Ostracodes reveal the sea-bed origin of tsunami deposits

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Ostracodes reveal the sea-bed origin of tsunami deposits

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[1] In Rikuzentakata City, Ostracode assemblages in sediment deposited by the Tohoku-Oki earthquake and tsunami of 11 March 2011 revealed that the sediment was derived from the seafloor from at least 9 m water depth, and was transported inland more than 1 km. The tsunami wave height at this location was higher than 10 m. Four hundred fifty seven modern ostracode assemblages were used in the modern analogue technique to estimate the depth source of the tsunami deposited assemblages. The application of this method to paleo-tsunami deposits may provide insight into past tsunami wave height and potentially earthquake slip and magnitude. **Citation:** Tanaka, G., H. Naruse, S. Yamashita, and K. Arai (2012), Ostracodes reveal the sea-bed origin of tsunami deposits, *Geophys. Res. Lett.*, *39*, L05406, doi:10.1029/2012GL051320.

1. Introduction

[2] Holocene tsunami events have been recognized from sedimentological, micropaleontological, geological, and historical evidence [e.g., *Nelson et al.*, 2008; *Sawai et al.*, 2009]. The terrestrial or marine origin of sediments in the geologic record must be ascertained in order to distinguish between deposits from tsunami events and deposits from other processes. Micropaleontological evidence can be used to determine sediment source [e.g., *Jenkins*, 1993]. For example, the inundation of terrestrial environments by marine waters during Holocene tsunami events has been recognized by examining marine phytoplankton assemblages [*Sawai et al.*, 2004; *Cisternas et al.*, 2005].

[3] Ostracodes are small crustaceans (0.3–30 mm long) with calcified valves that are adapted to practically every aquatic environment [e.g., *Horne et al.*, 2002]. Thus, fossilized valves are an important paleoenvironmental indicator, particularly with regard to Holocene oceanographic, climatologic, and geologic events [e.g., *Boomer et al.*, 2005; *Hussain et al.*, 2010; *Ruiz et al.*, 2010]. Marine podocopid ostracodes are exclusively benthic crustaceans that are abundant in marine sediments [e.g., *Horne et al.*, 2002]. Furthermore, most species show regional endemism, therefore they can serve as an important indicator of local bottom-water environment. Their valves can behave like sediment grains in the water column [*Ikeya and Cronin*, 1993].

[4] The modern analog technique (MAT) statistical method is used to infer paleoenvironmental conditions by comparing fossil ostracode assemblages in terrestrial sediments with similar assemblages in modern environments [*Ikeya and Cronin*, 1993]. In this paper we estimate the water depth of tsunami excavated ostracode assemblages from the Japan 2011 earthquake and tsunami at Rikuzentakata city.

2. Materials and Methods

[5] MAT is a method for estimating paleoenvironmental conditions by comparing modern and fossil assemblages [*Overpeck et al.*, 1985]. The squared chord distance (SCD), which is a measure of dissimilarity between a fossil assemblage and a modern assemblage, is calculated as follows:

$$SCD = \sum_{i=1}^{n} \left(Fp_i^{1/2} - Mp_i^{1/2} \right)^2$$

where Fp_i is the ith number of the specified fossil species, and Mp_i is the ith number of the specified modern species.

[6] *Ikeya and Cronin* [1993] used MAT to estimate the paleoenvironments of Pliocene and Pleistocene formations in Japan by comparing fossil ostracode assemblages with 273 recent samples from the seas around Japan. To examine the source origin of the Japan 2011 Rikuzentakata City tsunami deposits, we used a total of 476 ostracode samples, including 367 recent species from Japan and its adjacent seas, from the published sources [*Zhou*, 1993; *Tsukawaki et al.*, 1998; *Yamane*, 1998; *Ozawa et al.*, 1999; *Tsukawaki et al.*, 2000; *Yasuhara and Irizuki*, 2001; *Nakao and Tsukagoshi*, 2002; *Irizuki et al.*, 2006; *Tanaka*, 2008] and the modern analog data matrix from the U.S. Geological Survey [*Ikeya and Cronin*, 1993]. The SCD values are computed using the Microsoft 2007 with VBA software. The SCD values can range from 0 to 2.0. A value of 0 indicates that the fossil assemblage is completely concordant with the modern population with which it is being compared.

[7] We compared modern ostracode assemblages from 476 sampled stations around Japan (small black plots in Figure 1a) with ostracode assemblages recovered from sediments deposited by the Tohoku-Oki earthquake generated tsunami of 11 March 2011. Our study area is about 4 km southeast of Rikuzentakata City (samples, collected on 25 April; Figure 1b and Table 1). A total of 50 sediment samples were collected in the study area, and 21 samples were used for this study.

3. Results and Discussion

[8] Although we found ostracode assemblages from 5 samples, only one sample (sample c) consisted of more than 100 individuals. So, we only deal with sample c in the following discussion.

[9] The assemblage of sample c is characterized by inner bay species, such as *Bicornucythere bisanensis* (Figure 1c),

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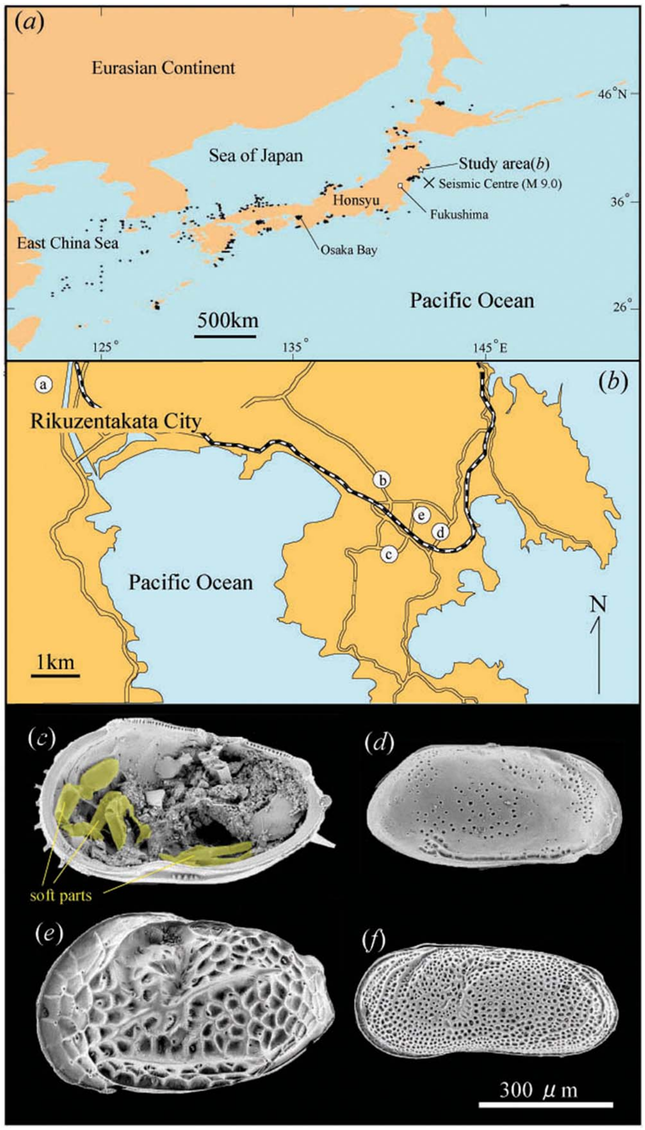

Figure 1. (a) Map of Japan showing the study area location and the epicenter of the Tohoku-Oki earthquake of 11 March 2011 and the black dots represent the 476 modern ostracode samples used in the MAT analysis. (b) Detailed map of the study area. Circled letters a–e show the sampling sites where ostracode specimens were found (see Table 1 for a complete list although only sample c is analyzed herein). Scanning electron microscope images of characteristic species recovered from sample c: (c) *Bicornucythere bisanensis* (preserved soft parts shown in yellow); (d) *Nipponocythere bicarinata*; (e) *Spinileberis quadriaculeata*; (f) *Cytheromorpha acupunctata.*

Nipponocythere bicarinata (Figure 1d), *Spinileberis quadriaculeata* (Figure 1e), and *Cytheromorpha acupunctata* (Figure 1f). This assemblage also contains as *Aurila corniculata* and *Xestoleberis hanaii* which also occur on sediment substrates that support plant growth (seaweed, seagrass) [*Kamiya*, 1988]. The two species indicate derivation from within the photic (shallow) zone (Table 1). *Pontocythere subjaponica* and *Semicytherura miurensis* has been found at the shallow, sandy bottom environments [*Kamiya*, 1988]. Living *Neonesidea oligodentata* has been found at calcareous algae of the intertidal zone [*Smith et al.*, 2005]. Some of the ostracode valves (18%) of sample c were well preserved (Figures 1d–1f) and translucent. Soft parts were preserved in one *B. bisanensis* specimen (Figure 1c) which implied immediate derivation from a biocoenosis. However, many of the ostracode valves (82%) were opaque and fragmented, indicating that the ostracode assemblage in sample c was derived from another part [*Zhou*, 1995] on the seafloor. *Brouwers* [1988] discussed autochthonous or allochthonous ostracode assemblages from recent sediments off Alaska, USA. She mentioned that the assemblage is identified as allochthonous when the ratio of the number of adult valves and that of juvenile valves in a sample is 1:3 to 1:5. Table 1 shows that the ratio of adult and juvenile of sample c is 1:3. Thus, the ostracode assemblages from our sample c is identified as autochthonous based on *Brouwers*' [1988] opinion. This is supported by the observation that 27% of total individuals from sample c were articulated carapace. To summarize, the ostracode assemblage in tsunami deposit appears autochthonous from the viewpoint of the ratio of adult and juvenile individuals in a sample. This characteristic ostracode assemblage and the preservation of soft parts are useful when we identify the tsunami deposit from the (deep) older sediments. Thus, it is appropriate to use MAT to compare the sample c assemblage with modern ostracode assemblages from around Japan.

[10] By applying MAT, we determined that the ostracode assemblage in sample c was most similar to the ostracode assemblage of sample OK 28 from Osaka Bay, which was collected in 9 m of water depth (Figure 1a and Table S1 in the auxiliary material).[1] Table S1 shows that the valves of SCD of five samples were calculated <0.8, with depths ranging from 9 m to 30 m. Among them, the most closely matched sample was derived from a water depth at 9 m. The frequency distribution of water depths of 476 samples are shown in Figure S1. The number of samples used the MAT which were collected from <10 m water depths (n > 20) is larger than that from 10 m to 20 m water depths. This result indicates that the database of the MAT used in this study is not artificially affected, for example by the difficulty of collecting sediment less than 10 m from a boat. Thus, sample c was derived from at least a depth of 9 m.

[11] Therefore, we infer that the sediments of sample c were derived from the seafloor at least 9 m water depth and deposited inland more than 1 km from the sea coast by the tsunami of 11 March 2011 (Figure 1b). These results suggest that the tsunami waves generated by the 2011 Tohoku-Oki earthquake eroded the seafloor under at least 9 m of water.

[12] Thus, the wave height of the tsunami and the sediment water depth source were similar. This suggests a relationship between tsunami wave height and wave excavation depth which is then translated onshore and preserved in the ostracode assemblage of tsunami deposits, although tsunami wave heights are generally influenced by many factors, such as width, depth and shape of a baymouth, dip, width, length and shape of the aggradation lowland [*Mizutani*, 2011].

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL051320.

Table 1. Ostracode Assemblages (Raw Numbers) Discovered From 5 Tsunami Deposit Samples in Rikuzentakata City

	a					b					c					d					e				
Species	ac	av	jc	jv	to	ac	av	jc	jv	to	ac	av	jc	jv	to	ac	av	jc	jv	to	ac	av	jc	jv	to
Ambtonia obai											1	0	2	0	3	0	0	0	1	1					
Angulicytherura miii	0	1	0	1	1																				
Aurila corniculata											1	4	1	8	14	2	0	3	6	11					
Bicornucythere bisanensis											0	6	2	28	36	0	5	0	12	17					
Bythoceratina hanaii											0	0	0	2	2										
Bythoceratina cf. *hanaii*											0	0	0	2	2										
Callistocythere japonica											0	0	0	1	1										
Callistocythere undulatifacialis											0	0	0	2	2										
Coquimba ishizakii											0	1	0	2	3										
Cornucoquimba tosaensis											0	1	0	2	3						1	0	0	0	1
Cytherois nakanoumiensis											1	0	0	1	2										
Cytheromorpha acupunctata											4	0	1	1	6	2	0	1	0	3					
Hemicytherura kajiyamai											3	0	0	0	3	1	0	0	0	1					
Howeina leptocytheroidea											3	0	0	0	3	0	1	0	0	1					
Kobayashiina donghaiensis											0	0	0	2	2										
Loxoconcha epeterseni											0	1	0	0	1						0	0	0	1	1
Loxoconcha japonica											0	1	0	1	2										
Loxoconcha ozawai											0	2	0	0	2										
Loxoconcha uranouchiensis											0	0	0	3	3	0	0	0	1	1					
Neonesidea oligodentata											0	0	1	8	9	0	0	1	1	2					
Nipponocythere bicarinata											0	3	3	2	8	0	1	0	0	1					
Parakrithella pseudadonta											1	0	0	0	1										
Pistocythereis bradyformis											1	0	0	1	2										
Pontocythere subjaponica						0	1	0	0	1	3	0	3	0	6	0	1	0	1	2	0	1	0	3	4
Schizocythere kishinouyei																0	0	0	2	2					
Semicytherura miurensis											5	0	0	0	5										
Spinileberis quadriaculeata											4	4	2	6	16	9	1	0	6	16					
Xestoleberis hanaii											0	2	0	17	19	0	1	0	2	3	0	0	0	1	1
Xestoleberis sagamiensis											0	0	0	1	1										
Xestoleberis setouchiensis																1	0	1	0	2					
Sub-total (Adult carapace)	0					0					27					15					1				
Sub-total (Adult valve)		1					1					25					10					1			
Sub-total (Juvenile carpace)			0					0					15					6					0		
Sub-total (Juvenile cvalve)				0					0					90					32					5	
Number of individual(s)					1					1					157					63					7
Carapace/total			0					0					0.27					0.33					0.14		
Adult/total			100					100					0.33					0.40					0.29		

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