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Dinoflagellate cysts from surface sediments of Saldanha Bay, South Africa: an indication of the potential risk of harmful algal blooms

L.B. Joyce[a,b,*], G.C. Pitcher[a], A. du Randt[a], P.M.S. Monteiro[c]

[a]*Marine and Coastal Management, Private Bag X2, Rogge Bay 8012, Cape Town, South Africa*
[b]*Zoology Department, University Cape Town, Rondebosch 7701, Cape Town, South Africa*
[c]*Council for Scientific and Industrial Research, P.O. Box 320, Stellenbosch 7759, South Africa*

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Abstract

The distribution and abundance of dinoflagellate cysts from recent coastal sediments in Saldanha Bay, was investigated, and compared to the cyst assemblages of the adjacent coastal upwelling system as reflected in the sediments off Lambert's Bay on the southern Namaqua shelf. Twenty-two cyst types were identified from three sample sites off Lambert's Bay with recorded abundances between 1726 and 1863 cysts ml^{-1} wet sediment. At least 21 distinctive cyst types were identified from 32 sample sites within Saldanha Bay. Cyst abundance in Saldanha Bay was relatively low, averaging 116 cysts ml^{-1} wet sediment. The region off Lambert's Bay is especially susceptible to the formation of harmful algal blooms attributed to high biomass dinoflagellate blooms. Owing to these blooms and the retentive circulation characteristics of this area, cyst formation and deposition is high. Blooms can be advected into Saldanha Bay, but their development and duration in the Bay is restricted by the system of exchange that operates between the Bay and the coastal upwelling system, in that there is a net export of surface waters from the Bay. Consequently, fewer cysts are formed and deposited within the Bay thereby reducing the likelihood of in situ bloom development initiated from the excystment of cysts.

Keywords: Dinoflagellate cysts; Harmful algal bloom; Saldanha Bay; Upwelling

1. Introduction

Some 200 of the approximate 2000 existing species of marine dinoflagellates are known to form resting cysts as part of their life history (Head, 1996). These life history stages form an important component of the ecology and biogeography of these dinoflagellates (Wall et al., 1977; Dale, 1983; Ellegaard et al., 1994). Functions attributed to cysts include species dispersal (Anderson et al., 1995), survival through unfavourable conditions (Dale, 1983; Nehring, 1993) and bloom initialisation (Anderson et al., 1983; Cembella et al.,

* Corresponding author. Tel.: +27 21 430 7023; fax: +27 21 434 2144.
E-mail address: ljoyce@deat.gov.za (L.B. Joyce).

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1988; Ishikawa and Taniguchi, 1996). Cysts are typically preserved in sediments (Head, 1996; Dale, 2001), thereby providing an integrated record over time of the presence of cyst-producing dinoflagellates. Surveys of cyst assemblages in sediments are also useful in that they may reveal species seldom observed in the plankton, owing to rare, short-lived, or difficult to identify vegetative stages (Hesse et al., 1996). Cyst surveys also provide a history of harmful species in a given area thereby providing an indication of the potential for future blooms.

The Benguela Current on the west coast of southern Africa is one of four major upwelling systems in the world. In the southern Benguela, three upwelling centres can be distinguished (Fig. 1A): the Namaqua (30°S), Cape Columbine (33°S) and Cape Peninsula (34°S), with upwelling most common during spring and summer (Nelson and Hutchings, 1983). The shelf is broad downstream of the Cape Columbine upwelling cell favouring stratification conducive to the development of a range of harmful and toxic dinoflagellate species (Pitcher et al., 1998; Pitcher and Calder, 2000).

Saldanha Bay is a semi-enclosed embayment situated upstream of the Cape Columbine upwelling cell (Fig. 1). With a maximum depth of 30 m Saldanha Bay is protected from the high-energy coastline, but remains a highly productive system owing to its link on its western side to the Benguela upwelling system (Pitcher and Calder, 1998). At the coastal-bay interface, upwelling processes on the shelf determine the advective transport of phytoplankton and the input of nutrients from the coastal upwelling system. These horizontal exchanges are dictated by event-scale fluctuations in wind stress and barotropic shelf waves (Pitcher and Calder, 1998).

Despite the recognition that cysts play an important role in the life history of many dinoflagellates, and in particular several harmful dinoflagellates, few studies of the composition, abundance and distribution of dinoflagellate cysts in the bottom sediments of South African coastal waters have been carried out. This paper provides the first description of the species composition, distribution and abundance of recent dinoflagellate cysts in the sediments of Saldanha Bay. These observations are compared to investigations of cyst composition and abundance in the adjacent coastal upwelling system as reflected by cyst assemblages off Lambert's Bay, located downstream of the Cape Columbine upwelling centre, on the southern Namaqua shelf. An explanation of the underlying mechanisms that control cyst distribution and abundance in each of these areas is provided. This knowledge and understanding provides an indication of the potential risk of harmful blooms in these respective areas.

2. Methods

2.1. Sediment collection and preparation

To determine the species composition, distribution and abundance of cysts, surface sediments were collected from three sites off Lambert's Bay (Fig. 1A), one in March 2001 and two in March 2003, and from 32 sites in Saldanha Bay (Fig. 1B) in September 2001, by means of a small Van Veen grab. Samples were stored in the dark at 4 °C, to prevent cyst germination, until further examination. For cyst identification and enumeration, samples were processed as described by Wall and Dale (1968), and Matsuoka and Fukuyo (2000). A small volume of sediment was removed from each sample to which a known volume of filtered seawater (FSW) was added prior to sonicating for 2 min to separate any cysts from detrital particles. From this, a 2 ml subsample was removed and filtered through a 125 μm and 20 μm mesh. The slurry remaining on the 20 μm mesh was thoroughly washed with FSW, before backwashing into a beaker and recording the final volume. From this, 1 ml of sample was removed by pipette, placed on a Sedgewick-Rafter chamber and cysts were enumerated using an Olympus BX-60 light microscope. Photographs were taken using a digital camera attachment. Cyst concentrations are presented as the number of cysts ml^{-1} wet sediment. Cyst diversity was estimated using the Shannon–Weaver index.

Mud and organic carbon distributions in Saldanha Bay were determined from sediment samples collected by diver operated PVC cores, in February 1995. The mud content was defined as the fraction of sediment that could be wet sieved through <63 μm mesh. Particulate organic carbon was determined by CHN analysis (Grasshoff, 1976), using a Carlo Erba analyser. The carbonate fraction was removed from

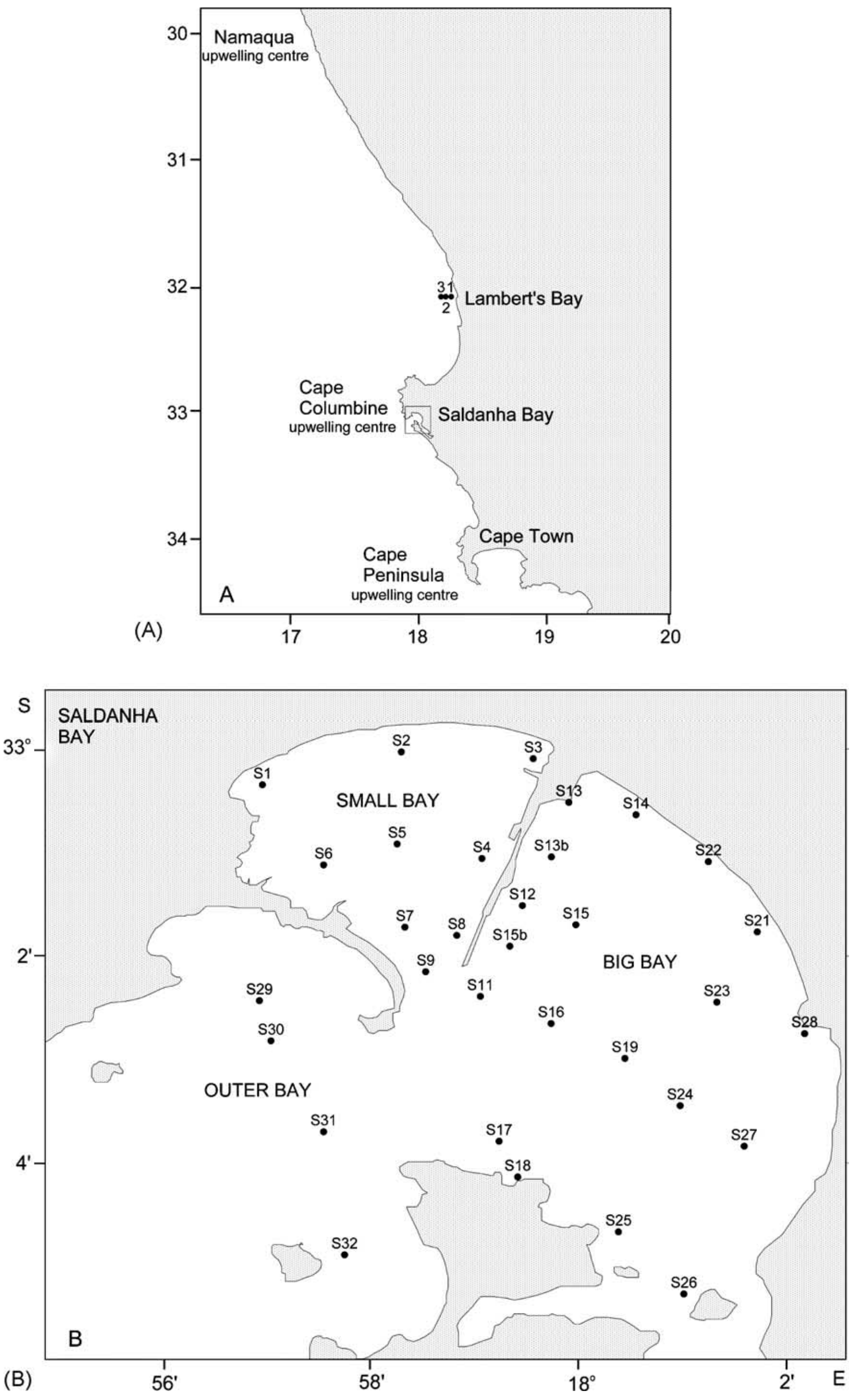


Fig. 1. Map of the study area. (A) The sites off Lambert's Bay (1–3), and the locations of the coastal upwelling centres. (B) Sampling sites within Saldanha Bay.

Table 1
Occurrence and abundance (cysts ml^{-1} sediment) of cyst types found in surface sediments from Saldanha Bay (S1–S32) and the coastal upwelling sites (1–3), South Africa

	Sample stations																																		
Cyst types	S1	S2	S3	S4	S5	S6	S7	S8	S9	S11	S12	S13	S13b	S14	S15	S15b	S16	S17	S18	S19	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30	S31	S32	1	2	3
Spiniferites delicatus																																	12		12
Spiniferites ramosus																																	25	12	
Lingulodinium polyedrum																																	12	12	
Protoceratium reticulatum			13	25	13		25	50		50		13		13	13	25	13	38	13		13			38			13				25		50	12	25
Alexandrium catenella																												13			13		175	163	113
Scrippsiella lachrymose							13	38			25											13				13							12	25	12
Scrippsiella trochoidea			50			63	63	25	100		25						13	25	75	38						13							75	75	25
Scrippsiella sp																																	12	12	12
Protoperidinium americanum				25				13						13		13															13		25	12	12
Protoperidinium claudicans										25									13														12	12	25
Protoperidinium compressum			13				13																										12	38	25
Protoperidinium conicum			13	13	13	63	38		13	25	13	13	13		38				25	13			63		13								88	76	38
Protoperidinium leonis			13			13	25	50	13	63	25		13	13	25			25	38	13				13						25	13		188	200	364
Protoperidinium oblongum			13					13		50	13		25		13	13																	25	25	75
Protoperidinium pentagonum							25																	13									12	12	12
Protoperidinium subinerme				13		13	13			38								38	13				13	13									25	25	12
Protoperidinium sp 3								25			13											13													
Protoperidinium sp 4										25					13																		38	38	12
Zygabikodinium lenticulatum			25				25				25		13		13			13	13					25					13	13	13		688	700	776
Polykrikos kofoidii							25			13						13																25	176	164	25
Polykrikos schwartzii						13	13	13		25	13					13								13						13		13	50	38	75
Unidentified round brown			75	50	13	50	38	63	25	50	38		25		50	25	13	13	38	38	13		38	13	25		13	25		25	25	38	101	113	38
Unidentified sp 1							13	13			13							25													13		50	50	38
Unidentified sp 2				25				38			13								13		13			13				13							
Unidentified sp 3							13	25												13															
Total cysts ml^{-1} sediment	0	0	215	151	39	215	342	366	151	364	216	26	89	39	165	102	39	177	241	115	39	26	114	141	38	26	26	51	13	76	128	76	1863	1814	1726

samples prior to analysis by acidification, achieved by the addition of 0.1 M HCl.

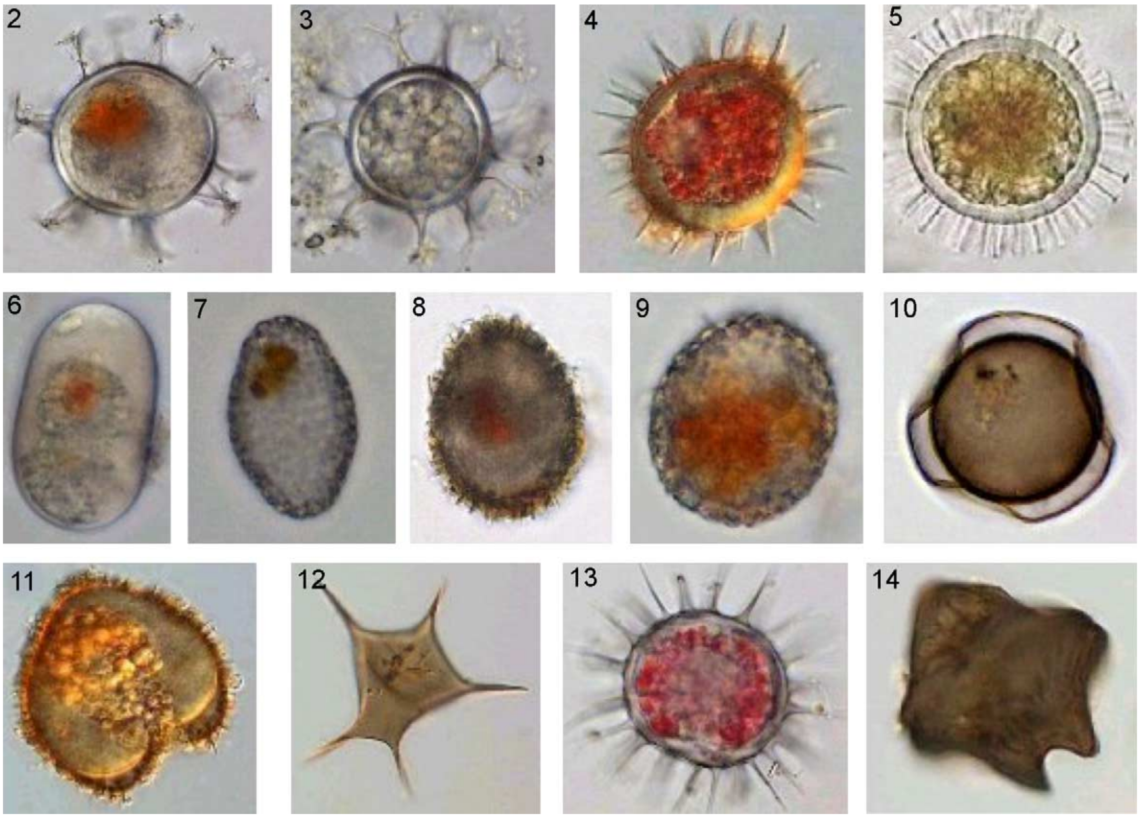
3. Results

3.1. Coastal upwelling sites

Twenty-two cyst types representing six dinoflagellate genera were observed in the sediments off Lambert's Bay (Table 1 and Figs. 2–14 Figs. 2–26). Cyst concentrations ranged from 1726 to 1863 cysts ml^{-1} wet sediment and cysts belonging to heterotrophic dinoflagellates comprised between 59 and 65% of the assemblage. Of the individual cyst types *Zygabikodinium lenticulatum* was the most abundant at each of the three sites, followed by *Protoperidinium leonis*, *Polykrikos kofoidii* and *Alexandrium catenella*. The diversity indices calculated for the three sites ranged from 1.9 to 2.3.

3.2. Saldanha Bay

From the thirty-two sites sampled in Saldanha Bay, twenty-one cyst types representing six dinoflagellate genera were recorded (Table 1 and Figs. 2–14 Figs. 2–26). The number of cyst types recorded at any single station ranged between 0 and 14, with an average of 5 cyst types per site. Cyst concentrations (ranging from 0 to 366 cysts ml^{-1} sediment; Fig. 27A) and diversity indices (ranging from 0 to 2.5; Fig. 27B) varied spatially with the highest values corresponding to stations at the entrance and centre of the Bay, and the lowest values to those stations situated around the



Figs. 2–14. Dinoflagellate cysts found in surface sediments from the west coast and Saldanha Bay. (2) *Spiniferites delicatus*, (3) *Spiniferites ramosus*, (4) *Lingulodinium polyedrum*, (5) *Protoceratium reticulatum*, (6) *Alexandrium catenella*, (7) *Scrippsiella lachrymosa*, (8) *Scrippsiella trochoidea*, (9) *Scrippsiella* sp., (10) *Protoperidinium americanum*, (11) *Protoperidinium claudicans*, (12) *Protoperidinium compressum*, (13) *Protoperidinium conicum*, (14) *Protoperidinium leonis*.

Figs. 15–26. Dinoflagellate cysts found in surface sediments from the west coast and Saldanha Bay. (15) *Protoperidinium oblongum*, (16) *Protoperidinium pentagonum*, (17) *Protoperidinium subinerme*, (18) *Protoperidinium* sp 3, (19) *Protoperidinium* sp 4, (20) *Zygabikodinium lenticulatum*, (21) *Polykrikos kofoidii*, (22) *Polykrikos schwartzii*, (23) Unidentified round brown cyst, (24) Unidentified sp 1, (25) Unidentified sp 2, (26) Unidentified sp 3.

fringes of the Bay (Fig. 27A and B). Again, cysts belonging to heterotrophic dinoflagellates comprised a higher percentage of the cyst assemblage (78%) than did autotrophic (22%) cysts. Unidentified round brown cysts were the most abundant type, followed by cysts of *Scrippsiella trochoidea*, *Protoceratium reticulatum*, *Protoperidinium conicum* and *Protoperidinium leonis* (Table 1; Fig. 28). Cysts of *Alexandrium catenella* were found at only two sites in Saldanha Bay, at concentrations of only 13 cysts ml^{-1} sediment.

Cyst abundance and diversity varied with the sediment characteristics. Central stations and those situated at the Bay entrance tended to be characterised by a higher content of mud and organic carbon (Fig. 27C and D), and the highest abundance and diversity of cysts. Organic carbon content was lower in the sandy sediments characterising the fringes of the Bay as was cyst abundance and diversity.

4. Discussion

Studies have shown that differences in cyst abundance and assemblage composition between areas are primarily caused by two factors: differences in the abundance of vegetative cells and in their cyst production efficiencies, and/or differences in the sedimentary regime (Balch et al., 1983; Blanco, 1989, 1995). Those factors controlling phytoplankton biomass and production in Saldanha Bay have been documented by Pitcher and Calder (1998), Monteiro et al. (1998) and Monteiro and Largier (1999), and cyst distribution within the Bay clearly coincides with the

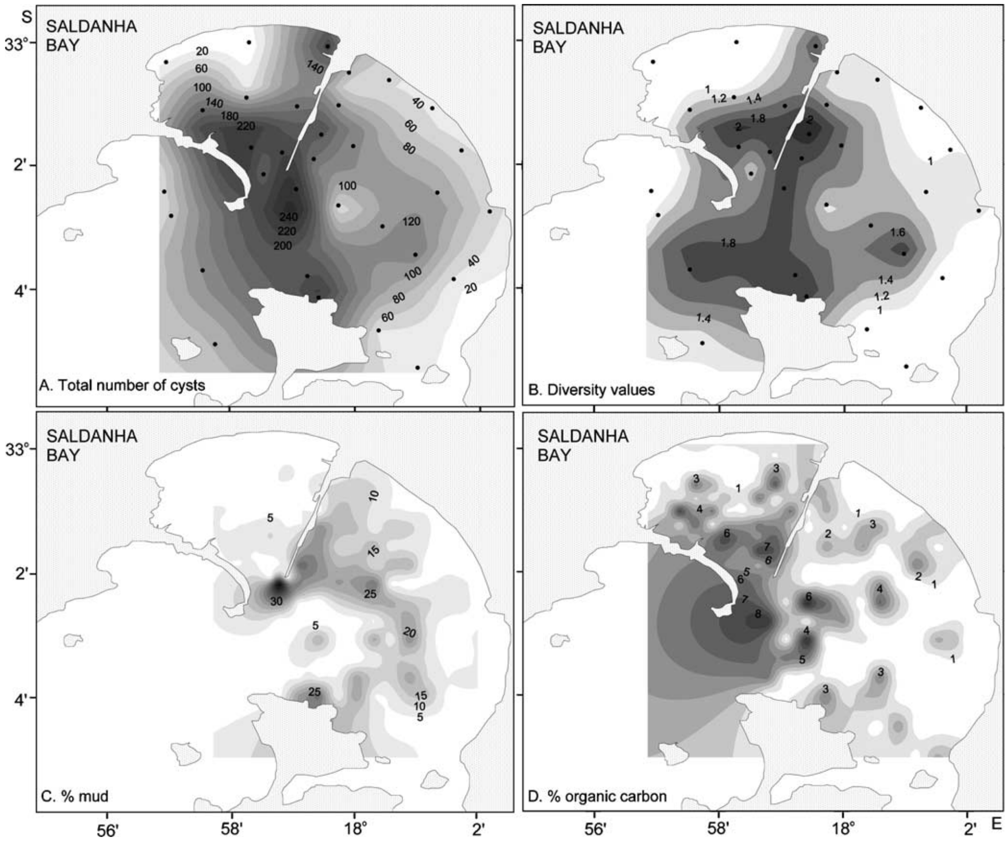


Fig. 27. (A) Total dinoflagellate cyst distribution and abundance (cysts ml^{-1} wet sediment); (B) distribution of diversity values; (C) distribution and % content of mud in the sediments; (D) distribution and % content of organic carbon in the sediments, in Saldanha Bay.

distribution of phytoplankton biomass (Pitcher and Calder, 1998). It is well known that dinoflagellate cysts behave like fine particles (Dale, 1983). Therefore it is common to find higher concentrations of dinoflagellate cysts in muddy rather than sandy sediments (Nehring, 1993). The distribution of cysts within Saldanha Bay appears therefore to correspond well with Bay sedimentology: the highest concentrations of cysts at the Bay entrance and at central stations corresponding to the higher percentage of mud in these areas, and the lower cyst concentrations around the edges of the Bay corresponding to sediments comprised mostly of sandy deposits.

Cyst abundance and diversity were considerably lower for stations in Saldanha Bay compared to those values recorded for the coastal upwelling sites although comparable values of diversity were observed at the entrance and centre of the Bay. Cyst composition also demonstrated some important differences. Some cyst types were common to both areas (e.g. unidentified round brown cysts, *Protoceratium reticulatum*, *Scrippsiella trochoidea*, *Protoperidinium leonis*, *Protoperidinium conicum*), whereas others tended to be more common or to be restricted to either the Bay (e.g. several unidentified species) or the coastal upwelling sites (e.g. *Spiniferites delicatus*, *Spiniferites ramosus*, *Lingulodinium polyedrum*). Of the cysts that were more abundant in the outer coastal stations were those of *Alexandrium catenella,* a dinoflagellate often responsible for paralytic shellfish poisoning in this region. Cysts of *Alexandrium catenella* were the third or fourth most abundant cyst type from the coastal upwelling sites, attaining concentrations between 113 and 175 cysts ml^{-1} wet sediment. In Saldanha Bay, cysts of *Alexandrium catenella* were found at only two sites (S28 and S31) at

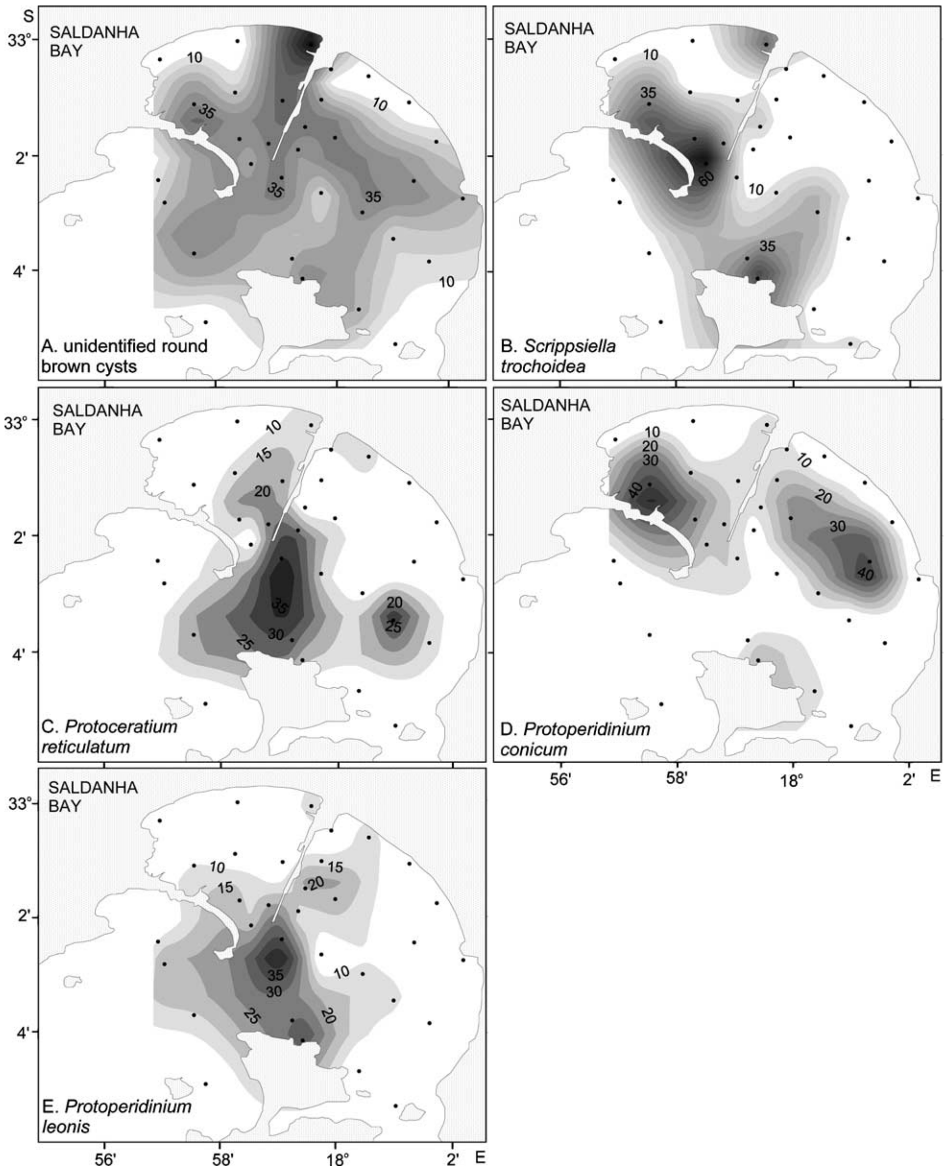


Fig. 28. Distribution and abundance (cysts ml^{-1} wet sediment) of the most abundant individual cyst types in Saldanha Bay.

very low concentrations (13 cysts ml^{-1} wet sediment). Of the cysts that were common in both areas were cysts of *P. reticulatum*, a toxic dinoflagellate that produces yessotoxins (Satake et al., 1997), and has been associated with large mussel mortalities on the west coast of South Africa (Grindley and Nel, 1968, 1970; Horstman, 1981).

The higher cyst concentrations in the coastal upwelling system as reflected in the sediments off Lambert's Bay, compared to the adjacent, semi-enclosed embayment of Saldanha Bay was not unexpected. The region off Lambert's Bay is located downstream of the Cape Columbine upwelling cell, and is characterised by stratified conditions favourable for dinoflagellate growth, and retentive circulation patterns that facilitate the build-up of dense blooms during late summer. Within the coastal upwelling system cyst-forming dinoflagellate species appear to utilise the physical regime, to prevent washout from the coastal environment (Joyce and Pitcher, 2004). Here, the dinoflagellate populations appear as surface blooms associated with equatorward flow in the region of the upwelling front, which is displaced from the coast during the active phase of upwelling (Pitcher et al., 1998). During these conditions cyst formation and their flux into the predominantly poleward undercurrent serves to maintain populations within their area of origin. Alternately, blooms accumulate inshore following a decline in wind stress causing cross-shelf currents to be directed onshore. Under these conditions the onshore movement of the upwelling front and associated bloom is often accompanied by barotropic poleward flow (Pitcher et al., 1998), thereby retaining both vegetative and cyst populations within their area of origin.

Under these conditions of downwelling harmful dinoflagellate blooms may be advected south from the Namaqua shelf and may in turn be advected into Saldanha Bay when the density gradient between the Bay and shelf drives surface inflow and bottom water outflow (Monteiro et al., 1998; Pitcher and Calder, 1998; Monteiro and Largier, 1999; Probyn et al., 2000), but, this is not common. These flows are reversed with the resumption of upwelling over the shelf, resulting in the intrusion and entrainment of cold bottom water and the outflow of surface water, with a consequent advective loss of phytoplankton from the Bay to the shelf. These processes dictate that the Bay acts as a net importer of bottom water and net exporter of surface water over a synoptic cycle (Probyn et al., 2000). This system of exchange between Saldanha Bay and the shelf environment restricts the development, duration and magnitude of dinoflagellate blooms in the Bay compared with those on the southern Namaqua shelf. These factors all contribute to the suitability of Saldanha Bay for mariculture, and presently all of the South African mussel industry is located in this Bay, where the mussel *Mytilus galloprovincialis* is cultivated on ropes suspended from rafts (Pitcher and Calder, 1998).

5. Conclusion

The net outflow of surface layer water from Saldanha Bay ultimately serves to limit the opportunities for harmful algal blooms to be imported into the Bay. This is vital to the mariculture industry that operates within Saldanha Bay, because it significantly lowers the risk of exposure to harmful algal blooms, which are common in the adjacent coastal upwelling system. Low cyst numbers within Saldanha Bay, particularly those of HAB species, e.g. cysts of *Alexandrium catenella*, do not appear to favour or indicate the in situ development of blooms initiated from excystment of cysts.

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