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Origin and internal organization of widespread composite soft-sediment deformation units in a deep-water forearc basin: The lower Pleistocene Kazusa Group on the Boso Peninsula, Japan

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ABSTRACT

Three main types of soft-sediment deformation structures were identified in a base-of-slope and basin-plain succession (the upper Kiwada Formation) and its age-equivalent submarine slope succession (the lower Takamizo Formation) in the early Pleistocene Kazusa forearc basin on the Boso Peninsula, Japan. The three main types are (1) folded muddy deposits, (2) chaotic muddy deposits, and (3) injected sandy deposits. Chaotic muddy deposits are dominant and are intruded by sandy deposits that locally contain abundant mudstone clasts, which are poorly sorted, and are lithologically similar to debris-flow deposits.

Chaotic muddy deposits in the upper Kiwada Formation are interpreted to have formed in response to downslope movements of unconsolidated surface and shallow subsurface muddy deposits, and are locally associated with folded muddy deposits in their basal part. In contrast, chaotic muddy deposits in the lower Takamizo Formation locally show a diapir-like geometry indicative of vertical intrusion, and are laterally associated with muddy deposits that are folded as a result of dragging of the host muddy sediments. In sequence-stratigraphic terms, the development of the soft-sediment deformation structures is interpreted to have occurred during a lowstand to early rise in glacioeuatatic sea-level cycles during the early Pleistocene. Although we cannot confirm which factor was the most effective triggering mechanism for the generation of the soft-sediment deformation structures in the studied successions, the interplay between (1) the seepage of methane and fossil brine, and (2) seismic shaking during the lowstand and early rise in relative sea level is interpreted to have been important in the Kazusa forearc basin during the early Pleistocene.

1. Introduction

Soft-sediment deformation structures have been reported from various depositional environments, and have been studied as indicators of paleoseismicity, overburden sediment accumulation, dissociation of gas hydrates, and changing seafloor gradients in the context of basin tectonics, paleoclimatic changes, and spatial and temporal variations in sedimentation dynamics (e.g., Jones and Preston, 1987; Maltman, 1994a,b; Mienert, 2004). Ancient soft-sediment deformation structures are observed within beds, bed sets, and larger-scale sedimentary packages with thickness of up to tens to a few tens of meters or more (e.g., Lowe, 1975; Martinsen, 1989; Owen, 1996; Jones and Omoto, 2000; Hurst and Cronin, 2001; Strachan, 2002; van der Merwe et al., 2009). Such structures are classified into three main types: (1) *in situ* deformation with negligible downslope movement, such as structures related to water escaping and sediment loading; (2) detached-deformation, such as slides, slumps, and debris flows; and (3) injection-related deformation, such as clastic dikes and sills (e.g., Maltman, 1994a,b; Oliveira et al., 2009). In terms of downslope sediment delivery in a sedimentary basin, detached-deformation processes have been investigated to obtain information on the timing, mechanisms, and flow transformation of subaqueous mass movements (e.g., Nemec, 1990; Mulder and Cochonat, 1996; Stow et al., 1996; Strachan, 2008). Furthermore, detached-deformation processes are considered one of the main causal mechanisms of geohazards, such as the destruction of seabed infrastructures and the generation of tsunamis, although the magnitude of geohazards varies in response to the scale, location, type, and process of the detached soft-sediment deformation structures (e.g., Masson et al., 2006).

The development of high-resolution marine geophysical techniques has enabled the collection of data relevant to the geometry, distribution patterns, and classification of soft-sediment deformation structures, as well as their generation processes (e.g., Masson et al., 2006; Hurst and Cartwright, 2007; Talling et al., 2007; Moscardelli and Wood, 2008; Bull et al., 2009; Gaferia et al., 2010). Although detailed observations of recent and subrecent soft-sediment deformation structures are important in terms of gaining a better understanding of

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the triggering mechanisms and deformation processes of unconsolidated sedimentary successions, the analysis of outcrop exposures may also provide insights into the detailed processes of deformation, the internal organization, and the spatial and temporal evolution of different types of soft-sediment deformation structures and their constituent facies, which remain poorly understood.

The aim of this study is to document outcrop-scale soft-sediment deformation structures and their constituent facies, and to investigate the spatial and temporal relationships between different types of such structures. In particular, the relationships between detached- and injection-related deformation structures are assessed in order to improve our understanding of the generation of composite soft-sediment deformation structures in submarine slope, base-of-slope, and basin-plain environments in a forearc basin setting. The focus is soft-sediment deformation structures and their constituent facies developed in bed sets and in larger-scale sedimentary successions within basin-plain, base-of-slope, and submarine slope deposits defined as the upper Kiwada Formation and the lower Takamizo Formation of the lower Pleistocene Kazusa Group on the Boso Peninsula, Japan (Figs. 1, 2, and 3). These features allow discussion on the interaction between active-margin tectonics and glacial-and-interglacial environmental changes on the controls in the generation of soft-sediment deformation structures in a deep-water environment.

2. Geological setting

The soft-sediment deformation structures and their constituent facies discussed in this paper occur in the upper Kiwada and lower Takamizo formations in the lower part of the Kazusa Group, which represents the infill of the Pleistocene Kazusa forearc basin on the Boso Peninsula, Japan (Figs. 1 and 3) (Katsura, 1984; Ito and Masuda, 1988). The basin is interpreted to have developed in response to subduction of the Pacific and Philippine Sea plates beneath the Eurasia plate (and later beneath the North American or Okhotsk plate: Seno et al., 1994; Nakajima and Hasegawa, 2010) at the Izu–Bonin Trench and Sagami Trough, respectively (Fig. 1) (Katsura, 1984; Ito and Masuda, 1988). The sedimentary basin was infilled mainly with marine siliciclastic deposits of up to as much as 3000 m in thickness during the period between 2.4 and 0.45 Ma (Fig. 2). The sedimentary successions of the Kazusa forearc basin record paleocurrent directions to the east and northeast, indicating that the paleoslope in the basin inclined to the east or northeast (Katsura, 1984; Ito and Katsura, 1992), and are characterized by marine environments ranging from deep-water basin plain, submarine-fan and slope, to shallow seas (Katsura, 1984; Ito and Katsura, 1992).

The Kiwada Formation is up to 670 m thick and was deposited from 1.8 to 1.2 Ma, as indicated by the age-framework of the Kazusa Group (Takano et al., 2004) (Figs. 2 and 4). The formation is characterized by siltstones and intercalated medium- to very fine-grained sandstones (beds 2–60 cm thick) and volcanic ash beds (Figs. 5 and 6A). Sandstones are graded or graded and parallel-laminated, and some sandstones are also characterized by parallel- and current-ripple cross lamination. Locally, some sandstones contain many volcaniclastic fragments such as pumice and scoria grains. In general, siltstones laterally coarsen in the southwestern proximal area and pass into sandy siltstones. These siltstones and sandy siltstones do not contain any distinct sedimentary structures, and are moderately and locally intensely bioturbated with *Chondrites*- and *Zoophycos*-type burrows. These deposits also contain molluscan and benthic foraminiferal assemblages that indicate a paleowater depth of 400–1500 m (Baba, 1990; Kitazato, 1997). Local occurrence of soft-sediment deformation structures in siltstones also characterizes the Kiwada Formation, which is interpreted to have formed in lower-slope, base-of-slope and basin-plain environments (Katsura, 1984; Ito and Katsura, 1992). In the northeastern distal area, the muddy deposits of the Kiwada Formation also locally contain debris-flow deposits.

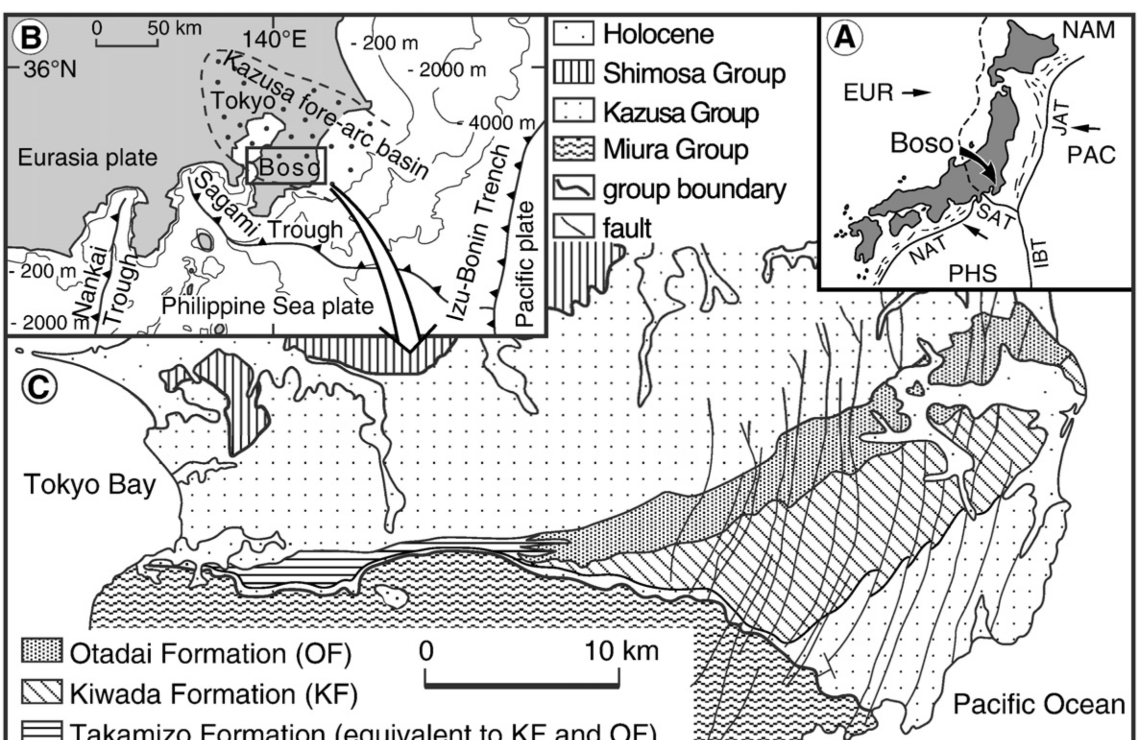

Fig. 1. (A) Plate-tectonic framework of the Japanese Islands. PAC = Pacific plate; PHS = Philippine Sea plate; EUR = Eurasia plate; NAM = North American plate; JAT = Japan Trench; IBT = Izu–Bonin Trench; SAT = Sagami Trough; NAT = Nankai Trough. (B) Index map of the Kazusa forearc basin and the Boso Peninsula, showing the plate-tectonic framework of the studied area. (C) Geologic sketch map of the central part of the Boso Peninsula.
Modified from Takano et al. (2004).