



# Quantitative relationship between surface sedimentary diatoms and water depth in North-Central Bohai Bay, China

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## ABSTRACT

To study the quantitative relationship between surface sedimentary diatoms and water depth, 67 surface samples were collected for diatom analysis on eight profiles with water depth variation from the muddy intertidal zone to the shallow sea area in North-Central Bohai Bay, China. The results showed that the distribution of diatoms changed significantly in response to the change in water depth. Furthermore, the quantitative relationship between the distribution of dominant diatom species, their assemblages, and the water depth was established. The water depth optima for seven dominant species such as *Cyclotella striata/stylorum*, *Paralia sulcata*, and *Coscinodiscus perforatus* and the water depth indication range of seven diatom assemblages were obtained in the study area above the water depth (elevation) of −10 m. The quantitative relationship between surface sedimentary diatoms and water depth provides a proxy index for diatom-paleo-water depth reconstruction in the strata in Bohai Bay, China.

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## 1. Introduction

Diatoms are very sensitive to changes in the chemical and physical environment of the water. Small changes in the chemical composition, salinity, pH, nutrients, light, turbidity, and water depth may change the distribution, composition, differentiation, dominant species, and concentration of the diatoms (Hendey NI, 1964; Yang SR et al., 1994; Hasle GR, 1997; Rivera-Rondón CA and Catalan J, 2020; Wu KY et al., 2020; Dalu T et al., 2022). Establishing the transformation relationship between modern diatoms and environmental variables is a prerequisite for quantitative research on paleo-geographic environments using sediment diatom records. Water depth is an important factor controlling the distribution of diatoms. The quantitative relationship between diatoms and water depth has been established in many regions such as

Europe, America, and Asia, and has been applied to paleo-water depth, paleo-sea level reconstruction and paleoclimate fluctuation research (Yang JR et al., 1995; Brugam RB et al., 1998; Jiang H et al., 2001; Yang XD et al., 2003; Ng LS and Sin FS, 2003; Moos MT et al., 2005; Laird KR et al., 2010; Yu SW et al., 2019; Hofmann AM et al., 2020; Hong I et al., 2021; Li JF et al., 2021; Zhang JP et al., 2022).

The research on diatom assemblage distribution characteristics in surficial sediments and their relationship with environmental control factors in the sea areas of China show that the distribution characteristics of surficial sedimentary diatoms in the Yellow Sea, Bohai Sea, the coast of the East China Sea, the Beibu Gulf of the South China Sea and the coast of western Guangdong Province are obviously controlled by water depth (Liu SC et al., 1984; Wang KF et al., 1985, 2001; Jiang H, 1987; Shang ZW et al., 2006, 2012). Along the east coast of Guangdong Province, the continental slope and deep sea of the South China Sea and East China Sea Okinawa Trough are greatly affected by ocean currents (Wang KF et al., 1988, 2001; Jiang H, 1987; Lu J, 2001; Ran LH et al., 2005). The shelf of the East China Sea is affected by both water depth and currents (Wang KF et al., 2001). The difference in temperature makes the dominant and

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characteristic species of diatoms in the surficial sediments of the Yellow Sea, Bohai Sea, and the South China Sea significantly different.

The above-mentioned studies in the Bohai Sea (Jiang H, 1987; Shang ZW et al., 2006, 2012) and other wider areas show that water depth is an important factor controlling the distribution of surface sedimentary diatoms in the Bohai Sea. To further find out the quantitative relationship between surface sedimentary diatoms and water depth, diatom analysis was carried out on 67 surface sediments collected from eight profiles with water depth variation from the muddy intertidal zone to the shallow sea area in North-Central Bohai Bay. The distribution characteristics of diatom dominant species and assemblages, response to the change of water depth (elevation), and the quantitative indication of water depth by diatoms were discussed in the study area.

## 2. Geological and environmental background

Bohai Bay is a semi-enclosed sea in northern China, with an average water depth of 12.5 m and an average tidal range of 2.4 m (Fig. 1). The shoreline is over 200 km long and covers an area of about 15900 km<sup>2</sup>, accounting for one-fifth of the Bohai Sea. The tectonic location is generally located in the North China Depression. The main three-level tectonic units in the area are the Jiyang Depression, the Chengning Uplift, the Huanghua Depression and the Cangxian Uplift, which are distributed alternately with a northeast-southwest direction. Quaternary sediments are 400500 m thick in the study area (He JS et al., 2015; Zhang KX et al., 2015).

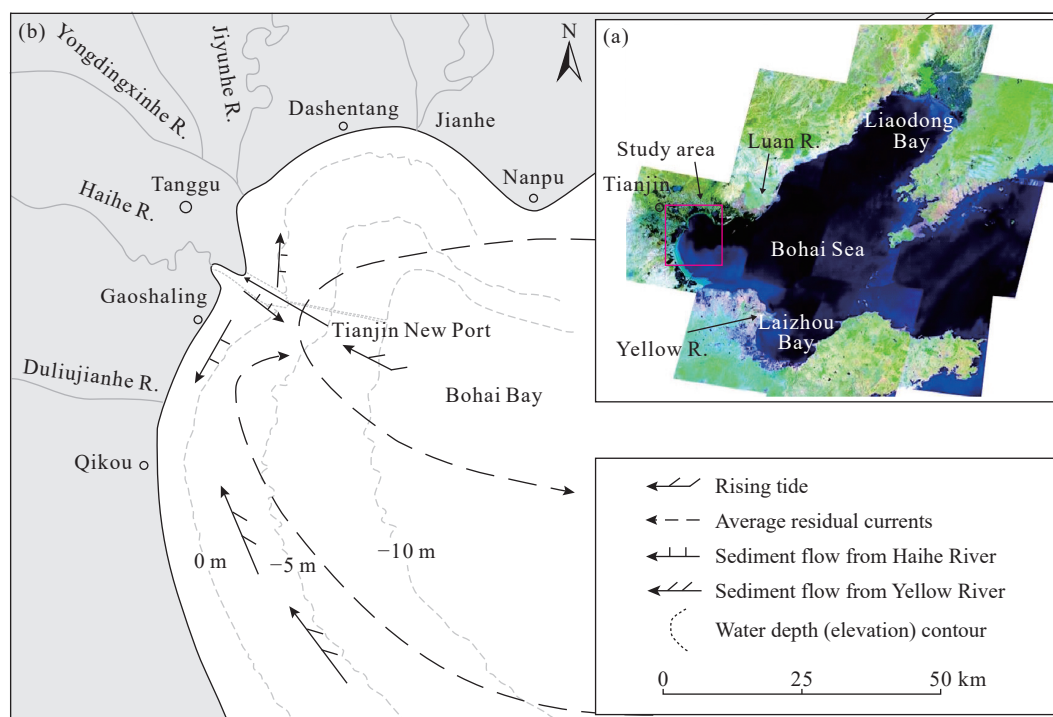
The Yellow River enters the sea from the southwest of Bohai Bay, and some small rivers enter the sea from the west

and northwest, including the Haihe River and Duliujianhe River in Tianjin. In the 1960s, a large number of gates were built in the upper reaches of the rivers, and the amount of sediment entering the sea decreased rapidly (Hu SX and Qi J, 2000). The littoral currents enter Bohai Bay from both the north and the south and meet at the Tianjin coast, then flow eastwards back to the sea (Fig. 1). Sediment particle size characteristics of the open intertidal zone in the Tianjin Sea Area of Bohai Bay is mainly muddy (clay-silt) (Pei YD et al., 2009). In the past 20 years, under the combined action of human activities and natural factors, the intertidal zone of Bohai Bay has undergone tremendous changes. The natural shorelines are basically replaced by artificial shorelines (Wang FC et al., 2019; Yang P et al., 2020), and the upper part of the intertidal zone has been reclaimed from the sea on a large scale (Wang F et al., 2010).

## 3. Materials and method

### 3.1. Study area and sampling sites

In the muddy intertidal zone and the shallow sea between Ziyaxinhe in the southern part of Bohai Bay and Jianhe in the northern part of Bohai Bay (Tianjin Sea Area), eight sampling profiles perpendicular to the modern shoreline were laid out. 67 surficial sedimentary samples were collected from the upper, middle, and lower parts of the intertidal zone to the shallow sea (Fig. 2). GPS positioning was carried out at each sampling site. The intertidal zone sites were leveled by Jie Chuangli 610 total station, and the elevation of each site was connected to the 1985 Yellow Sea Datum. The water depth of the shallow sea sampling sites was measured by the depth



**Fig. 1.** Map showing the Bohai Sea, China. a-Regional background and the location of the study area (marked with a red square); b-map showing the study area, Bohai Bay. R.—River.

sounder and corrected by the real-time tide level. In this paper, the 1985 Yellow Sea elevation data of the intertidal zone sampling sites and the bathymetric data of the shallow sea sampling sites were uniformly converted into the bathymetric data system with the sounding datum as the starting point. Therefore, the water depth (elevation) 0 point is the nautical datum of water depth in the Tianjin Sea Area in this paper (National marine data and information service, 2008). Among 67 samples, 48 samples have water depth (elevation) values, which are distributed between water depths of +4.5–9.6 m (Fig. 2).

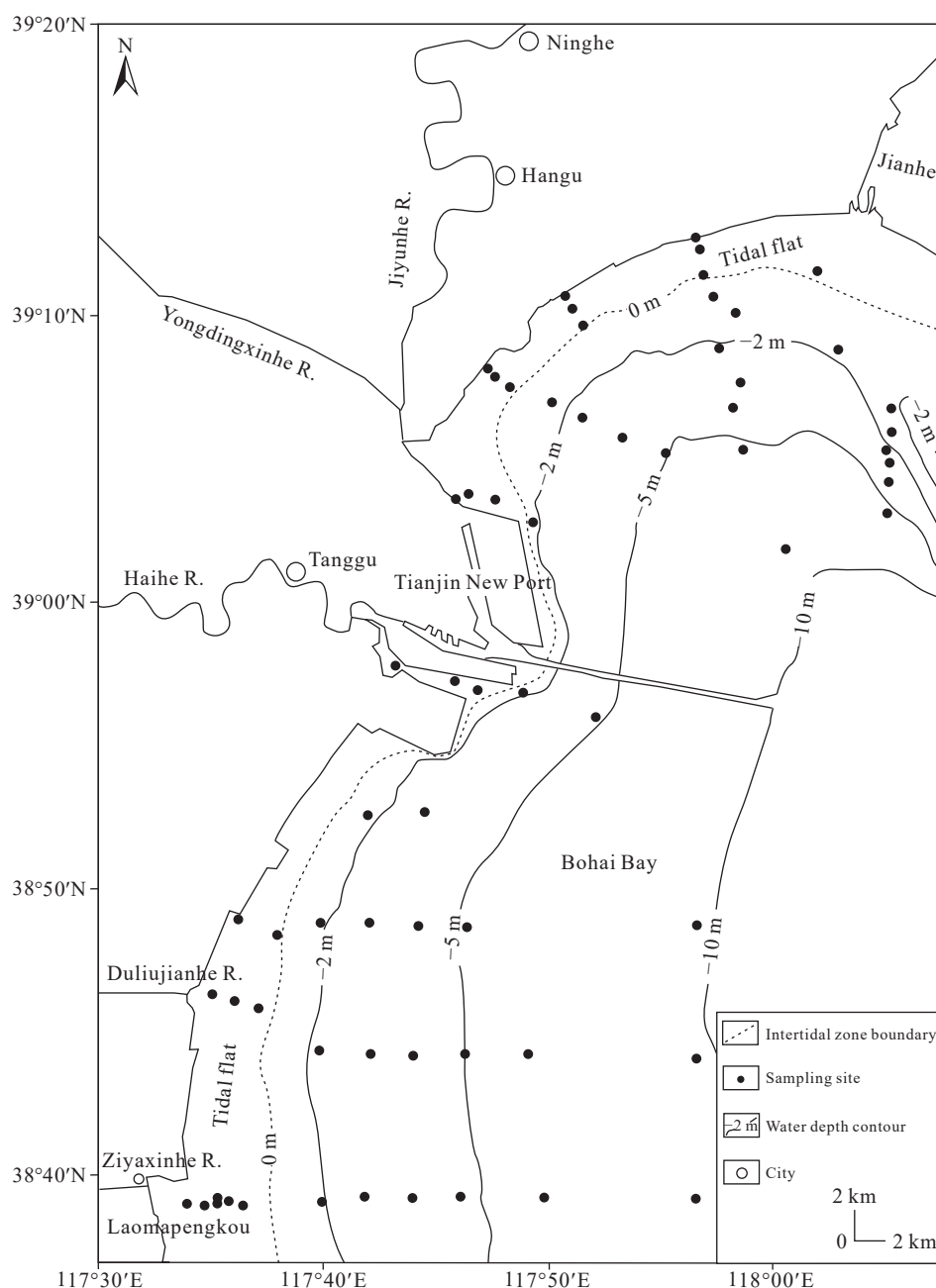
### 3.2. Diatom analysis method

The samples for diatom analysis were processed by

conventional methods (Richard W, 1986) in the Key Laboratory of Coast Geo-environment, China Geological Survey, Ministry of Natural Resources. The process is as follows: 30% hydrogen peroxide to remove organic matter, 10% hydrochloric acid to remove calcium,  $ZnBr_2$  heavy liquid with a specific gravity of 2.38 float twice and Canada gum sealing. After making slides, the genus and species were identified under a 400-fold microscope.

### 4. Results and discussion

Planktonic diatoms float in water, have no mobility, and can live in both shallow and deep water. On the contrary, non-planktonic diatoms live on the bottom of the water and have the ability to move. In places where the water depth is too



**Fig. 2.** Location map of the surficial sampling stations for diatom analysis in the North-Central Bohai Bay. The bottom water depth contours were drawn based on the measured data from 2006 to 2008. R.—River.

large, the light can not reach and make it unable to synthesize the required nutrients, non-planktonic diatoms mainly live in the shallow sea and shallow coastal areas. Therefore, the distribution of non-planktonic diatom species has a relatively close relationship with water depth, and it is more reliable to use the data of non-plankton species to reconstruct paleo-water depth (Jiang H, 1987). Therefore, this paper takes the non-planktonic diatoms of the surficial sediments in the study area as the research object and discusses the vertical zoning characteristics of the dominant species and assemblages' response to the change of water depth. The definition of diatom habitat is mainly based on Guo YJ et al. (2003), Jin DX et al. (1982, 1991) and Zhi CY et al. (2005).

The diatoms are abundant in the sampling sites in the study area, and 19 genera and 35 species of diatoms were found. In order to make the data analysis more representative, the relatively high frequency of occurrence (the number of samples which contains this species accounted for the percentage of 48 samples. For example, among the 48 samples, a total of 31 samples identified *Paralia sulcata*, then the frequency of this species is  $31/48 \times 100\% = 65\%$ ) and the content of seven non-planktonic dominant species, *Cyclotella striata/stylorum*, *Paralia sulcata*, *Actinoptychus undulatus*, *Coscinodiscus perforatus*, *Coscinodiscus decrescens*, *Cosinodiscus subconcaus*, and *Surirella armoricana* were selected and analyzed in detail (Table 1), and their cumulative percentages at each station reached 60%–93%.

#### 4.1. Distribution characteristics of dominant diatom species in surface sediments response to the change of water depth

The content distribution of the seven non-planktonic dominant species has obvious characteristics of changing with water depth (Fig. 3), indicating that each dominant species has a certain water depth distribution range. Although some species have a certain degree of variation in the high-content area due to the inhomogeneous distribution of diatoms or hydrodynamic differences, the general trend has obvious characteristics of distribution along the water depth. The specific distribution of each dominant species was detailed analysis as follows.

##### 4.1.1. *Cyclotella striata/stylorum* (*C. striata/stylorum*)

*C. striata/stylorum* has been recorded on the coasts of the North Yellow Sea, the East China Sea, and the Beibu Gulf of

the South China Sea. The content of *C. striata/stylorum* is more than 30% in the intertidal zone and the percentage is decreased from the coast to the sea (Jiang H, 1987).

The vertical distribution range of *C. striata/stylorum* in the study area is very wide. As the first dominant species, *C. striata/stylorum* appears in all sampling sites, but the content gradually decreases with the increase of the water depth, so it still shows obvious vertical distribution characteristics. In the intertidal zone with a water depth (elevation) of +4.5–0 m, the content is 50%–77%, and the average content is 60%. In the water depth of 0–9.6 m, the content is generally 12.8%–55%, and the average content is 45%, the minimum content is 12.8%. Among this water depth, the content in –7.0–9.6 m is slightly lower. The water depth distribution range shows that although this species can be widely distributed in the intertidal zone and shallow sea area while the content is higher in the intertidal zone. The water depth optimum for *C. striata/stylorum* is +4.5–0 m, so their abundance could be used as a sign of the intertidal environment (Fig. 3a).

##### 4.1.2. *Paralia sulcata* (*P. sulcata*)

*P. sulcata* is one of the most widely distributed species in the marine surface sediments in China. The content gradually increases from the shoreline to the shallow sea, while the content gradually decreases from the shallow sea to the deep sea area (Jiang H, 1987).

The vertical distribution range of *P. sulcata* is +4.5–9.6 m in water depth (elevation) in the study area, but it occurs sporadically at the water depth of +4.5–1.5 m, and the content is generally less than 2%. During –1.5–9.6 m, appearing almost continuously, and the content increases with the increase of water depth. Among them, the content is generally 2%–10% at the water depth of –1.5–4.0 m, and the content is generally >10% at about –4.0–9.6 m. The distribution range of water depth shows that this species is mainly distributed in the shallow sea area below the intertidal zone, and the water depth optimum for it is –4.0–9.6 m which is a typical shallow sea species (Fig. 3b).

##### 4.1.3. *Coscinodiscus perforatus* (*C. perforatus*)

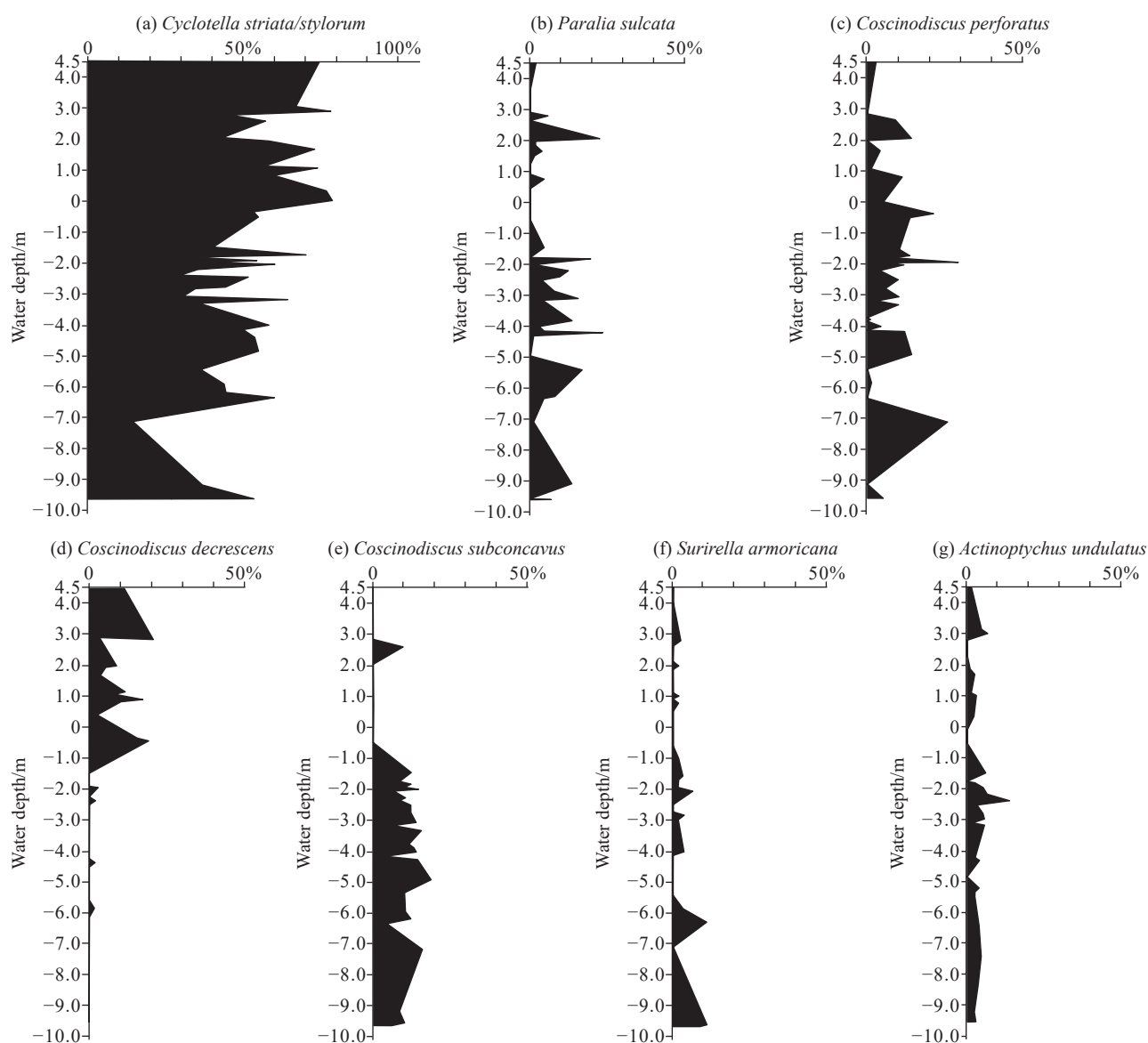
*C. perforatus* is coastal benthic species (Shang ZW et al., 2012). In this study, *C. perforatus* has a wide vertical distribution and appears at most stations. It appears continuously in the water depth (elevation) of +2.6–2.0 m with general content of >10% and the highest one is 30%. The content at +4.5–+2.6 m is less than 3%. In shallow sea areas (–2.0–9.6 m), the content is significantly reduced and appears intermittently with a general content lower than 10%. The distribution range of water depth shows that *C. perforatus* is mainly distributed in the mid-lower part of the intertidal zone and the nearshore, and the water depth optimum for it is +2.6–2.0 m which is a non-planktonic species along the coast (Fig. 3c).

##### 4.1.4. *Coscinodiscus decrescens* (*C. decrescens*)

*C. decrescens* is a marine species and was found in the

**Table 1. Frequency of occurrence and percentage of the dominant non-planktonic diatom species in the North-Central Bohai Bay, China.**

Name	Occurrence frequency and average content	
	Frequency/%	Average content/%
<i>Cyclotella striata/stylorum</i>	100	51.44
<i>Paralia sulcata</i>	65	5.20
<i>Actinoptychus undulatus</i>	85	3.05
<i>Coscinodiscus perforatus</i>	87	7.48
<i>Coscinodiscus decrescens</i>	48	3.70
<i>Coscinodiscus subconcaus</i>	67	7.01
<i>Surirella armoricana</i>	56	1.90



**Fig. 3.** Vertical distribution characteristics of the dominant non-planktonic diatom species response to the change of water depth of the surficial sediments in the muddy intertidal zone and the contiguous shallow sea area in the North-Central Bohai Bay, China.

intertidal zone of Xiamen in Fujian Province and the surficial sediments of the East China Sea Continental Shelf (Jin DX et al., 1982). In the paper, the vertical distribution range of *C. decrescens* is +4.5–0 m in water depth (elevation), and the content is 2%–40% (there is no water depth data for the station with 40% content, so it is not marked in Fig. 3). It occurs sporadically in shallow sea areas below the water depth of 0 m, and the content is generally less than 2%. The distribution range of water depth shows that this species is mainly distributed in the intertidal zone and the content of the upper part of the intertidal zone is higher than that of the lower part. The water depth optimum for *C. decrescens* is +4.5–0 m (Fig. 3d).

#### 4.1.5. *Coscinodiscus subconcausus* (*C. subconcausus*)

*C. subconcausus* is a wide-temperature marine species distributed in deep water areas (Jiang H, 1987). In the study area, the vertical distribution range of *C. subconcausus* is

0–9.6 m in water depth (elevation) (only sporadically appearing upwards, which can be ignored). It is mainly distributed in the shallow sea area, with less content in the intertidal zone. The content is generally <12% in the water depth of 0–4.2 m, and the content is generally >12% in the water depth of -4.2–9.6 m, but the overall content change is not obvious. The water depth optimum for *C. subconcausus* is -4.2–9.6 m which is a typical species in the shallow sea environment in the study area (Fig. 3e).

#### 4.1.6. *Surirella armoricana* (*S. armoricana*)

*S. armoricana* is a marine benthic species and it was found on the coasts of Fujian Province (Jin DX et al., 1982). In the study area, the vertical distribution range of *S. armoricana* is +3.0–9.6 m in water depth (elevation). It appears sporadically above 0 m, with content of <2%. 0–6 m, appears intermittently, and the content is 2%–5%. -6.0–9.6 m, the content is >7.5% and the highest is 11.7%. The

distribution range of water depth shows that it is mainly distributed in shallow sea areas, and is enriched in areas with large water depths. The water depth optimum for *S. armoricana* is  $-6.0$ – $-9.6$  m (Fig. 3f).

#### 4.1.7. *Actinopterychus undulatus* (*A. undulatus*)

*A. undulatus* is a widely distributed coastal benthic species. The highest content of this species occurs in the shallow waters of the South Yellow Sea and the East Sea at a depth of about 40 m. Above or below this water depth, the number decreases significantly (Jiang H, 1987). *A. undulatus* has a wide vertical distribution and appears at almost all stations in the study area. But the content is small, generally  $<7\%$ . In water depths (elevation) below  $-1.5$  m, the content is higher, ranging from 2% to 12%, and appears continuously. It appears intermittently above the water depth of  $-1.5$  m, and the content is generally  $<2\%$ . The water depth optimum for *A. undulatus* is  $-1.5$ – $-9.6$  m which is a shallow sea species (Fig. 3g).

In summary, each surface sediment diatom species has a certain vertical distribution range with the changes in water depth, and the content is different with the distribution ranges change (Fig. 3). Therefore, the authors take the area where the diatom species appears continuously and has relatively high content as class I indicator area for the water depth distribution of this species. The area where the diatom species appeared almost continuously and the content was slightly lower than that of class I was regarded as the class II indicator area for the water depth distribution of this species. The maximum occurrence range of each diatom species is used as the class III indicator area for the water depth distribution of this species. The water depth ranges indicated by the distribution of each diatom species are given in Table 2 and Fig. 3. Obviously, the class I indicator area is the water depth optima range for diatoms and class III indicator areas are the maximum occurrence range of diatoms.

In conclusion, each diatom species has a certain vertical distribution range at the depth near and below the mean spring tide line, indicating that water depth has a major controlling effect on the distribution of non-planktonic diatom species in the study area, which is the basis for paleo- water depth reconstruction. Different species have different sensitivity to water depth changes, so the accuracy of indicating water depth changes is also different. The narrower the vertical distribution range, the higher the sensitivity to changes in the environment and water depth. The indication accuracy of *C. perforatus*, *C. decrescens*, and *C. subconcaus* was relatively high. *S. armoricana*, *C. striata/stylorum*, *P. sulcata*, and *A. undulatus* have a wider range of distribution, and the indication accuracy is relatively low, but these genera and species begin to appear in large numbers, and the

characteristics that content changes with water depth still have important environmental indications.

#### 4.2. Distribution characteristics of diatom assemblages in surface sediments response to the change of water depth

The surface sampling sites in the intertidal zone and shallow sea areas of the study area are arranged according to the water depth (elevation). Cluster analysis on seven non-planktonic dominant diatom species was carried out by Tilia software. The diatom assemblages were divided into three zones and seven sub-zones (Figs. 4, 5). The diatom composition of each assemblage zone is different, and the indicated water depth (elevation) range is different. The diatom assemblage zone is the intersection of all single species in different water depth ranges, and their vertical distribution range is narrower than each single species. Therefore, their indication accuracy of water depth and geological environment is higher.

Assemblage I, which is dominated by *Cyclotella striata/stylorum*–*Coscinodiscus* spp. Among them, *Coscinodiscus* spp. was dominated by *C. decrescens* and *C. perforatus*. There can also see *A. undulatus*, *P. sulcata*, *C. subconcaus*, and *S. armoricana* et al. The water depth distribution range is  $+4.5$ – $-0.5$  m, mainly distributed in the muddy intertidal zone and above adjacent areas, which can be further divided into two sub-zones:

Sub-assemblage Ia. This zone was dominated by *Cyclotella striata/stylorum*–*Coscinodiscus decrescens*–*Actinopterychus undulatus*. The average contents of these three dominant species were 63%, 11%, and 2%. The distribution range of water depth is  $+4.5$ – $+2.6$  m, mainly located in the middle and upper part of the muddy intertidal zone and the adjacent supratidal zone.

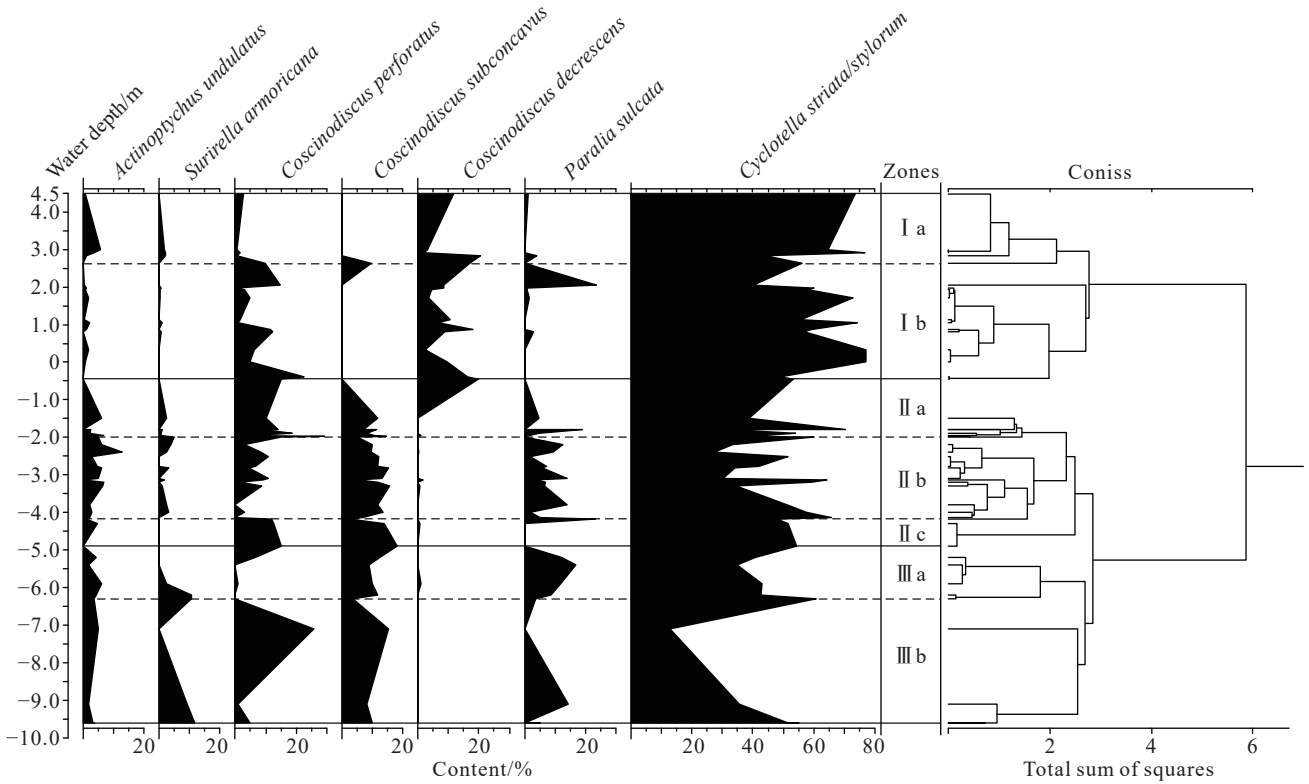
Sub-assemblage Ib. This zone was dominated by *Cyclotella striata/stylorum*–*Coscinodiscus decrescens*–*Coscinodiscus perforatus*. The average contents of the three dominant species were 62%, 10%, and 8%. The water depth distribution range is  $+2.6$ – $-0.5$  m, mainly distributed in the middle and lower part of the intertidal zone between the mean sea level and the 0 m water depth.

Assemblage II, which is dominated by *Cyclotella striata/stylorum*–*Coscinodiscus subconcaus*, and the content of the two is more than 45%. There can also see *S. armoricana*, *A. undulatus*, *P. sulcata*, *C. perforatus*, and *C. decrescens*. The water depth distribution range is  $-0.5$ – $-5.0$  m, which can be further divided into three sub-zones:

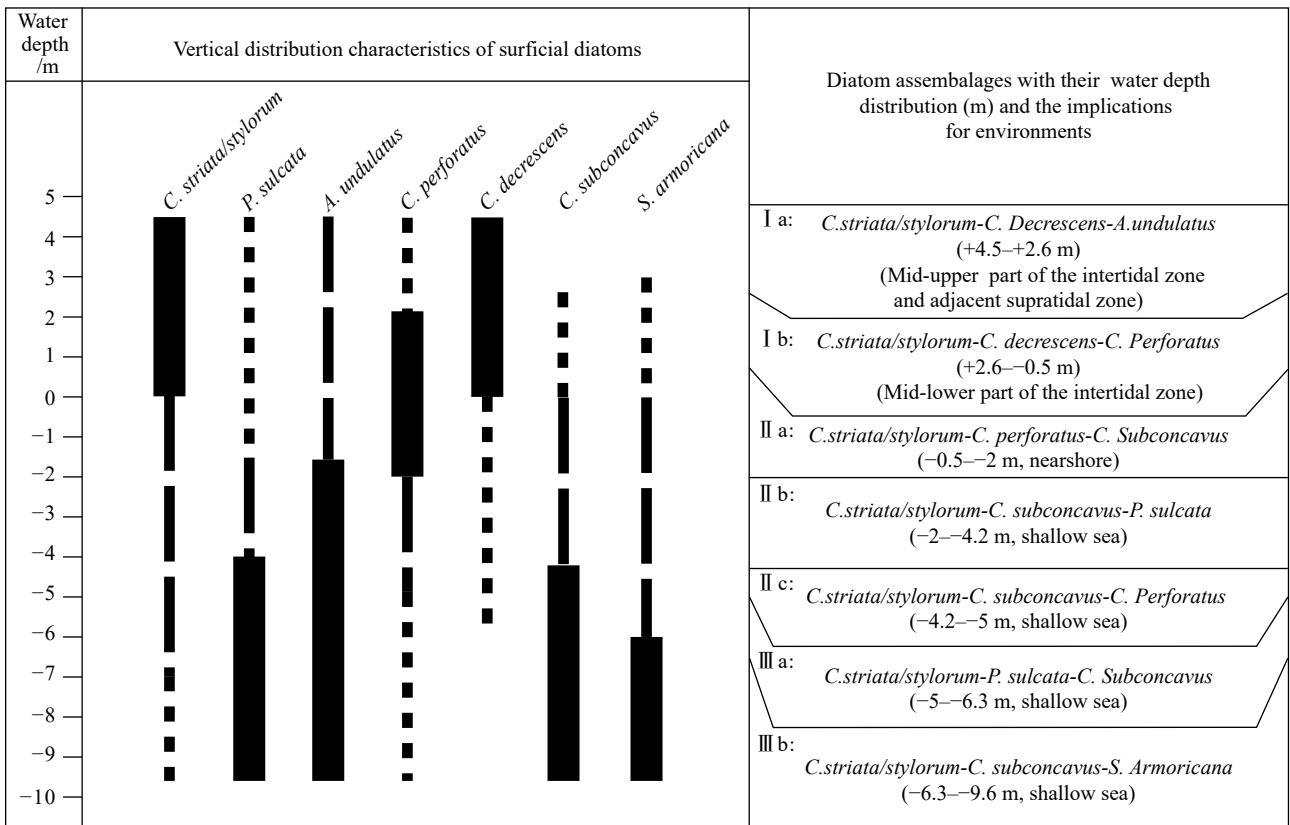
Sub-assemblage IIa. This zone was dominated by *Cyclotella striata/stylorum*–*Coscinodiscus perforatus*–*Coscinodiscus subconcaus*. The average contents of the three

**Table 2. Vertical distribution characters of the dominant non-planktonic diatom species in the response of the surficial sediment to the change of water depth in the muddy intertidal zone and the contiguous shallow sea area in the North-Central Bohai Bay, China.**

Vertical distribution indicator area/m	<i>C. striata/stylorum</i>	<i>P. sulcata</i>	<i>A. undulatus</i>	<i>C. perforatus</i>	<i>C. decrescens</i>	<i>C. subconcaus</i>	<i>S. armoricana</i>
Class I	+4.5–0	-4.0–-9.6	-1.5–-9.6	+2.6–-2.0	+4.5–0	-4.2–-9.6	-6.0–-9.6
Class II	+4.5–-7.0	-1.5–-9.6	+4.5–-9.6	+2.6–-4.9	+4.5–-5.9	0–-9.6	0–-9.6
Class III	+4.5–-9.6	+4.5–-9.6	+4.5–-9.6	+4.5–-9.6	+4.5–-5.9	+2.6–-9.6	+3.0–-9.6



**Fig. 4.** Vertical cluster characteristics of the surface sedimentary diatom assemblages' response to the water depth change in the muddy intertidal zone and the contiguous shallow sea in North-Central Bohai Bay, China.



**Fig. 5.** Vertical zonations of the surface sedimentary diatom species, assemblages, and their relationships with water depth in the muddy intertidal zone and the contiguous shallow sea in the North-Central Bohai Bay, China.

dominant species were 48%, 14%, and 10%. The distribution range of water depth is -0.5–2.0 m, mainly located in the

nearshore area with a water depth of less than -2.0 m. Sub-assemblage IIb. This zone was dominated by

*Cyclotella striata/stylorum*–*Coscinodiscus subconcaus*–*Paralia sulcata*. The average contents of the three species were 46%, 11% and 9%, respectively. There can also see *C. perforatus*, *S. armoricana*, *A. undulatus* and sporadic *C. decrescens*. The distribution range of water depth is –2.0–4.2 m in the shallow sea environment.

Sub-assemblage IIc. This zone was dominated by *Cyclotella striata/stylorum*–*Coscinodiscus subconcaus*–*Coscinodiscus perforatus*. The average contents of these three species were 53%, 16% and 14%. The distribution range of water depth is –4.2–5.0 m in the shallow sea environment.

Assemblage III, which is dominated by *Cyclotella striata/stylorum*–*Coscinodiscus subconcaus*, and the content of these two species were 42% and 9%. It can also see *S. armoricana*, *A. undulatus*, *P. sulcata*, and *C. perforatus*. The distribution of the water depth is –5.0–9.6 m, which can be further divided into two sub-zones:

Sub-assemblage IIIa. This zone was dominated by *Cyclotella striata/stylorum*–*Paralia sulcata*–*Coscinodiscus subconcaus*. The average contents of these three species were 44.4%, 10.6% and 9.3%. It also can see *S. armoricana*, *A. undulatus*. This assemblage represented a shallow sea environment with a water depth of –5.0–6.3 m.

Sub-assemblage IIIb. This zone was dominated by *Cyclotella striata/stylorum*–*Coscinodiscus subconcaus*–*Surirella armoricana*. The average contents of these three species were 38.7%, 9.7% and 7.3%. *A. undulatus*, *P. sulcata*, and *C. perforatus* also can be seen in this sub-assemblage. This assemblage represented a shallow sea environment with a water depth of –6.3–9.6 m.

The vertical distribution characteristics of diatom assemblages in the surficial sediments further illustrate that water depth is an important factor controlling the distribution of diatoms in the study area. Each diatom assemblage has a different vertical distribution range (Fig. 4). The assemblage Ia, Ib, and IIa have relatively higher indication accuracy for water depth changes.

Compared with a single species, the water depth indication range of diatom assemblage is narrower and the indication accuracy is higher. However, in the actual stratigraphic research, it is still necessary to comprehensively consider the water depth indication range of the assemblages and single species, and the specific situation should be analyzed in detail.

## 5. Conclusions

(i) Different species have different sensitivity to water depth changes, so the accuracy of indicating water depth changes is also different. The narrower the vertical distribution range, the higher the sensitivity to changes in water depth and the environment. The water depth (elevation) optima for seven dominant diatom species *C. perforatus*, *C. decrescens*, *C. subconcaus*, *S. armoricana*, *C. striata/stylorum*, *P. sulcata*, and *A. undulatus* are +2.6–2.0 m, +4.5–0 m, –4.2–9.6 m, –6.0–9.6 m, +4.5–0 m, –4.0–9.6 m and –1.5–9.6 m in the study area. Among them, the

indication accuracy of *C. perforatus*, *C. decrescens*, and *C. subconcaus* was relatively high. *S. armoricana*, *C. striata/stylorum*, *P. sulcata*, and *A. undulatus* have a wider range of distribution, and the indication accuracy is relatively low.

(ii) Three vertical surface sedimentary diatom assemblages and seven sub-assemblages were divided in the study area. From shallow to deep, the water depth (elevation) indication ranges of the seven sub-assemblages Ia, Ib, IIa, IIb, IIc, II and IIIb are +4.5–+2.6 m, +2.6–0.5 m, –0.5–2.0 m, –2.0–4.2 m, –4.2–5.0 m, –5.0–6.3 m and –6.3–9.6 m. Among them, zone Ia, Ib, and IIa have higher indication accuracy for water depth changes. Compared with the indication range of a single species, the water depth indication range of the diatom assemblage is narrower and the indication accuracy is higher.

(iii) The obvious vertical zoning characteristics of the surface sedimentary diatoms response to the change of water depth in the muddy intertidal zone and the shallow sea of the north central Bohai Bay shows that water depth plays an important role in controlling the distribution of non-planktonic diatoms in the study area. It can be used as a diatom proxy index for paleo-water depth and geological environment reconstruction in the open muddy intertidal zone and shallow sea.

## CRedit authorship contribution statement

Zhi-wen Shang and Pei-xin Shi conceived the presented idea and prepared the manuscript. Zhi-wen Shang drew all the figures. Jian-fen Li and Hong Wang supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

## Declaration of competing interest

The authors declare no conflict of interest.

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## References

- Brugam RB, McKeever K, Kolesa L. 1998. A diatom-inferred water depth reconstruction for an upper peninsula, Michigan, lake. *Journal of Paleolimnology*, 20, 267–276. doi: 10.1023/A:1007948616511.
- Dalu T, Cuthbert RN, Weyl OLF, Wasserman RJ. 2022. Community structure and environmental factors affecting diatom abundance and diversity in a Mediterranean climate river system. *Science of the Total Environment*, 810, 152366. doi: 10.1016/j.scitotenv.2021.152366.
- National Marine Data and Information Service. 2008. Vol. 1 from the Yalu river mouth to the Changjiang river mouth, Tide tables. Jinan, Shandong Cartographic Publishing House, 1–509 (in Chineses).
- Guo YJ, Qian SB. 2003. *Chinese Seaweed*. Beijing, Science Press,

- 1–493 (in Chinese).
- Hasle GR, Syvertsen E E. 1997. Marine Diatoms. In: Tomas CR (ed.), *Identifying Marine Phytoplankton*. California, Academic Press, 5–385.
- He JS, Liang X, Li J, Yang JL. 2015. Environmentally sensitive grain-size extraction of deep hole sediment from Tianjin coastal plain and its significance. *Earth Science*, 40(7), 1215–1225 (in Chinese with English abstract). doi: [10.3799/dqkx.2015.101](https://doi.org/10.3799/dqkx.2015.101).
- Hendey NI. 1964. An Introductory Account of the Smaller Algae of British Coastal Waters: Part V. Bacillariophyceae (Diatoms). *Fishery Investigations Series IV.*, London, Otto Koeltz, 1–317.
- Hofmann AM, Geist J, Nowotny L, Raeder U. 2020. Depth-distribution of lake benthic diatom assemblages in relation to light availability and substrate: Implications for paleolimnological studies. *Journal of Paleolimnology*, 64, 315–334. doi: [10.1007/s10933-020-00139-9](https://doi.org/10.1007/s10933-020-00139-9).
- Hong I, Horton BP, Hawkes AD, O'Donnell III RJ, Padgett JS, Dura T, Engelhart SE. 2021. Diatoms of the intertidal environments of Willapa Bay, Washington, USA as a sea-level indicator. *Marine Micropaleontology*, 167, 102033. doi: [10.1016/j.marmicro.2021.102033](https://doi.org/10.1016/j.marmicro.2021.102033).
- Hu SX, Qi J. 2000. Shrink of estuaries in Haihe Basin and its effects on the flood disaster. *Haihe Water Resources*, (1), 11–13 (in Chinese with English abstract).
- Jin DX, Cheng ZD, Lin JM, Liu SC. 1982. *Diatom of China Sea (I)*. Beijing, Marine Press, 1–323 (in Chinese).
- Jin DX, Cheng ZD, Liu SC, Ma JX. 1991. *Diatom of China Sea (II)*. Beijing, Marine Press, 1–437 (in Chinese).
- Jiang H. 1987. Diatoms of the surface sediments in the neritic seas of China. *Acta Oceanologica Sinica*, 9(6), 735–743 (in Chinese with English abstract).
- Jiang H, Seidenkrantz MS, Knudsen KL, Eiríksson J. 2001. Diatom surface sediments assemblages around iceland and their relationship to oceanic environmental variables. *Marine Micropaleontology*, 41(1–2), 73–96. doi: [10.1016/S0377-8398\(00\)00053-0](https://doi.org/10.1016/S0377-8398(00)00053-0).
- Laird KR, Kingsbury MV, Cumming BF. 2010. Diatom habitats, species diversity and water-depth inference models across surface-sediment transects in Worth Lake, northwest Ontario, Canada. *Journal of Paleolimnology*, 44, 1009–1024. doi: [10.1007/s10933-010-9470-0](https://doi.org/10.1007/s10933-010-9470-0).
- Li JF, Shang ZW, Wang F, Chen YS, Tian LZ, Jiang XY, Yu Q, Wang H. 2021. Holocene sea level trend on the west coast of Bohai Bay, China: Reanalysis and standardization. *Acta Oceanologica Sinica*, 40(7), 198–246. doi: [10.1007/s13131-021-1730-5](https://doi.org/10.1007/s13131-021-1730-5).
- Liu SC, Jin DX, Lan DZ. 1984. Diatoms of the surficial sediments in the coastal and neritic sea of the south Yellow Sea and East China Sea. *Acta Oceanologica Sinica*, 5(suppl.), 927–945 (in Chinese with English abstract).
- Lu J. 2001. Diatom distribution in surface sediments in the deep-sea area of the South China Sea. *Marine Geology & Quaternary Geology*, 21(2), 27–30 (in Chinese with English abstract).
- Moos MT, Laird KR, Cumming BF. 2005. Diatom assemblages and water depth in lake 239 (Experimental lake area, Ontario): Implications for paleoclimatic studies. *Journal of Paleolimnology*, 34, 217–227. doi: [10.1007/s10933-005-2382-8](https://doi.org/10.1007/s10933-005-2382-8).
- Ng SL, Sin FS. 2003. A diatom model for inferring sea level change in the coastal waters of Hong Kong. *Journal of Paleolimnology*, 30, 427–440. doi: [10.1023/B:JOPL.0000007233.09972.85](https://doi.org/10.1023/B:JOPL.0000007233.09972.85).
- Pei YD, Wang YS, Fan CF, Wang F, Tian LZ, Shang ZW, Che JY, Wang H. 2009. The surface sediment types and distribution of Tianjin intertidal zone, China. *Geological Bulletin of China*, 29(5), 682–687 (in Chinese with English abstract).
- Richard WB. 1986. *Diatom Analysis, Handbook of Holocene Palaeoecology and Palaeohydrology*. John Wiley & Sons Ltd, 527–570.
- Ran LH, Jiang H. 2005. Distributions of the surface sediment diatoms from the South China Sea and their palaeoceanographic significance. *Acta Micropaleontologica Sinica*, 22(1), 97–106 (in Chinese with English abstract). doi: [10.3969/j.issn.1000-0674.2005.01.010](https://doi.org/10.3969/j.issn.1000-0674.2005.01.010).
- Rivera-Rondón CA, Catalan J. 2020. Diatoms as indicators of the multivariate environment of mountain lakes. *Science of Total Environment*, 703, 135517. doi: [10.1016/j.scitotenv.2019.135517](https://doi.org/10.1016/j.scitotenv.2019.135517).
- Shang ZW, Tian LZ, Wang H, Li JF. 2012. Diatom assemblages from surficial sediments in north-central Bohai Bay and their implications for environments. *Geology in China*, 39(4), 1099–1107 (in Chinese with English abstract). doi: [10.3969/j.issn.1000-3657.2012.04.027](https://doi.org/10.3969/j.issn.1000-3657.2012.04.027).
- Shang ZW, Wang H, Che JY, Tian LZ, Pei YD, Fan CF, Wang F, Liu ZG. 2006. Diatom assemblages in the surface sediments of Bohai Bay. *Marine Geology & Quaternary Geology*, 26(5), 21–26 (in Chinese with English abstract).
- Wang FC, Shi PX, Shang ZW, Xiao GQ, Wang F. 2019. Research on the coastline of Tianjin. *Geological Survey and Research*, 42(4), 278–281 (in Chinese with English abstract).
- Wang F, Pei YD, Li JF, Shang ZW, Fan CF, Tian LZ, Song MY, Geng Y, Wang H. 2010. Current elevation of Tianjin tidal zone and the urban safety of Bohai New Area, China. *Geological Bulletin of China*, 29(5), 682–687 (in Chinese with English abstract). doi: [10.3969/j.issn.1671-2552.2010.05.007](https://doi.org/10.3969/j.issn.1671-2552.2010.05.007).
- Wang KF, Jiang H, Feng WK. 1988. Diatom assemblages from surface sediments in the northern south China sea and their relation with the environments. *Tropic Oceanology*, 7(3), 19–25 (in Chinese with English abstract).
- Wang KF, Jiang H, Zhang YL, Wang YJ, Xu JS. 1985. Environmental discussion on distribution of the diatom in the surface sediments on the Huanghai Sea. *Oceanologia et Limnologia Sinica*, 16(5), 400–407 (in Chinese with English abstract).
- Wang KF, Jiang H, Zhi CY, Tao MH, Wang HG. 2001. Study on the relationship between diatom assemblage in surface sediments and the environment in the East China Sea. *Acta Micropaleontologica Sinica*, 18(4), 379–384 (in Chinese with English abstract). doi: [10.3969/j.issn.1000-0674.2001.04.007](https://doi.org/10.3969/j.issn.1000-0674.2001.04.007).
- Wu KY, Zhao WQ, Li MJ, Picazo F, Soininen J, Shen J, Zhu LF, Cheng XY, Wang JJ. 2020. Taxonomic dependency of beta diversity components in benthic communities of bacteria, diatoms and chironomids along a water-depth gradient. *Science of the Total Environment*, 741, 140462. doi: [10.1016/j.scitotenv.2020.140462](https://doi.org/10.1016/j.scitotenv.2020.140462).
- Yang JR, Duthie HC. 1995. Regression and weighted averaging models relating surficial sedimentary diatom assemblages to water depth in lake Ontario. *Journal of Great Lakes Research*, 21(1), 84–94. doi: [10.1016/S0380-1330\(95\)71023-1](https://doi.org/10.1016/S0380-1330(95)71023-1).
- Yang P, Tian LZ, Wen MZ, Wang F, Liu B, Lin GQ. 2020. Application of shipborne sea-land integrated three-dimensional terrain surveying technology in monitoring of coastal zone erosion and deposition. *Geological Survey and Research*, 43(4), 348–352 (in Chinese with English abstract).
- Yang SR, Ji L. 1994. Fossil diatom studies in paleolimnology: Developments since the 1980s. *Journal of Lakes sciences*, 6(2), 177–185 (in Chinese with English abstract). doi: [10.18307/1994.0212](https://doi.org/10.18307/1994.0212).
- Yu SW, Wang JB, Li YM, Peng P, Kai JL, Kou QQ, Laug A. 2019. Spatial distribution of diatom assemblages in the surface sediments of Selin Co, central Tibetan Plateau, China, and the controlling factors. *Journal of Great Lakes Research*, 45(6), 1069–1079. doi: [10.1016/j.jglr.2019.09.006](https://doi.org/10.1016/j.jglr.2019.09.006).
- Yang XD, Kamenik C, Schmidt R, Wang SM. 2003. Diatom-based conductivity and water-level inference models from eastern Tibetan (Qinghai-Xizang) Plateau lakes. *Journal of Paleolimnology*, 30, 1–19. doi: [10.1023/A:1024703012475](https://doi.org/10.1023/A:1024703012475).
- Zhang JP, Tomczak M, Witkowski A, Zhen X, Li C. 2022. A fossil diatom-based reconstruction of sea-level changes for the Late Pleistocene and Holocene period in the NW South China Sea. *Oceanologia*. doi: [10.1016/j.oceano.2022.05.004](https://doi.org/10.1016/j.oceano.2022.05.004).
- Zhang KX, Pan GT, He WH, Xiao QH, Xu YD, Zhang ZY, Lu SN, Deng JF, Feng YM, Li JY, Zhao XM, Xing GF, Wang YH, Yin FG, Hao GJ, Zhang CJ, Zhang J, Gong YM. 2015. New division of tectonic-strata super region in China. *Earth Science*, 40(2), 206–233 (in Chinese with English abstract). doi: [10.3799/dqkx.2015.016](https://doi.org/10.3799/dqkx.2015.016).
- Zhi CY, Wang KF, Lan DZ, Li C. 2005. Diatom ecotype of habitation and their distribution in the surface sediments around Xiamen island and in Taiwan straits. *Journal of Tongji University*, 33(7), 971–975 (in Chinese with English abstract).