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Spatial distribution of benthic cysts of *Alexandrium catenella* in surface sediments of Puget Sound, Washington, USA

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ABSTRACT

Alexandrium catenella cyst distribution and abundance in the surface sediments throughout Puget Sound, Washington, were mapped for the first time in 2005. Cyst density varied from 0 to >12,000 cysts cm^{-3} surface sediment, with Quartermaster Harbor having the highest concentration of cysts. A higher resolution 2006 spatial survey of surface sediment cysts in two central Puget Sound bays, Quartermaster Harbor and Dyes Inlet, found cyst distribution to be patchy. Surface sediment properties were also determined for all samples. Given the diverse hydrographic conditions associated with the different basins in Puget Sound, no correlation was found between cyst abundance and grain size or total organic content (TOC) for the large scale Puget Sound wide survey, but cyst abundance was positively correlated with finer grained and higher TOC sediments within bays from the higher resolution survey. Sediment metal concentrations were also determined and cyst abundance was positively correlated only with Cd concentration. These results are consistent with previous studies in other locations.

1. Introduction

Paralytic shellfish poisoning (PSP) is often present in shellfish in Puget Sound, but little is known about the distribution, abundance and biology of either the motile cells or benthic cysts of the major causative species, *Alexandrium catenella*[1], even though it is a common, sometimes abundant, member of the local phytoplankton community (Horner, personal observation). Most of what is currently known about the distribution of *A. catenella* in Puget Sound is based on toxin in shellfish (Washington Department of Health [WDOH] records). Furthermore, when PSP occurs in shellfish, it is often said that a "bloom" is present without any sampling of the water column to determine whether there are motile cells of *A. catenella*.

It is evident from early records, such as those of George Vancouver in 1793 (Quayle, 1969), native Indian cultural taboos with regard to shellfish consumption (e.g., Cameron, 1981; Price et al., 1991), high levels of PSP in areas with low human habitation (Taylor and Horner, 1994), and adaptive responses by native marine mammals, birds and fish (Kvitek, 1993) that PSP has been present in the Pacific Northwest for hundreds, perhaps thousands of years. The only recorded fatalities in western Washington in modern times occurred near the entrance to the Strait of Juan de Fuca in 1942 when three people died after eating clams and mussels. At the same time, three people died across the Strait in Barkley Sound, British Columbia. However, PSP was thought to be only a coastal problem, so health authorities issued a blanket closure for the harvest of all shellfish (except razor clams) along the coast from Port Angeles, on the Strait of Juan de Fuca, south to the mouth of the Columbia River for the period 1 April–30 October. The open coast closure remains in effect to the present day, but areas along the Strait are now closed periodically based on toxin test results from WDOH (Cox, personal communication). However, despite the long record of PSP outbreaks in both Washington and British Columbia, it was not until 1965 that a causative organism, *Alexandrium acatenella* (as *Gonyaulax acatenella*), was directly linked to illness or fatality after consumption of shellfish in the region (Prakash and Taylor, 1966).

Studies in Puget Sound in the early 1980s (Nishitani and Chew, 1984) found that as few as 10 cells ml^{-1} in the water column could produce toxin levels above the health regulatory limit of 80 μg toxin 100 g^{-1} shellfish meat. Thus, high concentrations of *Alexandrium* cells are not necessary for toxin levels to be above the regulatory limit. When toxicity does occur, most often in July to October/November, it is frequently not present in all areas of Puget Sound at the same time (Moore et al., 2009). The causes of the

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[1] We recognize the current confusion over the identification of species in the *Alexandrium tamarense/catentella/fundyense* species complex, but *A. catenella* has been the species historically identified as the dominant species in Puget Sound so we have continued to use that name.

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distribution and timing of the blooms are uncertain, but may be related to specific cues such as temperature. The availability of dissolved oxygen and nutrients in the water column may also play a role in excystment and bloom development (Anderson et al., 1987; Figueroa et al., 2005). In addition, winter shellfish harvest closures occur (WDOH toxin data) when motile cells of *Alexandrium* are not expected to be present. It is unclear whether this unseasonable toxicity is derived from residual summer blooms or from shellfish grazing on toxic benthic cysts. There are many unanswered questions about PSP in Puget Sound and knowing where cysts occur and are likely to excyst and possibly initiate blooms is a first step toward answering them.

Based on WDOH toxin records, it is thought that PSP spread from the westernmost part of Puget Sound, Sequim and Discovery bays, north and east to the San Juan Islands, Bellingham Bay and the Whidbey Basin (Fig. 1) before moving southward into the Main and South basins (Trainer et al., 2003). The southward spread followed a massive bloom in the Whidbey Basin in 1978 when PSP levels reached 30,360 μg 100 g^{-1} shellfish meat. However, recent studies based on *Alexandrium* cyst concentrations in sediments suggest that only the spread of PSP into southern Puget Sound

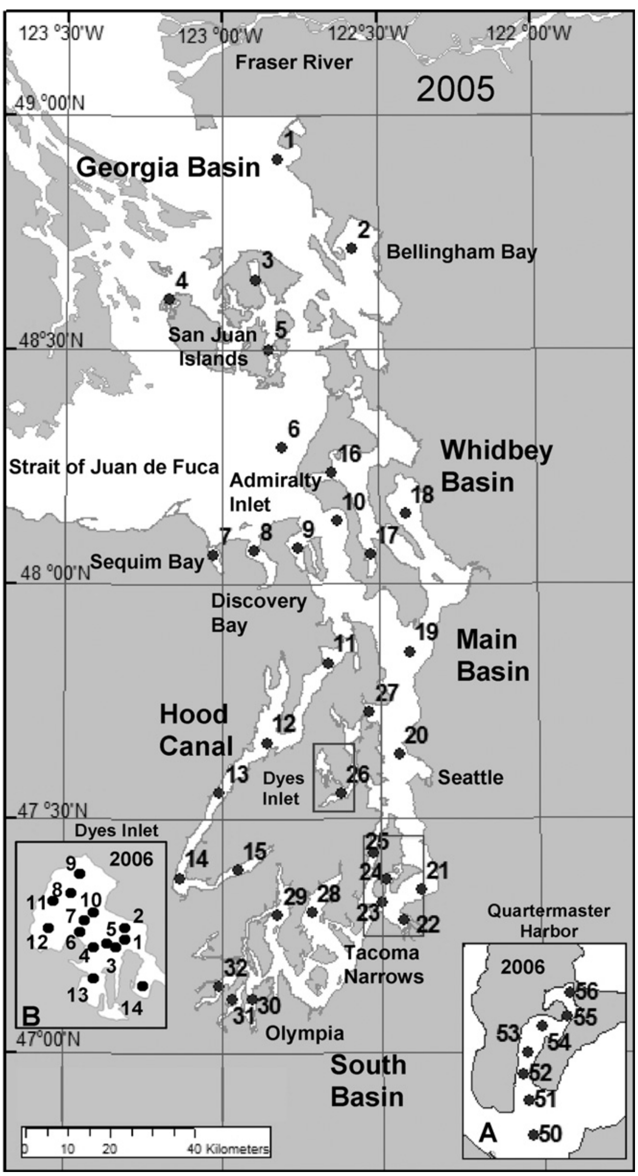

Fig. 1. Station locations in Puget Sound for *A. catenella* cyst survey in 2005. Inset A: Quartermaster Harbor cyst survey in 2006; Inset B: Dyes Inlet cyst survey in 2006.

occurred in this manner and that cysts were present in other areas, such as the Whidbey Basin, well before PSP was recorded in shellfish (Cox et al., 2008).

The purpose of this study was to determine the distribution of *Alexandrium* cysts in surface sediments in Puget Sound and to investigate possible correlations with local surface sediment properties. Surface sediment characteristics selected as potentially important for, or possibly correlated with, cyst presence were grain size distribution, total organic content, color as a general indicator of redox conditions, and presence/absence of bioturbation together with the presence/absence of sedimentary structures. Heavy metals, known to affect cyst distribution in other areas (Godhe and McQuoid, 2003) and present at high levels in some parts of Puget Sound, were also measured in surface sediments to determine their possible impact on cyst abundance and distribution. This is the first study to provide information on cyst distribution and abundance in Puget Sound, thus it is also important to provide information on sediment characteristics and the presence of metals that may later be shown to affect cyst germination.

2. Materials and methods

2.1. Site description

Puget Sound is a complicated fjord system located in the northwestern corner of the United States. Here we use the term Puget Sound to define a series of hydrographically complex basins extending from the Canadian border in the north, to Olympia in the south, and Sequim Bay and Hood Canal in the west (Fig. 1).

Puget Sound is divided into four basins, the Main Basin, the South Basin, Hood Canal and the Whidbey Basin, that are separated from each other by sills of varying depths that may limit water movement into and out of the individual basins. At its northwestern end, Puget Sound is connected to the Pacific Ocean through the Strait of Juan de Fuca (Fig. 1). Currents throughout Puget Sound are primarily tidally driven (Mofjeld and Larsen, 1984; Lavelle et al., 1988) with the effects of wind (Matsuura and Cannon, 1997), freshwater influx and coastal upwelling superimposed (Cannon et al., 1990; Ebbesmeyer and Cannon, 2001; Leonov and Kawase, 2009). The section north of the Strait is connected to the southern end of the Canadian Georgia Basin through the San Juan Islands and Bellingham areas forming one large estuarine system, now sometimes called the Salish Sea, that is strongly impacted by inflow from the Fraser River (Pawlowicz et al., 2007). To the south, the Main Basin extends from Admiralty Inlet at the eastern end of the strait southward to the Tacoma Narrows. It is bounded by sills at either end and consists of a large, deep central basin with adjoining, topographically complex shallower bays along the edges. Sills play a large role in enhancing turbulent mixing. South of the Tacoma Narrows sill is the South Basin consisting of a series of shallow inlets and is the basin farthest from the ocean. To the west is Hood Canal, a deep, natural fjord, with a shallow sill at its northern end. Due to the fjord structure of this basin, flushing of Hood Canal is infrequent and low dissolved oxygen frequently occurs in the lower layers of the water column at the southern end (Newton et al., 2006). The Whidbey Basin to the east, is shallow and dominated by freshwater input from the Skagit, Stillaguamish, and Snohomish rivers. It has the shortest mean residence time for surface waters of any Puget Sound basin (Babson et al., 2006). The average residence time for each basin is; Main Basin: 49 days; South Basin: 46 days; South Hood Canal: 86 days; and Whidbey Basin; 37 days (Babson et al., 2006).

Quartermaster Harbor (Fig. 1, inset) is a shallow, southward facing bay at the south end of Vashon Island that connects to the southern end of the Main Basin in central Puget Sound. It has a