

Decadal-scale variations of sedimentary dinoflagellate cyst records from the Yellow Sea over the last 400 years



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ABSTRACT

In recent decades, the Yellow Sea has experienced severe environmental deterioration due to increasing input of anthropogenic pollutants and consequently accelerated eutrophication. Whilst there have been significant advances in documenting historical records of metal pollution in the Yellow Sea region, changes in phytoplankton community structures affected by eutrophication remain understudied. Here, we present a new record of dinoflagellate cyst-based signals in age-dated sediment cores from the Yellow Sea mud deposits to provide better insight into eutrophication history and identification of associated responses of the regional phytoplankton community. It is worthy of note that there were significant variations in abundances and community structures of dinoflagellate cysts in three historical stages in association with increasing anthropogenic activity over the last 400 years. Pervasive effects of human interference altering the Yellow Sea environments are recognized by: 1) an abrupt increase of organic matter, including the diatom-produced biogenic opal concentrations (~1850); 2) a distinct shift in phytoplankton composition towards dinoflagellate dominance (~1940), and 3) recent acceleration of dinoflagellate cyst accumulation (~1990). Particularly in the central Yellow Sea shelf, the anomalously high deposition of dinoflagellate cysts (especially *Alexandrium* species) is suggested to be a potentially important source of inoculum cells serving as a seed population for localized and recurrent blooms in coastal areas around the Yellow Sea.

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1. Introduction

The Yellow Sea, a typical Pacific epi-continental sea surrounded by China and the Korean Peninsula (Fig. 1), is very productive and supports substantial populations of fish, birds, mammals, invertebrates, and a large human coastal population (Lin et al., 2005; UNDP/GEF, 2007). Recently, this sea has been considered as one of the most degraded marine areas and its ecosystem faces several serious environmental problems (Wang et al., 2003, 2009; UNDP/GEF, 2007; Liu et al., 2013a; Murray et al., 2015). During recent decades, rapidly increasing human activities have exerted a large

influence on the Yellow Sea environment by altering the biological and chemical dynamics of the region, and consequently have caused severe deterioration in the ecosystems of the coastal and shelf environments (Park et al., 1998; Lin et al., 2005; Song et al., 2007; Son et al., 2011). Particularly in the coastal regions of the sea, there is growing concern over recurrent and spatially widespread algal blooms caused by toxic and harmful cyst-forming dinoflagellate species, which often result in large-scale damage to coastal aquacultural areas (Lee, 2006; Tang et al., 2006; Chi, 2008; Kim, 2010). In addition, an ocean-dumping site in the central part of the Yellow Sea is a potential source of anthropogenic materials (Park and Choi, 1993; Park et al., 1998; Son et al., 2011) (Fig. 1). To understand effects of such drastic environmental changes on the Yellow Sea ecosystem, especially for the last 100 years coupled with the rapid economic development of Korea and China, numerous studies have been conducted in several coastal areas, mostly based

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on the accumulation history of heavy metals (e.g., Qin et al., 2006; Kim et al., 2009a; Lim et al., 2012; Zhang et al., 2012; Liu et al., 2013b). However, there is a lack of retrospective data to identify changes in phytoplankton community structure affected by eutrophication, especially in the shelf area of the Yellow Sea. Here, eutrophication is regarded as the suite of adverse symptoms resulting from anthropogenic nutrient loadings.

Marine plankton groups such as dinoflagellates, diatoms, foraminifers and coccoliths have been widely used to assess spatial and temporal changes in marine environments due to its sensitivity to hydrographic parameters. Notably, dinoflagellates constitute an integral part of phytoplankton communities in coastal marine waters and produce hypnozygotic cysts (dinoflagellate cysts) as a part of the sexual reproduction cycle (e.g. Taylor, 1987; Kremp, 2013). Organic-walled dinoflagellate cysts are of particular interest because they are extremely resistant to mechanical, chemical and bacterial deterioration and, therefore, can be preserved in bottom sediments for variable time scales (Harland, 1988; Head, 1996). Since assemblage composition of the dinoflagellates highly depends on different physical, chemical and biological water mass properties, their ecological preferences to environmental gradients make them ideal to identify a range of environmental signals (McKay et al., 2008; Marret and Kim, 2009; Zonneveld et al., 2013). Thus in polluted marine environments, dinoflagellate cysts can provide an integrated record over time of eutrophication (e.g., Anderson et al., 2005; Kim et al., 2009b; Liu et al., 2012, 2013b; D'Silva et al., 2013). It is of note that previous studies on surface sediments of the Yellow Sea revealed an intense sedimentation of dinoflagellate cysts in the central shelf area (Cho and Matsuoka, 2001; Hwang et al., 2011), including the ocean dumping site (Shin et al., 2013). However, the underlying details of such prominent dinoflagellate cyst deposition, particularly for toxic or harmful species, are still enigmatic and there has been no investigation on the historical changes of the dinoflagellate cysts in the shelf area of the Yellow Sea. The general paucity of adequate sedimentary dinoflagellate cyst records to track changes in phytoplankton community composition is an important factor limiting our understanding of past changes in marine environments of the Yellow Sea in response to recent eutrophication.

This study presents a new record of temporal-scale variations in the palynological and biogeochemical properties of two sediment cores from the central and southwestern Yellow Sea mud deposits. This paper provides the first description of the composition, abundance, and vertical distribution of dinoflagellate cysts in core sediments from Yellow Sea mud deposits with the aim of identifying trends in major phytoplankton shifts and, thus, tracking the eutrophication history of Yellow Sea marine environments in response to increased anthropogenic activities over recent decades.

2. Materials and methods

Two sediment core samples were collected with a box corer from the mud deposits of the central Yellow Sea (core AB-1: 35°49.861'N, 124°30.016'W; water depth: 84 m; 40 cm in length) and the southeastern Yellow Sea (core D-6: 35°00.019'N, 125°20.129'W; water depth: 72.5 m; 60 cm in length) (Fig. 1). For dinoflagellate cyst and geochemical composition analyses, core AB-1 was subsampled at 0.5–5 cm intervals ($n = 19$), and core D-6 was subsampled at intervals between 1 and 5 cm ($n = 25$). Each subsample was initially prepared for palynological analysis using the following procedure. After adding a marker spore tablet (*Lycopodium clavatum* spore) to each subsample in order to calculate the concentration of dinoflagellate cysts based on sediment dry weight (g), the samples were treated with 10% hydrochloric acid (HCl) and 40% hydrofluoric acid (HF) to remove calcium carbonate and silicate materials. The samples were passed through a mesh sieve of pore size 10 μm to remove particles smaller than this size. The final residues were mounted between a slide and cover slip in glycerin jelly and sealed with paraffin wax. Where possible, a minimum of 300 dinoflagellate cysts were counted using a Nikon (Eclipse 55i) microscope at 250 \times and 400 \times magnifications. All round, brown protoperidinioid cysts with an opening were grouped together as *Brigantedinium* spp. as the shape of the archaeopyle was not recognizable.

Total carbon (TC) and total inorganic carbon (TIC) concentrations of the subsamples were measured using a CHN elemental analyzer (FLASH 2000; Thermo Fisher Scientific, Waltham, MA, USA) and a CO₂ coulometer (model CM5014; UIC, Joliet, IL, USA), respectively. The analytical accuracies and precisions of these elements were within 5%, based on an analysis of standard reference materials (L-cysteine in TC analysis and calcium carbonate with 12.00 C% in TIC analysis) and replicate samples. The TOC concentration was calculated from the difference between TC and TIC concentrations. The biogenic silica (BSi) concentration was analyzed using a wet alkaline extraction method modified from Mortlock and Froelich (1989) and Müller and Schneider (1993). The relative error of BSi concentration in this study was less than 10%, based on an analysis of standard reference materials and replicate samples. BSi concentrations were converted to biogenic opal concentrations based on a weight percentage, using a multiplication factor of 2.14.

To reconstruct the chronologies of the two cores, sedimentation rates were determined using excess ²¹⁰Pb (²¹⁰Pb_{ex}) activity values, which is equivalent to the total ²¹⁰Pb activity (²¹⁰Pb_{tot}) minus the supported ²¹⁰Pb activity that is in equilibrium with sedimentary ²²⁶Ra. The analytical and calculation methods used to determine ²¹⁰Pb activity were described in detail in previous studies of Yellow Sea core sediments (e.g., Lim et al., 2007, 2012). The ²¹⁰Pb-derived linear sedimentation rates calculated from the gradient of ²¹⁰Pb_{ex} activity in each core were estimated to be 0.09 cm/yr and 1.68 cm/yr in cores AB-1 and D-6, respectively. These rates are similar to those reported previously in these areas (Lim et al., 2007, and references therein). The sedimentation rates yielded estimated dates of ca. 1570 and 1980 at the end of cores AB-1 and D-6, respectively.

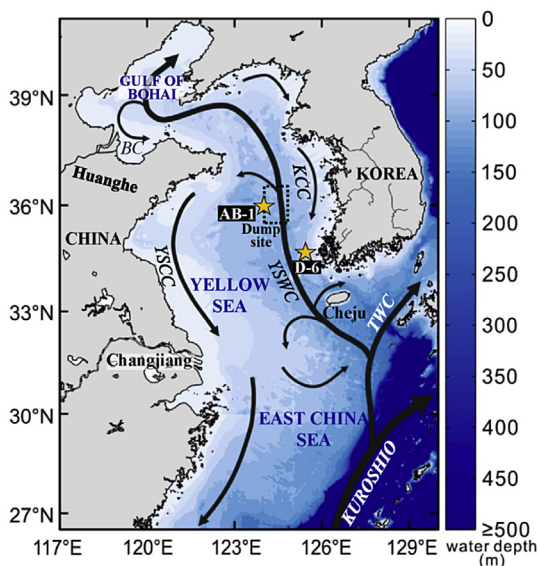


Fig. 1. Map of the study area with locations of sediment samples (AB-1 and D-6), as well as the Yellow Sea circulation system: BC, Bohai Current; YSCC, Yellow Sea Coastal Current; YSWC, Yellow Sea Warm Current; KCC, Korean Coastal Current; TWC, Tsushima Warm Current.

3. Results and discussion

3.1. Characteristics of dinoflagellate cyst assemblages and elemental compositions

The dinoflagellate cyst assemblages and elemental compositions of the age-constructed cores showed significant down-core variations (Figs. 2–4). Concentrations of the dinoflagellate cysts in core AB-1 and D-6 ranged from approx. 1400–20,000 and 280–2200 cysts/g, respectively (Fig. 2). In core AB-1, the dominant species were *Spiniferites bulloides* (8–92%), *Alexandrium tamarense/catenella* (0–51%), *Operculodinium centrocarpum* (0–43%), and *Brigantedinium* spp. (4–31%) (Fig. 3). Vertical variations in dinoflagellate cysts in core AB-1 showed a dominance of *Spiniferites* species in the lower section of the core (25–40 cm), reaching up to approx. 6886 cysts/g at 30 cm, followed by a sharp decline. The upper section of the core (above 6 cm) was characterized by a notable increase in *A. tamarense/catenella* type, *O. centrocarpum*, and *Brigantedinium* species. Of particular note was the remarkable occurrence of *O. centrocarpum* and *A. tamarense/catenella* type in the surface samples, in which both taxa reached up to approx. 8000 cysts/g. In core D-6, the most common species included *A. tamarense/catenella* type (0–74%), *Spiniferites bulloides* (15–65%), *Brigantedinium* spp. (0–47%), and *O. centrocarpum* (0–25%) (Fig. 3). The cyst assemblages showed large fluctuations throughout the core: the lower section below a core depth of 22 cm showed a higher occurrence of *Spiniferites* species and *A. tamarense/catenella* type, while the upper section was characterized by notable increases in *Brigantedinium* species and *O. centrocarpum*.

In core AB-1, TOC and TN concentrations exhibited a distinctive upward-increasing trend, fluctuating from 0.30% to 1.84% (average: $0.75\% \pm 0.33\%$) and 0.05%–0.19% (average: $0.11\% \pm 0.04\%$), respectively (Fig. 4). Biogenic opal concentration varied from 4.4% to 12.1% (average: $6.5\% \pm 1.7\%$), with an abrupt increase at approx. 13 cm: the concentration was low (4–5%) in the lower sediments below 13 cm, but increased markedly to >6% in the upper sediments of the core. Similar trends in down-core variations of these elemental compositions imply a significant environmental change in the Yellow Sea over the last 400 years. In contrast, there was no apparent down-core variation in core D-6 from the southeastern Yellow Sea mud deposits. TOC and TN concentrations ranged from 0.59% to 0.88% ($0.75\% \pm 0.07\%$) and 0.09%–0.14% ($0.11\% \pm 0.01\%$), respectively. Biogenic opal concentrations were between 6.6% and 9.9% (average: $7.5\% \pm 0.8\%$).

In general, down-core variations of dinoflagellate cyst assemblages in sediments are mainly controlled by a combination of biological and sedimentological factors. In this context, the interpretation of the dinoflagellate cyst record must consider not only the cyst production, but also changes in sediment accumulations of the depositional system. Nevertheless, considering asynchronous trends in the curves of the major dinoflagellate cyst concentrations and their percentages as well as biogeochemical properties as shown in Figs. 3 and 4, an influence of sedimentation changes was unlikely significant. This suggests that the dinoflagellate cyst assemblage changes observed in the present study may primarily reflect a marine plankton community response to environmental changes in the Yellow Sea water masses during the last 400 years.

3.2. Decadal-scale variations in dinoflagellate cyst records and their implications

As dinoflagellate cysts are a useful proxy of environmental changes, including anthropogenic activity (e.g., Matsuoka et al., 2003; Pospelova et al., 2005; Dale, 2009), their sedimentary records can provide retrospective data over time in marine

environments where long-term monitoring data are insufficient. In this study, temporal variations in the dinoflagellate cyst records of the Yellow Sea shelf core sediments imply significant environmental changes over the last 400 years, which can be divided into three stages (Stages A, B, and C in ascending order) in association with population growth and industrial development in China and Korea (Fig. 5).

3.2.1. Stage A (before ca. 1850)

This stage represents a period when the regions along the Yellow Sea coastline were free from anthropogenic pollution with a sparse population and little industrial development. The dinoflagellate cyst concentration, as well as the organic matter and biogenic silica concentrations, remain relatively low during this period, which probably reflects the earlier environmental conditions of the Yellow Sea. Of particular interest is a relatively high occurrence of *Spiniferites* species dominating the dinoflagellate cyst assemblage at up to 90–92% until ca. 1700, followed by a sharp decrease. As strong nutrient supplies from human activity are unlikely during this period, the preferential occurrence of *Spiniferites* species may be associated with other environmental and/or climatic factors. Further studies are required to determine the cause of such high production and/or deposition of this particular dinoflagellate cyst group.

3.2.2. Stage B (ca. 1850–1940)

This stage is characterized by rapid increases in TOC, TN, and biogenic opal concentration, while the dinoflagellate cyst concentration remains low (Fig. 5). As sediment burial of organic matter in the shelf is mostly derived from phytoplankton detritus, such large-scale increases in TOC and biogenic opal are indicative of increased local primary production in the central Yellow Sea stimulated by nutrient enrichment. It is noteworthy that a direct influence of nutrient input from the Yellow River to the study area is not likely because the Yellow River shifted its course from the south to the north at the beginning of this period, emptying into the Bohai Sea since 1855 (Saito et al., 2001; Liu et al., 2004). Therefore, the abrupt increase in the organic matter during this period may be closely related to anthropogenic impacts, particularly eutrophication around the Yellow Sea, rather than changes in the natural environment. This suggestion is well supported by eutrophication signals reported from coastal areas around the Yellow Sea (e.g., Lim et al., 2012, and reference therein) that correspond in time with the signals from the central offshore Yellow Sea presented in this study. Such coastal eutrophication, owing to the continuous discharge of industrial effluent and domestic sewage, would have enhanced nutrient availability in the entire Yellow Sea region, stimulating primary production accompanied by relatively dense and strong phytoplankton blooms offshore.

Of particular note is the pronounced increase of biogenic opal concentration from 1866, which indicates a very large increase of diatoms in phytoplankton assemblages resulting from enhanced nutrient supply. Changes in dinoflagellate cyst abundance, however, are relatively subtle or even negligible compared with the biogenic opal signal, implying that the improved nutrient conditions of the Yellow Sea did not yet considerably benefit *in situ* dinoflagellate productivity in the study area (Fig. 5). This result also points to preferential growth of diatoms over dinoflagellates at a given time, since they are at a competitive advantage among primary producers and thus have growth rates much higher than dinoflagellates (c.f., Chan, 1978; Falkowski et al., 1985; Furnas, 1990; Tang, 1995; Andren, 1999). The disparity between the timings of increases in the organic matter and dinoflagellate cysts in response to nutrient enrichment further suggests that observations of dinoflagellate cyst signals should be used critically in

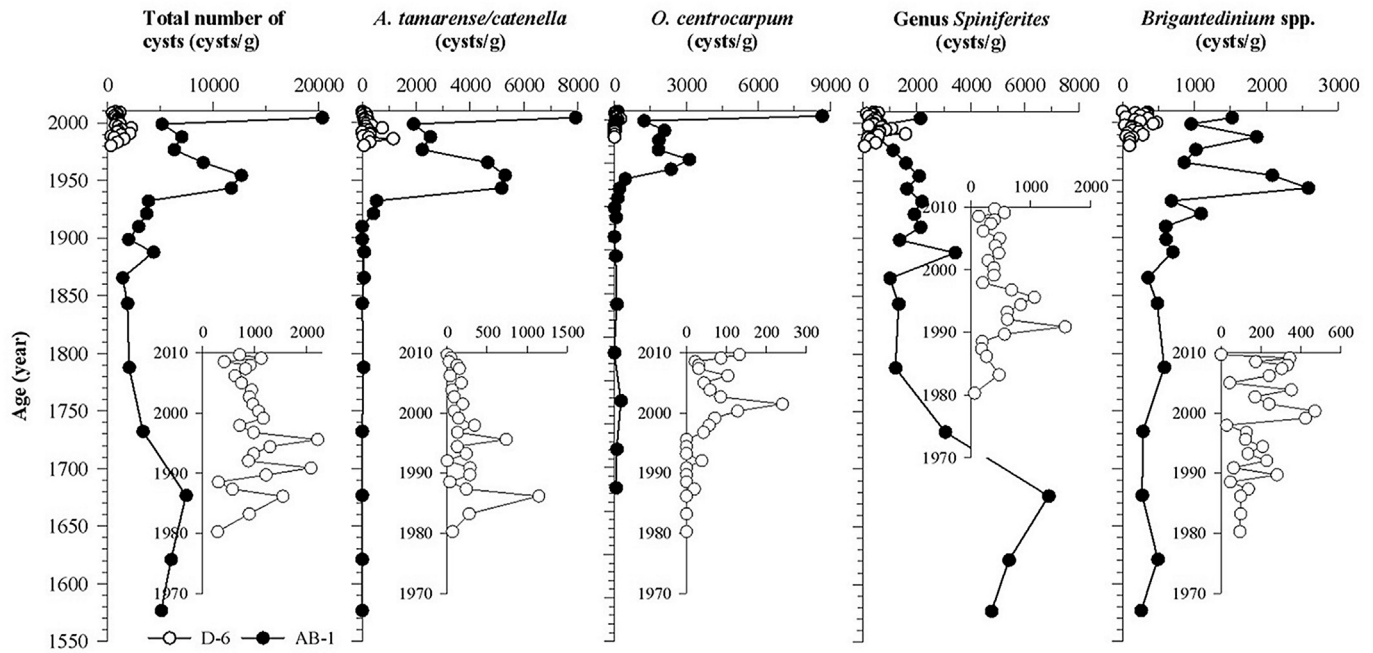


Fig. 2. Vertical variations in concentrations (cysts/g of dry sediment) of selected dinoflagellate cysts identified in core AB-1 (closed circle) and D-6 (open circle).

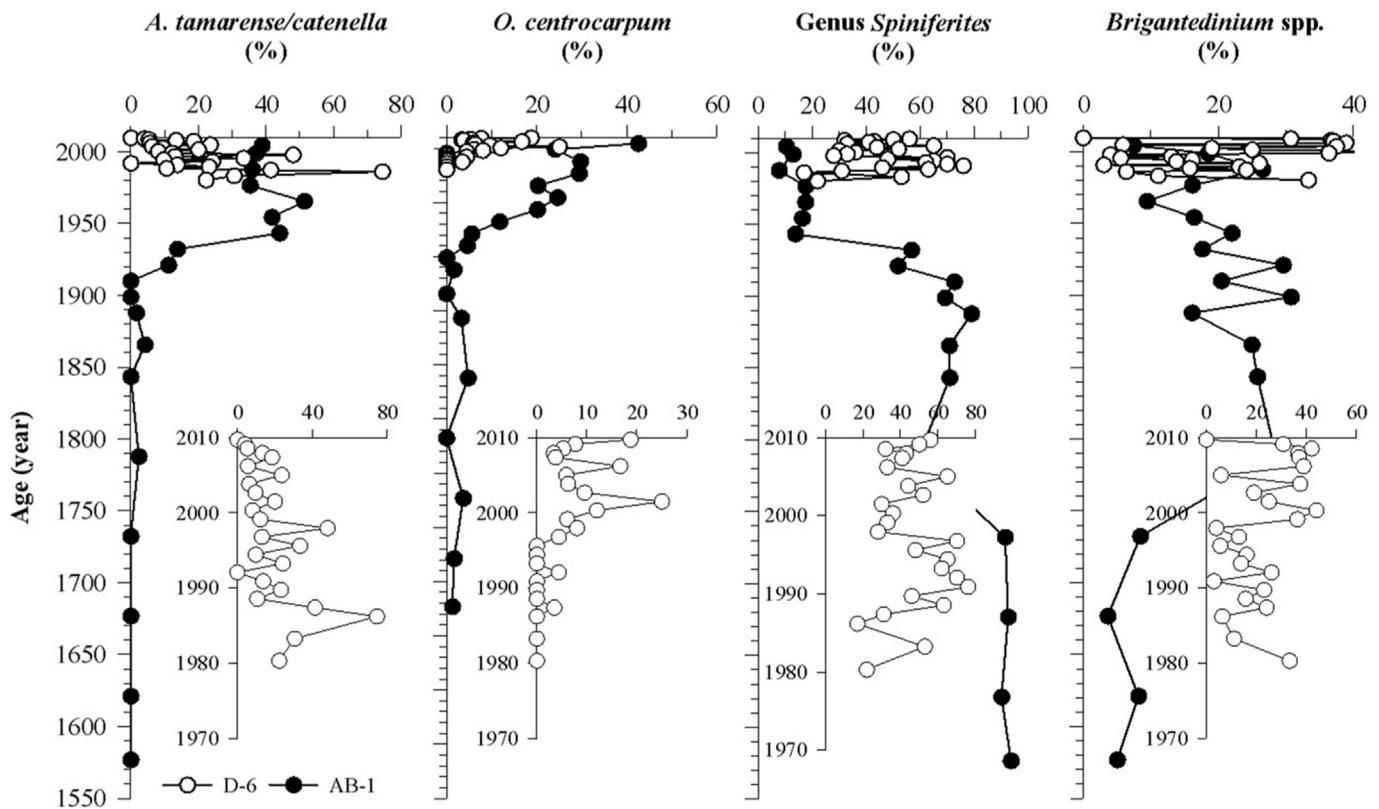


Fig. 3. Vertical variations in relative abundances (%) of selected dinoflagellate cysts identified in core AB-1 (closed circle) and D-6 (open circle).

support of other parameters that verify the accuracy of phytoplankton biomass estimates.

3.2.3. Stage C (1940–present)

This stage is marked by a pronounced increase in the abundance

of dinoflagellate cysts (especially *Alexandrium* species) as well as TOC concentration, while the biogenic opal signal remains rather constant. Owing to the continuous increase of organic matter burial associated with heavy nutrient supply, TOC, TN, and biogenic opal concentrations represent maximum values during this period and

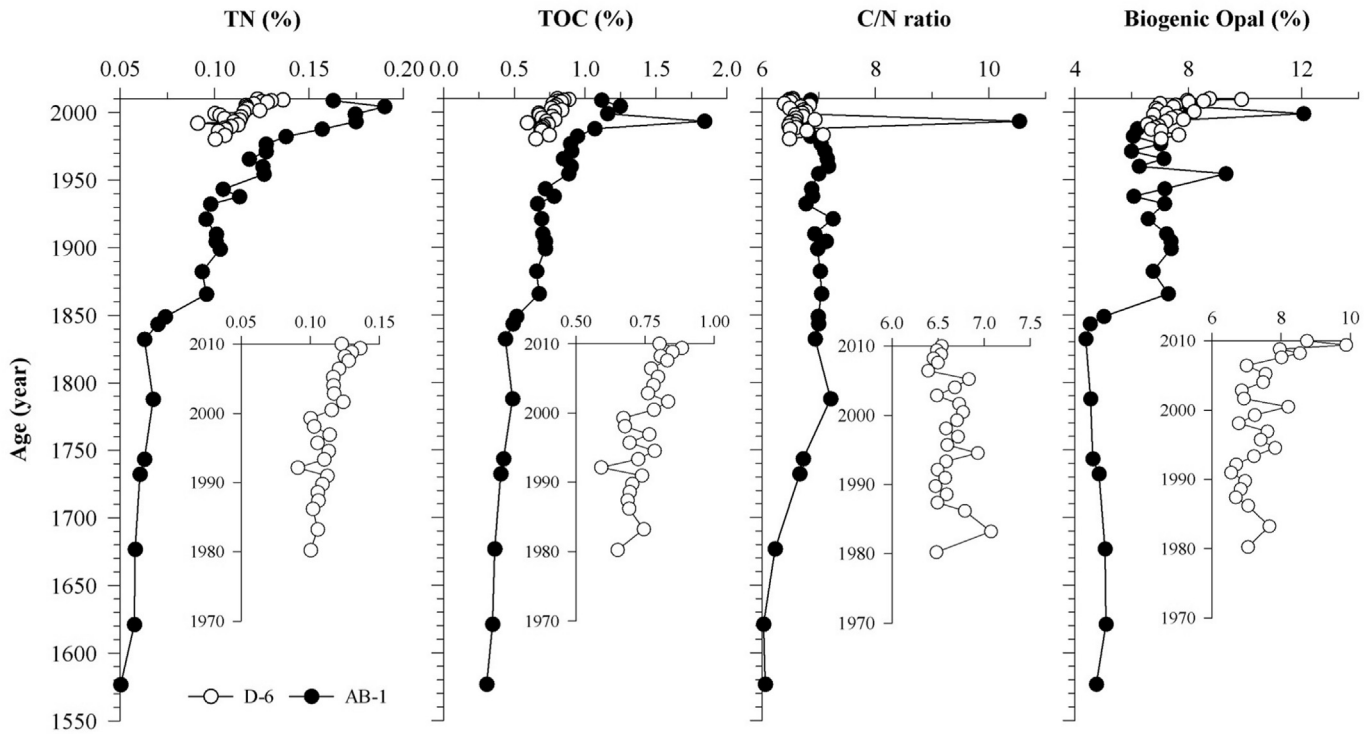


Fig. 4. Vertical variations of total nitrogen (TN), total organic carbon (TOC) and biogenic opal concentrations and the weight ratio of total organic carbon to total nitrogen (C/N ratio) in core AB-1 (closed circle) and D-6 (open circle) from the Yellow Sea.

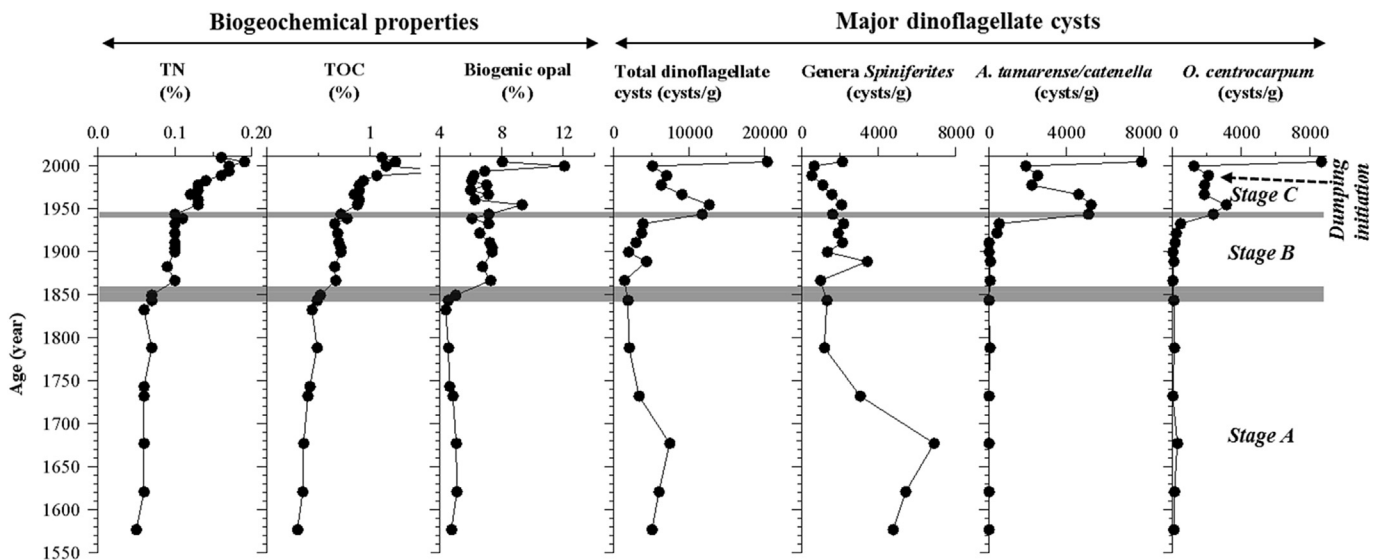


Fig. 5. Temporal variations of the organic matter concentrations and major dinoflagellate cyst groups divided into three major historical stages.

the dinoflagellate cyst signal begins to increase sharply from 1940, reaching its highest concentration at ca. 2000 (~20,000 cysts/g). Variations in the organic matter and dinoflagellate cyst signatures of this period can be divided into two sub-stages, namely, from the 1940s to the 1980s and from the 1990s to the present.

Early 1940s to late 1980s: In contrast to a constant or somewhat decreasing trend in the diatom-produced biogenic opal concentration, an abrupt increase in the dinoflagellate cyst concentration along with continued increase in TOC concentration is noteworthy. Such discrepancy can be explained to some extent by the fact that

excessive nutrient enrichment can cause a shift in dominant phytoplankton composition from diatoms to dinoflagellates (Wasmund, 2002; Lin et al., 2005; Lopes et al., 2007; Marshall et al., 2009). This suggests fundamental changes in the species composition of the plankton, rather than an increase in overall production, due to a pervasive effect of eutrophication altering the ecosystem of the Yellow Sea aquatic environment. Of particular interest is an abrupt and rapid increase in the accumulation of toxic or harmful dinoflagellate cyst species, such as *Alexandrium* species and *O. centrocarpum*, during this stage. High concentrations of

Alexandrium species in the central Yellow Sea sediments may be associated with the intrusion of the Yellow Sea Warm Current (a branch of the Tsushima Warm Current) as previously suggested in Shin et al. (2011, 2013), although *O. centrocarpum* has a very broad tolerance in terms of water temperature and salinity and therefore has a cosmopolitan distribution (Zonneveld et al., 2013). *Alexandrium* species are responsible for paralytic shellfish poisoning (PSP) (Hallegraeff, 1998) and *O. centrocarpum* is a toxic dinoflagellate that produces yessotoxins, which are associated with diarrhetic shellfish poisoning (DSP) (Satake et al., 1997). The sudden and large occurrence of these particular toxic dinoflagellate cyst species since 1940 raises a question of whether this signal can be fully explained by *in situ* dinoflagellate bloom populations only. Although there is a high possibility of endogenous origins for the very large dinoflagellate cyst accumulations caused by excessive nutrient loading to the central offshore Yellow Sea, we tentatively suggest that substantial amounts of dinoflagellate cysts can also be considered to have exogenous origins. Supporting this suggestion, some of the major circulatory currents travelling along the Bohai Sea and the Chinese and Korean coasts merge into a large cyclonic eddy in the central Yellow Sea shelf, forming the largest fine-grained muddy deposits in this region (Park and Khim, 1992; Uehara and Saito, 2003; Shi et al., 2004). As dinoflagellate cysts behave like fine-grained silt particles in hydrodynamic systems, and are transported and accumulated with this fraction in the sedimentary regime (Dale, 1983), we speculate that the major dinoflagellate cyst species deposited in the central Yellow Sea sediments since 1940 are newly introduced, at least in part, from coastal environments of the Yellow Sea (i.e., Bohai Sea). In support of this hypothesis, the dinoflagellate cyst and organic matter variations in core AB-1 correspond well to organic matter and metal accumulation data from Korean coastal regions (Lim et al., 2012, and references therein), which are relatively low during the “preindustrial stage” (before 1930), followed by a sharp rise during the “industrialization stage” (1940s–1970s). Furthermore, harmful algal bloom events in Chinese coastal waters have trebled in each 10-year period since the 1970s (Zhou et al., 2001). In particular, blooms of *Alexandrium* species have increased significantly in coastal waters of the northern Yellow Sea, such as the Dalian region (Song et al., 2009; Wang and Wu, 2009), and also in southern and western coastal areas of Korea (Han et al., 1992; Kim, 1997; Kim et al., 2002). Such continuous outbreaks of harmful dinoflagellate blooms in wide coastal areas of the Yellow Sea would have resulted in substantial amounts of dinoflagellate cyst production around the region (c.f. Lee and Matsuoka, 1996; Liu et al., 2012). This is also confirmed by the clear-cut increase in *Alexandrium* species since 1965 seen in Sishili Bay, a heavily polluted coastal region of China (Liu et al., 2013b), which corresponds well with the *Alexandrium* species curve of this study (Fig. 5). The marked decreases in major elements, such as biogenic opal concentration and dinoflagellate cyst abundance, since the 1980s are probably attributable to governmental control in surrounding countries over marine pollution by the regulation of point sources that discharge pollutants into the coastal waters of the Yellow Sea (c.f., Shi et al., 2007, 2010).

Early 1990s to late 2000s: The increasing trends in organic matter concentration and dinoflagellate cyst concentration accelerated and reached their highest values in this period. A steepening of these signatures coincides well with the time of initiation of ocean dumping in the central Yellow Sea (~1988). Several studies have reported marked changes in biological and chemical dynamics of the Yellow Sea since the commencement of ocean dumping (Park et al., 1998; Lin et al., 2005; Song et al., 2007; Son et al., 2011). For example, a significantly high chlorophyll-*a* patch has consistently been observed in the middle of the Yellow Sea, corresponding to a Korean dump site, while no such patch was observed in the

historical ocean color satellite imagery of the late 1970s to early 1980s (Son et al., 2011). Therefore, we speculate that the recent acceleration of dinoflagellate cyst accumulation in core AB-1 is primarily attributable to: 1) *in situ* productivity of dinoflagellate flora due to excessive nutrient supplies from the ocean dumped materials and 2) exogenous dinoflagellate cyst supplies from coastal areas, which may have co-occurred at the given time. In contrast, core D-6 from the southeastern Yellow Sea mud deposit, which represents changes in the major elements since 1995, does not match the overall patterns identified in core AB-1. The concentrations of total dinoflagellate cysts as well as *Alexandrium* species and *O. centrocarpum* remain very low compared with those of core AB-1. Such dissimilarity between these two fine-grained sedimentary deposits of the Yellow Sea indicates much higher production of dinoflagellates in the central Yellow Sea under the direct influence of ocean dumping in recent years, which can also be partly attributable to differences in the hydrodynamic regimes affecting sediment deposition at each site.

The rich deposit of harmful dinoflagellate cysts in the central offshore Yellow Sea is consistent with previous studies on dinoflagellate cyst distribution in Yellow Sea surface sediments (Cho and Matsuoka, 2001; Hwang et al., 2011; Shin et al., 2013). In particular, *Alexandrium* species are known to cause large algal blooms in the coastal area, forming a high offshore reservoir after migration along the sedimentary regime (Anderson et al., 2005; Aretxabaleta et al., 2014; Butman et al., 2014). As some dinoflagellate cyst taxa accumulating in sediments have the potential to germinate after several years (McQuoid et al., 2002; Mizushima and Matsuoka, 2004), the dinoflagellate cyst deposit in the central Yellow Sea sediment may tentatively supply seed populations for future harmful dinoflagellate bloom outbreaks in different locations (e.g., adjacent coastal areas). This study supports the hypothesis that the reported PSP outbreak events along with an increase in ellipsoidal *Alexandrium* cysts in Korean and Japanese coastal areas are likely to have originated from offshore regions (e.g., central East China Sea), being transported by oceanic circulation (Shin et al., 2010).

4. Conclusions

This study demonstrated that dinoflagellate cyst signals in aged core sediments from the central offshore Yellow Sea reflect progressive marine environmental changes in accordance with gradients of anthropogenic pollution and eutrophication over the past decades. Severe deterioration of the Yellow Sea ecosystem can be identified by: 1) a sharp increase in organic matter signals, including diatom-produced biogenic opal concentration (~1850), 2) a distinct shift in phytoplankton composition towards dinoflagellate dominance together with a sudden increase of harmful dinoflagellate species (~1940), and 3) escalating accumulation of dinoflagellate cysts after the late 1990s. This study also highlights the potential threat of a dinoflagellate cyst deposit in the central Yellow Sea sediments, which may be an important source of inoculum cells to the coastal regions and serve as a seed population for localized and recurrent blooms (Anderson et al., 2005; Shin et al., 2010; Aretxabaleta et al., 2014; Butman et al., 2014). Nevertheless, owing to limited long-term and continuous observational data, it is difficult to identify the extent and magnitude of dinoflagellate cyst transport between the bloom area and the ultimate location of their deposition. A great deal of fundamental work with improved spatial and temporal frequencies is still required to clarify the sediment dynamics of dinoflagellate cyst dispersal and population dynamics in the Yellow Sea.

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