

- 26 1. The ca. upper 25cm sediments of Ofunato Bay were re-deposited by the tsunami of the 2011
27 Great East Japan Earthquake.
- 28 2. The maximum density of ellipsoidal *Alexandrium* cysts at the 6–7cm depth was due to the
29 re-suspension of older sediments.
- 30 3. The first PSP incident on 1961 in this bay was resulted from the similar phenomena after the
31 Chilean tsunami in 1960.

32

33

34 **Abstract**

35 Shellfish aquaculture in Ofunato Bay, Northeast Japan, was seriously damaged by a
36 tsunami generated by the Great East Japan Earthquake, March 11th 2011, accompanied
37 by paralytic shellfish poisoning (PSP) outbreaks caused by *Alexandrium tamarense*
38 (Dinophyceae). To understand longer future trends of PSP, an investigation was made of
39 the historical occurrence and causes of *Alexandrium* outbreaks after the tsunami.
40 Vertical distributions of *Alexandrium* cysts in two sediment-cores from Ofunato Bay
41 revealed that the sediments above ca. 25 cm were eroded, re-suspended and
42 re-deposited, and they included unusually abundant *Alexandrium* cysts. This abundance
43 of cysts was due to re-deposition of older sediments by the tsunami. The first Ofunato
44 Bay PSP incident was in 1961 after the Chilean Earthquake tsunami and was probably
45 caused by similar unusual blooms of *Alexandrium* germinated from older sediments as
46 the Great East Japan tsunami, together with nutrient enrichment because of population
47 increase at the start of shellfish aquaculture.

48

49

50 **Introduction**

51 Under usual conditions, an ecosystem is in dynamic equilibrium but it may frequently be
52 disturbed by unexpected natural and/or artificial events. Consequently, it could be changed to a
53 new ecosystem both positively and negatively. Events which can alter marine ecosystems are
54 change of water temperature, salinity, light intensity, and water currents. In addition, unusual
55 phenomena such as a typhoon/hurricane, extraordinary high or low temperature change can
56 strongly affect the marine ecosystem (eg. Reynolds 2006). A tsunami (high sea wave) caused by
57 an earthquake, submarine landslide, or other disturbance is another unusual event that produces
58 exceptional conditions. For example, the tsunami following the 2004 Indian Ocean Sumatran
59 earthquake resulted in severe environmental impacts, mainly to the coastal zone ecosystems,
60 including mangroves, coastal wetlands, coral reefs, shallow sea floor, and shoreline habitats (eg.
61 Titov et al. 2005, "Impact of Tsunamis on Ecosystems." *UN Atlas of the Oceans*. Retrieved 10
62 March 2005), and it also changed phytoplankton production (Tang et al. 2009), and a benthic
63 ecosystem (Whanpetch et al. 2010).

64 The Great East Japan Earthquake on March 11th of 2011 (magnitude 9.0–9.1 Mw, offshore
65 of NE Japan) is considered one of the largest earthquakes ever recorded. It generated a wave
66 10m high that swept inland about 10 km, impacting the Fukushima nuclear plant and many
67 coastal communities ([https://www.britannica.com/event/Japan-earthquake-and-tsunami-of-](https://www.britannica.com/event/Japan-earthquake-and-tsunami-of-2011)
68 [2011](https://www.britannica.com/event/Japan-earthquake-and-tsunami-of-2011)). Many subsequent changes of coastal marine ecosystem and related environmental
69 parameters have been reported previously (eg. Fukuda et al. 2015, Yamada et al. 2015, Okamura
70 & Kaga 2016, Naiki et al. 2015, Okamura et al. 2015, Yamamoto et al. 2012, Yamada 2012,
71 National Institute for Land and Infrastructure Management, and Building Research Institute
72 2011). Special interest focused on outbreaks of paralytic shellfish poisoning (PSP) and intensive
73 studies were made of the distributions of causative dinoflagellate cysts such as *Alexandrium*
74 *tamarense/catenella* (Kamiyama et al., 2014, Nishitani et al. 2012, Natsuike et al. 2014,
75 Ishikawa et al. 2015).

76 These special PSP studies revealed a remarkable increase of *Alexandrium*
77 *tamarensis/catenella* cysts after the tsunami at the Great East Japan Earthquake site, probably
78 due to re-suspension of cysts accompanied with bottom sediments and newly introduced by
79 plankton blooms after the tsunami. However, no investigation of this subject was made in
80 Ofunato Bay where shellfish aquacultures were active before the Great East Japan Earthquake
81 and where the local fishermen needed information about the future trends of the PSP causative
82 plankton. Additionally, the PSP phenomena in Ofunato Bay are notable in Japanese studies
83 because the first scientific investigation of a PSP event was conducted in Ofunato Bay in 1961
84 (Kawabata et al. 1962), 13 years after a suspected PSP event occurred around Lake Hamana in
85 1948 (Imai & Itakura 2002). However, the causative plankton at Lake Hamana was not known.
86 The PSP causative plankton of Ofunato Bay was identified using preserved samples (Murano
87 1975) in addition to the characteristic symptoms of the PSP (Kawabata et al. 1962). After 1961,
88 the PSP event expanded throughout Japan, persisting until now.

89 The 1961 PSP event in Ofunato Bay happened just one year after the Chilean tsunami that
90 impacted the Sanriku coast of Northeast Japan in 1960. For many years, it was thought that the
91 Chilean tsunami might be related to the first PSP event in Ofunato Bay but there were no data to
92 support or interpret this hypothesis. New PSP studies of the 2011 tsunami after the Great East
93 Japan Earthquake, which had a similar impact on the coastal environments and marine
94 ecosystems in Ofunato Bay, might now provide a scientific explanation for the PSP events
95 following the Chilean tsunami.

96 In this study, we investigate the vertical distribution of the cysts of the PSP causative
97 plankton, *Alexandrium tamarensis/catenella* and their depositional mode in two sediment cores
98 from Ofunato Bay which contain all the re-deposited layers from the 2011 tsunami of the Great
99 East Japan Earthquake. We also present the basic information on a trend of *Alexandrium*
100 *tamarensis/catenella* thereafter and also to provide a scientific scenario that can reasonably
101 explain the first PSP event in Ofunato Bay following the 1960 Chilean tsunami.

102

103 **Environment of Ofunato Bay**

104 Ofunato Bay is located at the Pacific coast of Northeast Japan and is one of several bays that
105 characterize ria coasts (Administrator of Kamaishi Port, 1976). This bay is approximately 6 km
106 long from north to south, 2 km wide from east to west, 7.7km² in area, 1.24 x 10⁸ km³ in volume,
107 40m in maximum depth near the bay mouth, and it has an “L shaped” topography that opens in
108 an east-southeast direction. The Sakari River flows into the north end of this bay. A tsunami
109 break water was started to work in 1963 and built in 1967 after the Chilean tsunami. However,
110 this structure was destroyed by the Great East Japan Earthquake tsunami. Subsequently, a new
111 breakwater is being constructed again at the same site.

112 In the bay, shellfish aquacultures mainly dealing with scallops and oysters have been
113 developed, both before and after the Great East Japan Earthquake. These aquacultures are one
114 of the important industries around Ofunato Bay. Because of these circumstances, local
115 fishermen are always concerned about PSP phenomena and they need information on the
116 causative plankton and cysts which are called *Alexandrium tamarense* (Lebour) Balech and *A.*
117 *catenella* Whedon & Kofoid in this region, as explained in the next section.

118

119 **History of *Alexandrium* blooms and paralytic shellfish poisoning in Ofunato Bay**

120 On May 18th of 1961 in Ofunato Bay, a PSP incident happened that was caused by
121 Akazara-scallops (*Chlamys farreri akazara* (Kuroda, 1932)), with twenty people becoming
122 severely ill and one death (Kawabata et al. 1962). More than ten years later, the causative
123 organism was identified as *Gonyaulax* sp. which seemed to be similar to *Gonyaulax catenella*
124 Whedon & Kofoid by Murano (1975). Thereafter, Fukuyo (1979) corrected its species
125 identification as *Gonyaulax excavata* (Braarud) Balech and then, as now, as *Alexandrium*
126 *tamarense* (Lebour) Balech via *Protogonyaulax tamarense* (Lebour) Taylor. Furthermore,
127 recent progress in the taxonomy of the *A. tamarense* complex suggests that *A. tamarense* and *A.*

128 *catenella*, forming resting cysts and appearing in Ofunato Bay, should be called as *A. fundyense*
129 Balech and *A. pacificum* Litaker, respectively, if we follow John et al. (2014). However, we use
130 the names *A. tamarensis* and *A. catenella* to avoid taxonomic confusion in this article. At
131 present, *A. tamarensis* and *A. catenella* are the two major PSP causative dinoflagellates in
132 Ofunato Bay. *A. tamarensis* frequently blooms mainly in spring to early summer and has high
133 PSP concentrations. On the other hand, *A. catenella* appears in late summer to early autumn
134 with relatively low PSP concentrations (Kodama et al. 1982, Ogata et al. 1982).

135 According to Kaga et al. (2012) the history of toxin concentration in shellfish from Ofunato
136 Bay is as follows. In the early 1960's, toxin level in the Akazara-scallop and/or Yesso giant
137 scallop (*Pecten yessoensis* Jay 1857) was around 100 to 1000 MU/g digestive gland (DG). In
138 the late 1960's to the early 1970's, this value dropped to 10–100 MU/g DG, and thereafter, it
139 has been between 100 and 1000, sometimes 2000 MU/g DG, with a sharp drop (less than 10
140 MU/g DG) in 1985. During the huge bloom of *A. tamarensis* in May to June of 2011 after the
141 Great East Japan Earthquake tsunami in 2011, accumulation of PSP toxins through the ingestion
142 of *A. tamarensis* was studied in the blue mussel *Mytilus galloprovincialis* Lamarck 1819, Yesso
143 giant scallops and other species in Ofunato Bay. On May 13th of 2013, the toxin concentration in
144 scallops of Ofunato Bay was recorded as 4,647 MU/g DG, which was the maximum value for
145 the bay (Kaga et al. 2012, 2013).

146

147 **Material and Method**

148 ***Core Sampling sites***

149 Two core-sampling stations were selected in Ofunato Bay (Fig. 1). One was near Shizu where
150 the Iwate Fisheries Experimental Station and Iwate Fisheries Technology Center have continued
151 the PSP monitoring since 1970. Approximately 800m north from this site (St. O in Fig. 1), Port
152 and Airport Research Institute (2001) collected a core sample and measured the sedimentation
153 rate using the ²¹⁰Pb and ¹³⁷Cs methods before the Great East Japan Earthquake. After the

154 tsunami, the Kamaishi Office of Tohoku Regional Development Bureau (2012) collected a
155 sediment core at the same station of St. O and named that core as “P”. The other station was
156 near Nagasawa where dense concentrations of ellipsoidal *Alexandrium* cysts were found in a
157 previous investigation by Iwate Prefectural Fisheries Experimental Station (Iwate Prefectural
158 Fisheries Experimental Station 2013).

159 Two core samples were taken by divers using a transparent acrylic pipe with 6 cm diameter.
160 A 64cm-long core was collected near Shizu station (N 39°02.335”, E 141°43.935”, water depth
161 32m) on October 23 of 2012 and a 76cm-long core was taken near Nagasawa (N 39°02.689”, E
162 141°43.594”, water depth 21m) on August 27 of 2013. Both cores were kept vertically in dark
163 conditions, transported to a laboratory of Iwate Fisheries Technology Center and preserved in a
164 refrigerator of 4°C before observation and sub-sampling for further examination on water
165 content, grain size and palynomorphs including dinoflagellate cyst extraction.

166

167 *Sub-sampling of the cores*

168 After observation of the sediment facies, the cores kept at Iwate Fisheries Technology Center
169 were cut at 0.5 to 1cm intervals for the top 10cms, and at 1cm intervals below the 10cm depth.
170 Sub-samples were stored in plastic bags and kept in a refrigerator of 4°C before palynomorph
171 analysis, sediment grain size analysis, and measurement of water contents.

172

173 *Particle size analysis*

174 For sediment particle size analysis, a Laser diffraction type particle size distribution measuring
175 apparatus (SALD – 3100, Shimadzu Co. Ltd, Kyoto, Japan) was employed. Classification of
176 sediment grains was followed with JIS A1204: gravel (2000µm>), sand (75–2000µm), silt
177 (5–75µm), clay (<5µm). This classification is usually employed as test method for particle size
178 distribution of soils by the Japanese Geotechnological Society. Median particle size and mode
179 values were also calculated.

180

181 ***Water contents***

182 For calculating water contents, the following formula in Matsuoka and Fukuyo (2000) was
183 provided: 1g of wet samples was placed on a Petri dish and put in low temperature drying oven
184 (EYELANDO-400, Tokyo Rikakikai Co. LTD, Tokyo, Japan) at 70°C for 12 hours.

185
$$V = \{ (W_m - W_d) / W_m \} \times 100$$

186 V: water content (%), W_m : mud in wet condition (g), W_d : mud in dry condition (g)

187

188 ***Extraction of palynomorphs including dinoflagellate cysts***

189 For palynomorph extraction, the analytical method of Matsuoka and Fukuyo (2000) was
190 followed: after removing calcareous and silicate grains using 30% HCl and 37% HF
191 respectively at room temperature, the remaining organic material was sieved with stainless steel
192 screens of 125 μ m and 20 μ m mesh opening size. The residue trapped on the 20 μ m screens was
193 recovered and kept in a 20ml glass bottle. A 0.5ml aliquot from the 20ml glass bottle was
194 provided for observation and palynomorphs, mainly dinoflagellate cysts, were counted under an
195 inverted optical microscope Olympus IX 50 (Olympus Co Ltd., Tokyo, Japan) with 400
196 magnification. Such observations were performed twice for every sub-sample. Observation and
197 counting of marine palynomorphs including dinoflagellate cysts were carried out at every 1cm
198 interval above the 25cm depth and every 5cm interval below this depth for both cores. All
199 marine palynomorphs remains were represented as cyst numbers per dry weight of sediment.

200

201 ***Identification of dinoflagellate cysts***

202 Dinoflagellate cyst identification mainly followed Matsuoka & Fukuyo (2000) and Zonneveld
203 & Pospelova (2015). Although ellipsoidal cysts with transparent walls have been known to be
204 produced by *Alexandrium acatenella* (Whedon & Kofoid) Balech, *A. catenella* and *A.*
205 *tamarensis*, it is mostly impossible for differentiating these cysts as species based on only cyst

206 morphology. However, cyst of *A. acatenella* has been recorded only one time from surface
207 sediment of Hiroshima Bay by Yoshida et al. (2003). Therefore, in this study we treated these
208 cysts as cysts of ellipsoidal *Alexandrium*, that included cysts of both *Alexandrium catenella* and
209 *A. tamarense*. Dinoflagellate cyst concentrations including the cyst of ellipsoidal *Alexandrium*
210 were based on cysts filled with protoplasm and of empty.

211

212

Results

213 *Sediment*

214 The core taken at the Shizu station (Shizu core) was 64cm in total length. When the core sample
215 was collected (Fig. 2A), on the surface many organisms belonging to the Ampharetidae
216 (polychaetes) inhabited. Many small burrows probably formed by these polychaetes were also
217 observed around 24.5cm depth below the surface. The sediment from the top to 2.5cm depth
218 was mud of dark olive color, and from 2.5 to 24.5cm depth, it was rather soft and grey, with a
219 dark olive mottled structure yielding many small shell fragments. The sediment from 6 to 9cm
220 depth was sandy. Below 24.5cm depth, the sediment became slightly firm in texture. Around
221 22cm depth, a thin layer consisting of small shell fragments was observed. The sediment above
222 the 25cm depth became coarser than that below this depth. Between 32 and 38cm depth, the
223 sediment was greenish black to greenish grey in color. Around 41cm depth, the sediment had a
224 little sulfide smell of rotten eggs. Below 45cm, the sediment was rather homogeneous and
225 greenish grey in color and it included scattered small shell fragments.

226 The core collected at the Nagasawa station was 76cm in total length and generally
227 characterized by abundant shell fragments throughout the section (Fig. 2B). The sediment was
228 grayish to olive black mud, interspersed with small shell fragment layers at the 6, 9 and 17cm
229 depths. From the 16 to 20cm depth, there were lots of coarse sand grains. Many Ampharetidae
230 polychaetes were also observed on the surface and their slender burrows intruded to nearly the
231 25cm depth. Below approximately the 20cm depth, the sediment became a harder, greenish dark

232 grey mud with a marbled color. From 33–37cm depth, a shell fragment layer was observed.
233 From the 55cm depth to the bottom, the sediment became coarse and included larger shell
234 fragments and cobbles and barnacle shell fragments of ca. 2cm size were found around the
235 60cm depth.

236 In both cores, fine sediment particles of silt and clay generally comprise more than 80 % of
237 the weight; however, at several horizons, amounts of coarse sand grains increased. These sandy
238 horizons were at the 2.5, 6, and 24cm depth in the Shizu core (Fig. 3), and at 2, 5, 13–22, 40, 45,
239 55-75cm depth in the Nagasawa core (Fig. 4). Water content in the Shizu core was clearly
240 divided into two parts (Fig. 3). In the upper part above 22cm, water content ranged between 60
241 and 70% except for the top part, and in the lower part, it decreased below 60%. On the other
242 hand, in the Nagasawa core, in the upper part above 17cm, the water content was generally
243 constant around 65 %, although below 17cm depth, it decreased to less than 60% and below
244 62cm depth, it was less than 40% (Fig. 4). Median particle size ($md\phi$) in the Shizu core was
245 also divided into two parts by the 22cm depth. The upper part above 17cm was around 15 μm
246 and the lower part below 23cm was around 12 μm . Between 17 and 23cm in the Shizu core, the
247 median particle size increased to around 20 μm . In the Nagasawa core, median particle size
248 varied between 8 and 25 μm . In particular, in the 26 to 32cm and 36 to 44cm intervals, median
249 particle size was less than 10 μm . The mode of the Shizu core sediments showed a similar trend
250 to the median particle size and it was rather stable, generally 10 to 20 μm except for the 22-23cm
251 depth. On the other hand, the mode of the Nagasawa core sediment particle size was larger and
252 variable (8.8-26.5 μm) except for 71-72cm depth due to scattered larger shell fragments.

253

254 **Dinoflagellate cysts and other marine palynomorphs**

255 Various marine palynomorphs composed of dinoflagellate cysts, acritarchs, archeomonads,
256 tintinnomorphs, microforaminiferal linings, and crustacean remains were abundantly preserved
257 in these two core sediments. Among these palynomorphs, dinoflagellate cysts were most

258 abundant and composed of 3 gymnodinioid, 11 gonyaulacoid, and 27 peridinioid species.
259 Among them, there were 13 photo/mixotrophic species and 28 heterotrophic species. Important
260 dinoflagellate cysts were shown in Fig. 5. Acritarchs included two species: *Baltisphaeridium* sp.
261 and *Halodinium major* Bujak. Three different uniserial, biserial and coiled types of
262 microforaminiferal linings were also observed. These palynomorphs were listed in Table 1 and
263 their abundance were recorded in Supplemental Tables 1 and 2.

264 In the Shizu core, the most dominant dinoflagellate cyst was *Alexandrium*
265 *tamarense/catenella* (ellipsoidal *Alexandrium* cyst), followed by *Spiniferites bulloideus* s.l. and
266 *Brigantedinium* spp. The average number of ellipsoidal *Alexandrium* cyst was recorded as 11.4
267 $\times 10^3$ cysts/g above the 20cm depth, with a maximum of 26.3 $\times 10^3$ cysts/g at 18–19cm depth
268 (Fig. 6). Cysts filled with protoplasm were observed at the 50–51cm depth and empty forms
269 were seen at 60–61cm depth. However, the cyst density below 26cm was lower: 1.6 $\times 10^3$ cyst/g
270 on average. The density of the ellipsoidal *Alexandrium* cyst in sediments above 25cm depth,
271 fluctuated much more than below this level. Average cyst density of the gonyaulacoid species
272 was 2.2 $\times 10^3$ cyst/g above the 20cm depth, and 1.5 $\times 10^3$ cyst/g below this depth. *Spiniferites*
273 *elongatus* and *Lingulodinium machaerophorum* occurred rarely throughout the core.
274 *Tuberculodinium vancampoae* was observed sporadically, even below 20cm depth. Average
275 cyst density of the peridinioid species except for organic linings of phototrophic *Scrippsiella*
276 spp. cysts was 4.5 $\times 10^3$ cyst/g average above 20cm depth, and 3.2 $\times 10^3$ cyst/g below this depth.
277 *Brigantedinium* species, mostly *B. simplex*, were most abundant. *Selenopemphix quanta* and the
278 cyst of *Protoperidinium leonis* constantly occurred. *Votadinium spinosum*, *Dubridinium*
279 *caperatum*, and cyst of *Protoperidinium americanum* were few in number but they constantly
280 occurred throughout the core. Heterotrophic gymnodinioid species, *Polykrikos kofoidii* and
281 *Polykrikos schwartzii* were commonly present.

282 In the Nagasawa core, the most dominant dinoflagellate cyst was also the ellipsoidal
283 *Alexandrium* cyst, followed by *Spiniferites bulloideus* s.l. and *Brigantedinium* spp. (Fig. 7). The

284 ellipsoidal *Alexandrium* cyst was recorded with an average of 76.8×10^3 cyst/g above 20cm
285 depth, with a maximum of 155.21×10^3 cyst/g at 6–7cm depth; they showed also fluctuations as
286 in the Shizu core. Cysts filled with protoplasm were found at 74cm depth, but the cyst density
287 below 20cm depth became lower, averaging 1.12×10^3 cyst/g. Average cyst densities of the
288 gonyaulacoid species was 4.1×10^3 cysts/g above 20cm depth, and 1.7×10^3 cysts/g below this
289 depth. Average cyst density of the peridinioid species except for organic linings of *Scrippsiella*
290 spp. cysts were 7.9×10^3 cysts/g above 20cm depth and 3.9×10^3 cysts/g below this depth.

291

292 **Discussion**

293 **1. Re-depositional processes reflected in sediment graded-bedding**

294 Based on the water contents, grain size distribution and development of worm burrows formed
295 by polychaetes, the core sediments collected at Shizu and Nagasawa sites were divided into two
296 parts separated by a transitional zone. In the Shizu core, the transition was seen from 20 to
297 26cm depth where sand content slightly increased. Slender worm burrows reached down to
298 around the 25cm depth. In the Nagasawa core, the transitional zone was rather unclear with
299 regard to water content. However, worm burrows in this core were also continuously observed
300 to the 25cm depth. This means that the thickness of re-deposited sediments reached around the
301 25cm depth in both cores. The thickness of re-deposited sediments was nearly same of the depth
302 at Station P of the Kamaishi Office of Tohoku Regional Development Bureau (2013) which was
303 located at approximately 800m north of the Shizu core site (Data provided by Kamaishi Office
304 of Tohoku Regional Development Bureau 2013). However, the water contents around 20-25cm
305 depth in both cores did not changed from the below (undisturbed) sediments. This suggested
306 that these sediments were considered as mixture parts of re-suspended and non-eroded
307 sediments. Accordingly, the surface sediments from the sea floor to near 25cm depth in the
308 central part of Ofunato Bay were re-deposited after erosion and subsequent re-suspension by the
309 tsunami of the 2011 Great East Japan Earthquake.

310 Above the transitional part of the Shizu core, graded-bedding and reverse graded-bedding
311 also appeared repeatedly at 3 to 5cm intervals. If the velocity of tsunami flow increased with the
312 rising current, the sediment gradation was reversed as shown by Fujiwara et al. (2003). In the
313 Shizu core, normal and reverse gradations were observed repeatedly. Fujiwara et al. (2003)
314 showed that normal and reverse gradations in tsunami deposits were often observed and were
315 produced by different events in a single tsunami based on investigation of fossil beds in Boso
316 Peninsula of the East Japan. Such sedimentary features in the Shizu core might reflect the
317 number of surges associated with the tsunami event. The Port and Airport Research Institute
318 (2011) showed that several tsunami events (multiple surges) were recorded along the Sanriku
319 coast at the time of the Great East Japan Earthquake. Such depositional features are also
320 reflected in ellipsoidal *Alexandrium* cyst densities as discussed below. In fact, five tsunami
321 events at the time of the Great East Japan Earthquake were recorded off Kamaishi Bay located
322 at 26km NNE from Ofunato Bay (Port and Airport Research Institute, 2011). Since the tsunami
323 giant waves were repeated in approximately one-hour interval, re-suspended sediment particles
324 including ellipsoidal *Alexandrium* cysts filled with protoplasm would have started to sink to the
325 seafloor after each surge. However, before complete deposition on the sea floor, the next
326 tsunami surge disturbed the seafloor again. Such seawater motion would be reflected in
327 characteristics of the re-deposited sediments and ellipsoidal *Alexandrium* cysts of Ofunato Bay
328 as fluctuations in the sediment gradation and density of ellipsoidal *Alexandrium* cysts.

329 When the tsunami came into the bay, bottom sediments were eroded, and dinoflagellate
330 cysts including ellipsoidal *Alexandrium* cysts were re-suspended and transported together with
331 other sediment particles. After the tsunami encroachment, re-suspended particles were deposited
332 according to their specific gravities. Since the specific gravity of fine muddy sediments of md ϕ
333 (= ca. 2.5 μ m) saturated with sea-water (sludge) and the cysts of *A. tamarensis* filled with
334 protoplasm are 1.18-1.51g/cm³ (Nakagawa et al. 2004) and 1.24 g/ cm³ (Anderson et al. 1985)
335 respectively, these ellipsoidal *Alexandrium* cysts generally behaved as fine muddy sediment

336 particles but slower than coarse silt particles as suggested in Kamiyama et al. (2014). Therefore,
337 these ellipsoidal *Alexandrium* cysts would probably sink faster than finer sediment particles
338 (fluid mud) with a specific gravity of approximately 1.11g/cm^3 (Nakagawa et al. 2014;
339 Kamiyama et al. 2014). However, in the Shizu and the Nagasawa cores, the vertical depositional
340 profile of ellipsoidal *Alexandrium* cyst concentration showed several peaks in the re-suspended
341 layer, as well as other sediment particles (Figs. 3, 4). Such vertical distributions of the
342 ellipsoidal *Alexandrium* cysts reflect the several different tsunami events at the Great East Japan
343 Earthquake.

344

345 **2. Extremely unusual occurrences of *Alexandrium* cysts**

346 Abundance of *Alexandrium*, other gonyaulacoid, and peridinioid cysts shows remarkable
347 changes around 20cm depth in both cores. The effect of re-suspension and re-deposition of other
348 gonyaulacoid and peridinioid cysts is nearly twice as high compared to the lower part of the
349 records (Figs. 6, 7). As discussed previously, the sediment above the 20 to 25cm depth of both
350 cores were re-suspended and re-deposited after the tsunami. Ellipsoidal *Alexandrium* cysts filled
351 with protoplasts drastically increased in the re-deposited sediment as did the other dinoflagellate
352 cysts, but the aspect of the *Alexandrium* cysts is remarkably different from other dinoflagellate
353 cyst groups. In the Shizu core, the density of ellipsoidal *Alexandrium* cysts averages 11.4×10^3
354 cyst/g above 20cm depth, with a maximum amount of 26.3×10^3 cyst/g at 18–19cm depth. In
355 the Nagasawa core, the cyst density of *Alexandrium* filled with protoplasm showed a slightly
356 different distribution with larger average of 76.8×10^3 cyst/g above 20cm depth and a maximum
357 of 155.21×10^3 cyst/g at 6–7cm depth.

358 In the first report of a PSP causative dinoflagellate called *A. tamarense* in Ofunato Bay
359 (Fukuyo, 1980), the ellipsoidal cyst concentration maximum in surface sediments was recorded
360 as $2,189$ cysts/ cm^3 at the center of the bay, near the Nagasawa station. Thereafter, cyst
361 concentrations recorded annually by Iwate Prefectural Fisheries Station (1985–1989 and 1991)

362 ranged from 175 to 1200 cysts/cm³ (Sekiguchi et al. 1998). Unfortunately, since these data were
363 reported in cysts per wet sediment volume, it is impossible to directly compare these
364 concentrations with our data measured as cysts per dry sediment weight. However, we can
365 convert those data cysts per wet sediment volume to dry sediment weight using the data of the
366 specific gravity of sediments provided by Kamaishi Office of Tohoku Regional Development
367 Bureau (2013). The specific density of dry sediments of the top 2cm of the core collected in the
368 center of the bay was measured as 0.289g/cm³. Using this conversion value, the cyst
369 concentrations of Fukuyo (1980) and Iwate Prefectural Fisheries Station (1985–1989, 1991) can
370 be recalculated from cysts/cm³ to cysts/g of dry sediment. This re-calculation indicates that
371 from 197980 to 1991, cyst concentrations in the center of Ofunato bay are estimated to be 951
372 to 4,276 cysts/g.

373 As shown in Table 2, the highest previously recorded concentration of the *Alexandrium*
374 *tamarense* complex cysts was 220,872 cysts/g in Bedford Basin of Nova Scotia, Canada
375 (Lacasse et al. 2013). In Japan, the highest previously known concentration of ellipsoidal
376 *Alexandrium* cysts was 8,900 cysts/cm³ in Aso Bay of Tsushima Island (Matsuoka & Lee 1994).
377 After the Great East Japan Earthquake ellipsoidal *Alexandrium* cysts were recorded as 8,190
378 cysts/cm³ in Sendai Bay (Kamiyama et al. 2014). In comparison with these previous data, the
379 concentration of ellipsoidal *Alexandrium* cysts filled with protoplasm at the 6–7 cm depth of the
380 Nagasawa core (155.21 x 10³cyst/g) is the highest record presently known in Japan. Similar
381 extremely high ellipsoidal *Alexandrium* cyst concentrations were also recorded in several other
382 bays, Kesenuma Bay (Ishikawa et al. 2014) and Funka Bay (Natsuike et al. 2014) after the
383 tsunami at the Great East Japan Earthquake.

384 However, two points should be carefully considered in explaining the unusual abundances of
385 ellipsoidal *Alexandrium* cysts filled with protoplasm in the tsunami-impacted area of the Great
386 East Japan Earthquake. The first point is the effect of sediment erosion, re-suspension, and
387 re-deposition by the tsunami as suggested by Kamiyama et al. (2012). The second point

388 concerns the introduction of newly produced cysts during huge blooms of *A. tamarens* after the
389 tsunami (Natsuike et al. 2014, Ishikawa et al. 2015, Ogata et al. 2016). In the Shizu and
390 Nagasawa cores, the top 1cm sediments deposited after the huge bloom of *A. tamarens*
391 happened on May to June of 2011 (6,554 and 9,619cysts·g⁻¹, respectively) contained more
392 abundant ellipsoidal *Alexandrium* cysts compared with the period before 2011 (ca. 4,276cysts/g
393 as shown in our records). These *Alexandrium* cysts preserved in the top 1cm of the Shizu and
394 Nagasawa cores included ellipsoidal *Alexandrium* cysts newly produced during the bloom of
395 May to June of 2011. Such deposition of ellipsoidal *Alexandrium* cysts in the surface of
396 sediments was common to Sendai Bay, Kesenuma Bay and Funka Bay, but different from the
397 deeper parts of the Shizu and the Nagasawa cores.

398 Since higher cyst concentrations were recorded below the 2cm depth of the Shizu and
399 Nagasawa cores, there was no possibility that new ellipsoidal *Alexandrium* cysts produced one
400 year after the tsunami were preserved in deeper sediments. Therefore, explanation for such
401 extremely abundant occurrences of ellipsoidal *Alexandrium* cysts can be focused on different
402 eco-physiological and sedimentological factors: a higher cyst-forming capability of *A.*
403 *tamarens* and deeper erosion and transport of re-suspended and well-sorted sediments by the
404 tsunami. These events happened before the next bloom of *Alexandrium tamarens* on spring of
405 2012.

406

407 **2-1. Higher cyst forming capability of *Alexandrium tamarens***

408 In Ofunato Bay, *Alexandrium tamarens* and *A. catenella* which can produce ellipsoidal cysts
409 are known to be present (eg. Fukuyo 1982). *A. tamarens* usually forms blooms during the
410 relatively lower sea surface temperature period (ca. 10°C, January to June, mainly May to June).
411 On the other hand, *A. catenella* blooms are often observed during the relatively higher sea
412 surface temperature period (ca. 15°C, July to December, mainly November (eg. Ogata et al.
413 1982). Of these two species, the cell density and toxin level of PSP in *A. tamarens* is usually

414 higher than *A. catenella* in Ofunato Bay (Kodama et al. 1982). Thus, *A. tamarensis* is the more
415 important causative PSP *Alexandrium* species in this bay. Incidence of cyst formation for *A.*
416 *tamarensis* has been reported as 20% (Anderson et al. 1984), 30% (Ichimi et al. 2001), $23.8 \pm$
417 5.1 % at 14°C (Nagai et al. 2008) and 17% (Kaga 2010). These cyst production numbers are
418 significantly higher than for other photosynthetic gonyaulacacean dinoflagellates, including *A.*
419 *catenella* 1.2–2.1% (Matsuoka & Takeuchi 1995), *Gonyaulax digitale* (Pouchet) Kofoid (= *Spiniferites bentori* (Rossignol) Wall et Dale) 5.9% (Wall & Dale 1968), *Alexandrium*
420 *tamiyavanichii* Balech 6.2 ± 1.1 % in (Nagai et al. 2008), and a heterotrophic cyst-forming
421 dinoflagellate (*Protoperidinium oblongum* (Aurivillius) Parke et Dodge 1.4% (Wall & Dale
422 1968). This means that *A. tamarensis* is one of most prolific cyst-producing species among the
423 bloom-forming dinoflagellates.

425

426 **2-2 Large blooms of Alexandrium tamarensis frequently formed in the bay**

427 After the first species identification of *A. tamarensis* as an important PSP causative organism in
428 Ofunato Bay, monitoring for this species has continued until now at the Shizu site by Iwate
429 Prefectural Fisheries Experimental Station and subsequent Iwate Fisheries Technology Center.
430 Before the 2011 Great East Japan Earthquake, an *A. tamarensis* cell density of less than 10,000
431 cells/L was recorded in 1979, 1983–1988, 1991–1992, 1996, 1999, 2001–2002, 2004–2007, and
432 2009–2010. Over 10,000 but less than 50,000 cells/L was reported in 1980–1982, 1990, 1994,
433 1997, 2000, 2003, and 2008, and over 500,00 cells /L was found in 1989, 1995 and 1998. The
434 highest known density reported was 96,200 cells/L in 1998 (Sekiguchi et al. 1996; Iwate
435 Fisheries Technology Center 2013). The other PSP causative species, *A. catenella* which
436 usually appears in sea surface temperatures above 15°C, is reported to have lower cell densities
437 (eg. maximum of 20,300 cells/L according to Ogata et al. 1982) and amounts have never
438 exceeded that of *A. tamarensis*. Therefore, most of ellipsoidal *Alexandrium* cysts in Ofunato Bay
439 are probably formed by *A. tamarensis*, although ellipsoidal cysts can be produced by both *A.*

440 *tamarensis* and *A. catenella*. From the viewpoint of cyst-forming capability and cell density
441 during blooms, *A. catenella* seems to be lower than those of *A. tamarensis*. Therefore, *A.*
442 *tamarensis* is the most important and key species for producing unusually abundant cysts
443 compared with other cyst-forming species, and it also produced most of the resting cysts
444 preserved in the sediments of Ofunato Bay.

445

446 ***2-3 Deeply eroded, well sorted, and re-deposited bottom sediments***

447 It is impossible to know the depositional age of Shizu and Nagasawa cores based on radioactive
448 elements such as ^{210}Pb and ^{137}Cs measurements, because the upper part of these cores were
449 disturbed by the tsunami of the Great East Japan Earthquake. However, the sediment core of
450 50cm length of the P site, which was located at approximately 800m north of the Shizu site, was
451 collected on September of 2012 and investigated for ^{210}Pb and ^{137}Cs concentrations by
452 Administrator of Kamaishi Port (2013). The upper 21cm of this core was also re-deposited by
453 the several tsunamis including the Great East Japan Earthquake on 2011, Chilean tsunami on
454 1960, probably Showa Sanriku tsunami on 1933 and Meiji Sanriku tsunami on 1986. However,
455 based on the sedimentation rate ($0.2 \text{ g/cm}^2/\text{y}$) in another core collected on 2000 at the same site
456 (called the O site) provided by the Port and Airport Research Institute and Japan NUS (2001),
457 the depositional age of the 21cm depth in the P core was estimated as 1885 year by
458 Administrator of Kamaishi Port (2013). The un-disturbed lower parts of all these four cores
459 (Shizu, Nagasawa, P and O cores collected at the center of Ofunato Bay) were not different in
460 sediment facies, having sediments mainly consisted of silt with small shell fragments. Since the
461 re-suspension depth by the 2011 tsunami of the Great East Japan Earthquake was 20-25cm in
462 the Shizu and Nagasawa cores, the un-disturbed lower sediments seem to be deposited over
463 more than 100 years. The first report of ellipsoidal *Alexandrium* cysts from the surface
464 sediments of Ofunato Bay was only in 1980 (Fukuyo 1980). However, small amounts of
465 ellipsoidal *Alexandrium* cysts either filled with protoplasm or empty (ca. 210 cysts/g in Shizu

466 core and ca. 260 cysts/g in Nagasawa core) were recovered from deeper un-disturbed sediments
467 of the cores that were obviously deposited before 1980 according to depositional age of
468 sediments below 20-25cm depth. This means that *A. tamarensis* and/or *A. catenella* might have
469 inhabited Ofunato Bay for over 100 years. This conclusion is partially supported by the
470 evidence that appearance of *A. tamarensis* and/or *A. catenella* in Funka Bay, North Japan, more
471 than 100 years ago (Miyazono et al., 2012). The 25cm thick interval of sediments re-suspended
472 and re-deposited by the tsunami could cover more than 125 years. Although it is impossible to
473 know the exact number of ellipsoidal *Alexandrium* cysts re-suspended after the tsunami in all
474 Ofunato Bay area, the most likely explanation is that large amounts of ellipsoidal *Alexandrium*
475 cysts preserved in the sediments before disturbed by the tsunami were eroded, re-suspended and
476 re-deposited in Ofunato Bay.

477 Such unusual re-deposition of ellipsoidal *Alexandrium* cysts was also observed in Sendai
478 Bay after the 2011 Great East Japan tsunami (Kamiyama et al. 2014). However, the cyst density
479 of ellipsoidal *Alexandrium* cyst in Ofunato Bay was much higher than that of Sendai Bay. The
480 mechanism for accumulation of these *Alexandrium* cysts by the tsunami seems to be the same at
481 Ofunato Bay and Sendai Bay. However, different cyst densities preserved in the older,
482 non-disturbed sediments due to the pre-tsunami bloom histories of *A. tamarensis* might explain
483 the different cyst densities in the re-deposited sediments of both bays. Therefore, knowledge of
484 the vertical distribution and germination viability of living cysts in the sediments is important
485 for predicting future blooms, because living cysts in deeper bottom sediments can still be
486 capable of germination when brought back to the surface (Mizushima and Matsuoka, 2004).

487 In summary, the highly unusual abundance of ellipsoidal *Alexandrium* cysts (mainly *A.*
488 *tamarensis*) in the Shizu and Nagasawa cores was caused mainly by deep erosion (more than 20
489 cm thick), re-suspension, and re-deposition of bottom sediments by the tsunami at the Great
490 East Japan Earthquake, combined with the higher cyst production and more frequent
491 bloom-forming characteristics of *A. tamarensis* in Ofunato Bay. This explanation is supported

492 by additional information on tsunami-related sedimentation processes. Nishi et al. (2013)
493 studied change of sea floor environments and the mechanism of flow dynamics in several inner
494 bays including Ofunato Bay along the Sanriku Coast. In the central part of Ofunato Bay,
495 ignition loss was lower in sediments re-deposited after the tsunami (Nishi et al. 2013). In our
496 cores, re-deposited sediment became coarser as shown by median particle size increasing from
497 10 to 15 μ m. In addition, our two core sites were reported as sediment accumulation areas after
498 the tsunami (Kamaishi Office of Tohoku Regional Development Bureau 2012). These data
499 suggest that during the tsunami wave surges, re-suspended sediments were sorted, with the finer
500 silt to clay sediments containing organic materials being exported from the bay by the return
501 flow of the tsunami. As a result, coarser silt particles were concentrated in the center of the bay.
502 A similar change of sediment particles were also observed in Otsuchi and Funakoshi bays along
503 the Sanriku coast (Seike et al. 2013). Since the size of ellipsoidal *Alexandrium* cysts (35-56 μ m x
504 23-35 μ m in size) is like that of coarse silt, these cysts were preserved in re-deposited sediments.

505

506 **3. Relation between shellfish aquaculture and tsunami events**

507 In Ofunato Bay, the first mass PSP incident happened on May of 1961 due to ingestion of
508 Akazara-scallops that attached to cultured oysters (Kawabata et al., 1962), and later the
509 causative plankton was identified as *Gonyaulax* sp. (Murano 1975). Fishermen in Ofunato Bay
510 often ate Akazara-scallops, starting around March; however, this PSP incident occurred in May
511 of 1961. Because the year 1961 followed the 5.5m-high Chilean tsunami surge into Ofunato
512 Bay on May 23, 1960, a relation between the 1961 PSP incident and the Chilean tsunami event
513 was suspected. According to our core studies, a tsunami could erode and re-suspend the bottom
514 sediment, including ellipsoidal *Alexandrium* cysts which were then re-deposited on the sea floor
515 surface after the tsunami. Such huge amounts of cysts might have seeded of the unusually large
516 *A. tamarense* blooms that occurred along the coast of East and North Japan during June 2011.
517 The tsunami waves caused by the 2011 Great East Japan Earthquake on March 11, 2011 were

518 also observed in Alaska 6-9 hours later, with a height of 1.5m, and 2m-high waves reached
519 Chile 21 hours later. A PSP outbreak was noticed in Southeast Alaska in May to June 2011
520 (MMWR 2011), about 2 months after being hit by the tsunami of the Great East Japan
521 Earthquake. At present, however, it is uncertain if this PSP event was caused by the processes
522 similar to those in Ofunato Bay and Sendai Bay, because in Alaska PSP incidents frequently
523 occur in May to June with non-tsunami events.

524 The Chilean tsunami attacked Ofunato Bay with a wave of 1.9–5.7m height, which was
525 slightly lower than that of the Great East Japan Earthquake tsunami, but the effect on the bottom
526 sediment seemed to be nearly the same as the Great East Japan Earthquake tsunami.
527 Unfortunately, the sediments re-deposited by the Chilean tsunami did not remain in the present
528 location because the Great East Japan Earthquake tsunami eroded and re-suspended these
529 sediments as described above. However, it is reasonable to postulate that re-suspended
530 ellipsoidal *Alexandrium* cysts filled with protoplasm would become the seeding source for the
531 forthcoming 1961 bloom because ellipsoidal *Alexandrium* cysts were preserved in sediments
532 before the Chilean tsunami. Consequently, the first PSP incident in Ofunato Bay might be the
533 result of the *Alexandrium* bloom triggered by germination of living cysts one year after of the
534 Chilean tsunami in almost the same manner as the events following the 2011 tsunami of the
535 Great East Japan Earthquake.

536 Another environmental issues should be discussed here. In Ofunato Bay, the oyster
537 aquaculture first started at Akasaki on 1887 (Miyazawa & Hayakawa 1994) but no paralytic
538 shellfish poisoning was ever reported before the Chilean tsunami despite occurrences of several
539 huge earthquake-generated tsunamis that surged into this bay (Sekiguchi 2010). This lack of
540 pre-1961 PSP outbreaks may reflect the low scale of shellfish aquaculture industry development
541 in this bay before the Chilean tsunami. Interestingly, the opening of the scallop culture industry
542 in Ofunato Bay took place in 1961, just after the Chilean tsunami. This historical circumstance,

543 together with the environmental situation imposed by the tsunami of the Great East Jana
544 Earthquake, provided the following account of the first (1961) PSP incident in Ofunato Bay.

545 When the Chilean tsunami wave hit Ofunato Bay on May 24 of 1960, many ellipsoidal
546 *Alexandrium* cysts preserved in the old sediments might have been re-suspended and
547 re-deposited on the sea floor. It is very difficult to know whether in 1960 these re-deposited
548 cysts could germinate or not (probably not), because the re-deposited sediments were later
549 re-disturbed by the Great East Japan Earthquake tsunami. At the next spring of 1961, the bloom
550 season of *A. tamarense*, some of these cysts might have germinated into vegetative cells which
551 might form dense blooms of *A. tamarense*. These dense blooms were also supported by water
552 quality changes such as eutrophication in this bay because the water quality in this enclosed bay
553 is easily affected by increased population around the bay (eg. Matsuoka 1999). In the case of
554 Ofunato Bay, the population had increased nearly 10% per year since 1920 and reached
555 approximately 400,000 by 1980 (<http://demography.blog.fc2.com/blog-entry-4839.html> based
556 on National census data). This population increase was accompanied with transportation of
557 waste-water from land and resulting increase of nutrients (eutrophication). Unfortunately before
558 1971, there was no regulation of industrial and domestic wastewater from lands in Ofunato Bay.
559 Phytoplankton population might be also changed by such water quality change in Ofunato Bay
560 around 1960's. The vegetative cells forming dense blooms of *A. tamarense* would be consumed
561 by cultured and/or natural shellfish (oysters and scallops) in the bay. A part of these toxicated
562 shellfish (Akazara-scallops) were consumed by local people who then suffered with paralytic
563 shellfish poisoning. During the bloom, vegetative cells of *A. tamarense* produced many new
564 resting cysts, which also remained within the bay because of the semi-enclosed natural shape.
565 Thereafter, these preserved cysts could act as seeding sources for subsequent blooms. In
566 addition, since around 1960 oyster cultures have become popular in Ofunato Bay, and local
567 people would be more scientifically aware of PSP events. The scientific work informs us that
568 unpleasant phenomena for human society, such PSP, will often manifest after catastrophic

569 natural disasters (the tsunami in this case) and will be worsened by artificial changes by rapid
570 increase of populations and shellfish aquacultures for natural environments.

571

572 Summary

573 1. The sediment above ca. 25cm depth from the sea floor in the center of Ofunato Bay was
574 re-deposited by the tsunami of the 2011 Great East Japan Earthquake.

575 2. The fluctuation of vertical distribution of sediment grain size and density of ellipsoidal
576 *Alexandrium* cysts in bay sediment cores might reflect the multiple surges of the tsunami.

577 3. The maximum density of ellipsoidal *Alexandrium* cysts recorded at the 6–7cm depth in the
578 Nagasawa core was the result of the deep erosion and re-suspension of older sediments and
579 the specific cyst-forming capability of *Alexandrium tamarense*.

580 4. The first PSP incident on 1961 in Ofunato Bay probably resulted from huge blooms of
581 *Alexandrium tamarense* initiating from resting cysts which were moved to the sea floor by
582 deep erosion and re-suspension of sediments involving ellipsoidal *Alexandrium* cysts filled
583 with fresh protoplasm after the Chilean tsunami in 1960, combined with deterioration of water
584 quality due to rapid increase of population and development of shellfish aquacultures.

585

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801

802 Explanations of Figures. Tables and Supplemental Data

803

804 **Figure 1**

805 Coring sites in Ofunato Bay, Northeast Japan

806 The Shizu coring site was located at ca. 800m north of the core O series site by Port and Airport

807 Research Institute and Japan NUS (2001) and of the Station P in Kamaishi Office of Tohoku

808 Regional Development Bureau (2012).

809

810 **Figure 2**

811 Sediment characteristics of the Shizu core (A) and Nagasawa core (B). Vertical lines indicate

812 the depth of sediments which were re-deposited at the Great East Japan Earthquake tsunami on

813 March 11 0d 2011. Vertical curved lines showed slender tubes formed by polychaetes, which

814 may indicate the re-deposited parts of sediments.

815

816 **Figure 3**

817 Sediment characteristics; grain size composition, median particle size, and water content of the

818 Shizu core. Two horizontal dashed lines indicate changes of median particle size and water

819 content. The interval might suggest a transitional zone between re-deposited part by the Great

820 East Japan Earthquake tsunami and un-disturbed part. Lines with arrow indicate increase or

821 decrease of median particle size and water content.

822

823 **Figure 4**

824 Sediment characteristics; grain size composition, median particle size, and water content of the

825 Nagasawa core. Two horizontal dashed lines indicate changes of median particle size, and water

826 content. The interval might suggest a transitional zone between re-deposited part by the Great

827 East Japan Earthquake tsunami and un-disturbed part. Lines with arrow indicate increase or

828 decrease of median particle size and water content. Within the un-disturbed part, median particle
829 size was rather unstable.

830

831 **Figure 5**

832 Dominant dinoflagellate cysts in the Shizu and the Nagasawa core sediments.

833 1-4; Ellipsoidal *Alexandrium* cysts (1 & 3 cysts filled with protoplasm, 2 & 4 empty cysts), 5

834 *Spiniferites bulloideus* (Cookson et Deflandre) Sarjeant, 6 *Brigantedinium* sp. indet.

835 (*Protoperidinium* cyst filled with protoplasm), 7 *Votadinium spinosum* Reid (=cyst of

836 *Protoperidinium claudicans* (Paulsen) Balech)

837

838 **Figure 6**

839 Vertical distributions of total dinoflagellate cysts and major groups in the Shizu Core.

840 *Alexandrium* cysts included all of cysts filled with protoplasm and empty cysts. Dashed lines

841 show the 5cm interval of observed samples. Shadow indicates a transitional zone between the

842 re-deposited and un-disturbed sediments after the Great East Japan Earthquake tsunami.

843

844 **Figure 7**

845 Vertical distributions of total dinoflagellate cysts and major groups in the Nagasawa Core.

846 *Alexandrium* cysts included all of cysts filled with protoplasm and empty cysts. Dashed lines

847 show the 5cm interval of observed samples. Shadow indicates a transitional zone between the

848 re-deposited and un-disturbed sediments after the Great East Japan Earthquake tsunami.

849

850 **Table 1**

851 List of dinoflagellate cysts, acritarchs and other palynomorphs observed in the Shizu and

852 Nagasawa cores

853

854 **Table 2**

855 Cyst densities of *Alexandrium tamarense/cetenella* including *A. fudyense* in the previous
856 records.

857

858 **Table 3**

859 Highest occurrence of ellipsoidal *Alexandrium* cysts in Ofunato Bay (cysts/cm³)

860

861 **Supplemental Data 1**

862 Occurrence of dinoflagellate cysts in the Shizu core

863

864 **Supplemental Data 2**

865 Occurrence of dinoflagellate cysts in the Nagasawa core

866

Figure 1

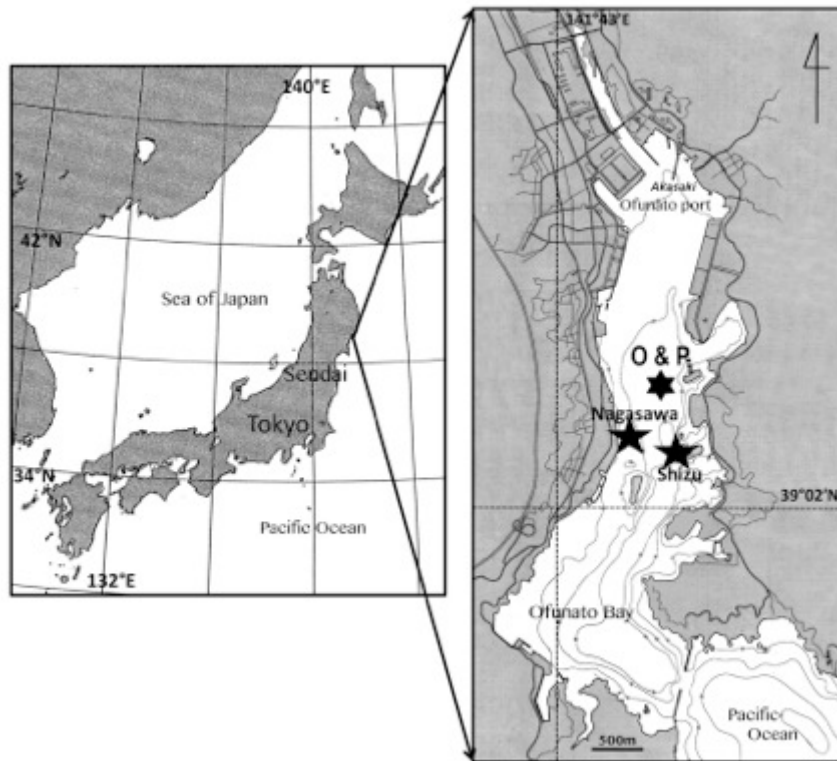


Figure 2

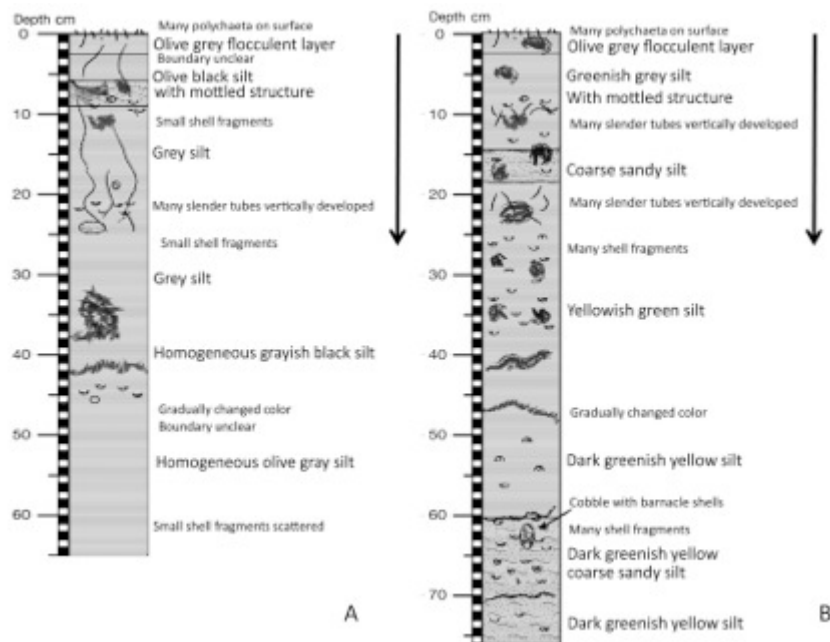


Figure 3

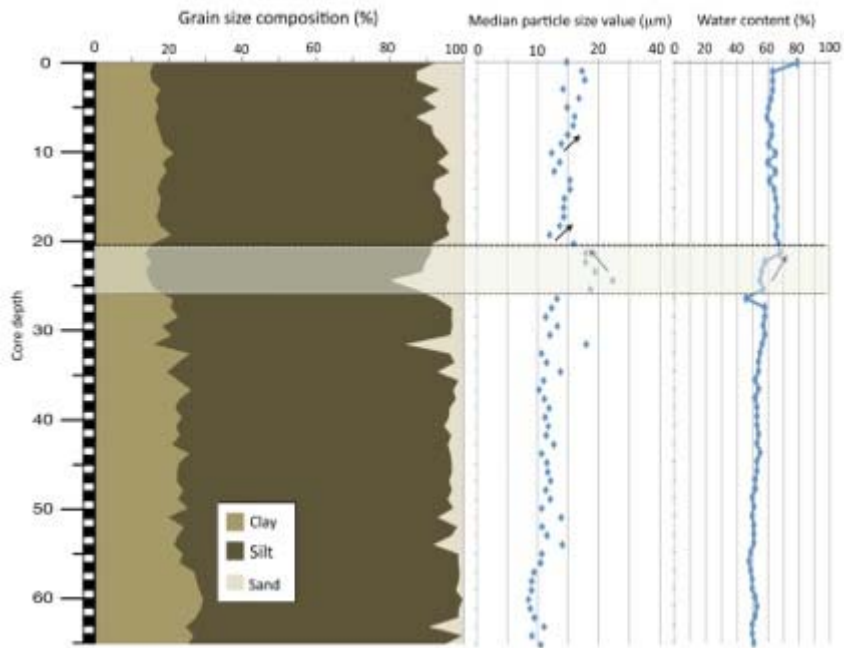


Figure 4

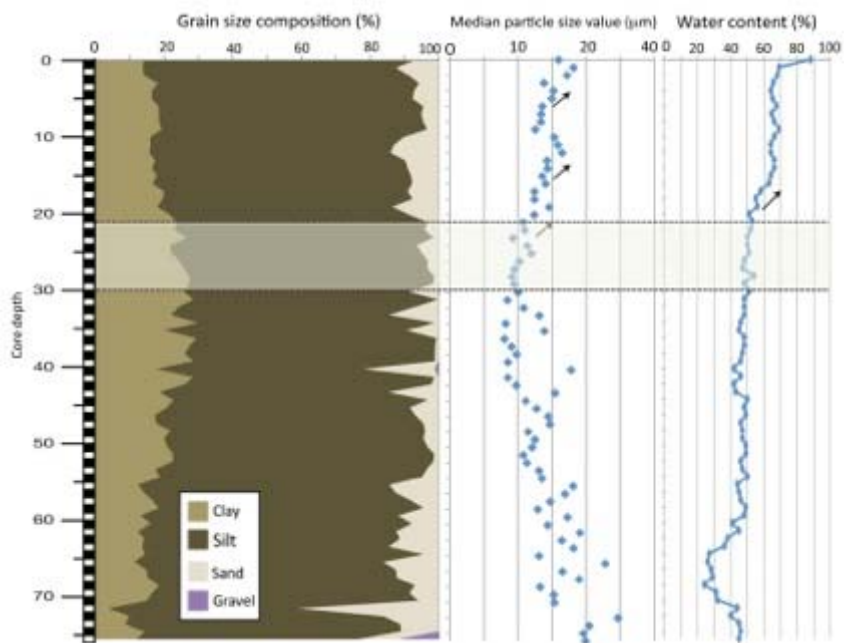


Figure 5

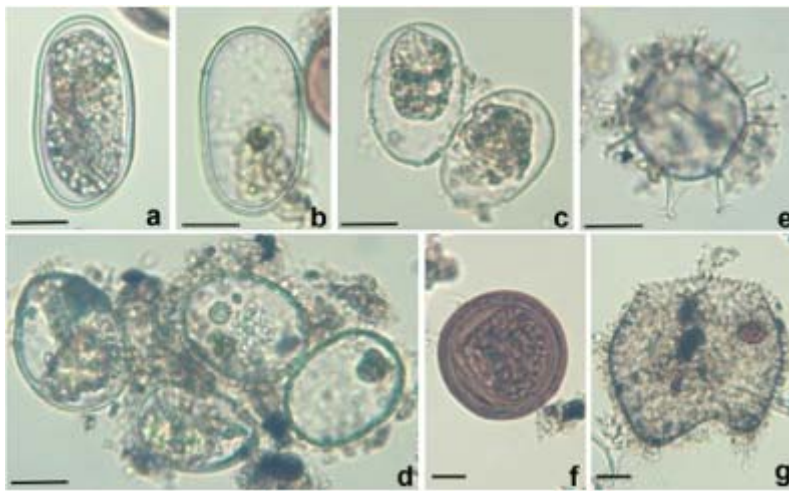


Figure 6

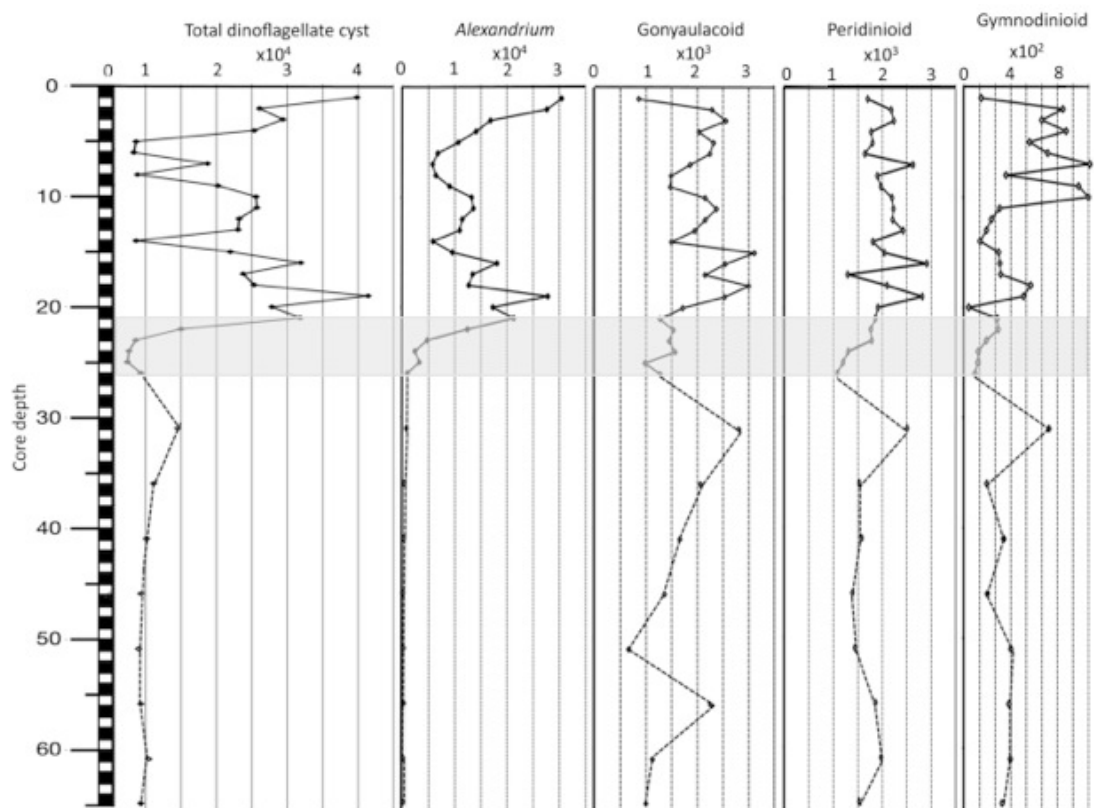


Figure 7

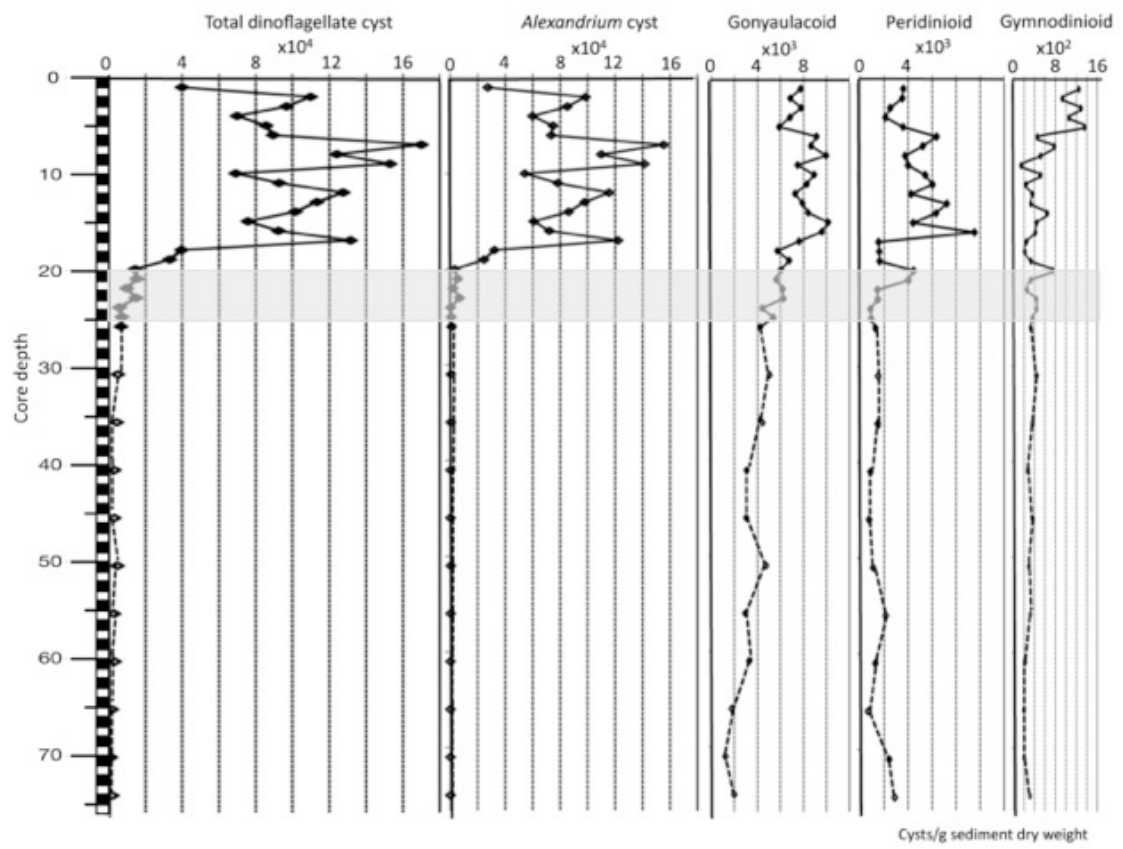


Table 1 **List of dinoflagellate cysts, acritarchs and other palynomorphs**

Photo/mixotrophic dinoflagellate cysts:

- Alexandrium tamarensense/catenella* (as ellipsoidal *Alexandrium* cyst)
Alexandrium fraterculus/minusculum/pseudogoniaulax[#] (as spherical *Alexandrium* cyst)
Spiniferites bulloideus (Deflandre & Cookson) Sarjeant ls*
Spiniferites delicatus Reid*
Spiniferites mirabilis (Rossignol) Sarjeant*
Spiniferites ramosus (Ehrenberg) Mantel*
Spiniferites hyperacanthus (Deflandre & Cookson) Cookson & Eisenack*
Spiniferites elongatus Reid*
Protoceratium reticulatum (Claparède & Lachmann) Bütschli = *Operculodinium centrocarpum*
(Deflandre & Cookson) Wall sensu Wall & Dale*
Lingulodinium machaerophorum (Claparède & Lachmann) Wall*
Tuverculodinium vancampoae (Rossignol) Wall *
Scrippsiella spp.
Polykrikos hartmannii Zimmermann

Heterotrophic dinoflagellate cysts:

- Polykrikos kofoidii* Charron
Polykrikos schwartzii Bütschli
Niea acanthocysta (Kawami, Iwataki & Matsuoka) T. Liu, K.N. Mertens & H. Gu
Protoperidinium leonis (Pavillard) Balech
Protoperidinium obtusum (Karsten) Park & Dodge
Protoperidinium latissimum (Balech) Balech
Protoperidinium latidorsale (P.-A. Dangeard) Balech
Protoperidinium paraoblongum Sarai, Yamaguchi, Kawami & Matsuoka
Protoperidinium steidingeriae Balech
Protoperidinium subinerme (Paulsen) A. R. Loeblich
Protoperidinium americanum (Gran & Braarud) Balech
Brigantedinium cariacense (Wall) Reid*
Brigantedinium simplex (Wall) Reid*
Brigantedinium majusculum Reid*
Brigantedinium irregulare Matsuoka ex Head

Stelladinium stellatum (Wall) Reid *

Dubridinium caperatum Reid*

Echinidinium aculeatum Zonneveld*

Echinidinium spp*.

Selenopenphix nephroides Benedek) Benedek & Sarjeant*

Selenopenphix quanta (Bradford) Matsuoka (large form)*

Selenopenphix quanta (Bradford) Matsuoka (small form)*

Trinovantedinium applanatum (Reid) Bujak & Davies*

Votadinium spinosum Reid*

Votadinium calvum Reid*

(* cyst-based biological name; # based on observation of plankton forms by Kaga et al. 2006)

Acritarchs:

Baltisphaeridium sp.

Halodinium major Bujak

Other marine palynomorphs:

Archeomonas sp.

Tintinnopsis sp.

Microforaminiferal linings (uni-serial type, bi-serial type, coiled type)

Crustacean resting eggs and body fragments

Table 2

Cyst densities of *Alexandrium tamarense*/*cetenella* including *A. fudyense*

Area	Maximum cyst density	References
	Surface sediment	
Gulf of Maine, USA/Canada	2,000 cysts cm ⁻³	Anderson et al. (2005)*
Okhotsuku Sea and Soya Strait, Hokkaido, Japan	2,022 cysts wet g ⁻¹	Shimada and Miyazono (2005)
Ise Bay, central Japan	2,254 cysts cm ⁻³	Ishikawa et al. (2007)
Funka Bay, Hokkaido, Japan	2,568 cysts wet g ⁻¹	Shimada and Miyazono (2005)
Yellow Sea	3,778 cysts dry g ⁻¹	Cho & Matsuoka (2001)
Hiroshima Bay, West Japan	4,454 cysts cm ⁻³	Yamaguchi et al. (2002)
Osaka Bay, West Japan	5,683 cysts cm ⁻³	Yamamoto et al. (2009)
Mikawa Bay, Central Japan	7,311 cysts cm ⁻³	Ishikawa et al. (2007)
Bay of Fundy, Canada	7,440 cysts cm ⁻³	Martin and Wildish (1994)*
Tokuyama Bay, West Japan	8,137 cysts cm ⁻³	Yamaguchi et al. (2002)
Aso Bay, Tsushima Island, West Japan	8,900 cysts cm ⁻³	Matsuoka & Lee (1994)
Chukchi Sea, the Arctic Ocean	10,600 cysts cm ⁻³	Natsuie et al. (2013)
Puget Sound, Washington, USA	12,125 cysts cm ⁻³	Horner et al. (2011) [#]
Bedford Basin, Nova Scotia, Canada	220,872 cysts dry g ⁻¹	Lacasse et al. (2013)**
	Surface sediment after the tsunami	
Sendai Bay, Northeast Japan	8,190 cysts cm ⁻³	Kamiyama et al (2014)
Kesennuma Bay, Northeast Japan	6,383 cysts cm ⁻³	Ishikawa et al. (2015)
Kesennuma Bay, Northeast Japan	4,170 cysts cm ⁻³	Nishitani et al. (2012)
Funka Bay, Hokkaido, Japan	3,200 cysts wet g ⁻¹	Natsuie et al. (2014)
Ofunato Bay, Northeast Japan	62,000 cysts dry g ⁻¹	Ikeda et al. (2013)
	Core sediment after the tsunami	
Ofunato Bay, Northeast Japan	155,210 cysts dry g ⁻¹	This study
		* <i>A. fundyense</i>
		** <i>A. tamarense</i>
		[#] <i>A. catenella</i>
		No mark <i>A.</i>
		<i>tamarense/catenella</i> or

Table 3

Highest occurrence of elongate *Alexandrium* cysts in Ofunato Bay (cysts/cm³)

Age	Innter Bay	Central Bay	Bay Mouth	Reference
1980	642	1326	62	Fukuyo (1980)
1985	143	490	25	Iwate PFES (1986)
1986	185	955	20	Iwate PFES (1987)
1987	320	490	ND	Iwate PFES (1988)
1988	1050	1200	30	Iwate PFES (1989)
1990	433	1000	500	Iwate PFES (1990)
1992		No iformation		Iwate PFES (1993)
1998	430	620	ND	Iwate FTC (1999)
1999	467	438	40	Iwate FTC (1999)
Average	458	815	113	

PFES: Prefectural Fisheries Experimental Station

FTC: Fisheries Techology Center

Supplemental Data 1
Shizu Core

Species	Sample depth																13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	30-31	35-36	40-41	45-46	50-51	55-56	60-61	64-65			
	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	3-3.5	4-4.5	5-5.5	6-6.5	7-7.5	8-8.5	9-9.5	10-11	11-12	12-13																									
Alexandrium																																								
<i>Alexandrium tamarense / catenella</i>	4857	6393	6575	18588	15833	12971	9315	6098	5333	5902	8473	12300	12829	10500	10457	5512	8777	16171	12264	10971	26294	16685	20303	4093	1952	3204	844	558	71	62		63	60							
<i>Empry-A.tamarense</i>	428	214	425	794	472	143	368	268	214	73	184	425	229	475	257	51	416	1257	323	1028	558	171	181	250	333		46	142	125			20	96	21						
<i>Alexandrium affine / lei</i>	785	286	450	794	555	1000	921	317	238	390	394	525	514	475	257	282	361	629	852	685	970	428	787	375	95	45	111	162	47			20								
<i>Empry-A.affine / lei</i>	142						105	98	24	48				28				57						31	23				23			80	115	42	40					
Other gonyaulacoid																																								
<i>Spiniferites</i>																																								
<i>Spiniferites mirabilis</i>																		29						31	47					21		20	173	21	20					
<i>Spiniferites ramosus</i>		36		58	166	57	105	415	286	292	316	350						29	147		29			62	71	22		139	333	166	489	638	220	269	191	142				
<i>Spiniferites hyperacanthus</i>	142	36	25									50									29								47	20	21	21		19						
<i>Spiniferites elongatus</i>	214	36			55		52		48			25						27		29						22	22		71	41	42	21	40	38		102				
<i>Spiniferites bentorii</i>																													125											
<i>Spiniferites bulloideus</i>	4357	2036	1900	2588	2333	1971	2157	1829	1524	1171	1158	1725	2371	2075	1914	1467	2972	2371	1794	2771	2441	1600	1181	1125	1309	1500	911	1069	2166	1604	1021	617	300	1711	787	612				
<i>Protocecratium reticulatum</i>							78	49	24	24	132							29	49	171									22	46	47		21	21	80		85	81		
<i>Tuberculodinium vancampoae</i>						86	26	24				25			25					55	29		57	29	28			31	23	22	22	23	95	20	42	21		38	21	20
Gymnodinioid																																								
<i>Phaeopolykrikos harmannii</i>																																								
<i>Polykrikos kojoidii</i>	285		50	58	55	86	26		71	24	53	125	57	25	29	51	27	29	29	57	29	28	60	62	71	45	44	69	142		83		42	21	40	76	127	81		
<i>Polykrikos schwartzii</i>	214	214	175	205	83	57	52	146	167	73	105	175	171	150	114	51	194	200	205	371	352		151	156	71	45	44		404	62	212	127	260	211	170	163				
Peridinioid																																								
<i>Protoperidinium conicum</i>	285	36	75	117	166	57	263	146	71	146	60	125	143	100	171	153	305	229	58	57	323	228	212	250	95	68	88	23	285		106	63	80	76	297	326				
<i>Protoperidinium leonis</i>	1714	571	575	617	527	543	526	537	1048	902	605	900	657	625	886	615	361	1114	382	1028	1058	428	696	531	71	272	400	279	595	145	212	170	280	403	127	265				
<i>Protoperidinium obtusum</i>	142	36																											22				354							
<i>Protoperidinium claudicans</i>	214	107	75	58	111	57	78	122	71	24	105	100	57	50	57	51	27	86	29	85	88			125	71	68	22	69	190		63	106	120	288	170	142				
<i>Votadinium calvum</i>				58												51	27	58	28	88			60	62				22		95	125	21	21	20	57	21				
<i>Protoperidinium latidorsale</i>							26																																	
<i>Protoperidinium inaequale</i>							52				79		28										30							23	47		21		20					
<i>Protoperidinium steidingeriae</i>						28	26																																	
<i>Protoperidinium symmetricum</i>	214	71	25	88				73	47	73																														
<i>Protoperidinium subinermis</i>	214	36	25	29		28	52	49	48	24	53	50		100		51	28	29	28	29			30		23	68	22	23	166	41	85	42	60	38	85	102				
<i>Protoperidinium americanum</i>	285		125	88	194	86	131		95	24	53	175	171	150	29	102	171		85	58	114	60	62	71	22	155	116	166	62.5	276	106	120	192	106	81					
<i>Stelladinium stellatum</i>	71	36									26			100																										
<i>Trinovantedinium applanatum</i>	71					28						50	29																											
<i>Bri.gantedinium spp.</i>	4071	1714	1325	1882	1638	1000	763	780	1976	1122	1184	1325	1057	1875	2371	1307	2027	2029	911	1142	2176	1000	1060	1093	976	1181	822	418	523	62.5	468	510	500	365	489	346				
<i>Bri.gantedinium simplex</i>	3500	607	975	1176	777	1200	1210	1171	881	1122	1132	1125	1314	725	1029	923	944	1371	588	914	1176	1628	1000	937	1928	590	511	860	2166	479	1361	1319	1140	1653	1702	897				
<i>Brigantedinium cariacense</i>	71	36	75		166			78	98	167	98	263	150	314	300	114	153	138	257	205	457	176	114	272	187	119	181	200	162	285	1312	255	170	340	96	276	61			
<i>Brigantedinium majusculum</i>	642	36	700	647	888	514	368	317	857	244	110	400	343	50																										
<i>Brigantedinium irregulare</i>							26							75																										
<i>Dubridinium caperatum</i>	357	107	175	205	277	114	105	122	357	98	105	350	314	200	200	179	222	200	205	171	264	85	30	218	166	90	111	93	214		63	127	40	192	340	551				
<i>Scrippsiella spp.</i>	642	357	225	176	83	314	131	195	190	49	289	125	57																											
Total (cysts/g)	23917	#####	13975	28226	24379	20340	17040	12853	13738	#####	#####	20600	20711	18200	18001	11052	16962	26913	18518	20305	36401	22849	26504	10024	7562	7534	4417	4339	9460	5595	5137	4353	4020	6471	5438	4336				

