

Inverted sediments in the coastal Antarctic lake: Evidence of paleostorm?

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Abstract

The faunal (foraminiferal and diatom abundance) and sedimentological analysis was carried out on two cores collected from a coastal lake in the Vestfold Hills region of Antarctica. Out of the couple of cores collected from the same lake, the one closer to the marine inlet, contained abundant foraminifera and the diatoms were dominant in the second core. The radiocarbon dating of the organic matter revealed that the sediments were inverted, with two sequences of younger sediments overlain by older sediments. The increased abundance of marine microfossils, including both the foraminifera and diatoms in inverted layers, suggests that the sediments were transported from the adjacent shelf. The transport from the shelf is further confirmed by the abundant presence of planktic foraminiferal shells in the sediments. The planktic foraminifera are relatively deeper dwellers and thus confirm the transport of material from relatively deeper water depths. The transport of older marine sediments from the nearby shelf, into the lake against gravity is inferred as a result of storm/cyclone. Two such past storm-cyclone events are inferred as the core includes two sets of inverted sediments. The study suggests that faunal and sedimentological analysis in conjunction with chronology can be applied to infer past instances of extreme events in the high latitude regions.

Key words: Lake, Antarctica, Inverted, Diatom, Foraminifera, Paleostorm

1. Introduction

One of the possible consequences of increasing concentration of green-house gases in the earth's atmosphere is changes in the intensity and frequency of storms and cyclones (Emanuel 2005; Webster et al., 2005; Elsner et al., 2008; Chen et al., 2011). To understand variation in the frequency and intensity of storms and cyclones, it is necessary to document its past trend. During the extreme events like cyclone/storm in the coastal regions, the seawater along with sediments and the fauna in the sediments, are re-suspended, transported to the shallow water regions or coastal lakes and are re-deposited there (Sabatier et al., 2008; Paris et al., 2010). The remains of marine microorganisms like foraminifera and diatoms, can be used to infer such sporadic events when marine sediments are transported into the shallower regions or coastal lakes (Hippensteel and Martin, 1999; Scott et al., 2003). Therefore, the marginal marine regions and coastal lakes are ideally suited to reconstruct past storms/cyclones.

Numerous such coastal lakes are present in marginal Antarctica. A few of these lakes lie in the proximity of the shore-line and thus are affected during the transgression and regression of the sea. The aquatic bodies situated in the vicinity of marginal marine areas and separated from the sea by low elevated land (sill) are also good locale to document times of high-sea stand. An increased influx of marine water into such aquatic bodies occurs during the high sea stands. During such periods, the salinity of the aquatic bodies increases, leading to the prolific growth of marginal marine flora and fauna, like foraminifera and diatoms. The lakes in the marginal regions of Antarctica, provide ample opportunity to reconstruct regional climatic changes (Roberts and McMinn, 1999; Roberts et al., 2000; Hodgson et al., 2001; Verleyen et al., 2004; Gibson et al., 2006), including changes in the ice-sheet extent and sea-level (Gillieson, 1991; Burgess et al., 1994; Zwartz et al., 1998). The past climate records as inferred from the lake sediments match well with the ice-core records, thus indicating the robustness of lake sediment based proxies and paleoclimatic records (Roberts et al., 2001). Therefore, coastal aquatic bodies can provide information about the past sea-level changes as well as sporadic extreme events like paleostorms/paleocyclones. Here we have studied two sediment cores collected from a coastal lake in the Vestfold Hills region, to infer past climatic and sea level changes including signatures of any sporadic event. The lake lies in the Vestfold Hills region, a permanent snow and ice-free oases of Antarctica (Pickard, 1986; Adamson and Pickard, 1986).

2. Materials and Methodology

The samples from two cores (IAE24 CC01 and IAE24 CC02) (Table 1) from the Cemetery Lake in the Vestfold Hills region of Antarctica were used (Fig. 1). The Cemetery Lake is ~650 m long and ~400 m wide marginal marine lake on the northern side of Mule Peninsula, in the Vestfold Hills region of Antarctica. The cores were collected by pushing a thick PVC pipe into the sediments. The samples were collected as a part of a comprehensive multi-institutional project namely, ‘Geophysical and Limnological Investigations of the Antarctic Lakes for Paleoclimatic Inferences (GLIALPI)’, coordinated by the National Center for Antarctic and Ocean Research, India. The project aimed to generate regional paleoclimatic history from different Antarctic lakes.

The core IAE24 CC01 was subsampled at 6 cm interval and the core IAE24 CC02 was subsampled at 2 cm interval upto 30 cm and subsequently at 4 cm. A total 24 samples were used. An appropriate quantity of sediment (10-15 g) was collected in properly labeled pre-weighed glass petri-dishes, for processing. The samples were dried overnight at ~45°C temperature. After 24 hours, the dried samples were cooled to the room temperature and weighed. The dried and weighed sediment samples were soaked overnight. The overlying water was decanted with the help of a narrow diameter pipe. The process was repeated until the overlying water became clear. Since, the samples contained clay lumps, 5 ml of 5% sodium-hexameta-phosphate ($\text{NaH}(\text{PO}_4)_2$) solution was added to each beaker. The overlying water was finally decanted and the sediment was wet sieved by using a 63 μm sieve. The fraction $>63 \mu\text{m}$ (coarse fraction) was dried, weighed and stored in properly labeled plastic vials. Foraminifera and diatoms were picked from $>63 \mu\text{m}$ fraction.

A gridded micropaleontological tray was used to pick foraminifera and diatoms. An appropriate aliquot of the sand fraction was separated, weighed and uniformly spread in the picking tray. The weight of coarse fraction taken for picking foraminifera varied from 1.26 g to 2.94 g. The complete coarse fraction was used for foraminifera in core IAE24 CC02, as only a few foraminiferal tests were present in the entire sample. Since the samples also contained diatoms, a part of the coarse fraction was used to pick diatoms. The picked foraminiferal tests and diatoms were mounted in micropaleontological slides. The fossils were categorized by morphological differences and segregated. The number of dominant diatom species was counted.

3. Chronology

Six radiocarbon dates were obtained for core IAE24 CC02, on the organic matter (Table 2). It was difficult to spare sample for radiocarbon dating in core IAE24 CC01, as very less sample was recovered. Since the reservoir effect in saline lakes of Vestfold Hills region is still not known, we

refrained from correcting the radiocarbon dates. Therefore, the dates referred to in the text are uncorrected radiocarbon dates.

4. Results

4.1. Coarse Fraction

The coarse fraction percentage in both the cores increases towards the top. While a steep increase in the coarse fraction percentage from bottom to top is reported in core IAE24 CC01 (Fig. 2), a constant gradual increase from bottom to top is also reported in IAE24 CC02 (Fig. 3). The lowest coarse fraction (44%) in core IAE24 CC01 is reported at the bottom while the highest (75 %) is at the top. In core IAE24 CC02, two distinct peaks of increased coarse fraction abundance are reported at ~38 cm and ~9 cm. The highest sand abundance (~62 %) in core IAE24 CC02 is found at ~9 cm, while the lowest coarse fraction (~11 %) occurs in the bottommost sample. A relatively less amount of coarse fraction is reported in core IAE24 CC02. A slight decrease in the coarse fraction percentage is reported towards the top of the core IAE24 CC02.

4.2. Foraminifera

A large number of foraminifera tests were recovered from core IAE24 CC01, whereas IAE24 CC02 contained only a few foraminiferal tests. Foraminiferal tests included both calcareous and agglutinated forms. A majority of the benthic foraminifera are either trochospiral or elongated biserial (Fig. 4). The coarse fraction also contained a large number of planktic foraminiferal tests. The tests are not filled with any secondary material. The planktic foraminiferal tests were very small and fragile. The tests were generally intact. However, a few of them were broken. The down core variation of the total foraminiferal number in the core IAE24 CC01 shows an increased abundance (23/g sediment) at 15 cm (Fig. 2). The lowest foraminiferal abundance (4/g sediment) is reported in the core top sample. Since the number of foraminiferal tests recovered in core IAE24 CC02 is almost negligible, its down core variation has not been plotted and discussed.

4.3. Diatoms

Diatoms comprise the larger part of the biogenic fraction in core IAE24 CC02. The foraminiferal tests are almost absent in this core. Therefore, the diatom abundance in core IAE24 CC02 is discussed in detail. A majority of the forms were triangular. Only a few of these were intact with attached frustules. The abundance of intact frustules and detached valves was counted separately. Except this, semispherical as well as disc-shaped forms with an opening in the center of the disc

were also found. The diatoms were identified as *Trigonium curvatus*, *Hyalodiscus radiatus* and *Hyalodiscus* spp (Fig. 5).

4.3.1. *Trigonium curvatus*

The down-core variation of *Trigonium curvatus* intact frustules with both valves attached shows three distinct peaks, with highest abundance (58/g dry sediment) at 42 cm and the species being absent at 11 cm (Fig. 3). The temporal variation of *T. curvatus* separate valves is similar to that of intact frustules. The highest number (164/g sediment) of *T. curvatus* valves is reported at 42 cm, whereas the lowest abundance (4/g sediment) is reported at 26 cm depth (Fig. 3).

4.3.2. *Hyalodiscus radiatus*

Hyalodiscus radiatus (Fig. 5) is the most abundant in core IAE24 CC02. The down core variation of *Hyalodiscus radiatus* matches well with that of the *T. curvatus*, except for the top portion of the core. Here, the abundance of *H. radiatus* does not show as steep an increase in its abundance as observed in case of *T. curvatus* (Fig. 3). The maximum abundance (390/g sediment) is at 42 cm, whereas *H. radiatus* is completely absent at 26 cm depth in the core. The maximum abundance of *H. radiatus* is at the same depth interval, as that of *T. curvatus*.

4.3.3. *Hyalodiscus* spp.

The down-core variations in both *Hyalodiscus* spp. (Fig. 3) frustules and separate valves are similar to that of *T. curvatus* and *H. radiatus* (Fig. 3). Three distinct peaks of increased *Hyalodiscus* spp. abundance are noted at 42 cm, 19 cm and 3 cm depth intervals. Intact frustules of *Hyalodiscus* spp. are almost absent between 26 to 31 cm and 9 to 15 cm intervals, whereas the highest abundance (33/g sediment) occurs at 3 cm interval. The highest abundance (68/g sediment) of *Hyalodiscus* spp. valves occurs at 42 cm depth interval and the valves are absent at 47 cm, 26 cm and 9 cm intervals.

4.4. Total Diatom

In general, three prominent peaks are observed in the down-core variation of total diatoms at 42 cm, 19 cm and 3 cm, respectively. The highest abundance of diatoms (702/g sediment) is at 42 cm, while the lowest abundance (5/g sediment) is at 26 cm depth interval (Fig. 3).

5. Discussion

The radiocarbon dating of the sediments, shows that the core IAE24 CC02 contains two sets of inverted sequences. The occurrence of inverted sedimentary strata is a common phenomenon worldwide (Reineck and Singh, 1974). But for such inversion to take place, it is necessary that the

sediments are compact and solidified into rocks. Only then, the tectonic activity may overturn the entire strata. But such inversion of strata by tectonic activity is not possible if the sediments are loose, as in this core. If the sediments are unconsolidated, deposition of older sediments above younger sediments can also take place by transport of older sediments, either from the land or the ocean. The older sediments can be periodically transported into the lake from the nearby land, by runoff, if old sedimentary deposits are present above the lake level.

The presence of foraminiferal tests in all intervals of the core IAE24 CC01 indicates deposition of sediments in marine environment. Foraminifera are preferentially marine microorganisms (Saraswat & Nigam, 2013). The fresh water foraminifera do not have good preservation potential and only the forms found in marine waters get preserved. The presence of definite marine benthic and planktic foraminifera in the core IAE24 CC01 clearly indicates the origin of foraminiferal tests bearing sediments in marine or brackish water environment. Foraminifera have been found in several Antarctic lakes and nearby terraces (Crespin, 1960; Setty et al., 1980; Zhang et al., 1983; Quilty, 1988). Earlier, though land deposits of marine sediments have been reported from ~50-60 m above present sea level in coastal Antarctica, they have been dated to be of the last interglacial, MIS 5e (Ward and Webb, 1986). Additionally, the last high sea-stand in the Vestfold Hills region was ~6200 ¹⁴C yr BP (Bird, 1991; Zwartz et al., 1998), which is older than the sediments recovered in the cores. The transport of older marine sediments from the formations exposed adjacent to the lake will equally redistribute such sediments throughout the lake. Contrary to that, foraminifera, are reported only in the core adjacent to the nearby marine inlet (Ellis Fjord) and not in the core located away from the marine inlet. The second core (IAE24 CC02), located away from the marine inlet, however, has only a few foraminiferal tests. A similar disparity in foraminiferal abundance in samples collected from comparable elevations was also observed in Deep Lake (Setty et al., 1980). The anomalous presence/absence of foraminifera was attributed to differential wind erosion and/or glacial debris and subsequent transport and deposition at secondary location. The near absence of foraminifera in core IAE24 CC02, located away from the sea shows that the influx of marine water in the lake is not continuous and further that the foraminifera are not in-situ. The broken tests further confirm the transport of foraminifera. If the foraminifera were autochthonous, they should be present in both the cores. A large variation in diatom and coarse fraction abundance is observed in this core. Therefore, the possibility of transport of older sediments from the land is ruled out since the older inverted sediments in the core are also of Late Holocene time and there are no land deposits of marine sediments of this age in the vicinity of the lake Cemetery.

Another possible explanation of the disturbed stratigraphy in the lake cores can be continuous scouring by tidal races and sea-ice bulldozing the soft sediments. However, this possibility is ruled out for two reasons. First, the tidal range in the Ellis Fjord is very low (0.1 m) (Gallagher and Burton, 1988); much lower than the elevation of the ridge/sill (2-4 m) separating the lake from the Ellis Fjord. Secondly, such scouring of soft sediments by the sea-ice will only bring locally deposited shallow marine sediments into the lake. Such shallow marine sediments should only contain shallow-water benthic foraminifera. Interestingly, even planktic foraminifera, mostly found in relatively deeper waters, have also been found in the core closer to the Ellis Fjord. The diatoms recovered in the cores are marine (Hendy, 1974, Scott and Thomas, 2005; Al-Handal and Wulff, 2008). Recently, the *Trigonium arcticum* with characteristic curved margins was differentiated as *Trigonium curvatus* (Nair et al., 2018). *Trigonium curvatus* is a comparatively large epiphytic benthic diatom abundant in the marginal marine regions of Antarctica, especially in the sediments below the sea-ice (Everitt and Thomas 1986; Nair et al., 2015). The anomalous presence of oceanic diatom taxa inshore has been reported previously and attributed to the possible intrusion of an oceanic water body, like a gyre (Everitt and Thomas, 1986). As compared to foraminiferal tests, diatom frustules and valves are lighter and can be transported easily.

The older intervals in the core are characterized by increased abundance of marine diatoms and reduced coarse fraction. In the lacustrine environment, grain size fluctuations through time usually indicate changes in lake water level. A relatively finer grain-size represents higher lake levels while the coarser grain-size indicates relatively low lake levels. Such changes have previously been attributed to wet and dry periods, respectively (Chen and Wan, 1999; Mahesh et al., 2015; Heinecke et al., 2017). However, the hydrological energy may also affect the grain-size fluctuations. The runoff can transport coarser material over longer distance within the lake, even to the center of the lake, when the energy is high enough, at the time of increased runoff (Yanhong et al., 2006). But the older intervals have relatively less coarse fraction and increased abundance of marine diatoms. Even the number of broken diatoms as well as valves is higher in the older sequences. Increased fresh water runoff from glacial melt should lead to an increase in coarse fraction and a fewer diatoms. Therefore, the older intervals do not indicate increased freshwater runoff from the glacial melt. Additionally, the coarse fraction content is higher in the core close to the sea than that in the core located landward. It indicates that the continuous wave action leading to the high-energy environment is the source of the coarse fraction. Since the core located away from the sea will come under comparatively low-energy environment, the coarse fraction is less in this core. Therefore, we propose that the older sediments overlying younger sediments in the lake were brought from the sea.

The bottommost sediments have been dated as 3666 ^{14}C yr BP old. It appears to be originally deposited undisturbed autochthonous sediments, since sediments younger than this interval (3609 ^{14}C yr BP) are reported at 9-10 cm depth. The sediments between 46-47 cm and 18-19 cm are inverted, and we infer it as allochthonous. We further propose that these sediments were transported into the lake from the nearby shelf region by extreme sporadic events like paleostorm. This storm event led to re-suspension and transport of sediments younger than 4946 ^{14}C yr BP from the adjacent shelf region. Such sediments were redeposited into the lake as an inverted sequence. The normal sedimentation followed this first severe sporadic paleostorm event leading to deposition of the younger strata reported at 9-10 cm interval. The sediments at the top are the oldest dated sediments throughout the core. It is proposed that these sediments were again transported from outside into the lake, from a deposit whose older sediments (younger than 4946 ^{14}C yr BP up to 3666 ^{14}C yr BP) have already been eroded away by the first storm event and re-deposited in the lake as an inverted sequence. The oldest exposed sediments were re-suspended by second storm event and transported into the lake. Here we would like to add that normal deposition of sediments of 3609 ^{14}C yr BP age might also have taken place in the shelf region, from where sediments younger than 4946 ^{14}C yr BP have already been eroded by storm. During a second proposed storm event, sediments of 3609 ^{14}C yr BP age would have been eroded first, transported into the lake and re-deposited over the sediments of similar age in the lake. Re-suspension and subsequent transport of normally deposited sediments from the adjacent shelf region might have exposed older (4946 ^{14}C yr BP) sediments in the shelf region, which were also re-suspended, transported and finally deposited into the lake.

The transport of marine sediments into the lake against the gravity requires tremendous energy. We propose that older marine sediments were brought into the lake by cyclone/storm. Earlier several workers have reported erosion of deeper marine sediments and redeposition in the shallow region by storms (Harris, 1995; Chang et al., 2001; Bentley et al., 2002). Later on variation in foraminiferal content and grain-size was used to infer paleostorm/cyclone events from marine sediments (Li et al., 1997; Collins et al., 1999; Hippensteel and Martin, 1999). Nigam and Chaturvedi (2006) inferred one such past storm event by analyzing foraminifera and grain-size in several cores off the west coast of India. Since the cores collected from a coastal lake in the Vestfold Hills region, contain two sets of inverted sediments, we infer at least two such paleostorm events in this region. The two events were separated by a period during which normal sedimentation took place which is younger than the bottommost sediments, as expected. The storms are common in Antarctica and have been shown to influence the coastal marine deposits of Holocene and fossils distribution therein (Berkman et al., 1998).

6. Inferences

The presence of inverted sequences with older sediments rich in marine microfossils and increased abundance of broken diatoms in cores collected from a coastal lake in the Vestfold Hills regions is inferred as a result of paleostorm. The increased abundance of foraminifera in the seaward core while the high abundance of marine diatoms in core located away from the sea, is attributed to the transport of lighter diatoms to a farther distance. We propose that the transport of foraminifera, especially the deeper dweller planktic foraminifera and marine diatoms from the sea into the lake against the gravity took place under the influence of storm.

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Legend to Figures:

- Fig. 1:** The location of cores in the Cemetery Lake. The inset map is Antarctica, with the Cemetery Lake marked by black arrow.
- Fig. 2:** Down-core variation of coarse fraction and foraminifera in core IAE24 CC01. The radiocarbon dates at six intervals have also been plotted.
- Fig. 3:** Down-core variation of coarse fraction and diatoms in core IAE24 CC02.
- Fig. 4:** Foraminiferal tests found in core IAE24 CC01. A-K Calcareous benthic foraminifera, L agglutinated benthic foraminifera, M-Q planktic foraminifera. The scale bar is 50 μm .
- Fig. 5:** The dominant diatom species in core IAE24 CC02. A. *Trigonium curvatus*, B. *Hyalodiscus radiatus*, C. *Hyalodiscus* sp.

Table 1: Details of core samples

S. No.	Name	Latitude	Longitude	Length (cm)
1.	IAE24 CC01	68° 37' 25.40" S	77° 58' 15.20" E	24
2.	IAE24 CC02	68° 37' 26.70" S	77° 58' 14.60" E	48

Table 2: Radiocarbon dates determined in core IAE24 CC02

S. No.	Lab Code	Depth Interval (cm)	¹⁴C Age (yr)	¹⁴C Age Error (yr)
1.	X13986A	0-2	4,946	42
2.	X13987A	9-10	3,609	47
3.	X13988A	18-19	4,513	48
4.	X13989A	28-29	4,846	48
5.	X13990A	39-40	3,704	47
6.	X13991A	46-47	3,666	47

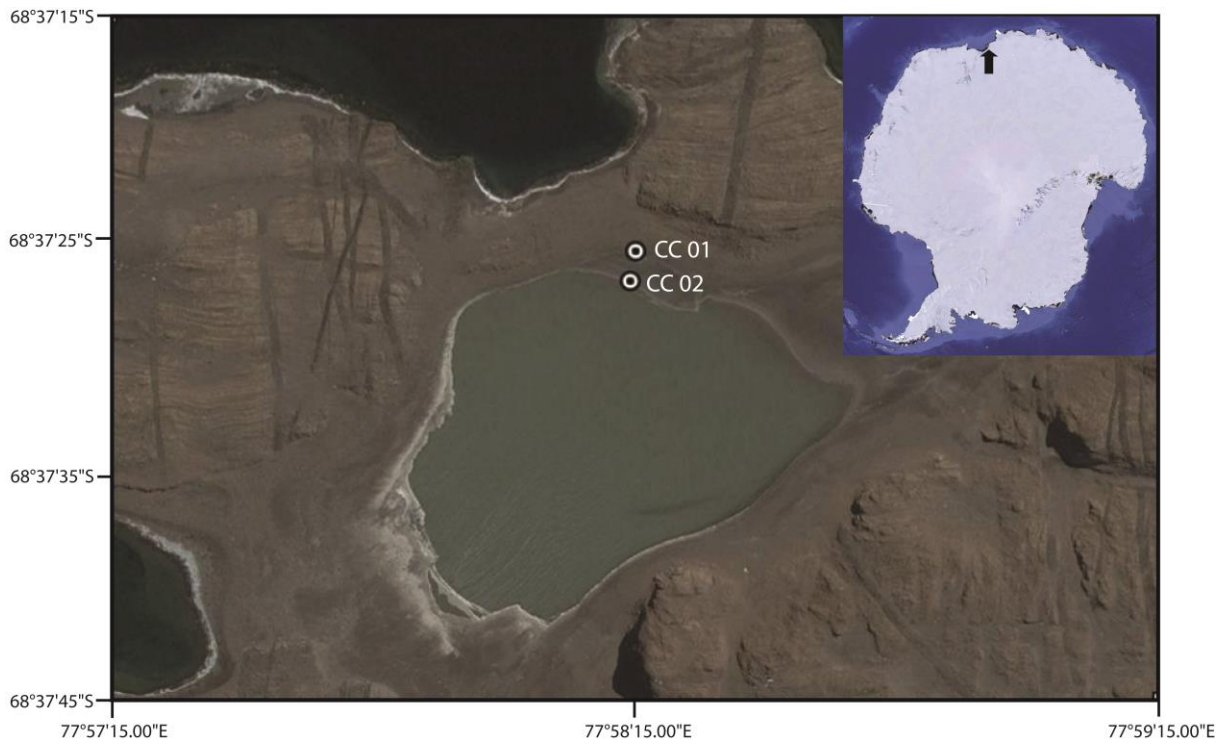


Figure 1

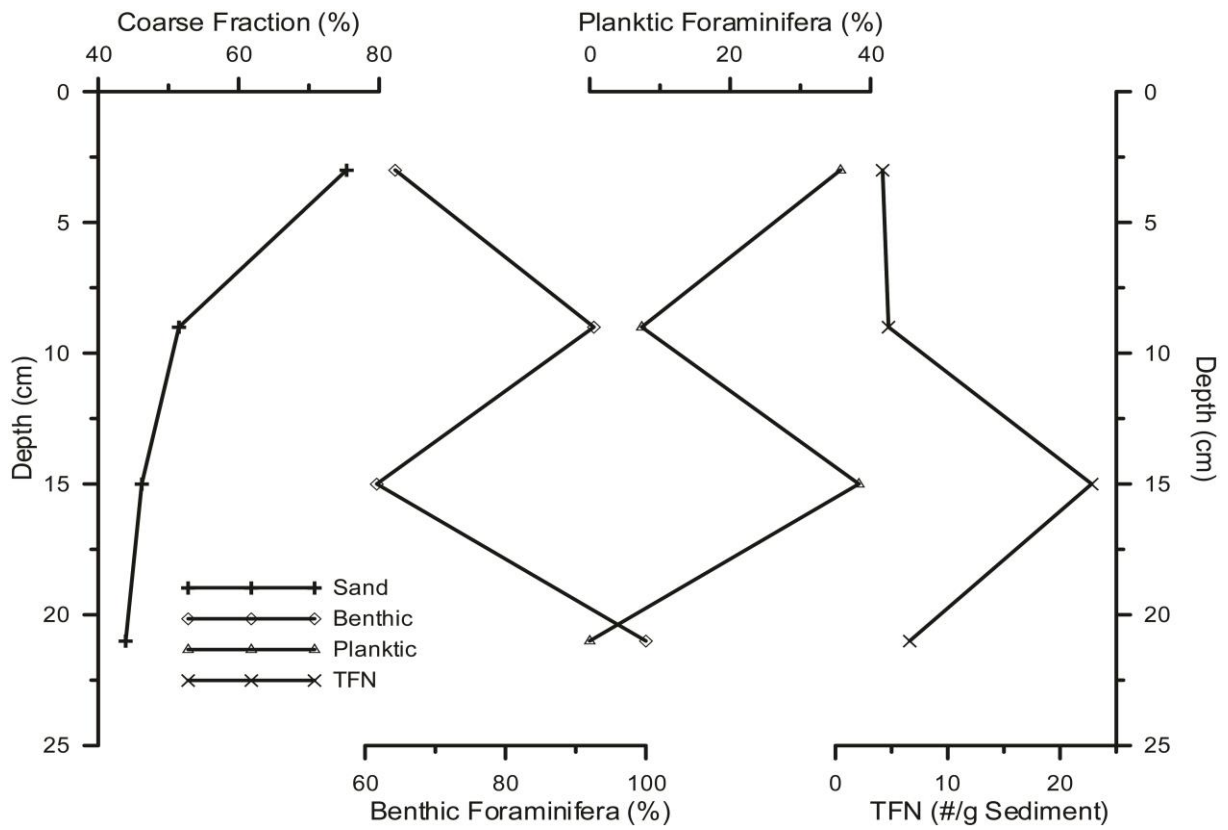


Figure 2

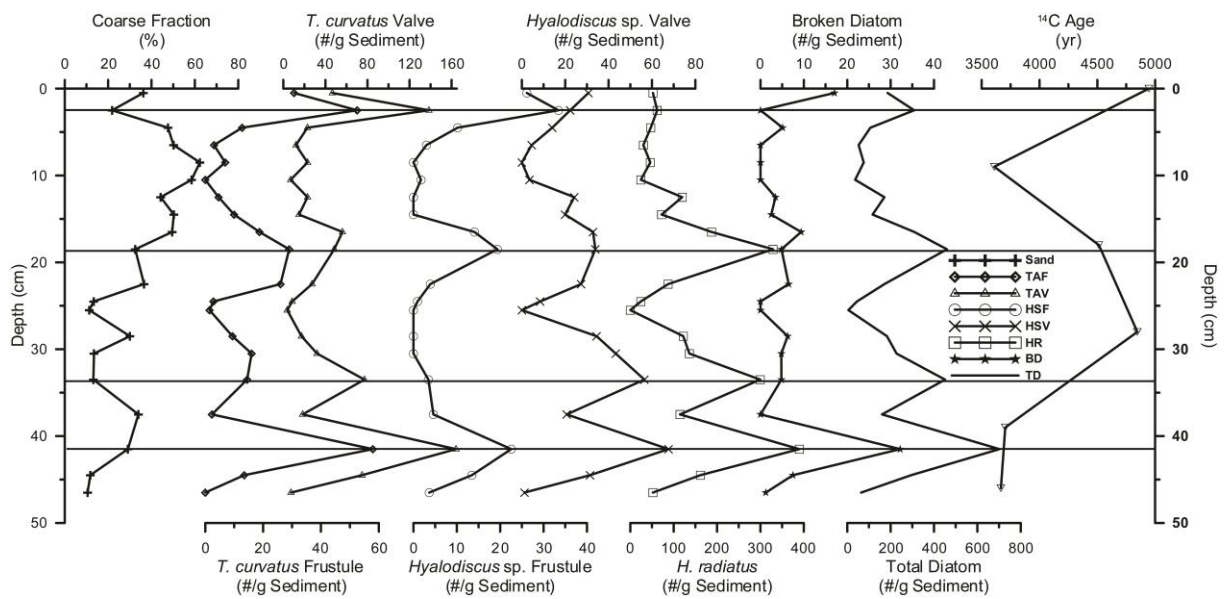


Figure 3

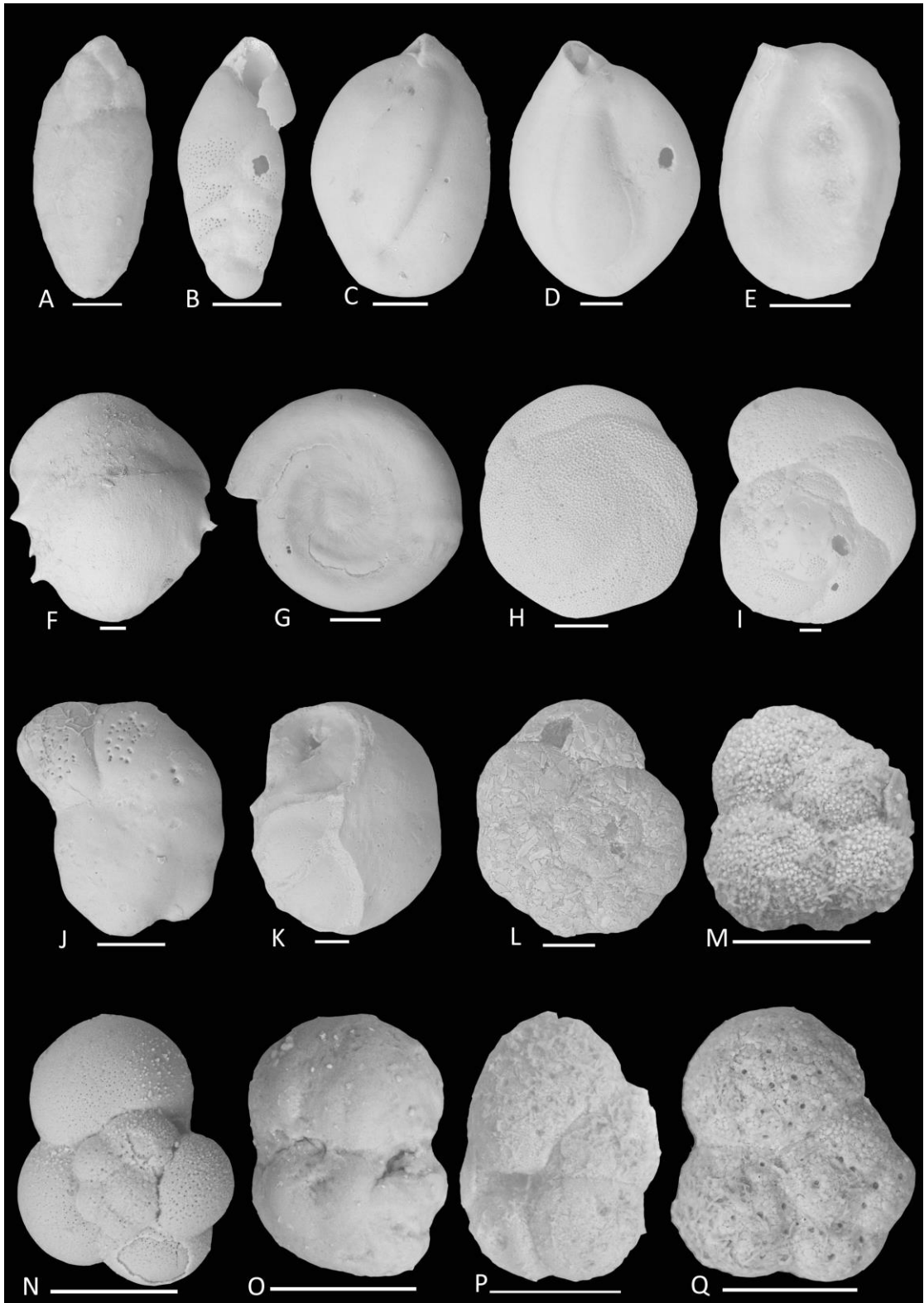


Figure 4

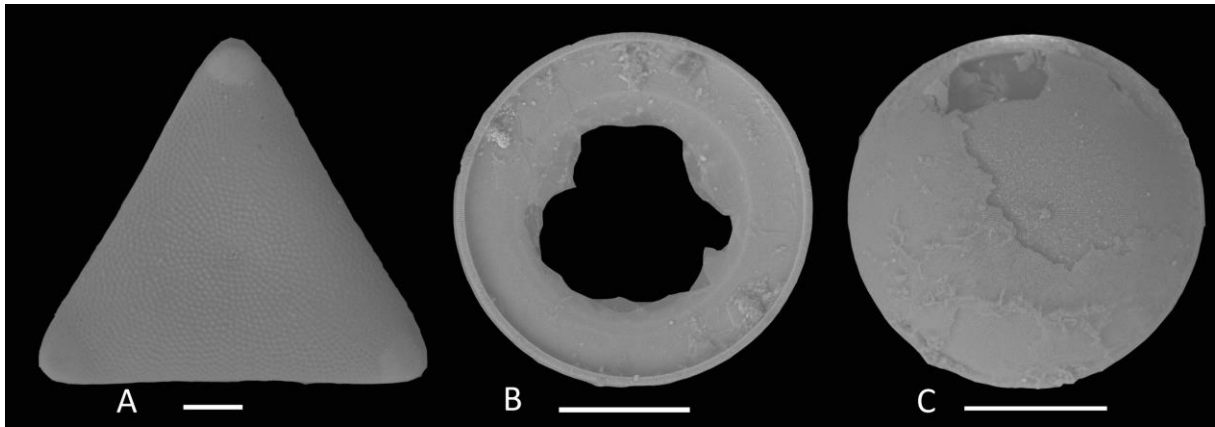


Figure 5