Korean Journal of Environmental Biology

Original article

https://doi.org/10.11626/KJEB.2019.37.3.268

Korean J. Environ. Biol.
37(3) : 268-277 (2019)
ISSN 1226-9999 (print)
ISSN 2287-7851 (online)

Vertical and horizontal distributions of ellipsoidal *Alexandrium* (Dinophyceae) cysts in coastal sediment with special reference to paralytic shellfish poisoning caused by tsunamis - a case study of Osaka Bay (Japan) and the southern coast of the Korean Peninsula

Kazumi Matsuoka*, Keigo Yamamoto[1], Satoshi Akiyama[1], Natsuhiko Kojima[2] and Hyeon Ho Shin[3]

C/O Institute for East China Sea Research, Nagasaki University, Nagasaki City 851-2213, Japan
[1]Research Institute of Environment, Agriculture, and Fisheries, Osaka Prefecture 599-0311, Japan
[2]Department of Biology, Osaka Institute of Technology, Osaka City 535-8585, Japan
[3]Library of Marine Samples, Korea Institute of Ocean Science and Technology, Geoje 53201, Republic of Korea

***Corresponding author**
Kazumi Matsuoka
Tel. +81-75-932-2062
E-mail. kazu-mtk@nagasaki-u.ac.jp

Received: 5 July 2019
Revised: 2 August 2019
Revision accepted: 14 August 2019

Abstract: Severe damages will result in human society, when several different critical natural phenomena coincide. One example relates to the resting cysts of *Alexandrium* species (dinoflagellates that cause paralytic shellfish poisoning), which are preserved in surface sediments throughout Osaka Bay, Japan. These cysts have been found to accumulate particularly densely in shallow areas in the inner parts of Osaka Bay, where a tsunami caused by an earthquake could occur any time. Damage by a tsunami could cause a change of the coastal ecosystems at Osaka Bay including the resuspension of surface sediments containing resting *Alexandrium tamarense* cysts and the subsequent redistribution of the cysts in newly deposited sediment. Under certain environmental conditions, these cysts could germinate and form dense blooms, leading to paralytic shellfish poisoning. Such a scenario could also affect other coastal areas, including the southern coast of the Korean Peninsula.

Keywords: *Alexandrium* cyst, PSP, Osaka Bay, Tsunami, Korean Peninsula

INTRODUCTION

Coastal ecosystems are affected by changes in environmental conditions (both natural and anthropogenic), and their ongoing continuous evolution is well documented. Unusual natural phenomena, such as typhoons/hurricanes or extreme temperatures, can have severe effects on coastal ecosystems (e.g., UN Atlas of the Oceans 2005: www.oceansatlas.org/results-search/en/?querystring=2005). In particular, a tsunami caused by an earthquake, submarine landslide, or other disturbance could cause an unusual set of conditions. The tsunami that followed the Great East Japan Earthquake in 2011 had a notable effect on the environment, mainly on coastal topography and ecosystems in coastal wetlands, on the shallow sea floor, and on the shoreline (Ecosystem Sub-Working Group 2011; Hara and Higuchi 2013). The tsunami that followed the Indian Ocean Sumatran Earthquake in 2004 reportedly affected phytoplankton populations recorded by IRS P4-Ocean Colour Monito data (Tang *et al.* 2009) and benthic ecosystems which showed large declines in abundance and diversity (Whanpetch *et al.* 2010). After the Great East Japan Earth Quake, several studies related with dinoflagellate cyst ecology were performed by Nishitani *et al.* (2012), Kamiyama *et al.* (2014), Natsuike *et al.* (2014), Ishikawa *et al.* (2015), and Matsuoka *et al.* (2018). These studies focused the unusual big blooms of *Alexandrium tamarense* (Lebour) Balech accompanied with paralytic shellfish poisoning (PSP) along the Sanriku Coast of East Japan.

Intensive *A. tamarense* blooms were first observed in Osaka Bay in 2002. This dinoflagellate species had not previously formed such dense blooms in Osaka Bay or caused any paralytic shellfish poisoning (PSP) incidents in the area (Yamamoto 2004). Several studies of the horizontal distributions of ellipsoidal dinoflagellate cysts identical to *A. tamarense* in Osaka Bay have been undertaken recently, and it was found that these ellipsoidal cysts are abundant in surface sediments (Yamamoto *et al.* 2009, 2011; Matsuoka and Ishii 2018). A high cyst density may play an important role in the formation of blooms by acting as a seed population. *A. tamarense* blooms now occur almost every year in the inner part of Osaka Bay and off its east coast. However, the accumulation of large numbers of *A. tamarense* cysts in coastal ecosystems can pose other important risks. For example, the coastal ecosystem and fishing industry of the Sanriku Coasts were badly affected by strong *A. tamarense* blooms caused by the germination of large numbers of cysts after the Great East Japan Earthquake (Ishikawa *et al.* 2015; Matsuoka *et al.* 2018). It has been predicted that a huge earthquake (referred to as the Tonankai Earthquake) will affect the Pacific coast of Western Japan in the near future. This earthquake and the tsunami likely to follow it will cause serious damage to the environment and to society as a whole (Osaka Prefecture 2013).

Here, we investigate the possibility of the occurrence of harmful algal blooms after the Tonankai Earthquake using data on the spatiotemporal distribution of ellipsoidal *Alexandrium* cysts in surface sediments in Osaka Bay. We also investigate the possibility of similar effects on the south and east coasts of the Korean Peninsula, where ellipsoidal *Alexandrium* cysts are also preserved in surface sediments.

MATERIALS AND METHODS

Three 10 cm long core samples, labelled OS 2, OS 19, and OS 23, were collected in 2017. The sampling sites are marked on Figure 1. Core OS 23 was collected from the inner part of Osaka Bay, and core OS 19 was collected from the southeast coast of the bay. The samples were collected using a KK-type gravity corer (Kimata *et al.* 1960). Core OS 2 was collected from the bed at the mouth of the Yodo-Gawa River. The sediment in each core was composed of medium to fine silt. The OS 19 and OS 23 cores were cut into 1 cm slices, and each slice was stored in a black plastic bottle to exclude light. Only the top and bottom 1 cm sections of the OS 2 core were analyzed due to the particular location of the sample. The samples were processed using a method described by Matsuoka and Fukuyo (2000). Each sample was treated with HCl and HF at room temperature to remove calcium carbonate and silicate particles, respectively. Each sample was then passed through 125 and 20 μm stainless steel sieves. The material that passed through the 125 μm sieve but retained by the 20 μm sieve was analyzed. Dinoflagellate cysts (including ellipsoidal *Alexandrium* cysts) in each sample were counted by examination using an optical microscope with a magnification of 400–600. Dinoflagellate cysts were identified following the procedure described by Matsuoka and Fukuyo (2000) and Matsuoka and Ishi (2017) (Table 1).

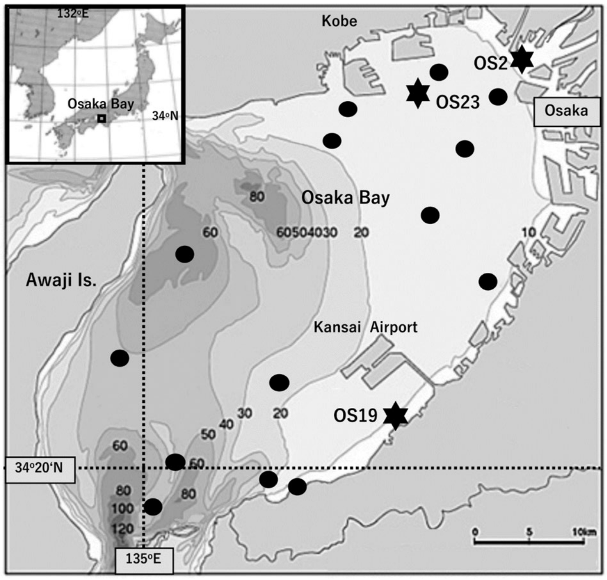


Fig. 1. Sampling locations in Osaka Bay. Closed circles (●) indicate stations used by Matsuoka and Ishii (2018), and stars (★) indicate the sites of the three cores in the present study. Numbers on the contour lines indicate water depths (m).

In recent studies, new species names and combinations have been proposed for the species previously known as *A. tamarense, Alexandrium fundyensei* Balech, and *Alexandrium catenella* (Whedon and Kofoid) Balech (John *et al.* 2014; Fraga *et al.* 2015). However, use of the new species name *A. catenella*, instead of the old name *A. tamarense* and use of the new species name *Alexandrium pacificum* R.W. Litaker instead of the old name *A. catenella*, causes confusion when

Table 1. List of dinoflagellate cyst species found in sediment from Osaka Bay

Cyst-based name	Plankton-based name	Remarks
	GONYAULACALES	
Spiniferites bentori (Rossignol 1964) Wall & Dale 1970	*Gonyaulax digitale* (Pouchet 1883) Kofoid 1911	
Spiniferites bulloideus sensu Wall (1965)	*Gonyaulax scrippsae* Kofoid 1911	non Deflandre & Cookson 1955
Spinferites delicatus Reid 1974	*Gonyaulax* sp.	
Spiniferites elongatus Reid 1974	*Gonyaulax elongate* (Reid 1974) Ellegaard *et al.* 2003	
Spiniferites hyperacanthus (Deflandre & Cookson 1955) Cookson & Eisenack 1974	*Gonyaulax* cf. *spinifera* (Claparéde & Lachmann 1859) Diesing 1866	
Spiniferites mirabilis (Rossignol 1964) Sarjeant 1970	*Gonyaulax* cf. *spinifera* (Claparéde & Lachmann 1859) Diesing 1866	
Lingulodinium machaerophorum (Deflandre & Cookson 1955) Wall 1967	*Lingulodinium polyedrum* Dodge 1989	
Operculodinium centrocarpum sensu Wall & Dale (1968)	*Protoceratium reticulatum* (Claparéde & Lachmann 1859) Bütschli 1885	non Deflandre & Cookson 1955
Tuberculodinium vancampoae (Rossignol 1964) Wall 1965	*Pyrophacus steinii* (Schiller 1935) Wall & Dale 1971	
Alexandrium tamarense/catenella (Ellipsoidal cyst)	*Alexandrium tamarense/catenella*	According to John *et al.* (2014), *Alexandrium catenella* is formarly attributed as *A. tamarense* and *A. fundyense,* and *A. pacificum* is formerly called as *A. catenella* in Japan.
	PERIDINIALES	
Brigantedinium simplex (Wall 1965) Reid 1977	*Protoperidinium conicoides* (Paulsen 1905) Balech 1974	
Brigantedinium cariacoense (Wall 1965) Reid 1977	*Protoperidinium avellana* (Meunier 1919) Balech 1974	
Brigantedinium majusclum Reid 1977	*Protoperidinium sinuosum* Lemmermann 1905	
Brigantedinium spp.	*Protoperidinium* spp.	
Quinquecuspis concreta (Reid 1977) Harland 1977	*Protoperidinium leonis* (Pavillard 1916) Balech 1974	
Lejeunecysta sp.	*Protoperidinium* sp.	
Selenopemphix nephroides (Benedek 1972) Benedek & Sarjeant 1981	*Protoperidinium subinerme* (Paulsen 1904) Loeblich III 1970	
Selenopemphix quanta (Bladford 1975) Matsuoka 1985	*Protoperidinium conicum* (Gran 1900) Balech 1974	
Stelladinium reidii Bradford 1975	*Protoperidinium compressum* (Abé 1927) Balech 1974	
Stelladinium stellatum (Wall 1965) Reid 1977	*Protoperidinium compressum* (Abé 1927) Balech 1974	
Trinovantedinium applanatum (Bradford 1977) Bujak & Davies 1983	*Protoperidinium shanghaiense* Gu, Liu & Mertens 2015	
Votatdinium spinosum Reid 1977	*Protoperidinium claudicans* (Paulsen 1907) Balech 1974	
Votatdinium calvum Reid 1977	*Protoperidinium latidosale* Balech 1974	
Votatdinium rhomboideum Gurdebeke, Mertens, Pospelova, Matsuoka, Li & Louwye 2019	*Protoperidinium quadriblongum* Sarai, Kawami, Yamaguchi & Matsuoka 2013	*Votatdinium calvum* (rhombic type)
Cyst of *Protoperidinium lattisinum*	*Protoperidinium lattisinum* (Kofoid 1907) Balech 1974	
Cyst of *Protoperidinium americanum*	*Protoperidinium americanum* (Gran & Braarud 1935) Balech 1974	
Cyst of *Protoperidinium acromaticum*	*Protoperidinium acromaticum* (Levander 1902) Balech 1974	

Table 1. Continued

Cyst-based name	Plankton-based name	Remarks
Cyst of *Protoperidinium* spp.	*Protoperidinium* spp.	
Cyst of *Peridinium quinquecorne* Abé	*Peridinium quinquecorne* Abé 1927	
Cyst of *Scrippsiella* spp.	*Scrippsiella* spp.	
Dubridinium cavatum Reid 1977	*Diplopsalopsis orbicularis* (Paulsen 1907) Meunier 1909	
Cyst of *Niea acanthocysta*	*Niea acanthocysta* (Kawami, Iwataki & Matsuoka 2006) Liu, Mertens & Gu 2015	
Echinidinium aculeatum Zonneverd 1997	Unknown	
Echinidinium spp.	Unknown	
	GYMNODINIALES	
Cyst of *Polykrikos kofoidii*	*Polykrikos kofoidii* Chatton 1914	
Cyst of *Polykrikos schwartzii*	*Polykrikos schwartzii* Bütschli 1873	
Cyst of *Levanderina fissa*	*Levanderina fissa* (Levander) Moestrup, Hakanen, Hansen, Daugbjerg & Ellegaard 2014	Formarly called as Cyst of *Gyrodinium instriatum*
Cyst of *Cocholodinium* sp.	*Cocholodinium* sp.	

attempting to interpret data published before 2014. We therefore use the old species names in this study.

RESULTS

Vertical distributions of dinoflagellate cysts in the three cores samples

Dinoflagellate cysts of >45 species in 21 genera were found in core OS 19. The cysts belonged to five genera and nine species in the Gonyaulacales, three genera and four species in the Gymnodiniales, and 13 genera and 39 species in the Peridiniales. The dinoflagellate cyst densities ranged from 1,109 cysts g^{-1} at 5–6 cm deep to 2,016 cysts g^{-1} at 8–9 cm deep, and the mean cyst density was 1,563 cysts g^{-1}. (Fig. 2, Table 2). Heterotrophic dinoflagellate cysts predominated, and contributed >70% of the cysts in each sample. The heterotrophic dinoflagellate cyst contribution increased from the bottom to the top of the sample. As shown in Figures 2 and 3, ellipsoidal *Alexandrium* cysts were most abundant at a depth of 1–2 cm, where the cyst density was 935 cysts g^{-1}, and least abundant at a depth of 9–10 cm, where the cyst density was 11 cysts g^{-1} (Fig. 2).

Dinoflagellate cysts from >40 species in 19 genera were identified in core OS 23. These cysts belonged to five genera and nine species in the Gonyaulacales, three genera and four species in the Gymnodiniales, and 13 genera and 39 species in the Peridiniales. The dinoflagellate cyst densities ranged from 1,684 cysts g^{-1} at 7–8 cm to 3,375 cysts g^{-1} at 6–7 cm, and the mean cyst density was 2,395 cysts g^{-1}. Heterotrophic dinoflagellate cysts were extremely abundant, and contributed >65% of the cysts throughout the core (Fig. 2, Table 2). Ellipsoidal *Alexandrium* cysts were most abundant at 0–1 cm, where the cyst density was 616 cysts g^{-1}, and least abundant at 4–5 cm, where the cyst density was 20 cysts g^{-1} (Fig. 2).

Dinoflagellate cysts from 12 genera and 20 species were abundant in the top 1 cm of core OS 2, but few ellipsoidal *Alexandrium* cysts, *Brigantedinium simplex* (Wall) Reid, and *Votadinium calvum* Reid were found (Table 2). Ellipsoidal *Alexandrium* cysts were most abundant at the top of the core, where the cyst density was 1,080 cysts g^{-1}, and least abundant at the bottom of the core, where the cyst density was 190 cysts g^{-1}.

Horizontal distribution of dinoflagellate cysts in surface sediment in Osaka Bay

The results of our study and Matsuoka and Ishii (2018) are combined in Figure 5. The dinoflagellate cyst densities were higher in the northern part of Osaka Bay than elsewhere. Ellipsoidal *Alexandrium* cysts were abundant in the northern part of Osaka Bay, at the mouth of the Yodo-Gawa River, and along the east coast of Osaka Bay (Fig. 4). The ellipsoidal *Alexandrium* cyst density was highest (3,610 cysts g^{-1}) at Station 7 in Matsuoka and Ishii (2018) and lowest (4 cysts g^{-1}) at Station 3 in the same work. Ellipsoidal *Alexandrium* cysts were abundant in the inner part of Osaka Bay, but were also found in the southern part of the bay. Other

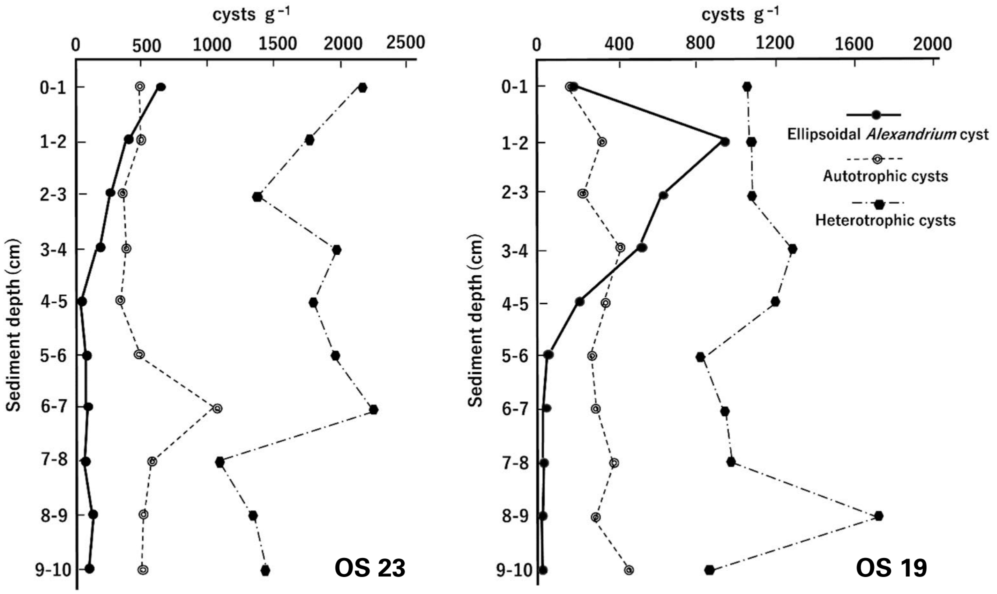


Fig. 2. Vertical distributions of three dinoflagellate cyst groups (ellipsoidal *Alexandrium* cysts, autotrophic dinoflagellate cysts, and heterotrophic dinoflagellate cysts) in cores OS 19 and OS 23.

Table 2. Occurrences of phototrophic, heterotrophic, and ellipsoidal *Alexandrium* cysts in sediment cores OS 19 and OS 23 from Osaka Bay

					OS19					
Sample depth (cm)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Cyst type	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}
Ellipsoidal *Alexandrium* cyst	168	935	620	516	195	36	33	12	12	11
Cyst of phototrophic species*	150	319	210	408	325	257	273	373	276	445
Cyst of heterotroph species	1,050	1,078	1,070	1,296	1,183	816	946	972	1,728	858
					OS 23					
Sample depth (cm)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Cyst type	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}	cysts g^{-1}
Ellipsoidal *Alexandrium* cyst	616	384	242	171	20	69	75	52	120	85
Cyst of phototrophic species*	464	464	330	361	320	460	1,050	552	494	493
Cyst of heterotrophic species	2,156	1,744	1,364	1,976	1,800	1,965	2,250	1,080	1,349	1,445

*: excluding ellipsoidal *Alexandrium* cysts.

dinoflagellate cysts were less abundant in the southern than in the northern part of Osaka Bay.

DISCUSSION

Concentrations of ellipsoidal *Alexandrium* cysts in sediment

Hamano *et al.* (2002) stated that the first recorded PSP events caused by bivalves *Ruditapes philippinarum* (Adams & Reeve 1850), *Mytilus galloprovincialis* Lamarck, 1819, and *Crassostrea gigas* (Thunberg 1793) occurred in Osaka Bay on 2002. Yamamoto (2004) reported that PSP in Osaka Bay could be caused by the dinoflagellates *Gymnodinium catenatum* H.W. Graham, *A. tamarense*, *A. catenella*, and *Alexandrium tamiyavanichii* Balech. The year 2007 saw the first red tide (discoloration) in Osaka Bay caused by *A. tamarense* (Yamamoto *et al.* 2009).

A PSP-causing dinoflagellate species found around Harina-Nada in the Seto Inland Sea and in Osaka Bay has been identified as *Protogonyaulax catenella* (Whedon & Kofoid) Taylor (= *A. catenella*) from the results of cyst germination

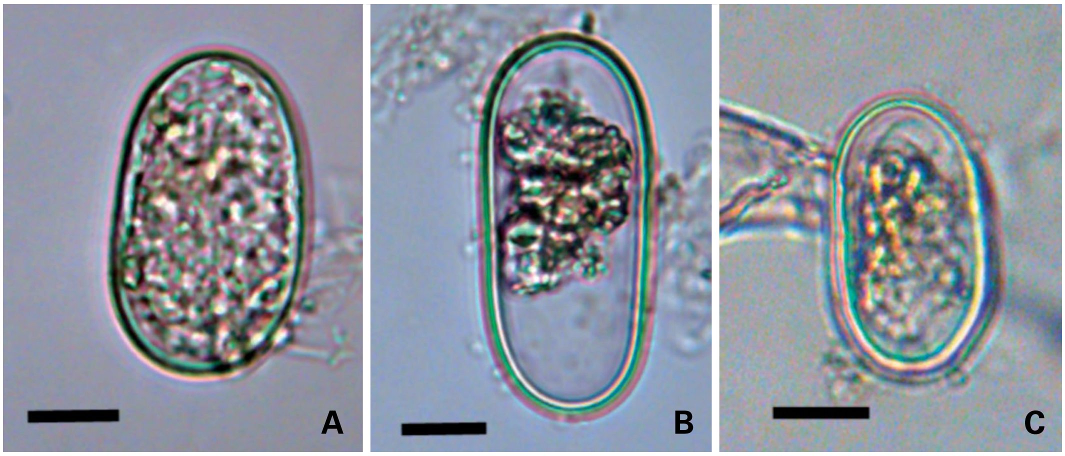
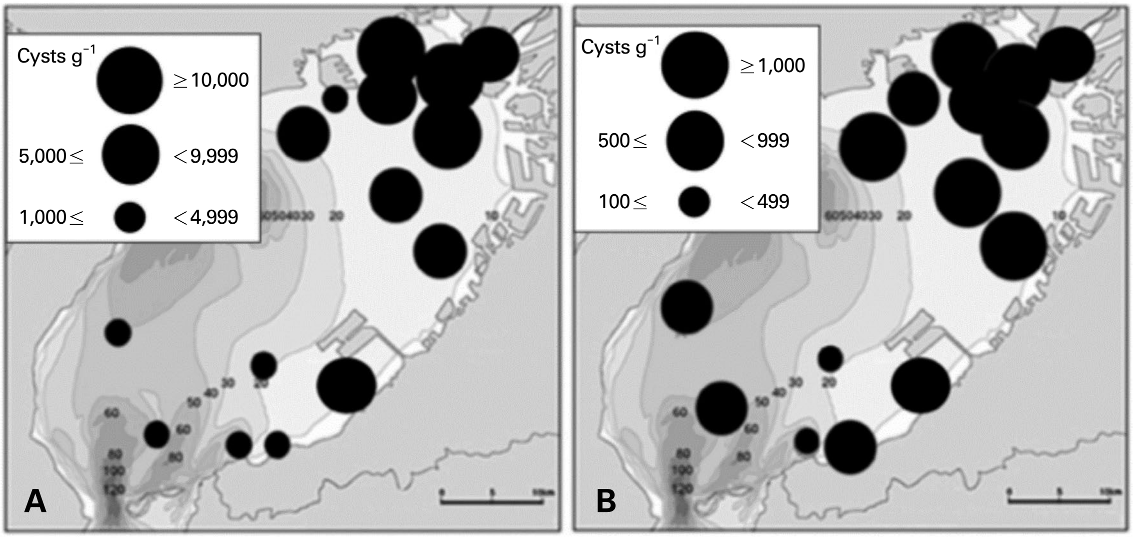


Fig. 3. Microphotographs of ellipsoidal *Alexandrium* cysts. (A) Living cyst filled with protoplasm, (B) and (C) cysts containing protoplasm but probably not alive. The scale bar indicates 10 μm.



Total dinoflagellate cysts

Ellipsoidal *Alexandrium* cysts

Fig. 4. (A) Horizontal distribution of total dinoflagellate cysts. (B) Horizontal distribution of ellipsoidal *Alexandrium* cysts. Data for cores OS 2, OS 19, and OS 23 were added to Figure 7A and 7B from Matsuoka and Ishii (2018).

experiments and plankton observations (Fukuyo 1983). Interestingly, no *A. tamarense* was detected at that time. Yamaguchi *et al.* (1996) investigated the distributions and abundances of *A. tamarense* and *A. catenella* cysts in surface sediment in the eastern Seto Inland Sea, including Osaka Bay, and found high cyst densities between the inner part and middle of the east coast of Osaka Bay. Yamamoto (2004) and Nagai *et al.* (2007) suggested that the cyst-producing dinoflagellate species might be *A. tamarense* because the cyst distribution found by Yamaguchi *et al.* (1986) was similar to those found after the *A. tamarense* blooms in 2002.

Seven PSP events and red tides caused by *A. tamarense* have been reported since 2002 (Yamamoto 2018). The ellipsoidal cysts with colourless walls found were identical to the cysts of *Alexandrium acathenella* (Whedon & Kofoid) Balech, *A. tamarense*, or *A. catenella*. However, these cysts could not be differentiated from their external morphologies, so Yamamoto *et al.* (2011) performed cyst incubation experiments and concluded that most of the ellipsoidal cysts preserved in the surface sediment were identical to *A. tama-*

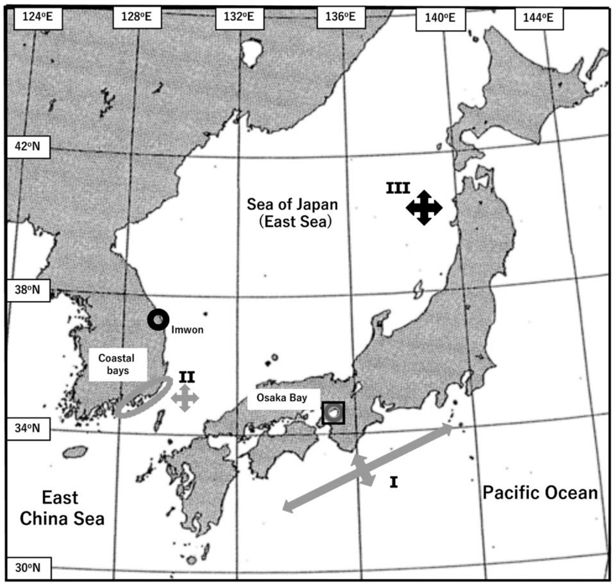


Fig. 5. Sites of possible earthquake epicenters and subsequent tsunamis that could affect coastal areas. (I) Tonankai Earthquake and Osaka Bay. The epicenter of the Tonankai Earthquake is estimated to cover a wide area along the Nankai Trough. (II) Nishiyama Fault and its northward extension and the east and south coasts of the Korean Peninsula. (III) Middle Japan Sea (Nihonnkai-Chubu) Earthquake and the east coast of the Korean Peninsula. The tsunami was 3.9 m high at Imwon according to Cho (2018a).

rense cysts. *A. acathenella* was found extremely rarely, and only small amounts of *A. catenella* have ever been found in Osaka Bay. The ellipsoidal cysts related to PSP events and red tide were therefore concluded to be *A. tamarense/catenella* (mainly *A. tamarense*) cysts.

Ellipsoidal cysts identical to *A. catenella/tamarense* cysts were found in all three cores, but the cyst densities varied. The cyst densities were lowest in the lower parts of the cores, and increased from the middle parts of the cores in an upward direction. The highest cyst densities were found at 0–1 cm in core OS 23 and 1–2 cm in core OS 19. A similar trend was found for core OS 2. This suggests that the production of *A. catenella/tamarense* ellipsoidal cysts has increased strongly in recent years.

The *A. tamarense* cyst densities in surface sediments around the world have been investigated, as shown in Table 3 in Matsuoka *et al.* (2018). The maximum cyst densities (915 cysts g^{-1} in core OS 19 and 616 cysts g^{-1} in core OS 23) were not high compared with those found in other areas. Matsuoka and Ishii (2018) found an ellipsoidal *Alexandrium* cyst density of 3,610 cysts g^{-1} at station OS 5 in Osaka Bay, which was ~3 km southwest of core OS 23. Yamamoto *et al.* (2009) found a maximum cyst density of 5,683 ± 631 cysts g^{-1} in wet sediment on the east coast of Osaka Bay (near core OS 19) in 2007 after an *A. tamarense* bloom. The highest cyst density recorded after that was 90,672 ± 11,269 cysts g^{-1} in 2017 (unpublished data). Mizushima and Matsuoka (2004) found that empty *A. tamarense* and *A. catenella* cysts representing after germination are not preserved well compared with the empty cysts of other dinoflagellates, because *A. tamarense* and *A. catenella* cysts are extremely weak and have thin autophragm. More resting cysts than were counted were therefore probably produced and deposited in the surface sediment. These data suggest that ellipsoidal *Alexandrium* cysts are widely distributed at high densities in the inner to southeastern shallow parts of Osaka Bay (Fig. 4B).

Erosion, resuspension, and redeposition of surface sediments containing ellipsoidal *Alexandrium* cysts as caused by a tsunami

Case study of Osaka Bay

The high densities of ellipsoidal *Alexandrium* cysts preserved in surface sediments appear to indicate a high potential risk of PSP incidents in future. *A. tamarense* blooms have occurred regularly along the Osaka Bay coast ever since the first bloom was recorded (Yamamoto 2004, 2018). This means that cysts preserved in surface sediments may play a role in initiating new blooms. The risks posed by a tsunami after the expected Tonankai Earthquake should also be considered. According to the Osaka Prefecture (2013), a tsunami 3.2–5.1 m high will reach the Osaka Bay coast after the expected Tonankai Earthquake off central Japan. The tsunami is expected to be 5.1 m high in the innermost part of Osaka Bay (Fig. 5). The Showa Nankai Earthquake of 1946 caused a tsunami that was ~3 m high when it reached the inner part of Osaka Bay. Unfortunately, no detailed data on sediment disturbance in Osaka Bay were recorded at the time. However, we can predict the effects of a large tsunami on a shallow bay by examining data recorded after the Great East Japan Earthquake. After the tsunami that followed the Great East Japan Earthquake, *A. tamarense* blooms were observed at Sendai Bay (Kamiyama *et al.* 2014), Kesennuma Bay (Nishitani *et al.* 2012; Ishikawa *et al.* 2015), Ofunato Bay (Kaga *et al.* 2012; Matsuoka *et al.* 2018), and Funka Bay (Natsuike *et al.* 2014). These blooms were initially caused by the germination of living cysts in sediment suspended by the tsunami. In Ofunato Bay, the maximum *A. tamarense* cell density reached 100,600 cells L^{-1} on 26 May 2011 and 179,500–676,500 cells L^{-1} in early June 2011 (Kaga *et al.*

2012). These extremely dense blooms appeared to be related to the environmental conditions. The tsunami on 11 March 2011 eroded the Ofunato Bay sea floor by more than 25 cm, and sediment containing *A. tamarense* cysts was resuspended and redeposited on the bottom of the sea. Ellipsoidal *Alexandrium* cysts are more abundant in the inner part of Osaka Bay, where the water is $<$20 m deep, than in other parts of the bay. This means that the sea floor could easily be eroded by a tsunami. The disruption caused by a tsunami will cause *A. tamarense* cysts to reach unusually high concentrations near the sea bed. A water temperature of around 10°C is suitable for the germination of *A. tamarense* cysts, so living cysts that resettle on the sea floor will start to germinate when the temperature reaches ~10°C, and dense blooms toxic to shellfish will form. A further environmental factor was also important to *A. tamarense* blooms in Ofunato Bay. Zooplankton that are predators of *A. tamarense* and other phytoplankton are scarce in Ofunato Bay (Yamada 2012). Strong *A. tamarense* blooms were therefore caused by resuspension and redeposition of ellipsoidal *Alexandrium* cysts and sediments by the tsunami, a water temperature of ~10°C (because it was early spring), and the absence of predation by zooplankton.

A high ellipsoidal *Alexandrium* cyst density in sediment can therefore act as a seed population for subsequent blooms and also cause extremely large blooms after a tsunami caused by an earthquake.

Case study of the Korean Peninsula

Ellipsoidal cysts identical to *A. tamarense* and/or *A. catenella* cysts are also found in surface sediments along the southern coast of the Korean Peninsula. Ellipsoidal *Alexandrium* cysts were first found in Jinhae Bay by Kim (1994) and Shin *et al.* (2017, 2018) and have since been found at several locations, including Masan Bay (Kim *et al.* 2002), Gwangyang Bay (Kim *et al.* 2003, 2009), Gamak Bay (Shin *et al.* 2008, 2010), and Yeoja Bay (Shin *et al.* 2009, 2010). However, the *Alexandrium* cyst densities in these locations were $<$200 cysts g^{-1}, which is low compared with the cyst densities found in Osaka Bay. The east coast of the Korean Peninsula has been affected by tsunamis several times (Cho 2018a). An earthquake called the Middle Japan Sea (Nihonkai-Chubu) Earthquake (magnitude 7.7) off Akita Prefecture in North Japan in 1983 caused a tsunami that reached the east coast of the Korean Peninsula and was 3.9 m high at Imwon, 1.56 m high at Sokucho, and 0.62 m high at Pohang (Japan Marine Science and Technology Center 1997; Cho 2018a, b) (Fig. 5). It can be seen that the Korean Peninsula experiences tsunamis of considerable height, and may be affected by tsunamis from either the Sea of Japan (East Sea) or from near Tsushima Island. Tsunami risk for the area around Tsushima Island provided by Nagasaki Prefecture is shown in Figure 5. The highest risk of a tsunami around Tsushima Island is from the possibility of an earthquake caused by the active submarine Nishiyama Fault and its northward extensions. Such an earthquake could cause a tsunami that could be 5 m high at the Tushima coast (Nagasaki Prefecture 2016). It can be seen that strong tsunamis could affect the east and south coasts of the Korean Peninsula. Such a tsunami would resuspend and redeposit sediment containing ellipsoidal *Alexandrium* cysts, and the cysts may then cause strong blooms and PSP. Such a scenario should be kept in mind and plans made to minimize damage that may be caused.

ACKNOWLEDGEMENT

This work was partly supported by the Research Fund of Rehabilitation and Creation of Osaka Bay Area on 2017, and KIOST project (PE99721).

REFERENCES

Cho TS. 2018a. Tsunami research in Korea: part 1. Numerical analysis and laboratory experiments. J. Korea Water Resour. Assoc. 51:941–950.

Cho TS. 2018b. Tsunami research in Korea: part 2. Field survey and disaster mitigation and laboratory experiments. J. Korea Water Resour. Assoc. 51:951–958.

Ecosystem Sub-Working Group. 2011. Survey for the actual condition of the marine ecosystem impact by the Great East Japan Earthquake and examine the measures to be taken in the future (proposal). JOS Newsletter (Oceanographic Society of Japan) 1:1–4.

Fraga S, N Sampedro, J Larsen, Ø Moestrup and AJ Calado. 2015. Arguments against the proposal 2302 by John *et al.* to reject the name *Gonyaulax catenella* (*Alexandrium catenella*). Taxon 64:634–635.

Fukuyo Y. 1983. Study of Taxonomy and Geographical Distribution of PSP Causative Dinoflagellate Cysts. Fisheries Agency of Japan. p. 6.

Hamano Y, K Kawatsu and T Tsukamoto. 2002. Occurrence of paralytic shellfish poisoning in the bivalves collected in Osaka Bay. Bull. Osaka Prefect. Inst. Pub. Health 40:11–18.

Hara K and H Higuchi. 2013. Effects of the 2011 Great East Japan Earthquake and Tsunami disasters on ecosystem. Chikyu Kankyo 18:23–33.

Ishikawa T, K Kusaka, A Oshino, G Nishitani and T Kamiyama. 2015. Distribution patterns of *Alexandrium* vegetative cells and resting cysts, and paralytic shellfish poisoning in Kesennuma Bay, after the Great East Japan Earthquake. Nippon Suisan Gakkaishi 81:256–266.

Japan Marine Science and Technology Center. 1997. Stationary Observation, Diving Observations and Observation by Ocean Bottom Seismometer at Aftershock Area of the Hokkaido-Nansei-Oki Earthquake. p. 16.

John U, RW Litaker, M Montresor, M Michael, C Brosnahan and DM Anderson. 2014. Formal revision of the *Alexandrium tamarense* species complex (Dinophyceae) taxonomy: the introduction of five species with emphasis on molecular-based (rDNA) classification. Protist 165:779–804.

Kaga S, R Watanabe, S Nagai, T Kamiyama and T Suzuki. 2012. Shellfish poisoning caused by *Alexandrium tamarense* in Ofunato Bay of Iwate Prefecture after the Great East Japan Earthquake. Kaiyo Mon. 44:321–327.

Kamiyama T, H Yamaguchi, S Nagai and M Yamaguchi. 2014. Differences in abundance and distribution of *Alexandrium* cysts in Sendai Bay, northern Japan, before and after the tsunami caused by the Great East Japan Earthquake. J. Oceanogr. 70: 185–195.

Kim CH. 1995. Paralytic shellfish toxin profiles of the dinoflagellate *Alexandrium* species isolated from benthic cysts in Jinhae Bay, Korea. J. Korean Fish. Soc. 28:364–372.

Kim SY, CH Moon and HJ Cho. 2003. Vertical distribution of dinoflagellate cysts in sediments from Gwangyang Bay, Korea. J. Korean Fish. Soc. 36:290–297.

Kim SY, CH Moon and HJ Cho. 2009. Dinoflagellate cysts in coastal sediments as indicators of eutrophication: a case of Gwangyang Bay, South Sea of Korea. Estuar. Coast. 32:1225–1233.

Kim YO, MH Park and MS Han. 2002. Role of cyst germination in the bloom initiation of *Alexandrium tamarense* (Dinophyceae) in Masan Bay, Korea. Aquat. Microb. Ecol. 29:279–286.

Kimata M, A Kawai and Y Ishida. 1960. The method for sampling of marine bottom muds. Bull. Japan. Soc. Sci. Fish. 26:1227–1280.

Matsuoka K and Y Fukuyo. 2000. Technical Guide for Modern Dinoflagellate Cyst Study. WESTPAC-HAB Asian Natural Environmental Science Center, Tokyo. p. 20.

Matsuoka K, Y Ikeda, S Kaga, M Kaga and T Ogata. 2018. Repercussions of the Great East Japan Earthquake tsunami on ellipsoidal *Alexandrium* cysts (Dinophyceae) in Ofunato Bay, Japan. Mar. Environ. Res. 135:123–135.

Matsuoka K and K Ishii. 2018. Marine and freshwater palynomorphs preserved in surface sediments of Osaka Bay, Japan. Bull. Osaka Mus. Nat. Hist. 72:1–17.

Mizushima K and K Matsuoka. 2004. Vertical distribution and germination ability of *Alexandrium* spp. cysts (Dinophyceae) in the sediments collected from Kure Bay of the Seto Inland Sea, Japan. Phycol. Res. 52:408–413.

Nagai S, CL Lian, S Yamaguchi, M Hamaguchi, Y Matsuyama, S Itakura, H Shimada, S Kaga, H Yamaguchi, Y Sonda, T Nishikawa, CH Kim and T Hogetsu. 2007. Microsatellite markers reveal population genetic structure of the toxic dinoflagellate *Alexandrium tamarense* (Dinophyceae) in Japanese coastal waters. J. Phycol. 43:43–54.

Nagasaki Prefecture. 2016. Estimated Floods Caused by Tsunami (2nd edition). p. 21.

Natsuike M, M Kanamori, K Baba, K Moribe, A Yamaguchi and I Imai. 2014. Changes in abundance of *Alexandrium tamarense* resting cysts after the tsunami caused by the Great West Japan Earthquake in Funka Bay, Hokkaido, Japan. Harmful Algae 39:271–279.

Nishitani G, M Yamamoto, M Natuike, D Ryu and I Yoshinaga. 2012. Dynamics of phytoplankton in Kesennnuma Bay and Moune Bay after the disaster 3.11. Aquabiology (Seibutu Kenkyuusha Co., Ltd.) 34:545–555.

Osaka Prefecture. 2013. Estimated Floods Caused by Tsunami. p. 17.

Shin HH, YH Yoon, H Kawami, M Iwataki and K Matsuoka. 2008. The first appearance of toxic dinoflagellate *Alexandrium tamarense* (Gonyaulacales, Dinophyceae) responsible for the PSP contamination in Gamak Bay, Korea. Algae 23:251–255.

Shin HH, K Mizushima, SJ Oh, JS Park, IH Noh, M Iwataki, K Matsuoka and YH Yoon. 2010. Reconstruction of historical nutrient levels in Korean and Japanese coastal areas based on dinoflagellate cysts assemblages. Mar. Pollut. Bull. 60:1243–1258.

Shin HH, K Matsuoka, YH Yoon and YO Kim. 2010. Response of dinoflagellate cyst assemblages to salinity changes in Yeoja Bay, Korea. Mar. Micropaleontol. 77:15–24.

Shin HH, Z Li, ES Kim, JW Park and WA Lim. 2017. Which species, *Alexandrium catenella* (Group I) or *A. pacificum* (Group IV), is really responsible for past paralytic shellfish poisoning outbreaks in Jinhae-Masan Bay, Korea? Harmful Algae 68:31–39.

Shin HH, Z Li, DG Lim, KW Lee, MH Seo and WA Lim. 2018. Seasonal production of dinoflagellate cysts in relation to environmental characteristics in Jinhae Bay, Korea: One-year sediment trap observation. Estuar. Coast. Shelf Sci. 215:83–93.

Tang DI, H Zhao, B Satyanarayana, GG Zheng, RP Singh, JH Lv and ZZ Yan. 2009. Variations of chlorophyll-a in the northeastern Indian Ocean after the 2004 South Asian tsunami. Int. J. Remote Sens. 30:4553–4565.

UN Atlas of the Oceans. 2005. "Impact of Tsunamis on Ecosystems" www.oceansatlas.org/results-search/en/?querystring=2005).

Whanpetch N, M Nakaoka, H Mukai, T Suzuki, S Nojima, T Kawai and C Aryuthaka. 2010. Temporal changes in benthic communities of seagrass beds impacted by a tsunami in the Andaman Sea, Thailand. Estuar. Coast. Shelf Sci. 87:246–252.

Yamada Y. 2012. Seasonal changes of zooplankton community structure in Moune-Kesennuma inlet and adjacent waters. Kaiyo to Seibutu (Aquabiology) 34:556–561.

Yamaguchi M, S Itakura, K Nagasaki and I Imai. 1996. Distribution and abundance of resting cysts of the toxic dinoflagellate *Alexandrium tamarense* and *A. catenella* in sediments of the eastern Seto Inland Sea, Japan. pp.177–180. In Harmful and Toxic Algal Blooms (Yasumoto T, Y Oshima and Y Fukuyo eds.). Intergovernmental Oceanographic Commission of UNESCO, Paris.

Yamamoto K. 2004. Occurrence of paralytic shellfish toxins in the spring of 2002 in east side of Osaka Bay. Bull. Osaka Prefect. Fish. Stat. 15:1–7.

Yamamoto K. 2018. Recent shellfish poisoning and occurrence of *Alexandrium tamarense* in Osaka Bay. p. 30. In Proceedings of Sub-Committee of Red-Tides and Shellfish Poisoning, Hiroshima.

Yamamoto K, H Ohmi and M Sano. 2011. Occurrence of a red tide of the toxic dinoflagellate *Alexandrium tamarense* in the estuary of the Yodo River in 2007-Dynamics of the vegetative cells and the cysts. Bull. Plankton Soc. Japan 58:136–145.

Yamamoto K, Y Nabeshima, M Yamaguchi and S Itakura. 2009. Distribution and abundance of resting cysts of the toxic dinoflagellates *Alexandrium tamarense* and *A. catenella* in 2006 and 2007 in Osaka Bay. Bull. Japan Fish. Oceanogr. 73:57–66.