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Stratigraphic variations in lacustrine sediment gravity-flow deposits intercalated in varved diatomite: An example from the Hiruzenbara Formation, Okayama Prefecture, southwest Japan

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ABSTRACT

The Hiruzenbara Formation, which is distributed within the Hiruzenbara Basin of southwest Japan, includes a section of varved diatomite, representing ca. 8000 y of deposition in a dammed lake formed during the Middle Pleistocene. The varve, on average, ca. 1.5 mm thick, consists of light- and dark-green laminae sets, and is predominately composed of planktonic diatoms. Several facies types of sediment gravity-flow deposits are intercalated in the varved diatomite. In this study, we examined the sedimentary facies, lateral changes, and stratigraphic variations of these sediment gravity-flow deposits. In addition, we also analyzed a time series of varve thickness fluctuations.

Based on their sedimentary facies, composition, and diatom species, sediment gravity-flow deposits in the varved diatomite can be classified as flood-generated or slope-failure-generated. Sedimentary facies analysis indicates that the slope-failure deposits were deposited by slope failure within the lake. Since no significant segregation of rip-up clasts is observed in the deposits, a proximal depositional setting at the base of the lake slope is suggested. The flood-generated deposits have eroded lower contacts, which indicate deposition by hyperpycnal flows. In contrast, deposits with no basal erosion indicate deposition by homopycnal or hypopycnal flows. The thickness time series of the varve shows a thickening-upward trend indicating an increase in diatom production or in diatom shells sizes. Running mean thicknesses show non-stationary periodicities of 200–500 y. The frequency of the deposit varies, but is approximately 10 events per 400 y. Flood deposits in the middle part of the section are dominated by volcaniclastic silt. This suggests that vegetation around the lake was reduced by ash fall, resulting in frequent flood events during this interval. The frequency and thickness of slope failure deposits increases in the lower part of the succession, together with the occurrence of slump scars. The frequency of the deposits in the upper part of the section is approximately 100–500 y, similar to the postulated interval at activity of the nearby Yamasaki Fault System. The results of this study improve our knowledge of paleoenvironmental changes in the study site, and also provide new criteria for classifying sediment gravity-flow deposits in lacustrine sedimentary cores.

1. Introduction

Sediment gravity-flows have been observed not only in deep-sea environments, but also in lake deposits (e.g., Kneller, 2003; Mulder et al., 2003). Because sediment gravity-flow deposits can be used as indicators of flood and earthquake events, deposits in Holocene lacustrine sediments have been correlated with historical records and other paleoenvironmental proxies (e.g., Inouchi et al.,

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1996; Osleger et al., 2009; Wirth et al., 2013; Moernaut et al., 2014). The paleoenvironmental changes recorded in lacustrine deposits can be investigated in greater detail when the sediment gravity-flow deposits created by these events are intercalated in varved sediments (e.g., Kato et al., 1998; Kaufman et al., 2011), because precise ages of the events can be reconstructed from the annually laminated deposits. However, the availability of varved sediments is limited because their preservation requires restricted activity of benthic organisms, sufficient water depth below the wave base (O'Sullivan, 1983), and the non-stationary emergence of a thermocline induced by seasonal environmental changes in the water body (Boygle, 1993). Furthermore, although sediment gravity-flow deposits have been observed in a number of sediment cores from Holocene lakes, reports of lateral changes based on core correlation are limited (e.g., Nakagawa et al., 2012). Thus, the analysis of sedimentary facies and lateral changes in the sediment gravity-flow deposits of lakes will improve the reliability of correlations made between the nature of events and the resultant deposits.

Deposits in deep-sea strata generally represent a diachronic record of allogenic factors such as climate and sea-level change, sediment supply, and tectonics (Kneller et al., 2009). Attempts have also been made to identify the event beds deposited by earthquake-induced debris flows or turbidity currents, and to deduce intervals for these events (e.g., Adams, 1990; Ikehara, 2000, 2001; Nakajima, 2000; Nakajima and Kanai, 2000; Nakajima, 2003; Beck, 2009; Blais-Stevens et al., 2011). Similarly, Holocene lacustrine deposits have often been used to compare to historical records and paleoclimate (e.g., Osleger et al., 2009; Schillereff et al., 2014), and it is thought that intercalated sediment gravity-flow deposits also record flood and slope failure events (e.g., Mangili et al., 2005). In other words, similar to deep-sea deposits, the analysis of the succession of event deposits in lacustrine environments can potentially provide environmental records. However, unlike deep-sea deposits, detailed sedimentary facies and the distribution of lacustrine sediment gravity flow deposits remains understudied. Greater knowledge of these deposits is necessary if we are to understand the events leading to their deposition, and determine whether deposit thicknesses represent event scales.

The Middle Pleistocene Hiruzenbara Formation, which is mainly composed of lacustrine varved diatomite intercalated by sediment gravity-flow deposits, is found throughout the Hiruzenbara Basin, Maniwa City, Okayama Prefecture, southwest Japan (Research Group for Hiruzenbara, 1975a, b; Ishihara and Miyata, 1999). In the varved diatomite, which represents a time span of about 8000 y, cyclical variations in layer thicknesses were induced by variations in solar activity (Ishihara and Miyata, 1999; Masuda et al., 2004). Sediment gravity-flow deposits intercalated in the varved diatomite are well preserved, which facilitates the analysis of thickness distributions and degrees of basal erosion. As the sediment gravity-flow deposits are fine-grained and thinly layered, the effects of depositional topography (e.g., the cyclic stacking of lobes in deep-sea fans; Straub et al., 2009), which can be a problem when extracting allogenic factors, were not observed. Furthermore, the formation forms outcrops in open mining pits, which allows for an analysis of the three-dimensional distribution of the deposits.

In the present study, we investigated the sedimentary facies and lateral changes in sediment gravity-flow deposits of the Hiruzenbara Formation. We analysed their stratigraphic fluctuations and the major trends in the varve thicknesses. Furthermore, based on changes in the sedimentary facies (e.g., compositional changes and fossil content), we investigated the origins of the sediment gravity-flow deposits (i.e., flood or slope failure), and extracted a time series of allogenic change. The results of the former provide new criteria for determining deposit types in sedimentary cores, while those of the latter highlight paleoenvironmental changes in the study area.

2. Regional setting

The Middle Pleistocene Hiruzenbara Formation, mainly composed of lacustrine diatomaceous deposits, occurs within the Hiruzenbara Basin, located near Maniwa City, northern Okayama Prefecture, southwest Japan. The formation is composed of a lower and upper part: the lower part is dominated by clay-bearing diatomite and volcanic sand beds deposited in the Paleo-Hiruzenbara Lake, while the upper part consists of fluvial gravel beds (Research Group for Hiruzenbara, 1975a). The formation extends 18 km from east to west, and 5.5 km from south to north, with the depocenter located near the diatomite mining pits of Showa Chemical Industry Co., Ltd (Fig. 1; Research Group for Hiruzenbara, 1975a). In the eastern part of the Hiruzenbara Basin, a diatomite belonging to the lower part of the formation is exposed, whereas the upper part gradually outcrops toward the western portion of the basin (Research Group for Hiruzenbara, 1975a). Based on the distribution of lacustrine diatomaceous deposits (Research Group for Hiruzenbara, 1975b) and a subsurface geological map based on test well data (Yamada, 1963), the Paleo-Hiruzenbara Lake is thought to have had a maximum depth of ~100 m. The Hiruzenbara Formation overlies Paleozoic metamorphic rocks, Mesozoic volcaniclastic rocks and granites, Pliocene volcanic rocks, and the Middle Pleistocene Hiruzen volcanic rocks (Fig. 1; Research Group for Hiruzenbara, 1975a).

2.1. Hiruzenbara Formation

The lower part of the Hiruzenbara Formation, which is dominated by diatomite, has a maximum thickness of ~60 m and is well exposed in the eastern lowland area of the basin, especially at a type locality of diatomite mining pits (Research Group for Hiruzenbara, 1975a). The diatomite of the lower formation is intercalated by sediment gravity-flow deposits, which consist of volcanic sand beds, gray-purple volcanic ash, and silty layers. The diatomite tends to become siltier toward the western part of the basin, while the study pit in the eastern part of the basin is most likely located in the diatomite-rich (roughly 95%) depocenter of the Paleo-Hiruzenbara Lake. The diatomite of the formation mainly consists of two dominant diatom species: *Stephanodiscus komoroensis* (*Stephanodiscus niagarae* in Research Group for Hiruzenbara, 1975a) and *Puncticulata radiosa* (*Cyclotella comta* in Research Group for Hiruzenbara, 1975a), together with plant and pollen fossils of *Styrax obassia*, *Fagus crenata*, *Tsuga* sp., *Cryptomeria japonica*, *Chamaecyparis obtuse*, *Castanea crenata*, *Aesculus turbinate,* and insect fossils of *Coleoptera* sp. The sediment gravity-flow deposits intercalated in the diatomite have thicknesses of between 1 mm and several cm (Research Group for Hiruzenbara, 1975a), as described in detail in Chapter 4.2.

The depositional ages of the lower Hiruzenbara Formation were estimated from natural remnant magnetism, pollen assemblages, the ages of volcanic basement rocks, and a fission track (FT) age of an intercalated pumice bed. The natural remnant magnetism of the diatomite (Okada, 1982) suggests that the Brunhes Chron and pollen assemblage (Research Group for Hiruzenbara, 1975b) represent Middle-Late Pleistocene interglacial periods. The Middle Pleistocene Hiruzen volcanic deposits, which form the basement rocks in the area, were produced by the Hiruzen volcanoes at 0.9 Ma (Tsukui et al., 1985), and the age of the Paleo-Hiruzenbara Lake postdates this volcanic activity. The FT age of zircon in a pumice bed intercalated in the lowermost part of the diatomite is 0.52 ± 0.11 Ma (Ishihara and Miyata, 1999). These ages and the observed cooling