence II could be also affected by tectonic differences, which fault, fold structure, and flexure. Three regions with different landforms and depositional systems were identified within the Osaka basin. The systems of the three regions correspond to the three major types of the latest Pleistocene to Holocene transgressive/regressive depositional sequences and alluvial plains recognized in Japan.

1. Introduction

Deposition and erosion in coastal areas is controlled by relative sea-level changes associated with global eustasy, tectonics, and sediment flux (Baum and Vail, 1988). Infilling of shallow marine basins along active plate margins, such as the Japanese Islands, is thus intensely affected by sea level changes and local tectonics. However, glacial eustatic changes likely have a greater influence than tectonics for deposition of upper strata, i.e., the strata corresponding to the latest Pleistocene to Holocene (e.g., Shugar et al., 2014).

Because Ice sheets were distributed in North American and European regions during the last glacial maximum, sea level is rising in many regions of the surrounding during the Holocene. In contrast, Asia regions including the Japanese islands are sites located far away from glaciated regions ("far field") and have not been affected by the ice sheets. However, in most coastal areas of the Japanese islands, the sea level was higher than present during ca. 6000–5000 cal BP (the Holocene marine transgression) due to the effect of the hydroisostatic (Nakata and Okuno, 2011). Therefore, the Japanese Islands have experienced a post-glacial transgressive stage (marine isotope stage (MIS) 2–1), a maximum sea-level highstand stage ca. 6000–5000 cal BP (MIS 1), and the present sea-level stagnation stage to small regressive stage (Masuda and Ito, 1999). In the latest Pleistocene to Holocene in Japan, the highstand to small regressive stage is considered a valuable research object for understanding how landform evolution and depositional processes interact by considering how relative sea

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level changes in detail. Population and industry are often concentrated in Japan's alluvial plains, which were formed during the latest Pleistocene to Holocene where extensive infrastructure can be affected by natural disasters. Therefore, understanding the geomorphological and geological systems of the latest Pleistocene to Holocene is also important for environmental conservation and disaster prevention.

Geological characteristics of the latest Pleistocene to Holocene sequence and alluvial plains in Japan have been revealed through aerial photograph interpretation, analysis of a borehole data, ^{14}C dating, and fossil analysis of sediments (Umitsu, 2012). For instance, the base of the latest Pleistocene to Holocene sequence was revealed through analysis of borehole log data and the formation process and sea level changes were defined through reconstruction of coastal areas of the Kanto Plain, Tokyo (Endo et al., 1982, 1995; Matsushima, 1988; Saito, 1995). Ishihara et al. (2011) recently studied alluvial lowlands in inland areas of the Kanto Plain. Kubo (1997) identified buried terraces below the alluvial lowlands, and reconstructed the geomorphological changes since MIS 5e in the lower reaches of the Sagami River Plain, Kanagawa Prefecture. Matsushima (1988) reconstructed paleo sea-level change from fossil shell ages in the Tama River lowlands, Tokyo and Kanagawa. Landform development, depositional processes, and three-dimensional structure of strata have been reconstructed in the coastal areas of the Nobi Plains, Gifu Prefecture and Aichi Prefecture by Iseki (1956), Umitsu (1992), Yamaguchi et al. (2003), and Ogami et al. (2015). The Osaka Plain has been the subject of lithology and geological classification studies for latest Pleistocene to Holocene deposits (Huzita and Maeda, 1966; Mitamura and Hashimoto, 2004; Masuda et al., 2013a) and reconstruction of geologic history (Kajiyama and Ichihara, 1972; Matsuda, 2001). Other studies of the latest Pleistocene to Holocene have been carried out in the Chikugo Plain, Fukuoka Prefecture (Shimoyama et al., 1994), the Ishikari Plain, Hokkaido (Matsushita, 1979; Sagayama et al., 2010), and the Echigo Plain, Niigata Prefecture (Ono, 2012; Tanabe et al., 2012; Tanabe, 2013).

In recent years, a number of local governments, research institutes, and companies have built “geological borehole information databases” in many countries, prefectures, and local areas. Some examples of borehole databases are GeoRecords Plus+ from the British Geological Survey, the borehole database of the Geographical Survey of Ireland, and borehole datasets from the U.S. National Centers for Environmental Information. Some examples in Japan include Kunijiban from the Ministry of Land, Infrastructure, Transport and Tourism, Geo-Station from the National Research Institute for Earth Science and Disaster Resilience, the Tokyo metropolitan government's Geo-webmap, and the Kansai Geoinformatics Network's Kansai Geoinformatics Database. Borehole databases in general are mainly borehole data obtained from building certification applications and public works such as roads and highways. Borehole databases are widely used in fields such as engineering geology, hydrology, hydrogeology, and geotechnical engineering (e.g., Okimura and Torii, 2007; Mielby and Ditlefsen, 2008; Tanaka et al., 2009; Yamamoto et al., 2010; Koshigaya et al., 2011). However, academic studies of the latest Pleistocene to Holocene using borehole databases is limited to analyses of three-dimensional geological models for geologic expression or seismic response characteristics assessment (Yamaguchi et al., 2006; Eto et al., 2008; Funabiki et al., 2011) and of the basal topography of the latest Pleistocene to Holocene (Mitamura and Hashimoto, 2004; Tanabe et al., 2006; Komatsubara, 2014). In particular, a few case studies (e.g., Komatsubara et al., 2010; Styllas, 2013; Masuda et al., 2016) applied sequence stratigraphy knowledge to strata analysis using borehole databases. In addition, although a comparison of the latest Pleistocene to Holocene in different basins has been attempted (e.g., Endo et al., 1995), there have been few studies comparing landforms and strata, and few detailed studies have discussed the processes that occurred in sea-level change (e.g., Kimura et al., 2006; Ishihara et al., 2012). Because the density of data is relatively low and distribution is weighted in certain regions, most previous studies either conducted an overview of the entire basin or investigated only part of the basin in detail. However, geological interpretations that emphasize spatial continuity as sequence stratigraphy can be used to consider the various elements within a basin in detail by using information with a high-density spatial distribution. For this purpose, continuous and three-dimensional analysis of strata using a geoinformation database containing high-density data from urban areas is considered an effective method.

In this study, we carried out a high-resolution spatial analysis of late Quaternary (mainly the latest Pleistocene to Holocene) depositional sequences and landforms of the Osaka intra-arc basin, and estimated a sedimentary system (paleo-landforms) using high-density borehole database and new sequence stratigraphy (Masuda et al., 2013b). We clarify the depositional sequences formed in association with how landforms and strata were affected by relative sea-level changes within the Osaka Basin and describe commonalities and regional characteristics. The Osaka Basin is well-suited for examination of high-resolution spatial analysis and a wide comparison of landforms and strata because the borehole database in this basin has a higher density than those in other areas of Japan and other countries.

2. Study area

2.1. Osaka intra–arc basin

The Osaka intra-arc basin about 70 km east to west and about 50 km north to south. It is surrounded by mountains of about 500–1000 m elevation such as the Rokko, Hokusetsu, Ikoma, and Kongo mountains (Fig. 1). The Osaka inner bay is formed in the seawater inflow area in the center of the basin. Several faults caused by tectonic activities (e.g., the Rokkofault, the Arima-Takatsuki tectonic line, Itami fault and the Ikoma fault (National Institute of Advanced Industrial Science and Technology, 2012)) are distributed around the basin and at the boundary of the mountains. Uemachi fault also extends across the middle of the Osaka basin and the estimated rate of the fault displacement is 0.7–0.2 m/ky for the last 1.2 Ma according to Uchiyama et al. (2001). The interior of the basin is relatively subsiding.

In the Kobe lowlands of the east side of the Osaka Basin, alluvial fans are developed from the front of the Rokko Mountains on the northwest side to the lowlands of the southeast side (Fig. 1). The total catchment area of the river channel network that fed these alluvial fans is about 10–40 km^2 and the rivers are about 8–12 km long and have steep gradients. Many of these rivers are raised bed rivers and are associated with low highlands that act as natural levees. A part of the alluvial fan changes the terrace which corresponds to the lower terrace surface (Geo-Database Information Committee of Kansai, 1998). The alluvial lowland is ranges from 1 to 5 km wide from the coast inland where elevation is below ca. 5 m. The elevation of the Rokko Mountains extending from the northeast to the southwest becomes lower towards the west. A number of active faults are recognized in the base of the southeast Rokko Mountains, which indicates that the southeast portion of the mountains was surface uplift (Huzita et al., 1971). The relative vertical displacement rate between the Rokko Mountains and Osaka Bay is ≥ 1 mm y^{-1} according to Huzita and Kasama (1982, 1983).

In the Nishinomiya–Amagasaki lowlands, the Ina and Muko

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