



HAL
open science

shell encrustation: A potential indicator of organic enrichment conditions in sediments in the southern Strait of Georgia, British Columbia, Canada

Brenda Burd, Robie Macdonald, Albert van Roodselaar, Cindy Wright

► **To cite this version:**

Brenda Burd, Robie Macdonald, Albert van Roodselaar, Cindy Wright. shell encrustation: A potential indicator of organic enrichment conditions in sediments in the southern Strait of Georgia, British Columbia, Canada. *Marine Environmental Research*, 2008, 66, 10.1016/j.marenvres.2008.08.008 . hal-00563051

HAL Id: hal-00563051

<https://hal.science/hal-00563051>

Submitted on 4 Feb 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accepted Manuscript

Axinopsida serricata shell encrustation: A potential indicator of organic enrichment conditions in sediments in the southern Strait of Georgia, British Columbia, Canada

Brenda Burd, Robie Macdonald, Albert van Roodselaar, Cindy Wright

PII: S0141-1136(08)00200-6
DOI: [10.1016/j.marenvres.2008.08.008](https://doi.org/10.1016/j.marenvres.2008.08.008)
Reference: MERE 3282

To appear in: *Marine Environmental Research*

Received Date: 29 October 2007
Revised Date: 5 August 2008
Accepted Date: 17 August 2008

Please cite this article as: Burd, B., Macdonald, R., van Roodselaar, A., Wright, C., *Axinopsida serricata* shell encrustation: A potential indicator of organic enrichment conditions in sediments in the southern Strait of Georgia, British Columbia, Canada, *Marine Environmental Research* (2008), doi: [10.1016/j.marenvres.2008.08.008](https://doi.org/10.1016/j.marenvres.2008.08.008)

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.



1 8/5/2008

2
3
4
5
6
7 ***Axinopsida serricata* shell encrustation: A potential indicator of**
8 **organic enrichment conditions in sediments in the southern Strait**
9 **of Georgia, British Columbia, Canada**

10
11
12
13
14 *By*

15
16
17 *Brenda Burd*¹
18 *Robie Macdonald*²
19 *Albert van Roodselaar*³
20 *Cindy Wright*²
21

22
23
24 1. Ecostat Research Ltd., N. Saanich, B.C.

25 2. Fisheries and oceans Canada, Institute of Ocean Sciences, Sidney, B.C.

26 3. Metro Vancouver (formerly Greater Vancouver Regional District)

27

28

29 **ABSTRACT**

30

31 We evaluate the potential of the geographic and within-sediment distribution patterns of rust-
32 coloured shell encrustations on an abundant subtidal bivalve, *Axinopsida serricata* (Carpenter,
33 1864) as geochemical indicators of organic enrichment from marine municipal outfalls. The
34 progressive development of shell encrustation over the life of the animals is suggested by heavier
35 encrustations on large shells compared to smaller shells regardless of the geochemical conditions
36 of the habitat. Heavy encrustations decline in an exponential manner at sediment acid volatile
37 sulphide levels >7 $\mu\text{mol/g}$. Analyses show that the reddish shell encrustations are from an
38 amorphous iron oxide or hydroxy-oxide likely micro-biologically mediated; the oxides appear to
39 be embedded within the inner matrix of an organic layer, with a chemically distinct outer layer.
40 A schematic model is proposed which shows how enrichment of labile organic carbon around
41 outfalls affects the availability of dissolved iron in sediments and leads to less extensive
42 encrustations on bivalve shells. Predominantly sandy sediments with low organic loading have
43 much less potential for iron oxide deposition than silty sediments due to greater oxygen
44 penetration into the surface sediment.

45

46 Shell encrustation appears to be relatively persistent and indicative of long-term conditions,
47 regardless of spatial and temporal fluctuations in sediment geochemistry. With more research on
48 development over the life-cycle of the animal, the pattern of *A. serricata* shell encrustation has
49 the potential to rapidly provide a map of cumulative labile organic loading and oxygen
50 penetration of sediments around municipal outfalls on the west coast of North America where
51 this species is common. However, caution must be used in interpreting results, since

52 background sediment characteristics (substrate type, bottom currents and sediment transport) can
53 affect encrustation patterns.

54

55 Key words: bivalves, shell encrustation, iron oxidation, acid volatile sulphides, sediment, outfall

56

57 **1.0 Introduction**

58 One of the difficulties in determining the effects of organic enrichment on the biology and
59 chemistry of sediments is relating periodic sediment chemistry measurements to the long-term
60 ambient conditions experienced by the organisms inhabiting the benthos. For environments such
61 as seabeds surrounding municipal outfalls, it would be particularly helpful to develop a simple
62 method for evaluating the intensity of organic loading within sediments, integrated over time.

63 The bivalve *Axinopsida serricata* (F. Thyasiridae) proved to be of interest when, during the
64 processing of taxonomic samples from a monitoring survey of the Iona outfall receiving
65 environment in the Strait of Georgia on the west coast of Canada, it was noted that the shells
66 showed considerable rust-coloured encrustations that appeared to be related to distance from the
67 outfall.

68

69 *A. serricata* is a small infaunal bivalve (<5mm), which can be found from southern California to
70 Alaska and is an abundance dominant in a variety of subtidal substrate types and depths (Bright,
71 1991; Burd, 1992, 2002, 2003a,b; Llansó, 1998; McPherson et al., 2004a,b,c), including the
72 receiving environment of the Iona and Lions Gate outfalls (south-eastern margin Strait of
73 Georgia – McPherson et al. 2007a,b) and the Macaulay Point outfall near Victoria, BC (Burd,
74 2003b) (see Fig. 1). It appears to be relatively tolerant of conditions near these three major

75 outfalls, but the population declines within the zone of maximum particulate deposition north of
76 the Iona outfall (McPherson et al., 2007a) and near the Macaulay Point outfall (Burd, 2003b).
77 Distributional patterns for particulates from the Lions Gate outfall in Burrard Inlet have not been
78 clearly defined (McPherson et al., 2007b), however.

79
80 Acid-volatile sulphides (AVS) have been used to infer general sediment geochemical conditions
81 and particle loadings in the 3 outfall monitoring programs (McPherson et al., 2007a,b; CRD,
82 2005), and is highest in areas that receive the greatest organic loading. Because AVS values tend
83 to be spatially heterogeneous and ephemeral in sediments (Morse and Rickard, 2004), confident
84 extrapolations from these geochemical parameters to the long-term sediment conditions
85 experienced by the benthos cannot presently be made.

86
87 Organic deposition from a source such as an outfall depletes oxygen in sediments and, depending
88 on the strength of depletion and diffusion of oxygen, other electron acceptors (e.g. nitrate,
89 sulphate and oxides of Mn and Fe) can become important in the oxidation process (Bender et al.,
90 1989; Brendel and Luther, 1995). During redox processes, iron and manganese shift between
91 dissolved phase components subject to diffusion and solid-phase precipitated minerals which
92 may be manifest as deposition on shells. Based on the rusty colour of the shell encrustations,
93 and the burrowing nature of this bivalve, it is probable that the encrustations derive from oxides
94 of either iron or manganese, as found in bivalves from other habitats (Swineheart and Smith,
95 1979; Gillan and De Ridder, 1997; Huettel et al., 1998).

96

97 The purpose of this paper is to contribute to the understanding of geochemical conditions under
98 which shell encrustation occurs, or does not occur. Shell encrustation patterns may provide
99 insights into the sediment redox conditions and organic loading experienced by the sediments,
100 and provide a more biologically-relevant monitoring tool than spot-measurements of sediment
101 geochemistry. The geographic and within-sediment distribution patterns of shell encrustations
102 on *A. serricata* in relation to organic enrichment gradients revealed by sediment AVS, were
103 examined near 3 municipal outfalls in the Strait of Georgia, BC, and a background area
104 elsewhere in the Strait. The composition of the encrustations, and the mechanisms for producing
105 these encrustations were also explored. Finally, we propose a schematic model to show how shell
106 encrustation on *A. serricata* might occur under different sediment conditions.

107 **2.0 Methods**

108 ***2.1 Composition and inner/outer structure of shell encrustation***

109
110 Rust-coloured encrustations from the upper valves of a few shells from the 2003 Iona monitoring
111 samples (station 15 – see Fig. 1) were scraped and combined to undergo analyses for crystalline
112 metal oxides and trace metals, using X-ray diffraction. The combined scrapings were ground
113 into fine powder in a corundum mortar and smeared onto a zero-diffraction quartz plate with
114 ethanol. Step-scan X-ray powder-diffraction data were collected over a range $3-70^{\circ}2\theta$ with
115 $\text{CuK}\alpha$ radiation on a standard Siemens (Bruker) D5000 Bragg-Brentano diffractometer equipped
116 with a diffracted-beam graphite monochromator crystal, 2 mm (1°) divergence and anti-scatter
117 slits, 0.6 mm receiving slit and incident-beam Soller slit. The long sample holder used (43 mm)
118 ensured that the area irradiated by the X-ray beam under these conditions was completely

119 contained within the sample. The long fine-focus Cu X-ray tube was operated at 40 kV and 40
120 mA, using a take-off angle of 6°. The X-ray diffractogram was analyzed using the International
121 Centre for Diffraction Database PDF-4 and Search-Match software by Siemens (Bruker AXS).

122

123 An intact upper valve of *Axinopsida serricata* from the 2003 Iona monitoring station 15 (see Fig.
124 1) and from the ER67 location (Satellite Channel) were examined using scanning electron
125 microscopy (SEM) with an energy dispersive spectrometer (EDS) attached. Specimens from
126 these two areas were chosen to determine whether or not the shell encrustations were formed in
127 the same way regardless of sediment conditions or location. This analysis determines relative
128 bulk elemental composition of the shell encrustation. Scans were done a) on the external coating
129 of the encrustations for each location; b) on the shell itself from the Iona location (no
130 encrustations) and; c) within the cross section of broken edges of the encrusted shell material for
131 each location.

132

133 ***2.2 Axinopsida serricata* size classes, abundance distribution and shell encrustation related to** 134 ***sediment geochemistry***

135 *Axinopsida serricata* were extracted from archived grab samples collected during various
136 monitoring programs over 8 years in the Strait of Georgia (Table 1). Only shells from live
137 organisms (at the time of sampling) were examined. The general sampling areas, ranging from
138 32-136 m in water depth, are shown in Fig. 1. Consistent field (sampling) and laboratory
139 protocols for monitoring benthic infauna were utilized by Biologica Environmental Services Ltd.
140 (Victoria, BC, Canada), and are described in the original monitoring reports; for example,
141 benthic samples were collected using a 0.1 m² Van Veen grab and gently washed through a 1

142 mm mesh screen. All specimens were preserved in 70% ethanol. Sediment AVS samples were
143 available from all studies in Table 1 except the 2000 ER67 Ecological Reserve monitoring
144 program conducted in Satellite Channel (Fig. 1). Sediment Acid volatile sulphide (AVS)
145 samples were prepared by decanting the overlying water in the grab sample, removing and
146 discarding the surface layer of potentially oxidized sediment, and then homogenizing the
147 material from the remaining top 2 cm of the grab prior to chemical analysis in accordance with
148 the method described by USEPA (1991). Hydrochloric acid (6.0 N HCl) was added to each
149 sediment sample within a purge and trap system. To measure AVS, the resulting hydrogen
150 sulphide (H₂S) was carried into a basic zinc acetate solution by argon gas and the AVS was
151 determined colourimetrically (using a method in which sulphide reacts with N-N-dimethyl-
152 phenylenediamine and the resulting methylene blue is then measured). Concentrations were
153 reported on a $\mu\text{mol/g}$ dry weight basis (see also McPherson et al. 2007a).

154
155 The lengths of *A. serricata* specimen shells from the preserved samples were measured by
156 passing each specimen over an optical grid with 0.5 mm gradations. The specimens divided
157 naturally into shell length groups as follows: ≥ 2.70 mm (size class A: SC-A), and 2.70 mm to 1.0
158 mm. (size class B: SC-B) (see also McPherson et al. 2004a; 2005a; 2006a; 2007a). All
159 specimens from each sample were counted and assigned into four categories based on the level
160 of shell encrustations: no encrustations (0), light encrustations (1), moderate encrustations (2)
161 and heavy encrustations (3) (Fig. 2). An example of a series of shells with moderate-heavy
162 encrustation on the external surfaces is also shown in Fig. 2. In this paper, encrustations were
163 classified as “light” (categories 0 and 1) or “heavy” (categories 2 and 3); data are presented as
164 proportions of shells with light encrustations.

165

166 Data from the 2004 Iona monitoring program were used to show an example of a distribution
167 pattern for abundance and shell encrustation of the two size classes of *Axinopsida serricata*
168 relative to the organic enrichment gradient around the outfall (as evidenced by sediment AVS -
169 see McPherson et al., 2007a). The proportion of bivalves from all monitoring location (Table 1)
170 samples with light shell encrustation, was plotted against sediment AVS to show trends for the
171 two size classes.

172

173 **2.3 *Axinopsida serricata* vertical distribution, shell encrustation and AVS within sediment** 174 **depth layers**

175 In addition to the archived samples from monitoring programs, duplicate 0.1 m² Smith-McIntyre
176 grab samples were obtained on October 22/23, 2004 at the Iona monitoring stations 8 and 15
177 (Fig. 1). Station 8 is located less than 0.5 km north of the Iona outfall, where particulate
178 deposition from the outfall is known to be at a maximum (Hodgins and Hodgins, 2000), while
179 Station 15 is located 8 km south of the outfall and outside the influence of the sewage particulate
180 deposition.

181

182 Sediment was extracted from the grabs at 1 cm depth intervals, to within 1 cm of the grab sides.
183 This was done to a maximum sediment depth of 10 cm, to provide equal volume samples. Below
184 10 cm, the wall curvature of the grab begins to reduce the sample volume. From each 1 cm depth
185 layer, a 30 mL sub-sample was removed by plastic spatula and then frozen for chemical analysis
186 of AVS (see methods above), silver and elemental sulfur (for analytical methods see McPherson
187 et al., 2004a). In this study, Ag was measured as an indicator of exposure to municipal outfall

188 particulates (e.g., see Gordon, 1997; Gobeil 1999), whereas elemental sulphur indicates redox
189 condition of sediments. Live specimens of *A. serricata* were preserved in 70% ethanol and later
190 sized and classified according to the degree of shell encrustation.

191

192 **3.0 Results**

193 Shell encrustation occurred primarily in the vicinity of the inhalant aperture and secondarily in
194 the region of the exhalant aperture, on the outside of the upper shell. Figure 2 shows a close-up
195 photograph of encrustations on the external surface of the upper valve. The density and extent of
196 encrustation was highly variable, and thick layers of encrustation sometimes flaked off during
197 mechanical handling. Despite this, some reddish accretions were typically evident which
198 appeared to be more persistent, even after the loose material was sloughed off.

199 **3.1 Composition of Shell encrustation**

200 The X-ray diffraction showed that the metallic crystalline phases of the composite sample of
201 shell scrapings contained rock-forming minerals commonly found in sediment (magnesium,
202 potassium, aluminum), along with a large proportion of aragonite, likely indicative of bivalve
203 shell. No crystalline Fe-oxides or hydroxides were detected. The only phases found that may
204 contain significant Fe are chlorite and dolomite (if solid solution to ankerite is present).

205

206 The results of the SEM/EDS analysis of shell encrustations for the Iona and ER67 shells are
207 summarized as relative proportions of elements in Table 2. Included are data from the most
208 reliable scans showing a) un-encrusted shell composition; b) outer surface of encrustations, and;
209 c) inner surface (broken edges) of encrustations. All analyses revealed that oxygen was the

210 dominant element in the encrustations, and the only notable element evident in the scan of bare
211 shell material. The interior part of the encrustation of the Iona shells had much higher iron and
212 calcium levels, and higher phosphorous levels, than the exterior of the encrustation, whereas the
213 reverse was true for aluminum and magnesium. There was no notable difference in relative
214 composition between Iona and ER67 samples.

215

216 **3.2 Distribution of *Axinopsida serricata* size classes and light shell encrustation relative to** 217 **sediment AVS**

218 Figure 3 shows mean abundance for three replicates (number per 0.1 m²) of the two size classes
219 of *A. serricata* from the 2004 Iona outfall monitoring program samples taken along the 80m
220 depth contour north and south of the outfall (see Fig. 1). Also plotted in Fig. 3 are the
221 corresponding mean AVS levels in sample sediments. Figure 3 shows that for both size classes,
222 abundance declined in the region of elevated sediment AVS. The mean abundance of *A.*
223 *serricata* in the smaller size class demonstrated a dramatic increase at distances >4 km north and
224 >1 km south of the Iona outfall, with near-zero abundance within the maximum deposition zone
225 for the outfall particulates (McPherson et al., 2005a). Abundance of the larger individuals (>2.7
226 mm) showed a more moderate decrease in the maximum deposition zone around the outfall.
227 However, the abundance of both size classes of *A. serricata* tended to vary in the maximum
228 deposition zone from year to year (McPherson et al., 2007a), and did not always show such a
229 clear pattern in relation to sediment AVS. In addition, other factors clearly affect the abundance
230 of this species, which varies considerably over time and space outside the maximum deposition
231 zone (McPherson et al. 2007a), regardless of sediment AVS levels.

232

233 There was a clear but variable predominance of shells with light encrustations (i.e. categories 0
234 or 1) within the maximum deposition zone for the outfall (Fig. 4). By extrapolation, specimens
235 with heavy shell encrustation predominated outside the Iona outfall's deposition zone. However,
236 Fig. 4 also shows that outside the maximum deposition zone for the outfall, the proportion of the
237 small size class of bivalves (1.00 to 2.7 mm) with light shell encrustation (categories 0 or 1) was
238 sometimes higher and more variable relative to the enrichment gradient, than for larger bivalves
239 (>2.7 mm).

240

241 The proportion of the two size classes of *Axinopsida serricata* with light shell encrustation was
242 plotted against sediment AVS levels (Fig. 5), for all monitoring samples (see Table 1). Figure 5
243 demonstrates that shell encrustations were not linearly related to sediment AVS; rather there was
244 a variable response at sediment AVS levels <7 $\mu\text{mol/g}$ for the larger size class animals, followed
245 by a more consistent increase in proportion at AVS levels higher than this (power regression line
246 fit for all large size class data: $r^2=0.54$, $p<0.001$). At sediment AVS levels >7 $\mu\text{mol/g}$, an
247 increasing proportion of the larger size class *Axinopsida serricata* had light encrustations. A
248 similar pattern was found for the smaller size class, but with a higher variability (power
249 regression line fit for all small size class data: $r^2=0.36$, $p<0.01$).

250

251 The *A. serricata* samples from ER67 (Satellite Channel) did not have concurrent sediment AVS
252 measurements, but sediments in this location are generally considered to be well oxygenated and
253 flushed. The area is also subject to low natural sedimentation and has low silt/clay content (i.e.
254 10-25% silt/clay, Ellis 1968) compared with the other sampling areas in this study (45-98%
255 silt/clay, McPherson et al., 2007a,b). For simplicity, the ER67 samples were plotted with a

256 presumed AVS = 1.0 $\mu\text{mol/g}$, although experience with similar habitats suggests that it was
257 probably even lower for these samples (Macdonald et al., in press). The proportion of shells
258 from ER67 samples with light encrustation tended to be higher than those found at low AVS
259 levels for the other 4 sampling locations listed in Table 1.

260 ***3.3 Shell encrustation and AVS in sediment depth layers***

261 More than 90% of *A. serricata* of both size classes were found within the top 4 cm of sediments
262 (Fig. 6a,b) at station 8 and station 15 (reference area). *A. serricata* in the smaller size class were
263 rare at station 8 (near the outfall), with only 8 individuals found in both grabs.

264

265 Fig. 6c,d shows the proportion of *A. serricata* with light shell encrustation through all sediment
266 depth layers in the grab samples. Most of the large size class *A. serricata* at station 8 had light
267 shell encrustation regardless of sediment depth, whereas almost none of the large size class of
268 bivalves at station 15 had light shell encrustation. The smaller size class *A. serricata* are shown
269 only for station 15, due to the near-zero abundance of small *A. serricata* in both station 8
270 samples. At station 15, the proportion of smaller size class bivalves with light shell encrustation
271 ranged from 0 to 0.3.

272

273 AVS levels in sediments at station 15 were consistently lower than at station 8 (Figs. 6,e,f). The
274 proportion of large size class *Axinopsida serricata* with light shell encrustation was higher in all
275 sediment depth samples regardless of AVS levels at station 8 than at station 15. The small size
276 class bivalves found at station 15 showed more variable shell encrustations relative to AVS
277 levels than for the large size class.

278

279 Silver and elemental sulfur were much higher in all depth layers in sediments at station 8 than at
280 station 15 (Fig. 7).

281 **4.0 Discussion**

282 Encrustations such as those found on *A. serricata* shells have been documented for sediment-
283 dwelling bivalves from various locations globally (Swinehart and Smith, 1979; Dando et al.,
284 1994). Gillan and De Ridder (1997) describe a rust colored biofilm and iron oxide deposit on
285 shells of the bivalve *Montacuta ferruginosa*, which is commensal in burrows of sand urchins
286 (spatangoids). Gillan and De Ridder (1997) found that biofilms are laid down over bivalve shells
287 by a complex microbial community with filamentous bacteria similar to *Thiothrix* and
288 *Beggiatoa*, both of which can oxidize sulphide. Similarly, active pumping of water through the
289 burrow (since this species lack siphons) by *A. serricata* to support their metabolism creates two
290 zones (inflow and outflow) of reliable O₂ supply in direct contact with the shell, which would
291 become favoured habitat for microbes that produce biofilms and aid in preserving oxidized iron
292 precipitates. Gillan et al. (2000) and Gillan and De Ridder (2004) proposed possible ontogenetic
293 scenarios relating to the development of rust-coloured bivalve shell encrustations.

294
295 In the current study, the lack of calcium or other elements in the clean shell surface scan, and the
296 differences in outer and inner scans for both locations could be due to the presence of a
297 biological film or periostracum. In bivalves, shell colour is mostly concentrated in the
298 periostracum, a horny layer covering the shell. The encrustations found herein do occur on the
299 outside of the periostracum, but their persistence upon mechanical abrasion of the accretions
300 suggests that the material may also become “cemented” to the shells, possibly within biological
301 films, or the periostracum itself. Swinehart and Smith (1979) found considerable concentrations

302 of Fe and Mn within the periostracum of freshwater molluscs, with reduced amounts found in the
303 periostracum of the marine bivalve *Mytilus californianus*. The authors describe the minerals as
304 being concentrated in amorphous regions in a proteinaceous matrix (see also Gillan and De
305 Ridder, 1997). How the shell encrustation patterns vary on live versus dead shells has not been
306 documented.

307
308 The depth distribution of the bivalves primarily in the top 4 cm of sediments, appears to be
309 related to their size and ability to maintain a viable burrow for bringing overlying oxygenated
310 water to the inhalant aperture. Thyasirids lack siphons, and build an inhalant tube in sediments
311 using their elongated foot (Allen 1958, Slack-Smith 1994). This limits burial depth (see Dufour
312 and Felbeck, 2003), particularly in the non-chemosynthetic species (Dufour, 2005) and is an
313 unusual feature of endobenthic bivalves, making this taxon uniquely situated to reflect
314 geochemical conditions in near-surface sediments. This species is considered by Word (1990) to
315 be an interface detrital (suspension) feeder (see also Zhukova et al., 1992, Dufour 2005). Dufour
316 (2005) did not find any bacterial symbionts in the gills of *A. serricata*, which suggests that it is
317 unlikely to have any nutritional augmentation from chemoautotrophic symbiosis, as some
318 thyasirid bivalves do.

319
320 The decrease in abundance of *A. serricata* in the maximum deposition zone around Iona (e.g.
321 Fig. 3), and the low abundance of this species in the maximum deposition zone around the
322 Macaulay Point outfall (Burd, 2003b) suggest that sediment geochemical conditions in
323 organically enriched sediments near outfalls can be detrimental. Contaminants associated with
324 outfalls might also play a role in near field bivalve declines, although Ag (Gordon, 1997),
325 nonylphenol ethoxylates (Shang et al., 1999) and PBDEs (Johannessen et al., in press) all show

326 enrichments that can be assigned to the Iona outfall, these contaminants are rarely found at levels
327 exceeding provincial and national guidelines at any of the three outfalls (Payne, 2003, 2004,
328 McPherson et al. 2007a,b), and are thus not expected to have adverse effects at this level of the
329 food chain. Some sediment contaminants (e.g., PCBs; Johannessen et al., in press) are unusually
330 low near the Iona outfall, possibly due to dilution from the continuous supply of sediment from
331 the Fraser River. In contrast to the uncertainty related to contaminant effects on biota, Burd et al.
332 (2003a,b) describe biotic changes at both the Iona and Macaulay Point outfalls typical of organic
333 enrichment of sediments. This organic enrichment has been inferred from consistently elevated
334 AVS levels (CRD, 2005; McPherson et al. 2007a), from the elevated elemental sulfur and silver
335 in sediments near the Iona outfall, and from the redox profile in a recent sediment core at station
336 8 (Macdonald et al., in press).

337

338 The small size class *A. serricata* were less tolerant of conditions near the Iona outfall than the
339 large size class (Fig. 3). This may be related to lack of maturity of physiological coping
340 mechanisms or more limited metabolic requirements for smaller specimens, which would
341 prevent successful recruitment in the organically enriched sediments. Other possible reasons
342 include reduced predation on large specimens due to changes in juvenile fish and megafauna
343 composition in the high outfall deposition area (Metro Vancouver, unpublished Iona monitoring
344 data), or to other unknown reasons related to the life history and variable survival of colonizing
345 individuals. In addition, the population distribution of this species may be complicated in the
346 Iona region by the documented transport of sediment down-slope (see Hodgins and Hodgins,
347 2000). The potential for sediment transport to shift recently settled bivalves in laboratory
348 experiments has been shown by Roegner et al. (1995). Along with potential patchiness in

349 sediment conditions, this could explain why there are some bivalves with heavy encrustations in
350 the maximum deposition zone around the outfall (Fig. 4). Conversely, Gillan and De Ridder
351 (2004) noted that the thick shell encrustation in larger bivalves commensal in echinoid burrows
352 can sometimes get scraped off during burrowing under laboratory conditions, which may help to
353 explain why, in the present study, there was often a small proportion of larger *Axinopsida*
354 *serricata* with light shell encrustation in areas where most of the bivalves had heavy shell
355 encrustation. To further complicate this picture, the reduced encrustations overall in the smaller
356 size class *A. serricata* compared with the large size class suggests that encrustations accumulate
357 progressively over the life of these animals. Gillan and De Ridder (2004) also noted that the
358 smallest size class of the commensal bivalve *Montacuta ferruginosa* had a much higher
359 incidence of uncoated or weakly coated iron shell encrustation than the larger size class, and that
360 the encrustations were thicker in larger specimens, suggesting that they build up over time. The
361 above factors could result in a mosaic of shell encrustation patterns, explaining the variable
362 results in the current study.

363

364 The pattern and intensity of shell encrustations are presumably related to characteristics of the
365 water pumped through the shell over time. Figure 5 suggests that there are geochemical
366 thresholds (AVS >7umol/g) above which shell encrustation frequencies decrease. However,
367 between about 3 and 7 umol/g AVS, results were highly variable, which means that periodic
368 measurements of AVS might not provide the most reliable measure of sediment geochemical
369 conditions due to spatial and temporal patchiness in sediments (Morse and Rickard, 2004). For
370 example, in outer Burrard Inlet (Lions Gate sampling area -Fig. 1) samples from 2005, the
371 proportion of larger size class *A. serricata* with light encrustations was unusually high at one of

372 the stations. Although AVS levels were not very high at this station in 2005, they have
373 historically been much higher and more variable than at any other station in the survey area. The
374 proportion of shells with light encrustations in this location remained relatively high throughout
375 the sampling period (2002-2006) regardless of variability in sediment AVS conditions. This may
376 partially explain why there is considerable scatter in the relationship between shell encrustation
377 and sediment AVS (Fig. 5).

378

379 Results suggest that the pattern of shell encrustation is not ephemeral, but rather a cumulative
380 product of substrate conditions. If there is a progressive increase in shell encrustation over the
381 life of the animals, the degree of encrustation in these animals provides a life-long picture of
382 sediment geochemical conditions, which could be verified and clarified by more in-depth studies
383 of the ontogeny of shell encrustation under varying geochemical conditions over the life of the
384 animals.

385

386 ***4.1 The biogeochemical mechanism of encrustation***

387 The formation of shell encrustations in *A. serricata* clearly occurs throughout the southern Strait
388 of Georgia and likely in other coastal seas. However, the degree of encrustation and its
389 distribution in the various sampling areas suggests a relationship with sediment composition and
390 organic loading. Although the organic and geochemical composition of the shell encrustations
391 and the mechanisms of microbiological precipitation of iron on shells have been discussed by
392 Gillan et al. (2000), there has been no work done on the geochemical conditions required within
393 the sediments to facilitate the shell encrustation.

394

395 The results of this study suggest that increasing enrichment of labile organic carbon related to
396 municipal outfall particulate deposition (as evidenced by sediment silver distributions; Gordon
397 1997 and Fig. 7), reduces the concentration of oxygen in the sediments (as evidenced by
398 elemental sulfur distributions – Fig. 7) and leads to reduced encrustations on the bivalve shells.
399 The process of advecting oxygenated water in through the anterior, inhalent siphon and out
400 through the exhalant siphon affects the redox environment surrounding the bivalve's burrow. In
401 particular, given the location, coloration and composition of the encrustations documented here
402 (Fig. 2), it appears that bivalve ventilation produces encrustations by bringing together dissolved
403 oxygen and dissolved iron (Fe II), a process known to lead to ferric iron precipitation in
404 permeable sediments (Brendel and Luther, 1995; Huettel et al., 1998). This process may be
405 mediated on the bivalve shells in part by microbes (e.g. Gillan and De Ridder, 2004) and the
406 coincident formation of a biofilm, which would help to protect precipitated Fe from re-dissolving
407 during subsequent episodes of hypoxia in surrounding sediments.

408
409 The distribution of shell encrustations as a function of distance from an extraordinary labile
410 carbon source (Fig. 4) together with a notable relationship between AVS and shell encrustation
411 (Fig. 5) suggest that the complexity in the shell encrustation process derives from the manner in
412 which the redox cycle affects iron phases (dissolved/particulate) in sediments.

413
414 Before proposing a relationship between the oxygen/iron rich encrustations observed on *A.*
415 *serricata* shells, and sediment geochemistry, it is necessary to examine how redox chemistry
416 might produce dissolved iron (Fe^{2+}) and precipitated Fe phases (Fe^{3+} oxy-hydroxide phases).
417 Metabolism of organic matter involving the consumption of oxygen creates a gradient in the

418 porewater which then supports diffusion of O_2 from bottom water into the sediments. At a depth
419 in sediments where O_2 has been completely consumed, other electron acceptors may be
420 employed in metabolism, but with decreasing energetic return (Bender et al., 1989).
421 Accordingly MnO_2 may be reduced producing dissolved Mn^{2+} which can diffuse upward to re-
422 precipitate when it reaches dissolved O_2 , and NO_3^- can likewise be reduced during the process of
423 denitrification. With considerably less free-energy return, iron oxy-hydroxides associated with
424 solid phases can be reduced to produce soluble Fe^{2+} (Brendel and Luther, 1995), at a depth below
425 the availability of dissolved O_2 . When other electron acceptors have been exhausted, SO_4^{2-} may
426 be used but this provides a very poor energetic return to microbes (Emerson and Hedges 2003)
427 and also releases S^{2-} (sulphide) as an important byproduct. Therefore, shell encrustation could
428 occur because Fe^{2+} may precipitate when it comes in contact with dissolved O_2 and also when it
429 comes in contact with S_2^- pyritization (Berner, 1982).
430
431 The processes outlined above are organized vertically in sediments because O_2 is supplied from
432 the sediment surface and because microbes have a preference for O_2 as an electron acceptor due
433 to the available free-energy return. Dissolved Fe^{2+} , which may be produced below the oxic zone
434 within the sediments during metabolism, can then diffuse upward to precipitate in oxy-
435 hydroxides, but it may also be sequestered by precipitation as sulphides which occur at depth in
436 sediments provided organic metabolism is sufficiently robust to produce S^{2-} . AVS in sediments
437 is clear evidence of S^{2-} production and precipitation (Morse and Rickard, 2004). Thus the depth
438 at which dissolved Fe^{2+} may buildup in sediment porewater is bounded above by oxic conditions
439 where Fe^{2+} is oxidized to Fe^{3+} and precipitated as oxyhydroxide, and below by sulphidic
440 conditions where Fe^{2+} is precipitated as sulphide.

441
442 Figure 8 is a proposed schematic diagram which shows how Fe^{2+} buildup in sediments may be
443 affected by labile organic carbon loading and O_2 penetration. *A. serratica* live predominantly in
444 the top 4-cm of the sediments, and pump water to supply themselves with O_2 . Therefore, it is the
445 supply of dissolved Fe^{2+} in porewater, and not O_2 , that controls whether or not strong
446 encrustation occurs. To construct this figure we have used measured AVS profiles from dated
447 cores for the Iona monitoring stations 8 (near the outfall) and station 15 (reference area),
448 (Macdonald et al., in press) and a hypothetical AVS profile at Satellite Channel. Reasonable
449 porewater Fe^{2+} profiles are proposed based on literature (Reimers et al., 1996; Huettel et al.,
450 1998). Note that annually measured AVS levels have been relatively consistent at the 2 Iona
451 sampling stations over time (McPherson et al., 2007a).

452
453 As we lack sediment geochemical data for Satellite Channel, it is only possible to propose the
454 sediment variables that must exist there in support of the comparatively lighter shell encrustation.
455 compared with the other three locations. This difference may be related to availability and
456 concentration of Fe^{2+} through porewater advection (Huettel et al., 1998). It is likely that
457 predominantly sandy sediments in Satellite Channel (75-90% - Ellis, 1968) with low organic
458 loading would have low potential to produce iron oxide shell encrustation because O_2 penetration
459 into the surface sediment would be facilitated, thus precipitating out Fe^{2+} in the region the
460 bivalves tend to inhabit (upper 4 cm of sediments), and making pore-water Fe^{2+} less available for
461 microbial precipitation onto bivalve shells. Therefore, Fe^{2+} can build up in porewater only to
462 small concentrations in a restricted zone somewhat below the main habitat of *A. serratica*. At
463 Iona station 15, sediments are less porous, and have more mud (low O_2 diffusivity) with higher

464 carbon flux supported by terrestrial (Fraser River particulates) and marine carbon. Here, the
465 oxygen penetrates shallowly, and AVS accumulates weakly (due to a moderate supply of carbon)
466 below about 3 cm. As a result, Fe^{2+} can build up strongly in *A. serratica*'s prime habitat.
467 Finally, in the right-hand panel, Station 8 (near the Iona outfall) exhibits low oxygen
468 permeability (or more rapid biological use of oxygen than can be balanced by diffusion into
469 sediment – see Macdonald et al., in press) and high organic loading, supported partly by outfall
470 particulates (Hodgins and Hodgins, 2000) and partly by marine and terrestrial organic carbon
471 (Macdonald et al., 2005). In this case, the zone of Fe^{2+} build up is again constrained narrowly
472 near the sediment surface because of strong AVS production supported by high organic carbon
473 loading. Redox boundaries shown in Fig. 8 would vary seasonally or interannually with carbon
474 loading (Gobeil et al., 2001). Furthermore, sedimentation tends to bury Fe sequestered in solid-
475 phase sulphides, whereas when oxyhydroxides near the surface become buried, the iron can be
476 reduced and remobilized into pore water.

477 **5.0 Conclusions**

478
479 The shell encrustations on the *Axinopsida serricata* from both locations were primarily iron
480 oxides or hydroxy-oxides possibly biologically mediated; the oxides appear to be mostly
481 embedded within an “inner” iron and phosphorus-rich matrix with a different external
482 composition, possibly suggesting a biofilm coating the encrustations. The encrustations appear to
483 be persistent regardless of short-term or small scale changes in sediment geochemistry. These
484 facts suggest that the rust-coloured encrustations on *A. serricata* shells are similar to those
485 described by Gillan and De Ridder (1997).

486

487 How can *Axinopsida serricata* shell encrustation be used to diagnose sediment geochemical
488 conditions of interest? Here, we show that the frequency and intensity of *A. serricata* shell
489 encrustation, particularly in the larger animals, has the potential to provide a map of cumulative
490 labile organic loading and potential oxygen penetration of sediments around a municipal outfall,
491 where sediment AVS levels are >7 $\mu\text{mol/g}$. However, given the many variables that can
492 potentially affect the shells of these animals, it is likely that this approach would only be feasible
493 in areas where abundance of the bivalves is naturally high, and sufficient samples are collected to
494 see a pattern in spite of the variability. In addition, interpretation of results must take into
495 account oxygen permeability of sediments (typically substrate type), as well as possible
496 confounding due to sediment transport, which may move animals in and out of the organic
497 enrichment zone.

498
499 Given a pre-survey of shell encrustation within a relatively homogenous and low current
500 substrate regime, a more thorough biogeochemical/contaminant sampling program can be
501 planned in projected areas of organic enrichment impact for sediment geochemistry and benthic
502 ecology. With a better understanding of the development of the encrustations over the life of the
503 bivalves, they may ultimately provide a useful tool to assess integrated organic input in locations
504 where loading is patchy in time or space, for example around fish farms.

505

506 **6.0 Acknowledgements**

507
508 The authors thank the many people involved in the various monitoring programs that contributed
509 data to this project. In particular, Metro Vancouver (formerly Greater Vancouver Regional
510 District) provided most of the funding for the work. A great deal of help and cooperation were

511 also gratefully obtained from Biologica Environmental Services, Victoria, BC., the Capital
512 Regional District (Victoria, BC), the British Columbia Ministry of Environment, field personnel
513 from Fisheries and Oceans Canada, and several incredibly constructive and professional
514 reviewers.

515

ACCEPTED MANUSCRIPT

516 **7.0 References**

517

518 Allen, J.A., 1958. On the basic form and adaptations to habitat in the Lucinacea

519 (Eulamellibranchia). Philosophical transactions of the Royal Society, Series B 241, 421-

520 484.

521 Bender, M., Jahnke, R., Weiss, R., Martin, W., Heggie, D.T., Orchardo, J., Sowers, T., 1989.

522 Organic carbon oxidation and benthic nitrogen and silica dynamics in San Clemente

523 Basin, a continental borderland site. *Geochimica Cosmochimica Acta* 53, 685-697.

524 Berner, R.A., 1982. Burial of organic carbon and pyrite sulfur in the modern ocean: its

525 geochemical and environmental significance. *American Journal of Science* 282, 451-473.

526 Brendel, P.J., Luther III, G.W., 1995. Development of a gold amalgam voltametric

527 microelectrode for the determination of dissolved Fe, Mn, O₂ and S(-II) in pore-waters of528 marine and freshwater sediments. *Environmental Science & Technology* 29, 751-761.529 Bright, D., 1991. Tissue variability in the infaunal bivalve *Axinopsida serricata*

530 (Lucinacea:Thyasiridae) exposed to a marine-tailings discharge and associated population

531 effects. Department of Biology, University of Victoria. Ph.D., 215 pp.

532 Burd, B.J., 1992. Qualitative and quantitative studies of benthic infaunal communities in British

533 Columbia coastal waters. Department of Biology, University of Victoria. Ph.D., 375 pp.

534 Burd, B.J., 2002. Evaluation of mine tailings effects on a benthic marine infaunal community

535 over 29 years. *Marine Environmental Research* 53, 481-519.

536 Burd, B.J., 2003a. Ecological Significance of IONA 2000-2002 Monitoring Results for Benthic

537 Infaunal Communities, in: Greater Vancouver Regional District (Ed.), Greater Vancouver

538 Regional District, Cautions, Warnings & Triggers: A Process for Protection of the

- 539 Receiving Environment. Appendices: Technical Reports and Monitoring Programs,
540 Prepared for the Ministry of Environment Land and Air Protection, January, 2004, BC,
541 pp. Diii-D70.
- 542 Burd, B.J., 2003b. Ecological Significance of the Benthic community Effects Related to the
543 Outfall Particulates Discharge Determined from Macaulay Point Monitoring Program:
544 1994-2001. Draft Report to Environmental Services Department, Capital Regional
545 District, Victoria, British Columbia.
- 546 Burd, B.J., Glaholt, R., 2000. Reconnaissance Level Baseline Survey of Benthic Infaunal
547 communities at Ecological Reserve 67 and Adjacent Satellite Channel, June 4, 2000,
548 Georgia Strait Crossing Pipeline Ltd., 14 pp. + appendices.
- 549 Capital Regional District (CRD), 2003. Macaulay and Clover Point Wastewater and Marine
550 Environment Program 2002 Annual Report, Capital Regional District, Environmental
551 Services Department, Victoria, BC, Canada.
- 552 Capital Regional District (CRD), 2004. Macaulay and Clover Point Wastewater and Marine
553 Environment Program 2003 Annual Report, Capital Regional District, Environmental
554 Services Department, Victoria, BC, Canada.
- 555 Capital Regional District (CRD), 2005. Macaulay and Clover Point Wastewater and Marine
556 Environment Program 2004 Annual Report, Capital Regional District, Environmental
557 Services Department, Victoria, BC, Canada.
- 558 Dando, P.R., Ridgway, S.A., Spiro, B., 1994. Sulphide mining by lucinid bivalve mollusks:
559 demonstrated by stable sulphur isotope measurements and experimental models. Marine
560 Ecology Progress Series 107, 167-175.

- 561 Dufour, S., 2005. Gill anatomy and the evolution of symbiosis in the bivalve family Thyasiridae.
562 Biological Bulletin 208, 200-212.
- 563 Dufour, S. C., Felbeck, H., 2003. Sulphide mining by the superextensible foot of symbiotic
564 thyasirid bivalves. Nature 426, 65-67.
- 565 Ellis, D.V., 1968. Quantitative benthic investigations. III. Locality and Environmental data for
566 selected stations (mainly from Satellite Channel, Straits of Georgia and adjacent inlets),
567 February 1965-December 1967. Fisheries Research Board of Canada Technical Report
568 59, 61 pp. + figures and appendices.
- 569 Emerson, S., Hedges, J., 2003. Sediment diagenesis and benthic flux, in: Elderfield, H. (Ed.),
570 The Oceans and Marine Geochemistry. Elsevier-Pergamon, Oxford, pp. 293-320.
- 571 Gillan, D.C., De Ridder, C., 1997. Morphology of a ferric iron-encrusted biofilm forming on the
572 shell of a burrowing bivalve (Mollusca). Aquatic Microbial Ecology 12, 1-10.
- 573 Gillan, D., De Ridder, C., 2004. Iron encrustation of the bivalve *Montacuta ferruginosa*. Journal
574 of the Marine Biological Association of the United Kingdom 84, 1213-1214.
- 575 Gillan, D.C., Warnau, M., De Vrind-de Jong, E., Boulvain, F., Preat, A., De Ridder, C., 2000.
576 Iron oxidation and deposition in the biofilm covering *Montacuta ferruginosa* (Mollusca,
577 Bivalva). Geomicrobiology Journal 17, 141-150.
- 578 Gobeil, C., 1999. Silver in sediments from the St. Lawrence River and estuary and the Saguenay
579 Fjord. Environmental Science and Technology 33, 2953-2957.
- 580 Gobeil, C., Sundby, B., Macdonald, R.W., Smith, J.N., 2001. Recent changes in organic carbon
581 flux to Arctic Ocean deep basins: Evidence from acid volatile sulfide, manganese and
582 rhenium discord in sediments. Geophysical Research Letters 28, 1743-1746.

- 583 Gordon, K., 1997. Sedimentary Tracers of Sewage Inputs to the Southern Strait of Georgia.
584 University of British Columbia. M.Sc., 217 pp.
- 585 Hodgins, D.O., Hodgins, S.L.M., 2000. A re-evaluation of Iona effluent solids deposition based
586 on sediment grain size characteristics, in: Greater Vancouver Regional District (Ed.),
587 Development of a Receiving Environment Monitoring Approach to Liquid Waste
588 Management. Progress Workshop 2 December 6, 2000. Support Material Part 2 of 3 Iona
589 WWTP Receiving Environment. Draft Technical Report, GVRD, Burnaby, BC, pp. 1-1 -
590 1-24.
- 591 Huettel, M., Ziebis, W., Forster, S., Luther III, G.W., 1998. Advective transport affecting metal
592 and nutrient distributions and interfacial fluxes in permeable sediments. *Geochimica*
593 *Cosmochimica Acta* 62, 613-631.
- 594 Johannessen, S.C., Macdonald, R.W., Wright, C.A., Burd, B., Shaw, D.P., van Roodselaar, A., *In*
595 *press*. Joined by geochemistry, divided by history: PCBs and PBDEs in the Strait of
596 Georgia sediments. *Marine Environmental Research*.
- 597 Llansó, R.J., 1998. The distribution and structure of soft-bottom macrobenthos in Puget Sound in
598 relation to natural and anthropogenic factors, in: Puget Sound Water Quality Action
599 Team (Ed.), *Puget Sound Research '98*, Seattle, Washington, 760-771 pp.
- 600 Macdonald, R.W., Harner, T., Fyfe, J., 2005. Recent climate change in the Arctic and its impact
601 on contaminant pathways and interpretation of temporal trend data. *Science of the Total*
602 *Environment*, Special Issue 342, 5-86.
- 603 Macdonald, R.W., Johannessen, S.C., Gobeil, C., Wright, C., Burd, B., van Roodselaar, A., *In*
604 *Press*. Sediment redox tracers in Strait of Georgia sediments – can they inform us of the

- 605 loadings of organic carbon from municipal wastewater? Submitted to Marine
606 Environmental Research.
- 607 McPherson, C.A., Bailey, H.C., Chapman, M.K., Lee, M.K., Burd, B.J., Fanning, M.L., Paine,
608 M.D., Hamilton, M.C., Chen, F., 2003. Iona Deep-sea Outfall, 2002 Environmental
609 Monitoring Program: Sediment Effects Survey, Prepared for the Greater Vancouver
610 Regional District by EVS Consultants Ltd., Burnaby, BC, 223 pp. + appendices.
- 611 McPherson, C.A., Chapman, M.K., Fanning, M.L., Olson, J., Chen, F., 2004c. Georgia Strait
612 Ambient Monitoring Program - Data Report, Prepared for the Greater Vancouver
613 Regional District by EVS Consultants Ltd, Burnaby, BC, 28 pp. + appendices.
- 614 McPherson, C.A., Chapman, M.K., Lee, M.K., Burd, B.J., Fanning, M.L., Hamilton, M.C.,
615 Chen, F., 2004a. Iona Deep-sea Outfall, 2003 Environmental Monitoring Program:
616 Sediment Effects Survey, Prepared for the Greater Vancouver Regional District by EVS
617 Consultants Ltd., Burnaby, BC, 262 pp. + appendices.
- 618 McPherson, C.A., Chapman, M.K., Lee, M.K., Fanning, M.L., Olson, J., Chen, F., 2004b. Lions
619 Gate Outfall, 2003 Sediment Effects Survey, Prepared for the Greater Vancouver
620 Regional District by EVS Consultants Ltd., Burnaby, BC, 99 pp. + appendices.
- 621 McPherson, C.A., Chapman, M.K., McKinnon, S., Burd, B.J., Fanning, M.L., Olson, J.,
622 Hamilton, M.C., Chen, F., 2005a. Iona Deep-sea Outfall, 2004 Environmental
623 Monitoring Program: Sediment Effects Survey, Prepared for the Greater Vancouver
624 Regional District by EVS Consultants Ltd., Burnaby, BC, 222 pp. + appendices.
- 625 McPherson, C.A., Chapman, M.K., McKinnon, S., Burd, B.J., Fanning, M.L., Olson, J.,
626 Hamilton, M.C., Chen, F., 2006a. Iona Deep-sea Outfall, 2005 Environmental

- 627 Monitoring Program: Sediment Effects Survey, Prepared for the Greater Vancouver
628 Regional District by EVS Consultants Ltd., Burnaby, BC, 262 pp. + appendices.
- 629 McPherson, C.A., Chapman, M.K., McKinnon, S., Burd, B.J., Fanning, M.L., Olson, J.,
630 Hamilton, M.C., Chen, F., 2007a. Iona Deep-sea Outfall, 2006 Environmental
631 Monitoring Program: Sediment Effects Survey, Prepared for the Greater Vancouver
632 Regional District by EVS Consultants Ltd., Burnaby, BC, 240 pp. + appendices.
- 633 McPherson, C.A., Chapman, M.K., McKinnon, S., Fanning, M.L., Burd, B.J., Olson, J., Chen,
634 F., Brooks, G., 2006b. Lions Gate Outfall, 2005 Sediment Effects Survey, Prepared for
635 the Greater Vancouver Regional District by EVS Consultants Ltd., Burnaby, BC, 212 pp.
636 + appendices.
- 637 McPherson, C.A., Chapman, M.K., McKinnon, S.J., Fanning, M.L., Burd, B.J., Olson, J., Chen,
638 F., Brooks, G., 2005b. Lions Gate Outfall, 2004 Sediment Effects Survey, Prepared for
639 the Greater Vancouver Regional District by EVS Consultants Ltd, Burnaby, BC. 212 pp,
640 + appendices.
- 641 McPherson, C.A., Chapman, M.K., McKinnon, S.J., Fanning, M.L., Burd, B.J., Olson, J., Chen,
642 F., Brooks, G., 2007b. Lions Gate Outfall, 2006 Sediment Effects Survey, Prepared for
643 the Greater Vancouver Regional District by EVS Consultants Ltd., Burnaby, BC. 238 pp,
644 + appendices.
- 645 Morse, J.W., Rickard, D., 2004. Chemical dynamics of sedimentary acid volatile sulfide.
646 Environmental Science & Technology 38, 132A-136A.
- 647 Paine, M.D., 2003. Environmental significance of sediment quality and tissue residue monitoring
648 data for the GVRD Iona and Lions Gate outfall study areas. Draft report, Prepared for

- 649 Greater Vancouver Regional District (GVRD), Burnaby, BC by Paine, Ledge and
650 Associates (PLA), North Vancouver, BC, 31 pp. + Tables + Figures.
- 651 Paine, Ledge and Associates, 2004. Trend Analysis of Macaulay Point Invertebrate Community
652 Data 1994-2002, Prepared for the Capital Regional District, Environmental Services
653 Department, Victoria, BC, Canada.
- 654 Reimers, C.D., Ruttenberg, K., Canfield, D.E., Christiansen, M.B., Martin, J.B., 1996. Porewater
655 pH and authigenic phases formed in the uppermost sediments of the Santa Barbara Basin.
656 *Geochimica Cosmochimica Acta* 60, 4037-4057.
- 657 Roegner, C., Andre, C., Lindegarth, M., Eckman, J.E., Grant, J., 1995. Transport of recently
658 settled soft-shell clams (*Mya arenaria* L.) in laboratory flume flow. *Journal of*
659 *Experimental Marine Biology and Ecology* 187, 13-26.
- 660 Shang, D.Y., Macdonald, R.W., Ikonomu, M.G., 1999. Persistence of nonylphenol and
661 ethoxylate surfactants and their principle primary degradation products in sediments
662 from near a municipal outfall in the Strait of Georgia, British Columbia, Canada.
663 *Environmental Science & Technology* 33, 1366-1372.
- 664 Slack-Smith, S.M., 1994. *Axinopsida serricata* (Carpenter, 1864), its burrowing behavior and the
665 functional anatomy of its pallial organs (Mollusca: Thyasiridae). *Veliger* 37, 30-35.
- 666 Swineheart, J.H., Smith, K.W., 1979. Iron and manganese deposition in the periostraca of several
667 bivalve molluscs. *Biological Bulletin* 156, 369-381.
- 668 USEPA, 1991. Draft analytical method for determination of acid volatile sulphide in sediment,
669 US Environmental Protection Agency, Office of Science and Technology, Washington,
670 DC.

- 671 Word, J.Q., 1990. The Infaunal Trophic Index, a Functional Approach to benthic community
672 analysis, University of Washington, Ph.D., 237 pp. + appendices.
- 673 Wright, C.A., Johannessen, S.J., Macdonald, R.W., Burd, B.J., Hill, P. Van Roodselaar, A.,
674 Bertold, S., 2008. The Strait of Georgia Ambient Monitoring Program: Phase I 2002-
675 2007. Canadian Data Report Fisheries and Aquatic Sciences xxx: yy + yy p.
- 676 Zhukova, N.V., Kharlamenko, V.I., Svetashev, V.I., Rodionov, I.A., 1992. Fatty acids as
677 markers of bacterial symbionts of marine bivalve mollusks. Journal of Experimental
678 Marine Biology and Ecology 162, 253-263.
- 679

680 **Figure Captions**

681

682 Figure 1. (Right) Locations from which *Axinopsida serricata* specimens, collected as part of
683 previous monitoring studies, were used for shell encrustation classification. Historical sediment
684 chemistry data were obtained from monitoring reports specific to these locations. Left panel
685 shows details of the two stations (stations 8 and 15), located along the 80 m depth contour north
686 and south of the Iona outfall, that were sampled in this study to obtain *A. serricata* for
687 classification of shell encrustation and to determine sediment depth at which these bivalves are
688 found, as well as chemical analysis of sediments from specific depths in the grabs.

689 Figure 2. Illustration of the range of shell encrustation for *A. serricata* corresponding to the
690 following categories: no encrustations (0), light encrustations (1), moderate encrustations (2)
691 and heavy encrustations (3).

692 Figure 3. Abundance of *Axinopsida serricata* (number per 0.1m²) at the 2004 Iona outfall
693 monitoring stations and corresponding sediment AVS levels in relation to distance (km) from the
694 Iona outfall (McPherson et al. 2005a). The Iona outfall is located at 0 km; negative and positive
695 distances in km are south and north of the outfall, respectively.

696 Figure 4. Proportion of *Axinopsida serricata* shells with either no encrustations (Category 0) or
697 light encrustations (Category 1) in relation to distance (km) north and south of the Iona outfall
698 (data combined for 2001-2006). The Iona outfall is located at 0 km; negative and positive
699 distances are km south and north of the outfall, respectively.

700 Figure 5. Empirical relationship between the proportion of *Axinopsida serricata* shells with light
701 encrustations (category 0 or 1) and sediment AVS for all sample areas. AMP in the figure key

702 stands for the Ambient Monitoring Program in south Georgia Strait (Wright et al. 2008). CRD
703 2001 samples are from Macaulay Point area. Included are 7 samples from Satellite Channel
704 location (ER67); Since AVS data are not available, an estimated value of 1.0 $\mu\text{mol/l}$ has been
705 given to these samples simply to show how they compare with the samples from the other four
706 locations. A is for the large size class *A. serricata*; B is for the small size class

707 Figure 6. Large (A) and small (B) size class abundance of *A. serricata* per each 1 cm layer of
708 sediment in Smith-McIntyre grab. Each section had about the same surface area and volume.
709 The low value at the surface in one station 15 replicate was confounded by the presence of a
710 large Dungeness crab in the sample; Proportion of abundance of “light” encrustation (categories
711 0/1) large (C) and small (D) size class *A. serricata* in layers at stations 8 and 15. The low value
712 for adults at station 8 at 8 cm depth represents only 2 animals found in that layer; Comparison of
713 light encrustation *A. serricata* (category 0/1) with sediment AVS in grab layers for large (E) and
714 small (F) size classes for stations 8 and 15. Values for small size class bivalves for station 8 are
715 not shown because there were so few specimens that proportions were meaningless.

716 Figure 7. Differences in mean sediment elemental sulfur and silver concentrations with depth
717 layers for stations 8 and 15.

718 Figure 8. A schematic diagram showing how the flux of labile organic carbon to the sediment
719 surface influences *A. serricata* (represented by small circles grouped on each set of profiles)
720 shell encrustation. In the left-hand panel, low organic flux into porous sediments (such as those
721 found in Satellite Channel) creates a deep oxic surface zone where Fe^{2+} precipitates as Fe oxy-
722 hydroxides maintaining low $[\text{Fe}^{2+}]$ in *A. serratica*'s prime habitat. In the middle panel, moderate
723 organic loading together with less permeable sediments (such as found near Iona station 15 off

724 the south arm of the Fraser River), creates a zone favourable to Fe^{2+} in the pore water
725 sandwiched between the surface oxic layer where Fe oxy-hydroxides are precipitated and a
726 deeper, mildly sulphidic layer (AVS buildup) where Fe sulphides are precipitated. This narrow,
727 Fe^{2+} enriched zone lies in *A. serratica*'s habitat. In the right hand panel, high organic loading,
728 supported partly by outfall particulates (such as that found at Iona station 8 near the outfall),
729 rapidly consumes oxygen and supports strong SO_4^{2-} reduction in near-surface sediments as
730 evidenced by high AVS buildup. Because all living *A. serratica* bivalves pump O_2 containing
731 water through their siphons, we propose that the shell encrustation process is controlled by the
732 diffusion of dissolved Fe^{2+} in porewater for which the conditions in the middle panel are most
733 favorable.

734

735

736

Figure 6a-f Burd, Macdonald, Wright, van Roodseelaar, Fig. 1

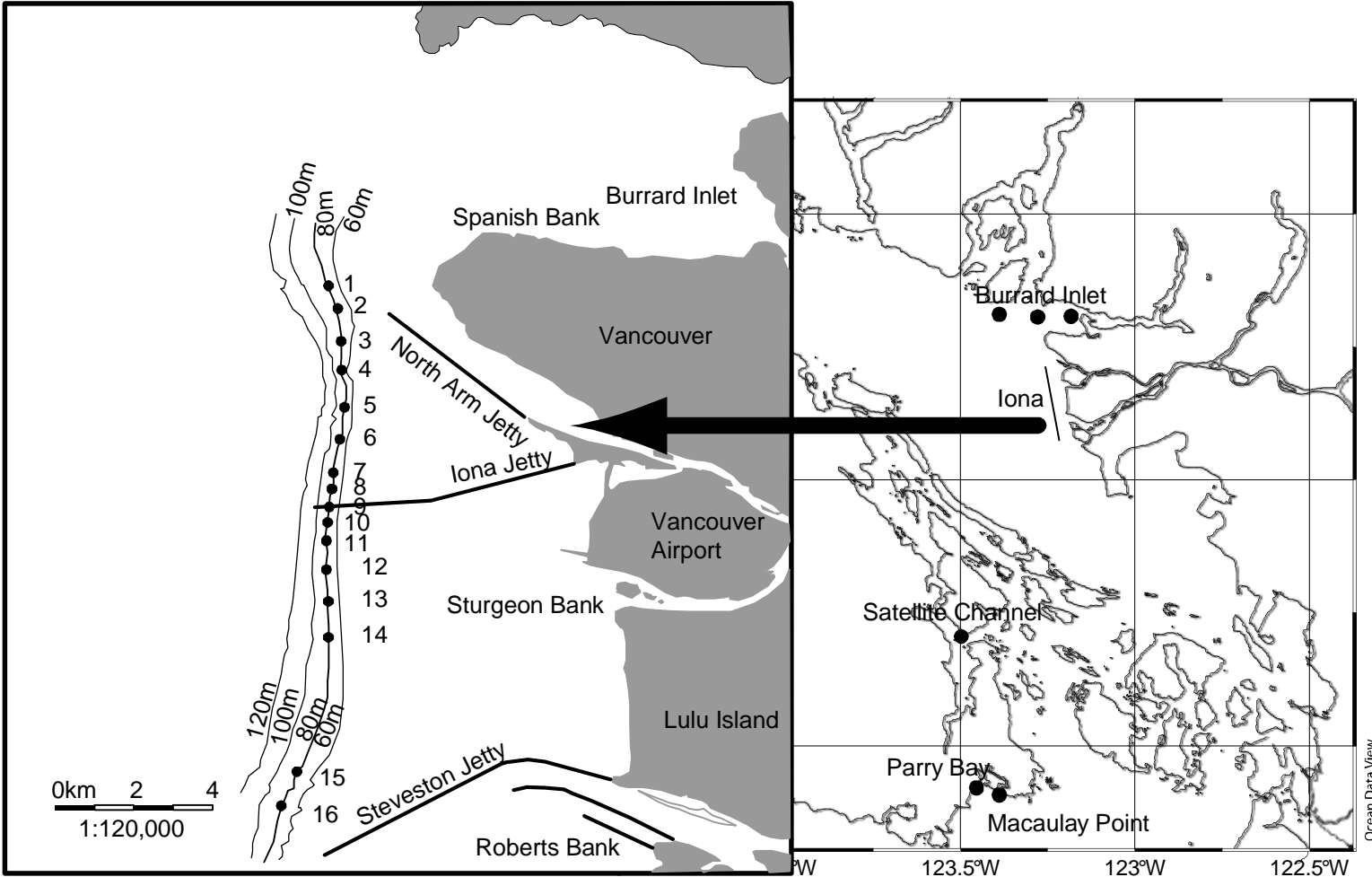


Figure 2

Burd,
MacDonald,
Wright, van
Roodselaar;
Fig. 2

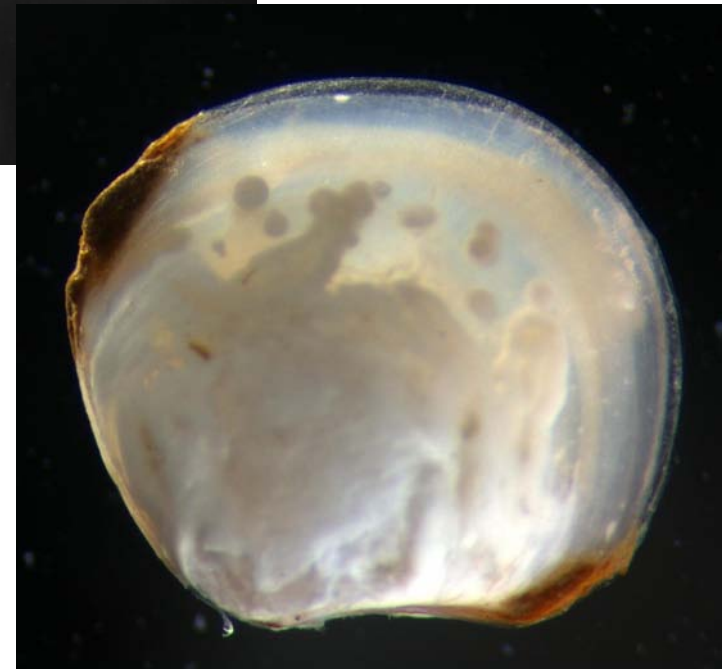
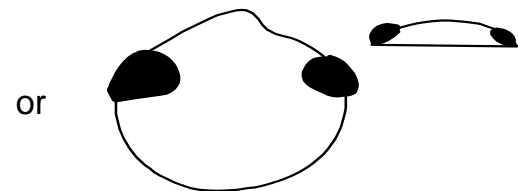
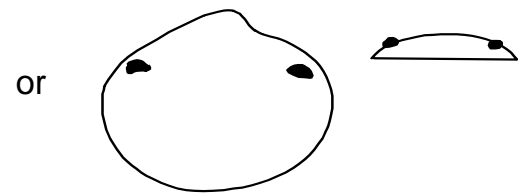
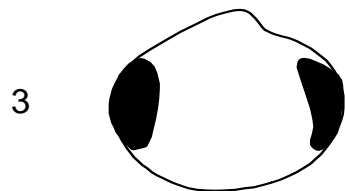
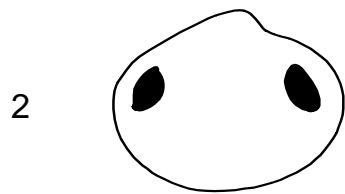
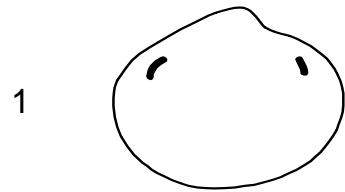
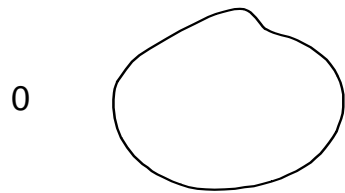
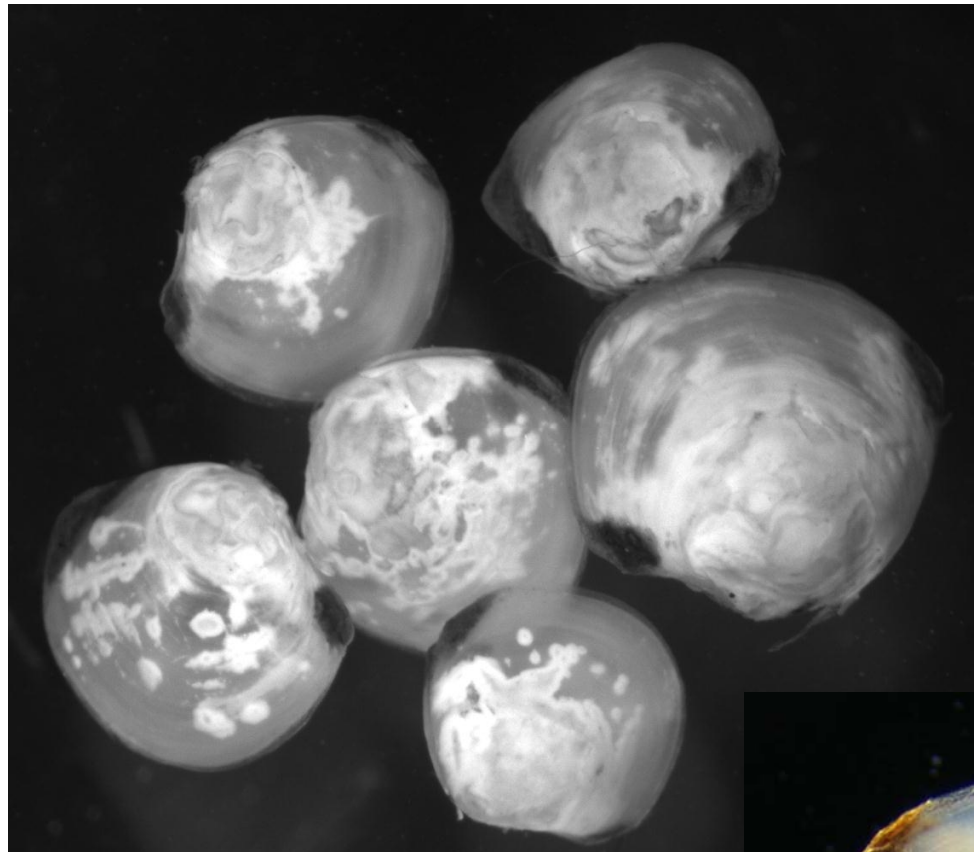


Figure 3

Burd, Macdonald, Wright, van Roodselaar, Fig. 3

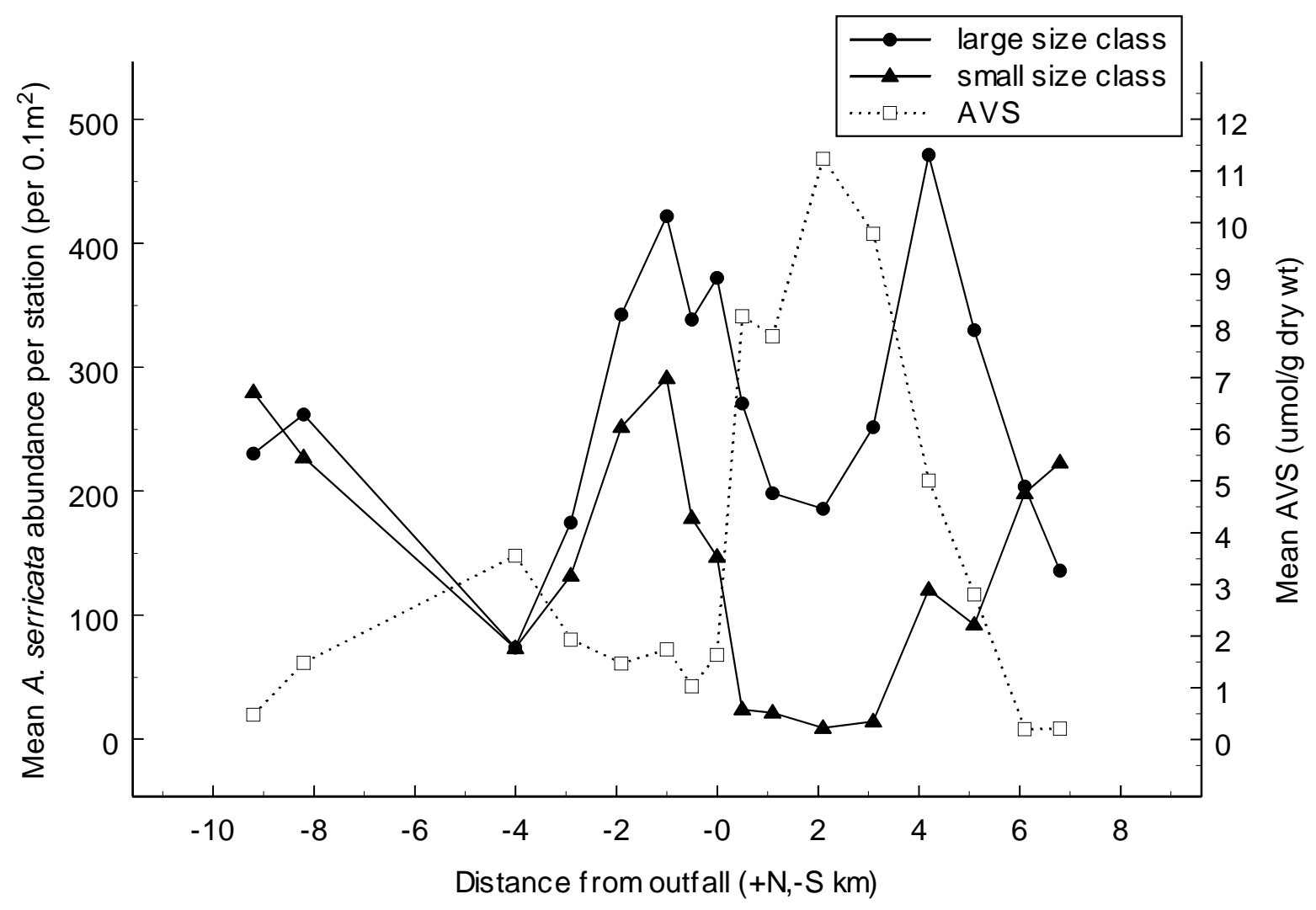
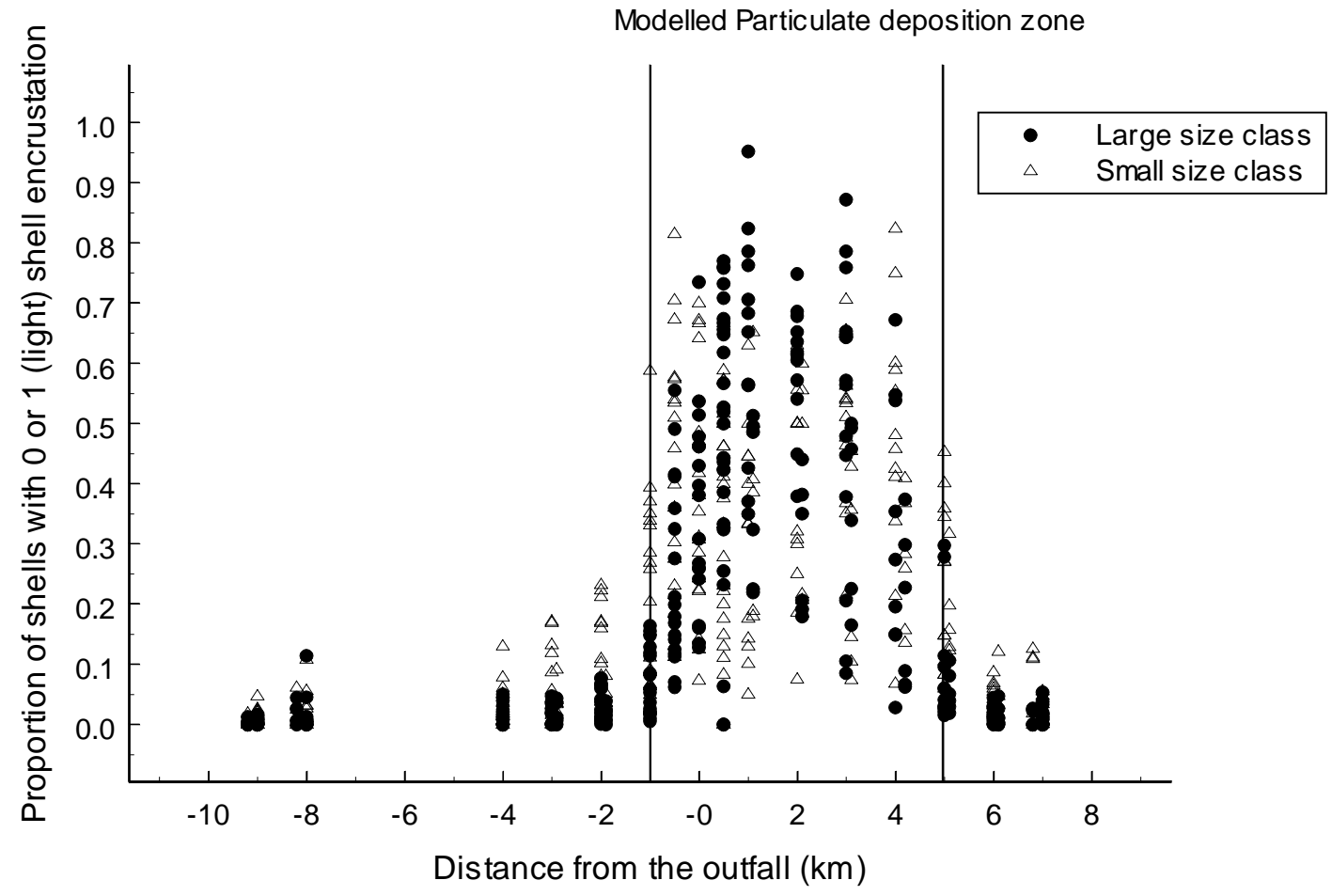


Figure 4

Burd,
Macdonald,
Wright, van
Roodselaar
Fig. 4



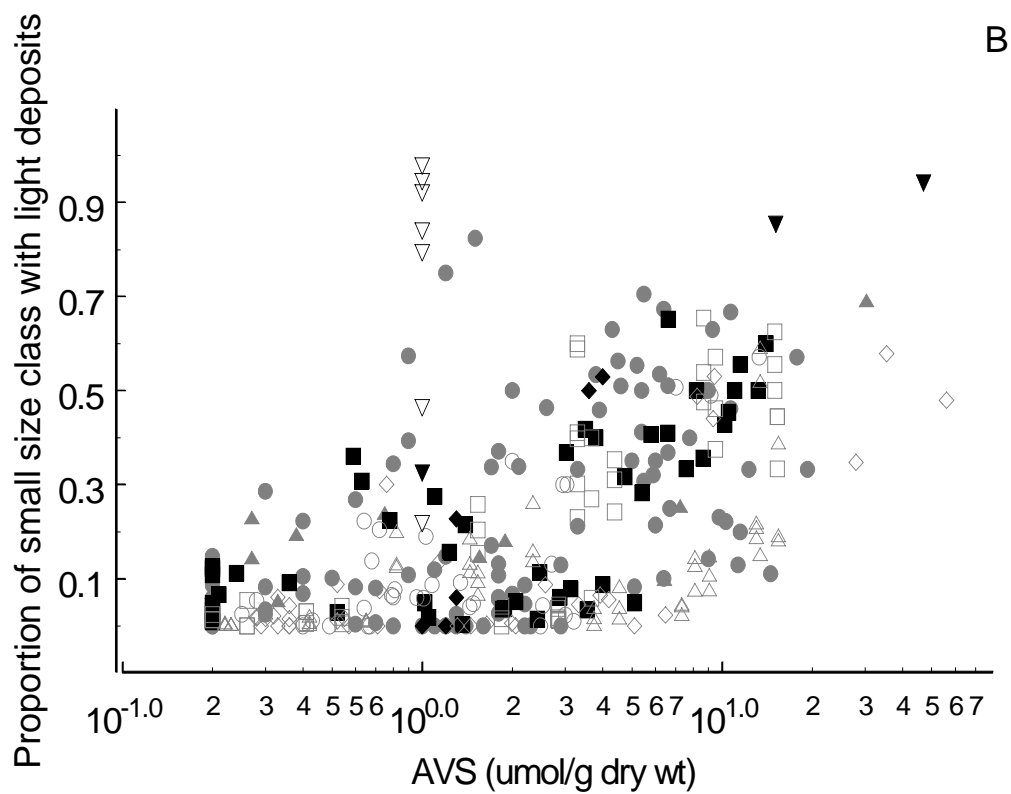
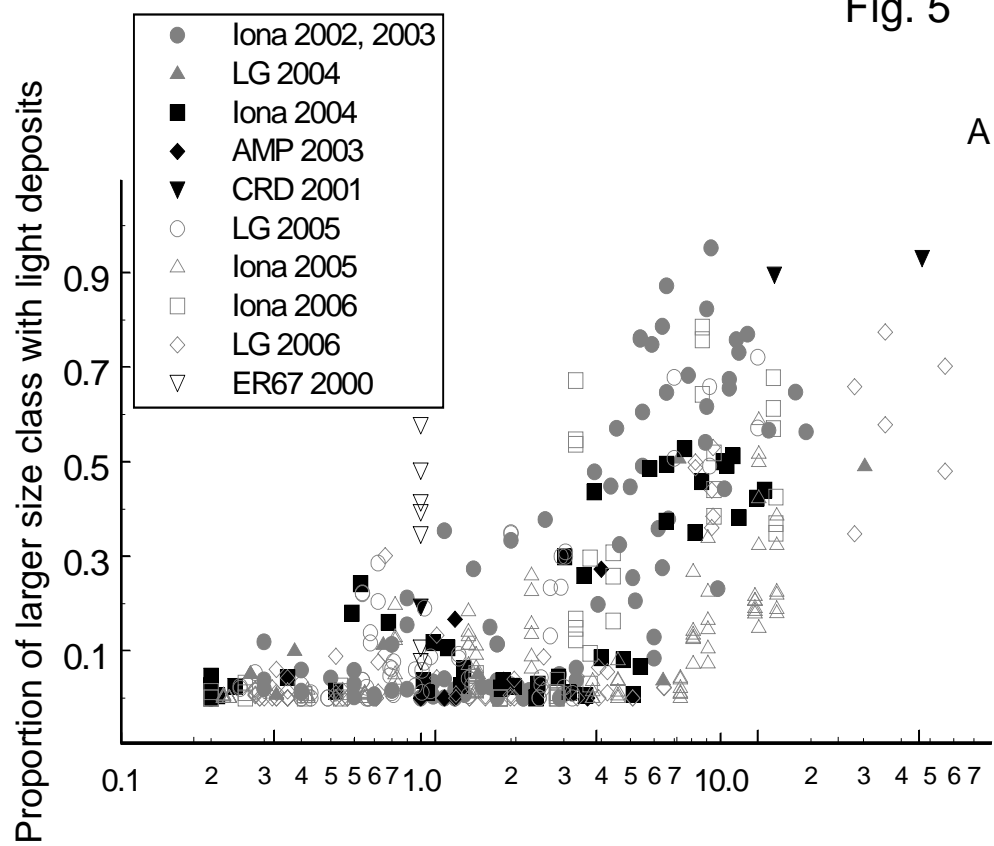
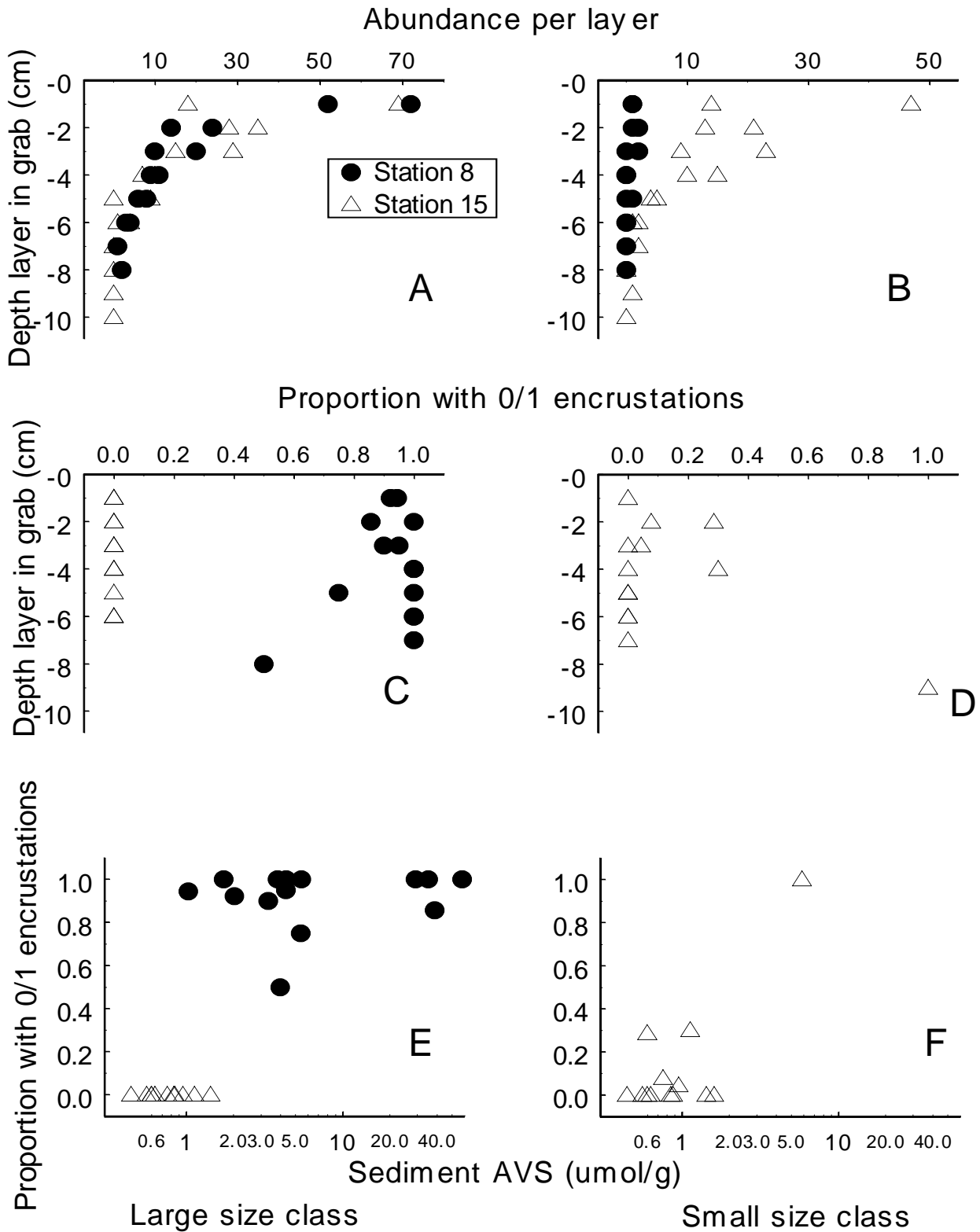
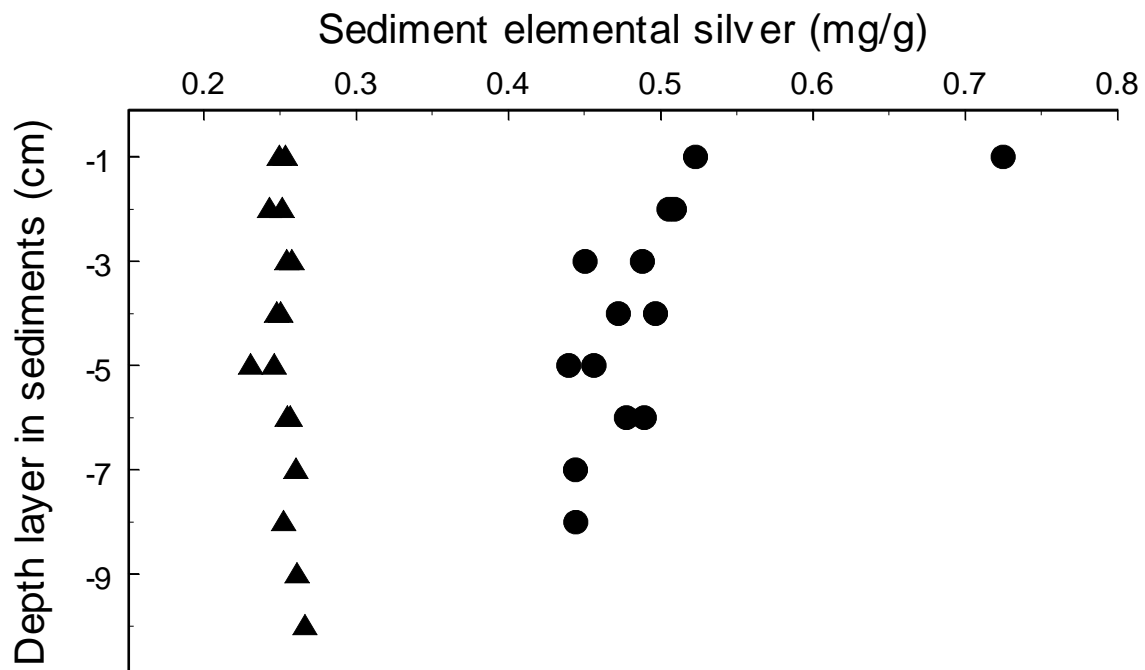
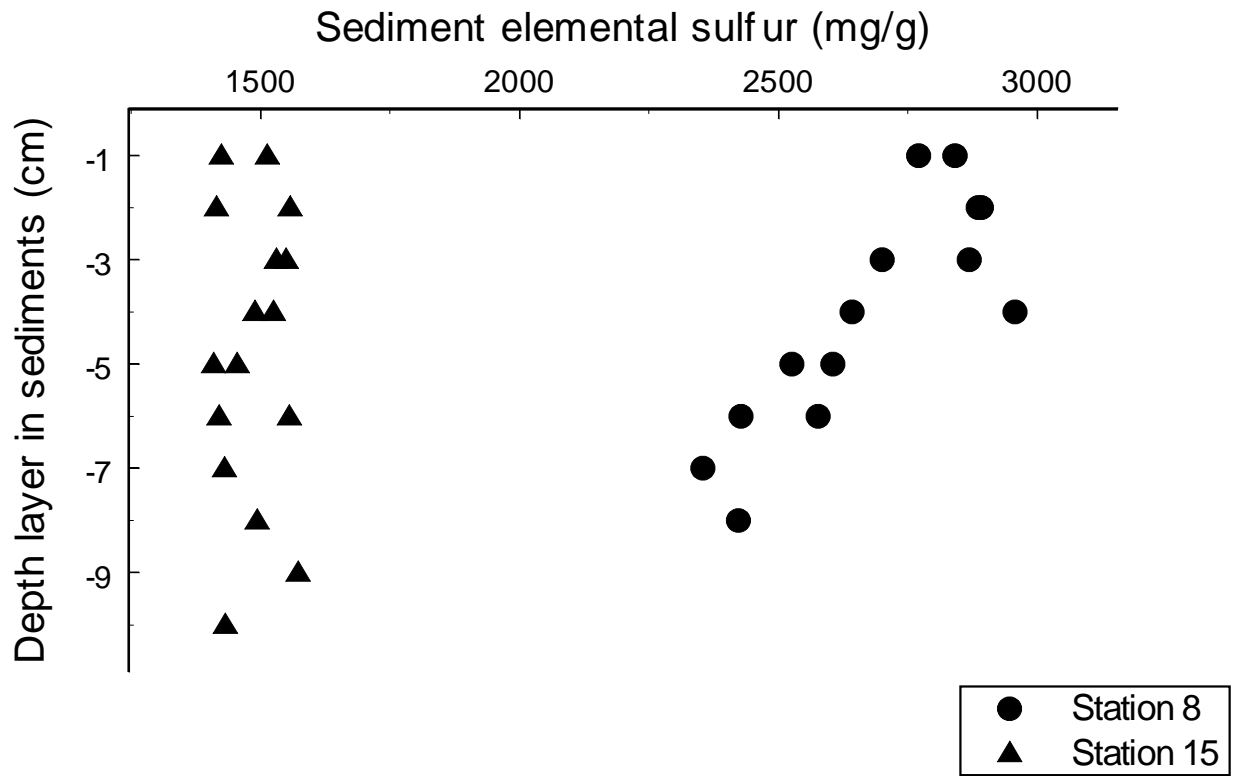
Burd, Macdonald, Wright, van Roodselaar
Fig. 5

Figure 6a-f Burd, Macdonald, Wright, van Roodselaar



Burd, Macdonald,
Wright, van
Roodselaar, Fig. 7



Burd, Macdonald, Wright, van Roodselaar, Fig. 8

Organic Carbon Flux

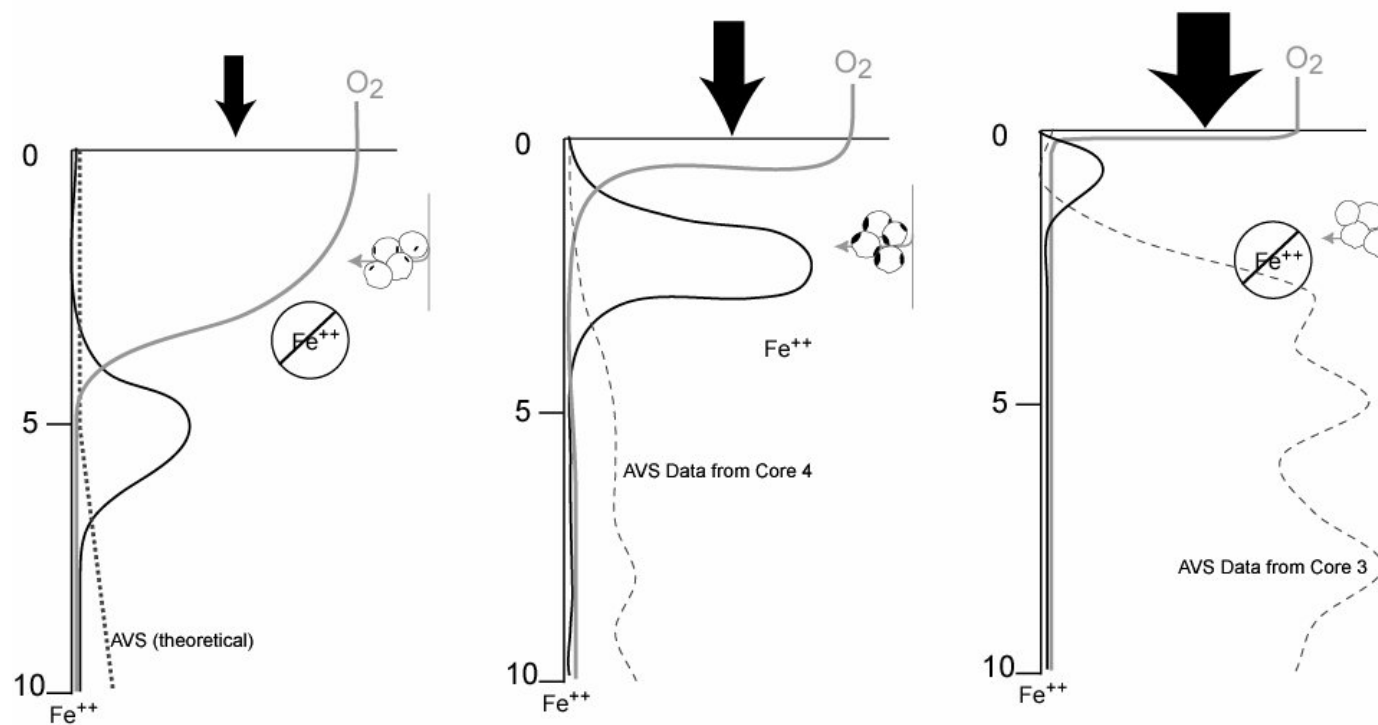


Table 1

Table 1. Summary of specimen and data sources used to examine *Axinopsida serricata* shell deposits on the BC coast. Key: SO = sewer outfall; *includes nearby reference area (Parry Bay).

Project	Study Area	Year	Depth Range (m)	<i>A. serricata</i> Abundance range (# per 0.1m ²)	Sediment Geochemical Data	Reference
Ambient Monitoring Program (DFO, NRC, GVRD)	S. Georgia Strait (outside Burrard Inlet)	2003, 2004, 2006	85 - 136	3*-99	Yes	McPherson et al., 2004c, Wright et al. 2008
Assessment of the Proposed GSX Pipeline	ER67 Ecological Reserve (Satellite Channel)	2000	73 - 86	49-263	No	Burd and Glaholt, 2000
Iona SO Receiving Environment Monitoring Program	E. Strait of Georgia - 16 km gradient N and S of the SO	2002	80	163-978	Yes	McPherson et al., 2003
Iona SO Receiving Environment Monitoring Program	E. Strait of Georgia - 16 km gradient N and S of the SO	2003	60 - 120	12-1541	Yes	McPherson et al., 2004a
Iona SO Receiving Environment Monitoring Program	E. Strait of Georgia - 16 km gradient N and S of the SO	2004	80	81-965	Yes	McPherson et al., 2005a
Iona SO Receiving Environment Monitoring Program	E. Strait of Georgia - 16 km gradient N and S of the SO	2005	80	194-624	Yes	McPherson et al., 2006a
Iona SO Receiving Environment Monitoring Program	E. Strait of Georgia - 16 km gradient N and S of the SO	2006	80	101-608	Yes	McPherson et al., 2007a
CRD SO Monitoring Program*	Macaulay Pt SO: Juan de Fuca Strait	2001	54 - 67	8-274	Yes	CRD 2003, 2004, 2005, Paine et al. 2004
Lion's Gate SO Monitoring Program	Outer Burrard Inlet	2004	32 - 87	42-445	Yes	McPherson et al., 2005b
Lion's Gate SO Monitoring Program	Outer Burrard Inlet	2005	32 -87	34-355	Yes	McPherson et al., 2006b
Lion's Gate SO Monitoring Program	Outer Burrard Inlet	2006	32 -87	40-501	Yes	McPherson et al., 2007b

Table 2. Comparison of the relative elemental composition, determined using SEM/EDS, of *Axinopsida serricata* shell deposits. Atomic % is the relative percent composition of noted elements. * indicates < 2 sigma or below detectable range.

Elements	shell only (no deposits)	Outer Coating Iona	Inner Coating Iona	Outer Coating ER67	Inner ER67
	Atomic %	Atomic %	Atomic %	Atomic %	Atomic %
O	97.51	83.1	78.1	80.3	74.63
Mg	.52*	1.47	1.39	0.85	1.41
Al	1.09	4.03	1.33	2.49	1.48
Si	.84*	7.59	3.33	6.72	5.95
P	-.34*	1.33	4.52	0.73	3.66
S	.37*	0.13*	.37	1.02	0.53
K	.01*	0.67	.33	0.32	0.49
Ca	0.00*	0.9	2.36	5.14	2.73
Fe	0.00*	0.78	8.26	2.42	9.11
Total	100	100	100	100	100