Baseline information describing sediment physicochemistry of Totten Inlet and the macrobenthos of the proposed North Totten Inlet mussel farm

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Abstract.

Background. Healthy shellfish populations are important to the proper function of estuarine ecosystems. Estuaries like Chesapeake Bay once held large numbers of American oysters (*Crassostrea virginica*). Historically, these oysters filtered the entire bay's water volume every 3.3 days. Several centuries of over exploitation compounded by diseases such as *Perkinsus marinus* and MSX, coupled with water pollution, reduced oyster abundance to the point where in 1988 the remnant population filtered the bay only once every 325 days – a one hundred fold decrease (Newell, 1988). The result has been increased turbidity in the water which has reduced light penetration to the point where submerged aquatic vegetation (SAV) has died off, reducing valuable estuarine habitat for fish and other shellfish such as the blue crab (*Callenectes sapidus*). Several other authors (Cloern, 1982; Officer *et al.*, 1982; Cohen *et al.*, 1984; Peterson and Black, 1991) have demonstrated the importance of bivalves for controlling phytoplankton and increasing water clarity. Haamer (1996) used an empirical model to assert that mussel farms covering 1 to 2.4% of a eutrophic Swedish fjord would result decrease dissolved inorganic nitrogen by 20% and that bivalves would reduce biological oxygen demand (BOD) in deep basin water by 26%. Haamer (1996) cautioned that mussel farms should be located such that feces and pseudofeces could not collect in deep basins where there is no flushing and consequently little oxygen. It should be noted that mussel farms, as proposed in Totten Inlet by Taylor Resources would cover only 0.034% of the inlet or 29 to 71 times less than proposed by Haamer (1996) as a eutrophication control.

Unlike natural populations of animals, whose population size tends to be controlled by competition for food, space and predation, intensive aquaculture of bivalves has the potential to exceed the carrying capacity of estuaries (i.e. depleting organic seston to the point where the ecosystem is adversely affected) and to transfer organic matter filtered from the water to sediments in the form of feces and pseudofeces to an extent that sediment chemistry and the macrobenthos are affected. In sediments containing low amounts of organic matter, moderate amounts of added aquaculture waste are seen as food for detritivores and can result in significant increases in both the diversity and abundance of macrobenthic communities. If these waste products exceed the assimilative capacity of sediments for organic carbon, sediment oxygen can be diminished by aerobic bacteria. Facultative anaerobes, like *Desulfovibrio* bacteria, then strip oxygen from sulfate and excrete sulfides as a metabolic waste product that affects macrobenthic communities. Physicochemical changes in sediment chemistry and their effects on the macrobenthos have been extensively studied in association with salmon farms in the Pacific Northwest by Brooks (2001a, 2001b), Brooks, *et al.* (2002), Brooks and Mahnken (2003a, 2003b), and Brooks (2003a, 2003b) and are reasonably well understood. Unlike salmon aquaculture, in which organic matter in the form of feed is added to coastal ecosystems, bivalve culture relies on naturally produced food. The net result is that bivalve aquaculture removes nutrients from coastal bays. Rice (unpublished) concluded that for each kilogram of shellfish meats harvested from an aquaculture farm, 16.8 grams of nitrogen were removed from the

growing waters. Furthermore, he concluded that the production of 225 kg of oyster meats would remove the nitrogen produced by a single human being.

Some of the organic matter filtered from the water by bivalve populations is converted into feces and pseudofeces that once ejected, settle to the bottom in the immediate vicinity of the farm. The result is an organic enrichment of the benthos. This enrichment is generally minor in comparison to that associated with fed aquaculture. Kaspar *et al.* (1985) found that sediments under suspended mussel cultures contained 8.0 to 8.7% total volatile solids (TVS) in comparison with 7.0 to 7.1% TVS found at reference sites. This relatively small addition of organic material was sufficient to increase the concentration of ammonium (NH_4^+) from an annual average of 8.6 mmoles/m^2 at the reference site to 32.5 mmoles/m^2 under the mussel rafts. Differences in sediment nitrate (NO_3^-) and nitrite (NO_2^-) were not significantly different. This biological activity had little effect on oxygen consumption from the overlying water. Dame *et al.* (1991) observed that mussels take up seston, including phytoplankton and detritus, and release ammonium (NH_4^+) orthophosphate and silicate. These nutrients are released in a dissolved form and as a component of feces. Nutrients are also released by epibionts from the suspended culture and by microbial processing of sedimented feces and pseudofeces. Dame *et al.* (1991) estimated a nutrient turnover time of one to 38 weeks from sediment underlying suspended mussel culture in the Western Wadden Sea and Eastern Scheldt estuaries of Northern Holland. This slow release of nutrients tends to reduce fluctuations in phytoplankton production by cropping phytoplankton during periods of high production and cycling the nutrients into sediments where they are slowly released to sustain moderate phytoplankton production over longer periods of time. Similar increased ammonium production has been observed by Grant *et al.* (1995).

Shaw (1998) evaluated sediment organic content (TVS), redox potential (Eh), sulfides (S^+) and infauna in ten estuaries with extensive mussel culture and ten reference areas around Prince Edward Island. Seven of the ten estuaries had been continuously producing mussels for 12 or more years. Table (1) summarizes the endpoints evaluated by Shaw (1998). With the exception of redox potential, observed differences between mussel culture areas and reference areas were not statistically significant. Unfortunately, Shaw (1998) did not evaluate sediment grain size and water depth – important parameters for comparing his results with other areas. However, the relatively high organic content in reference area samples suggests a fine-grained sediment grain size distribution.

However, benthic effects have been observed under intensive bivalve culture and these effects should be managed to insure that they do not extend over large areas and that the effects remain reversible in some reasonable period of time. Brooks (2003c) has shown that chemical and biological remediation of the benthos under and adjacent to salmon farms usually occurs within six months to a year of fallow. However, Brooks *et al.* (2004) showed that the worst known case of benthic effects in British Columbia was taking greater than seven years of fallow to fully remediate.

The Ria de Arosa, located on the coast of Spain just north of Portugal, covers approximately 250 km^2 and is an area heavily used for the production of mussels. Production was estimated at 160,000 metric tons total wet weight of mussels per year by Tenore and Gonzalez (1975). This is equivalent to a of density of ca. 640 grams wet tissue weight/m^2, which is three times higher than the proposed density of 206 g/m^2 in Totten Inlet (total bivalve culture of 5,085 metric tones (whole wet bivalve weight) divided by an area 24.71 km^2). Because of its long history of high mussel production, the Ria de Arosa has been the subject of numerous studies examining the environment's response to intensive mussel culture. Tenore and Gonzalez

(1975) found significant fecal and pseudofecal deposits in the inner core of mussel cultures on Spanish rafts. The symbionts associated with newly established cultures containing small mussels were generally detritus feeders (70%) as opposed to suspension feeders (3.6%). In contrast, older cultures (larger mussels) were dominated by suspension feeding symbionts (67.7%) rather than detritivores (26.6%). Tenore and Gonzalez (1975) hypothesized that a significant amount of the waste was processed on the mussel lines by symbionts rather than falling to the benthos.

The result is that invertebrate production in the vicinity of mussel rafts shifts from the benthic environment to the mussel culture. Lopez-Jamar *et al.* (1984) also found that mussel culture diminished the contribution of infauna to fish diets but that fish shifted to the more abundant epifauna associated with the suspended cultures.

Naturally productive and diverse infauna are typically found in sediments where the redox potential is >100 mV and where sulfides are <200 μmoles. The high organic matter, low redox and high sulfides in reference area sediments suggest that the evaluated estuaries are naturally deposition and support a significantly reduced infauna. Brooks (1995) has observed 6,000 to 11,000 invertebrate organisms/m^2 and 100 to 140 species in 0.1 m^2 van Veen grab samples collected 66 meters down current from a poorly flushed salmon farm. However, Shaw (1998) clearly demonstrated that not all natural benthic environments have ideal physicochemical characteristics and that some do not support diverse and abundant infaunal communities.

Table 16. Mean $\pm$ 1.0 standard deviations of endpoints measured by Shaw (1998) in mussel culture and reference areas adjacent to Prince Edward Island.

Endpoint	Mussel Culture Areas	Reference Areas
Organic matter (%)	10.427 $\pm$ 5.141	9.492 $\pm$ 4.543
Redox potential (mV)	-127 $\pm$ 45	-100 $\pm$ 67
Sulfides (μM)	1320 $\pm$ 879	1121 $\pm$ 682
Infauna abundance (#/m^2)	135 $\pm$ 152	158 $\pm$ 87
Infauna biomass (g/m^2)	32.74 $\pm$ 12.45	15.38 $\pm$ 12.45
Percent deposit feeders (%)	36.7 $\pm$ 35.4	45.7 $\pm$ 36.6
Shannon-Wiener Index[1]	0.275 $\pm$ 0.242	0.369 $\pm$ 0.245

[1]The Shannon-Wiener Index (Shannon and Weaver, 1949) is a metric commonly used to describe the diversity of communities of organisms. It is equal to $H' = -\sum p_i \log(p_i)$ where p_i is the proportion of the total abundance attributed to the *i*th taxa. Low values are indicative of populations dominated by a few taxa; whereas, increasing values are associated with more evenly distributed and diverse communities. The maximum value of H' is ln(number species).

10.3.1. **Total volatile solids (TVS) as a measure of organic enrichment.** Total volatile solids or the loss in weight of dried material combusted at 450 to 550 ^oC is commonly used to assess organic enrichment in sediments. Volatile solids under suspended mussel culture have been measured at concentrations as high as 25% of the dry sediment weight (Dahlback and Gunnarsson, 1981). The degree and spatial extent of significant TVS increases are dependent on currents and depths. In general, it appears that significant increases are restricted to the immediate vicinity of the cultures. Mattsson and Linden (1983) observed that high TVS levels of 22% decreased to 15% at 5 m from the cultures and were further reduced to 8% at 15 m distance.

10.3.2. **Sediment cycling of sulfur.** Dahlback and Gunnarsson (1981) observed that sulfate reduction in sediments on the west coast of Sweden is modeled by the following stoichiometric relationship describing the catabolism of organic material via the striping of oxygen from sulfate to reduce this compound to sulfide, which combines in the sediments with hydrogen ions to form the toxic compound hydrogen sulfide (H_2S).

$$(CH_2O)_{2n} + nSO_4^{=} \rightarrow 2nCO_2 + 2nH_2O + nS^{=}$$

As oxygen is replenished during remediation, the sulfide is oxidized back to sulfate.

$$H_2S \rightarrow H_2 + S^{=} + 2O_2 \rightarrow SO_4^{=}$$

Dahlback and Gunnarsson (1981) estimated that during May and July, 13% and 24% respectively of the sedimented organic carbon under mussel lines was mineralized through sulfate reduction in the absence of free oxygen. They also calculated the oxygen consumption during subsequent oxidation of the sulfide back to sulfate at 1.4 liters O_2/m^2-day. Assuming that the length of the high TVS sediment is 76.8 m (North Totten), we can roughly estimate the oxygen lost from the overlying water at 107.5 liters per day – equivalent to 75.26 grams of oxygen. Assuming an average current speed of 5 cm/sec and mixing to a depth of 50 cm as the water flows over the substrate implies that oxygen will be supplied to the sediments from a volume of 2,160,000 liters of water. This leads to a predicted decrease in the dissolved oxygen concentration of 0.03 mg/L. This prediction is consistent with the conclusion of Dahlback and Gunnarsson (1981) that there was no risk of anoxia in the water column at their study site – or that the hydrogen sulfide would affect fauna in the overlying water column. These results suggest that significantly less sulfide is produced in sediments under mussel farms than has been associated with marine fish culture (Holmer and Kristensen, 1992) – even though the levels of TVS were similar. That is likely because fish waste is nearly entirely organic and very labile – whereas mussel waste is less labile because it contains higher levels of more refractory cellulose in feces and pseudofeces and protein in the shells of fallen mussels.

10.3.3. **Cycling of nitrogen and other nutrients from sediments into the water column.** Baudinet *et al.* (1990) conducted an elegant study describing the flux of nutrients at the sediment-water interface and the response of infaunal communities in the Gulf of Fos, France. Baudinet *et al.* (1990) cite Cerco's (1989) observation that ammonium release from sediments was 70% higher from anaerobic sediments when compared with aerobic conditions. Consistent with other reports reviewed in this document, these authors found that ammonium was cycled at a rate 100 times faster from sediments to the overlying water column than was nitrate (NO_3). Ammonium releases were temporally correlated with mussel biodeposits and peaked in the spring. Mussel cultures covered less than 0.4% of Carteau Cove and increased nutrient releases by 1.4 to 2.3%. The authors concluded that the mussel cultures were not endangering the equilibrium of the ecosystem.

10.3.4. **Biodeposition of volatile solids under intensive mariculture.** As previously noted, because cultured salmon are fed optimum quantities of food and reach market size of 4 to 8 kilograms in 16 to 24 months, the biodeposits associated with netpens are greater than expected from suspended bivalve culture. Chapter 4.3 of this review (Table 2) predicted total biodeposits of 11.7 g/m^2-yr-g DBW mussel tissue. The deposit of volatile solids (TVS) was predicted to be 2.1 g/m^2-yr-g DBW mussel tissue.

Mussel feces will likely sink at a rate of two to four centimeters per second. Pseudofeces, with their higher particulate inorganic matter (silt and clay) content, will likely sink somewhat faster at six to eight cm/sec. Average water depths at the Gallagher Cove site were recorded by Brooks (1999, unpublished) at 7.47 meters. A fecal particle will therefore take 249 seconds to reach the bottom. Current meter data are not available for the Gallagher Cove site. However, the fine-grained sediments indicate that this is a depositional area with maximum current speeds of perhaps 8 cm/sec. Therefore, a fecal particle will travel a maximum distance of ca 20 meters before being sedimented. Because the currents are harmonic in this region, it is reasonable to assume that the impacted area will extend 20 meters beyond each end of the culture in the direction of the currents. Therefore the area of the deposition will be equal to the length of the raft arrays + 2 x 20 meters times the width of the arrays x the number of arrays = 6,881.81 m^2. A total of 1.89 x 10^7 mussels, with an average annual DBW of 0.75 grams each, will be grown here in 16 months. This is equivalent to 10,631 kg DBW mussels per year. These mussels will produce biodeposits equal to 22,326 kg TVS/year and the deposition rate is predicted to be 3.24 kg/m^2-year. A similar analysis for the North Totten Inlet site where mean current speeds of 18.7 cm/sec have been measured and where water depths are ca. 21.9 meters, predicts lower biodeposits of 1.75 kg/m^2-year because the waste will be spread over a larger area.

Cross (1990) used sediment canisters to determine sedimentation rates at salmon farms and reference areas in British Columbia, Canada. Total (PIM plus POM) sedimentation rates at reference stations varied between 0.87 and 10.2 kg/m^2-year. The organic (TVS) portion of these reference area deposits varied between 0.29 and 2.6 kg TVS/m^2-year. The predictions for Gallagher Cove exceed the range observed at the eight reference sites studied by Cross (1990) by 25%. However, the predicted TVS sedimentation rate at the North Totten site (1.75 kg/m^2-yr) is less than the median value (1.65 kg/m^2-yr) reported by Cross (1990). In another study conducted for the British Columbia Ministry of Agriculture, Fisheries and Food, Brooks (1999) determined the mean annual rate of biodeposits under salmon farms at 8.8 kg TVS/m^2 (Brooks, 1999). This rate is 2.7 times higher than at the Gallagher Cove site and 5 times higher than predicted for the North Totten Inlet site. Therefore, organic loading associated with suspended mussel culture is predicted to average 20 to 37% of that associated with netpen culture of salmon.

10.3.5. **Recovery of sediments under intensive aquaculture** begins with what Brooks chemical remediation. This involves the aerobic and/or anaerobic microbial catabolism of excess organic material. Once this occurs, oxygen diffuses into the sediments and sulfides are oxidized back to sulfate (Dahlback and Gunnarsson, 1981). Biological remediation begins during the later stages of chemical remediation with the recruitment of organic carbon tolerant opportunists like *Capitella capitata* and in British Columbia *Ophryotrocha cf. vivipara.* These early recruits significantly increase the catabolism of organic material and can be found in very high abundance in remediating sediments. These opportunistic annelids are followed, in succession, by omnivorous annelids like *Nephtys cornuta* (Brooks, 1993) that flourish in the presence of the large biomass of prey organisms. Chemical remediation takes weeks or months in moderately loaded sediments, but may take several years in heavily impacted sediments under a few salmon farms. However, sediments have remediated naturally in all cases studied. Precise definitions of *Chemical* and *Biological Remediation* from Brooks (1999) are provided below for reference:

10.3.5.1. **Chemical remediation.** Chemical remediation is the reduction of accumulated organic carbon under and adjacent to salmon farms to a level at which aerobic organisms can recruit into the area. It appears that initially high levels of sedimented organic carbon decline exponentially and approach baseline conditions asymptotically. Chemical remediation results in increased levels of oxygen in sediment pore water and decreased levels of sulfide and/or ammonia. Chemical remediation is accomplished through chemical, biological and physical processes.

10.3.5.2. **Biological remediation.** Biological remediation, as used in this report, is defined as the restructuring of the infaunal community to include those taxa representing at least 1% of the total invertebrate abundance observed at a local reference station. Recruitment of rare species (those representing < 1% of the reference area abundance) into the remediating area is not considered necessary for Biological Remediation to be considered complete.

Similar studies describing the chemical and biological remediation of sediments under intensive bivalve culture were not found. However, because the TVS loading is significantly less under bivalve cultures, it seems reasonable to expect reduced effects and faster remediation. The point that should be emphasized is that all of the organic material deposited under mussel cultures is natural. The chemical and biological response under these rafts will be no different than the response in a naturally depositional area where macroalgae, eelgrass and terrigenous organic material accumulates and is biologically recycled back into the environment.

10.4. Infaunal response to suspended mussel culture in Gallagher Cove. NOAA (1981) reported that on average the subtidal benthic macrofauna standing biomass averaged between 10 and 17 g/m^2 throughout much of Puget Sound. WDOE (1996) describes infaunal community characteristics in more detail. For habitats located in less than 150' of water, the abundance (number of invertebrates) and the number of different species is inversely correlated with the percent fines (silt and clay) found in sediments. For instance, in coarse-grained sediments containing less than 20% fines, Puget Sound reference stations (on average) yielded 491 organisms/ 0.1 m^2 with 69 species/0.1m^2. The infaunal community in fine grained sediments containing between 50 and 80% fines is significantly less abundant (307 organisms/0.1 m^2) with significantly fewer species (33 per 0.1 m^2 sample)

Brooks (unpublished data) examined sediments in Gallagher Cove and at the North Totten site. The data are summarized in Table (17). The numbers in parentheses are Puget Sound Reference Station values for the observed percent fines at water depths < 150'. In the sampled area of Totten Inlet, the infaunal community appeared more abundant, but less diverse, than is observed at Puget Sound Reference Stations. Benthic biomass at the new farm site and at the Gallagher Cove reference station was strongly correlated with total abundance (as should be expected) but was highly variable.

The data in Table (17) suggest a significant decrease in invertebrate biomass under the existing Gallagher Cove mussel rafts. The raft design (30' x 34') covers an area of 94.76 m^2. The difference between the reference biomass and that found under the raft is 43.63 grams/m^2. Therefore, the total loss in infauna is predicted to be 4.13 kg/raft. Assuming a similar commensal invertebrate community on Totten Inlet rafts to that reported by Tenore and Gonzales (1975) in the Ria de Arosa, the rafts could be expected to support a commensal fish prey biomass of 47.4 kg/raft. That would represent an 11-fold increase (1147%) in the biomass of fish prey items associated with the areas covered by mussel rafts. This discussion is hypothetical because the community of invertebrates commensal with cultured mussels in Totten Inlet has not been characterized. However, while the community can be expected to be somewhat different, the biomass results will likely be similar.

Table 17. Physicochemical and biological endpoints measured in Totten Inlet sediments at the location of an existing mussel raft culture site in Gallagher Cover, a fine-grained reference station, and at three locations transecting the proposed mussel farm north of Gallagher Cove.

Site	Depth	% Fines	TVS (%)	Number Species[1]	Total Abundanc	Wet Tissue Wt. (g/m^2)
Center of existing farm	24.5	90.13	9.41	3 (33)	119 (307)	1.6
Perimeter of existing farm	24.5		7.15	10 (33)	800 (307)	73.15
5.0 m from perimeter	24.5		7.46	5 (33)	382 (307)	27.06
30.0 m from perimeter	23.5		3.55	4 (33)	93 (307)	6.83
Gallagher Cove Reference	25.0	82.09	6.61	7 (33)	231 (307)	45.23
SE corner of new site	40.2	56.91	4.52	18 (52)	1356 (344)	60.24
Center of north site	72.0	47.86	5.81	9 (64)	533 (494)	6.32
NW corner of new site	85.5	37.94	3.53	13 (64)	800 (464)	15.0

[1]The reported number of species from Totten Inlet in this study was based on Petite Ponar grab samples with a footprint of 0.0225 m^2. The Puget Sound Reference Station data is based on van Veen grab samples with a footprint that is 4 times larger at 0.1 m^2. Therefore, the number of species observed in Petite Ponar samples collected in Totten Inlet by Brooks (unpublished) are not directly comparable with the means published in WDOE (1996).

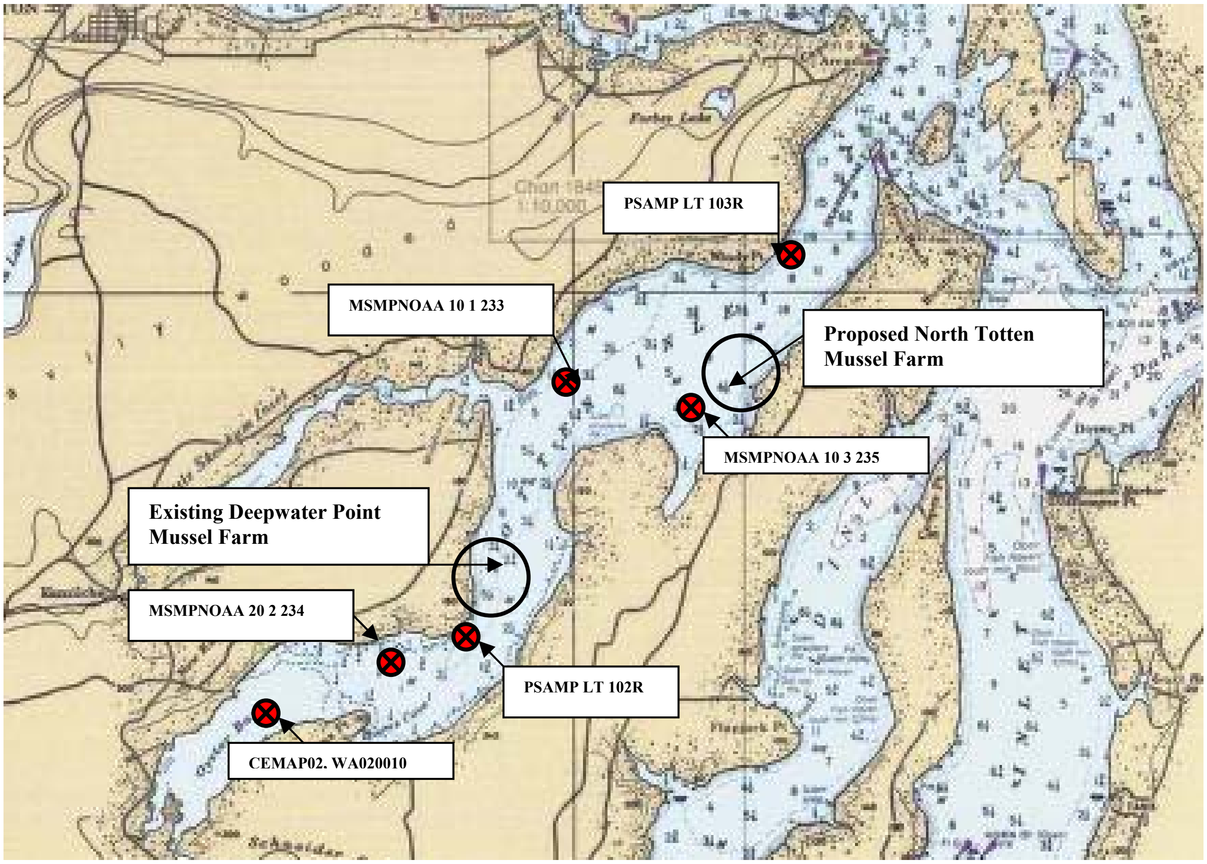

Figure 1. Location of sediment sampling stations included in the 2004 Washington State Department of Ecology Sediment Quality Database.

Benthic response to raft culture of mussels at Deepwater Point.

Site description.

Production history.

Deposition of organic and inorganic matter near Deepwater Point.

Sediment geochemistry at Deepwater Point.

<u>Sediment grain size distribution</u>

<u>Sediment TVS</u>

<u>Free sediment sulfides</u>

<u>Redox potential</u>

Reflux of nutrients from sediments

Macrobenthic response at Deepwater Point

Macrofauna at the reference location

Abundance of macrofauna.

Number of taxa.

Shannon's Index.

Distribution of annelids, mollusks, crustaceans and other taxa.

Multi-dimensional analyses.

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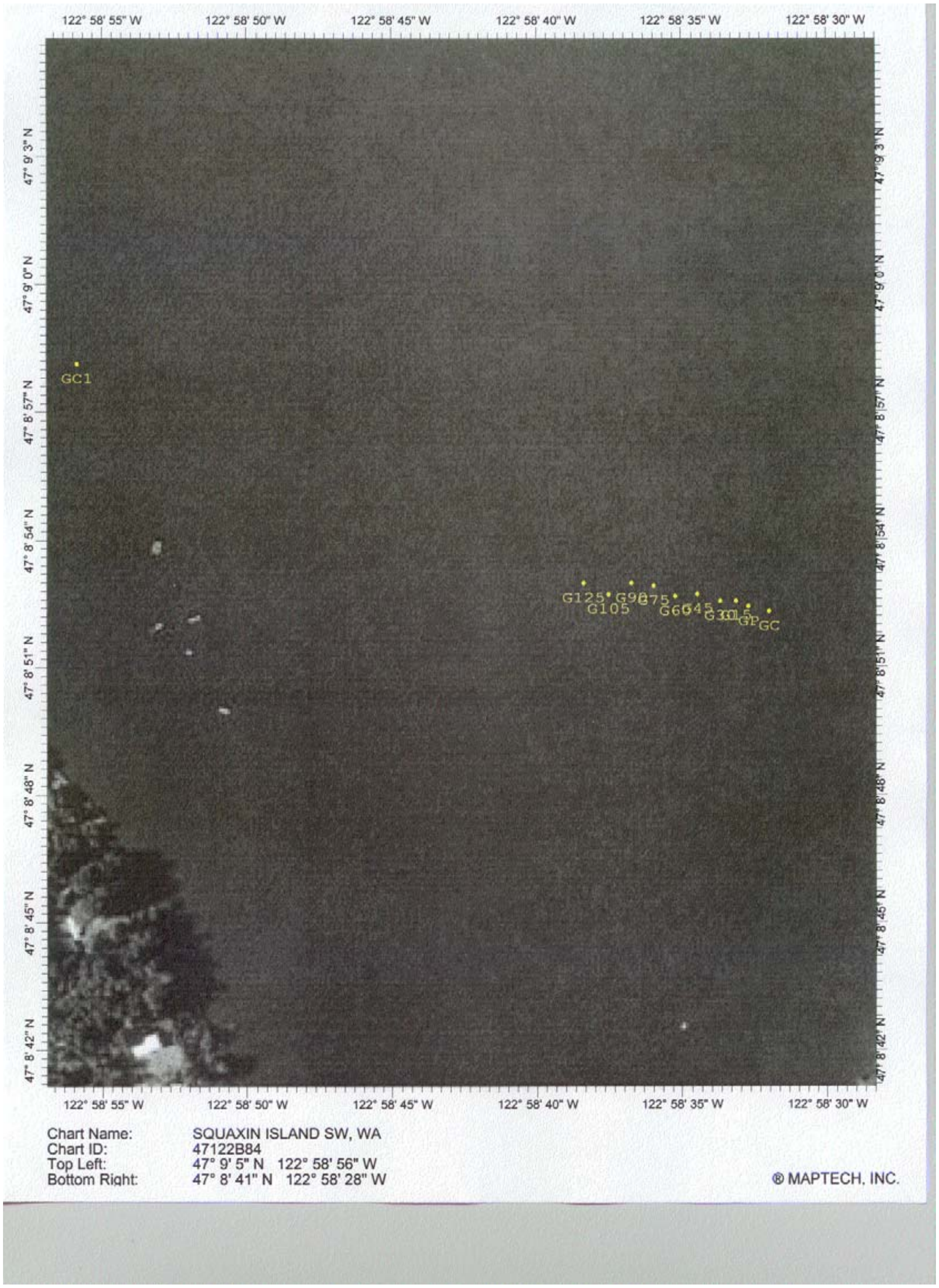
North
South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