Sedimentary Geology 289 (2013) 62–73

Contents lists available at SciVerse ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Lonestones as indicators of tsunami deposits in deep-sea sedimentary rocks of the Miocene Morozaki Group, central Japan

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ARTICLE INFO

Article history:
Received 5 June 2012
Received in revised form 21 November 2012
Accepted 12 February 2013
Available online 26 February 2013

Editor: B. Jones

Keywords:
Lonestone
Tsunami
Laterally discontinuous distribution
Deep-sea
Non-glacial
Miocene

ABSTRACT

Lonestones are isolated larger clasts enclosed in muddy fine-grained deposits, and are usually interpreted as iceberg-rafted dropstones. This interpretation implies the existence of glaciers (continental ice sheets) and, consequently, a cool climate. However, alternative interpretations are possible, as lonestones may also be deposited by non-glacial processes. Therefore, clarification of the depositional processes associated with lonestones is fundamental for studies based on lonestone-bearing deposits. A field survey of lonestone-bearing deposits from Early Miocene deep-sea sedimentary rocks found around the Chita Peninsula of central Japan suggests that tsunami-induced flows on the sea bottom may also form lonestones. These lonestones are associated with sandy to gravelly deposits, and were deposited by high-energy episodic currents. The main features of these deposits are the multiple stacking of normally graded units, and the laterally discontinuous distribution of coarse-grained clastic material (sands and gravels). Such features are consistent with deposition by tsunamis and suggest that lonestone-bearing depositional successions must be carefully interpreted, especially where lonestones are used as glacial indicators, as some lonestones were probably put in place by ancient tsunami events.

1. Introduction

Lonestone is a term used to describe an isolated gravel-sized clast surrounded by much finer muddy sediments (Bennett et al., 1996; Miller, 1996; Martini et al., 2011). Their unusual appearance presents something of a hydrodynamic paradox because they are found within fine-grained deposits that must have been deposited under low energy conditions. Most lonestones are interpreted as dropstones that were carried by some sort of rafting material, subsequently dropped from it, and then settled into the soft, mud-dominated seafloor or lake bottom. This interpretation resolves the paradox. Although several potential rafting processes have been described (Bennett et al., 1996; Doublet and Garcia, 2004), most dropstones are interpreted as having been rafted by icebergs (e.g., Condon et al., 2002; Kumpulainen, 2007; Fielding et al., 2008; Kawai et al., 2008; Gostin et al., 2010; Perez Loinaze et al., 2010). This interpretation implies the existence of glaciers (continental ice sheets) and a cool climate. In addition, lonestones are easy to recognize in marine depositional successions because of their remarkable appearance. Hence, lonestones have attracted attention as glacial indicators in paleoclimatic studies (Frakes and Francis, 1988; Frakes et al., 1995; Hoffman and Schrag, 2002; Stern et al., 2006).

However, the interpretation of lonestones as iceberg-rafted dropstones could be misleading, because lonestones may also be deposited by non-glacial processes (Bennett et al., 1996; Markwick and Rowley, 1998). Non-glacial lonestones have been classified into two categories: (a) non-glacial dropstones, which are either volcanic projectiles, gastroliths, or wood-rafted dropstones; or (b) dropstone-like outsized clasts formed by mass flows. This range of potential formative processes for lonestones means that they can appear in various sedimentary environments as erratic deposits. Iceberg-rafted lonestones are usually deposited in high latitude sea or lake bottom (St. John, 2008; Knies et al., 2009; Lekens et al., 2009), but occasionally in mid to low latitude one (Waldmann et al., 2010; Hoffman and Halverson, 2011). Lonestones can be deposited in fine-grained shallow marine deposited in warm environments by driftwood (Doublet and Garcia, 2004; Vogt and Parrish, 2012). Gastroliths are possible to be deposited where animals bearing stones in their body live (e.g, Wings, 2007). Lonestones by sedimentary gravity flows are potentially deposited in various environments such as fan delta (Kim et al., 1995), limestone platform (Jones and Desrochers, 1992), alluvial fan (Eyles and Januszczak, 2004). Such lonestones occasionally lead to controversy regarding paleoclimatic reconstructions (Eyles and Januszczak, 2007; Hoffman et al., 2009).

Therefore, in studies using lonestone-bearing deposits, especially glaciomarine deposits, identifying the formation process of the lonestones presents a fundamental problem. As a prerequisite to solving this problem, the processes that may potentially form lonestones must be better understood. In this paper, it is proposed that lonestones may also be deposited by tsunamis; i.e., that tsunami-induced long-period oscillatory flows can deposit dropstone-like outsized clasts onto the sea bottom.

The purpose of this paper is to test the tsunami deposited lonestone hypothesis and consider its implications. It describes and

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0037-0738/$ – see front matter
http://dx.doi.org/10.1016/j.sedgeo.2013.02.008

examines detailed sedimentological data collected from well-exposed outcrops of Miocene deep-sea sedimentary rocks in central Japan, which were deposited in the upper bathyal (a few hundred meters deep) environment of a fore-arc basin. The principal features of the lonestones and associated deposits, i.e. high-energy event origin, multiple stacking of normal graded units, discontinuous distribution of coarse grained portion, and alternation of paleocurrent directions, are consistent with deposition by tsunamis on the offshore sea bottom.

2. Geological background

The lonestones described here are from the Miocene sedimentary rocks of the Morozaki Group, and are found in the southwestern coast of the Chita Peninsula, approximately 50 km south of Nagoya, central Japan (Fig. 1).

Miocene sedimentary rocks, including the Morozaki Group, were deposited in terrestrial to deep-sea environments and occur in several basins around the Tokai area (on the Pacific side, near Nagoya City). The Miocene rocks overlie accretionary belts that comprise the Southwest Japan Island Arc, which consists mainly of sedimentary and metamorphic rocks ranging in age from Triassic to Paleogene. The basement rocks of the Morozaki Group are Cretaceous metamorphic and granitic rocks known as the Ryoke Belt (Fig. 1). In this belt, scattered gneiss bodies, the source rock of the lonestones, are found. Paleontological and geological studies of these Miocene rocks have facilitated the paleogeographic reconstruction of the area (paleocoastline in Fig. 1; Itoigawa and Shibata, 1992). This reconstruction shows that the Morozaki Group was deposited in a deep-sea environment south of the paleocoastline. These Miocene rocks were deposited in forearc basins that were located west of the subduction zone along which the Pacific Plate subducts beneath the Eurasian Plate. It is probable that this area was strongly influenced by earthquakes and accompanying tsunamis at that time.

The Morozaki Group comprises four formations (Fig. 2; Kondo and Kimura, 1987). The basal Himaga Formation is composed predominantly of sandstones and sandstone–mudstone alternations deposited in a shallow marine environment. The Toyohama Formation conformably overlies the Himaga Formation, is about 700 m thick, and composed predominantly of sandstone–mudstone alternations. This is in turn conformably overlain by the Yamami Formation, which is about 220 m thick, and composed predominantly of mudstone and sandstone–mudstone alternations (Fig. 2b). Several beds of bouldery conglomerate appear in this formation. The conglomerates contain meter-scale boulders and are interpreted as tsunami deposits (Yamazaki et al., 1989; Shiki and Yamazaki, 1996; Tachibana and Tsuji, 2011). The depositional succession in the study area correlates with part of the lower Yamami Formation (Fig. 2b). The Utsumi Formation, conformably overlying the Yamami Formation, is composed predominantly of sandstone–mudstone alternations ranging in thickness to more than 70 m. The Morozaki Group yields abundant marine fossils, such as molluscs, fish, sea urchins, and starfish (The Tokai Fossil Society, 1993). Fossil molluscs show that the Himaga Formation was deposited on the lower shelf, while the three other formations were deposited in an upper bathyal environment (a few to several hundred meters deep) (Shibata, 1977). Dating based on foraminifera and fission-track methods shows that the Morozaki Group was deposited during the Early Miocene (Itoigawa and Shibata, 1992).

3. Depositional features of the lonestones and associated deposits

3.1. Geological overview of the study area

In the study area, a depositional succession of Miocene deep-sea sedimentary rocks around 30 m thick outcrops (Fig. 3a) is composed predominantly of mudstones with occasional intercalated sandstones and conglomerates. The mudstones are dark to yellow gray silty-clay, and massive, but occasionally contain thin layers of white or yellow-white silt and very fine sand. These silty layers are strongly bioturbated.

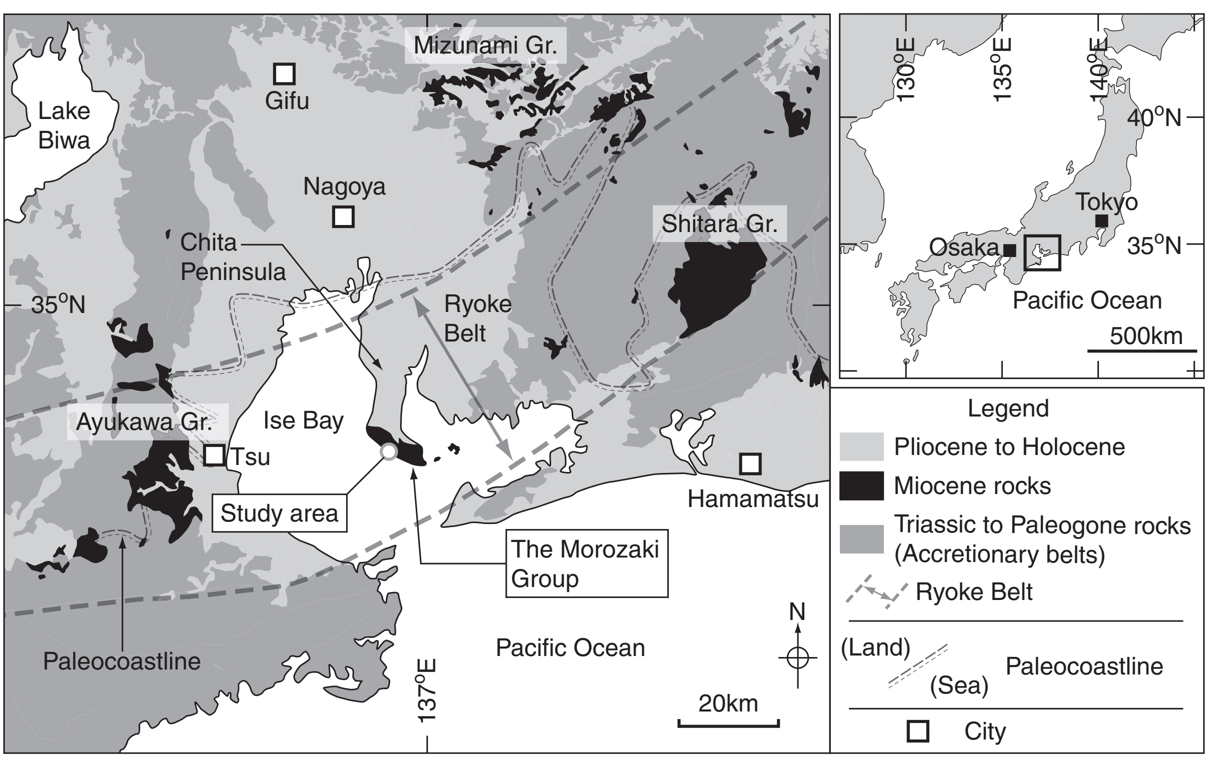

Fig. 1. Simplified geological map of the Tokai area, modified from Seamless Digital Geological Map of Japan (Geological Survey of Japan, 2010). The study area, where the Morozaki Group is found, is located in the south of the Chita Peninsula. The Morozaki Group is situated in the Ryoke Belt. Estimated paleocoastlines are modified from Itoigawa and Shibata (1992).