

# University of Alberta

Sedimentology and Neochronology of a Wave-Dominated, Tidally-Influenced, Fully  
Marine Bay, Oregon, USA

by

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## **Dedication**

This thesis is dedicated to all of those who persevere, stick to their principles, follow their hearts and have a passion for all things they strive for and achieve in life. For those who always ask why and are willing to pour their heart and soul into the pursuit of truth and science.

## **Abstract**

In the field of ichnology it is understood that modern process ichnological observations of biogenically generated structures, in response to various physicochemical parameters, have substantial applicability to deciphering trace fossil assemblages observed in the rock record. Previous research has described various animal-sediment distributions within a fully marine realm. However, limited modern studies have directly assessed trace genesis in high energy, constantly shifting sandy substrates or the paleoecology of firmgrounds in a fully marine bay. In this thesis the effects of hydraulic energy, sediment erosion, sediment deposition, substrate firmness, and overall paleoecological aspects of various substrate types on macrofaunal burrowing behaviour and resultant trace distributions were assessed. This was achieved through detailed sedimentological and neoichnological observations conducted along transect locations within Netarts Bay, Oregon. The knowledge gained through this study strengthens ichnofacies models and offers new insight into trace distributions within shallow, fully marine environments.



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## Table of Contents

	Page
<b>CHAPTER 1: INTRODUCTION.....</b>	<b>1</b>
<b>BIBLIOGRAPHY.....</b>	<b>4</b>
<b>CHAPTER 2: SEDIMENTOLOGY AND NEOICHOLOGY IN RELATION TO VARYING HYDRAULIC ENERGY LEVELS AND ASSOCIATED SEDIMENTATION RATES IN THE OUTER TO EXPOSED REGIONS OF NETARTS BAY, OREGON.....</b>	<b>7</b>
<b>INTRODUCTION.....</b>	<b>7</b>
<b>STUDY AREA.....</b>	<b>8</b>
<b>Geologic Setting.....</b>	<b>11</b>
<b>Modern History.....</b>	<b>12</b>
<b>METHODOLOGY.....</b>	<b>13</b>
<b>EXPOSED SHOREFACE-SPIT BAY REGION DESCRIPTION AND RESULTS....</b>	<b>18</b>
<b>Morphological and Sedimentological Features .....</b>	<b>18</b>
<i>Bay Mouth North Foreshore Sub-Environment.....</i>	<i>18</i>
<i>Recurved Spit Sub-Environment.....</i>	<i>25</i>
<i>Shoreface-Spit Sub-Environment.....</i>	<i>31</i>
<b>Total Organic Carbon and Salinity Values.....</b>	<b>36</b>
<i>Bay Mouth North Foreshore Sub-Environment.....</i>	<i>36</i>
<i>Recurved Spit Sub-Environment.....</i>	<i>37</i>



<i>Shoreface-Spit Sub-Environment</i> .....	37
<b>Neoichnological Characteristics</b> .....	38
<i>Bay Mouth North Foreshore Sub-Environment</i> .....	38
<i>Recurved Spit Sub-Environment</i> .....	43
<i>Shoreface-Spit Sub-Environment</i> .....	45
<b>INTERPRETATION OF EXPOSED SHOREFACE-SPIT BAY REGION</b> .....	50
<b>Morphological and Sedimentological Interpretation</b> .....	50
<b>Neoichnological Interpretation</b> .....	63
<b>OUTER SHELTERED SANDY TIDAL FLAT BAY REGION DESCRIPTION AND RESULTS</b> .....	68
<b>Morphological and Sedimentological Features</b> .....	68
<i>Sand Flat High Sub-Environment</i> .....	68
<i>Eelgrass Flat Low Sub-Environment</i> .....	76
<i>Isolated Sand Bar Sub-Environment</i> .....	79
<b>Total Organic Carbon and Salinity Values</b> .....	85
<i>Sand Flat High Sub-Environment</i> .....	85
<i>Eelgrass Flat Low Sub-Environment</i> .....	85
<i>Isolated Sand Bar Sub-Environment</i> .....	86
<b>Neoichnological Characteristics</b> .....	87
<i>Sand Flat High Sub-Environment</i> .....	87
<i>Eelgrass Flat Low Sub-Environment</i> .....	96
<i>Isolated Sand Bar Sub-Environment</i> .....	105
<b>INTERPRETATION OF OUTER SHELTERED SANDY TIDAL FLAT BAY REGION</b> .....	114
<b>Morphological and Sedimentological Interpretation</b> .....	114
<b>Neoichnological Interpretation</b> .....	124

<b>OUTER-MIDDLE SANDY TIDAL FLAT BAY REGION DESCRIPTION AND RESULTS.....</b>	<b>135</b>
<b>Morphological and Sedimentological Features.....</b>	<b>135</b>
<i>Sandy Eelgrass Field Sub-Environment.....</i>	<i>135</i>
<i>Sand Flat High-Tidal Creek Sub-Environment.....</i>	<i>139</i>
<i>Tidal Creek Sub-Environment.....</i>	<i>144</i>
<i>Sandy Tidal Flat Ridge and Furrow Sub-Environment.....</i>	<i>147</i>
<i>Firmground Sub-Environment.....</i>	<i>150</i>
<b>Total Organic Carbon and Salinity Values.....</b>	<b>150</b>
<i>Sandy Eelgrass Field Sub-Environment.....</i>	<i>150</i>
<i>Sand Flat High-Tidal Creek Sub-Environment .....</i>	<i>151</i>
<i>Tidal Creek Sub-Environment .....</i>	<i>151</i>
<i>Sandy Tidal Flat Ridge and Furrow Sub-Environment.....</i>	<i>151</i>
<i>Firmground Sub-Environment.....</i>	<i>152</i>
<b>Neoichnological Characteristics.....</b>	<b>152</b>
<i>Sandy Eelgrass Field Sub-Environment.....</i>	<i>152</i>
<i>Sand Flat High-Tidal Creek Sub-Environment.....</i>	<i>158</i>
<i>Tidal Creek Sub-Environment .....</i>	<i>162</i>
<i>Sandy Tidal Flat Ridge and Furrow Sub-Environment.....</i>	<i>164</i>
<i>Firmground Sub-Environment.....</i>	<i>169</i>
<b>INTERPRETATION OF OUTER-MIDDLE SANDY TIDAL FLAT BAY REGION.....</b>	<b>169</b>
<b>Morphological and Sedimentological Interpretation.....</b>	<b>169</b>
<b>Neoichnological Interpretation.....</b>	<b>177</b>



<b>DISCUSSION.....</b>	<b>183</b>
<b>Physico-chemical Factors Affecting Biological Distribution and Behaviour.....</b>	<b>183</b>
<b>Effects of Hydrodynamics and Associated Sedimentation Rate on Macrofauna.....</b>	<b>188</b>
<b>Ichnological Implications of a Fully Marine Micro- to Meso-tidal, Wave Dominated, Tidally Influenced Bay on Associated Archetypal Substrate Controlled Ichnofacies.....</b>	<b>192</b>
<i>Exposed Shoreface-Spit Bay Region – .....</i>	<i>193</i>
<i>Outer Sheltered Sandy Tidal Flat Bay Region – .....</i>	<i>195</i>
<i>Outer-Middle Sandy Tidal Flat Bay Region – .....</i>	<i>199</i>
<b>Preservation Potential and Applicability to the Rock Record.....</b>	<b>208</b>
<b>SUMMARY AND CONCLUSIONS.....</b>	<b>209</b>
<b>BIBLIOGRAPHY.....</b>	<b>214</b>
<b>CHAPTER 3: SPATIAL, TEMPORAL, AND PALEOECOLOGICAL SIGNIFICANCE OF EXHUMED, COMPACT FIRM-GROUNDS AND OTHER ASSOCIATED SUBSTRATE TYPES IN NETARTS BAY, OREGON.....</b>	<b>231</b>
<b>INTRODUCTION.....</b>	<b>231</b>
<b>SETTING.....</b>	<b>233</b>

<b>METHODOLOGY.....</b>	<b>235</b>
<b>RESULTS.....</b>	<b>237</b>
<b>Exhumed Compacted Peaty-Clay Firmground.....</b>	<b>237</b>
<i>Firmground Spatial Geometry and Sediment</i>	
<i>Characteristics.....</i>	<b>237</b>
<i>Neoichnological Characteristics.....</i>	<b>241</b>
<b>Exhumed Compacted Silty Sand Firmground.....</b>	<b>243</b>
<i>Firmground Spatial Geometry and Sediment</i>	
<i>Characteristics.....</i>	<b>243</b>
<i>Neoichnological Characteristics.....</i>	<b>245</b>
<b>Modern Silty Sand to Clay Stiffgrounds.....</b>	<b>247</b>
<i>Stiffground Spatial Geometry and Sediment</i>	
<i>Characteristics.....</i>	<b>247</b>
<i>Neoichnological Characteristics.....</i>	<b>248</b>
<b>Surficial Softground Veneer.....</b>	<b>250</b>
<i>Areal Extent of Veneer and Sediment Characteristics.....</i>	<b>250</b>
<i>Neoichnological Characteristics .....</i>	<b>251</b>
<b>Woodground Associated with Exhumed Compacted Peaty-Clay</b>	
<b>Firmground.....</b>	<b>255</b>
<i>Spatial and Neoichnological Woodground</i>	
<i>Characteristics.....</i>	<b>255</b>

<b>DISCUSSION.....</b>	<b>257</b>
<b>The Integral Role of Substrate Control on Trace Form</b>	
<b>Genesis.....</b>	<b>257</b>
<b>Importance of Quantitative Substrate Firmness</b>	
<b>Measurements.....</b>	<b>264</b>
<b>Designation of Substrate Types to a Particular Ichnofacies</b>	
<b>Assemblage .....</b>	<b>266</b>
<b>Spatial and Temporal Significance of Firmground and Woodground</b>	
<b>Deposits in Netarts Bay.....</b>	<b>269</b>
<b>SUMMARY AND CONCLUSIONS.....</b>	<b>271</b>
<b>BIBLIOGRAPHY.....</b>	<b>273</b>
<b>CHAPTER 4: CONCLUSIONS.....</b>	<b>280</b>
<b>BIBLIOGRAPHY.....</b>	<b>284</b>

## List of Tables

	Page
<b>Table 2-1: Summary of Sedimentological and Physico-Chemical Characteristics of the Exposed Shoreface-Spit Bay Region.....</b>	<b>20</b>
<b>Table 2-2: Summary of Trace Making Organisms and Associated Traces of the Exposed Shoreface-Spit Bay Region.....</b>	<b>40</b>
<b>Table 2-3: Summary of Sedimentological and Physico-Chemical Characteristics of the Outer Sheltered Sandy Tidal Flat Bay Region.....</b>	<b>74</b>
<b>Table 2-4: Summary of Trace Making Organisms and Associated Traces of the Outer Sheltered Sandy Tidal Flat Bay Region.....</b>	<b>89</b>
<b>Table 2-5: Summary of Sedimentological and Physico-Chemical Characteristics of the Outer-Middle Sandy Tidal Flat Bay Region.....</b>	<b>140</b>
<b>Table 2-6: Summary of Trace Making Organisms and Associated Traces of the Outer-Sandy Tidal Flat Bay Region.....</b>	<b>154</b>
<b>Table 3-1: Sedimentological and Neoichnological Summary of the Various Substrate Types.....</b>	<b>238</b>

## List of Figures

	Page
<b>Figure 2-1: Location of Netarts Bay, Oregon.....</b>	<b>9</b>
<b>Figure 2-2: Exposed Shoreface-Spit bay region study area and associated transects of the various sub-environments.....</b>	<b>14</b>
<b>Figure 2-3: Outer Sheltered Sandy Tidal Flat bay region study area and associated transects of the various sub-environments.....</b>	<b>15</b>
<b>Figure 2-4: Outer-Middle Sandy Tidal Flat bay region study area and associated transects of the various sub-environments.....</b>	<b>16</b>
<b>Figure 2-5: Morphological photographs of the Bay Mouth North Foreshore sub-environment.....</b>	<b>19</b>
<b>Figure 2-6: Sedimentological photographs of surface features of the foreshore terrace bar area along the Bay Mouth North Foreshore sub-environment .....</b>	<b>21</b>
<b>Figure 2-7: Sedimentological photograph of subsurface features of the foreshore terrace bar area along the Bay Mouth North Foreshore sub-environment.....</b>	<b>23</b>
<b>Figure 2-8: Photograph of trenches dug at or near the foreshore-backshore boundary of the Bay Mouth North Foreshore sub-environment.....</b>	<b>24</b>

<b>Figure 2-9: Main tidal channel bank characteristics along the Recurved Spit sub-environment.....</b>	<b>27</b>
<b>Figure 2-10: Foreshore terrace morphology and surface sedimentary features of the Recurved Spit sub-environment.....</b>	<b>28</b>
<b>Figure 2-11: Morphology and sedimentology of foreshore terrace zone of the Recurved Spit sub-environment.....</b>	<b>29</b>
<b>Figure 2-12: Surface and sub-surface sedimentology of the foreshore region of the Recurved Spit sub-environment.....</b>	<b>30</b>
<b>Figure 2-13: Surface and sub-surface sedimentology of the backshore region of the Recurved Spit sub-environment.....</b>	<b>32</b>
<b>Figure 2-14: Morphological and sedimentological features of the foreshore terrace along the Shoreface-Spit sub-environment.....</b>	<b>34</b>
<b>Figure 2-15: Morphological and sedimentological features of the foreshore terrace along the Shoreface-Spit sub-environment.....</b>	<b>35</b>
<b>Figure 2-16: Neoichnology of tidal creek within Bay Mouth North Foreshore sub-environment.....</b>	<b>39</b>
<b>Figure 2-17: Ichnology of the foreshore-backshore boundary within Bay Mouth North Foreshore sub-environment.....</b>	<b>42</b>
<b>Figure 2-18: Neoichnology of the foreshore terrace zone along the Recurved Spit sub-environment.....</b>	<b>44</b>

<b>Figure 2-19: Neoichnology of shallow tidal inlet located along the Shoreface-Spitsub-environment.....</b>	<b>46</b>
<b>Figure 2-20: Neoichnology of troughs located within the foreshore terrace along the Shoreface-Spitsub-environment.....</b>	<b>47</b>
<b>Figure 2-21: Surficial neoichnology of the swash zone-surf zone boundary at the base of the foreshore along the Shoreface-Spitsub-environment.....</b>	<b>48</b>
<b>Figure 2-22: Subsurface Neoichnology of the swash zone-surf zone boundary at the base of the foreshore along the Shoreface-Spitsub-environment.....</b>	<b>49</b>
<b>Figure 2-23: Subsurface sedimentary structures of the foreshore along the Shoreface-Spitsub-environment.....</b>	<b>51</b>
<b>Figure 2-24: Neoichnology of the foreshore-backshore boundary along the Shoreface-Spitsub-environment.....</b>	<b>52</b>
<b>Figure 2-25: Schematic Cross Section of the Bay Mouth North Foreshore Sub-Environment (N7-N7').....</b>	<b>53</b>
<b>Figure 2-26: Schematic Cross Section of the Recurved Spit Sub-Environment (N3-N3').....</b>	<b>54</b>
<b>Figure 2-27: Schematic Cross Section of the Shoreface-Spitsub-Environment (N9-N9').....</b>	<b>55</b>

<b>Figure 2-28: Morphology and sedimentology of the sandy ridge zone along the Sand Flat High sub-environment.....</b>	<b>70</b>
<b>Figure 2-29: Subsurface sedimentary structures of the sandy ridge zone along the Sandy Flat High sub-environment.....</b>	<b>71</b>
<b>Figure 2-30: Morphology and sedimentology of the foreshore zone along the Sand Flat High sub-environment.....</b>	<b>73</b>
<b>Figure 2-31: Overall morphology of the Eelgrass Flat Low sub-environment.....</b>	<b>77</b>
<b>Figure 2-32: Morphology of the Isolated Sand Bar sub-environment.....</b>	<b>80</b>
<b>Figure 2-33: Subsurface sedimentary features along the Isolated Sand Bar sub-environment.....</b>	<b>82</b>
<b>Figure 2-34: Biogenic features associated with <i>Neotrypaea californiensis</i>.....</b>	<b>88</b>
<b>Figure 2-35: Neoichnology of the undulatory ridge and furrow sandy tidal flat zone along the Sand Flat High sub-environment.....</b>	<b>93</b>
<b>Figure 2-36: Neoichnology of the foreshore zone along the Sand Flat High sub-environment.....</b>	<b>95</b>



<b>Figure 2-37: Protected channel ridge morphology and neoichnology along the Eelgrass Flat Low sub-environment.....</b>	<b>97</b>
<b>Figure 2-38: Neoichnology of the sandy tidal flat zone along the Eelgrass Flat Low sub-environment.....</b>	<b>99</b>
<b>Figure 2-39: Traces of the lower foreshore-eelgrass flat boundary along the Eelgrass Flat Low sub-environment.....</b>	<b>101</b>
<b>Figure 2-40: Vermiform traces along the hummocky eelgrass zone of the Eelgrass Flat Low sub-environment .....</b>	<b>102</b>
<b>Figure 2-41: Neoichnology of the hummocky eelgrass field along the Eelgrass Flat Low sub-environment.....</b>	<b>104</b>
<b>Figure 2-42: Robust polychaete generated structures near the MLLW mark along the protected channel bank of the Isolated Sand Bar sub-environment.....</b>	<b>106</b>
<b>Figure 2-43: Cross section indicating orientation of tube created by <i>Pista pacifica</i>.....</b>	<b>107</b>
<b>Figure 2-44: Bivalves and associated traces along the Isolated Sand Bar sub-environment .....</b>	<b>109</b>
<b>Figure 2-45: Traces created by <i>Neotrypaea californiensis</i> in the Isolated Sand Bar sub-environment.....</b>	<b>110</b>

<b>Figure 2-46: Meandering surface traces of the Isolated Sand Bar sub-environment.....</b>	<b>112</b>
<b>Figure 2-47: Schematic Cross Section of the Sand Flat High Sub-Environment (N8-N8').....</b>	<b>115</b>
<b>Figure 2-48: Schematic Cross Section of the Eelgrass Flat Low Sub-Environment (N10-N10').....</b>	<b>116</b>
<b>Figure 2-49: Schematic Cross Section of the Protected Channel Sand Flat (N11-N11') and Exposed Channel Sand Flat (N12-N12') Micro-Environments.....</b>	<b>117</b>
<b>Figure 2-50: Schematic Cross Section of the Mixed Channel Sand Flat Micro-Environment (N14-N14').....</b>	<b>118</b>
<b>Figure 2-51: Morphology of the tidal ridge next to the main channel along the Sandy Eelgrass Field sub-environment.....</b>	<b>136</b>
<b>Figure 2-52: Morphology of the eelgrass field zone along the Sandy Eelgrass Field sub-environment.....</b>	<b>138</b>
<b>Figure 2-53: Morphology of the tidal creek and tidal ridge along the Sand Flat High-Tidal Creek sub-environment.....</b>	<b>142</b>
<b>Figure 2-54: Morphology of the sand flat high zone along the Tidal Creek sub-environment.....</b>	<b>145</b>

<b>Figure 2-55: Tidal creek morphology of the Tidal Creek sub-environment.....</b>	<b>146</b>
<b>Figure 2-56: Morphology of the Sandy Tidal Ridge and Furrow sub-environment.....</b>	<b>148</b>
<b>Figure 2-57: Mollusc traces along the Sandy Eelgrass Field sub-environment .....</b>	<b>153</b>
<b>Figure 2-58: Vermiform traces along the Sandy Eelgrass Field sub-environment .....</b>	<b>159</b>
<b>Figure 2-59: Morphology and traces associated with the sand flat high zone along the Sand Flat High-Tidal Creek sub-environment .....</b>	<b>161</b>
<b>Figure 2-60: Neoichnology of the Tidal Creek sub-environment .....</b>	<b>163</b>
<b>Figure 2-61: Neoichnology of the sandy flat low zone along the Sandy Tidal Flat Ridge and Furrow sub-environment.....</b>	<b>165</b>
<b>Figure 2-62: Neoichnology of the sandy flat high zone along the Sandy Tidal Flat Ridge and Furrow sub-environment .....</b>	<b>167</b>
<b>Figure 2-63: Neoichnology of the tidal creek and firmground zones along the Sandy Tidal Flat Ridge and Furrow sub-environment.....</b>	<b>168</b>
<b>Figure 2-64: Schematic Cross Section of the Sandy Eelgrass Field Sub-Environment (N1-N1').....</b>	<b>170</b>

<b>Figure 2-65: Schematic Cross Section of the Sand Flat High-Tidal Creek Sub-Environment (N2-N2')</b> .....	<b>171</b>
<b>Figure 2-66: Schematic Cross Section of the Tidal Creek Sub-Environment (N5-N5')</b> .....	<b>172</b>
<b>Figure 2-67: Schematic Cross Section of the Sandy Tidal Flat Ridge and Furrow Sub-Environment and Firmground Sub-Environment (N6-N6')</b> .....	<b>173</b>
<b>Figure 2-68: Schematic Block Diagram of the Exposed Shoreface-Spit Bay Region</b> .....	<b>194</b>
<b>Figure 2-69: Schematic Block Diagram of the Outer Sheltered Sandy Tidal Flat Bay Region</b> .....	<b>197</b>
<b>Figure 2-70: Schematic Block Diagram of the Outer-Middle Sandy Tidal Flat Bay Region</b> .....	<b>201</b>
<b>Figure 2-71: Summary diagram comparing sedimentary, physico-chemical and biogenic features of each bay region</b> .....	<b>205</b>
<b>Figure 3-1: Netarts Bay, Oregon study area location maps</b> .....	<b>234</b>
<b>Figure 3-2: Sedimentological features of the exhumed compacted peaty-clay firmground</b> .....	<b>239</b>

<b>Figure 3-3: Neoichnological characteristics of the exhumed compacted peaty-clay firmground.....</b>	<b>240</b>
<b>Figure 3-4: Morphological and sedimentological features of the exhumed compacted silty-sand firmground.....</b>	<b>244</b>
<b>Figure 3-5: Neoichnological characteristics of the exhumed compacted silty-sand firmground.....</b>	<b>246</b>
<b>Figure 3-6: Morphological, sedimentological and neoichnological features of the modern stiffgrounds.....</b>	<b>249</b>
<b>Figure 3-7: Sedimentological and neoichnological features of the softground veneer substrate.....</b>	<b>252</b>
<b>Figure 3-8: Vermiform organisms and surface trails of the softground veneer substrate.....</b>	<b>253</b>
<b>Figure 3-9: Neoichnological elements of the woodground substrate.....</b>	<b>256</b>
<b>Figure 3-10: Schematic diagram of the study area.....</b>	<b>259</b>

## List of Symbols

### Chapter 2






#### Legend for Neoichnology Summary Tables (Tables 2-2, 2-4, 2-6)

? = Plausible, but not certain

\* Amongst other mentioned traits this one is most dominant







#### Schematic Cross Section Key

##### Burrow Density

-  Large open burrow (>/equal to 2mm)
-  Small open burrow (<2mm)
-  Woodground Trace
-  Large meandering surface trace
-  Small meandering surface trace

5 + 1 = 5 large diameter and 1 large meandering surface trace per 50cm<sup>2</sup> area.

##### Grain Size Bar

-  Upper medium sand to granule
-  Lower medium sand
-  Upper fine sand
-  Lower fine sand
-  Upper very fine sand to silt/clay
-  Clayey-peat firmground layer

% TOC = 0.30 (number in red font)

Relative Hydraulic  
Energy Levels

















Sedimentation  
Rate (Inferred)



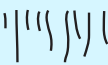














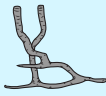

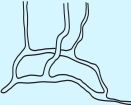


## List of Symbols (continued)

### Symbols on Cross Section

#### Physical Structures

	Wavy laminae		Sediment micro-faulting
	Unidirectional ripples		Sediment deformation
	Bidirectional ripples		Clay or organic clast lenses/ laminae
	Climbing ripple		Large (>1cm) Sporadic clay or organic clasts
	Low angle cross stratification		Thin Fragmented Shell Debris Layer(s)
	Planar cross stratification		Pebble lag
	Trough cross stratification		
	Planar laminae		

#### Biogenic Structures and Organisms

	<i>Trichichnus</i> / <i>Skolithos</i> -like assemblage (high density)		<i>Planolites</i> -like traces
	<i>Trichichnus</i> / <i>Skolithos</i> -like assemblage (low density)		<i>Palaeophycus</i> -like traces
	<i>Skolithos</i> -like trace		Indeterminate horizontal trace
	<i>Arenicolites</i> -like traces		<i>Cylindrichnus</i> -like trace (Terebellid generated)
	<i>Skolithos</i> -like traces		<i>Arenicolites</i> -like trace ( <i>Abarenicola pacifica</i> specific)
	Diminutive <i>Pylonichnus</i> -like traces		Lined <i>Skolithos</i> -like sand or parchment tube(s)
	<i>Polykladichnus</i> -like burrow network		Lined <i>Skolithos</i> -like robust tubes of <i>Pista pacifica</i>
	<i>Polykladichnus</i> -like trace		Lined <i>Thalassinoides</i> -like trace ( <i>Neotrypaea</i> generated)
	<i>Macaronichnus</i> -like mottled traces		<i>Thalassinoides</i> -like trace ( <i>Neotrypaea</i> generated)
	<i>Thalassinoides</i> ( <i>Upogebia</i> generated)		
	<i>Pylonichnus</i> -like trace		

## List of Symbols (continued 2)



Hermit crab



*Macoma balthica/inquinata*



*Olivella biplicata*



*Macoma nasuta*



*Emerita analoga*



*Mya arenaria*



Burrowing  
Holothurian



*Clinocardium nuttallii*



*Nephtys* sp.



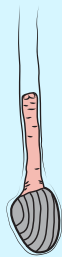
*Protothaca staminea*



Eelgrass



*Macoma secta*



Deep burrowing bivalves  
(*Tresus* sp., *Saxidomus gigantea*)



*Nuttallia obscurata*



























## List of Symbols (continued 3)











### Chapter 3

### Legend for Figure 3-10

#### Comparative Trace and Tracemaker Legend for Figure 3-10

	<i>Caulostrepis</i>		Lined- <i>Skolithos</i> / possible <i>Cylindrichnus</i>
	<i>Palaeophycus</i>		<i>Ppsilon</i>
	<i>Gyrolithes</i>		<i>Rhizocorallium</i>
	<i>Trypanites</i>		<i>Thalassinoides</i> ( <i>Upogebia</i> specific)
	<i>Planolites</i>		<i>Hemigrapsus</i> sp.
	<i>Meandropolydora</i>		<i>Teredolites</i>
	<i>Nereis</i> sp.		<i>Polykladichnus</i>
	<i>Gastrochaenolites</i>		<i>Pagurus</i> sp.
	<i>Arenicolites</i>		<i>Nephtys</i> sp.
	<i>Arenicolites</i> ( <i>Abarenicola pacifica</i> specific)		<i>Diplocraterion</i>
	<i>Skolithos/Trichichnus</i>		<i>Olivella biplicata</i>
	Open sub-vertical to horizontal trace		Salt marsh grass

#### Sedimentological Legend for Figure 3-10

	Woodground		Unknown Subsurface Strata
	Surficial Softground Veneer		Salt Marsh Deposit
	Exhumed Compacted Silty-Sand Firmground		Exhumed Compacted Peat-Clay Firmground
	Modern Silty Sand to Clay Stiffground		Inferred Peat-Clay Firmground Layer
	Iron oxide layer in illuviated clays of northern stiffground		Inferred Bottom of Surficial Peat-Clay Firmground

## **CHAPTER 1: INTRODUCTION**

Neoichnological studies are important as they can greatly aid in the endeavour to decipher ancient sedimentary strata. Such studies observe how modern organisms create various biogenic structures in response to an array of physicochemical parameters. Such parameters include substrate consistency, sediment cohesiveness, food resource availability, sedimentation rate, salinity fluctuations, oxygen content, water turbidity, temperature, and desiccation (Gingras et al., 2007; MacEachern et al., 2010). Since these parameters are essentially defined by the depositional geometry, bathymetry and hydraulic energy of the surrounding environment, the study of how organisms respond to such parameters help identify the nature of the depositional environments these traces were created in (Gingras et al., 2007). These traces are therefore ultimately very useful interpretational elements contained within ensuing preserved sedimentary strata. Specific modern sedimentological investigations and related observations of animal behavioural response to varying hydraulic energy levels and associated sedimentation rates are thus important to study. In the majority of Netarts Bay a relatively constant sandy substrate in an intertidal marine environment is ideal for the study of the effects of hydraulic energy and associated sedimentation rate on the burrowing behaviour of organisms. Additionally, the intermingled firmground, woodground, stiffground, and softground areas along the eastern margin of the bay are ideal locations for studying the distribution of traces on the basis of specific substrate type and consistency.

Chapter 2 focuses on the role of varying hydraulic energy levels and associated sedimentation rate on organism behaviour and ensuing trace formation as well as distribution. Hydraulic energy and sedimentation rate are inter-related stresses affecting the burrowing behaviour of organisms, where sedimentation rate is the most important factor affecting the rates of bioturbation most directly (Dashtgard, 2011; Gingras et al., 2011). Organisms of

Netarts Bay are subject to high hydraulic energy levels in areas such as wave exposed beaches and high velocity tidal channels or flats. Dashtgard (2011) indicates that higher hydraulic energy levels lead to greater variation in sedimentation rate (sediment aggradation) and denudation rate (sediment degradation). If sedimentation rate occurs at a sporadic or episodic rate then a wide range of bioturbation rates can occur, resulting in heterogeneously distributed traces (Wheatcroft, 1990; Pollard et al., 1993; Dafoe et al., 2008; Gingras et al., 2008; Dashtgard, 2011). In such dynamic, high energy settings food is usually held in suspension and an array of suspension feeders as well as carnivores are usually present that characteristically define the *Skolithos* Ichnofacies (Seilacher, 1967; MacEachern et al., 2007). Only in the Exposed Shoreface-Spit region are traces directly attributable to a *Skolithos* Ichnofacies assemblage, whereas in other parts of the bay assemblages may be similar to the *Skolithos* Ichnofacies assemblage but not attributable as they make up their own distinct assemblage of traces. In the protected tidal flats and eelgrass fields of Netarts Bay organisms are typically subject to lower hydraulic energy levels and lower rates of sedimentation. In these lower energy areas a slow and steady accumulation of fine grained sediments typically occur allowing organisms that deposit feed to construct semi-permanent to permanent feeding, as well as dwelling structures, leading to a trace assemblage that may resemble the *Cruziana* Ichnofacies (Seilacher, 1967; Pemberton and Frey, 1984; MacEachern et al., 2007). However, the assemblage itself is not attributable to a *Cruziana* Ichnofacies assemblage, but instead displays its own similar but separate trace assemblage. Higher rates of bioturbation occur in conjunction with homogeneously distributed traces in these lower energy settings since sedimentation rate is relatively constant, allowing organisms a longer period of time to colonize the substrate (Wheatcroft, 1990; Pollard et al., 1993; Dafoe et al., 2008; Gingras et al., 2008; Dashtgard, 2011).

Chapter 3 discusses trace genesis in relation to organismal behaviour in an environment consisting of firmground, woodground, stiffground and

softground substrates. Gingras et al. (2007) state that sediment consistency and texture are the main controls affecting animal burrowing behaviour, therefore these various substrate types were studied to ascertain the ecological and stratigraphic importance of exhumed firmgrounds, associated woodgrounds and modern stiffgrounds. Traces associated with specific substrate types can be attributed to a particular ichnofacies assemblage, in the case of firmground substrates namely to the *Glossifungites* Ichnofacies assemblage and in the case of woodground substrates namely to the *Teredolites*-Ichnofacies assemblage. Robust, sharp walled, unlined and passively filled traces in unlithified marine substrate typify the *Glossifungites* Ichnofacies (Seilacher, 1967; Frey and Seilacher, 1980; Pemberton and Frey, 1985; MacEachern et al., 1992; MacEachern et al., 2007). These distinct traces can form along surfaces that may be of stratigraphic importance if they have appreciable lateral extent and can be mapped (MacEachern et al., 1992; Pemberton and MacEachern 1995; MacEachern et al., 2007). In contrast, woody *in situ* material in a marine to marginal marine setting displaying traces akin to *Teredolites* typifies the *Teredolites* Ichnofacies (Bromley et al., 1984; Savrda, 1991). In the rock record the *Teredolites* Ichnofacies assemblage is usually monopolized by *Teredolites*-like traces likely due to erosional effects; however in the modern a vast array of traces are typically found associated together (Gingras et al., 2004; MacEachern et al., 2007). Pleistocene marine terrace deposits exposed along the eastern margins of Netarts Bay retaining *in situ* tree stumps was therefore the ideal place to study trace associations within a variety of interrelated substrate types.

In summary, this thesis focuses on studying the effects of varying hydraulic energy levels and associated sedimentation rate on trace distribution along an exposed to protected outer fully marine bay system, specifically, by studying the sedimentological and biogenic aspects of the three main bay regions at Netarts Bay. Additionally, this thesis also assesses the nature of trace assemblages associated with softground, stiffground, firmground and

woodground substrate occurrences in a modern intertidal marine setting. The sedimentological and neoichnological data obtained particular to each substrate will help ascertain the overall ecological and stratigraphic importance of these substrates.

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## **CHAPTER 2: SEDIMENTOLOGY AND NEOICHOLOGY IN RELATION TO VARYING HYDRAULIC ENERGY LEVELS AND ASSOCIATED SEDIMENTATION RATES IN THE OUTER TO EXPOSED REGIONS OF NETARTS BAY, OREGON**

### **INTRODUCTION**

Ichnology, the study of fossilized animal traces (tracks, trails, and burrows), is an essential analytical field that aids in the interpretation of ancient sedimentary successions. Unravelling the significance of trace fossil assemblages depends heavily upon neoichnology, or more specifically process ichnology. Process ichnological studies observe biogenic structures created by modern organisms in response to a variety of physicochemical parameters to further our understanding of similar structures preserved in the rock record (Gingras et al., 2011). Historically, interpretations of animal-sediment interactions, represented by trace fossils, have drawn strongly from examples in the rock-record. Sedimentological investigations based on observations of animal behavioural response to varying hydraulic energy levels and associated sedimentation rate is lacking, and yet such investigations are the only way to clearly link biological behaviour with biogenic structures.

Organisms subjected to high hydraulic energy are usually exposed to changes in tides throughout the day and/or to wave dynamics acting on the shoreface. If hydraulic energy is high then there is a greater chance for substrate erosion as well as sediment aggradation and accumulation of coarser sediment (Dashtgard, 2011). If hydraulic energy is low, then there tends to be very slow, but steady accumulation of finer grained sediment. Trace assemblages commonly ascribed, or similar, to the *Cruziana* Ichnofacies typically display feeding structures and permanent dwellings of inferred deposit feeders which are characteristic of lower energy ambient depositional settings (Seilacher, 1967; Pemberton and Frey, 1984; MacEachern et al., 2007). On the other hand, the *Skolithos* Ichnofacies suite or similarly related suites, such as those that occur in this study, characteristically records activities

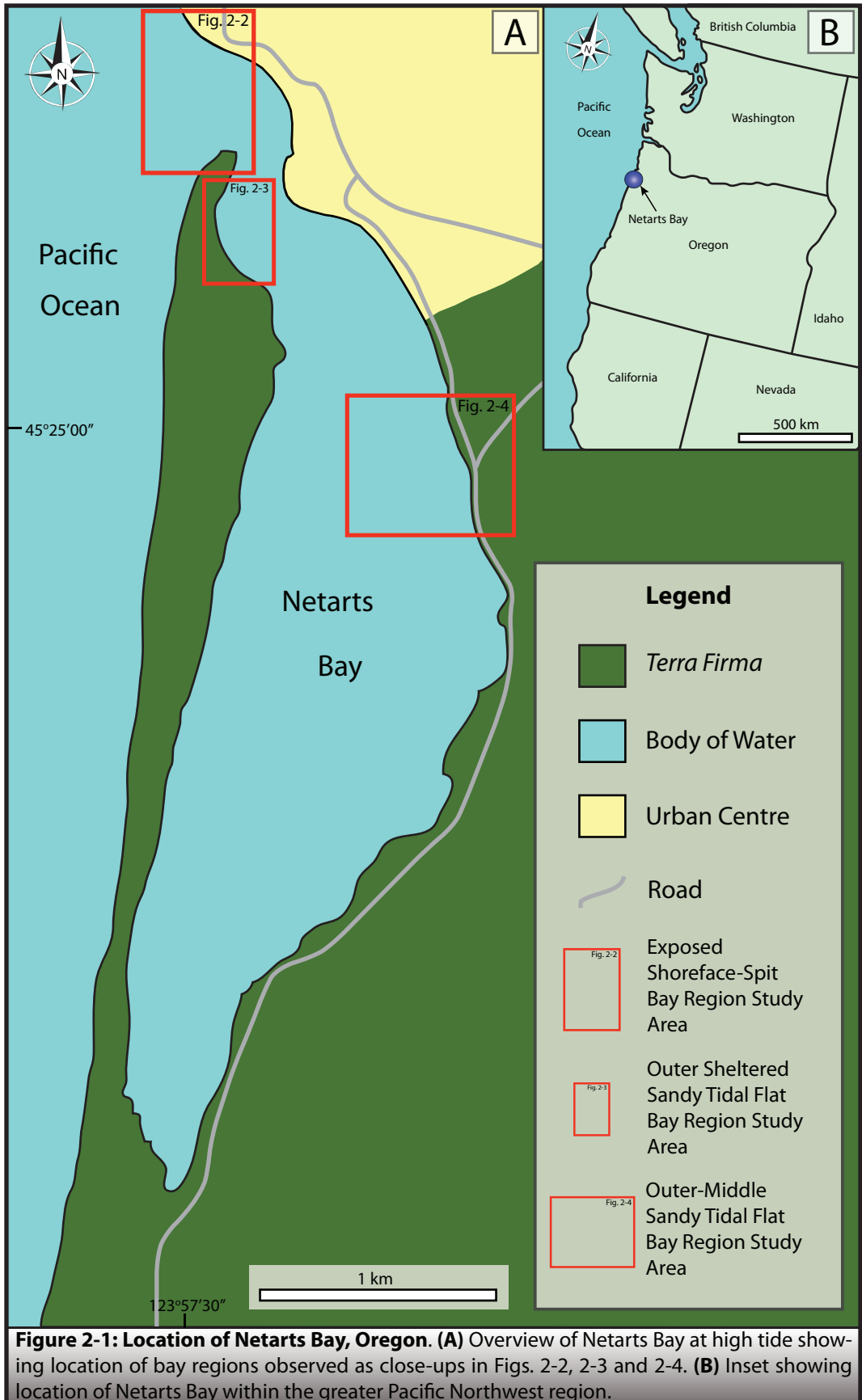


associated with suspension feeders and carnivores in dynamic, high energy depositional settings where shifting sandy substrates, clean water columns, and abundant suspended food dominate (Seilacher, 1967; MacEachern et al., 2007).

The outer- middle to outer regions of Netarts Bay, as well as the exposed foreshore along the spit, provide a *sui generis* case study into the effects of varying hydraulic energy levels on sedimentation rate within an exposed to protected fully marine bay system. This chapter focuses on integrating sedimentological and biogenic aspects of 3 main bay regions, as well as the various sub-environments that comprise them, to delineate the effects of hydraulic energy levels and associated sedimentation rate on organismal distribution. The Exposed Shoreface-Spiti bay region, residing along the open ocean reaches around the recurved spit, is comprised of three sub-environments: 1) Bay Mouth North Foreshore; 2) Recurved Spit; and 3) Shoreface-Spiti. Bayward of the main tidal inlet along the northern tip of the spit is the Outer Sheltered Sandy Tidal Flat bay region comprised of three sub-environments: 1) Sand Flat High; 2) Eelgrass Flat Low; and 3) Isolated Sand Bar. Finally, along the middle to upper eastern margins of the bay, are the sand flats, tidal creeks and firmground areas of the Outer-Middle Sandy Tidal Flat bay region comprised of five sub-environments: 1) Sandy Eelgrass Field; 2) Sand Flat High-Tidal Creek; 3) Tidal Creek; 4) Sandy Tidal Flat Ridge and Furrow; and 5) Firmground.

## **STUDY AREA**

Netarts Bay, Oregon is located approximately 90km south of the Columbia River mouth along the north Oregon coast, between the headlands of Cape Meares to the north and Cape Lookout to the south (Fig. 2-1). It is indeed a bay in the classical sense where Ricketts et al. (1985) state that “a bay is simply a quiet arm of the sea”. Specifically, Netarts Bay is a well mixed, wave-dominated, tidally influenced, micro- to meso-tidal, essentially fully marine



temperate bay occupying an indent amongst the northwest Pacific coastline (Glanzman et al., 1971; Hunger, 1966). The 6km long NNE trending Netarts Sand spit varies in width between approximately 0.12-1.2km where it acts as a barrier protecting the bay from the full onslaught of the mighty Pacific Ocean (Bonacker et al., 1979). In the past the foredune was breached, in the narrowest southern portion of the spit, by several storms although in the last 70 years this type of event has not occurred, likely due to the planting of European beach grass (*Ammophila arenaria*) that has caused stabilization of an otherwise bare dune (Bonacker et al., 1979). During the summer month of July air temperature averages around 17°C with precipitation accumulations typically around 5cm, while in the winter month of January air temperature is generally around 7°C with an average precipitation of approximately 35cm (Hunger, 1966; Shabica et al., 1976).

The bay is approximately 9.4km<sup>2</sup> with one main narrow tidal channel approximately 100m wide entering the bay at the northern end of the spit (Glanzman et al., 1971). Smaller secondary tidal channels also meander between the large sandy tidal flats. The rest of the bay is therefore occupied by vast, mainly sandy tidal flats with muddy silt flats in the far south which are all exposed at low tide. Glanzman et al. (1971) indicate that there are strong horizontal velocity gradients within tidal channels where most of the water is transported, while the tidal flats act as storage areas that may drain via small tidal creeks in a direction almost perpendicular to that of main channel flow direction. The entire bay watershed is quite small being only about 41km<sup>2</sup>, having 12-16 intermittent creeks that feed the bay (Glanzman et al., 1971). Occasionally there is enough heavy rain in winter months to temporarily cause the salinity to drop; however the rapid flushing rate of 1.34 tidal cycles means that any freshwater input into the bay is flushed out every day and replaced by fresh marine waters (Shabica et al., 1976). Dominant swell directions during both summer and winter months are generally from the NW-W direction, while the overall seas generally come in from the SW-SSE in winter and N-NW in

summer (Glanzman et al., 1971; Peterson et al., 1986). Wind generated waves within the bay are typically around 0.4m in height but can attain heights of up to 1.5m under very strong consistently windy conditions at high tide (Glanzman et al., 1971).

### **Geologic Setting**

Geologically speaking, a small syncline developed in and around the Netarts Bay area during the late Oligocene (approximately 25 million years ago) where sediments eroded from the Coast Range were subsequently deposited in this shallow coastal region (Shabica et al., 1976; Bonacker et al., 1979). Accumulation of this sandstone became the Astoria Formation which underlies most of the Netarts Bay area (Shabica et al., 1976; Bonacker et al., 1979). The resistant basaltic headlands of Cape Meares and Cape Lookout were extruded 15 to 20 million years ago, during the same time the Astoria Formation was accumulating on the sea floor and around the time basalts of the Columbia River Gorge were being extruded (Shabica et al., 1976; Bonacker et al., 1979). As the area was uplifted differential erosion occurred where the soft underlying sandstones of the Astoria Formation were eroded much faster than the resistant basaltic headlands thus creating a re-entrant along the coastline where Netarts Bay now lies (Hunger, 1966; Shabica et al., 1976; Bonacker et al., 1979). Wave, tidal and aeolian forces formed the sand spit, while it is thought that over time various storm events led to the formation of the main channel inlet in the northern portion of the bay (Shabica et al., 1976).

Heavy mineral sands that appear brown-green to blue-black in colour are regularly seen as darker laminae within otherwise lighter beige quartz and feldspar rich beach sands. They are prominent features especially along the foreshore-backshore boundary along Netarts Bay spit and upper intertidal flat-supratidal boundary within the bay. This accumulation of heavy mineral sand laminae along these boundaries was readily observed by Peterson et al. (1986) along other Oregon beaches. Accumulations of these heavy mineral sands are

also readily observed on ripple crests throughout the bay, especially within the higher energy outer reaches. Peterson et al. (1986) also noted that the heavy mineral sands were denser and smaller in diameter compared to the lighter beach sand. XRD analysis performed at the University of Alberta was able to distinguish quartz, anorthite, albite, augite, an undetermined clinopyroxene, rutile, magnetite, hematite and ilmenite as minerals within the beach sands. The least dense and largest beige coloured sands are likely quartz, anorthite and albite, while the medium density and size darker brown-green sands are likely composed of augite and an undetermined clinopyroxene. The blue-black sands, which are the densest and smallest amongst the three, likely consist of ilmenite, hematite, rutile and magnetite. This composition of beach sands is also comparable to what Peterson et al. (1986) observed, although there were a few minor differences likely attributed to slightly different sources. Ultimately the heavy mineral placer sand deposits were derived from the Coast Range Mountains and later basaltic deposits, both of which have been eroded over time ending up on Oregon coast beaches via wave, tide and riverine activity (Peterson et al., 1986).

### **Modern History**

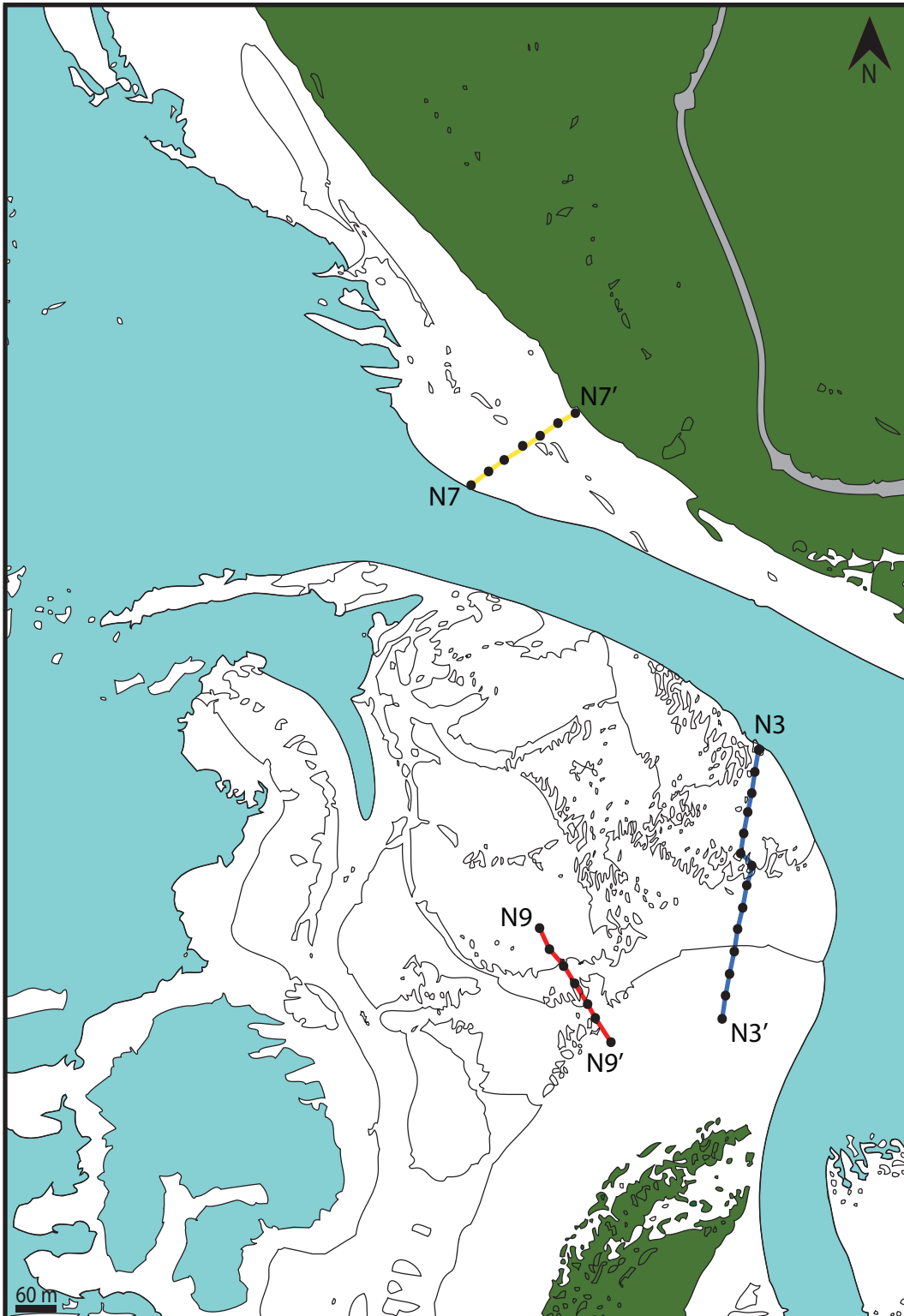
Historically, the Netarts Bay area was first settled by the Tillamook people around 1400AD consisting of various tribes that spoke Tillamook, a language belonging to the Salish linguistic group (Shabica et al., 1976; Bonacker et al., 1979). They named this area "Ne to at" meaning "near the water" and thus the anglicized version "Netart" was then created to name the bay (Shabica et al., 1976). Beginning around 1775 limited trade began between Tillamook tribes and Europeans (Bonacker et al., 1979). It was not until 1865 that Europeans began actively settling the area after the Homestead Act was passed in 1862 before which the first formal government survey of Netarts Bay was conducted in 1856 (Bonacker et al., 1979).

## **METHODOLOGY**

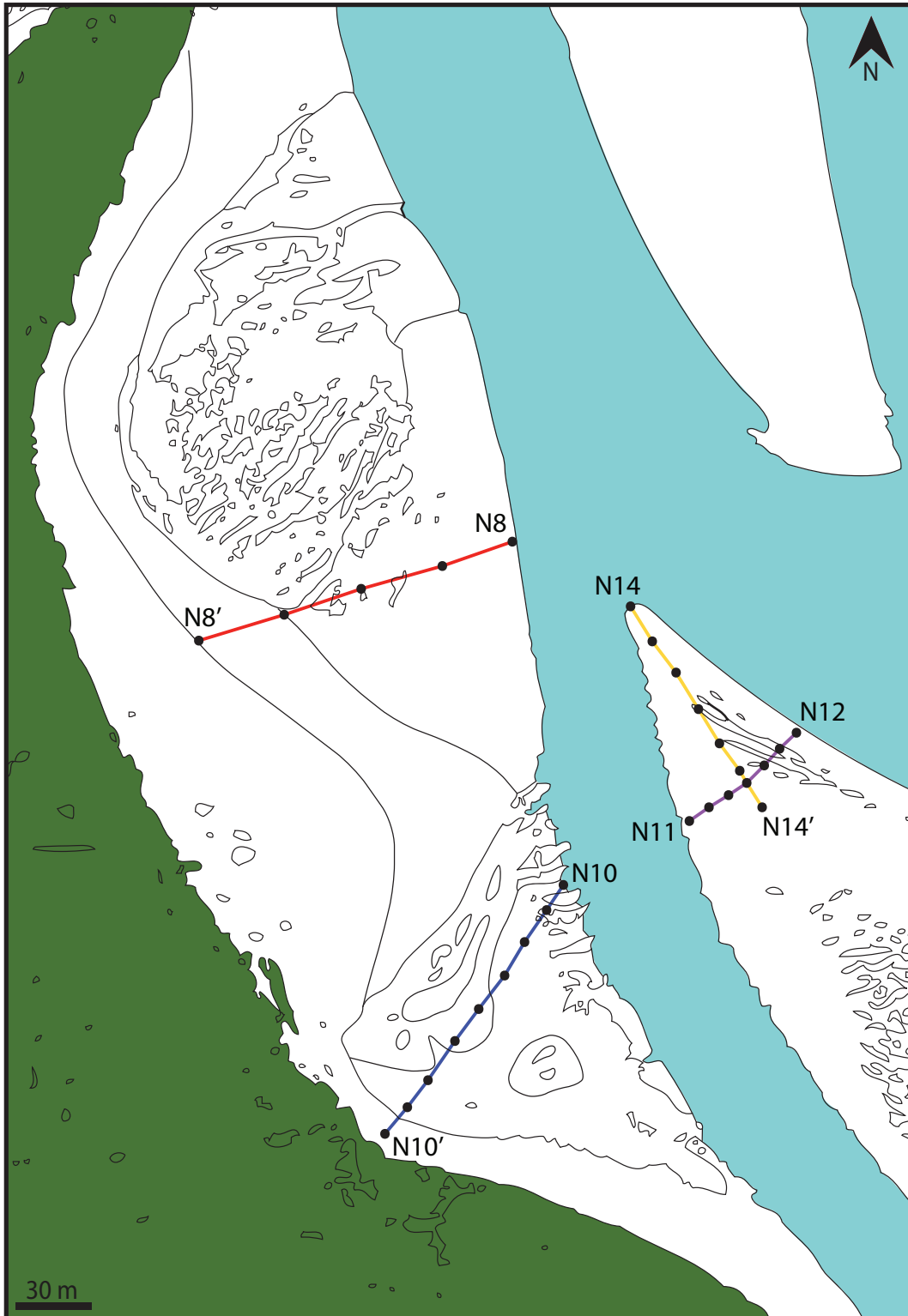
Research was conducted along the outer-middle, outer and exposed spit-beach regions of Netarts Bay during the summer of 2012. Access to study sites was accomplished via inflatable boat fitted with an outboard motor for the outer tidal flat and exposed spit areas and by foot for one exposed beach location and the entire outer-middle tidal flat area. The three sub-environments studied along the exposed spit-beach areas were collectively termed the Exposed Shoreface-Spits bay region (Fig. 2-2). Continually, the three sub-environments studied along the outer areas were collectively termed the Outer Sheltered Sandy Tidal Flat bay region (Fig. 2-3). Finally, the five sub-environments of the outer-middle areas were collectively termed the Outer-Middle Sandy Tidal Flat bay region (Fig. 2-4). In total, three transects were conducted across the Exposed Shoreface-Spits bay region, four across the Outer Sheltered Sandy Tidal Flat bay region and four across the Outer-Middle Sandy Tidal flat bay region.

Along each transect a measuring tape was laid out to record distances between stations and the GPS coordinates of each station point were also recorded via a Garmin eTrek 20 GPS unit. Most transects were conducted perpendicular to shore with two short sections conducted perpendicular to the long axis of tidal channels or creeks. Detailed surface and subsurface descriptions of biogenic and sedimentary structures were recorded in a notebook and subsequent photos were also taken with an Olympus Stylus Tough series camera. Sample organisms obtained were preserved in glass jars using an 80% ethyl alcohol solution and subsequently stored at the University of Alberta for further analysis and classification of organisms. Salinity measurements were obtained using a Lohand LH-T28 salinity meter.

Trenches were manually dug via shovel to a depth of approximately 35-40cm. Sediment samples, each 350-500 grams in size, were also taken from the upper 5cm of sediment by hand and from sediment 35-40cm below the surface via can corer from each station location. At select stations boxcores with

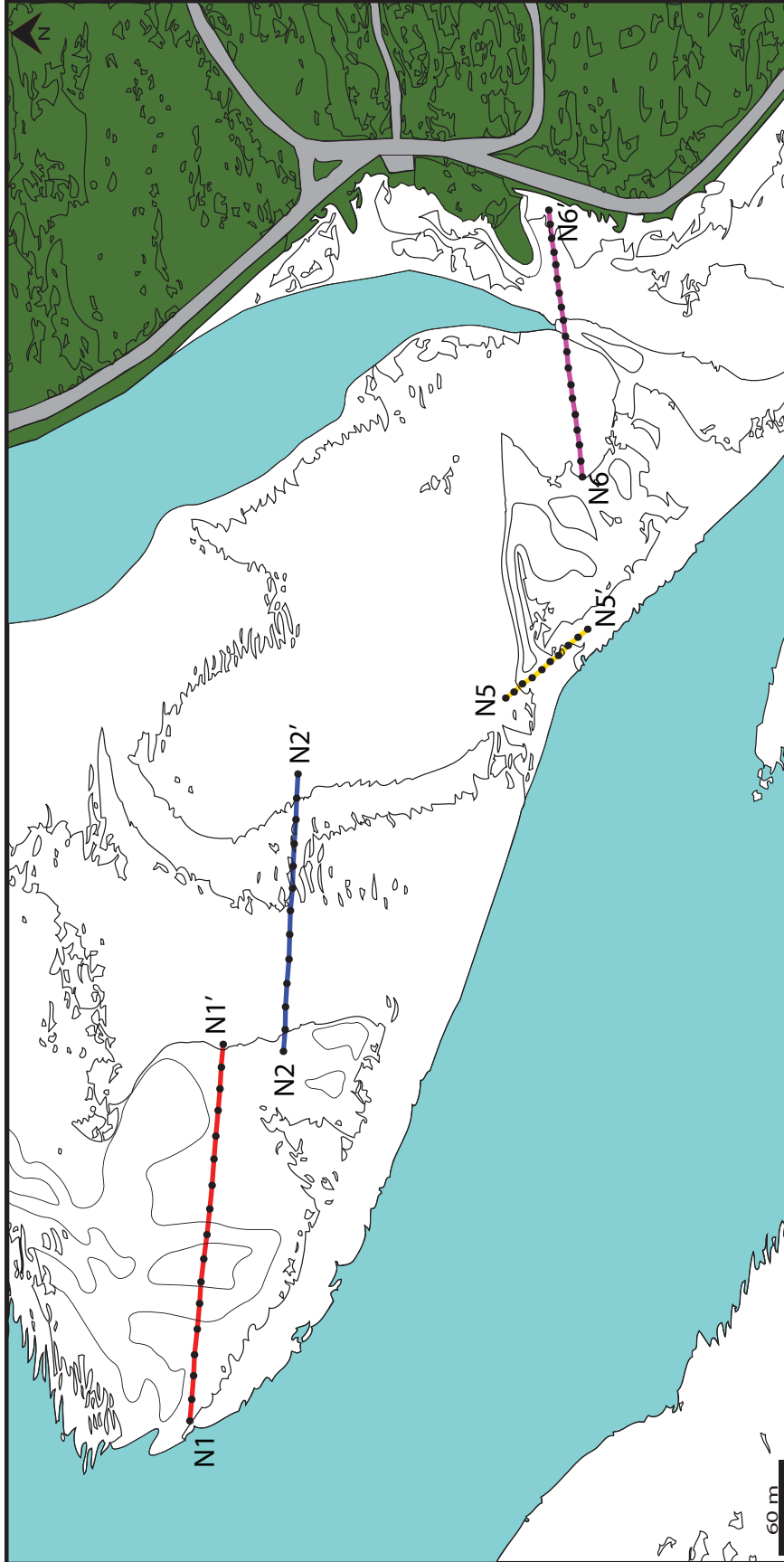


**Figure 2-2: Exposed Shoreface-Spit bay region study area and associated transects of the various sub-environments.** The Bay Mouth North Foreshore sub-environment is represented by N7-N7' (schematic fig. 2-25). The Recurved Spit sub-environment is represented by N3-N3' (schematic fig. 2-26). The Shoreface-Spit sub-environment is represented by N9-N9' (schematic fig. 2-27).



**Figure 2-3: Outer Sheltered Sandy Tidal Flat bay region study area and associated transects of the various sub-environments.** The Sand Flat High sub-environment is represented by N8-N8' (schematic fig. 2-47). The Eelgrass Flat Low sub-environment is represented by N10-N10' (schematic fig. 2-48). The Isolated Sand Bar sub-environment is represented by N11-N12 and N14-N14' (schematic figs. 2-49, 2-50, respectively).





**Figure 2-4: Outer-Middle Sandy Tidal Flat bay region study area and associated transects of the various sub-environments.** The Sandy Eelgrass Field sub-environment is represented by N1-N1' (schematic fig. 2-64). The Sandy Flat High-Tidal Creek sub-environment is represented by N2-N2' (schematic fig. 2-65). The Tidal Creek sub-environment is represented by N5-N5' (schematic fig. 2-66). The Sandy Tidal Flat Ridge and Furrow and Firmground sub-environments are represented by N6-N6' (schematic fig. 2-67).

dimensions 30cm x 21cm x 6cm were collected usually in pairs at right angles to each other, one parallel to transect line and one perpendicular to transect line. PVC (polyvinyl chloride) pipe core measuring 50cm long were also taken at select locations. Sediment peels of boxcore samples were performed in the field for further analysis back at the University of Alberta. To obtain the sediment peel 5mL of MEKP (methyl ethyl ketone peroxide) was mixed with 300mL of epoxy resin. This mixture was slowly poured over cheesecloth resting on the sediment surface within the boxcore where it was then left to dry for 24 hours before peeling. After peeling the peels were shipped back to the University of Alberta where they underwent X-ray analysis using a Soyee SY-31-100P portable X-ray machine with associated digital imaging software. PVC core pipe was also shipped back to the University of Alberta where it was cut in half using a saw allowing one half to be analyzed via X-rays in 30cm x 7cm x 2.5cm x-ray trays, while the other half was stored as core demonstration material.

Sediment samples obtained were shipped back to the University of Alberta for grain size analysis. During initial stages of analysis sediment was dried for 24 hours at 110°C in a Quincy Lab Incorporated Model 21-250 Bench Oven. Each sediment sample was then lightly ground for three minutes using mortar and pestle to separate grain clumps. A portion of the dried sediment sample was set aside for TOC (total organic carbon) analysis while the remaining amount was then weighed for an initial grain size using a Mettler AE100 scale. The grain size analysis sample was then added to a stack of Fisher Scientific test sieves ranging from US Std. No. 10 to US Std. No. 230. The sieve stack was shaken in a Hostein Model RX-29 scientific sieve shaker for 10 minutes. Each sieve receiver was then weighed using the previously mentioned Mettler scale and recorded under its respective grain size column in an excel spreadsheet. The process of drying, initial weighing, sieve shaking, and sieve receiver weighing was repeated for each sediment sample obtained. TOC analysis was conducted on pre-dried samples as previously mentioned

where the sediment sample was then added to a small porcelain crucible for initial weight recording. After which the sample and porcelain crucible were put inside an SLE Omega CN76000 oven set at 550°C for 12 hours where a loss on ignition of organic carbon took place. After 12 hours the sediment and crucible were removed from the oven and left to cool to room temperature before final weight was recorded. Beach sand was analyzed via XRD (X-ray diffraction) at the University of Alberta to delineate the specific minerals making up the three major types of beach sands observed.

## **EXPOSED SHOREFACE-SPIT BAY REGION DESCRIPTION AND RESULTS**

### **Morphological and Sedimentological Features**

#### ***Bay Mouth North Foreshore Sub-Environment***

The area between the MLLW (Mean Lower Low Water) mark and the gentle shoreward slope of the tidal creek is the foreshore terrace zone, followed by the swash zone of the foreshore and then the backshore zone. The overall morphological aspects of the sub-environment are shown in Figure (2-5A,B) and summarized in Table 2-1. Along the foreshore terrace zone, smooth to slightly rippled sands were present at the surface from MLLW extending 25m shoreward. Linear surface features were also present, with the lineation oriented approximately perpendicular to shoreline and parallel to the main channel bay mouth as well as to the swashing direction (Fig. 2-6A). Small ripples once again became more pronounced over a distance of 15m before grading into noticeably larger ripples that continued shoreward for an additional 20m (Fig. 2-6B). Ripples then became smaller again continuing this pattern up until the prominent tidal creek. Ripples were dominantly sinuous crested occasionally grading into linguoid. Ripple ridges were generally oriented parallel to shoreline, except in the tidal creek where ripple ridges were oriented perpendicular to the shoreline. The tidal creek was oriented parallel to shoreline with the asymmetrical ripples within the tidal creek indicating the most recent flow within the creek to be towards the main channel bay mouth



**Figure 2-5: Morphological photographs of the Bay Mouth North Foreshore sub-environment.** (A) View from near the MLLW mark looking NE towards the shoreline. A dominantly featureless surface with linear surface features oriented perpendicular to shoreline and faint ripple marks observed. (B) View from just seaward of the foreshore-backshore boundary looking towards the SSE. The foreshore face and pebbly tidal creek with logs are the prominent foreground features of the photograph with the spit an obvious background feature across the main channel bay mouth. Shovel (~1.1m) and person (1.83m) for scale.

Table 2-1: Summary of Sedimentological and Physico-Chemical Characteristics of the Exposed Shoreface-Spit Bay Region						
Sub-Environment	Sedimentological and Physico-Chemical Properties					
	Common Sedimentary Features	Sediment Analysis	TOC (%)	Salinity (PSU)	Average Overall Grain Size (wt%)	
<b>Recurved Spit</b>	<b>Foreshore terrace zone:</b> planar surfaces (w/ parting lineation) occasionally observed. Sinuous to lunate combined tidal current-wave generated subaqueous dune forms dominate with superimposed asymmetric sinuous to linguoid ripples. <b>Swash zone:</b> planar surface w/ inclined planar subsurface laminae. Wavy laminae occasionally observed in uppermost sediment at the base of the swash zone. Concentration of heavy mineral sand laminae increase shoreward. <b>Foreshore-backshore zone:</b> heavy mineral defined planar laminae. Sinuous aeolian formed ripples in the backshore. Bioturbation non-evident to sparse across sub-environment.	Very well sorted, near symmetrical, platykurtic, dominantly lower medium grained sand (0.29φ, -0.04Sk, 0.82K, 2.01M)	Lowest Value (0.08) Highest Value (0.25) Top Average (0.16) Bottom Average (0.17) <b>Overall Average (0.16)</b>	--	Upper medium grained sand to granule (2.2) Lower medium grained sand (43.6) Upper fine grained sand (49.9) Lower fine grained sand (3.9) Upper very fine grained sand to silt/clay (0.4)	
<b>Bay Mouth North Foreshore</b>	<b>Foreshore terrace zone:</b> planar surface (w/ parting lineation) grading to small asymmetric wave generated sinuous to linguoid ripples. Massive bedding to planar laminae in subsurface w/ occasional wavy laminae near top and shell debris laminae. <b>Tidal creek zone:</b> small asymmetric ebb drainage generated sinuous ripples. Subsurface features same as foreshore with addition of basal pebble lag. <b>Swash zone:</b> planar surface w/ horizontal to inclined planar subsurface laminae. <b>Foreshore-backshore zone:</b> concentrated heavy mineral defined planar laminae and soft sediment deformation. Bioturbation non-evident to sparse across sub-environment.	Very well sorted, near symmetrical, platykurtic, dominantly lower medium grained sand (0.30φ, 0.00Sk, 0.77K, 2.00M)	Lowest Value (0.06) Highest Value (0.20) Top Average (0.11) Bottom Average (0.15) <b>Overall Average (0.12)</b>	--	Upper medium grained sand to granule (2.1) Lower medium grained sand (39.1) Upper fine grained sand (40.6) Lower fine grained sand (3.7) Upper very fine grained sand to silt/clay (0.6)	
<b>Shoreface-Spits</b>	<b>Foreshore terrace-tidal inlet zone:</b> Sinuous to lunate combined tidal current-wave generated subaqueous dune forms dominate with superimposed asymmetric sinuous to linguoid ripples. Horizontal planar laminae to cross laminae evident in the subsurface. <b>Swash zone:</b> planar surface w/ inclined planar laminae and cross laminae in the subsurface. <b>Foreshore-backshore zone:</b> concentration of planar heavy mineral sand laminae greatest. Sinuous aeolian formed ripples in the backshore. Bioturbation sparse across sub-environment.	Very well sorted, fine skewed to near symmetrical, platykurtic to mesokurtic, dominantly lower medium grained sand (0.30φ, 0.10Sk, 0.90K, 1.93M)	Lowest Value (0.03) Highest Value (0.27) Top Average (0.17) Bottom Average (0.15) <b>Overall Average (0.16)</b>	35	Upper medium grained sand to granule (6.0) Lower medium grained sand (55.3) Upper fine grained sand (34.4) Lower fine grained sand (3.1) Upper very fine grained sand to silt/clay (1.1)	





**Figure 2-6: Sedimentological photographs of surface features of the foreshore terrace bar area along the Bay Mouth North Foreshore sub-environment. (A)** Photograph showing linear surface features oriented perpendicular to shoreline and parallel to swashing direction. The linear features are oriented in photograph from approximately the bottom left to top right corners. **(B)** Small, dominantly wave generated, near symmetric, sinuous to linguoid crested ripples shoreward from the essentially planar flat bed containing linear surface features.

where the tidal creek drains during ebb tide. Sinuous crested asymmetric ripples were superimposed on larger dune structures within the tidal creek. The tidal creek had a steep seaward bank and a gently sloping shoreward bank. Shoreward of the tidal creek, along the swash zone, the sediment surface was smooth with very few features. The only prominent features would be the occurrence of ever increasing heavy mineral sand near the top of the swash zone and linear surface features once again present oriented perpendicular to shoreline and parallel to swashing direction. The backshore zone, located immediately after the strandline at the top of the swash zone, displayed much drier sand with small aeolian ripples featured on the surface.

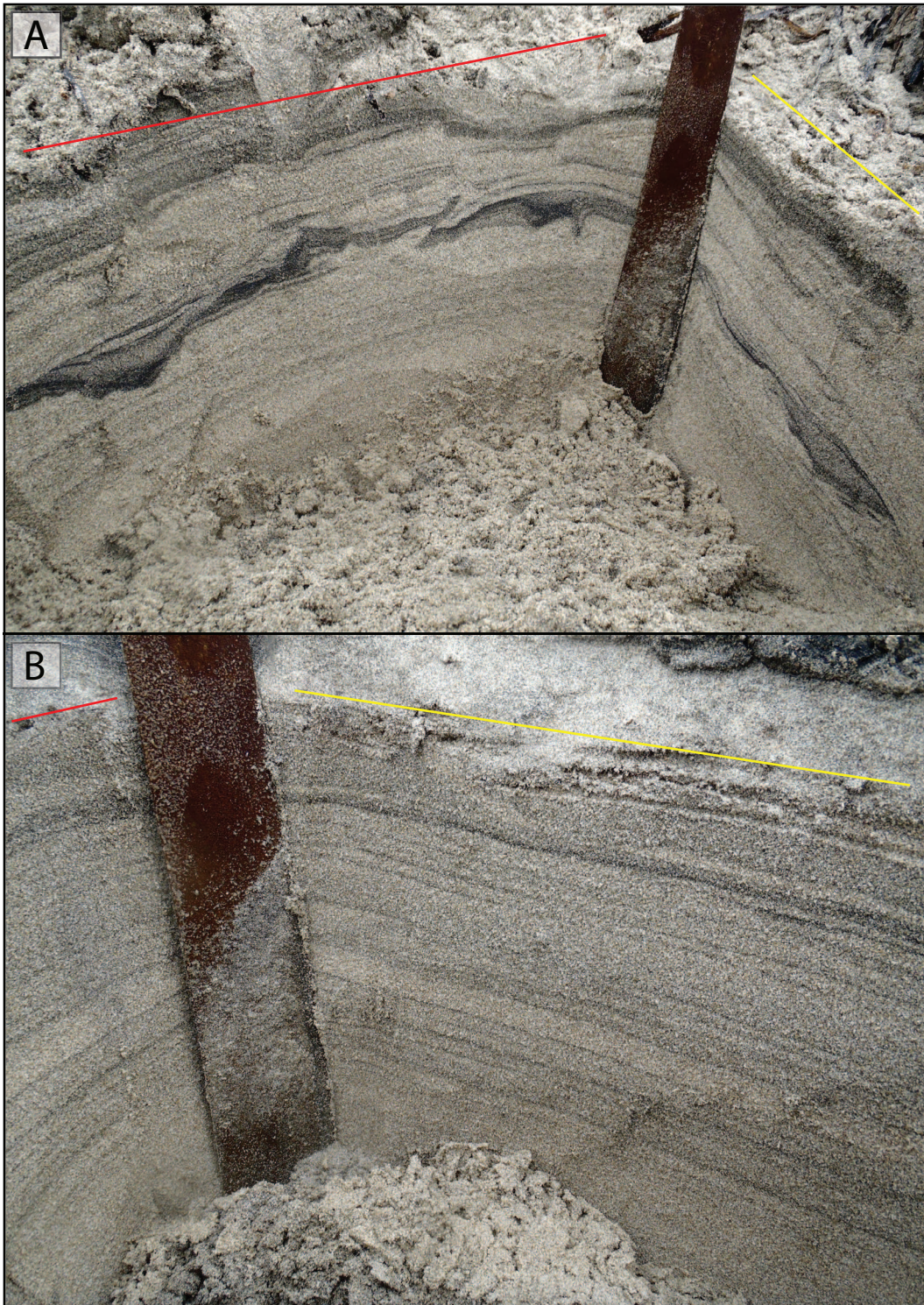
In the subsurface planar laminae were present from the MLLW mark up until the tidal creek defined mainly by light beige sands. Occasionally, one or two heavily disarticulated shell layers with minor heavy mineral sands displayed planar laminae approximately 1cm thick and were present 6cm to over 25cm below the sediment surface (Fig. 2-7). The grain size associated with these disarticulated shell layers is thus noticeably coarser. A pebble layer was also occasionally encountered. Sub-rounded pebbles 2-4cm long and 1-3cm wide were sporadically seen between MLLW and 30m up beach, with pebble frequency decreasing past this zone until the tidal creek. The tidal creek is 25m wide and begins approximately 115m up beach from the low tide mark where sand to cobble sized grains as well as shell fragments fill the creek. The tidal creek had mainly thixotropic sediment so distinguishing subsurface features was very difficult if not impossible; however a distinctive pebble to cobble sized layer was present from the sediment surface to a depth of 20cm below within the tidal creek. Micro-faulting and soft sediment deformation structures were clearly evident in the near surface of the foreshore-backshore boundary, enhanced by the heterogeneous mix of variously coloured sands (Fig. 2-8A). However, along most of the foreshore and backshore stretches of planar laminae were dominant with wavy laminae present only near the sediment surface where there was an abrupt change from dominantly light beige sands





**Figure 2-7: Sedimentological photograph of subsurface features of the foreshore terrace bar area along the Bay Mouth North Foreshore sub-environment.** Note disarticulated shell layers with minor heavy mineral sands as indicated by the black arrows. Length of machete exposed in the left side of the photograph is approximately 25cm.





**Figure 2-8: Photograph of trenches dug at or near the foreshore-backshore boundary of the Bay Mouth North Foreshore sub-environment.** Sedimentary features are enhanced by bands of heavy mineral sand laminae. Red lines are oriented perpendicular to shoreline. Yellow lines are oriented parallel to shoreline. **(A)** Photograph of trench at the foreshore-backshore boundary at the strand line located at the top of the swash zone. Note soft sediment deformation features and micro-faulting. Machete part shown in photograph is ~30cm long. **(B)** Photograph of trench showing planar laminae common directly before or after the strand line. Machete part shown in photograph is ~20cm long.

near the surface to a mixed light beige and darker heavy mineral sand laminae assemblage at the foreshore-backshore boundary (Fig. 2-8B).

Average grain size across the Bay Mouth North Foreshore sub-environment was dominantly upper fine- (47.34 wt%) to lower medium- (45.59 wt%) grained sand; top sediments ranged from dominantly 47.67 wt% lower medium-grained sand to 44.58 wt% upper fine-grained sand, and bottom sediments ranged from dominantly 50.10 wt% upper fine-grained sand to 43.51 wt% lower medium-grained sand (Table 2-1). Most sample locations across the Bay Mouth North Shoreface transect display grain sizes that are slightly dominant towards the lower medium-grained fraction, however the top sediment from 90m and 120m up beach from the low tide mark and both the top and bottom sediment 180m up beach from the low tide mark are slightly more dominant in the upper fine-grained sand fraction.

Grain size analysis indicates that overall, the grains of the Bay Mouth North Foreshore sub-environment are very well sorted (inclusive standard deviation (Folk, 1974):  $0.30\phi$ ), near symmetrical (inclusive graphic skewness (Folk, 1974):  $0.00Sk$ ), platykurtic (graphic kurtosis (Folk, 1974):  $0.77K$ ), dominantly upper fine- to lower medium-grained sand with a mean size of  $2.00M$  (graphic mean (Folk, 1974)) (Table 2-1).

### ***Recurved Spit Sub-Environment***

The Recurved Spit sub-environment crosses two main zones; a high velocity sandy tidal flat zone that is bombarded by waves and strong currents during the incoming and outgoing flood and ebb tidal currents, respectively; followed by a foreshore-backshore zone where the beach gradient of the foreshore becomes steeper (foreshore face) eventually grading into the flatter, mainly aeolian, backshore area. The high velocity sandy tidal flat zone is dominantly lower medium-grained sand. There is an overall trend of decreasing grain size in the foreshore-backshore zone from dominantly mixed lower medium- to upper fine-grained sand to that of dominantly upper fine-



grained sand. Shell debris is common on the upper part of the Foreshore-Backshore zone. Heavy mineral sand laminae were occasionally seen to be gradational with the light beige sand; however sharp contacts were also seen between the heavy mineral sand laminae and beige sand. At the base of a set of laminae there appeared to be a sharp contact between heavy mineral lamina above and light beige sand below. The heavy mineral sand laminae appeared to grade upward into ever increasing amounts of beige sand until only beige sand was present followed by another sharp contact with heavy mineral sands above.

The high velocity tidal flat (foreshore terrace) zone is bound to the north by the main tidal channel inlet into Netarts Bay. At this locality steeply dipping banks often slump and are scoured by the high velocity flow of incoming and outgoing tidal currents along the channel bank (Fig. 2-9A). Rill marks may also form on the sides of the steep channel bank as water escapes the sediment at that particular level (Fig. 2-9B). Subordinate asymmetric sinuous to lunate ripples often form between megaripples or on the stoss side of exposed dune bedforms that were formed subaqueously (Fig. 2-10A,B). In some areas smooth planar bedding is seen with barely visible linear features on the surface. Actively draining channels on the flat during low tide displayed stationary undulatory water waves. Dominantly sinuous ripples occur within scoured depressions, located in the troughs between dune crests, displaying rapid shifts in orientation. The subordinate asymmetric sinuous to linguoid ripples were oriented anywhere from parallel to perpendicular on the mixed tidal current-wave generated dune bedforms (Fig. 2-11A). On the sediment surface heavy mineral sands were mainly prevalent on dune crests (Fig. 2-11B). Subsurface features were not observed.

In the foreshore-backshore zone the sediment surface was smooth along the steeper gradient foreshore (swash zone) face (Fig. 2-12A). Heavy mineral sand laminae were evident in the subsurface, especially in the first few centimetres, with the laminae becoming more prominent shoreward (Fig. 2-



**Figure 2-9: Main tidal channel bank characteristics along the Recurred Spit sub-environment.** Wooden stakes in photographs are approximately 90cm long. **(A)** View looking SE along main tidal channel inlet near the bay mouth opening at low tide. Slump marks, scoured walls and antidune features evident along the bank in the right of the photo. **(B)** View of main tidal channel bank showing multiple rill marks along the steep face due to rapid drop in water level. Note heavy sands concentrated along rill mark troughs.





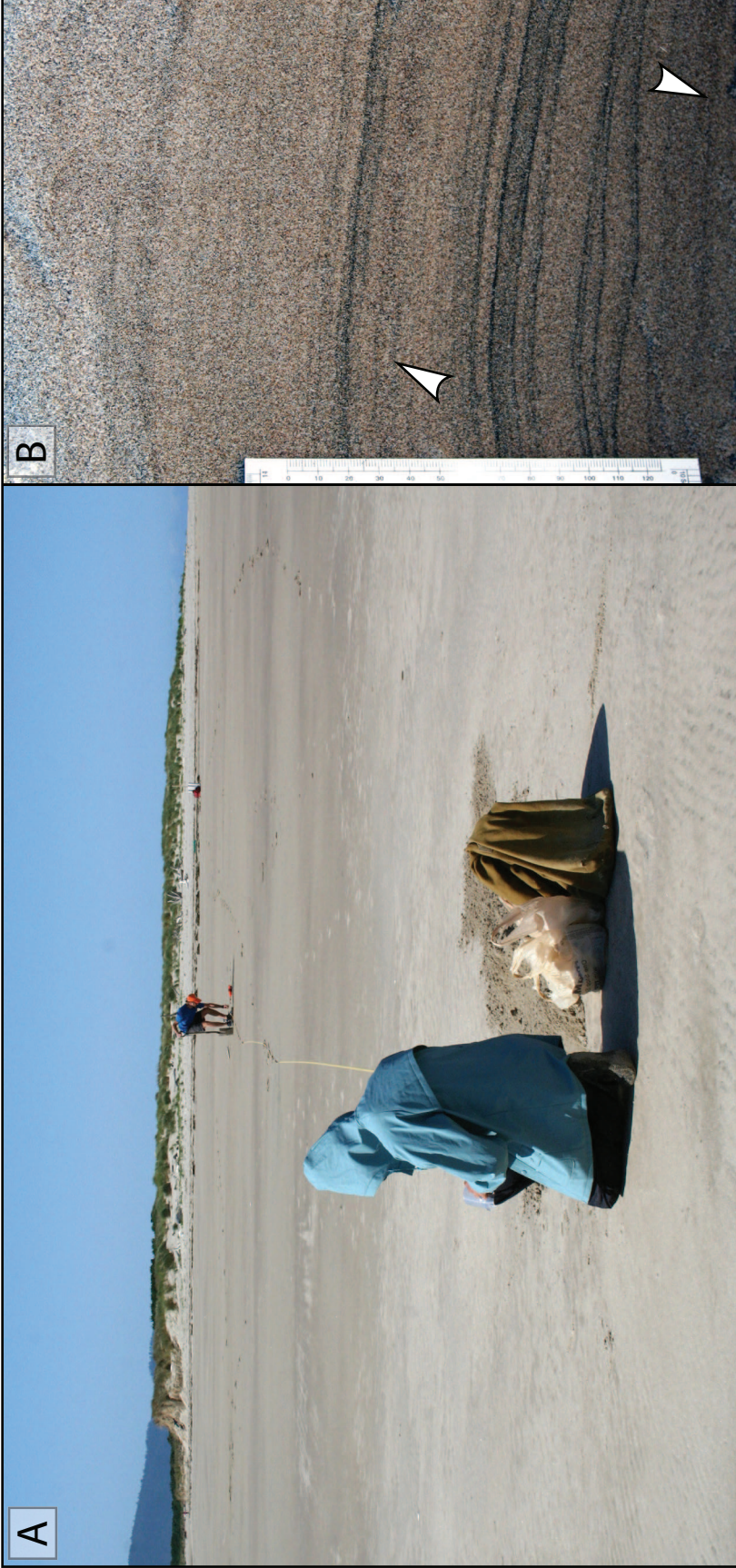
**Figure 2-10: Foreshore terrace morphology and surface sedimentary features along the Recurved Spit sub-environment. (A)** Prominent sinuous to lunate crested subaqueously formed dune features oriented along ebb-tide direction across the spit. Note a full range of superimposed forms upon the dunes such as sinuous to linguoid ripples as well as planar bedding in some areas. Frame of reference across the bottom of the photograph is approximately 3m for scale. Blue arrow indicates general ebb tidal current flow direction. **(B)** Complex linguoid like ripples superimposed on subaqueously formed dune forms. Note the accumulation of heavy mineral sands along ripple crests. Seaweed strand in picture is approximately 26cm long for scale.





**Figure 2-11: Morphology and sedimentology of foreshore terrace zone of the Recurved Spit sub-environment.** Blue arrow indicates general ebb tidal current flow direction. **(A)** View facing south displaying dunes with steep lee slopes that show subsequent tide levels upon drainage. Also note the oozing of water laden sands along this face as a result of rapid drop in water level. Rounded oscillatory wave ripples and asymmetric combined flow ripples are obvious surface features in the foreground. **(B)** View facing west showing the expanse of sinuous to lunate dune forms over the foreshore terrace. Note accumulation of heavy mineral sands at the crest of dunes as well. The frame of reference along the bottom of the photograph is ~3m for scale.





**Figure 2-12: Surface and sub-surface sedimentology of the foreshore region of the Recurved Spit sub-environment. (A)** Planar bedding is the most common feature observed along the foreshore with very slight ripples evident along the top and bottom margins of the foreshore zone. **(B)** In the subsurface heavy mineral sand laminae become very evident, especially in the upper 15-20cm of sediment. Planar to wavy laminae from the lower reaches of the foreshore zone are observed. Mottling is only apparent in various thin layers (as indicated by the white arrows), while the layers in between appear fully intact. Scale in the photo displays increments in millimeters. The length of the entire scale is 150mm long.

12B). The laminae were mainly planar with some wavy intervals seen in the more seaward stations (Fig. 2-12B). These laminae were typically less than 2mm in thickness. In the backshore area aeolian ripples were present on the dry sediment surface (Fig. 2-13A). Dried tree material, various disarticulated sea shells, sand dollar test fragments, dried seaweed as well as various flotsam and jetsam were also present in the backshore area. In the areas along the foreshore-backshore boundary vesicular (bubble) porosity was witnessed in the upper few centimetres of sediment (Fig. 2-13B).

Average grain size across the Recurved Spit sub-environment was dominantly upper fine- (49.92 wt%) to lower medium- (43.64 wt%) grained sand; top sediments ranged from dominantly 52.84 wt% upper fine-grained sand to 40.27 wt% lower medium-grained sand, and bottom sediments ranged from dominantly 47.01 wt% lower medium-grained sand to 47.00 wt% upper fine-grained sand (Table 2-1).

Grain size analysis indicates that overall, the grains of the Recurved Spit sub-environment are very well sorted (inclusive standard deviation (Folk, 1974):  $0.29\phi$ ), near symmetrical (inclusive graphic skewness (Folk, 1974):  $-0.04S_k$ ), platykurtic (graphic kurtosis (Folk, 1974):  $0.82K$ ), dominantly upper fine- to lower medium-grained sand with a mean size of 2.01M (graphic mean (Folk, 1974))(Table 2-1).

### ***Shoreface-Spit Sub-Environment***

Morphologically, the Shoreface-Spit sub-environment is very similar to the Recurved Spit sub-environment, except the high velocity tidal flat zone (foreshore terrace) isn't as extensive and the foreshore face is thinner and steeper. In the middle of the high velocity tidal flat zone of the Shoreface-Spit sub-environment the dominant grain size is upper medium-grained sand. At the foreshore- backshore boundary at the top of the swash zone the dominant grain size is upper fine-grained sand instead of lower medium-grained sand common throughout most of the Shoreface-Spit sub-environment. Along the





**Figure 2-13: Surface and sub-surface sedimentology of the Recurved Spit sub-environment. (A)** Aeolian formed ballistic ripples readily seen on the sediment surface. Frame of reference across the bottom of the photograph is approximately 3.5m for scale. **(B)** Along the foreshore-backshore boundary of the Recurved Spit sub-environment horizontal to inclined planar laminae are observed. The slightly mottled appearance of the laminae is especially enhanced by the presence of heavy mineral sands and appears *Macaronichnus*-like in appearance. In the upper 2cm of sediment vesicular (bubble) porosity is present (indicated by white arrows) as a result of air being trapped between layers of water during subsequent tidal cycles.

foreshore-backshore boundary heavy mineral sands are abundant and therefore there is a noticeable fraction of lower fine-grained sand.

In a large, very shallow, tidal inlet that cross cuts the recurved spit, asymmetric subaqueously formed dunes indicate the last main flow direction as coinciding with the ebb tide (Fig. 2-14A). Subordinate sinuous to linguoid mixed tide and wave generated ripples were present on the stoss side of the dunes (Fig. 2-14A,B). Dunes on the large tidal inlet margin also occasionally possessed scoured walls in areas where smaller longshore bars drained into the larger tidal inlet (Fig. 2-14B). Excess coarser grained sediment accumulated in the troughs directly after the steep lee side of the dunes. On well drained sandy high barred terrace zones of the tidal inlet-foreshore terrace area the dominantly light beige sands are relatively compact and easy to trench in order to study sedimentary structures in the subsurface if any are readily observable. In the trough lows within the tidal inlet-foreshore terrace area the sand is generally thixotropic, therefore observations of sedimentary structures in the subsurface is very limited if not impossible. Sedimentary structures observed in trenches or PVC core from the tidal inlet-foreshore terrace area displayed horizontal planar- to cross- laminae within the uppermost 6cm of sediment with massive appearing sands below.

At the boundary between the tidal inlet-foreshore terrace area and the steeper foreshore swash zone face area low angle planar- to cross- laminae were present within the uppermost 10cm of sediment with massive sands below. This trend continued up the swash zone, but with the addition of ever increasing heavy mineral sand laminae and disarticulated shell laminae (Fig. 2-15A). At the surface, smooth and essentially featureless shoreface sands were noted with barely visible linear features oriented parallel to sub-perpendicular to the shoreline and perpendicular to swashing direction (Fig. 2-15B).

The boundary between steeply dipping foreshore face (swash zone) and backshore occurred where there was an abrupt change from more compact sands to distinctly lighter sands which displayed bubble escape structures





**Figure 2-14: Morphological and sedimentological features of the foreshore terrace along the Shoreface-Spit sub-environment.** Blue arrow indicates general ebb tidal current flow direction. **(A)** View facing ENE showing undulatory bar and trough morphology of the large tidal inlet that bisects the recurved spit. Note spur and groove features on the lee side of sinuous crested dune forms in the foreground. **(B)** Shallow longshore trough channels are seen converging with the large tidal inlet at an oblique angle scouring the sides of bars. Linguoid to lunate ripples clearly seen in foreground while sinuous ripples are also observed in the midground.



**Figure 2-15: Morphological and sedimentological features of the foreshore terrace along the Shoreface-Spit sub-environment. (A)** View looking south along the foreshore-backshore boundary of the exposed spit beach. Note heavy mineral sands concentrated along the boundary defining the strandline. Slight antidune bedforms are observed on the foreshore in the right side of the photograph. The surf zone-swash zone boundary where *Emerita analoga* is found is observed in the upper right side of the photograph where the water mark is. **(B)** View facing east of the foreshore. Heavy mineral streaks help define parting lineation and rhomboid rill marks. Field of view along the bottom of the photograph is approximately 2m.



(bubble porosity) within the uppermost 2 centimetres of sediment. Planar to wavy laminae, as well as soft sediment deformation and micro-fractures were seen within the upper 5-10cm of sediment with trough cross laminae becoming evident 15cm below the surface.

Average grain size across the Shoreface-Spit sub-environment was dominantly 55.27 wt% lower medium-grained sand to 55.27 wt% upper fine-grained sand; top sediments ranged from dominantly 53.58 wt% lower medium-grained sand to 32.91 wt% upper fine-grained sand, and bottom sediments ranged from dominantly 56.96 wt% lower medium-grained sand to 35.97 wt% upper fine-grained sand (Table 2-1).

Grain size analysis indicates that overall, the grains of the Shoreface-Spit sub-environment are very well sorted (inclusive standard deviation (Folk, 1974): 0.30 $\phi$ ), fine-skewed to near symmetrical (inclusive graphic skewness (Folk, 1974): 0.10Sk), platykurtic to mesokurtic (graphic kurtosis (Folk, 1974): 0.90K), dominantly lower medium-grained sand with a mean size of 1.93M (graphic mean (Folk, 1974)) (Table 2-1).

## **Total Organic Carbon and Salinity Values**

### ***Bay Mouth North Foreshore Sub-Environment***

Average TOC over the Bay Mouth North Foreshore sub-environment transect was 0.12% with average top TOC values at 0.11% and average bottom TOC values at 0.15% (Table 2-1). For all stations with recorded TOC values for both top and bottom measurements, the top TOC values were lower than bottom TOC values except for the last station where the TOC values for top and bottom were equal at the boundary between foreshore and backshore. A couple of stations did not have any bottom TOC measurements due to the presence of a pebble to cobble sized layer. The lowest TOC value obtained was 0.06% from the top sediment 150m shoreward from the low tide mark on the beach face slope area, essentially half way up the swash zone of the foreshore

beach face. The highest TOC value obtained was 0.20% from the bottom sediment of the foreshore terrace area 30m shoreward from the MLLW mark.

#### ***Recurved Spit Sub-Environment***

Average TOC over the Recurved Spit sub-environment transect was 0.16%, with average top TOC values at 0.16% and average bottom TOC values at 0.17% (Table 2-1). In the majority of stations (9/14 stations) bottom TOC values were higher than top TOC values, with two stations having equal top and bottom TOC values, and a further three stations having top TOC values higher than bottom TOC values. Overall, both top and bottom TOC values seemed to be highest closest to the bay mouth opening and decreased shoreward. The lowest TOC value obtained was 0.08% from two stations along the foreshore-backshore zone, mainly where the beach is dominantly dry and aeolian influenced. The highest TOC values were obtained from bottom sediments along the bank of the main channel mouth into the bay and 30m shoreward of the channel bank with a measured TOC of 0.25%.

#### ***Shoreface-Spit Sub-Environment***

Average TOC over the Shoreface-Spit sub-environment transect was 0.16%, with the average top TOC values at 0.17% and average bottom TOC values at 0.15% (Table 2-1). Overall top TOC values were higher than bottom TOC values except for on a sandy, well drained high on the foreshore terrace and at the boundary between foreshore and backshore. The lowest TOC value obtained was 0.03% at the boundary between foreshore and backshore. The highest TOC value obtained was 0.27% from top sediment in the prominent shallow tidal inlet along the high velocity tidal flat zone of the lower foreshore. A salinity sample was obtained when the low tide mark was half way up transect for the Shoreface-Spit sub-environment and was analyzed to have a salinity measurement of 35 PSU (practical salinity units) (Table 2-1).

## Neoichnological Characteristics

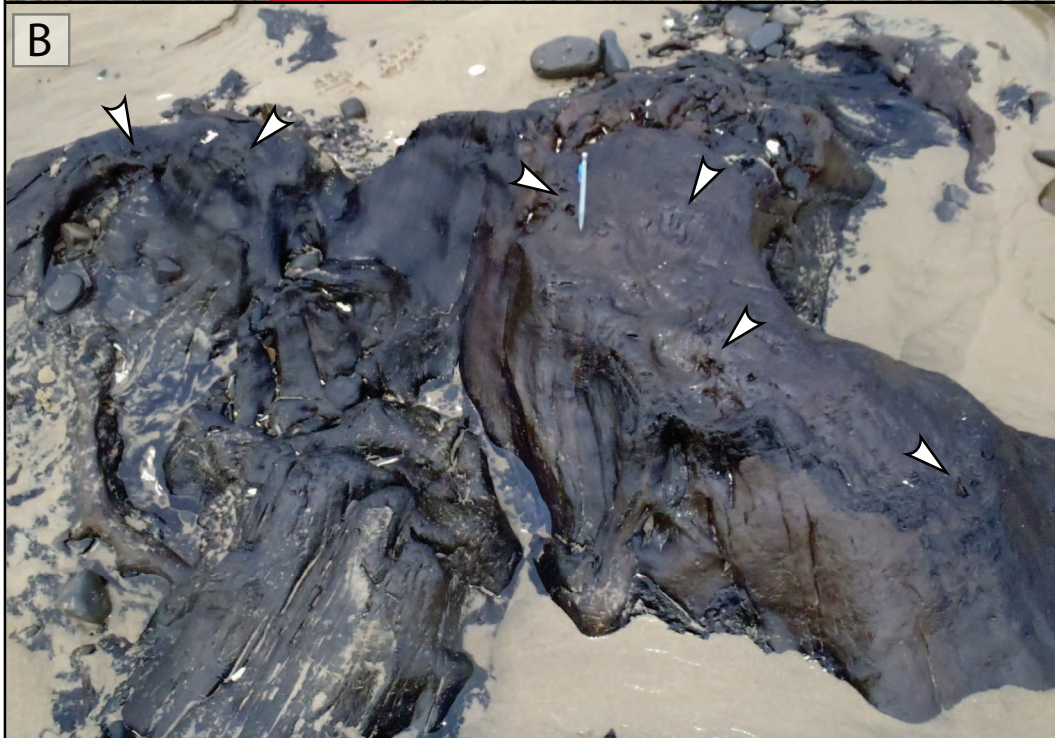
### ***Bay Mouth North Foreshore Sub-Environment***

Pelicans were observed hunting for fish near the mouth of the main channel; their footprints were occasionally seen throughout the Exposed Shoreface-Spit region. A deceased Columbian black-tailed deer (*Odocoileus hemionus columbianus*) and a live Pacific mole crab (*Emerita analoga*) were found directly northward of the transect location at the edge of the swash zone. Overall very few burrows were observed along transect, with burrows only observed on sandy ridges within the tidal creek and near the foreshore-backshore boundary.

Usually 1-2 sporadic burrow openings were seen per sand ridge within the tidal creek (Fig. 2-16A). Burrows were commonly within 1-2 meters of each other. Due to the thixotropic nature of the substrate within the tidal channel subsurface burrow morphology was not observed. Two organisms, a juvenile Dungeness crab (*Cancer magister*) and a juvenile amphipod, were observed resting at the surface or slightly beneath the surface, on one of the exposed sand ridges. Tree stumps occasionally seen within the tidal creek were slightly burrowed creating *Teredolites*-like traces (Fig. 2-16B, Table 2-2).

After the tidal creek burrows became more frequent following a progression up the foreshore face with most frequent burrow openings occurring at the foreshore-backshore boundary. Average burrow openings along the upper foreshore face and foreshore-backshore boundary were 7 and 24 per 50cm<sup>2</sup>, respectively (Fig. 2-17A). The most likely trace-maker along the upper foreshore and foreshore-backshore boundary is the talitrid amphipod *Megalorchestia californiana*. *Megalorchestia californiana* adults are usually around 2cm long and observed out of their burrows right before dawn. *M. californiana* created open, vertical to J-shaped unlined burrows, which were occasionally infilled in less consolidated drier sands if left vacant or as a result of trenching (Fig. 2-17B, Table 2-2). The burrows are akin to *Skolithos*- and *Psilonichnus*- like traces (Fig. 2-17B, Table 2-2). Burrows were typically around



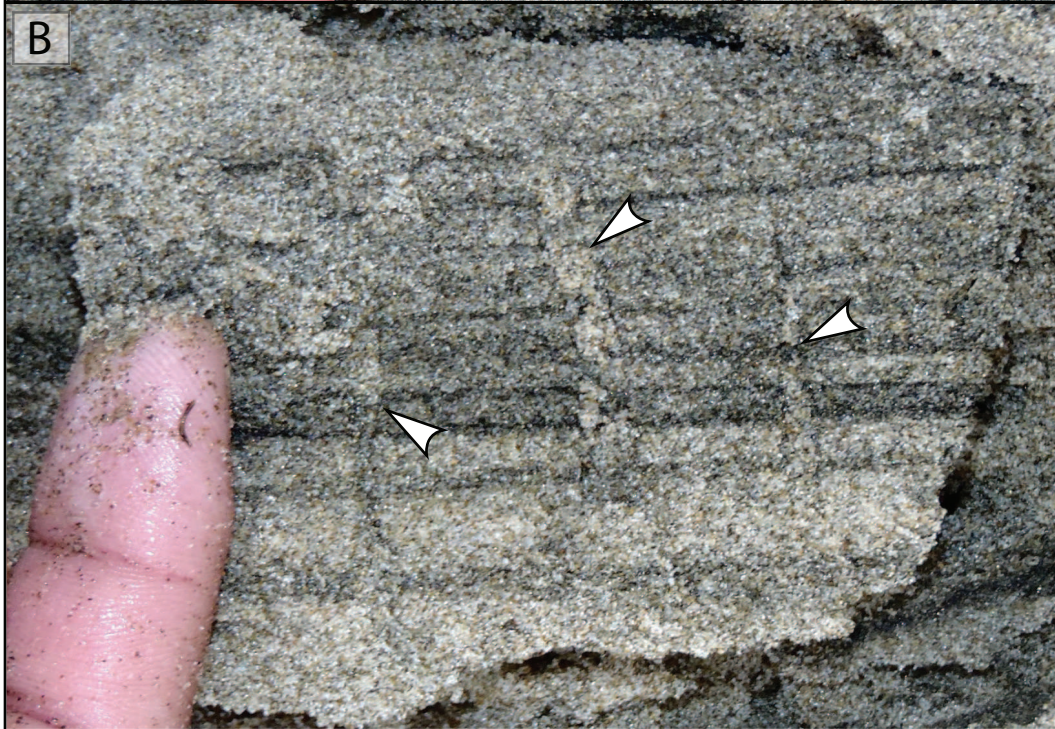


**Figure 2-16: Neoichnology of tidal creek within the Bay Mouth North Foreshore sub-environment. (A)** Burrow opening on a sand ridge within tidal creek as indicated by black arrow. Juvenile *Cancer magister* a possible tracemaker. Handle of machete is ~11 cm long for scale. **(B)** One of the bored tree stumps within the tidal creek with white arrows indicating sporadic clusters of burrows. Mechanical pencil on tree stump for scale is 15cm long.



Table 2-2: Summary of Trace Making Organisms and Associated Traces of the Exposed Shoreface-Spit Bay Region				
	Organism	Trophic Behaviour	Trace Fossil Equivalent to Modern Trace Form	Environmental Zone
Mollusca	? <i>Siliqua patula</i>	Filter Feeder	<i>Skolithos</i> ? <i>Siphonichnus</i> , ? <i>Fugichnia</i> , ? <i>Equilibrichnia</i>	Foreshore Terrace
	<i>Olivella biplicata</i>	* Surface Deposit Feeder, Filter Feeder, Scavenger, ? Carnivore	<i>Olivellites</i>	Foreshore Terrace
Crustacea	? <i>Excirolana</i> sp.	Scavenger, ? Deposit Feeder	? <i>Macaronichnus</i>	Foreshore (Swash Zone)
	<i>Emerita analoga</i>	Filter Feeder	<i>Cruziana</i> to <i>Diplichnites</i> , <i>Cubichnia</i>	Foreshore (Swash Zone)
	<i>Cancer</i> sp.	Carnivore, Scavenger, Facultative Filter Feeder	<i>Cubichnia</i>	Tidal Creek
	<i>Megalorchestia californiana</i>	Scavenger	<i>Skolithos</i> , Diminutive <i>Psilonichnus</i>	Foreshore- Backshore Boundary
	<i>Traskorchestia traskiana</i>	Scavenger	<i>Skolithos</i>	Backshore
Insecta	Tenebrionid Beetle	Scavenger	<i>Skolithos</i>	Backshore

<b>Table 2-2: Summary of Trace Making Organisms and Associated Traces of the Exposed Shoreface-Spit Bay Region (continued)</b>				
	<b>Organism</b>	<b>Trophic Behaviour</b>	<b>Trace Fossil Equivalent to Modern Trace Form</b>	<b>Environmental Zone</b>
<b>Vermiform</b>	<i>Nephtys</i> sp.	* Carnivore, Scavenger	Sediment Disruption/Navichnia, ? Cryptic Bioturbation	Foreshore Terrace
	? <i>Euzonus</i> sp.	Subsurface Deposit Feeder	? <i>Macaronichnus</i>	Foreshore (Swash Zone)
	? <i>Ophelia</i> sp.	Subsurface Deposit Feeder	? <i>Macaronichnus</i>	Foreshore (Swash Zone)



**Figure 2-17: Ichnology of the foreshore-backshore boundary within Bay Mouth North Foreshore sub-environment.** Finger for scale is ~1.5cm across. **(A)** Photograph of burrow openings, as shown by white arrows, produced by *Megalorchestia californiana*. Note the distribution of excavated sediment around the burrow with the burrow on the furthest right displaying the 0-180 degree sediment excavation pattern typical of *M. californiana*. **(B)** Subsurface burrow architecture produced by *M. californiana* displays *Skolithos*-like trace as shown by white arrows. Finger pointing way-up.

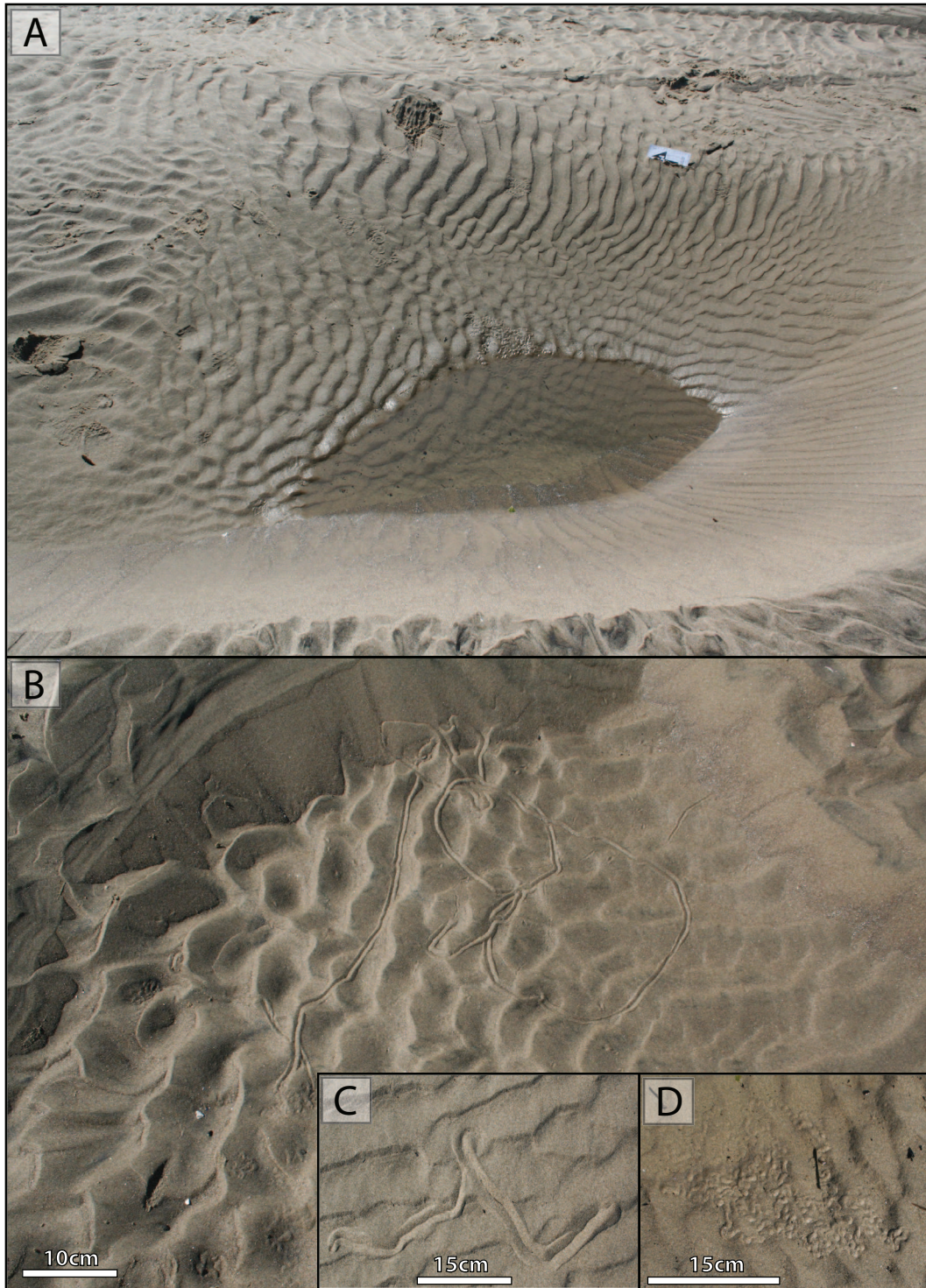


5-10mm in diameter and extended below the subsurface up to a depth of approximately 3-5cm. *M. californiana* were observed to tuck in their red antennae and burrow head first into the sediment. They slightly curl inward and then flick quickly back to their normal elongate shape, periodically switching between 0° and 180° while burrowing, causing sand to be ejected backward out of the burrow via their legs. Smaller talitrid sand fleas (*Traskorchestia traskiana*) were also common and were typically found hiding below wrack piles at the top of the swash zone potentially creating cryptic bioturbation, where the majority of both *M. californiana* and *T. traskiana* seek refuge and construct burrows.

#### ***Recurved Spit Sub-Environment***

Meandering surface traces of the purple dwarf olive snail (*Olivella biplicata*) were common in the wetted scoured troughs of the high velocity tidal flat zone (Fig. 2-18A,B,C,D). These surface traces are akin to the *Olivellites*-like trace, which is similar to the *Aulichnites*- and *Gordia*-like traces. These meandering surface traces were the only traces found in the high velocity tidal flat zone besides one vertical, unlined burrow created by an unknown tracemaker.

In the upper foreshore-backshore zone the only traces observed were single, unlined, vertical burrows akin to the *Skolithos*-like trace. These burrows were typically 5mm in diameter and became more frequent shoreward. At the foreshore-backshore boundary burrows were typically 1-2 meters apart. A tenebrionid beetle was seen associated with one of these burrows at the foreshore-backshore boundary. Tenebrionid beetles became progressively more common shoreward in the aeolian backshore area.



**Figure 2-18: Neochronology of the foreshore terrace zone along the Recurved Spit sub-environment. (A)** *Olivellites*-like surface traces likely created by *Olivella biplicata* along water laden dune troughs. Also note the developed ripple fan within the trough. Scale in sand is 15cm across. **(B)** The different types of *Olivellites*-like surface meandering traces are displayed. **(C)** This inset shows the broader less tightly wound meandering surface traces. **(D)** This inset shows the tightly wound meandering surface traces.

### ***Shoreface-Spit Sub-Environment***

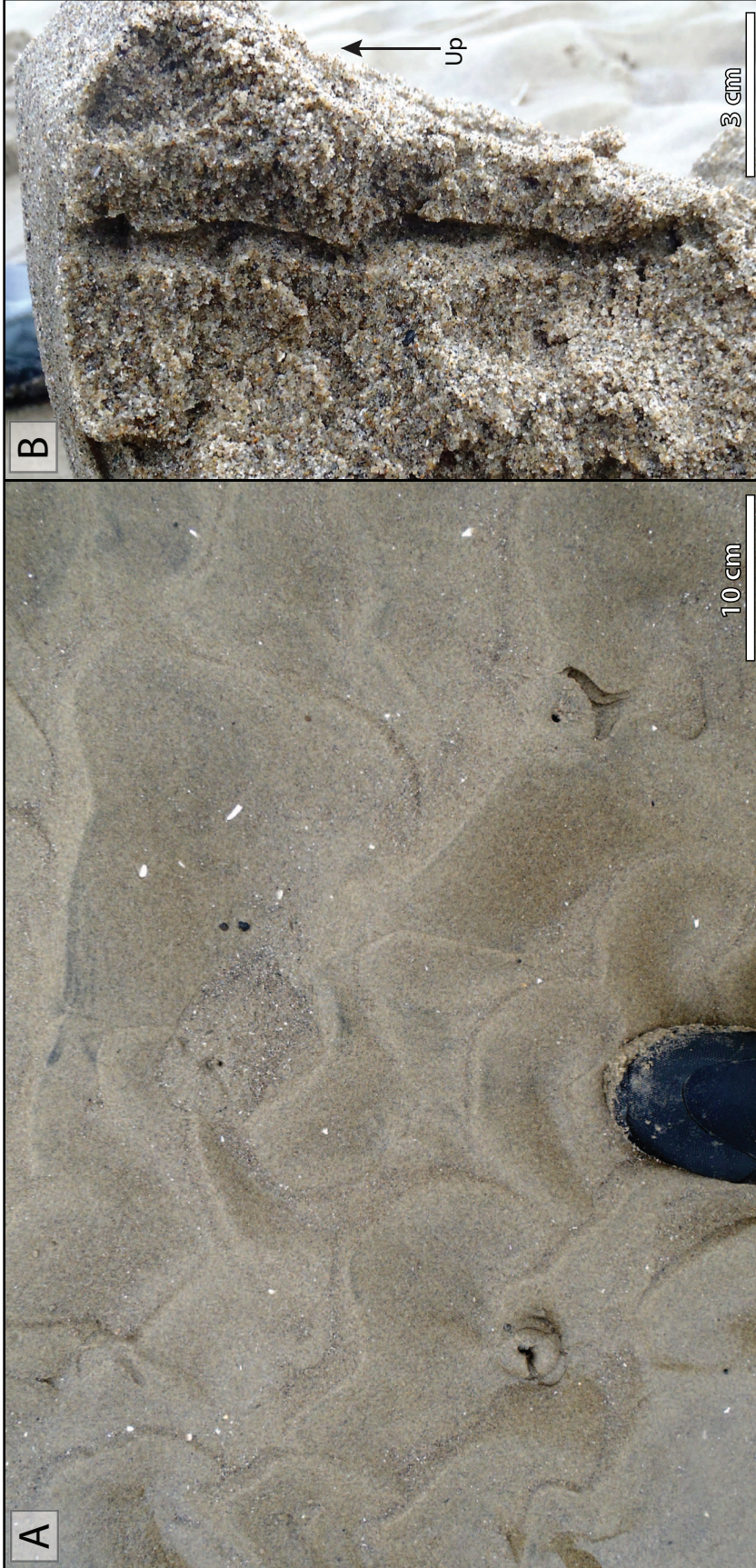
Three vertical, unlined burrows with entrances 5-10mm in diameter were observed within 30-35cm of each other in the large, shallow tidal inlet within the tidal inlet-foreshore terrace area (Fig. 2-19A). A siphon was potentially briefly observed but no bivalve, or any other organism, was discovered. One of the burrows displayed a slight vertical zigzag pattern (Fig. 2-19B). These burrows are akin to a *Skolithos*-like trace and perhaps a *Siphonichnus*-like trace if bivalves were indeed the tracemaker (Fig. 2-19B, Table 2-2).

Many *O. biplicata* were seen within the lows of the tidal inlet-foreshore terrace area, up to 10 individuals per 50cm<sup>2</sup> (Fig. 2-20A). As indicated previously, the trace produced by *O. biplicata* is akin to the *Olivellites*-like trace (Fig. 2-20B,C, Table 2-2). Two *Nephtys* sp. were also found on the tidal inlet-foreshore terrace area swimming through the sand creating sediment disruption structures (Table 2-2).

*Emerita analoga* was present at the boundary between the tidal inlet-foreshore terrace area and the steeper foreshore swash zone face area. The surface traces created by *E. analoga* are akin to *Cruziana*- or *Diplichnites*-like traces, while the under-trace created appears to be a near surface resting or feeding trace with faint scrape marks visible in the sand (Fig. 2-21A, B, Table 2-2). *E. analoga* were usually found in groups commonly with 1-2 adults and 1-2 juveniles present within a few centimetres of each other, with groups generally occurring a meter or two away from each other. *E. analoga* were witnessed to burrow backward after quickly crawling across the surface when exposed. They burrow just beneath the sediment surface resting near vertical with their heads closest to the surface (Fig. 22A,B). The open burrow created above their heads is generally 2-10mm in diameter, depending on amount of infilling (Fig. 2-22C).

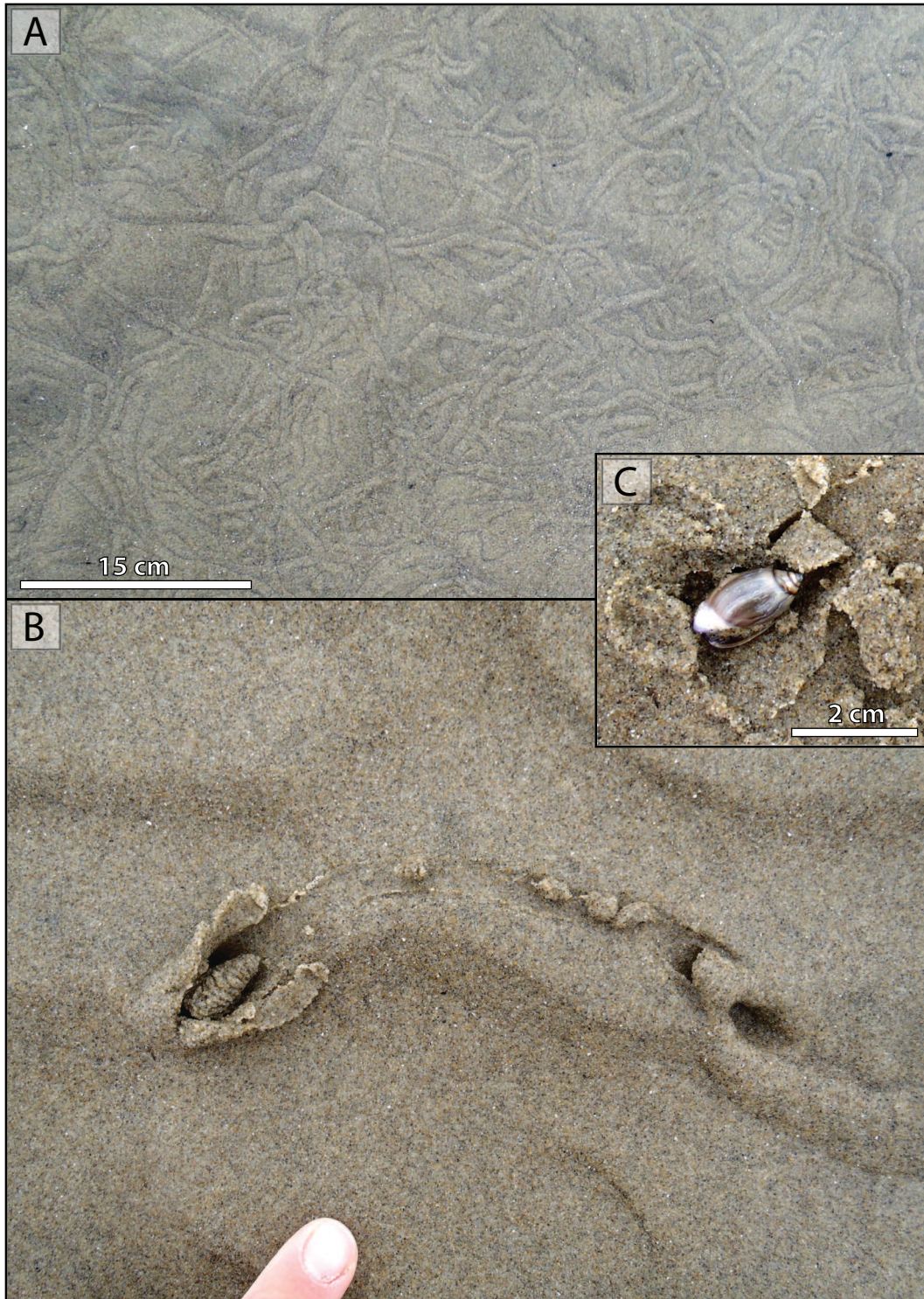
In the middle of the swash zone small (less than 5mm in diameter), vertical, open, unlined burrows akin to *Skolithos*-like traces began to appear





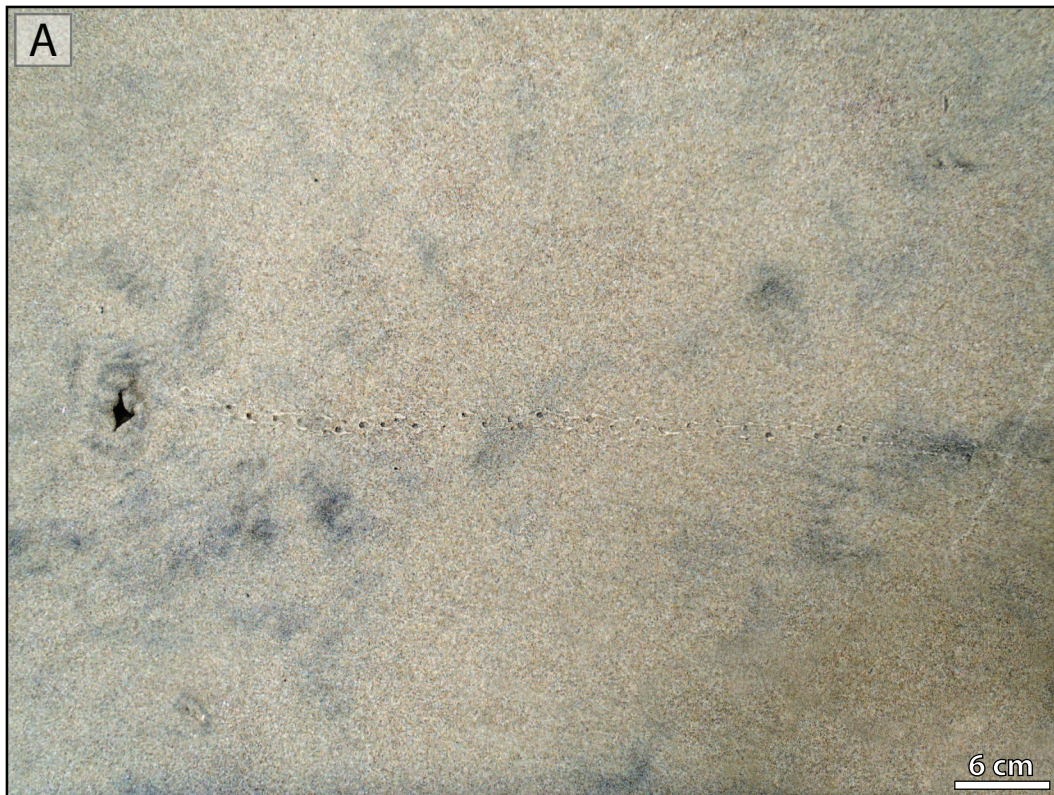
**Figure 2-19: Neochronology of shallow tidal inlet located along the Shoreface-Spit sub-environment. (A)** Plan view of burrow openings potentially created by a bivalve, possibly *Siliqua patula*. **(B)** Cross sectional view of zig-zag *Skolithos*-like trace potentially created by *Siliqua patula*.





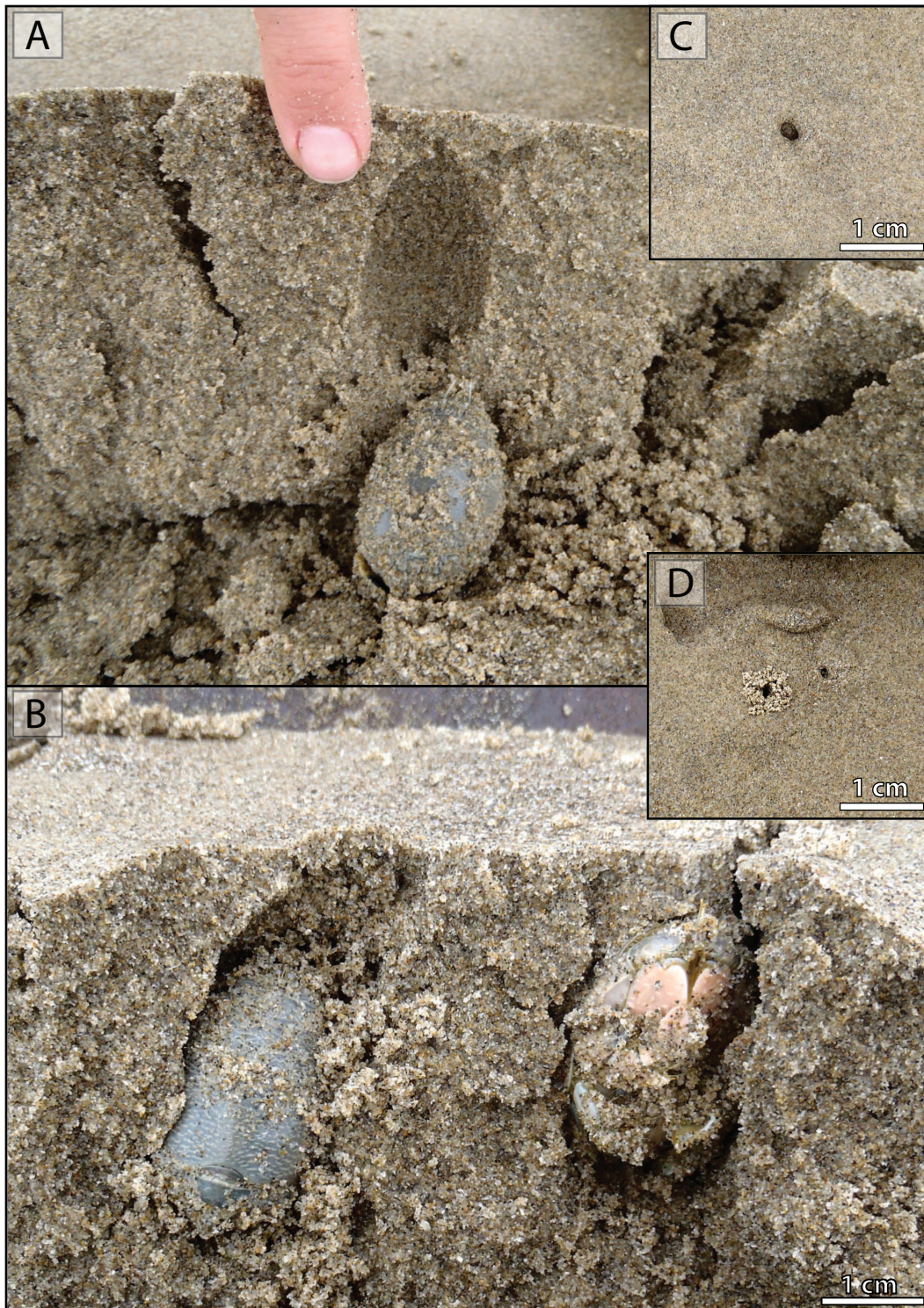
**Figure 2-20: Neoichnology of troughs located within the foreshore terrace along the Shoreface-Spit sub-environment. (A)** High density of meandering surface traces akin to *Olivellites* created by *Olivella biplicata* in a water laden trough. **(B)** Simple arcuate *Olivellites*-like trace created by *O. biplicata* in a trough that was devoid of water. *Olivella biplicata* is covered by sand in the left corner of the trace. **(C)** The same *O. biplicata* from the photo in (B) uncovered.





**Figure 2-21: Surficial neoihcnology of the swash zone-surf zone boundary at the base of the foreshore along the Shoreface-Spit sub-environment. (A)** Fresh surface trace created by *Emerita analoga* alongside plan view of freshly created burrow opening. **(B)** *E. analoga* tracks on slightly drier sand than (A) showing *Cruziana*-like to *Diplichnites*-like trace marks.





**Figure 2-22: Subsurface Neoichnology of the swash zone-surf zone boundary at the base of the foreshore along the Shoreface-Spit sub-environment. (A)** Cross section of *Emerita analoga* burrow where it hides during low tide. Note the burrow mold with *E. analoga* just below. The head is facing in the up direction. **(B)** Cross section of a common occurrence where two *E. analoga* were found together, often with one or two juveniles. Dorsal view on the left and ventral view on the right. The head is facing in the up direction as well. **(C)** Plan view of burrow opening for photograph in (A). **(D)** Plan view of burrow openings for photograph in (B).

and increased in frequency shoreward. Possible bioturbation occurs 30cm below the surface as is evident from PVC core analysis. Near the top of the swash zone possible cryptic bioturbation or *Macaronichnus*-like structures were also seen in analysis of PVC core (Fig. 2-23).

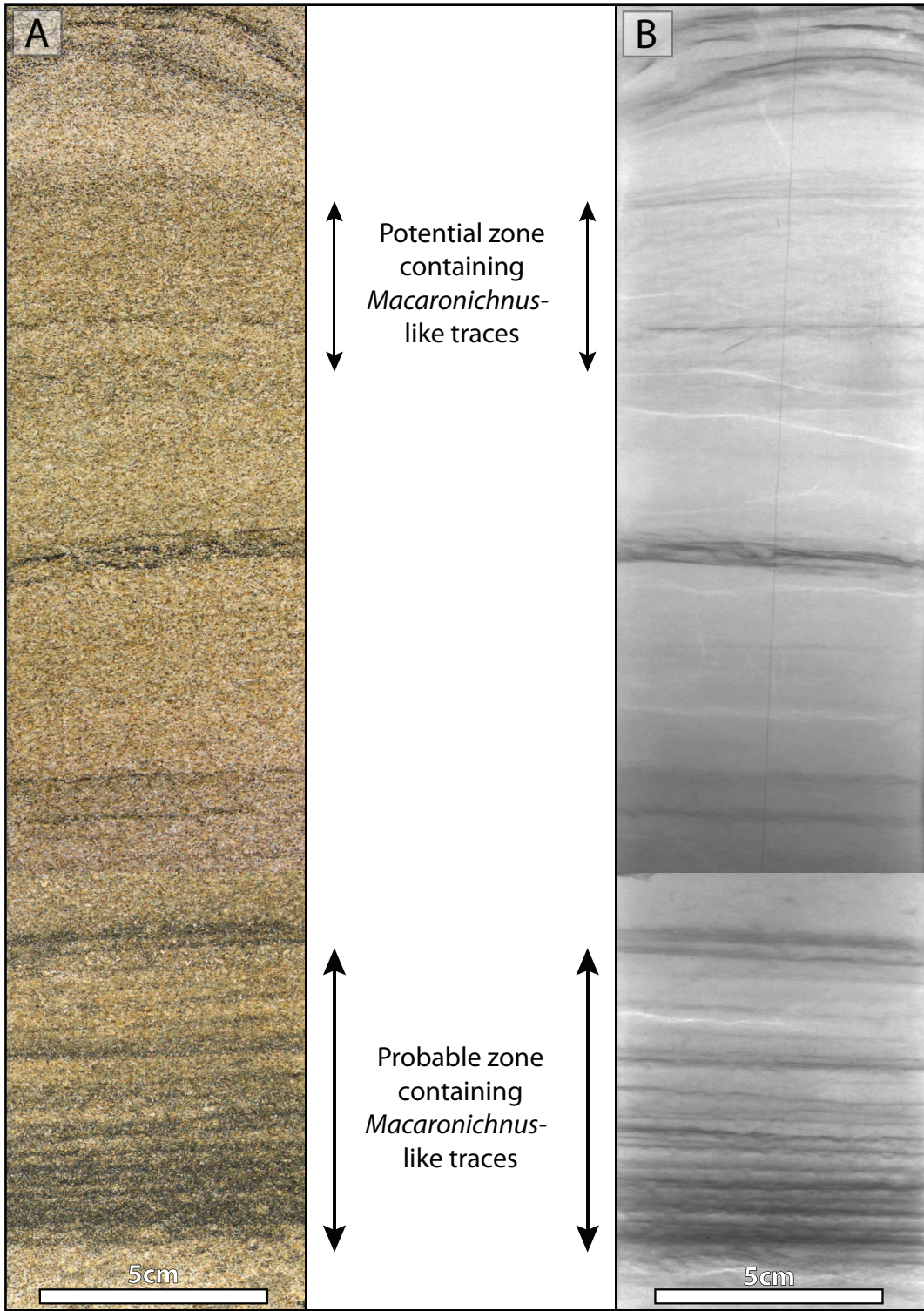
Burrows witnessed along the foreshore-backshore boundary were typically 5-10mm in diameter, with burrow openings flush, raised or indented with respect to the sediment surface (Fig. 2-24A). These burrows extended to a depth of approximately 10cm below the surface displaying vertical to J-shaped unlined burrow morphologies, with sand infilling burrows in the drier, less stable, backshore area (Fig. 2-24B). These burrows are again akin to *Skolithos*- and *Psilonichnus*- like traces, and likely result due to the activity of *M. californiana*, *T. traskiana*, and/or tenebrionid beetles. Juvenile talitrid amphipods or *T. traskiana* may also produce cryptic bioturbation. There was a progression towards wider and deeper vertical, unlined burrows as the vegetated dunes of the backshore were approached.

## **INTERPRETATION OF EXPOSED SHOREFACE-SPIT BAY REGION**

### **Morphological and Sedimentological Interpretation**

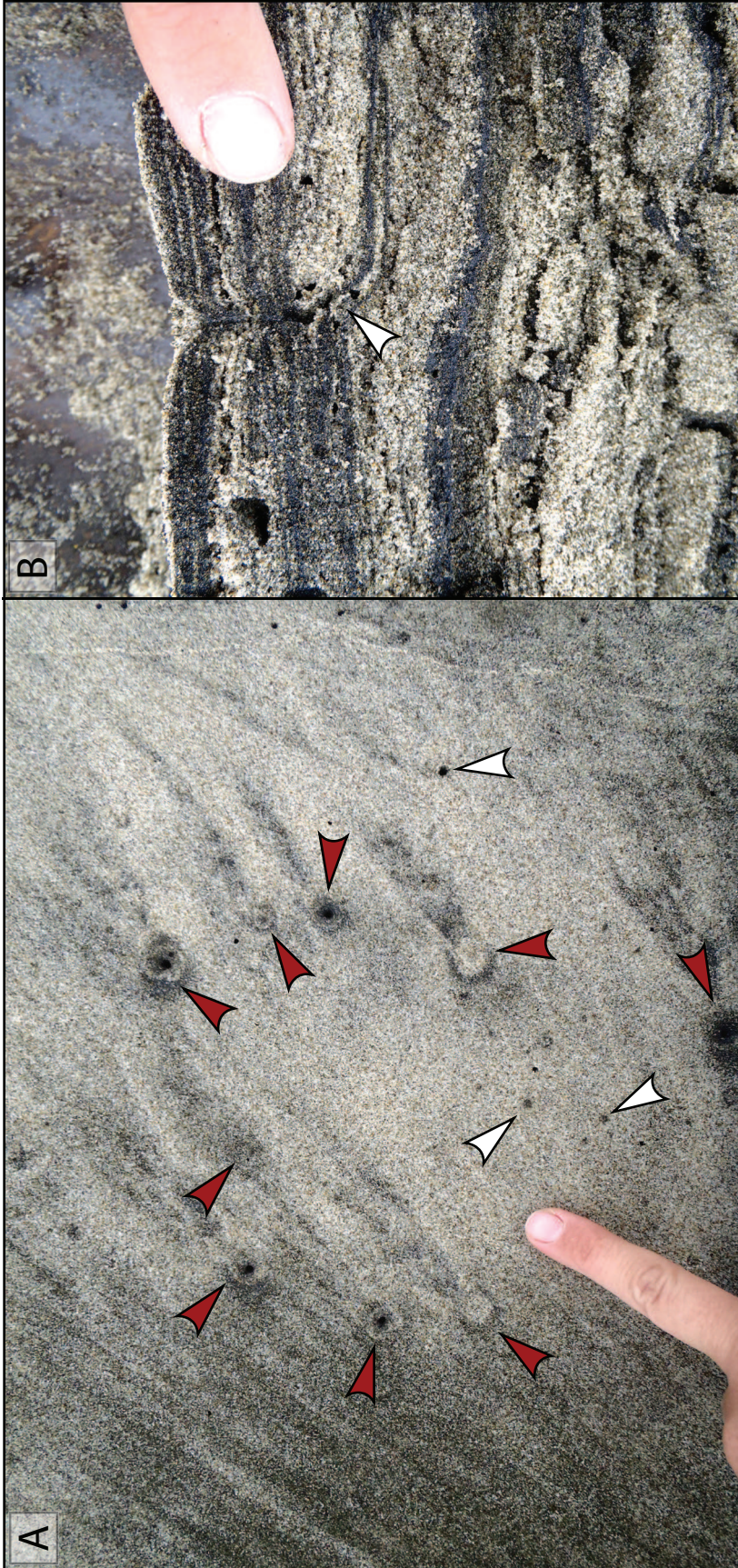
Three sub-environments comprise the morphological character of the Exposed Shoreface-Spits bay region (Fig. 2-2): **1**) the Bay Mouth North Foreshore (Fig. 2-25), **2**) the Recurved Spit (Fig. 2-26), and **3**) the Shoreface-Spits (Fig. 2-27). These sub-environments all possess similar morphology consisting of a low tide terrace of at least one bar and one trough associated with the surf zone; a foreshore region associated with the swash zone; and finally a backshore region consisting of dominantly aeolian features. A variety of sedimentary structures are present throughout the region, especially those associated with higher flow velocities. The Bay Mouth North Foreshore sub-environment consists of a simple bar and trough foreshore terrace continuing on to the more landward, steeper dipping, swash zone of the foreshore and finally the gently dipping backshore. Troughs generally run parallel to the





**Figure 2-23: Subsurface sedimentary structures of the foreshore along the Shoreface-Spit sub-environment.** Note that two core samples are spliced together so a distinct change is seen where the core is actually continuous. **(A)** Sedimentary features as seen in core. Sand is dominantly upper fine- to lower medium-grained with lower fine-grained heavy mineral sand laminae clearly evident. **(B)** X-ray of the core in (A) showing defined heavy mineral laminae with *Macaronichnus*-like traces observed within the lower 10cm of sediment.





**Figure 2-24: Neoichnology of the foreshore-backshore boundary along the Shoreface-Spit sub-environment. (A)** Surface morphology of traces displays slightly raised to slightly indented openings (as noted by the red arrows) approximately 0.5cm in diameter. Note vesicular (bubble) porosity of the beach sand as indicated by the white arrows. **(B)** Cross section through a J-shaped diminutive *Psilonichnus*-like trace (as shown by the white arrow) likely made by *Megalorchestia californiana*. Completely vertical traces are also common. Note the heavy mineral sand laminae highly concentrated in the upper layers of sediment.

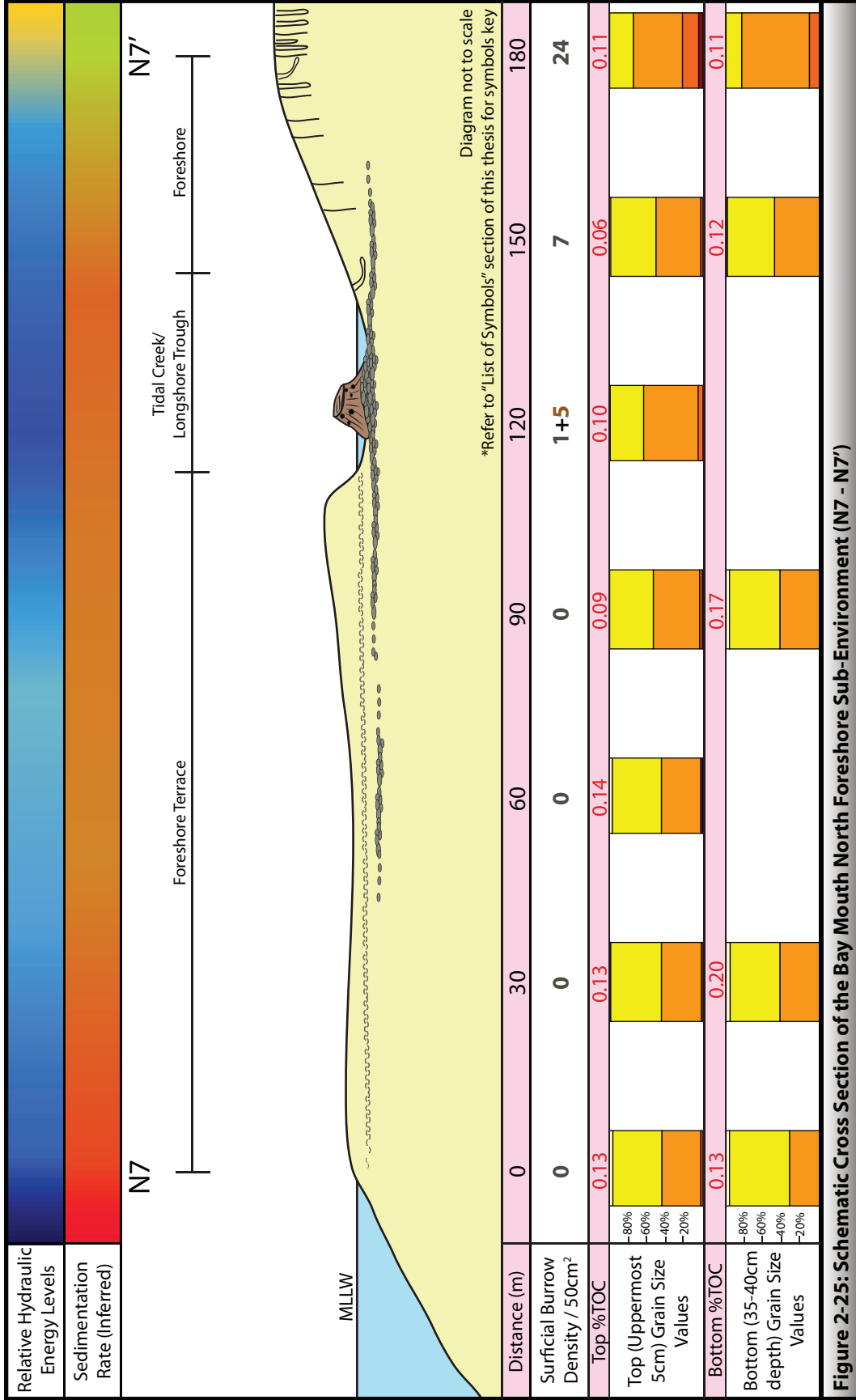


Figure 2-25: Schematic Cross Section of the Bay Mouth North Foreshore Sub-Environment (N7 - N7')

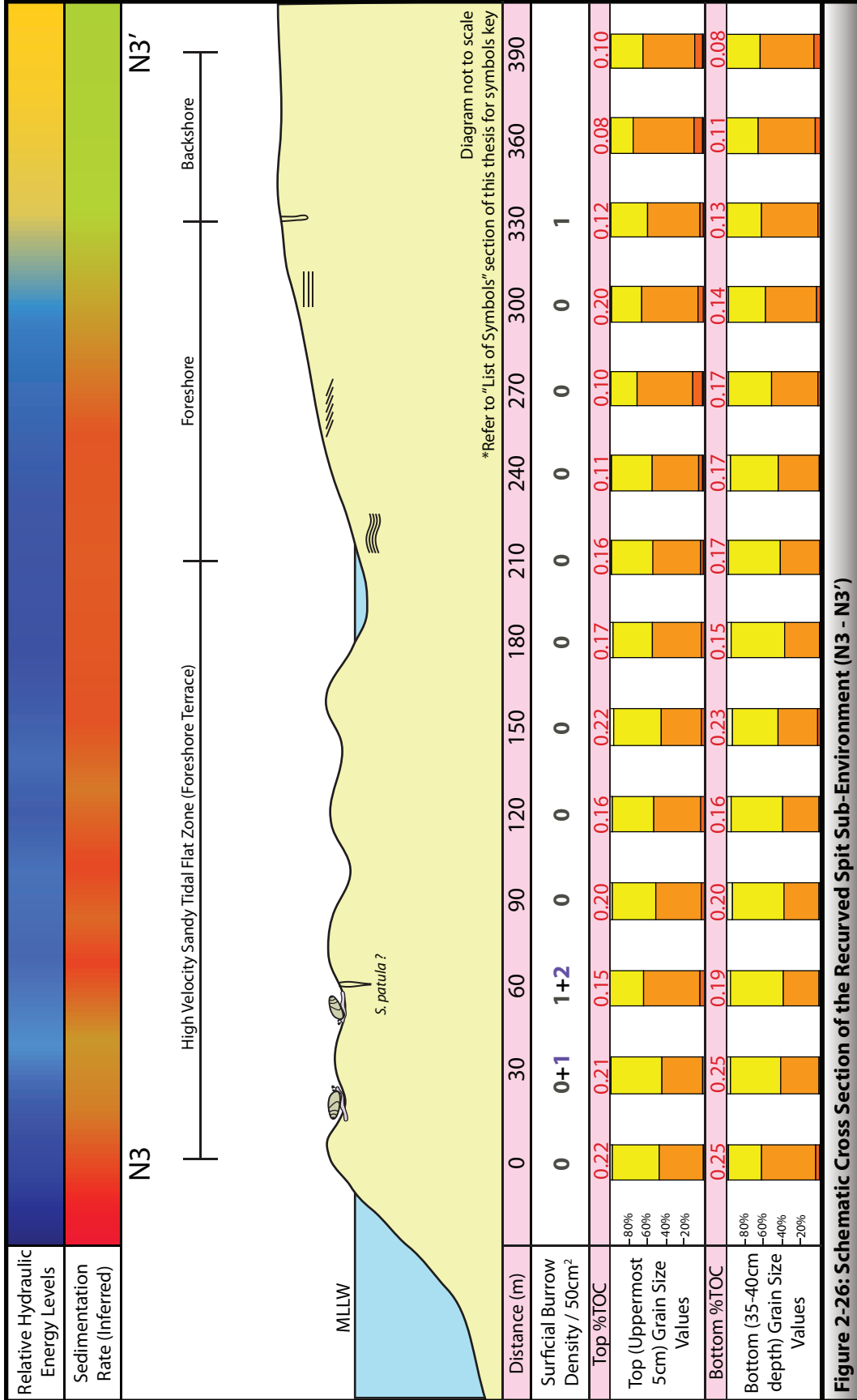


Figure 2-26: Schematic Cross Section of the Recurved Spit Sub-Environment (N3 - N3')



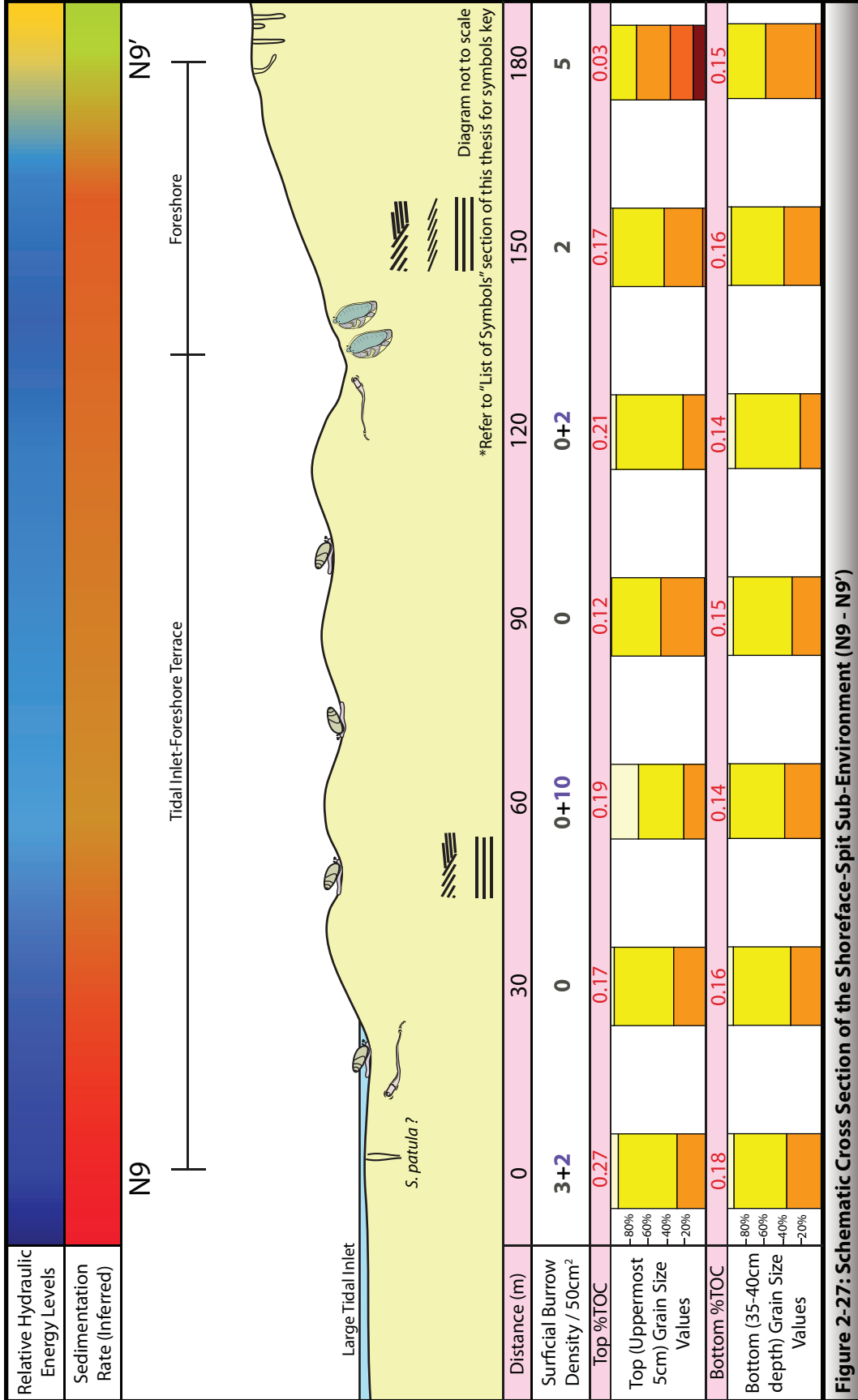


Figure 2-27: Schematic Cross Section of the Shoreface-Spit Sub-Environment (N9 - N9')



shoreline and drain into the main tidal channel of the bay from the spit or occasionally towards the ocean in rip-current channels. The Recurved Spit and Shoreface-Spit sub-environments are morphologically similar in that they too both consist of a low tide foreshore terrace with bars and troughs, followed by a steeper dipping shoreface, and finally a gently dipping backshore area. In the Recurved Spit sub-environment the low tide foreshore terrace is more extensive while the foreshore is slightly less steep and broader in comparison to that of the Shoreface-Spit sub-environment. Netarts Bay, along with the surrounding exposed beaches outside the bay, are wave-dominated, tide-influenced systems.

Due to the violent nature of the shallow nearshore and surf zone environment, detailed scientific observation of sedimentological features and biological distribution analysis is extremely difficult to obtain (Clifton et al., 1971). Nonetheless it is important to obtain insight into this challenging modern environment to further ascertain spatial-temporal relationships that may be useful in the aid of interpreting ancient depositional environments seen in the rock record. The section of exposed beach between Cape Mearns and Cape Lookout, which includes the entirety of beach along the Netarts Spit, display a dissipative to mainly intermediate beach state. The specific type of intermediate beach classification as described by Wright and Short (1984) becomes difficult near the terminus of the spit due to the complex interplay of wave and tidal currents affecting the mouth of the bay which gives way to a shoreline that follows almost the entire range of intermediate beach morphologies including longshore bar and trough, rhythmic bar and beach, transverse bar and rip, and finally low tide terrace. Sediment throughout the Exposed Shoreface-Spit bay region is dominantly upper fine- to lower medium-grained in size and is very well sorted. The constant wave energy of this high energy system allows the sediment grains to become very well sorted and to consist of an essentially uniform grain size.

Beyond the strandline is the backshore which is dominated by aeolian processes. The backshore of the Exposed Shoreface-Spits region of Netarts Bay is split into two different types: 1) a backshore consisting of a small sandy zone comprised of ballistic ripples ending in a high sandy-rocky cliff along the Bay Mouth North Foreshore sub-environment, and 2) a sandy backshore consisting of ballistic ripples grading into sand dunes that may be partially to fully stabilized dominantly by invasive European beachgrass (*Ammophila arenaria*) along the tip of Netarts spit comprising the Recurved Spit and Shoreface-Spits sub-environments. The backshore cliff of the Bay Mouth North Foreshore sub-environment may at least be a partial source of pebble to cobble sized grains as well as tree stumps to the longshore trough, referred to as a tidal creek, running parallel to shore as a probable slump deposit is observed in satellite imagery that likely occurred during the 1997-1998 winter El Niño (Oregon Partnership for Disaster Resilience; Google™ Earth, 2013). Overall, aeolian processes dominate the backshore region with occasional inundation during high tides, especially during winter or storm events. Aeolian formed slightly sinuous to almost straight crested ballistic ripples, essentially lacking internal structure, are the predominant feature of the backshore occurring immediately after the strandline continuing until dunes or cliffs are encountered (Allen, 1982a). Sharp's (1963) study of wind generated ripples indicated that, in stark contrast to water formed ripples, aeolian formed ripples display coarser materials on the crests and finer materials in the trough. Aeolian ripples are formed as a consequence of bombardment of saltating sand grains where the wavelength of ripples is directly influenced by the saltation length of grains (Allen, 1982a).

At the foreshore-backshore boundary, defined by the strandline, heavy mineral sands are commonly well concentrated. Peterson et al. (1986) noticed that proximal backshore accumulation of heavy minerals on Oregon beaches was greatest where the shoreline bends and wave-swash velocities, as well as long shore current velocities, decrease allowing the sorting of lighter quartz

sand from denser heavy mineral sand. In addition, currents flow northward during stormy winter months exposing lots of heavy mineral (placer) sands as the lighter sands are deposited offshore (Peterson et al. 1986). While in the fair-weather summer months southward flowing currents allow deposition of lighter quartz sand as well as heavy mineral sand burying dense accumulations of placer sands, allowing for an overall net transport of heavy mineral sands northward (Peterson et al., 1986). Therefore, heavy mineral laminae are common on Netarts Spit and on the beaches directly north of the bay mouth opening. Due to sediment liquefaction by wave action soft sediment deformation as well as microfracturing sometimes occurs along the foreshore-backshore boundary. When the upper fine- to lower medium-grained quartz rich sand becomes thixotropic and contains heavy mineral sand laminae then soft sediment deformation may occur when the smaller, denser heavy mineral sand begins to create a sag deposit into the less dense, liquefied quartz rich sand (Stewart, 1963; Lowe, 1975; Allen, 1982a). This is one plausible mechanism for the soft sediment deformation structures observed at the foreshore-backshore boundary throughout the outer parts of Netarts Bay including the adjunct exposed beaches near the bay mouth opening. Another more probable mechanism for the creation of soft sediment deformation structures, as well as possible microfractures, is that of cyclical liquefaction created by the reverse loading of water waves as continuous wave trains pass over (Allen, 1982a). The dominantly upper fine- to lower medium-grained cohesionless sands are then no longer supported by neighbouring grains and are held in suspension within the pore fluid until the mechanism causing liquefaction is removed (Allen, 1982a). Swash marks define the strandline at the point of MHHW (mean higher high water) where seaweed, shell fragments and other types of debris gather (Reineck and Singh, 1973). Sands along the strandline exhibiting vesicular structure, or bubble porosity, occur when air becomes trapped in the well drained sand usually when the flood tide brings

water in fast and left over water from below traps the air between the two water laden horizons (Stewart, 1963; Allen, 1982b).

The foreshore consists of the steeper dipping swash zone and is affected by very high energy during high tide, as well as during parts of the flood- and ebb-tides. However, the exposed face of the outermost seaward bar of the foreshore terrace also develops a swash zone at low tide and thus develops similar features (Hunter et al., 1979). The resulting bedforms are planar features associated with the upper flow regime. The essentially featureless plane bed of the swash zone is mainly marked by primary current (parting) lineation, rhomboid rill marks and antidunes. The surface lineation features described in Netarts Bay will herein be referred to as parting lineation as termed by Crowell (1955). Parting lineation is common in coarse silt- to medium-grained sand where the wave action of the swash zone produces these features, which are aligned parallel to flow direction (Stokes, 1947; Allen, 1964; Allen, 1982a). Parting lineation can also occur in other areas displaying upper flow regime plane bed features such as witnessed on the seaward face of the outer bar of the Bay Mouth North Foreshore sub-environment (Allen, 1964; 1968). Heavy mineral sands seemed to accumulate in the hollows with other finer grained materials between parting lineation ridges containing coarser sands, a phenomenon also observed by Allen (1964). The formation of the parting lineation features witnessed is due to the actions of boundary layer streaks where high-speed streak zones within the hollows alternate between periods of laminar and turbulent flow. When the turbulence associated with the high-speed streak zone encounters the wall region of the low-speed streak zone, atop the coarser grained ridge, then oscillatory motion along this wall transfers the turbulence to the low speed streak zone creating lift vortices and eventual grain settling along the wall (Corino and Brodkey, 1969; Grass, 1971; Kim et al., 1971; Offen and Kline, 1974; Mantz, 1978, Allen, 1982a). Backwash waves that are obliquely oriented create another type of feature, the V-shaped rhomboid ripple mark (Allen, 1982a; 1982b). As in many instances of parting

lineation formation, these features also form on top of planar sands in areas of supercritical flow (Karcz, 1970; Allen, 1982a). This backwash flow also produces antidunes oriented parallel to shoreline where parting lineation and rhomboid ripples are occasionally seen to cross these features (Komar, 1976). Broome and Komar (1976) noted that on Oregon beaches antidune formation can occur during subcritical backwash flow as well, due to the fact that Oregon beaches have typically larger wave heights and periods. Heavy minerals were seen to be concentrated on the upper beach portion of antidunes, an observation also invoked by Allen (1982a). Predominantly low angle planar swash laminae to massive bedding are the main elements observed in the subsurface. The observation of low angle planar swash laminae is in agreement with what has been witnessed on other Oregon beaches as well as other beaches worldwide (Clifton, 1969; Clifton et al., 1971; Hunter et al., 1979). The presence of massive bedding along the swash zone, and along the surf zone for that matter, likely results when there is a rapid drop in hydraulic energy allowing abrupt deposition of grains that were initially in suspension. If these grains are very well sorted and essentially the same size, which is evident through grain size analysis of exposed shoreface sediment along Netarts Spit, then this further increases the chance that the bedding will appear massive. The occasional presence of smaller, denser heavy sand grains is mainly what is able to bring to prominence the particular laminae structure within these zones. Massive sands can also be caused by large amounts of bioturbation; however in such a physically dominated environment the previous suggestions are more plausible or at least more dominant.

Along the surf zone of the upper shoreface, above MLLW, is the foreshore terrace. The foreshore terrace is usually transversed by at least one longshore bar and one longshore trough, with occasional rip current channels leading back out to the open ocean. The foreshore terrace of the recurved spit portion is a complicated environment where the main channel of Netarts Bay enters the ocean and includes a vast low tide terrace riddled with exposed



subaqueous dunes (referred to as megaripples by some authors) oriented in the ebb-current direction; as well as troughs mainly trending along shore or along the main channel axis. The ebb-tide is slightly more dominant than the flood-tide and an ebb-tidal delta is evident oceanward of the bay mouth opening (Glanzman et al., 1971). The large, very shallow tidal inlet that cuts across the recurved spit is hypothesized to form as a result of increased hydrodynamic flow during storm events. Upper flow regime features are more common on bars (ridges) and swash zone, while lower flow regime features are more common in the troughs (runnels). Subaqueous dunes commonly form in longshore troughs oriented in the direction of longshore flow where these currents act in their formation. Many two-dimensional, long-crested, sinuous asymmetric subaqueously formed dunes are present on the low tide terrace of the Netarts Bay recurved spit, with regions of much shorter-crested, more strongly three-dimensional linguoid to lunate dunes also present. Other authors have also mentioned these common features of the low tide terrace along the Oregon coast and referred to them as megaripples (Clifton et al., 1971; Hunter et al., 1979). These features are attributed to formation in the lower flow regime with bed configurations between that of ripples and dunes, especially if ripples are superimposed on the dune (megaripple) surface (Clifton et al., 1971; Simons et al., 1965; Allen, 1982a). During late stage drainage of the ebb tide as energy levels drop on the foreshore terrace asymmetric combined-flow ripples may form superimposed on dune crests, troughs and lee slopes, while wind generated waves can round out dune or ripple crests. In shallow water, wind generated surface waves may also have an effect in creating asymmetric wave ripples. These ripples are oriented in the direction of dominant flow at the time of formation. Current ripples are commonly seen in a concentric pattern around dune troughs and were described by Allen (1968; 1982a) as ripple fans. Coarser material often gathers in dune troughs due to the turbulent nature of that particular location on the dune. In the flume experiments of Brady and Jobson (1973) small asymmetrical ripples were

formed once the flume was turned off superimposed on the flat bed created by larger flow velocities, so in other words the sudden decrease in flow created asymmetric current ripples superimposed on the flat bed created by strong and steady flow conditions. In Netarts Bay small scale combined-flow ripples are found superimposed on planar beds in hollows between parting lineation features or on exposed subaqueously formed dunes. Therefore, it is thought that these ripples were created when flow decreased rapidly during the transition to low tide. Heavy mineral sands commonly appeared on the stoss side up to the crest of these asymmetric ripples. Heavy mineral accumulation on the crest of dunes was also a common feature. A phenomena where smaller, denser heavy mineral grains accumulate in zones of less turbulence while larger, less dense quartz grains that have a lower critical shear stress are entrained more easily and become mobile (Brady and Jobson, 1973). In areas where the tide has receded quickly and the slope of the bedform is relatively steep, rill marks sometimes occur where water oozes out and meanders along the slope face (Allen, 1982a;1982b). Gilbert (1914) first ascribed the term antidunes to standing waves observed along low tide channel run-off during low tide. Antidunes are a common feature seen on the low tide terrace of Netarts Bay. The antidunes were typically long crested two-dimensional features that occasionally moved slightly upstream or downstream, but for the most part maintained a static position. Antidunes are associated with the upper flow regime where free surface flow over erodible beds reaches supercritical values (Kennedy, 1963). In the subsurface an array of internal sedimentary structures may be present. Horizontal to low angle planar stratification is common in areas of higher flow dominated by upper flow regime plane bed features, especially on the exposed seaward face of the outer bars as mentioned previously. In areas of lower flow regime features large swaths of exposed subaqueous dunes possess internal structures consisting of tabular to trough cross stratification. Occasionally wavy to asymmetric ripple laminae are also observed owing to the presence of superimposed slightly-

strongly-asymmetric ripples on subaqueous dunes. These observations of subsurface structure are also mentioned by Clifton et al. (1971) and Hunter et al. (1971) in their studies of non-barred and barred nearshore environments of the Oregon coast, respectively.

### **Neoichnological Interpretation**

The factors that seem to have the largest control of the ecological distribution and behaviour of the Exposed Shoreface-Spits bay region are hydraulic energy and sedimentation rate. Desiccation and temperature become important factors for organism living in the upper foreshore to backshore zones. Turbidity levels are potentially locally important in areas of highly turbulent flow that continuously lift sand; however the water quality in and around Netarts Bay is relatively pristine (Shabica et al., 1976). Overall TOC values were low throughout the region, ranging from 0.03% to 0.27%, but usually in the average range of 0.12% to 0.16%. The lowest values were usually recorded from the foreshore or foreshore-backshore boundary, while the highest values were recorded from tidal run-off channels/creeks or troughs. The lack of TOC in the sediment indicates that organisms within this environment likely obtain most of their energy needs from suspension feeding vs. deposit feeding unless they are small and live in the subsurface allowing them to selectively feed on different sediment grains. Salinity recorded from one station indicated a fully marine salinity value of 35 PSU, with salinity values remaining relatively constant, therefore salinity is a nominal factor affecting ecological distribution and abundance. Due to the high energy environment and suspension of food particles the trace assemblage present across the Exposed Shoreface-Spits bay region dominantly represents that of the *Skolithos* ichnofacies.

The Exposed Shoreface-Spits bay region displays limited diversity and abundance of traces due to the highly turbulent nature of the environment. In the troughs and associated channels within the low tide terrace *Olivella*

*biplicata* was by far the most abundant tracemaker, creating *Olivellites*-like traces. *O. biplicata* is a generalist in terms of its feeding habits, although generally a deposit feeder *O. biplicata* also suspension feeds on macroscopic algae and if the opportunity allows is also a carnivore that consumes live prey (Edwards, 1969). The highly mobile gastropod is able to plough just below the sediment surface and highly favours environments possessing uniform, well-sorted, clean water laden sands of intertidal beach pools or troughs to shallow (<5m depth) subtidal reaches (Edwards, 1969); prevalent features amongst the exposed beaches of Netarts Bay spit.

Possible rapid or deep burrowing filter feeding bivalves may also be present within the troughs of the low tide terrace as is evident from bivalve shows and a possible siphon sighting; however no bivalve was actually observed. The resulting trace is a zigzag *Skolithos*-like trace; possibly *Siphonichnus*-like if a bivalve was present. However, if the bivalve was trying to readjust quickly to varying sedimentation rates or to escape potential predators, such as humans, then the trace could also be referred to as a fugichnia (escape) trace. The normally shallow burrowing suspension feeder *Siliqua patula*, found along the open coast surf zones of Oregon and Washington, is a fast burrower able to escape 15-50cm of newly deposited sediment (Fitch, 1952; Stanley, 1970; Kranz, 1974, McLachlan, 1990). Although they have short siphons and usually rest near the surface they are able to rapidly burrow to a safer depth to avoid predation by clearing a passage to the sediment-water interface via directed water jets generated by the strong mantle ("mantle fusion") of the organism (Kranz, 1974). In contrast, deeply burrowing bivalves, such as *Panopea generosa*, are for the most part sedentary and favour long periods of stability where they can extend their siphons to the surface to suspension feed (Stanley, 1970; Gingras et al., 2007). *Siliqua patula* is a likely trace making candidate because it is a bivalve capable of rapid, as well as deep, burrowing in a high energy environment where large amounts of sediment aggradation and degradation can occur (Reineck and Singh, 1973). In



areas such as the surf and swash zones of the exposed sandy beach, where high hydraulic energies and high sedimentation rates occur, there may be a shift from suspension feeding to deposit feeding as the filtering mechanisms of sedentary, suspension feeding bivalves may be hindered by the increasing amount of sediment (Rhoads and Young, 1970; Gingras et al., 2007). The strong water jets produced by highly mobile bivalves of the surf zone, such as *S. patula*, may aid in anti-filter clogging capacity during high sedimentation events, allowing these animals to thrive in this harsh environment. The gastropod *O. biplicata* also seems to thrive in this otherwise inhospitable environment, likely due to its broad feeding strategy and substrate preference.

*Nephtys* sp. was sporadically found actively swimming throughout the sediment of the bars and troughs of the low tide terrace creating cryptic bioturbation or possible navichnia structures as it disrupted sediment. Clifton (1984) was able to observe linear features highlighted by heavy mineral sands caused by the swimming movement of an errant *Nephtys* sp. polychaete through the sand. Care needs to be taken not to evoke the immediate belief that deformation seen in heavy mineral laminae highlights the result of cryptobioturbation or *Macaronichnus*-like traces. As mentioned previously deformed laminae could be the result of heavier mineral deposits sagging into fluidized sands, which is a likely occurrence in Netarts Bay along the foreshore-backshore. However, it is also likely in some instances, especially if present within the foreshore swash zone, that the deformation in heavy mineral laminae is indeed a result of bioturbation.

*Macaronichnus*-like structures and possible cryptic bioturbation observed along the foreshore of the Shoreface-Spit sub-environment are possibly the result of errant opheliid polychaetes such as *Euzonus* sp. that are common along the exposed beaches of the Oregon coast (Kemp, 1985). Clifton and Thompson (1978) observed the opheliid polychaete *Ophelia limacina* in Willapa Bay, Washington experiments where the polychaete created purely locomotory traces akin to navichnia or cryptic bioturbation and *Macaronichnus*-

like deposit feeding traces. They also noticed that the polychaete only ingested grains with rough surface texture, such as quartz and feldspar, while leaving a thin lining around their feeding trail of the rejected smoother grains such as micas and heavy minerals. This feeding strategy may explain the pattern observed in PVC core from Netarts Bay along the foreshore that displays almost crenulate, through to ovate or circular, patches of light sands in otherwise disrupted heavy mineral sand laminae layers. It is possible that *Ophelia* sp. is present on the Netarts Bay spit as it prefers the clean sands of spits and can be locally abundant (Shabica et al., 1976; Rudy and Rudy, 1983). It is also possible that *Excirolana* sp. is present and creates a *Macaronichnus*-like trace (Shabica et al., 1976; Nara and Seike, 2004).

*Emerita analoga* was locally abundant and almost strictly observed along the intertidal surf-swash boundary at the base of the foreshore during low tide, an observation also shared by Dugan et al. (2000) and Jaramillo et al. (2000). When *E. analoga* was exposed it created *Cruziana*- to *Diplichnites*-like surface traces before burrowing rapidly backwards into the sediment where the filter feeder rested just below the surface possibly creating cubichnia with slight scratch marks. The suspension feeding *E. analoga* is able to thrive in a harsh physical environment partly due to its ability to burrow rapidly. The unconsolidated, uniform and sometimes thixotropic nature of the very well sorted sand of the upper shoreface to foreshore environment makes it easier for these organisms and other rapidly burrowing creatures to burrow (Dugan et al., 2000, Jaramillo et al., 2000). Animals that are substrate generalists (*sensu* Alexander et al., 1993), such as *E. analoga*, are able to burrow rapidly in a larger range of grain sizes relative to a substrate specialist whom is unable to cope with large ranges or changes in grain size and has difficulty burrowing in grain sizes outside its narrow, optimal range (Dugan et al., 2000, Jaramillo et al., 2000). However, the sands of the exposed sandy intermediate beaches of Netarts spit and the Bay Mouth North Foreshore sub-environment are very well sorted, uniform, upper fine- to lower medium-grained sands. Thereby

potentially allowing some substrate specialists to burrow rapidly and thrive, which may be the case for some isopods or beach crustaceans (Dugan et al., 2000).

Clark and Haderlie (1962) discovered a similar association of locally abundant *E. analoga*, with sporadic (up to 4-8/m<sup>2</sup>, but usually less) *Nephtys californiensis*, and common opheliid polychaetes on multiple exposed sandy California beaches with a grain size ranging from upper fine- to upper medium-grained sand. In Coos Bay, Oregon Edwards (1969) noted the main beach fauna, from most abundant to least abundant, as *O. biplicata*, *S. patula*, opheliid polychaetes, other polychaetes, and amphipods, amongst other smaller numbers of organisms. This observation is comparable to what is observed on the exposed sandy beaches of Netarts Spit and north of the bay mouth opening if inferred organisms such as *S. patula* and foreshore opheliids or isopods are actually present.

A juvenile *Cancer* sp. crab and juvenile amphipod were witnessed resting just below the surface within the tidal creek (trough) of Bay Mouth North Foreshore sub-environment. Hauck (2008) was able to note that rock crabs disturb the sediment around them as they burrow only up to their eyestalks. The juvenile *Cancer* sp. crab and amphipod likely created faint resting (cubichnia) trace; however the trace was likely destroyed or only left behind a slight disruption structure. The rocky tidal creek likely acted as a protected environment for such vulnerable creatures in an otherwise tumultuous environment.

The talitrid amphipods *Megalorchestia californiana* and *Traskorchestia traskiana*, as well as tenebrionid beetles, were common supratidal tracemakers present from the foreshore-backshore boundary into the backshore. *Skolithos*-like traces were the main trace forms of these organisms, with *M. californiana* also creating small J-shaped *Psilonichnus*-like traces and *T. traskiana* potentially creating cryptic bioturbation as well. Pelletier et al. (2011) noticed that *M. californiana* was usually present in the upper foreshore as it follows the ebb

tide out along the foreshore, possibly in search of fresh wrack deposits, only to return to their burrows near the driftline at the foreshore-backshore boundary as the tide rises again, rarely venturing into the supralittoral zone. In contrast, *T. traskiana* was found to highly favour the supralittoral zone, feeding on and living under dried wrack, while tending to avoid moist substrate seaward (Pelletier et al., 2011). Koch (1991) indicates that *T. traskiana* is a “non-substratum modifying talitrid amphipod”, but it was observed along the backshore of Netarts Spit and the Bay Mouth North Foreshore sub-environment in the subsurface. *T. traskiana* was observed in a burrow that looked like that of *M. californiana* and in another instance a couple centimetres below the sediment with no discernable trace around it. However, it is possible that the *T. traskiana* witnessed at Netarts could have passively occupied the burrows of *M. californiana* or accidentally been caught beneath the sediment surface. On the other hand, a similar burrowing amphipod *Talorchestia longicornis* was noted by Dashtgard and Gingras (2005) as the creator of multiple small unlined *Skolithos*-like traces along a New Brunswick beach, furthering the substantiality that *T. traskiana* is an active burrower. Another possible tracemaker common along the American west coast, although not observed in this particular area, is *Excirolana* sp. that burrows along the high tide mark and come out of their burrows only to feed at high tide (Enright, 1972; Klapow, 1972).

## **OUTER SHELTERED SANDY TIDAL FLAT BAY REGION DESCRIPTION AND RESULTS**

### **Morphological and Sedimentological Features**

#### ***Sand Flat High Sub-Environment***

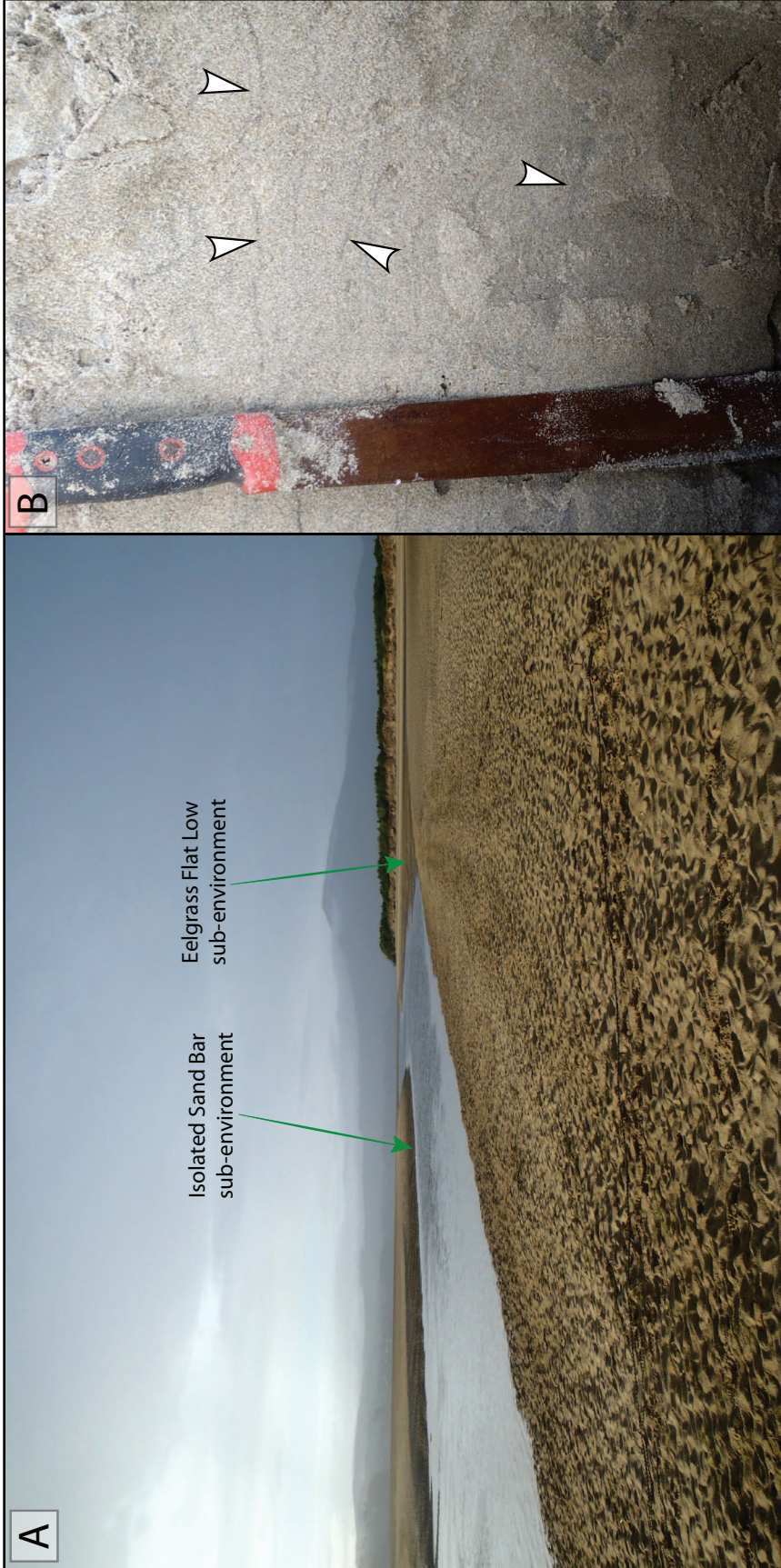
The Sand Flat High transect is split into three main zones. Firstly, a sandy ridge zone bordering the tidal channel that quickly grades into an extensive sandy tidal flat zone that dominates most of the sub-environment. The extensive sandy tidal flat zone is defined by subtle rolling topography with thixotropic sands in the exposed highs and standing water in the lows. This



area is also referred to as the ridge and furrow zone. The ridges and furrows are oriented sub-perpendicular, at an angle of almost 45°, to a prominent secondary tidal channel at the beginning of the Sand Flat High transect. The final zone consists of an upper tidal flat to supratidal area. Grain size and TOC measurements were not sampled for the supratidal region, with only surface observations recorded. Coarsest sediment occurred along the tidal channel bank, while the finest sediments mainly occurred in the ridge and furrow zone where extensive burrows were common, especially from bottom sediments. Sand dollar test fragments, whole cockle shell fragments, various disarticulated shell fragments and seaweed fragments were discovered scattered across the ridge and furrow zone. Various seaweed species were sporadically seen *in situ* across the ridge and furrow zone as well.

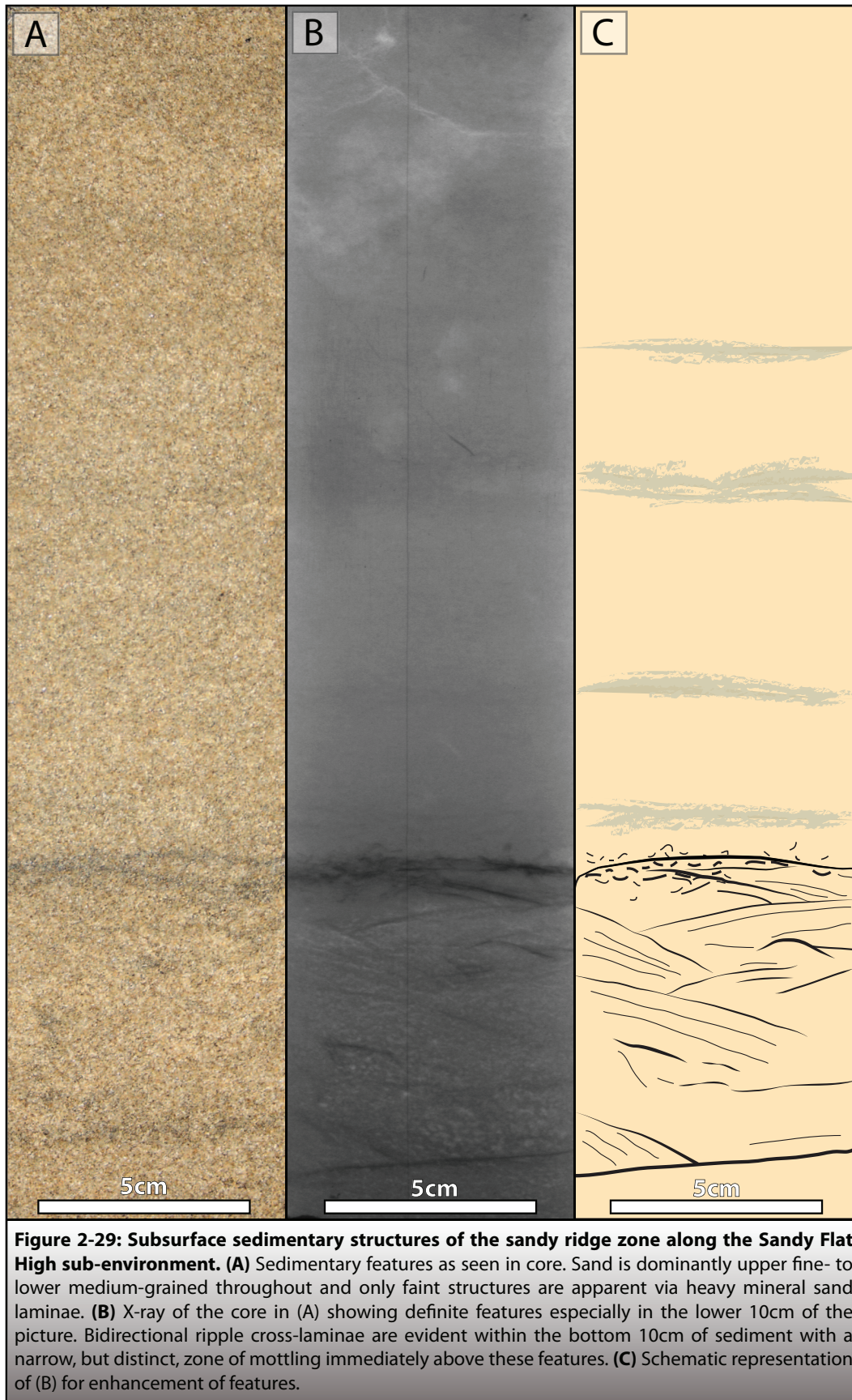
Ripples on the ridge are dominantly linguoid, although sinuous ripples were also observed in some instances (Fig. 2-28A). Bubble escape structures appear within the upper 5cm of sediment. The very well drained, porous sand crumbled easily upon trenching. However, the sand quickly stabilized after the first 5-10cm below the surface once it became more compact and moist allowing for observation of subsurface features. Current- and wave-generated ripple laminae were present within the top 20cm of sediment at the highest point of the ridge (Fig. 2-28B). A slight shoreward shift revealed bidirectional ripple cross laminae as was evident from PVC core X-ray analysis (Fig. 2-29A,B,C). These cross laminae began 20cm below the surface and continued downward at least another 10cm. Above these cross laminae the sands appear to be massive, although wavy laminae were evident in the trenches constructed.

In the vast majority of the ridge and furrow tidal flat zone planar to slightly current- to dominantly wave-generated cross laminated sands are seen in the subsurface and are primarily evident 15cm below the surface or lower. Bioturbation is quite prevalent in this zone and therefore the sands may appear massive with any primary structures seen appearing mottled. Anoxic to



**Figure 2-28: Morphology and sedimentology of the sandy ridge zone along the Sand Flat High sub-environment.** (A) View looking SSE along the sandy tidal ridge of the Sand Flat High sub-environment. Note dominantly linguoid ripples on the surface. In the midground is the protected channel with the Isolated Sand Bar sub-environment bordering it to the left and the Eelgrass Flat Low sub-environment bordering it to the right. Just left of the photograph is where the protected channel merges with the exposed channel at the point of the Isolated Sand Bar sub-environment. Field of view at the bottom of the picture is approximately 3m. (B) Subsurface sedimentary features of the sandy tidal ridge. Notice slight wavy laminae as indicated by white arrows. Machete part exposed in photograph is approximately 45cm long.





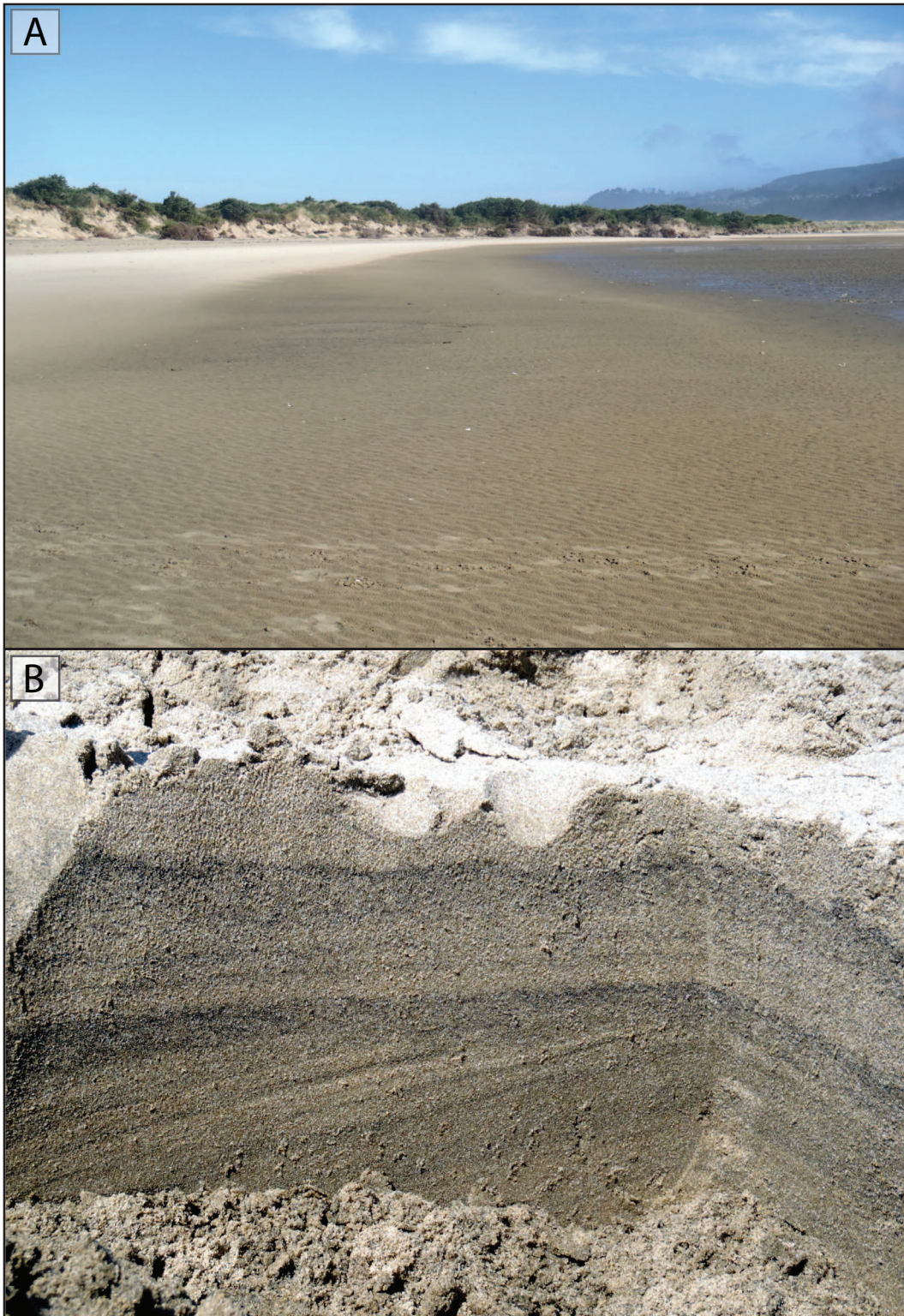
**Figure 2-29: Subsurface sedimentary structures of the sandy ridge zone along the Sandy Flat High sub-environment. (A)** Sedimentary features as seen in core. Sand is dominantly upper fine- to lower medium-grained throughout and only faint structures are apparent via heavy mineral sand laminae. **(B)** X-ray of the core in (A) showing definite features especially in the lower 10cm of the picture. Bidirectional ripple cross-laminae are evident within the bottom 10cm of sediment with a narrow, but distinct, zone of mottling immediately above these features. **(C)** Schematic representation of (B) for enhancement of features.

suboxic sediment, which is almost black to grey in colour, respectively, is common 5-10cm below the surface within the ridge and furrow zone. Sinuous to linguoid ripples are common upon the ridge and furrow topography, but extensive burrow openings and recent rain drops mask the definition of surface ripples.

Small linguoid ripples along the base of the upper tidal flat quickly graded to sinuous ripples and then to smooth planar sands up-dip along the inclined upper tidal flat surface (Fig. 2-30A). In the lower part of the upper tidal flat-supratidal zone, along the lower edge of the inclined upper tidal flat face, planar to slight current- to mainly wave-generated ripple laminae were common in the upper 5-7cm of sand that became mottled to non-existent further below due to bioturbation. Suboxic sediment is still present in some pockets at various depths below the surface in the lower inclined face of the upper tidal flat area. Half way up the inclined upper tidal flat face the laminae became mainly planar to inclined planar with a distinct increase in the amount of heavy mineral sand defined laminae, especially in the upper 5-10cm of sediment with bioturbation increasing below causing mottling of laminae and occasionally complete obliteration of primary sedimentary structure. A trench was dug revealing forests below a set of planar laminated sands along the middle upper tidal flat (Fig. 2-30B). At the upper part of the upper tidal flat inclined planar laminae were defined by even greater amounts of heavy mineral sand with amount of bioturbation decreasing, but with mottling of sand still present. The supratidal zone was not trenched or sampled but small sinuous aeolian ripples were surficially common.

Average grain size across the Sand Flat High sub-environment was dominantly upper fine- (59.11 wt%) to lower medium- (30.19 wt%) grained sand; top sediments ranged from dominantly 56.38 wt% upper fine-grained sand to 33.59 wt% lower medium-grained sand, while bottom sediments ranged from dominantly 61.84 wt% upper fine-grained sand to 26.80 wt%





**Figure 2-30: Morphology and sedimentology of the upper intertidal flat zone along the Sand Flat High sub-environment. (A)** Lower upper intertidal (dark beige) and upper upper intertidal (light beige). View looking NNW. Along the upper intertidal ripples grade quickly from small linguoid to small sinuous crested ripples. Field of view along bottom of photograph is about 3m. **(B)** Trench showing foresets within the middle upper intertidal area. Note planar bedding on top and inclined planar below. Heavy mineral sands help define laminae especially at the top of each set. Trench is approximately 35cm deep.

Table 2-3: Summary of Sedimentological and Physico-Chemical Characteristics of the Outer Sheltered Sandy Tidal Flat Bay Region					
Sub-Environment	Sedimentological and Physico-Chemical Properties				
	Common Sedimentary Features	Sediment Analysis	TOC (%)	Salinity (PSU)	Average Overall Grain Size (wt%)
<b>Sand Flat High</b>	<p><b>Sandy ridge zone:</b> Combined tidal current-wave generated sinuous to linguoid crested ripples dominate the surface. Subsurface displays wavy ripple laminae in the upper 20cm with bubble porosity within the uppermost 5-10cm. Bidirectional cross laminae is evident below 20cm. <b>Ridge and furrow zone:</b> Dominantly wave generated, slightly tidal current generated sinuous to linguoid crested ripples present upon undulatory topography but high burrow density masks ripple structure. In the subsurface mottled to massive appearing sands evident in upper 15cm with planar to cross laminated sands becoming evident below 15 cm. <b>Foreshore-backshore zone:</b> Planar surface with inclined planar slightly mottled laminae evident in the subsurface of the foreshore. Heavy mineral sand laminae achieve greatest concentration at foreshore-backshore boundary. Small, sinuous aeolian formed ripples common in the backshore. Bioturbation common to abundant across sub-environment.</p>	<p>Very well sorted, coarse skewed, mesokurtic, dominantly upper fine grained sand (0.29φ, -0.11Sk, 1.00K, 2.10M)</p>	<p>Lowest Value (0.08) Highest Value (0.28) Top Average (0.11) Bottom Average (0.16) <b>Overall Average (0.14)</b></p>	--	<p>Upper medium grained sand to granule (1.2) Lower medium grained sand (30.2) Upper fine grained sand (59.1) Lower fine grained sand (8.7) Upper very fine grained sand to silt/clay (0.8)</p>
<b>Eelgrass Flat Low</b>	<p><b>Protected channel ridge and furrow zone:</b> Ridge and furrows sub-perpendicular to tidal channel. Sinuous ripples common in furrows, linguoid ripples common on ridges. Subsurface displays wavy combined flow ripple laminae. <b>Sandy tidal flat zone:</b> Sinuous to linguoid crested ripples taper off to planar surface shoreward. In the subsurface wavy ripple laminae give way to massive to mottled bedding. <b>Hummocky eelgrass tidal flat zone:</b> eelgrass common on otherwise planar to hummocky surface. Mottled to massive bedding in the subsurface. <b>Foreshore-backshore zone:</b> Planar surface features with inclined planar to slightly mottled laminae in the subsurface of the foreshore. Heavy mineral sand laminae achieve greatest concentration at foreshore-backshore boundary. Small, sinuous aeolian formed ripples common in the backshore. Bioturbation common to abundant across sub-environment.</p>	<p>Well sorted, near symmetrical, leptokurtic, dominantly upper fine grained sand (0.39φ, 0.05Sk, 1.41K, 2.18M)</p>	<p>Lowest Value (0.10) Highest Value (1.06) Top Average (0.37) Bottom Average (0.18) <b>Overall Average (0.28)</b></p>	32.5	<p>Upper medium grained sand to granule (1.3) Lower medium grained sand (24.2) Upper fine grained sand (56.7) Lower fine grained sand (11.5) Upper very fine grained sand to silt/clay (6.3)</p>



Table 2-3: Summary of Sedimentological and Physico-Chemical Characteristics of the Outer Sheltered Sandy Tidal Flat Bay Region (continued)						
Environment	Sedimentological and Physico-Chemical Properties					
	Common Sedimentary Features	Sediment Analysis	TOC (%)	Salinity (PSU)	Average Overall Grain Size (wt%)	
Isolated Sand Bar Sub-Environment	Protected Channel Sand	Tidal channel bank: Dominantly linguoid crested ripples on the surface. Subsurface consisted of horizontal to inclined planar laminae, combined flow ripple laminae and climbing ripple trough cross laminae. Tidal ridge: Combined flow sinuous to linguoid crested ripples common on the surface. Subsurface same as the tidal channel bank except climbing ripple trough cross laminae less evident. Sand flat saddle: Dominantly sinuous crested ripples on the surface. Subsurface displayed combined flow ripple laminae to massive sands. Sediment disruption common at 15cm depth or greater. Bubble porosity common in uppermost 5-10cm. Bioturbation common.	Very well sorted, near symmetrical, leptokurtic; dominantly upper fine grained sand (0.29φ, -0.03Sk, 1.28K, 2.25M)	Lowest Value (0.14) Highest Value (0.22) Top Average (0.15) Bottom Average (0.19) <b>Overall Average (0.17)</b>	34.5	Upper medium grained sand to granule (1.2) Lower medium grained sand (16.5) Upper fine grained sand (66.2) Lower fine grained sand (15.0) Upper very fine grained sand to silt/clay (1.1)
	Exposed Channel Sand	Tidal channel bank: Steep planar to scoured walls dominate the surface. Subsurface dominated by horizontal to inclined planar laminae and combined flow ripple laminae with occasional climbing ripple trough cross laminae. Tidal ridge: Combined flow sinuous to linguoid crested ripples common on the surface. Climbing ripple trough cross laminae and combined flow ripple laminae dominate. Sand flat saddle: Dominantly sinuous crested ripples on the surface. Subsurface displayed combined flow ripple laminae to massive sands with sediment disruption common at 15cm depth or greater. Bubble porosity common in uppermost 5-10cm. Bioturbation common.	Very well sorted, near symmetrical, leptokurtic; dominantly upper fine grained sand (0.29φ, -0.03Sk, 1.32K, 2.25M)	Lowest Value (0.12) Highest Value (0.29) Top Average (0.19) Bottom Average (0.17) <b>Overall Average (0.18)</b>	34	Upper medium grained sand to granule (1.1) Lower medium grained sand (16.5) Upper fine grained sand (66.9) Lower fine grained sand (14.2) Upper very fine grained sand to silt/clay (1.4)
	Mixed Channel Sand Flat	Lower sand flat: Linguoid ripples dominate the surface. Subsurface dominated by distinct bidirectional combined flow ripple tabular to trough cross laminae. Upper sand flat ridge: Combined flow sinuous to linguoid crested ripples common on the surface. Inclined planar laminae to combined flow wavy ripple laminae common in subsurface with sediment disruption becoming more common. Sand flat saddle: Dominantly sinuous crested ripples on the surface. Subsurface same as upper sand flat ridge except massive bedding more common due to sediment disruption from bioturbation. Bubble porosity common in uppermost 5-10cm. Bioturbation common.	Very well sorted, near symmetrical, leptokurtic; dominantly upper fine grained sand (0.29φ, -0.015k, 1.28K, 2.25M)	Lowest Value (0.08) Highest Value (0.22) Top Average (0.12) Bottom Average (0.14) <b>Overall Average (0.13)</b>	34	Upper medium grained sand to granule (0.9) Lower medium grained sand (15.7) Upper fine grained sand (66.3) Lower fine grained sand (15.8) Upper very fine grained sand to silt/clay (1.4)

lower medium-grained sand (Table 2-3). There is also a sizeable proportion of lower fine-grained sand (7-12 wt%) at the majority of stations.

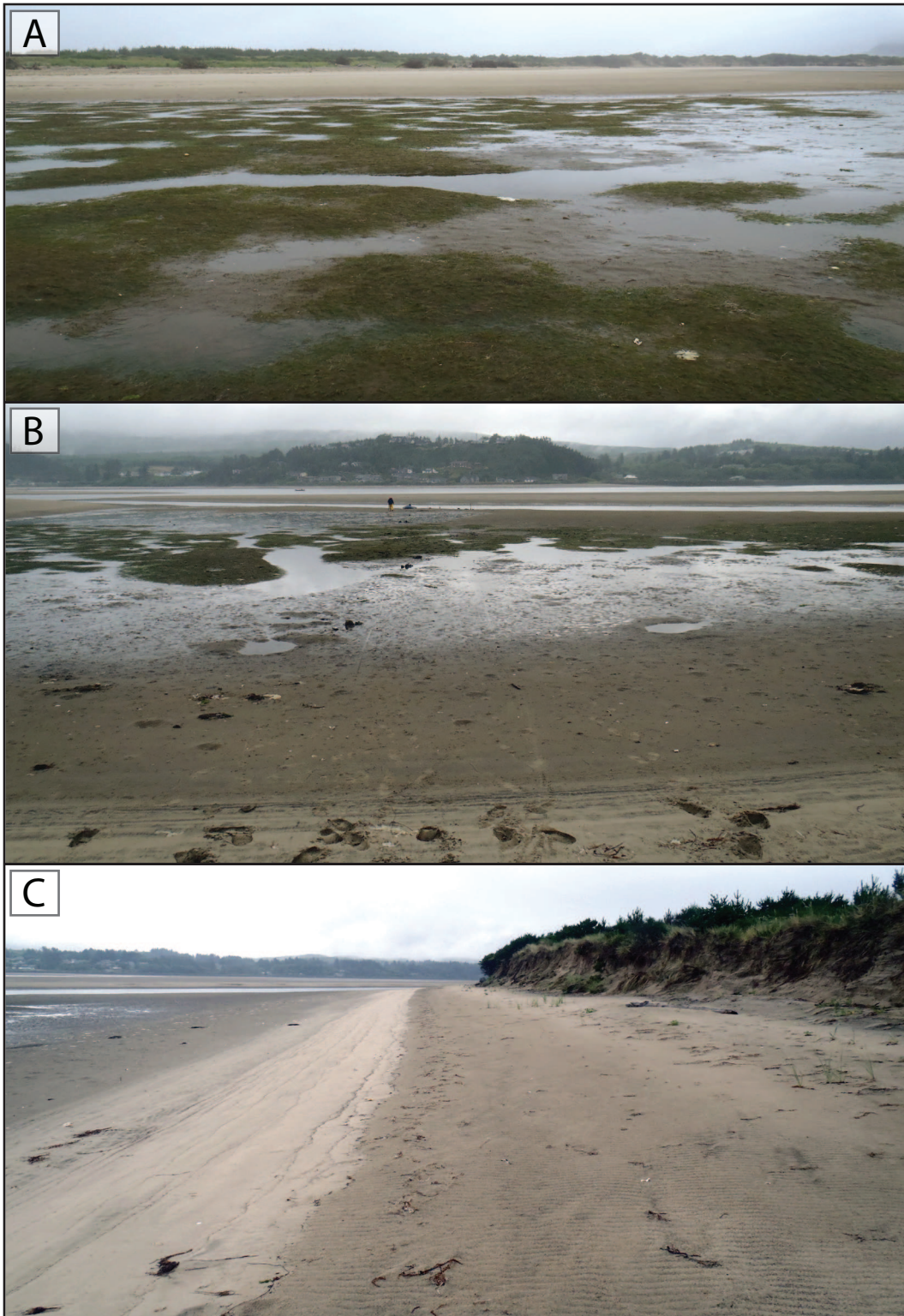
Grain size analysis indicates that overall, the grains of the Sand Flat High sub-environment are very well sorted (inclusive standard deviation (Folk, 1974): 0.29 $\phi$ ), coarse skewed (inclusive graphic skewness (Folk, 1974): -0.115k), mesokurtic (graphic kurtosis (Folk, 1974): 1.00K), dominantly upper fine-grained sand with a mean size of 2.10M (graphic mean (Folk, 1974)) (Table 2-3).

### ***Eelgrass Flat Low Sub-Environment***

The Eelgrass Flat Low sub-environment is split into four main zones with overall morphology evident in Figure 2-31 (A, B, C). A protected tidal channel ridge and furrow zone quickly grades shoreward into a sandy tidal flat zone. This in turn eventually grades into a hummocky eelgrass tidal flat zone, and finally into an all too familiar steeper dipping upper intertidal flat and gently dipping supratidal zone. The small ridge and furrow features along the protected tidal channel are sub-perpendicular to the channel axis, occurring on both channel banks. Grain size and TOC measurements were not sampled for the supratidal region, with only surface observations recorded. The coarsest sediment occurred at the edge of the tidal channel, while the finest sediment mainly occurred in the eelgrass flat zone where diverse and extensive burrows were common. Finest grained sediments were found from top sediment samples in the middle of the eelgrass flat, which coincided with the location of highest TOC levels from this sub-environment. Over the course of the sub-environment lower medium-grained sands decreased while the upper fine-grained sands increased in terms of weight percentage, relative to the other sub-environments of this region.

Sinuuous to linguoid ripples were common at the surface extending from the protected channel until halfway between the channel and eelgrass tidal flat. Afterward, the ripples tapered off quickly and the surface became flatter until eventually leading into the hummocky eelgrass tidal flats. After the





**Figure 2-31: Overall morphology of the Eelgrass Flat Low sub-environment.** Field of view at the bottom of pictures is approximately 3m. **(A)** View looking NW with eelgrass meadow in the foreground and ridge that extends onto the Sand Flat High sub-environment in the background. **(B)** View looking east with person for scale in the distance along the protected channel. Can see the progression from sand flat to hummocky eelgrass flat to foreshore. **(C)** View looking SE along the upper intertidal flat-supratidal boundary. Ballistic ripples common along the supratidal zone.

eelgrass zone the sediment surface was essentially featureless, with a steeply dipping short upper tidal flat. The supratidal zone consists of a small area dominated by small aeolian surface ripples before abruptly encountering a cut face of grass covered dunes along the spit.

Current- and wave-generated ripple (combined flow ripple) laminae were common in the subsurface near the protected tidal channel bank areas but quickly tapered off to massive appearing, mainly bioturbated sands until the upper intertidal flat. Slightly current- and dominantly wave-generated ripple cross-laminae were present at the boundary between tidal flat and inclined upper intertidal flat, while horizontal to low angle planar laminae dominated the rest of the upper intertidal flat.

At the edge of the relatively calm, protected, secondary tidal channel the top 5cm of sediment appeared oxic and therefore beige in colour while the sediment below 5cm was suboxic to anoxic displaying a dark grey to black colour, respectively. A 15m long trench was dug perpendicular to the channel edge showing the progression of an anoxic lens. Along the sandy tidal flat zone the upper 30cm of sediment appeared oxic; however this anoxic lens quickly widened channel-ward and the anoxic zone was observed only in the upper 5cm of sediment around the channel bank. The eelgrass flats began halfway through the sub-environment and were composed mainly of the invasive Japanese Eelgrass (*Zostera japonica*). The eelgrass possessed slight hummocky topography, partly a result from previous clam diggers, and tapered off just shy of the upper intertidal flat zone. Anoxic, organic rich sediment is dominant in the subsurface of the eelgrass flats. Occasionally 1cm thick horizons were seen which were composed almost entirely of black organic matter. Rootlets were common within the upper 5-7cm of sediment.

Average grain size across the Eelgrass Flat Low sub-environment was dominantly upper fine- (56.70 wt%) to lower medium- (24.24 wt%) grained sand; top sediments ranged from dominantly 53.43 wt% upper fine-grained sand to 22.70 wt% lower medium-grained sand, while bottom sediments

ranged from dominantly 59.98 wt% upper fine-grained sand to 25.79 wt% lower medium-grained sand (Table 2-3). There is also a sizeable proportion of lower fine-grained sand (6-21 wt%) from all of the samples. The samples that had the lowest amount of lower fine-grained sand (less than 10 wt%) were observed at the main channel, from bottom sediments before the eelgrass field started, and lastly from the bottom sediment of the upper intertidal flat-supratidal boundary.

Grain size analysis indicates that overall, the grains of the Eelgrass Flat Low sub-environment are well sorted (inclusive standard deviation (Folk, 1974):  $0.39\phi$ ), near symmetrical (inclusive graphic skewness (Folk, 1974):  $0.05Sk$ ), leptokurtic (graphic kurtosis (Folk, 1974):  $1.41K$ ), dominantly upper fine-grained sand with a mean size of  $2.18M$  (graphic mean (Folk, 1974)) (Table 2-3).

#### ***Isolated Sand Bar Sub-Environment***

The Protected Channel Sand Flat micro-environment was continuous with the Exposed Channel Sand Flat micro-environment. The two micro-environments joined within the central part of the saddle of the sand flat. The edges of the saddle were defined by sand ridges that marked the highest points along each transect, bound by tidal channel banks (Fig. 2-32A). The Protected Channel Sand Flat bank was less steep grading into a protected, lower energy, tidal channel, while the Exposed Channel Sand Flat bank was steeper dipping into an exposed, higher energy, tidal channel (Fig. 2-32A). Along the protected channel bank a series of ridges and furrows were oriented obliquely to the channel, while the bank along the exposed channel was scoured (Fig. 2-32A). The Mixed Channel Sand Flat Point micro-environment, which bisects the Protected Channel Sand Flat and Exposed Channel Sand Flat micro-environments (Fig. 2-32B), is composed of three main zones: The lower sand flat, the upper sand flat ridge and finally the saddle zone where it bisects the other two micro-environments. Overall, sinuous to linguoid ripples were the surface features present along the Isolated Sand Bar sub-environment, with





**Figure 2-32: Morphology of the Isolated Sand Bar sub-environment. (A)** View looking SE of the Isolated Sand Bar sub-environment looking parallel down the Mixed Channel micro-environment and perpendicular to the Exposed Channel and Protected Channel micro-environments. Note the steeper bank along the exposed channel on the left side of the bar and the gentler dipping bank along the protected channel to the right displaying slight ridge and furrow (undulatory) topography. Sinuous to linguoid ripple are observed on the sediment surface with sinuous ripples more common on the higher saddle flat zone while the linguoid ripples are more common on the lower sandy areas and along tidal channel banks. Field of view along bottom of photo is ~3m. **(B)** View looking NE showing the point of the Isolated Sand Bar sub-environment where the protected tidal channel and exposed tidal channel converge. Linguoid ripples are common surface features. Shovel for scale is ~1.1m tall.



sinuous ripples more common on the higher saddle flat zone and linguoid ripples common on lower sandy areas along the tidal channel banks (Fig. 2-32A,B). Across most of this sub-environment heavy mineral sand laminae helped define sedimentary structures.

Along the protected tidal channel of the Protected Channel Sand Flat micro-environment light beige oxic sands are present within the top 15cm with a dark grey to black suboxic to anoxic zone below. There was a gradational change between oxic and suboxic sand. Sand only appeared suboxic to anoxic near the protected tidal channel, while the rest of the micro-environment displayed oxic sands within the trenches dug. A sporadic layer composed of organic material, such as wood fragments and fish vertebrae, were encountered 30cm below the surface at the low tide mark. In the subsurface horizontal planar- to inclined planar-laminae to combined flow ripple laminae were visible in addition to climbing ripple-trough cross laminae along the tidal channel bank. At the top of the sand ridge flanking the protected tidal channel bank there were occasional climbing ripple-trough cross laminae; however horizontal planar- to slightly inclined planar- and combined flow ripple laminae became more abundant. The most common sedimentary structures observed in the subsurface of the saddle area were wavy to combined flow ripple laminae in addition to relatively thick intervals of massive appearing sands (Fig. 2-33A). Sediment disruption also became common in the subsurface beneath the ridge and saddle, particularly in the saddle at depths greater than 15cm. Sand was also quite vesicular, commonly in the upper 5-10 cm within the ridge and saddle areas of the Protected and Exposed Channel Sand Flat micro-environments.

Along the exposed tidal channel inclined planar laminae to combined flow ripple laminae appeared in the subsurface along with occasional climbing ripple-cross laminae. Planar laminae to wavy ripple laminae dominated the upper 10cm of sediment along the exposed channel bank with massive sands present below (Fig. 2-33B). Sediment disruption structures were also present



**Figure 2-33: Subsurface sedimentary features along the Isolated Sand Bar sub-environment.** Machete in photographs is approximately 55cm long for scale. **(A)** Wavy laminae were commonly observed along the saddle zone. Note sub-horizontal burrow 1.5cm in diameter created by *Neotrypaea californiensis* as indicated by the white arrow. **(B)** Inclined parallel laminae is commonly observed in the subsurface along the exposed channel bank with slightly wavy laminae apparent in the uppermost 5cm.

along the tidal channel bank. Combined flow ripple laminae, and climbing ripple trough cross laminae became evident further up the channel bank near the ridge, particularly in the upper 15cm of sediment. Massive to disrupted combined flow ripple laminae dominated the subsurface in the transitional area between ridge and saddle.

The lower sand flat zone of the Mixed Channel Sand Flat micro-environment displays distinct bidirectional cross laminae. These laminae were typically tabular in nature but occasionally were expressed as trough cross laminae. Sediment disruption became apparent in the upper sand flat ridge zone, becoming most common at and after the boundary between the upper sand flat ridge zone and saddle zone. In areas of heavy sediment disruption bedding appeared massive. Inclined planar laminae to combined flow ripple laminae were common in the upper sand flat ridge zone when not disrupted, steadily declining in appearance saddleward. Sediment disruption features dominated the saddle zone and therefore precise identification of laminae or bedding features was difficult. Combined flow ripple laminae were occasionally present in the upper 10cm of sediment.

Average grain size across the Protected Channel Sand Flat micro-environment was dominantly upper fine- (66.22 wt%) to lower medium- (16.51 wt%) grained sand; top sediments ranged from dominantly 68.35 wt% upper fine-grained sand to 20.70 wt% lower medium-grained sand, while bottom sediments ranged from dominantly 64.10 wt% upper fine-grained sand to 20.45 wt% lower fine-grained sand (Table 2-3). There is a noticeable grain size difference between top and bottom sediments where the top sediments, ranging from dominantly upper fine- to lower medium-grained sand, are slightly larger than bottom sediments, which had dominantly lower fine- to upper fine-grained.

Average grain size across the Exposed Channel Sand Flat micro-environment was dominantly upper fine- (66.86 wt%) to lower medium- (16.51 wt%) grained sand; top sediments ranged from dominantly 69.36 wt% upper



fine-grained sand to 16.72 wt% lower medium-grained sand, while bottom sediments ranged from dominantly 64.37 wt% upper fine-grained sand to 16.31 wt% lower medium-grained sand (Table 2-3). Although there was a sizable proportion of lower fine-grained sand (9-18 wt%), most stations were dominated by upper fine- to lower medium-grained sand except the bottom sediments located in the middle of the tidal flat furthest from the channel where the Protected and Exposed Channel micro-environments conjoin.

Average grain size across the Mixed Channel Sand Flat micro-environment was dominantly upper fine- (66.28 wt%) to lower fine- (15.76 wt%) grained sand with a sizable proportion of lower medium-grained sand (15.67 wt%); top sediments ranged from dominantly 68.35 wt% upper fine-grained sand to 17.98 wt% lower medium-grained sand, while bottom sediments ranged from dominantly 64.20 wt% upper fine-grained sand to 19.51 wt% lower fine-grained sand (Table 2-3). There appears to be a slight trend where sediments become progressively coarser ever so slightly away from the sand flat point onto the sand flat ridge.

Grain size analysis indicates that overall, the grains of the Protected Channel Sand Flat micro-environment are very well sorted (inclusive standard deviation (Folk, 1974): 0.29  $\phi$ ), near symmetrical (inclusive graphic skewness (Folk, 1974): -0.03Sk), leptokurtic (graphic kurtosis (Folk, 1974): 1.28K), dominantly upper fine-grained sand with a mean size of 2.25M (graphic mean (Folk, 1974)) (Table 2-3).

Grain size analysis indicates that overall, the grains of the Exposed Channel Sand Flat micro-environment are very well sorted (inclusive standard deviation (Folk, 1974): 0.29  $\phi$ ), near symmetrical (inclusive graphic skewness (Folk, 1974): -0.03Sk), leptokurtic (graphic kurtosis (Folk, 1974): 1.32K), dominantly upper fine-grained sand with a mean size of 2.25M (graphic mean (Folk, 1974)) (Table 2-3).

Grain size analysis indicates that overall, the grains of the Mixed Channel Sand Flat micro-environment are very well sorted (inclusive standard



deviation (Folk, 1974): 0.29  $\phi$ ), near symmetrical (inclusive graphic skewness (Folk, 1974): -0.01Sk), leptokurtic (graphic kurtosis (Folk, 1974): 1.28K), dominantly upper fine-grained sand with a mean size of 2.25M (graphic mean (Folk, 1974)) (Table 2-3).

### **Total Organic Carbon and Salinity Values**

#### ***Sand Flat High Sub-Environment***

Average TOC over the Sand Flat High sub-environment transect was 0.14% with average top TOC values at 0.11% and average bottom TOC values at 0.16% (Table 2-3). Top TOC values were lower than bottom TOC values except for at the end of the ridge and furrow zone directly adjacent to the steeper dipping upper intertidal flat. The lowest TOC value obtained was 0.08% from the top sediment in the middle of the ridge and furrow zone, with the highest TOC value of 0.28% obtained from the bottom sediment, also in the middle of the ridge and furrow zone.

#### ***Eelgrass Flat Low Sub-Environment***

Average TOC over the Eelgrass Flat Low sub-environment transect was 0.28% with average top TOC values at 0.37% and average bottom TOC values at 0.18% (Table 2-3). Top TOC values were higher than bottom TOC values except for at the edge of the protected tidal channel. At one location, 15m spitward from the protected tidal channel, top and bottom TOC values were equal. The lowest TOC value obtained was 0.10% from bottom sediment of the upper intertidal flat-supratidal boundary, with the highest TOC value of 1.06% obtained from top sediment in the middle of the eelgrass flat zone. A salinity measurement of 32.5 PSU was analyzed from water taken from the base of the upper intertidal flat area (Table 2-3).

### ***Isolated Sand Bar Sub-Environment***

Average TOC over the Protected Channel Sand Flat micro-environment transect was 0.17% with average top TOC values at 0.15% and average bottom TOC values at 0.19% (Table 2-3). Top TOC values were lower than bottom TOC values at each respective station. The lowest TOC value obtained was 0.14% from the top sediment halfway up the protected tidal channel bank, with the highest TOC value of 0.22% obtained from the bottom sediment, at the crest of the protected tidal channel bank ridge. A salinity measurement of 34.5 PSU was analyzed from water taken from the low tide mark along the protected tidal channel bank.

Average TOC over the Exposed Channel Sand Flat micro-environment transect was 0.18% with average top TOC values at 0.19% and average bottom TOC values at 0.17% (Table 2-3). The lowest TOC value obtained was 0.12% from the top sediment halfway up the exposed tidal channel bank, with the highest TOC value of 0.29% obtained from the top sediment just along the sand flat saddle edge next to the crest of the exposed tidal channel bank ridge. A salinity measurement of 34 PSU was analyzed from the low tide mark along the exposed tidal channel bank.

Average TOC over the Mixed Channel Sand Flat micro-environment transect was 0.13% with average top TOC values at 0.12% and average bottom TOC values at 0.14% (Table 2-3). The lowest TOC value obtained was 0.08% from the top sediment along the sand flat ridge, with the highest TOC value of 0.22% obtained from the bottom sediment, near the point. A salinity measurement of 34 PSU was analyzed from water taken from the low tide mark at the point of the sandy tidal flat.

## Neoichnological Characteristics

### *Sand Flat High Sub-Environment*

On the sand ridge burrows with raised openings were often encountered. Burrow density on the sand ridge comprised 3 burrow openings/50cm<sup>2</sup>, with these burrows solely being constructed by the Bay Ghost Shrimp (*Neotrypaea californiensis*). *N. californiensis* was typically found 50cm below the sediment surface in this area around the water table mark. Sub-vertical, unlined to occasionally slightly lined tunnels were constructed by these crustaceans and resemble the *Thalassinoides*- and at times *Ophiomorpha*-like traces (Fig. 2-34A,B,C,D; Table 2-4).

Burrows were extensive in the ridge and furrow zone with equal amounts of burrowing occurring on both the ridges and furrows (Fig. 2-35A). Roughly circular mounds or indents were equally common around burrow openings in this zone with visible open-to-surface burrows having a diameter of 5-10mm (Fig. 2-35D,F). Occasionally grey suboxic sands were excavated to the surface via burrow networks causing the circular patches around burrow openings to appear dark in color (Fig. 2-35D). An assortment of microfauna on the ridge and furrow tidal flat zone leads to the development of yellow-brown surface film, especially in low areas (Fig. 2-35A,C,D). In the ridge and furrow zone burrow density was typically around 12-24 burrow openings and 3-4 small, meandering surface traces per 50cm<sup>2</sup> area. The probable tracemaker for the small (2mm across) meandering surface traces that are *Gordia*-like to *Crossopodia*-like in appearance, are *Exciorolana* sp. or other related isopods (Fig. 2-35B; Table 2-4). The amphipods, *Eohaustorius* sp. and *Corophium* sp. were also observed at the surface but were not found to be actively making any traces, although it is possible that they can also create small, meandering *Gordia*-like to *Crossopodia*-like surface traces as observed in another region. Various threadworms (*Mediomastus* sp. and *Capitella* sp.) were observed and created *Trichichnus*-, and *Skolithos*-like traces (Table 2-4). In the subsurface of the entire ridge and furrow zone *N. californiensis* burrows were frequently





**Figure 2-34: Biogenic features associated with *Neotrypaea californiensis*.** (A) Sub-vertical burrow of *N. californiensis* resembling *Thalassinoides* which is typically observed along tidal ridges and along the base of the upper intertidal flat zone. Width of finger is ~1.5cm. (B) The tracemaker *N. californiensis*. *Neotrypaea californiensis* is 3cm long. (C) Plan view of *N. californiensis* burrow openings that are typically *Thalassinoides*-like in the subsurface. White arrows indicate the *Gordia*-like traces likely from *Eohaustorius* sp. or *Corophium* sp. Burrow opening is 1.5cm in diameter. (D) Plan view of *N. californiensis* burrow openings along exposed channel that are also *Thalassinoides*-like in the subsurface. Entire chimney like burrow opening structure is 2.5cm across.



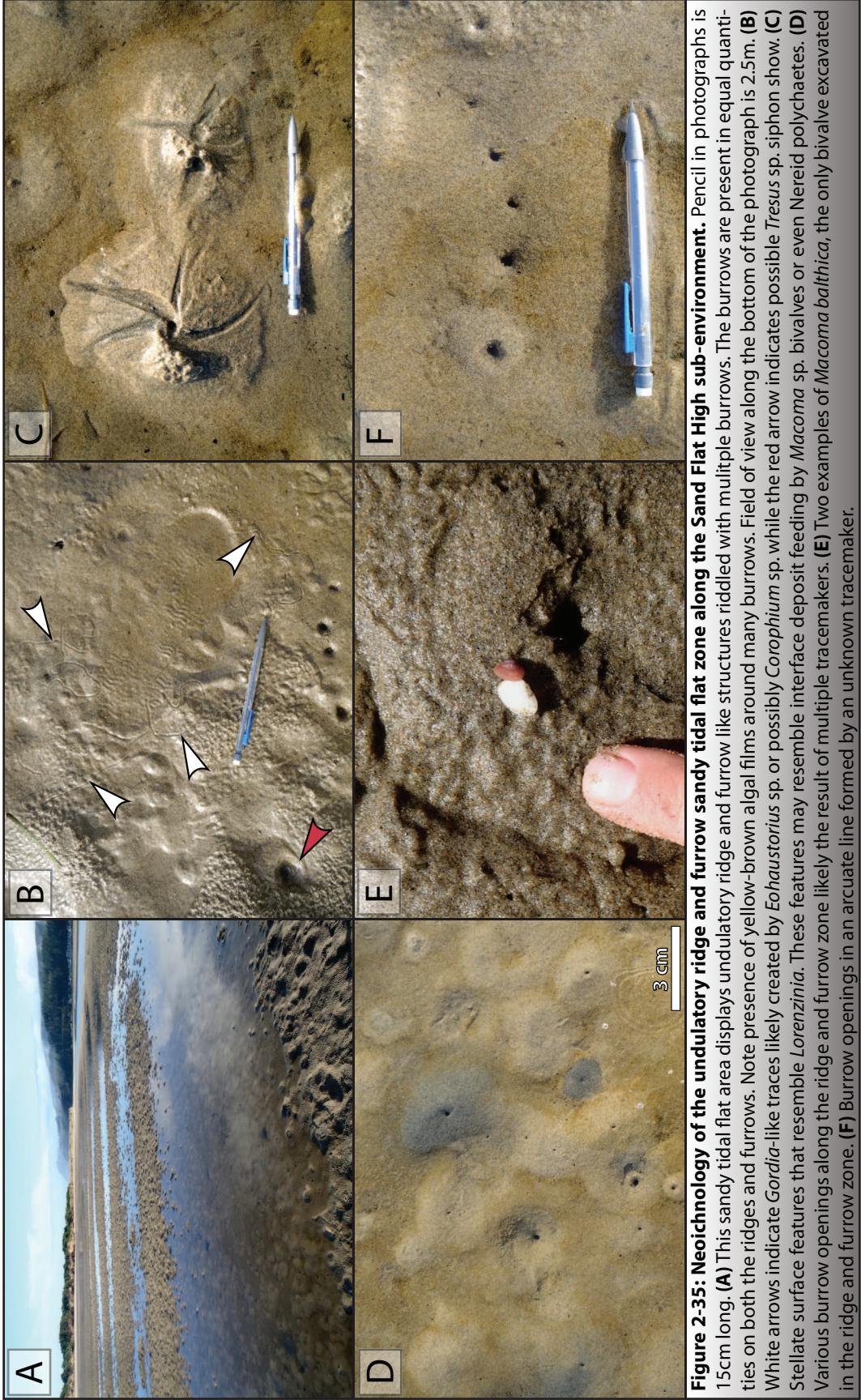
<b>Table 2-4: Summary of Trace Making Organisms and Associated Traces of the Outer Sheltered Sandy Tidal Flat Bay Region</b>				
	<b>Organism</b>	<b>Trophic Behaviour</b>	<b>Trace Fossil Equivalent to Modern Trace Form</b>	<b>Environmental Zone</b>
<b>Mollusca</b>	<i>Macoma balthica</i>	Filter Feeder, Interface Deposit Feeder	Dual-siphon <i>Siphonichnus</i> , Stellate Surface Trace ( <i>Lorenzinia</i> )	Undulatory Sand Flat, Eelgrass Flat
	<i>Macoma nasuta</i>	* Filter Feeder, Interface Deposit Feeder	Dual-siphon <i>Siphonichnus</i>	Eelgrass Flat
	<i>Macoma secta</i>	Filter Feeder, Interface Deposit Feeder	Dual-siphon <i>Siphonichnus</i>	Protected Channel Bank
	<i>Macoma inquinata</i>	* Interface Deposit Feeder, Filter Feeder	Dual-siphon <i>Siphonichnus</i>	Eelgrass Flat
	<i>Mya arenaria</i>	Filter Feeder	<i>Siphonichnus</i>	Eelgrass Flat, Low Sand Flat
	<i>Saxidomus gigantea</i>	Filter Feeder	<i>Siphonichnus</i>	Eelgrass Flat
	<i>Tresus capax</i>	Filter Feeder	<i>Siphonichnus</i>	Eelgrass Flat, Protected Channel Bank
	<i>Tresus nuttallii</i>	Filter Feeder	<i>Siphonichnus</i>	Eelgrass Flat

Table 2-4: Summary of Trace Making Organisms and Associated Traces of the Outer Sheltered Sandy Tidal Flat Bay Region (continued)				
	Organism	Trophic Behaviour	Trace Fossil Equivalent to Modern Trace Form	Environmental Zone
Mollusca	<i>Clinocardium nuttallii</i>	Filter Feeder	<i>Lockeia</i> , ? <i>Protovirgularia</i> , ? <i>Siphonichnus</i>	Protected Channel Bank
	<i>Nuttallia obscurata</i>	Filter Feeder, Interface Deposit Feeder	<i>Siphonichnus</i>	Ridge and High Saddle Sand Flat of Isolated Bar
	<i>Olivella biplicata</i>	* Surface Deposit Feeder, Filter Feeder, Scavenger, ? Carnivore	<i>Olivellites</i>	Channel Margins near MLLW
Crustacea	<i>Neotrypaea californiensis</i>	* Deposit Feeder, Filter Feeder	<i>Thalassinoides</i>	Exposed Tidal Channel Bank and Ridge, Isolated Bar Sand Flat
	<i>Upogebia pugettensis</i>	Filter Feeder	<i>Thalassinoides</i>	Eelgrass Flat and Surrounding Low Sand Flat
	<i>Corophium</i> sp.	* Deposit Feeder, Filter Feeder	<i>Skolithos</i> , ? <i>Arenicolites</i>	Intertidal Sandy Flats
	<i>Eohaustorius</i> sp.	Deposit Feeder	* <i>Gordia</i> , <i>Crossopodia</i> , Sediment Disruption, ? <i>Cryptic Bioturbation</i>	Intertidal Sandy Flats
	<i>Excrolana</i> sp.	Scavenger	? <i>Macaronichnus</i>	Upper Intertidal Flat Zone

Table 2-4: Summary of Trace Making Organisms and Associated Traces of the Outer Sheltered Sandy Tidal Flat Bay Region (continued...2)				
	Organism	Trophic Behaviour	Trace Fossil Equivalent to Modern Trace Form	Environmental Zone
Crustacea	<i>Megalorchestia californiana</i>	Scavenger	<i>Skolithos</i> , Diminutive <i>Psilonichnus</i>	Upper Intertidal Flat- Supratidal
	<i>Traskorchestia traskiana</i>	Scavenger	<i>Skolithos</i>	Supratidal
Vermiform	<i>Mediomastus</i> sp.	Subsurface Deposit Feeder	<i>Trichichnus</i> , <i>Skolithos</i> , <i>Planolites</i>	Tidal Flats, Eelgrass Flats
	<i>Capitella</i> sp.	Subsurface Deposit Feeder	<i>Trichichnus</i> , <i>Skolithos</i> , <i>Planolites</i>	Tidal Flats, Eelgrass Flats
	<i>Nephtys</i> sp.	* Carnivore, Scavenger	Sediment Disruption/ <i>Navichnia</i> , ? Cryptic Bioturbation	Tidal Flats, Eelgrass Flats
	<i>Nereis</i> sp.	* Subsurface and Interface Deposit Feeder, Scavenger, Carnivore	<i>Polykladichnus</i> , <i>Palaeophycus</i> , <i>Skolithos</i>	Eelgrass Flat and Surrounding Low Sand Flat
	<i>Glycera</i> sp.	Subsurface Deposit Feeder	<i>Palaeophycus</i> , <i>Planolites</i> , Subordinate <i>Polykladichnus</i>	Eelgrass Flat and Surrounding Low Sand Flat
	<i>Pista pacifica</i>	* Suspension Feeder, Interface Deposit Feeder	Lined <i>Skolithos</i>	Inclined Protected Channel Bank

Table 2-4: Summary of Trace Making Organisms and Associated Traces of the Outer Sheltered Sandy Tidal Flat Bay Region (continued...3)				
	Organism	Trophic Behaviour	Trace Fossil Equivalent to Modern Trace Form	Environmental Zone
Vermiform	<i>? Axiothella rubrocincta</i>	Deposit Feeder	Lined <i>Skolithos</i>	Inclined Protected Channel Bank
	<i>? Pygospio elegans</i>	* Deposit Feeder, Suspension Feeder	Lined <i>Skolithos</i>	Inclined Protected Channel Bank
	<i>Cerebratulus</i> sp. (Nemertean)	Carnivore	<i>Palaeophycus</i>	Inclined Protected Channel Bank and Eelgrass Flat
Echinoderm	<i>Paracaudina chilensis</i> (Holothurian)	* Suspension Feeder, Deposit Feeder	<i>? Arenicolites, ? Diplocraterion</i>	Inclined Protected Channel Bank





**Figure 2-35: Neoichnology of the undulatory ridge and furrow sandy tidal flat zone along the Sand Flat High sub-environment.** Pencil in photographs is 15cm long. **(A)** This sandy tidal flat area displays undulatory ridge and furrow like structures riddled with multiple burrows. The burrows are present in equal quantities on both the ridges and furrows. Note presence of yellow-brown algal films around many burrows. Field of view along the bottom of the photograph is 2.5m. **(B)** White arrows indicate *Gordia*-like traces likely created by *Eohaustorius* sp. or possibly *Corophium* sp. while the red arrow indicates possible *Tresus* sp. siphon show. **(C)** Stellate surface features that resemble *Lorenzinia*. These features may resemble interface deposit feeding by *Macoma* sp. bivalves or even Nereid polychaetes. **(D)** Various burrow openings along the ridge and furrow zone likely the result of multiple tracemakers. **(E)** Two examples of *Macoma balthica*, the only bivalve excavated in the ridge and furrow zone. **(F)** Burrow openings in an arcuate line formed by an unknown tracemaker.

observed again to be simple, unlined, vertical to sub-vertical traces, with slight occasional lining, around 5-10mm in diameter akin to the *Thalassinoides*-like trace or *Cylindrichnus*- to *Ophiomorpha*-like trace if slightly lined. Tiny bivalves (1cm in length or less) of the *Macoma sp.* were often observed (Fig. 2-35E). The two separate inhalant and exhalant siphons of these bivalves usually left two small, unlined, slightly sub-vertical traces. If the bivalves are found *in situ* and a siphon trace is observed above them then this trace is similar to *Siphonichnus* (Table 2-4). However, if the bivalve was not seen and only the vertical parts of the potential siphon traces were seen then the traces were considered *Skolithos*-like (Table 2-4). Alternatively, if the trace included the branching, U-shaped, portion of the trace followed by a conjoining of the traces into one tube like trace below then the trace was considered *Polykladichnus*-like. *Lorenzinia*-like traces were rarely seen on the surface surrounding *Skolithos*- or *Siphonichnus*-like traces, but may result when *Macoma sp.* deposit feeding via their siphons just outside their inhalant burrow opening and in another separate instance when nereid polychaetes come to the surface to interface deposit feed (Fig. 2-35C; Table 2-4). Sand dollar tests, empty *Clinocardium nuttallii* shells, and empty *Macoma sp.* shells were often found scattered along the surface within the ridge and furrow zone, with at least one half of the shell usually intact. Various seaweeds were sporadically found to be *in situ*, but otherwise were scattered as fragments. No live *C. nuttallii* were discovered, but it is possible that they were present in sporadic amounts in the ridge and furrow zone.

At the lower part of the upper intertidal flat zone 14 open-to-surface burrows were counted in an area 50cm<sup>2</sup>. Density of burrows decreased up the upper intertidal flat with only 4 burrow openings per 50cm<sup>2</sup> halfway up the upper intertidal flat and 0 burrow openings per 50cm<sup>2</sup> at the upper part of the upper intertidal flat. In the lower upper intertidal flat zone unlined to small, oxidized, orange-lined *Skolithos*-like burrows were observed (Fig. 2-36A,B,C,D). A few *N. californiensis* were dug up in the lower upper intertidal flat zone, but





**Figure 2-36: Neoichnology of the upper intertidal flat zone along the Sand Flat High sub-environment.** Width of finger is ~1.5cm for scale in B,C,D. **(A)** *Skolithos*-like burrow indicated by the white arrow possibly formed by a bivalve siphon. **(B)** Another *Skolithos*-like burrow likely created by a bivalve siphon. Note the excavation of less oxic sands to the surface. These sands can also infill the upper portion of the trace, as seen in this photograph, if the siphon is retracted. **(C)** White arrows indicate small, unlined *Skolithos*-like traces. The red arrow indicates a wider *Skolithos*-like to *Palaeophycus*-like burrow that possesses an oxidized halo. **(D)** Small slightly lined *Skolithos*-like to *Arenicolites*-like burrow indicated by the white arrow likely created by *Corophium* sp.

less than were commonly found within the ridge and furrow zone. After the lower upper intertidal flat, transitioning into the higher reaches of the upper intertidal flat, no *N. californiensis* were present. Very little open-to-surface burrows were seen at the surface in the upper intertidal flat zone; however after scraping away the top few centimetres of sediment more burrow openings were evident than originally appeared on the surface. Therefore, burrows that were once open to the surface may have been infilled due to rain or abandonment. Also, some burrows may be sub-vertical to horizontal which do not penetrate the sediment surface. After carefully scraping away the first few centimetres of sediment in the lower to middle upper intertidal flat reaches an exhumed-to-surface burrow count yielded 63 burrows per 50cm<sup>2</sup>. Over the entire upper intertidal flat area mottled laminae were evident within the top 15cm on photographs and X-rays from boxcore and PVC core samples. Burrowing behaviour of meiofauna and organisms such as *Excirrolana* sp. likely created the mottled laminae and therefore a *Macaronichnus*-like trace (Table 2-4). A few small (less than 5mm), unlined, vertical *Skolithos*-like burrows were observed in the supratidal area. *T. traskiana*, *M. californiana* and common black ants were observed crawling on the sediment surface of the supratidal area. *M. californiana* was associated with small, unlined *Skolithos*-like traces identical to those observed at the upper intertidal flat-supratidal boundary along the exposed beach areas.

### ***Eelgrass Flat Low Sub-Environment***

The sediment next to the channel edge was saturated and displayed a thixotropic nature, therefore traces and sedimentary structures were difficult, if not impossible, to observe. However, the multiple meandering surface traces produced by *O. biplicata* were readily observed (Fig. 2-37C,E). These traces were abundant in the furrowed areas next to the channel and gradually decreased until the gentle slope of the channel ridge flattened out onto the sandy tidal flat where *O. biplicata* were no longer found (Fig. 2-37A,D). *Olivella*



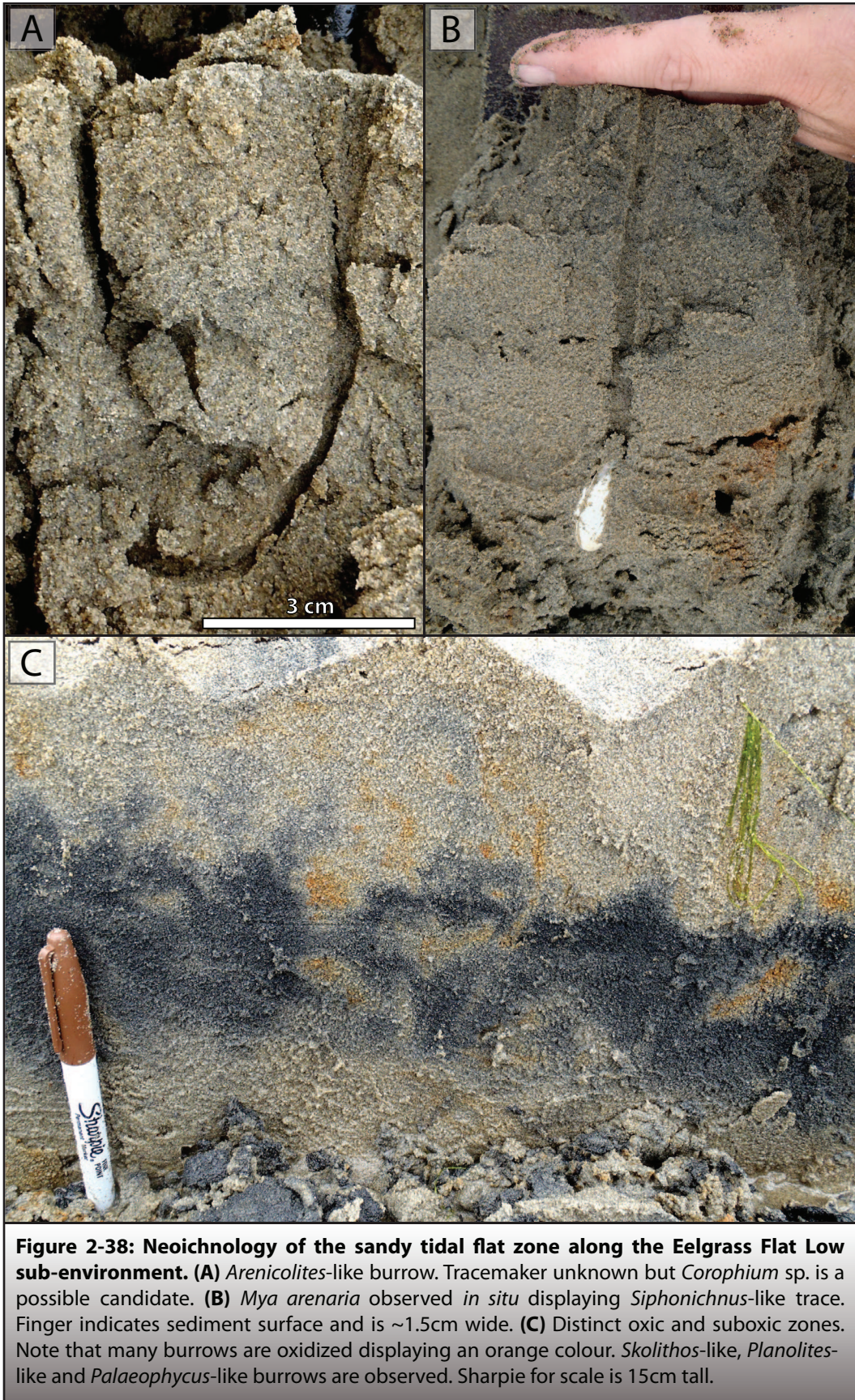


**Figure 2-37: Protected channel ridge morphology and neochnology along the Eelgrass Flat Low sub-environment.** (A) Small ridge and furrow structures form along the channel margins and are sub-perpendicular to the long axis of the protected tidal channel. White arrows indicate ridges. Person for scale  $\sim 1.83$ cm tall. (B) Siphon show (burrow openings) of *Tresus nuttallii*. (C) *Olivellites*-like trace created by *Olivella biplicata*. (D) View looking East across the tidal channel to the Isolated Sand Bar sub-environment. Boat is landed within a furrow or trough sub-perpendicular to the channel. Shovel in midground is  $\sim 1.1$ m tall. (E) One small *Clinocardium nuttallii* and twenty one *Olivella biplicata* observed within an area  $50\text{cm} \times 50\text{cm}$ . White arrows indicate extruded siphons of submerged *Olivella biplicata*. Finger for scale is  $\sim 1.5\text{cm}$  wide. (F) *Tresus nuttallii*, tracemaker of siphon show in (B). Note the leathery plate (indicated by white arrow) part of the siphon is what reaches to the surface while the lighter part is attached to the live *T. nuttallii*.

*biplicata* were observed to travel approximately 10cm in 2 minutes within sediment that displayed thixotropy. In an area 50cm<sup>2</sup>, next to the protected tidal channel, 21 *O. biplicata* and 1 small (approximately 3cm wide) Nuttall's Cockle (*Clinocardium nuttallii*) were observed within the top 5cm of sediment (Fig. 2-37E). *O. biplicata* continued to make *Olivellites*-like traces much as they did in the Exposed Shoreface-Spitt region, while *C. nuttallii* was observed in a resting position near surface thereby creating a *Lockeia*-like trace (Table 2-4). *C. nuttallii* is also able to produce *Protovirgularia*-like traces, but this was not seen here as the bivalve did not show any previous, or at the time, current signs of movement. Near this area 3 siphon openings of Pacific Gaper Clams (*Tresus nuttallii*) (Fig. 2-37F) were seen within an area of 2m<sup>2</sup>. The clams were approximately 1m away from each other and 40-50cm below the sediment surface with their burrow openings usually 10-15mm in diameter. There may be an indent or mounded surface around the burrow openings, but indented surfaces seemed to be the most common (Fig. 2-37B). Occasionally, when *T. nuttallii* was disturbed it would squirt water out of the burrow via its siphon. If *T. nuttallii* was observed *in situ* within the subsurface also displaying a corresponding siphon trace leading to the surface then the trace would be *Siphonichnus*-like (Table 2-4). However, if the bivalve was not seen and only the vertical, unlined siphon trace was observed, then the trace would be *Skolithos*-like. *T. nuttallii* was commonly observed throughout most areas except the upper intertidal flat and supratidal zones. *Tresus nuttallii*, like many other large bivalves in the bay, usually possessed 1-2 parasitic Pea Crabs (*Pinnixa* sp.).

Other large clams, besides the common *T. nuttallii*, observed in the hummocky eelgrass tidal flats included the less common Fat Gaper (*Tresus capax*) and Butter Clam (*Saxidomus gigantea*). Soft shell clams (*Mya arenaria*), were typically smaller and 2.5-3cm in length. *In situ* *M. arenaria* usually had siphons fully extended at around 6cm in length upon excavation with the trace of the siphon clearly extending to the surface, creating a *Siphonichnus*-like trace (Fig. 2-38B). Various *Macoma* sp., such as the Bent-nosed Clam (*Macoma*





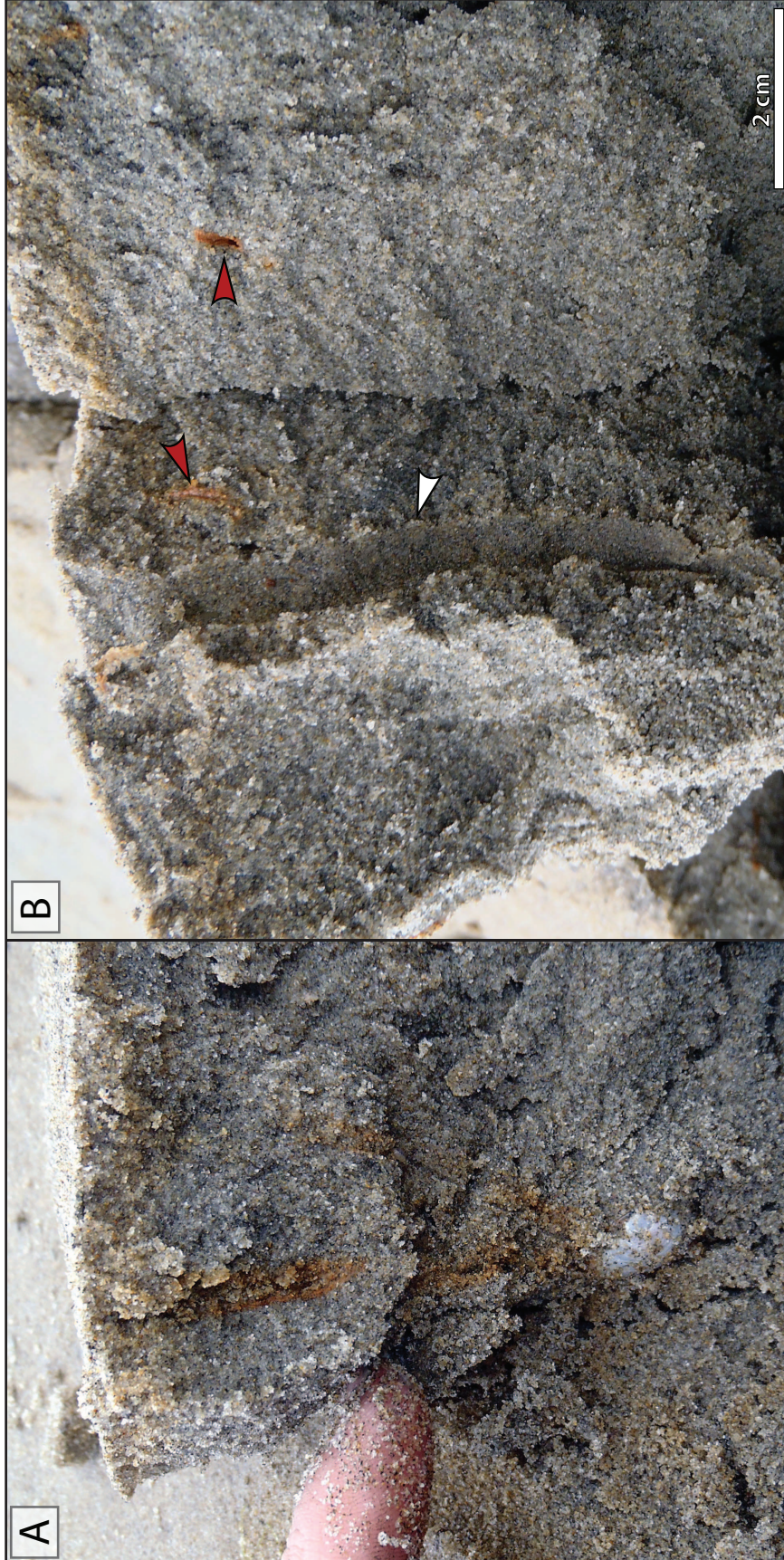
**Figure 2-38: Neoichnology of the sandy tidal flat zone along the Eelgrass Flat Low sub-environment. (A) *Arenicolites*-like burrow. Tracemaker unknown but *Corophium* sp. is a possible candidate. (B) *Mya arenaria* observed *in situ* displaying *Siphonichnus*-like trace. Finger indicates sediment surface and is ~1.5cm wide. (C) Distinct oxic and suboxic zones. Note that many burrows are oxidized displaying an orange colour. *Skolithos*-like, *Planolites*-like and *Palaeophycus*-like burrows are observed. Sharpie for scale is 15cm tall.**



*nasuta*) and Baltic Clam (*Macoma balthica*) were observed throughout the hummocky eelgrass tidal flat area. *In situ* *Macoma* sp. displayed dual *Siphonichnus*-like traces due to the separation of their inhalant and exhalant siphons (Fig. 2-39A; Table 2-4). If the *Macoma* sp. were not seen the V- to Y-shaped dual siphon traces appeared to be unlined to orange-lined *Polykladichnus*-like burrows.

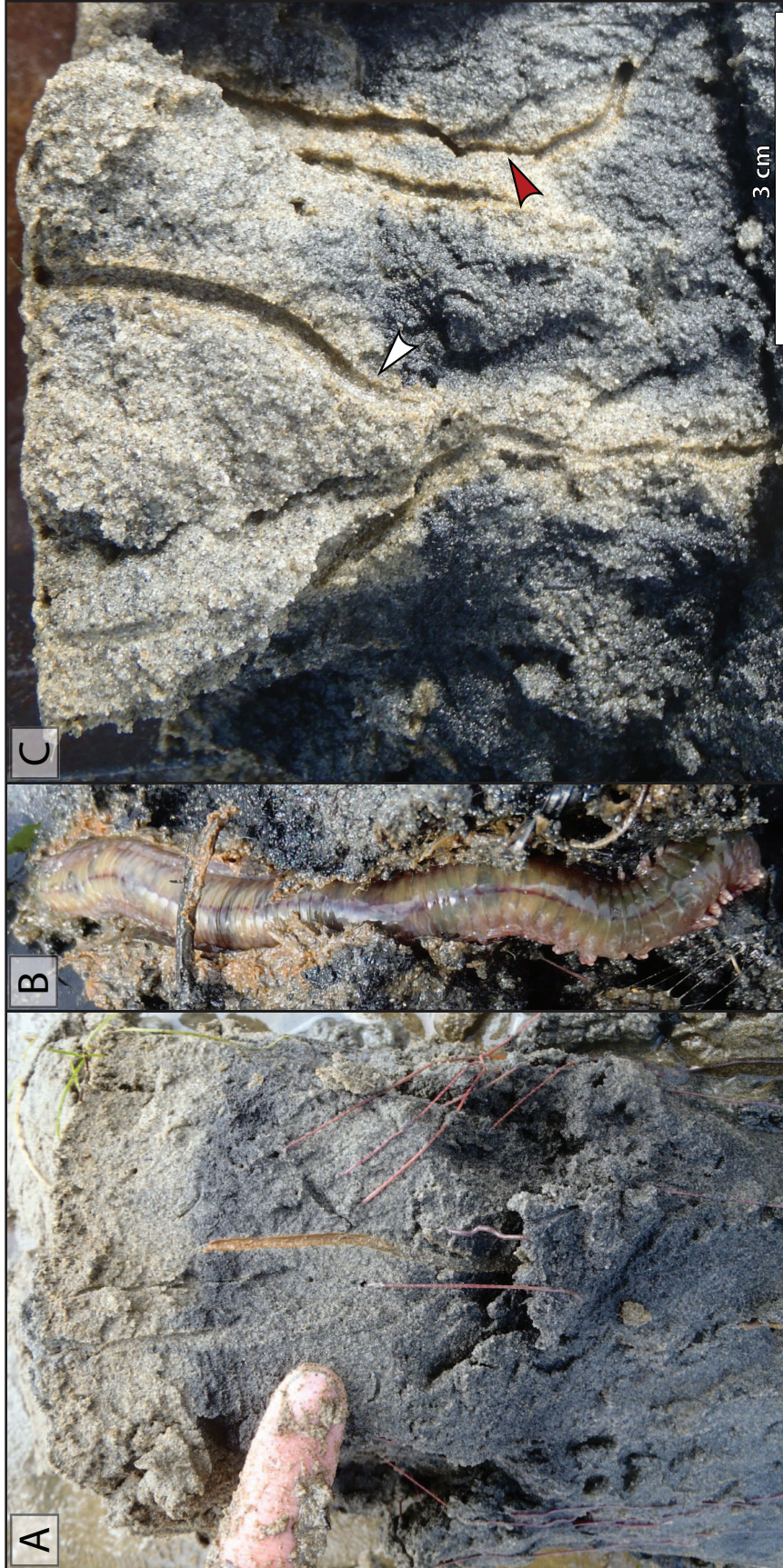
Multiple threadworms (*Mediomastus* sp. and *Capitella* sp.) and bloodworms (*Glycera* sp.) were observed moving through the sediment, especially in the sandy tidal flat and hummocky eelgrass tidal flat areas. The highest abundance of threadworms and bloodworms occurred within the hummocky eelgrass area. Threadworms leave behind multiple traces that appear to move in multiple different directions ranging from vertical to horizontal in orientation and are up to 1.5mm in diameter, with the burrows either being surrounded by oxidized orange sediment or simply unlined depending on the horizon they occur in. Unlined to orange rimmed burrows can also be infilled with lighter beige sands that stand out when burrows are located in grey, suboxic to black, anoxic sediment. Traces observed such as *Trichichnus*-, *Skolithos*- and *Planolites*-like traces are seen to be a product of threadworm bioturbation (Fig. 2-40A; Table 2-4). Bloodworms typically left slightly larger burrows (diameter of 2-3 mm) and usually appeared to have an orange border or lining around the outside of the burrow that was approximately 1-2mm thick. These burrows were usually sub-vertical to sub-horizontal in orientation. Bloodworms were observed to create *Palaeophycus*-, *Planolites*-, and subordinate *Polykladichnus*-like traces (Fig. 2-38C, Table 2-4). *Nereis* sp. (Fig. 2-40B) worms were also present, but due to their larger size left even larger diameter burrows than bloodworms (usually 4-8mm in diameter) that were generally mucous lined. *Nereis* sp. created *Palaeophycus*-, *Polykladichnus*-, and *Skolithos*-like traces (Fig. 2-38C, Fig. 2-40C, Table 2-4), with larger *Nereis* sp. occasionally producing small *Thalassinoides*-like traces. Although *Nereis* sp. create burrows oriented anywhere from vertical to





**Figure 2-39: Traces of the lower upper intertidal flat-eelgrass flat boundary along the Eelgrass Flat Low sub-environment. (A) *Macoma* sp. observed *in situ* displaying dual siphon trace akin to dual *Siphonichnus*. Note oxidation around siphon burrows. Finger for scale is ~1.5cm wide. (B) Unlined *Skolithos*-like trace, as indicated by the white arrow, potentially created by the siphon of a bivalve or *Neotrypaea californiensis*. Red arrows indicate small, slightly lined although highly oxidized, *Skolithos*-like to *Arenicolites*-like traces likely formed by a species of amphipod or threadworm.**





**Figure 2-40: Vermiform traces along the hummocky eelgrass zone of the Eelgrass Flat Low sub-environment. (A)** Unlined to lined *Skolithos*-like traces indicated by the white arrows. Threadworms (*Mediomastus* sp. and *Capitella* sp.) commonly seen usually create small *Skolithos*-like, *Trichichnus*-like and *Planolites*-like traces. Finger for scale is ~1.5cm wide. **(B)** *Nereis* sp. is a common *Polykladichnus*-like and *Palaeophycus*-like trace maker. The length of the nereid exposed in this photo is 8cm. **(C)** Y-shaped *Polykladichnus*-like trace is the most prominent trace as indicated by the white arrow. *Skolithos*-like traces grading into a *Palaeophycus*-like trace also indicated by red arrow.

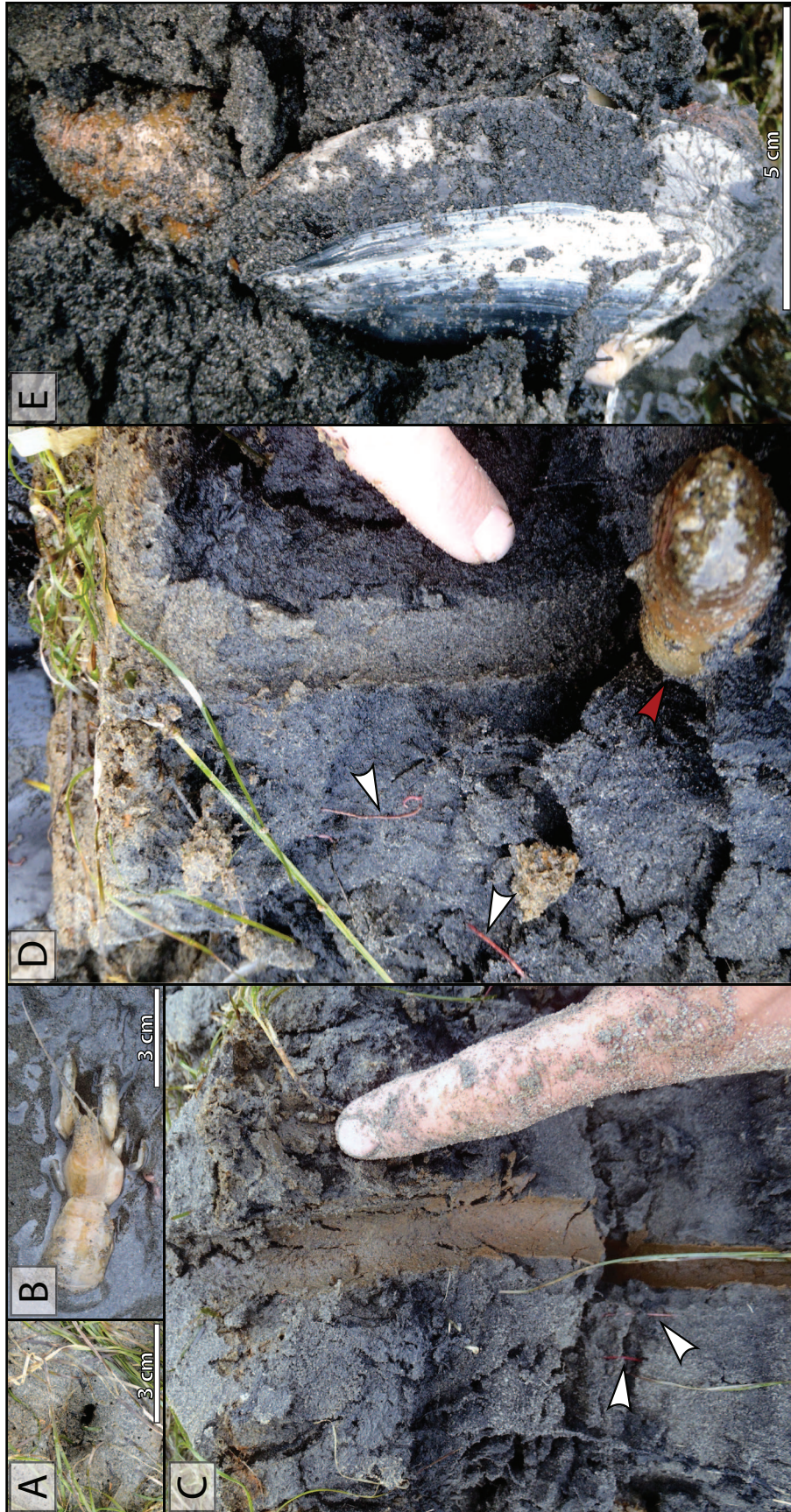
horizontal, they are generally found in the sub-vertical to horizontal position upon active burrow exhumation, forming vertical burrow parts when it wants to reach the surface to deposit feed. Mucous lined *Palaeophycus*-like trails were left behind by the sporadically seen nemertean *Cerebratulus* sp. worm (Table 2-4). The polychaete *Nephtys* sp. was also sporadically present, but due to its errant nature only leaves behind traces of sediment disruption or cryptic bioturbation.

*N. californiensis* was occasionally found in the sandy tidal flat area within unlined, vertical to sub-vertical burrows, whereas the Blue Mud Shrimp (*Upogebia pugettensis*) was commonly found in the hummocky eelgrass tidal flat area, with large amounts of *U. pugettensis* mounds located at the edge of the eelgrass field adjacent to the upper intertidal flat zone in association with multiple *T. nuttallii* (Fig. 2-41A,B,C,D,E). Long, branching, vertical to sub-vertical, orange-brown lined burrows defined the structures created by *U. pugettensis* (Fig. 2-38C). *Neotrypaea californiensis* and *U. pugettensis* burrows resembled *Thalassinoides*-like traces. The surface trace created by *U. pugettensis* resembled *Protichnites*. The amphipod *Corophium* sp. was a probable trace maker of some of the smaller *Skolithos*-like to *Arenicolites*-like burrows observed in the sandy to hummocky eelgrass tidal flats (Fig. 2-38C). Isopods such as *Exciorolana* sp. were the probable trace maker of the *Macaronichnus*-like traces observed at the end of the eelgrass flats along the upper intertidal flat zone (Fig. 2-39B), since they were observed along the upper intertidal flat boundary as the tide rose, while other possible tracemakers like *Euzonus* sp. were not observed.

The demersal Tidepool Sculpin (*Oligocottus maculosus*) were commonly seen within lower areas of the flats, such as tidal creeks, that still possessed standing water. These fish occasionally burrowed just beneath the sediment surface potentially creating resting (cubichnia) traces.

Burrow density in the sandy tidal flat zone was 6-22 large, and 45-66 small burrow openings per 50cm<sup>2</sup>. In the hummocky eelgrass tidal flat zone 6-





**Figure 2-41: Neoichnology of the hummocky eelgrass field along the Eelgrass Flat Low sub-environment. (A)** Plan view of burrow opening created by *Upogebia pugettensis*. **(B)** Trace maker *U. pugettensis* which creates unlined to slightly lined *Thalassinoides*-like traces. **(C)** A portion of a slightly lined *Thalassinoides*-like trace created by *U. pugettensis*. These burrows are usually Y-shaped and deeply penetrating. White arrows indicate threadworms. Finger for scale ~1.5cm wide. **(D)** *Skolithos*-like trace created by a bivalve siphon (red arrow). The entire trace likely includes bivalve mold and surrounding deformation and is probably *Siphonichnus*-like in appearance if fully excavated. White arrows indicate threadworms. Finger for scale ~1.5cm wide. **(E)** *Tresus capax* trace maker of *Skolithos*-like to *Siphonichnus*-like traces.



24 large and 111-480 small burrow openings were counted in a 50cm<sup>2</sup> quadrat. At the base of the upper intertidal flat zone burrow density was approximately 18 burrows per 50cm<sup>2</sup>, while at the upper intertidal flat-supratidal boundary only 3 burrow openings per 50cm<sup>2</sup> were observed.

### ***Isolated Sand Bar Sub-Environment***

At the low tide mark along the protected tidal channel dark grey to black sands were actively being excavated out of burrows to the surface; however tracemakers were elusive. *C. nuttallii* was found resting within the top 5cm of sediment creating a possible *Lockeia*-like trace. An open burrow 5mm in diameter, with slightly raised edges, was observed containing the tracemaker, a Rattail sea cucumber (*Paracaudina chilensis*). However, the sediment was thixotropic therefore subsurface traces were not observed. Small, fragile tubes creating lined *Skolithos*-like traces were exposed 1.5cm-2cm above the sediment surface and 1-2mm in diameter (Fig. 2-42A). These tubes usually occurred in clusters of 3 with each cluster spaced half a meter to a meter away from each other (Fig. 2-42A). The probable tracemaker of these tubes is the spionid polychaete *Pygospio elegans*, or possibly the maldanid polychaete *Axiiothella rubrocincta*. *O. biplicata* was a common tracemaker along the water line creating *Olivellites*-like traces in densities averaging 7 per 50cm<sup>2</sup>. The nemertean worm *Cerebratulus californiensis* was observed burrowing in the sediment along the low tide water mark leaving behind a slight mucous trail and creating a small *Palaeophycus*-like trace. *Planolites*- and *Cylindrichnus*-like traces were also observed in X-rays of PVC core from the lower protected tidal channel.

Along the shallow inclined bank of the lower energy tidal channel fringed-hood lined tubes, akin to lined *Skolithos*, created by the terebellid polychaete *Pista pacifica* was observed (Fig. 2-42A, Fig. 2-43). These tubes were usually clustered and occurred within the slight furrows of the bank and not on the ridges. In an area 1m<sup>2</sup>, there were 28 fringed-hood lined tubes. A large



**Figure 2-42: Robust polychaete generated structures near the MLLW mark along the protected channel bank of the Isolated Sand Bar sub-environment. (A)** Small, fragile sand tubes that are akin to lined *Skolithos* traces. The probable tracemaker of these tubes is the spionid polychaete *Pygospio elegans*, or possibly the maldanid polychaete *Axiiothella rubrocincta*. Finger for scale is ~1.5cm wide. **(B)** Multiple robust tubes of the terebellid polychaete *Pista pacifica* that are *Skolithos*-like in appearance.



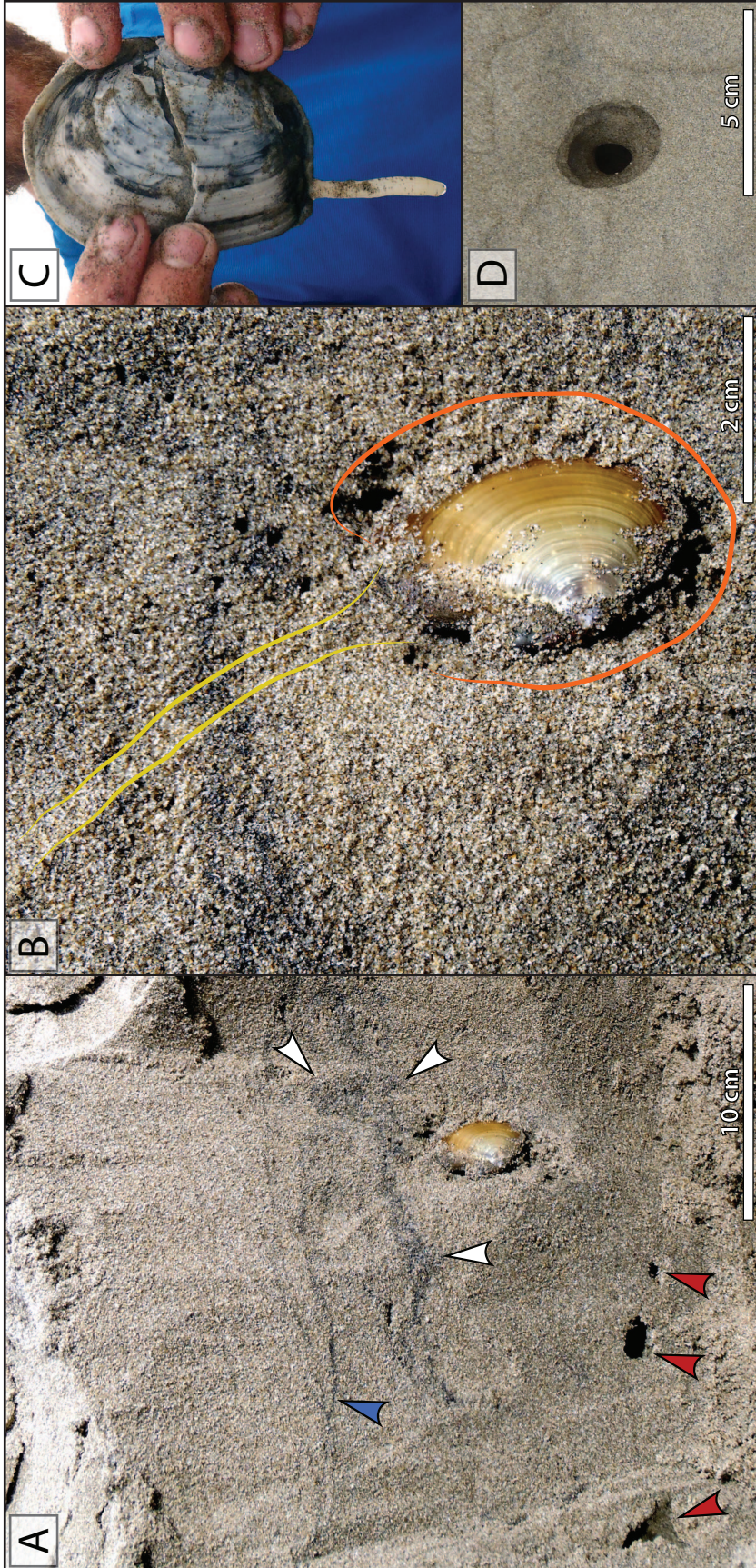


**Figure 2-43: Cross section indicating orientation of tube created by *Pista pacifica*.** The heavily lined tube created by *P. pacifica* creates a lined *Skolithos*-like trace. Note the fringed hood at the top of the tube which was found oriented perpendicular to ebb flow direction and facing up bank away from the channel. The tube is 1.5-2cm in diameter. Finger for added scale is ~1.5cm wide.

burrow opening was seen with an initial diameter of 32mm which tapered to a diameter of 13mm over a span of 20mm (Fig. 2-44D). Water was ejected out of the burrow when disturbed and a large siphon of a *Tresus* sp. bivalve was observed. Usually, a single burrow opening belonging to one of these large clams was seen every 2.5-5 metres along the gently sloped protected tidal channel bank. A large *Macoma secta* was also found 30cm below the surface of an open burrow (Fig. 2-44). The siphon traces of these large bivalves created *Siphonichnus*- or *Skolithos*-like traces.

A common organism encountered was the *Nephtys* sp. worm that was usually observed gliding through the sandy sediment in multiple directions creating cryptic bioturbation, sediment disruption or *Navicunia* traces. Various threadworms (*Mediomastus* sp. and *Capitella* sp.) were also occasionally observed and created *Trichichnus*-, *Skolithos*- and *Planolites*-like traces. Generally unlined, vertical to sub-vertical (rarely horizontal), burrows akin to *Thalassinoides* in their appearance were observed along the tide channel bank, ridge and saddle (Fig. 2-45A,C). These burrows extend at least down to 50cm, which is where the water table was encountered. Bay ghost shrimp (*N. californiensis*) were commonly seen at or near the water table within these burrows (Fig. 2-45B). Occasionally the burrows were slightly lined, especially at the near horizontal portions (Fig. 2-45C). These lined burrows were initially thought to be akin to *Ophiomorpha*-like traces if lined (with usually what appears to be seaweed fragments) and slightly bumpy, and to *Cylindrichnus*-like traces if lining possessed smooth, finely laminated layers and no branching of trace. However, even though other authors have ascribed similar traces as being *Ophiomorpha*-like, the traces in this study are thought to only be lined *Thalassinoides*-like traces in the higher energy zones. The burrow openings are usually flush with the sediment surface or raised like columns with entrances usually only 0.5cm in diameter with the subsurface trace approximately 1-2cm in diameter. The Purple Mahogany Clam (*Nuttallia obscurata*) was by far the most abundant bivalve found within the channel ridges and saddle zones of





**Figure 2-44: Bivalves and associated traces along the Isolated Sand Bar sub-environment.** (A) Observation of *Nuttallia obscurata* *in situ* approximately 20cm below the sediment surface along the higher sand flat saddle zone. Sediment disruption structures are observed around *N. obscurata* as indicated by the white arrows. The blue arrows indicate relatively undisturbed wavy laminae above the zone of disruption. Slightly lined *Thalassinoides*-like burrows created by *Neotrypaea californiensis* are highlighted by the red arrows. (B) Magnified image of *N. obscurata* in photo (A) with yellow outline highlighting the most current siphon trace and orange outline indicating the more obvious region of sediment disruption around the bivalve. (C) *Macoma secta* was discovered in the clean sands along the protected tidal channel bank. Width of an individual finger is ~1.5cm for scale. (D) Siphon show (burrow opening) belonging to a *Tresus* sp. bivalve.





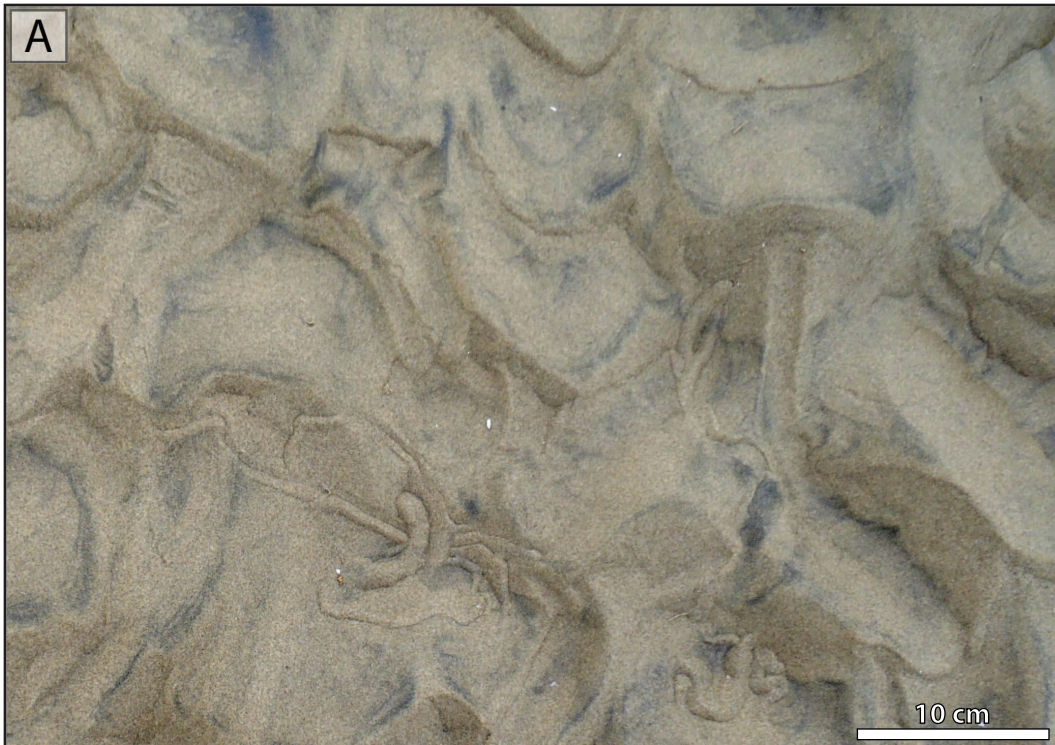
**Figure 2-45: Traces created by *Neotrypaea californiensis* in the Isolated Sand Bar sub-environment.** (A) Burrow openings along the high saddle flat zone of the Isolated Sand Bar sub-environment. The white arrows indicate burrow openings of *N. californiensis* that display a *Thalassinoides*-like architecture in the subsurface. (B) Inset of the tracemaker *N. californiensis*. Finger for scale is ~1.5cm wide. (C) Subsurface view of a slightly lined *Thalassinoides*-like trace constructed by *N. californiensis*. This particular view is of a small horizontal section of two burrows before continuing downward in a sub-vertical fashion. Two closely spaced burrow pairs were commonly observed in the subsurface. Finger for scale is ~1.5cm wide. (D) Chimney-like burrow openings created by *N. californiensis* along the exposed channel bank that display a *Thalassinoides*-like architecture in the subsurface.

the sub-environment (Fig. 2-44A,B). The bivalve was commonly found 15-20cm below the sediment surface and created unlined, vertical siphon traces (Fig. 2-44A,B). If the bivalve was observed *in situ* along with the siphon trace then the trace was akin to *Siphonichnus*, but if *N. obscurata* was not observed then the trace produced by the siphon would be *Skolithos*-like. The parasitic pea crab (*Pinnixa* sp.) was frequently found residing within live *N. obscurata* shells. Small, meandering *Gordia*-like surface traces were commonly seen on the surface of the upper channel bank, channel ridge and saddle zones (Fig. 2-46B). The probable tracemaker is that of the haustoriid amphipod *Eohaustorius* sp. as it was commonly encountered gliding along sandy tidal flats especially if wetted. *Macaronichnus*-, *Cylindrichnus*-, *Planolites*- and *Siphonichnus*-like traces were also observed via X-rays of PVC core from the tidal channel ridge. The *Siphonichnus*-like trace had an associated V-shaped disruption of laminae pointing down along the burrow wall. *Navichnia*, *Thalassinoides*-, *Planolites*-, and *Macaronichnus*-like traces were observed in the X-rays of PVC core from the saddle zone.

Two large, meandering *Olivellites*-like surface traces were observed along the low tide level along the exposed channel edge, but no tracemaker was found although the most probable tracemaker is *O. biplicata* (Fig. 2-46A). Bay ghost shrimp displayed *Skolithos*-like and *Thalassinoides*-like burrows along the steeper, exposed channel bank with the lined *Thalassinoides*-like burrows possessing raised columnar openings around the burrow entrance. A large Dungeness crab (*Cancer magister*) was observed on the tidal channel ridge next to the exposed channel and became prey to seagulls. *Cylindrichnus*- and *Planolites*-like traces were also observed in PVC core X-ray analysis of sediments along the exposed tidal channel bank and ridge.

At the MLLW mark of the protected tidal channel bank the largest proportion of burrow openings was observed with a density of 21 per 50cm<sup>2</sup>. The number of burrow openings gradually decreased up the channel bank to the smallest proportion of burrow openings observed on the ridge with a





**Figure 2-46: Meandering surface traces of the Isolated Sand Bar sub-environment. (A)** *Olivellites*-like traces produced by *Olivella biplicata* along the MLLW along the protected and exposed tidal channel banks. **(B)** Small *Gordia*-like surface meandering traces potentially created by *Eohaustorius* sp.

density of 3 per 50cm<sup>2</sup>. Midway up the exposed channel bank the density of burrow openings was also 21 per 50cm<sup>2</sup> and the burrow opening density at the exposed ridge was also 3 per 50cm<sup>2</sup>. However, the exposed channel had far less open-to-surface burrow densities along the MLLW mark with densities only reaching 3 per 50cm<sup>2</sup>. The burrow densities within the saddle increased with open-to-surface burrow densities as high as 17 per 50cm<sup>2</sup>.

At the low tide level of the lower sand flat 3 meandering *Olivellites*-like surface traces created by *O. biplicata* were observed in an area of 50cm<sup>2</sup>. *Olivella biplicata* is only present in the lower sand flat zone. Vertical, unlined *Skolithos*-like burrows were common throughout the Mixed Channel micro-environment. *Eohaustorius* sp. and various threadworms were sparse but observed throughout the micro-environment as well. *Gordia*-like to *Crossopodia*-like surface traces were likely created by *Eohaustorius* sp. and increased in abundance towards the saddle, while *Trichichnus*-, *Skolithos*- and *Planolites*-like subsurface traces were likely the result of threadworms. The invasive species *N. obscurata* comprised at least 90% of bivalves (alive or dead) found within the micro-environment. The bivalve, along with the trace of its siphon, created *Siphonichnus*-like traces and if the bivalve was not seen the siphon would leave behind an unlined *Skolithos*-like trace. Unlined, vertical burrows associated with the siphon of *N. obscurata* are usually 1cm or less, and typically between 0.25-0.5cm in diameter. Occasionally valves of *C. nuttallii*, 5cm across, were found as intact debris, but no live ones were found. Bay ghost shrimp burrows, resembling *Thalassinoides*-like traces, may display slightly raised entrances 0.5cm in diameter or be flush with the sediment surface along the upper sand flat ridge and saddle zones. Whereas, in the subsurface the vertical to sub-vertical *Thalassinoides*-like traces of *N. californiensis* were 1-3cm in diameter and were occasionally lined with a slightly gray-green muddy mucous like substance or oxidized orange lining in the more horizontal areas of the trace. The lined traces were similar to *Cylindrichnus* in appearance if they appeared to taper off and not branch.

Cylindrical fecal pellets that were 3mm long and about 0.7mm in diameter were common in ripple troughs around many *N. californiensis* burrows. A *Nephtys sp.* worm was observed gliding through the lower, wetter sediment of the saddle zone creating possible cryptic bioturbation, sediment disruption and navichnia.

Density of burrow openings steadily increased from the lower sand flat zone up through to the saddle zone. In the lower sand flat zone burrow density was 3 large meandering surface traces per area of 50cm<sup>2</sup>. Throughout the upper sand flat ridge density of burrow openings averaged 6 per 50cm<sup>2</sup>, while in the saddle zone burrow density increased to an average of 12 per 50cm<sup>2</sup>.

## **INTERPRETATION OF OUTER SHELTERED SANDY TIDAL FLAT BAY REGION**

### **Morphological and Sedimentological Interpretation**

Three sub-environments comprise the morphological character of the Outer Sheltered Sandy Tidal Flat bay region (Fig. 2-3): the Sand Flat High (Fig. 2-47), the Eelgrass Flat Low (Fig. 2-48), and the Isolated Sand Bar composed of the Protected Channel Sand Flat and Exposed Channel Sand Flat Micro-environments (Fig. 2-49), as well as the Mixed Channel Sand Flat micro-environment (Fig. 2-50). The Sand Flat High and Eelgrass Flat Low sub-environments are similar yet distinct entities. The Sand Flat High sub-environment displays a prominent ridge near a deeper, faster secondary tidal channel creating a steep sandy bank. Whereas the Eelgrass Flat Low sub-environment displays a rather flat channel bank that possess small, undulatory ridge and furrow features oriented sub-perpendicular to the main axis of the shallow, protected, secondary tidal channel. The tidal flat zone of the Sand Flat High is dominated by ridge and furrow features that are oriented sub-perpendicular to the secondary tidal channel; however they are of greater wavelength than the smaller, more confined, ridge and furrow structures along the protected tidal channel margin of the Eelgrass Flat Low sub-environment. The sandy tidal flats of both zones have abundant bioturbation and micro-



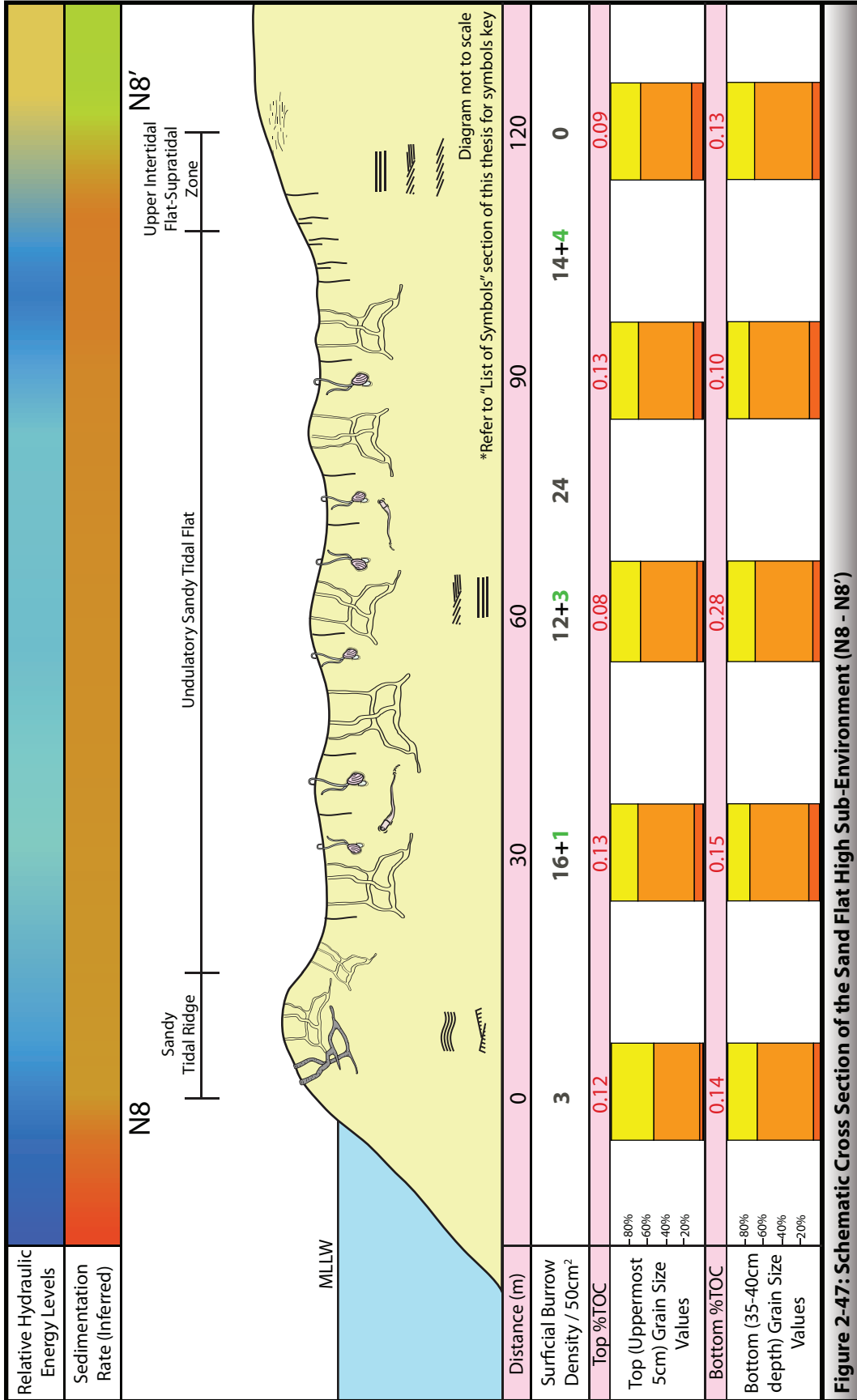
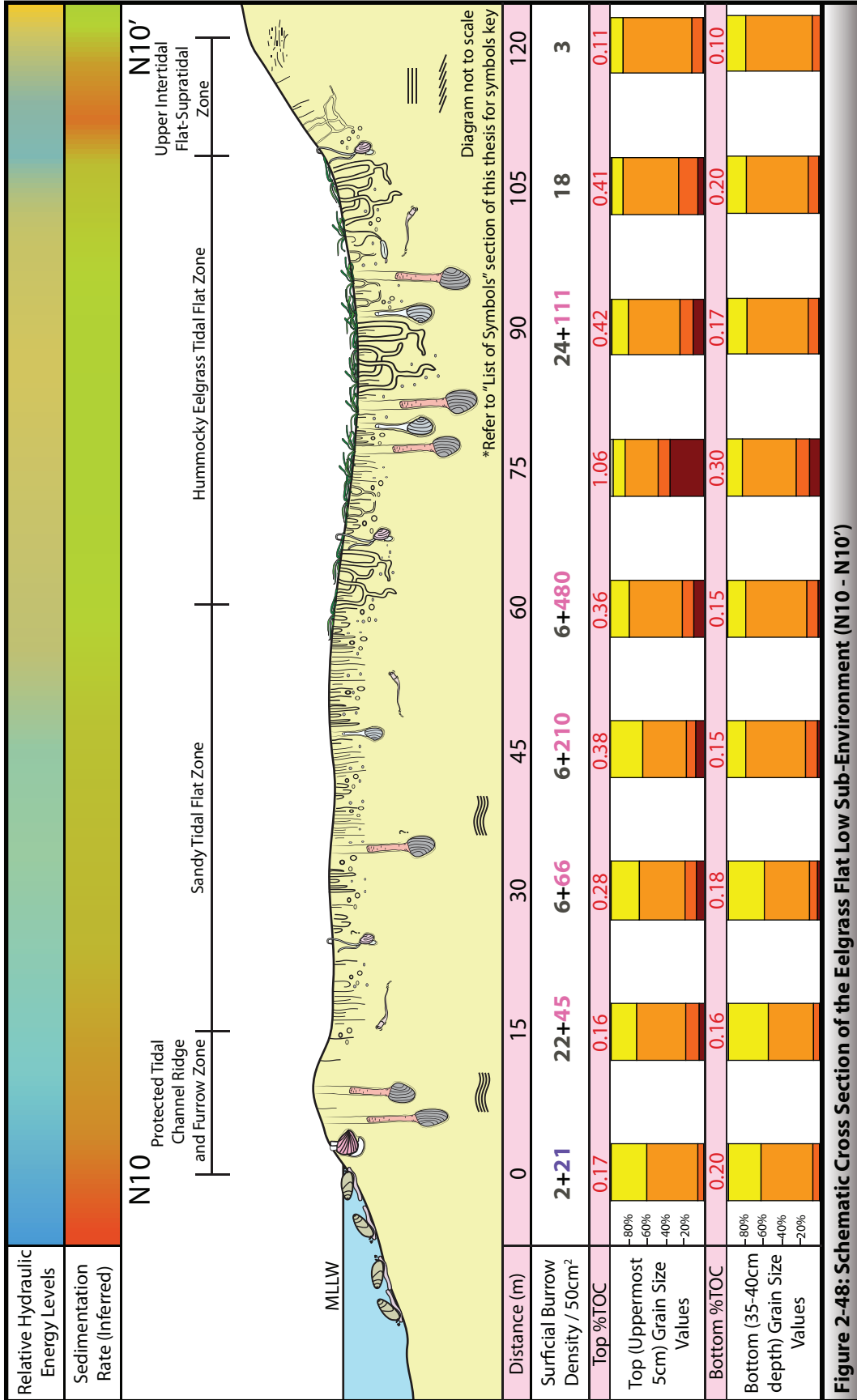


Figure 2-47: Schematic Cross Section of the Sand Flat High Sub-Environment (N8 - N8')



**Figure 2-48: Schematic Cross Section of the Eelgrass Flat Low Sub-Environment (N10 - N10')**

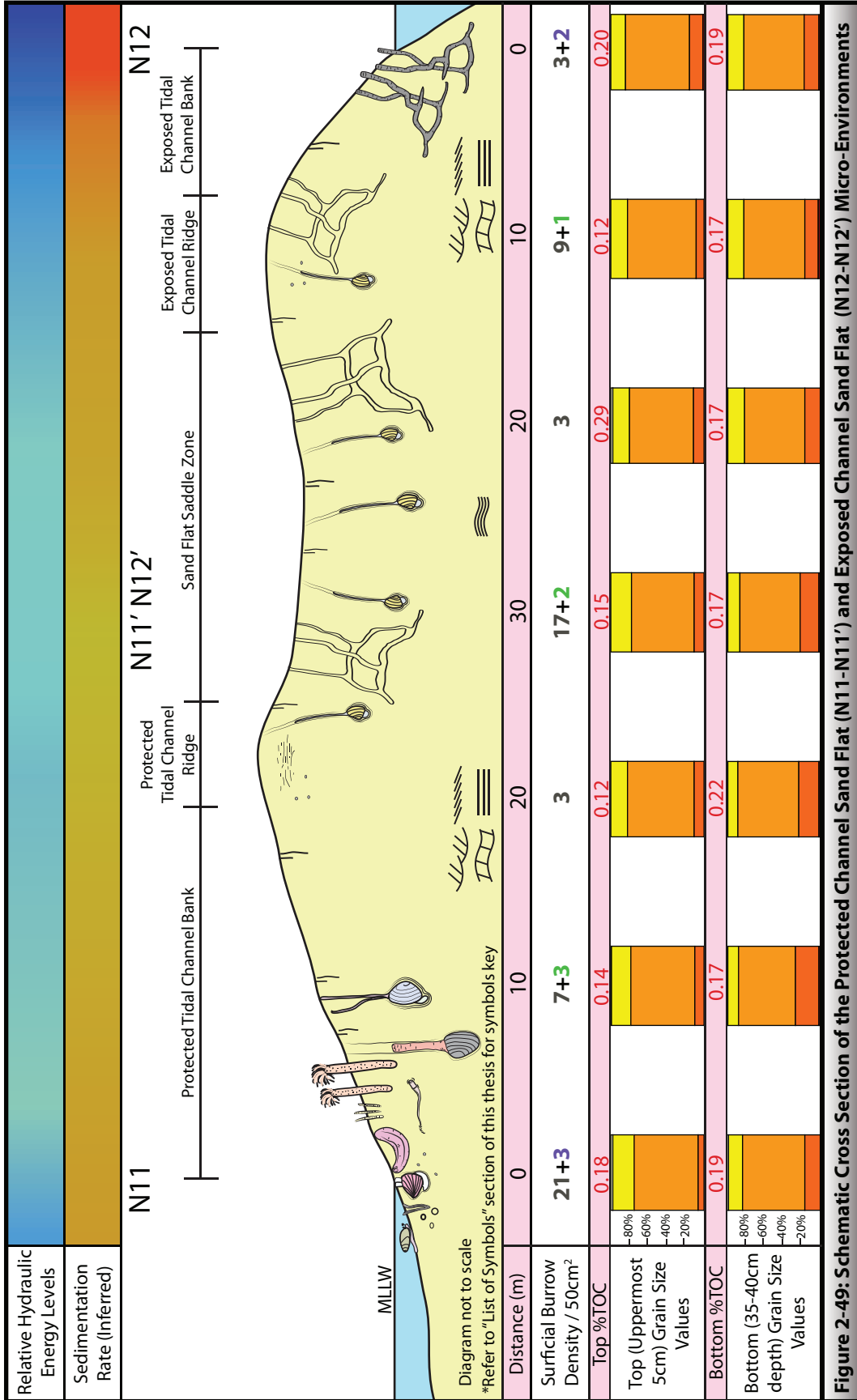


Figure 2-49: Schematic Cross Section of the Protected Channel Sand Flat (N11-N11') and Exposed Channel Sand Flat (N12-N12') Micro-Environments



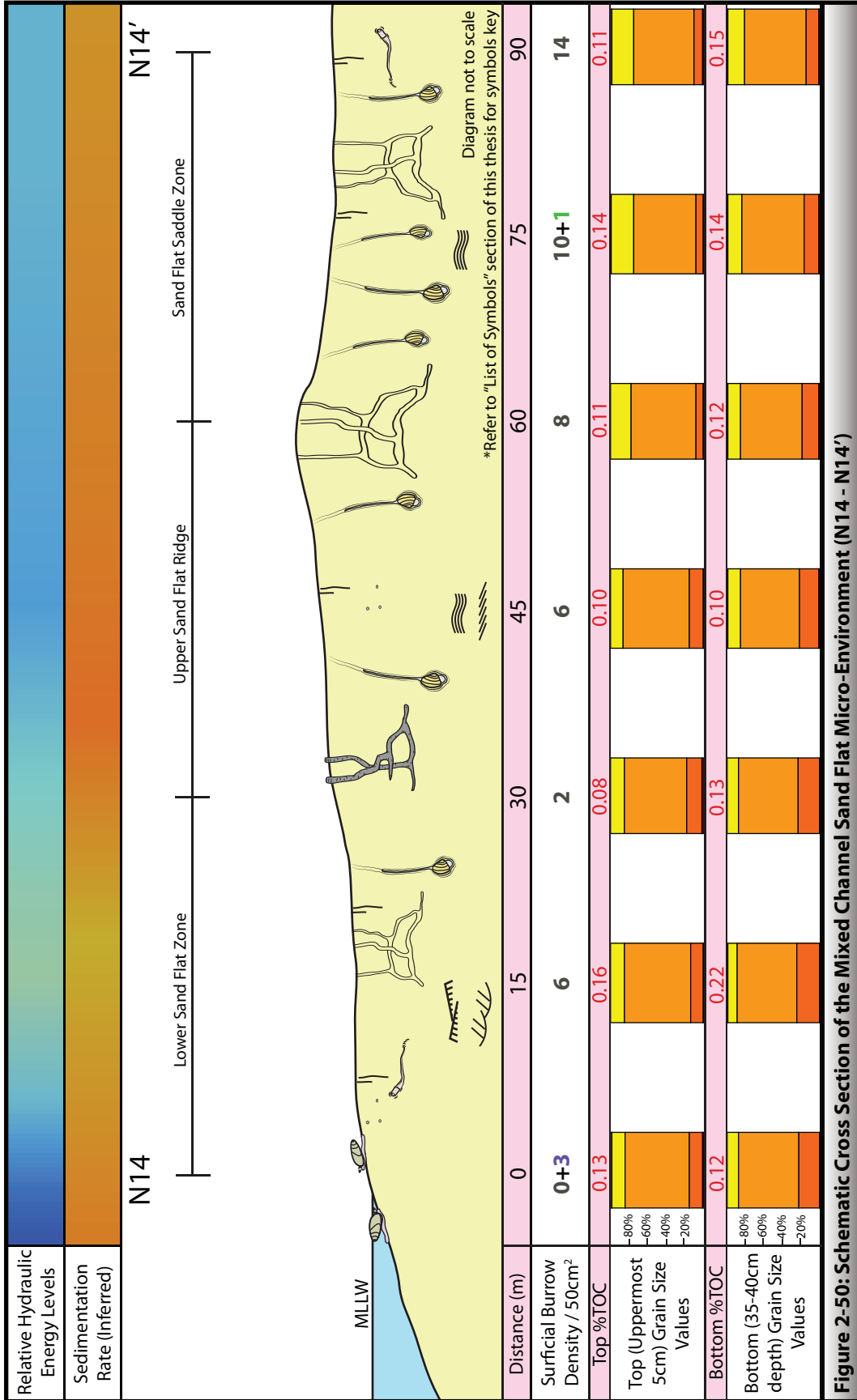


Figure 2-50: Schematic Cross Section of the Mixed Channel Sand Flat Micro-Environment (N14 - N14')

algae growing on the sediment surface, although the Eelgrass Flat Low sub-environment also has abundant macroalgae as well in the form of *Zostera japonica*. The upper intertidal flat-supratidal zone of both sub-environments displays very similar features, where both are subject to dominantly aeolian influences in the supratidal area creating small wind generated ripples, while the upper intertidal flat is composed of a short, relatively steep dipping face. However, the supratidal region of the Eelgrass Flat Low sub-environment is shorter in length and encounters a cut bank of vegetated eelgrass; whereas the supratidal area of the Sand Flat High sub-environment is longer with a less abrupt change into vegetated dunes. The Isolated Sand Bar sub-environment is quite different than the other two sub-environments of this region. It is essentially the point of a large sandy tidal flat located away from the bay margins. The point is at a junction between an exposed tidal channel that is directly connected to the main channel and a protected tidal channel. The exposed tidal channel is overall deeper and experiences faster currents than the protected tidal channel.

In Netarts Bay the ebb tide is slightly longer than the flood tide thereby allowing the bay to undergo a faster rate of tidal flushing (Glanzman et al., 1971). This region of the bay is highly dynamic sedimentologically and the morphology of tidal channels and especially tidal flats can change rapidly after a period of relative calm. The Eelgrass Flat Low sub-environment once occupied the area now occupied by the Sandy Flat High sub-environment. In the last decade it appears that the sands of the Sandy Flat High sub-environment have been steadily encroaching on the lower eelgrass dominated flats of the Eelgrass Flat Low sub-environment to the south (Google Earth). Dolch and Reise (2010) suggest that ridge and furrow sand flats comprised of fine- to medium-grained sand, which they call large sandy bedform fields, expand in association to increased hydrodynamic pressures such as an increase in mean high tide level and increased frequencies of elevated tide levels due to storm activity. In their study Dolch and Reise (2010) also indicate that the

expansion and migration of large sandy bedforms can displace seagrass fields as they migrate over them due to increasing hydraulic energy levels caused by higher fair-weather and storm-weather tides. In this region of Netarts Bay the shift of tidal channels likely led to an increase in hydraulic energy levels causing higher flow regime features and bed form migrations to occur more commonly. The bar point of the isolated extensive sand flat attributed to the Isolated Sand Bar sub-environment has undergone massive changes as it constantly shifts position. The increase in storm wave height, particularly by strong stormy seasons of associated El Niño and La Niña events of the late 1990s, may be a partial cause of tidal channel migration as well as ridge and furrow sandy tidal flat expansion (Allan and Komar, 2002).

In areas of higher current velocities a prominent ridge usually develops with a steeper dipping bank along the transition from sandy tidal flat to a relatively deep tidal channel, such as along the Sand Flat High sub-environment and Exposed Channel Sand Flat micro-environment. In areas of lower current velocities and shallower tidal channel depths a gentler dipping bank is developed such as along the Eelgrass Flat Low sub-environment and Protected Channel Sand Flat micro-environment. Along the lower velocity banks a series of ridge and furrow or bar and troughs are produced sub-perpendicular to the channel. These ridge and furrow structures are possibly the result of helical motion oriented along the ridge and furrow axes, sub-perpendicular to the flow in the main drainage channel, caused by the relatively rapid flow of water on and off the tidal flats during flood and ebb tide, respectively. Allen (1969) described similar features formed experimentally describing them as spurs or ridges and furrows or grooves that form with long axes oriented along current flow direction, especially in the troughs of dune features or similar large bar forms. Linguoid ripples commonly occupied the ridges and furrows with occasional asymmetric sinuous crested ripples observed within the troughs oriented perpendicular to its long axis indicating the direction of flow was along the trough off the tidal



flat and into the main channel during the recent ebb-tide. Ridge and furrow structures, or simple undulatory topography, are also associated with most of the tidal flat zone of the Sandy Flat High sub-environment. Although, these features are larger in amplitude to the ones witnessed along the protected tidal channel and they occur on a flatter horizon. Much like the ridge and furrow structures of the protected tidal channel, the ridge and furrow structure formed here may be a combined result of helical flow due to wave action in addition to tidal flat water flow patterns during drainage and submergence (Allen, 1982a; 1982b).

The sinuous to linguoid ripples formed on top of the larger bedform features of this region are likely the result of waning flow velocities in an overall shallow area. As flow velocity decreases the larger bedforms such as dunes will cease to form or migrate and ripples become the more dominant features produced (Allen, 1982a; 1982b). Wind generated waves also impart a significant signature upon the topography, therefore the ripples generated are usually the result of both tidal currents and oscillatory wave action leading to combined flow ripple formation that is either wave- or current-dominated (Harms, 1969). Although the bay is wave-dominated and tide-influenced ripples seem to be dominated by tidal currents closer to the tidal channels with ripples dominated by wave action increasing away from the tidal channels towards the shoreline or onto the tidal flats. In the subsurface there was a large range of structures including: horizontal planar laminae; inclined planar laminae; combined flow ripple trough cross laminae; climbing ripple laminae; and massive bedding. This wide variety of internal structures indicates widely differing hydraulic conditions that occur over this area at any given time. At the confluence between the protected channel and the exposed channel, where the Mixed Channel Sand Flat micro-environment ends at a point, bidirectional cross laminae were observed in the subsurface lending an indication to the shifting back and forth of the flood and ebb tidal currents over this point.

Various ripple forms were a common feature of the Isolated Sand Bar sub-environment that received the highest hydraulic energy levels out of all three of the sub-environments of the Outer Sheltered Sandy Tidal Flat bay region. The channel banks and ridges along the Sand Flat High and Eelgrass Flat Low sub-environments also had common ripple forms. However, the remainder of the Sand Flat High sub-environment that was subject to intermediate hydraulic energy levels in relation to the other two sub-environments possessed either wavy to planar lamina as energy levels were less. The rest of the Eelgrass Flat Low sub-environment on the other hand was comprised of planar to massive sands as it was affected by the lowest amounts of hydraulic energy levels compared to the other two sub-environments. The Eelgrass Flat Low sub-environment has a relatively planar surface with small hummocks densely populated by eelgrass and shallow tidal pool troughs sporadically populated by eelgrass. A similar observation of eelgrass density on hummocks and troughs was made by Dashtgard (2011) at Boundary Bay, British Columbia. In addition to possibly being shaped initially by low amplitude sand waves that have almost completely worn away (Swinbanks and Murray, 1981), the shape of the slight hummock-trough terrain may be due in part to clam diggers as was observed in the Outer-Middle Sandy Tidal Flat bay region over consecutive days. *Zostera marina* mainly found in the Outer-Middle Sandy Tidal flat bay region tends to live in the lower intertidal to subtidal zone, whereas the shorter, thinner *Zostera japonica* present in the Outer-Sheltered Sandy Tidal Flat bay region tends to live in the middle to upper intertidal zone. This trend in vertical zonation between the two *Zostera* species was also observed by Shafer et al. (2007) from Padilla Bay, Washington and Ruesink et al. (2010) from Willapa Bay, Washington. Cyanobacteria (blue-green algae) and other types of microalgae are common in the calmer undulatory flats of the Sand Flat High sub-environment as well as the protected, planar to slightly hummocky sand flats of the Eelgrass Flat Low sub-environment. Hagadorn and McDowell (2012) performed flume experiments using

cyanobacteria growing on unconsolidated medium grained sand and discovered that these microbial communities had the potential to almost double flow velocities required to produce traditional, idealized bedforms. They also indicated that the growth of undulatory bedforms can even be completely inhibited with the bed stress instead being translated into the formation of flip-over, roll-up and rip-up structures associated with the microbial mats. This microbial mediated mechanism may explain the overall smooth features, as well as small scale soft sediment deformation structures possibly being attributed to roll- or rip-up formation of the Eelgrass Flat Low sub-environment.

Along the upper intertidal flat inclined planar laminae were the most prominent features observed with occasional tabular cross laminae observed. The topset-foreset pair observed in a trench of the upper intertidal flat along the Sand Flat High sub-environment indicates that there was an erosional period followed by deposition along the upper intertidal flat. This erosion could have resulted from cyclical occurrences such as neap-spring tidal changes, seasonal changes, or the expansion or shift of the supratidal area along the spit bayward. Like the foreshore-backshore boundary of the exposed beaches along the coast, the upper intertidal flat-supratidal boundary of the outer bay region also displays vesicular structure, or bubble porosity. When the flood tide rises bringing water in fast over clean, well drained sand air bubbles become trapped between water laden horizons near the surface causing the bubbly texture to form in the upper few centimetres of sand (Stewart, 1963; Allen, 1982b). The Isolated Sandy Bar sub-environment and tidal ridge along the Sand Flat High sub-environment also display bubble porosity due to the same mechanism. Also identical to the backshore of the exposed beaches of the coast, the supratidal area along the protected bay portion of the spit wind generated sinuous to straight crested ripples formed by the saltation, impact and creep of upper fine- to lower medium-sand grains (Bagnold, 1941; Sharp, 1963; Harms, 1969).



### **Neoichnological Interpretation**

The overall water quality of the bay is very pristine and remarkably clear with salinity values for most of the bay remaining around that of the open ocean. The only exception may occur when the bay head experiences lower salinity levels during parts of the winter months due to brief run-off periods associated with heavy rainfall (Glanzman et al., 1971; Shabica et al., 1976). As with other marginal marine settings desiccation is always an issue at low tide. Temperature is mainly an issue in Netarts Bay during the summer months at low tide on the tidal flats where solar insolation can raise temperatures significantly (Shabica et al., 1976). Otherwise, the water temperature is relatively stable normally ranging from 8°C to 11°C in winter and up to 16°C in summer (Glanzman et al., 1971). Since this area of the bay is dominantly influenced by large gradients in hydraulic energy levels and sedimentation rate these factors have the most profound effect on the distribution of organisms within the Outer Sheltered Sandy Tidal Flat bay region. Massive bedding was mainly seen in areas with large amounts of bioturbation, especially under the calmer, protected eelgrass fields where organisms are able to come to the surface and feed in the protection of the sheltered eelgrass area. In addition the sand is well- to very well-sorted mainly upper-fine sand and therefore makes the observation of any primary sedimentary structures difficult to ascertain especially if the sand is dropped abruptly out of suspension. The presence of common to abundant amounts of bioturbation likely mask any faint primary sedimentary structures present. The top 5-15 centimetres of sediment were usually dominated by observable primary sedimentary structures with massive appearing sands below, some of them noticeably bioturbated with obvious traces seen. Therefore, it is likely that the top 5-10cm of sediment is the more dynamic zone that experiences continual erosion and deposition of sediment in response to high hydraulic energy levels and is not a favourable environment for large, diverse amounts of organism dwellings.

Indeed the larger amount of vertical traces in the higher energy areas, especially those on the Isolated Sand Bar, are supporting evidence that animals prefer to live and/or feed deeper out of harms way. The Eelgrass Flat Low sub-environment, and to some extent the undulatory topography of the Sand Flat High sub-environment, are the only environments within this area that are protected enough from higher energy levels to allow abundant and diverse organism colonization to occur. *Zostera* fronds baffle the currents as well as silt and other detritus from the water column creating a protected, nutrient rich environment for organisms to frolic (Den Hartog, 1970; Shabica et al., 1976). Incidentally the highest TOC levels of this bay region were amongst the eelgrass fields as TOC levels seemed to be inversely related to grain size as was also found by Shabica et al. (1976) in their research conducted on Netarts Bay. The baffling of sediment by *Zostera* may also aid in the formation of the slight hummocky features observed.

The crustacean formerly known as *Callianassa californiensis* (now *Neotrypaea californiensis*) was commonly found along the higher energy clean sandy areas of tidal channel banks and ridges, along the base of the upper intertidal flat, as well as throughout the Isolated Sand Bar micro-environment saddle zone. On the exposed banks that were subject to high tidal current velocities *N. californiensis* initially generated what was thought to be *Ophiomorpha*-like, *Cylindrichnus*-like, and *Thalassinoides*-like traces. Along the protected channels and in the saddle zone *N. californiensis* commonly only created *Thalassinoides*-like traces. Many traces generated by *N. californiensis* were sub-vertical to branched with *Thalassinoides*-like traces being unlined; *Ophiomorpha*-like traces possessing sporadic, seagrass lined interior walls with slightly bumpy exterior walls exhibiting raised columnar entrances; and *Cylindrichnus*-like traces displaying very thin, consecutively lined walls. However, both the *Ophiomorpha*-like traces and *Cylindrichnus*-like traces were finally interpreted to be that of line *Thalassinoides*-like traces, as no definitive traces could be found that were *Ophiomorpha*-like or *Cylindrichnus*-like in

appearance. Male *N. californiensis* possess a pronounced cheliped that is used for defence, while swimmerets keep water flowing through their ever expanding burrow networks for respiration purposes (MacGinitie, 1934). The dactyl hairs on the second and third legs of *N. californiensis* are used for deposit feeding as they sift through sand looking for detritus (MacGinitie, 1934). *Neotrypaea* burrows were indicated by Frey et al. (1978) to be common features on sandy tidal flats with moderately high current energies. In contrast, *Upogebia pugettensis* preferred the quieter, more detritus rich areas along the ridge and furrow zone of the Sand Flat High sub-environment and especially the protected Eelgrass Flat Low sub-environment. The first two hairy pairs of legs of *U. pugettensis* allow it to pick up mud and feed on suspended detritus that enters its semi-permanent burrow, while four pairs of swimmerets keep water flowing through the burrow (MacGinitie, 1930). Like *N. californiensis*, *U. pugettensis* created *Thalassinoides*-like burrow networks. Their burrows were typically unlined with occasional thinly, oxidized lining forming a halo around some. The three types of traces created may be a continuum beginning with freshly excavated burrows akin to *Thalassinoides*-like traces. Followed by slight, progressive lining of the trace with seaweed and other materials displaying a *Cylindrichnus*-like characteristic if only concentric smooth layers are observed or an *Ophiomorpha*-like characteristic if there are bumpy structures and raised columnar entrances at least sporadically present. However, after further scrutiny, all traces were eventually thought to represent some form of unlined to lined *Thalassinoides*-like trace. In some instances authors have debated the intergradational nature between thalassinid generated *Ophiomorpha*- and *Thalassinoides*-like traces as well (Frey et al., 1978; Swinbanks and Luternauer, 1987). Swinbanks and Luternauer (1987) observed *N. californiensis* creating *Thalassinoides*-like traces and *U. pugettensis* creating *Ophiomorpha*-like traces. While Frey et al. (1978) observed *Neotrypaea* species creating *Ophiomorpha*-like traces that may eventually grade into *Thalassinoides*-like traces. Collapse of *Thalassinoides*- and *Ophiomorpha*-like structures in unconsolidated sediment



could produce V-shaped structures that resemble fugichnia or anemone escape traces so careful observation is warranted (Frey et al., 1978). In Netarts Bay, especially in the Outer Sheltered Sandy Tidal Flat region, it is likely that *N. californiensis* creates more robust lined *Thalassinoides*-like traces in areas of higher energy levels. Mixed lined and unlined *Thalassinoides*-like traces may be observed in areas that have high energy levels and potentially significant levels of sedimentation and/or erosion. While only unlined *Thalassinoides*-like traces are found in areas of calmer, steady energy levels with lower rates of sedimentation. It appears that the sediment of Netarts Bay is ideal enough for *U. pugettensis* to dwell within an unlined to slightly oxidized, thinly lined burrow with no robust or rough outer wall observed. The thinly lined traces of *U. pugettensis* may resemble *Ophiomorpha* in some instances in the bay; however no obvious traces were found that display lumpy exteriors.

As indicated previously the deposit feeding generalist *Olivella biplicata*, which creates *Olivellites*-like traces, is highly mobile and favours uniform, well-sorted sandy sediment and clear waters (Edwards, 1969). The channel margin environment is ideal for *O. biplicata* and this is primarily where they are found. If the opportunity allows *O. biplicata* will also shift to predatory mode and consume live prey in addition to also being able to suspension feed on top of their usual deposit feeding lifestyle (Edwards, 1969). During low tide *O. biplicata* that are aurally exposed are almost always found buried just below the sediment surface, most likely to avoid desiccation.

*Siphonichnus*-like traces are associated with vertically oriented filter feeding and/or surface deposit feeding bivalves (Gingras et al., 2008). The trace itself includes the cavity the bivalve is currently residing in, a sub-vertical to vertical siphon trace, and finally slight to substantial sediment disruption indicating upward or downward movement of the bivalve (Gingras et al., 2008). *Lockeia*-like traces are commonly seen when bivalves leave an impression of their foot during resting periods (Gingras et al., 2008). It is commonly seen amongst bivalves residing near the surface that can also move sizable

horizontal distances, although it can also be associated with deep burrowing adult bivalves that cannot readjust themselves within the sediment anymore (Gingras et al., 2008). *Protovirgularia*-like traces are produced when the bivalve moves laterally across the sediment surface (Gingras et al., 2008), which was not observed in the Outer Sheltered Sandy Tidal Flat bay region, but was on occasion witnessed along the Outer-Middle Sandy Tidal Flat bay region. *Macoma balthica* was the only bivalve observed along the Sand Flat High sub-environment within the ridge and furrow zone. *Nuttallia obscurata* was solely found along the ridge and saddle area of the Isolated Sand Bar sub-environment and in rather large abundance. Byers (2002) also found high densities of invasive *N. obscurata* living in soft sandy sediments up to 25 cm deep in the upper intertidal zone of the San Juan Islands, Washington and discovered that they prefer this type of environment over others. Gillespie et al. (1999) also discovered *N. obscurata* residing high on sand ridges in large abundances. It was also noticed by Byers (2002) that the shell of *N. obscurata* is quite thin and easy to break therefore causing it to burrow rather deeply in upper intertidal sediments to avoid most predators. *Nuttallia obscurata* is capable of both deposit feeding and suspension feeding (Gillespie et al., 1999). *Macoma secta* was only found along the protected channel bank of the Protected Channel Sand Flat micro-environment, while *Clinocardium nuttallii* and *Tresus capax* were observed on both sides of the protected channel bank. Marriage (1954) states that *M. secta* prefers sandy substrates, a possible reason as to why *M. secta* is only found on the protected channel sand bank of the Isolated Sand Bar sub-environment where hydraulic rates are moderately high and sedimentation rates are relatively low in a clean, sandy environment. It appeared that only live *C. nuttallii* were present along the protected channel bank and nowhere else in the Outer Sheltered Sandy Tidal Flat bay region. The short siphon of the cockle *C. nuttallii* confines it to the near surface, very rarely being able to attain burrowing depths greater than 7 centimetres (Marriage, 1954). The muscular foot of *C. nuttallii* allows it to travel short horizontal

distances (Marriage, 1954), therefore it is most likely to create *Lockeia*- and *Protovirgularia*-like traces. However, there is still potential for it to create very short *Siphonichnus*-like traces as it is a filter feeder that can move up and down within the first few centimetres of sediment. There were multiple scattered empty *C. nuttallii* shells around, a possible relic of movement caused by exposure to tidal currents and wave action in conjunction with predation due to birds. Shorebirds were observed to prey on *C. nuttallii* shells as they dropped these shells from a height to try and break them in the Outer-Middle Sandy Tidal Flat bay region, therefore it is hypothesized that this may be the main reason for scattered *C. nuttallii* shells across the tidal flat surface. This behaviour was also observed by Zonneveld (pers. comm., 2011) in Craig Bay, British Columbia where birds would prey on similar shallow burrowing bivalve species and drop them on the tidal flats to break them open and obtain the meat inside. Multiple bivalve species were present within the Eelgrass Flat Low sub-environment including, in rough order of most abundant to least abundant: *Tresus nuttallii*, *Mya arenaria*, *Macoma balthica*, *Macoma nasuta*, *Tresus capax*, *Clinocardium nuttallii*, and *Saxidomus gigantea*. Alexander et al. (1993) classified *M. arenaria* as a substrate generalist that can burrow slowly into a wide range of grain sizes. They also classified *C. nuttallii* and *M. nasuta* as substrate sensitive species that are able to tolerate a wider range of substrates than substrate specialists, but burrow slower in progressively coarser sediments compared to substrate generalists. *M. nasuta* is able to burrow up to depths of 20cm, while *T. nuttallii* and *S. gigantea* can dig to depths of 40cm and 30cm, or more, respectively (Marriage, 1954).

Worm burrow morphologies varied widely, with dominantly sessile organisms producing mainly vertical to helical or U-shaped traces and more mobile organisms generating complex three-dimensional branching to unbranching traces (Dashtgard and Gingras, 2012). In addition, burrows were usually mucous to mud lined, either thick or thin, and may be hollow or infilled, either passively or actively (Dashtgard and Gingras, 2012). Errant worms did

not create lined burrows, while others created elaborate burrows lined with shell fragments, sand, and other debris bound together by mucous and mud. Overall, unlined to thinly lined burrows were common along most of the Outer Sheltered Sandy Tidal Flat bay region except along the Eelgrass Flat Low sub-environment where typically lined branching forms were more commonly seen and along the protected channel of the Isolated Sand Bar sub-environment where worms built raised tubes. The errant nephtyid polychaete *Nephtys* sp. was sporadically observed burrowing throughout the Outer Sheltered Sandy Tidal bay region in much the same way as it did in the Exposed Shoreface-Spit bay region, disrupting sediment and creating possible navichnia structures as well as cryptic bioturbation. *Nereis* sp. was only observed in the protected eelgrass of the Eelgrass Flat Low sub-environment. Various capitellid threadworms (*Mediomastus* sp. and *Capitella* sp.) were observed throughout the bay region in areas that had wet, firm sands but were found in highest abundance amongst the eelgrass flat. Bloodworms (*Glycera* sp.) were only observed along hummocky eelgrass flats. Threadworm bioturbation resulted in *Trichichnus*- (essentially diminutive *Skolithos*), *Skolithos*- and *Planolites*-like traces. The larger bloodworms typically left behind traces akin to *Palaeophycus*-, *Planolites*-, and subordinate *Polykladichnus*-like traces. The nemertean *Cerebratulus* sp. was sporadically witnessed throughout the Eelgrass flats, and along the protected channel bank of the Isolated Sand Bar micro-environment creating slightly mucous lined *Palaeophycus*-like traces. Gingras et al. (2008) described a succession of vermiform burrow types beginning with the simplest vertical tube, next transforming into Y-shaped tubes, followed by horizontal tubes running along the bottom of the Y-shaped and other vertical tubes eventually connecting them and potentially branching. The vertical shafts give rise to usually mucous lined *Skolithos*-like traces, while the Y-shaped burrows give rise to *Polykladichnus*-like traces, with lined tubes giving rise to *Palaeophycus*-like traces, and finally actively filled horizontal tubes giving rise to potential *Planolites*-like traces (Gingras et al., 2008). Nereid polychaetes



commonly make Y-shaped *Polykladichnus*-like burrows that are connected via basal horizontal burrows, using the vertical components only to come to the surface to deposit feed (Gingras et al., 2008; pers. obs. Hodgson, 2013). These various semi-permanent burrow morphologies constructed by vermiform organisms allow the animal to carry out many functions such as protection from predators, allowing for deposit and interface feeding, and potentially creating an environment for passive carnivory (Gingras et al., 2008). Among the more unusual worms discovered were those that created distinct lined tubes akin to lined *Skolithos* traces, including the tubes of the probable spionid polychaete *Pygospio elegans*, or possibly the maldanid polychaete *Axiothella rubrocincta*, as well as the much larger tube of *Pista pacifica*. These polychaete tubes were only observed along the protected channel of the Isolated Bar sub-environment. The sediment along the protected channel bank became soupy when agitated, that coupled with the fact the fragile tubes of either *P. elegans* or *A. rubrocincta* broke very easily, made it very difficult to observe the nature of these thin, fragile tubes in the subsurface. Wilson (1983) described *A. rubrocincta* tubes as U-shaped along the Californian coast and vertical along the Washington coast, therefore the tubes in Netarts Bay may have possessed either morphology. Taghon et al. (1980) suggest that organisms capable of switching between deposit and suspension feeding modes, such as *P. elegans*, are typical of environments that display rapid changes in flow conditions. The sedentary spionid polychaete *P. elegans* creates small, fragile, mucous-lined, sandy tubes (Taghon et al., 1980; Bolam and Fernandes, 2003). As low velocity flows become moderate to high *P. elegans* switches from deposit feeding to suspension feeding as more suspended particles become more prevalent over deposited detritus (Taghon et al., 1980). The deposit feeding terebellid, *Pista pacifica*, lives in parchment like fringed headed tube that are oriented vertically within sandy intertidal flats (Winnick, 1981). The organism itself may be up to 39cm in length, while its tube may be up to a meter in length in the subsurface with tube and hood projecting a few centimetres above the sediment surface

(Winnick, 1981; Rudy and Rudy, 1983). *Pista pacifica* usually orients itself at right angles to the main direction of water flow unless there is a constant flow of sediment from one direction, where it would then orient itself so that the hood would be protecting the opening of the tube from sediment input (Winnick, 1981). In this way, the orientation of the hooded tube may act as indicators of sediment transport direction, as they orient themselves at right angles to main current direction and away from main sediment input direction (Winnick, 1981).

Another more unusual creature discovered along the protected channel margin of the Isolated Bar sub-environment was the rattail sea cucumber *Paracaudina chilensis*. A peculiar specimen no doubt, *P. chilensis*, like all holothurians, possesses strong longitudinal muscles allowing it to burrow. *Paracaudina chilensis* only resides in fully marine environments and usually suspension feeds, although it also has the ability to deposit feed via tentacles (Smilek and Hembree, 2012). Due to the thixotropic nature of the sediment the evaluation of *P. chilensis* burrow morphology was unfortunately impossible. Thankfully, holothurian burrowing abilities were studied by Smilek and Hembree (2012) whom observed the burrowing behaviour of the holothurian *Thonella gemmata*, where the organism used the mid portion of its body to first pierce the sand via muscle contractions. The mid portion of the body continued penetrating downward as further muscle contractions allowed it to burrow deeper eventually forming an irregular U-shaped burrow akin to *Arenicolites* or *Diplocraterion*. It was noted by Smilek and Hembree (2012) that although the organism moved from the top down in consecutive movements forming what one would assume to be a *Diplocraterion*-like trace, no spreite were seen. This is likely due to the homogenous and in some cases possibly even thixotropic nature of the sediment, plus the fact that the organism does not line its burrow. A downward deflecting U-shaped sediment disruption structure would likely be the most common trace left by a burrowing holothurian in sand. It is therefore hypothesized that the holothurian *P.*

*chilensis* observed along the protected channel of the Isolated Sand Bar sub-environment burrowed in a similar manner. The only difference that may arise is that *T. gemmata* possesses numerous podia that help it move sediment away from itself while burrowing in addition to muscular contractions (Smilek and Hembree, 2012) and *P. chilensis* does not possess such podia. Thus, it is likely that *P. chilensis* only burrow through the aid of full body muscular contractions.

The amphipod trace makers *Corophium* sp. and *Eohaustorius* sp. were common trace makers among the sandy intertidal flats. The corophiid amphipod *Corophium* sp. was sporadically observed just below the surface along the flats although the thixotropic nature of water laden sands made it very difficult to ascertain its burrow structure in areas where it was seen in the subsurface. However, it is thought that some small *Arenicolites*-like to *Skolithos*-like features witnessed near the surface were occasionally those produced by *Corophium* sp. as was also witnessed along the sandy flats of the Outer-Middle Sandy Flat bay region. Ingle (1966) noted that the sand-loving *Corophium arenarium* constructs shallow U-shaped tubes which aid in respiration, elimination of wastes, as well as filter feeding as water is circulated through the burrow. It was also noted by Ingle (1996) that the mud loving *Corophium volutator* also constructs very similar burrows to *C. arenarium* except *C. arenarium* likes to probe the sediment beforehand and may deepen its burrow with time. Dashtgard and Gingras (2012) also mention that *C. arenarium* create single, unlined vertical traces, which may very well happen after burrow deepening, creating a shift from *Skolithos*-like to *Arenicolites*-like traces. Uchman and Pervesler (2006) attributed meandering surface traces similar to the *Gordia*- and *Crossopodia*-like ones observed in this study to those created by various isopods and *Corophium* sp. amphipods. Therefore, it is also likely then that *Corophium* sp. is also the creator of the *Gordia*-like to *Crossopodia*-like traces witnessed, in addition to *Eohaustorius* sp. even though *Corophium* sp. were not directly seen making the traces. The haustoriid amphipod *Eohaustorius* sp. was a very common epifaunal creature that created obvious

*Gordia*-like to *Crossopodia*-like surface traces (Dashtgard and Gingras, 2012). Haustoriid amphipods constantly move through the sediment by excavating then backfilling their burrows thereby possibly creating cryptic bioturbation by smaller haustoriids and *Navicinia* or sediment disruption structures by larger haustoriids (Dashtgard and Gingras, 2012). This sort of disruption within the tidal flat zones of the region, causing the massive appearing sands commonly seen, may in small part be caused by *Eohaustorius* sp. subsurface burrowing behaviour. Shabica et al. (1976) indicated that although the mobile *Eohaustorius* sp. amphipod is normally found on open ocean beaches, the high salinity, fine to medium grained sand, and rapidly flowing waters of the tidal channels in association with shallow tidal flats in the north end of the bay make it an ideal place for *Eohaustorius* sp. to thrive. This also brings into light the possible creator of *Macaronichnus*-like traces. Dashtgard and Gingras (2012) indicated that haustoriid amphipods are capable of creating sediment disruption structures or cryptic bioturbation, while Shabica et al. (1976) indicated that the haustoriid amphipod *Eohaustorius* sp. is usually found along the open ocean. These two deductions lead to the hypothesis that *Eohaustorius* sp. may be a plausible creator of *Macaronichnus*-like traces although not the most likely one, adding to the number of potential trace makers already mentioned and an area of future research to be followed.

Common upper intertidal flat-supratidal tracemakers included the isopod *Exciorolana* sp., as well as the talitrid amphipods *Traskorchestia traskiana* and *Megalorchestia californiana*. No *Euzonus* sp. were observed along the inclined upper intertidal flat, although they could have still been present, therefore the most likely tracemaker of the *Macaronichnus*-like traces in this zone is the abundant *Exciorolana* sp. At higher tide levels *Exciorolana* sp. was observed swimming along the water-upper intertidal flat interface, occasionally nipping at bare ankles and burrowing quickly beneath the sand. In other studies, *Exciorolana* sp. were also observed to come out of their burrows at high tide to feed (Enright, 1972; Klapow, 1972). These observations strengthen the



hypothesis that *Exciorolana* sp. may be the possible tracemaker of *Macaronichnus*-like traces in the upper intertidal flat. As mentioned earlier, *T. traskiana* is a plausible tracemaker of *Skolithos*-like traces, even though Koch (1991) identified it as a “non-substratum modifying talitrid amphipod”, since Dashtgard and Gingras (2005) showed that a similar burrowing amphipod *Talorchestia longicornis* was the creator of multiple small unlined *Skolithos*-like traces along a New Brunswick beach. *Traskorchestia traskiana* was observed within an infilled burrow; however it may have been a passive occupant of the burrow and not the actual creator of it. Therefore, since it was not observed actively making a burrow it is only identified as a plausible tracemaker due to its passive association with small, unlined *Skolithos*-like burrows. On the other hand, *M. californiana* was observed flicking sand out of a burrow in its typical fashion and is therefore ascribed as a trace maker of small, unlined *Skolithos*-like burrows near the upper intertidal flat-supratidal boundary. *Megalorchestia californiana* was mainly observed in the wetted sands of the upper intertidal flat-supratidal boundary while *T. traskiana* was found exclusively in the supratidal zone under dry wrack and on top of dry sand. These observations were identical to what was witnessed on the more exposed, open ocean reaches of the spit and also coincides with the talitrid behaviour witnessed by Pelletier et al. (2011).

## **OUTER-MIDDLE SANDY TIDAL FLAT BAY REGION DESCRIPTION AND RESULTS**

### **Morphological and Sedimentological Features**

#### ***Sandy Eelgrass Field Sub-Environment***

The Sandy Eelgrass Field transect consists of a low lying sandy tidal flat covered by a thick eelgrass field bordered by two ridges on either side. The ridge closest to the tidal channel consists of strongly ebb-oriented, sinuous to linguoid crested mainly tidal current generated ripples (Fig. 2-51A,B). Ridge and furrow structures are commonly seen on the ridge oriented almost



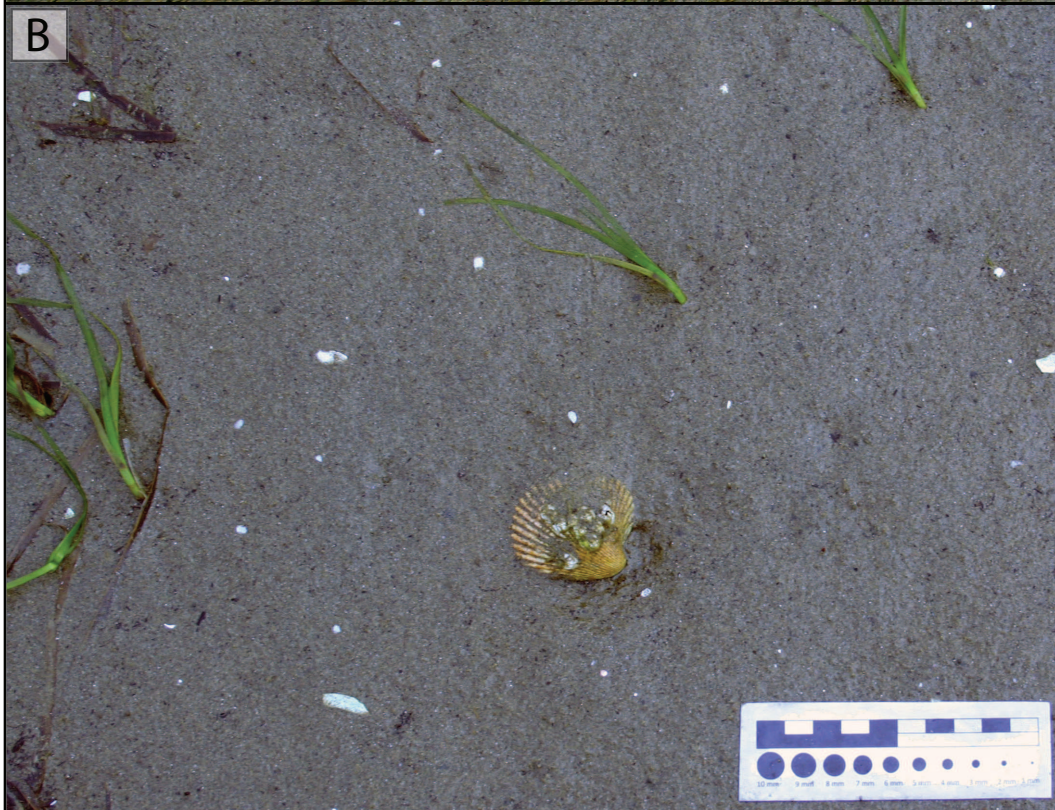
**Figure 2-51: Morphology of the tidal ridge next to the main channel along the Sandy Eelgrass Field sub-environment.** Shovel for scale is ~1.1m. Ebb tidal current flow direction is indicated by the blue arrow. **(A)** View SW towards the bay head with main tidal channel in the midground. The foreground displays ridge (bar) and furrow (trough) structures. Sinuous to linguoid ripples are superimposed on the larger undulatory bar forms. Bedforms are oriented according to the most recent ebb tidal current flow direction. **(B)** View E towards the bay margin with the hummocky eelgrass mounds prominent in the midground. Dominantly sinuous ripples grade into linguoid ripples in this portion of the sandy tidal ridge.

perpendicular to the main tidal channel (Fig. 2-51A). Next to this ridge there is a mixed sand-eelgrass area where the eelgrass, in this case *Zostera japonica*, is most common on small hummocks (Fig. 2-51B, Fig. 2-52A). Ripples become more linguoid and mixed wave-, current-dominated (Fig. 2-51B). The eelgrass field, comprised of dominantly *Zostera marina*, is an area where only eelgrass is present at the surface in a large pool of standing water. This area is quite extensive with occasional sandy mounds above water that possess shorter and smaller eelgrass fronds compared to those constantly submerged by water. At the edge of the eelgrass field furthest from the main channel is another sandy ridge that had almost symmetric to asymmetric dominantly wave generated and subordinately tidal current generated ripples ranging from sinuous to linguoid in shape.

On the sand ridge closest to the main tidal channel analysis of boxcore and boxcore peels revealed both planar laminae and cross ripple laminae in the subsurface. Boxcore analysis of subsurface features from the eelgrass field displayed prominently massive bedding with laminae evident only in the uppermost 2-5cm. The massive bedding trend continued into the eelgrass patchy zones beside the sand ridge on the eastern side of the eelgrass flats, with shell fragments also common in the subsurface. On the eastern ridge ripple cross laminae was observed within the top 2-5cm of sediment while planar to wavy laminae were observed below.

The majority of the sub-environment is mainly characterized by apparently structureless sand (Fig. 2-52B). The sand is beige in color within the upper 10cm of sediment that slowly to abruptly grades into grey to black suboxic to anoxic sands below. The oxic zone is often mottled with anoxic sands, and *vice versa*, although the latter occurs to a lesser extent. Eelgrass (dominantly *Z. marina*) is prevalent in this area and therefore rootlets are a common feature within the top few centimetres of sand. In the transitional hummocky zones, outside the extensive water-laden *Z. marina* field, *Z. japonica*





**Figure 2-52 Morphology of the eelgrass field zone along the Sandy Eelgrass Field sub-environment. (A)** View W towards the main tidal channel. Tidal channel ridge next to the tidal channel is seen in the mid- to back-ground. *Zostera japonica* is occupying hummocks in the midground while the water laden eelgrass field (composed mainly of *Zostera marina*) is observed in the foreground. Field of view across the bottom of the photograph is ~2.5m. **(B)** View of the sediment surface along a sandy non water laden patch in the middle of the eelgrass field. The surface is essentially planar with no prominent ripples.



is common on sandy mounds while virtually absent within the surrounding water laden hollows. Disarticulated shell debris is common throughout.

Average grain size across the Sandy Eelgrass Field sub-environment was dominantly upper fine- (53.88 wt%) to lower fine- (20.24 wt%) grained sand; top sediments ranged from dominantly 51.52 wt% upper fine-grained sand to 23.08 wt% lower fine-grained sand, while bottom sediments ranged from dominantly 56.24 wt% upper fine-grained sand to 17.46 wt% lower medium-grained sand, with a sizable portion (17.39 wt%) of lower fine-grained sand (Table 2-5). Largest average grain size occurred closet to the main channel along the tidal ridge. There were noticeable portions of very fine-grained sand and silt in areas where dense eelgrass was exceptionally prevalent.

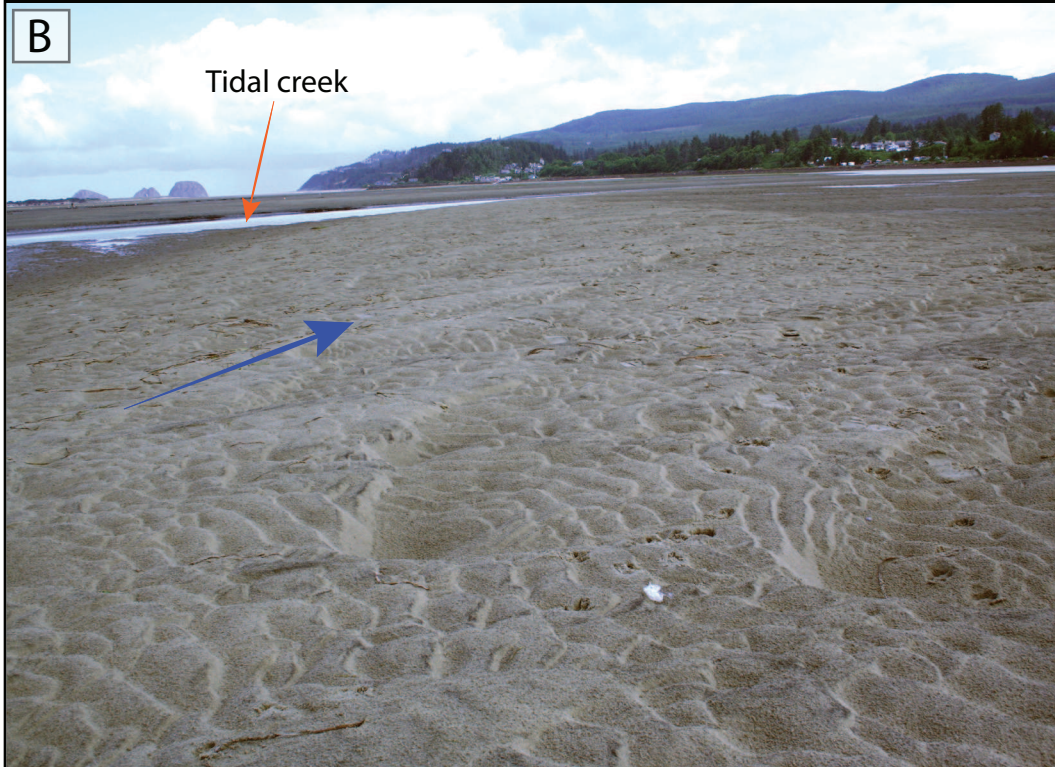
Grain size analysis indicates that overall, the grains of the Sandy Eelgrass Field sub-environment are well sorted (inclusive standard deviation (Folk, 1974): 0.43 $\phi$ ), fine-skewed (inclusive graphic skewness (Folk, 1974): 0.18Sk), leptokurtic (graphic kurtosis (Folk, 1974): 1.35K), dominantly upper fine-grained sand with a mean size of 2.35M (graphic mean (Folk, 1974)) (Table 2-5).

### ***Sand Flat High-Tidal Creek Sub-Environment***

The Sand Flat High-Tidal Creek transect is split into two main zones, one being the sand flat high zone and the other a sandy tidal creek zone. The sand flat high zone displays sand hummocks that may also extend into ridges in addition to water filled pools that may extend into furrows. Combined flow, wave- and current-generated, sinuous to linguoid crested ripples are common on the surface of the sand flat high zone. The shallow tidal creek displayed occasional bars or ridges extending into the channel and was approximately 50m wide (Fig. 2-53A). On the eastern side of the channel is a high sandy tidal ridge. Small sinuous to lunate dunes with ripple fans are present on the sandy tidal ridge (Fig. 2-53B). Ebb-oriented sinuous to linguoid ripples are superimposed on crests of small dunes with occasional ripple crests oriented perpendicular to the dune crests upon which they formed (Fig. 2-53B).

Table 2-5: Summary of Sedimentological and Physico-Chemical Characteristics of the Outer-Middle Sandy Tidal Flat Bay Region						
Sub-Environment	Sedimentological and Physico-Chemical Properties					
	Common Sedimentary Features	Sediment Analysis	TOC (%)	Salinity (PSU)	Average Overall Grain Size (wt%)	
<b>Sandy Eelgrass Field</b>	<p><b>Main tidal channel ridge:</b> Strongly ebb-oriented, sinuous to linguoid crested mainly tidal current generated ripples. Ripples become more linguoid and mixed wave-, tidal current-generated nearer the eelgrass fields along patchy eelgrass hummock area. Planar laminae and cross ripple laminae are evident in the subsurface. <b>Eelgrass field:</b> Planar surface or covered by eelgrass. Subsurface displays massive bedding with mottled laminae evident only in the uppermost 2-5cm. <b>Sand flat ridge:</b> Nearly symmetric to asymmetric mainly wave generated sinuous to linguoid crested ripples. Subsurface displayed planar to wavy laminae with cross laminae in top 2-5cm. Bioturbation common.</p>	Well sorted, fine skewed, leptokurtic, dominantly upper fine grained sand (0.43φ, 0.18Sk, 1.35K, 2.35M)	<p>Lowest Value (0.17)  Highest Value (2.89)  Top Average (0.46)  Bottom Average (0.53)  <b>Overall Average (0.49)</b></p>	--	<p>Upper medium grained sand to granule (1.9)  Lower medium grained sand (15.6)  Upper fine grained sand (53.9)  Lower fine grained sand (20.2)  Upper very fine grained sand to silt/clay (8.4)</p>	
<b>Sand Flat High-Tidal Creek</b>	<p><b>Sand flat high zone:</b> Combined flow, wave- and tidal current-generated, sinuous to linguoid crested ripples common on surface. Subsurface consists of planar laminae to massive appearing bedding. <b>Sandy tidal creek zone:</b> Sporadic ridges extend into creek. Planar to ripple cross laminae seen in subsurface along western margin of tidal creek. <b>Sandy tidal ridge:</b> Ebb-oriented sinuous to linguoid crested ripples superimposed on sinuous to lunate subaqueously formed dunes. Ripple fans present in dune troughs. Subsurface dominated by planar laminae and secondarily by ripple trough cross laminae. Bioturbation sparse to common throughout.</p>	Well sorted, near symmetrical, leptokurtic, dominantly upper fine grained sand (0.35φ, 0.02Sk, 1.47K, 2.25M)	<p>Lowest Value (0.20)  Highest Value (1.24)  Top Average (0.29)  Bottom Average (0.46)  <b>Overall Average (0.38)</b></p>	30	<p>Upper medium grained sand to granule (1.3)  Lower medium grained sand (18.8)  Upper fine grained sand (60.2)  Lower fine grained sand (16.2)  Upper very fine grained sand to silt/clay (3.5)</p>	
<b>Tidal Creek</b>	<p><b>Sand flat high zone:</b> Mainly linguoid ripples which grade into mainly sinuous ripples creekward. Subsurface displays tabular to trough cross laminae with tabular laminae displaying bidirectionality especially 15cm or lower due to sediment disruption in upper 15cm. <b>Tidal creek zone:</b> Planar surface in troughs and sinuous crested near symmetric combined flow ripples on bars w/ sporadic eelgrass. Subsurface consists of wavy laminae to ripple trough cross laminae w/ common lenses or laminae of clay clasts. <b>Sand flat low zone:</b> Dominantly planar surface with planar to wavy laminae in subsurface. Bioturbation common to abundant throughout.</p>	Well sorted, near symmetrical, leptokurtic, dominantly upper fine grained sand (0.40φ, 0.05Sk, 1.12K, 2.25M)	<p>Lowest Value (0.20)  Highest Value (0.52)  Top Average (0.34)  Bottom Average (0.26)  <b>Overall Average (0.30)</b></p>	35	<p>Upper medium grained sand to granule (1.6)  Lower medium grained sand (24.3)  Upper fine grained sand (49.3)  Lower fine grained sand (19.5)  Upper very fine grained sand to silt/clay (5.4)</p>	

Table 2-5: Summary of Sedimentological and Physico-Chemical Characteristics of the Outer-Middle Sandy Tidal Flat Bay Region (continued)					
Sub-Environment	Sedimentological and Physico-Chemical Properties				
	Common Sedimentary Features	Sediment Analysis	TOC (%)	Salinity (PSU)	Average Overall Grain Size (wt%)
<b>Sandy Tidal Flat Ridge and Furrow</b>	<p><b>Sandy flat low zone:</b> Dominantly planar surface. Subsurface heavily mottled due to bioturbation. Organic lenses common.</p> <p><b>Sand flat ridge and furrow high zone:</b> Sinuous crested combined flow, but mainly wave generated, ripples are common in the furrows while linguoid crested ripples are common on the ridges. Wavy laminae to ripple cross laminae are faint but distinct in the subsurface with mainly mottled bedding in upper 20cm. <b>Tidal creek zone:</b> Small hummocks with patchy eelgrass common on the banks with planar surface in creek. Bedding appears mainly massive with very faint planar laminae in subsurface. Multiple clay clasts and organics scattered throughout. Bioturbation sparse to abundant throughout sub-environment.</p>	<p>Well sorted, near symmetrical, leptokurtic, dominantly upper fine grained sand (0.39φ, 0.04Sk, 1.12K, 2.19M)</p>	<p>Lowest Value (0.17) Highest Value (0.65) Top Average (0.24) Bottom Average (0.31) <b>Overall Average (0.28)</b></p>	--	<p>Upper medium grained sand to granule (2.0) Lower medium grained sand (26.6) Upper fine grained sand (50.8) Lower fine grained sand (16.6) Upper very fine grained sand to silt/clay (4.0)</p>
<b>Firm-ground</b>	<p>Two dominant types of firmground are observed. One firmground consists of a clayey-peat layer while the other consists of a raised, compacted silty sand layer. The clayey-peat layer has a layer of compacted dark brown peat on the surface which ranges in thickness having an average thickness of about 6cm. Below the compacted peat is clay that eventually grades into silty, then silty sand before potentially encountering another compacted peat layer. The compacted silty sand layer, where present, resides on top of the compacted peat layer and also ranges in thickness with an average thickness of about 60cm. Old tree stumps also create sporadic woodground zones. Bioturbation is abundant throughout.</p>	<p>Moderately sorted, fine skewed, very platykurtic, dominantly upper very fine grained sand (0.87φ, 0.13Sk, 0.57K, 3.25M)</p>	<p>Lowest Value (0.24) Highest Value (5.35) Top Average (1.26) Bottom Average (1.01) <b>Overall Average (1.13)</b></p>	--	<p>Upper medium grained sand to granule (1.5) Lower medium grained sand (3.1) Upper fine grained sand (20.6) Lower fine grained sand (22.7) Upper very fine grained sand to silt/clay (52.1)</p>



**Figure 2-53: Morphology of the tidal creek and tidal ridge along the Sand Flat High-Tidal Creek sub-environment.** Frame of reference along the bottom of the photographs is ~2.5m. **(A)** View facing NNE showing tidal creek that drains into a deep branch of the main channel ahead. Linguoid ripples are most common on this lower western bank of the tidal creek. **(B)** View facing NW showing the higher sand ridge on the eastern margin of the tidal creek. Dominantly sinuous to occasionally linguoid ripples are superimposed on flat lunate dune forms. The blue arrow indicates direction of flow over the bed.



In the subsurface, planar laminae are occasionally observed during X-ray analysis of boxcore peels; however the laminae appear to be highly disrupted in the sand flat high zone before the tidal creek is encountered and appear massive. On the western margin of the tidal creek planar laminae to ripple cross laminae are evident in X-ray analysis of boxcore peels with only slight sediment disruption. However, structures within the tidal creek that covered most of the tidal creek zone were difficult to observe due to the watery, soupy nature of the sandy sediment. An intact gastropod shell was observed 25cm below the surface during boxcore analysis along the western margin of the tidal creek. On the high sand ridge on the eastern flank of the tidal creek laminae were intact displaying mainly planar laminae. Ripple trough cross laminae are also evident. On average the upper 15cm of beige coloured sediment is anoxic with a gradual to abrupt change into suboxic to anoxic grey to black coloured sand below. Mottling of anoxic sediment into oxic sediment and *vice versa* is encountered once again.

Average grain size across the Sand Flat High-Tidal Creek sub-environment was dominantly upper fine- (60.23 wt%) to lower medium- (18.78 wt%) grained sand; top sediments ranged from dominantly 61.52 wt% upper fine-grained sand to 20.05 wt% lower medium-grained sand, while bottom sediments ranged from dominantly 58.95 wt% upper fine-grained sand to 17.52 wt% lower fine-grained sand, with a sizable portion of lower medium-grained sand (17.50 wt%) (Table 2-5). Sizable portions of lower fine-grained sand are present in the sandy tidal low zone and tidal creek zone, where the smallest grain sizes were found. Highest overall grain size from both top and bottom sediments was from the high sand ridge on the east side of the tidal creek.

Grain size analysis indicates that overall, the grains of the Sand Flat High-Tidal Creek sub-environment are well sorted (inclusive standard deviation (Folk, 1974): 0.35 $\phi$ ), near symmetrical (inclusive graphic skewness (Folk, 1974): 0.025sk), leptokurtic (graphic kurtosis (Folk, 1974): 1.47K), dominantly upper

fine-grained sand with a mean size of 2.25M (graphic mean (Folk, 1974)) (Table 2-5).

### ***Tidal Creek Sub-Environment***

The Tidal Creek transect is comprised of three main zones: a sand flat high zone, a tidal creek zone, and a sand flat low zone. The entire transect is parallel to the main tidal channel and runs perpendicular along a prominent tidal creek which drains into the main tidal channel. Occasional large anomalous clay clasts are found upon the surface of the sand flat high zone in an area otherwise typified by dominantly linguoid ripples that grade into dominantly sinuous ripples creekward (Fig. 2-54A,B). The tidal creek zone has sporadic occurrences of eelgrass and sinuous crested combined flow (wave- and current-generated) ripples (Fig. 2-55A,B). Organic debris is common in ripple troughs. The sand flat low zone displays a dominantly planar surface (Fig. 2-55A).

In the sand flat high zone tabular to trough cross laminae are present with tabular laminae displaying bidirectionality that is especially evident 15cm or deeper through analysis of boxcore peels, with sediment disruption occurring in the upper 15cm of sediment. Clay clasts and shell fragments were occasionally encountered 15cm below the surface in boxcore analysis. In the tidal creek zone shell fragments and larger flattened to rounded clay clasts (1-2.5cm in diameter) become more abundant. Clay clasts of various sizes (1mm-2.5cm) occasionally occur as lenses within the subsurface. Wavy laminae to ripple trough cross laminae are well formed and common in the subsurface of the tidal creek zone. In the sand flat low zone small clay clasts form laminae to bedding features 1-2cm thick around 20cm below the sediment surface. Lenses of clay are also encountered, usually above the thicker continuous clay layer. Planar to wavy laminae are present in the subsurface of the lower sand flat zone. The anoxic zone appears closer to the surface in the tidal creek and lower sand flat zone in comparison to the high sand flat zone.



**Figure 2-54: Morphology of the sand flat high zone along the Tidal Creek sub-environment. (A)** View facing S perpendicular to long axis of tidal channel where people are for scale. Sinuous to dominantly linguoid ripples are common on the surface of the sand flat high zone. Frame of reference along bottom of photograph is ~2.5m. **(B)** Ripped up clasts from the firmground zone along the bay margin are found along the sand flat high zone of the Tidal Creek sub-environment near the mouth of the tidal creek. This is an example of an exceptionally large clast, as most clasts found are typically 1-3cm in diameter. Pencil for scale is 15cm long.





**Figure 2-55: Tidal creek morphology of the Tidal Creek sub-environment.** Field of view along the bottom of each photo is 2.5m. **(A)** SW facing view of the tidal creek mouth emptying into the main channel. Planar bedding or sinuous ripples are the surface features observed within the tidal creek. **(B)** East facing view up the tidal creek towards the bay margin. Patches of eelgrass and other macroalgae sporadically occur within the tidal creek.



Average grain size across the Tidal Creek sub-environment was dominantly upper fine- (49.29 wt%) to lower medium- (24.26 wt%) grained sand; top sediments ranged from dominantly 48.36 wt% upper fine-grained sand to 27.80 wt% lower medium-grained sand, while bottom sediments ranged from dominantly 50.22 wt% upper fine-grained sand to 22.78 wt% lower fine-grained sand (Table 2-5). Sizable portions of lower fine-grained sand are present in the sand flat low zone and in the tidal creek zone. In contrast, the largest grain size was found in the sand flat high zone north of the tidal creek.

Grain size analysis indicates that overall, the grains of the Tidal Creek sub-environment are well sorted (inclusive standard deviation (Folk, 1974):  $0.40\phi$ ), near symmetrical (inclusive graphic skewness (Folk, 1974):  $0.05S_k$ ), leptokurtic (graphic kurtosis (Folk, 1974):  $1.12K$ ), dominantly upper fine-grained sand with a mean size of  $2.25M$  (graphic mean (Folk, 1974)) (Table 2-5).

### ***Sandy Tidal Flat Ridge and Furrow Sub-Environment***

The Sandy Tidal Flat Ridge and Furrow sub-environment is comprised of three main zones. Closest to the main channel is the sandy flat low zone, followed by the sandy flat ridge and furrow high zone (Fig. 2-56C), then a tidal creek zone (Fig. 2-56A,B) next to the Firmground sub-environment (Fig. 2-56D,E).

A dominantly planar surface defines the sandy tidal low zone. Sinuous crested combined flow, but mainly wave generated, ripples are common in the furrows while linguoid crested ripples are common on the ridges of the sandy flat high ridge and furrow zone. Along the bank of the tidal creek are small hummocks with patchy eelgrass extending into the tidal creek.

Subsurface sedimentary structures are hard to decipher in the sandy flat low zone due to heavy sediment disruption. A distinct shift in grain sizes from dominantly upper fine- to lower medium-grained sand to that of dominantly lower fine- to upper fine-grained sand occurs 15cm below the sediment



**Figure 2-56: Morphology of the Sandy Tidal Flat Ridge and Furrow sub-environment.** (A) View NNE along the tidal creek zone towards the deep arm of the main channel along the bay margin where it drains. Firmground zone is directly right of the creek and the sandy flat high zone displaying undulatory bar and trough morphology is directly left. Sparse eelgrass occupies mounds along the tidal creek. Field of view along the bottom of the photograph is ~2.5m. (B) View of the same tidal creek looking SSW. Note relatively planar features within the creek while the troughs next to the creek display dominantly sinuous crested ripples and the bars display dominantly linguoid crested ripples. Field of view along the bottom of the photograph is ~2.5m. (C) View facing SW showing the sandy flat high zone. Note again that sinuous to linguoid crested ripples dominate the bars while sinuous crested ripples dominate the troughs. Sinuous crested ripples within the troughs are more symmetric than the sinuous to linguoid ripples of the bars that are oriented in the direction of last major ebb tidal current flow. (D) View facing west of the firmground zone along the bay margin. (E) Close up view of the firmground zone where compacted clayey-peat is present at the surface interrupted by *Psilonichnus*- and *Thalassinoides*-like burrows created by *Hemigrapsus* sp. and *Upogebia pugettensis*, respectively.

surface. A lens of organic material occurs in the uppermost 3-4cm in both the coarser sediment above and finer sediment below. In the middle of the sandy flat high ridge and furrow zone wavy laminae to ripple cross laminae are faint but distinct, especially in the uppermost 3cm as well as 20cm or lower. Near the centre of the tidal creek zone organic fragments, clay clasts, and iron oxide clasts are scattered throughout the surface and subsurface. Distinct grain size differences are observed once again about 15cm below the surface where dominantly upper fine- to lower medium-grained sand occurs above while dominantly lower fine- to upper fine-grained sand appears below. Bedding appears massive as it is highly disrupted. On the eastern flank of the tidal creek clay clasts and bivalve shell debris are common in the upper 5-7cm of sediment while faint planar laminae are observed below.

Average grain size across the Sandy Tidal Flat Ridge and Furrow sub-environment was dominantly upper fine- (50.79 wt%) to lower medium- (26.58 wt%) grained sand; top sediments ranged from dominantly 50.77 wt% upper fine-grained sand to 34.39 wt% lower medium-grained sand, while bottom sediments ranged from dominantly 50.81 wt% upper fine-grained sand to 22.69 wt% lower fine-grained sand (Table 2-5). Sizable portions of lower fine-grained sand are present in the sandy flat low zone near a small eelgrass field and in the tidal creek zone. In contrast, the largest grain sizes were encountered on the higher parts of the ridge and furrow zone.

Grain size analysis indicates that overall, the grains of the Sandy Tidal Flat Ridge and Furrow sub-environment are well sorted (inclusive standard deviation (Folk, 1974):  $0.39\phi$ ), near symmetrical (inclusive graphic skewness (Folk, 1974):  $0.04Sk$ ), leptokurtic (graphic kurtosis (Folk, 1974):  $1.12K$ ), dominantly upper fine-grained sand with a mean size of  $2.19M$  (graphic mean (Folk, 1974)) (Table 2-5).

### ***Firmground Sub-Environment***

The Firmground sub-environment is only mentioned briefly here as it is covered extensively in the next chapter. The firmground is defined by a firm surface composed of compressed peaty material and clay (Fig. 2-56E). There is a veneer of silty sand creekward and landward of the firmground surface. There is another distinctive firmground feature above the veneered surface in some areas displaying highly burrowed compacted sand. In the firmground zone the peaty-clay layer is observed at the surface and up to a depth of 15cm. Occasionally clay clasts are observed resting at the surface of the peaty-clay layer at any depth. The compacted sand firmground is normally seen 50cm in relief above the peaty-clay ground to about 50cm below the peaty-clay ground.

Average grain size across the Firmground sub-environment was dominantly silt-clay (45.34 wt%) with large portions of lower fine- (22.70 wt%) to upper fine- (20.61 wt%) grained sand; top sediments ranged from dominantly 30.55 wt% silt-clay with large portions of lower fine- (28.77 wt%) to upper fine- (26.66 wt%) grained sand, while bottom sediments ranged from dominantly 60.13 wt% silt-clay with large portions of lower fine- (16.62 wt%) to upper fine- (14.56 wt%) grained sand (Table 2-5).

Grain size analysis indicates that overall, the grains of the Firmground sub-environment are moderately sorted (inclusive standard deviation (Folk, 1974): 0.87 $\phi$ ), fine-skewed (inclusive graphic skewness (Folk, 1974): 0.13Sk), very platykurtic (graphic kurtosis (Folk, 1974): 0.57K), dominantly upper very fine-grained sand with a mean size of 3.25M (graphic mean (Folk, 1974)) (Table 2-5).

### **Total Organic Carbon and Salinity Values**

#### ***Sandy Eelgrass Field Sub-Environment***

Average TOC over the Sandy Eelgrass Field sub-environment transect was 0.49% with average top TOC values at 0.46% and average bottom TOC



values at 0.53% (Table 2-5). The lowest TOC values obtained were 0.17% and 0.18% from top and bottom sediment, respectively, located on the sandy tidal ridge next to the main tidal channel. The highest TOC value of 2.89% obtained from the bottom sediment in the middle of an eelgrass field where the lowest grain size is also found. Higher TOC values corresponded with eelgrass zones.

#### ***Sand Flat High-Tidal Creek Sub-Environment***

Average TOC over the Sand Flat High-Tidal Creek sub-environment transect was 0.38% with average top TOC values at 0.29% and average bottom TOC values at 0.46% (Table 2-5). Top TOC values were generally lower than bottom TOC values. The lowest TOC value obtained was 0.20% from top sediment at the high sand ridge on the east side of the tidal creek, with the highest TOC value of 1.24% obtained from bottom sediment in the ridge and furrow area just west of the tidal creek. Salinity levels were measured to be 30 PSU within the tidal creek.

#### ***Tidal Creek Sub-Environment***

Average TOC over the Tidal Creek sub-environment transect was 0.30% with average top TOC values at 0.34% and average bottom TOC values at 0.26% (Table 2-5). Top TOC values were generally higher than bottom TOC values. Highest TOC values were from the middle of the tidal channel. The lowest TOC value obtained was 0.20% from the top sediment at the sand flat high area before the tidal creek, with the highest TOC value of 0.52% obtained from top sediment near the middle of the tidal creek. Salinity levels were measured to be 35 PSU within the tidal creek

#### ***Sandy Tidal Flat Ridge and Furrow Sub-Environment***

Average TOC over the Sandy Tidal Flat Ridge and Furrow sub-environment transect was 0.28% with average top TOC values at 0.24% and average bottom TOC values at 0.31% (Table 2-5). Top TOC values were

generally lower than bottom TOC values except in the highest part of the sandy tidal flat ridge and furrow zone where grain sizes are highest. The lowest TOC value obtained was 0.17% from the top sediment at the flanks of the sandy tidal flat ridge and furrow zone, while the highest TOC value of 0.65% was obtained from the bottom sediment, at the edge of the tidal creek.

### ***Firmground Sub-Environment***

Average TOC over the Firmground sub-environment transect was 1.13% with average top TOC values at 1.26% and average bottom TOC values at 1.01% (Table 2-5). Top TOC values were lower than bottom TOC values except where the peaty-clay firmground was encountered at the surface. TOC values were equal in sediment closest to the edge of the bay at an uplifted Pleistocene terrace section. The lowest TOC value obtained was 0.24% from the top sediment close to the uplifted Pleistocene terrace section, with the highest TOC value of 5.35% obtained from the peaty-clay layer exposed at the surface.

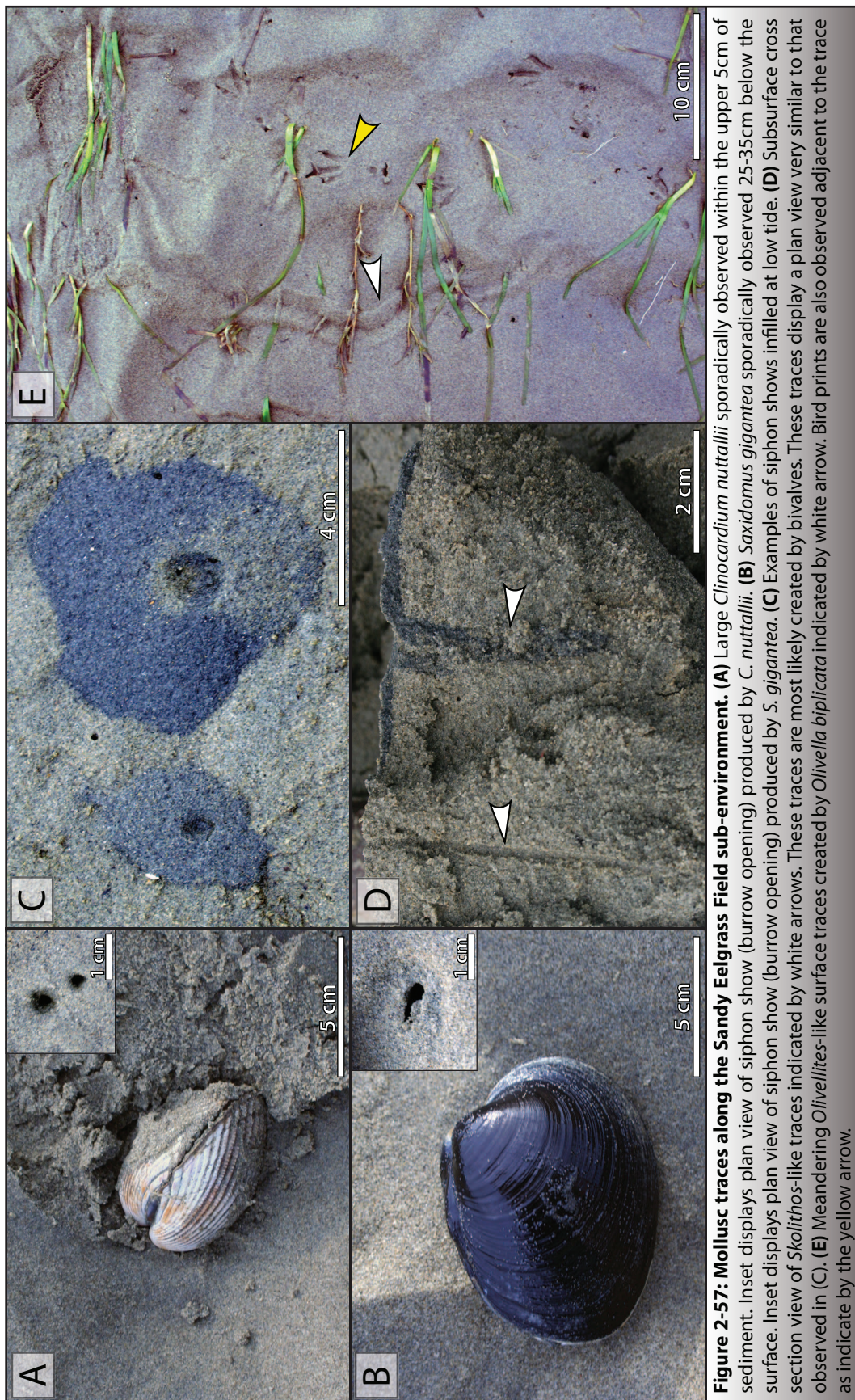
## **Neoichnological Characteristics**

### ***Sandy Eelgrass Field Sub-Environment***

Bioturbation is common to abundant along most of the Sandy Eelgrass Field sub-environment. Burrow and trace counts within the ridge next to the main tidal channel and hummocky eelgrass area on the western flank of the eelgrass field ranged from 1-5 large burrow openings, and 1-2 large meandering traces in an area of 50cm<sup>2</sup>. In areas directly adjacent to the eelgrass field 20-29 large burrow openings were observed in a 50cm<sup>2</sup> area. The eelgrass was too thick in the eelgrass fields and therefore burrow openings could not be counted. On the high sandy tidal ridge on the eastern flank of the eelgrass fields 7 large burrow openings were counted per 50cm<sup>2</sup> area.

Gastropods, especially *O. biplicata*, were common within the tidal flat lows surrounding the hummocky eelgrass mounds. *Olivella biplicata* created meandering surface traces that are akin to *Olivellites* (Fig. 2-57E, Table 2-6).





**Figure 2-57: Mollusc traces along the Sandy Eelgrass Field sub-environment.** (A) Large *Clinocardium nuttallii* sporadically observed within the upper 5cm of sediment. Inset displays plan view of siphon show (burrow opening) produced by *C. nuttallii*. (B) *Saxidomus gigantea* sporadically observed 25-35cm below the surface. Inset displays plan view of siphon show (burrow opening) produced by *S. gigantea*. (C) Examples of siphon shows infilled at low tide. (D) Subsurface cross section view of *Skolithos*-like traces indicated by white arrows. These traces are most likely created by bivalves. These traces display a plan view very similar to that observed in (C). (E) Meandering *Olivellites*-like surface traces created by *Olivella biplicata* indicated by white arrow. Bird prints are also observed adjacent to the trace as indicated by the yellow arrow.

<b>Table 2-6: Summary of Trace Making Organisms and Associated Traces of the Outer-Middle Sandy Tidal Flat Bay Region</b>				
	<b>Organism</b>	<b>Trophic Behaviour</b>	<b>Trace Fossil Equivalent to Modern Trace Form</b>	<b>Environmental Zone</b>
<b>Mollusca</b>	<i>Macoma</i> sp.	Filter Feeder, Interface Deposit Feeder	Dual-siphon <i>Siphonichnus</i> , Stellate Surface Trace ( <i>Lorenzinia</i> )	Eelgrass Field, Sporadic Occurrence on Sand Flats
	<i>Saxidomus gigantea</i>	Filter Feeder	<i>Siphonichnus</i>	Eelgrass Field, Sporadic Occurrence on Sand Flats
	<i>Tresus nuttallii</i>	Filter Feeder	<i>Siphonichnus</i>	Eelgrass Field, Sporadic Occurrence on Sand Flats
	<i>Clinocardium nuttallii</i>	Filter Feeder	<i>Lockeia</i> , ? <i>Protovirgularia</i> , ? <i>Siphonichnus</i>	Eelgrass Field, Tidal Creek Margins
	<i>Protothaca staminea</i>	Filter Feeder, ? Deposit Feeder	<i>Protovirgularia</i> , <i>Lockeia</i>	Silty Sand Flats
	<i>Olivella biplicata</i>	* Surface Deposit Feeder, Filter Feeder, Scavenger, ? Carnivore	<i>Olivellites</i>	High Energy Tidal Creeks, Margin of Main Tidal Channel
<b>Crustacea</b>	<i>Upogebia pugettensis</i>	Filter Feeder	<i>Thalassinoides</i>	Firmground, Tidal Creek Adjacent to Firmground
	<i>Hemigrapsus</i> sp.	Carnivore, Scavenger, Facultative Filter Feeder	<i>Psilonichnus</i>	Tidal Creeks, Firmground



Table 2-6: Summary of Trace Making Organisms and Associated Traces of the Outer-Middle Sandy Tidal Flat Bay Region (continued)				
	Organism	Trophic Behaviour	Trace Fossil Equivalent to Modern Trace Form	Environmental Zone
Crustacea	<i>Corophium</i> sp.	* Deposit Feeder, Filter Feeder	<i>Skolithos</i> , ? <i>Arenicolites</i>	Intertidal Sandy Flats
	<i>Eohaustorius</i> sp.	Deposit Feeder	* <i>Gordia</i> , <i>Crossopodia</i> , Sediment Disruption, ? <i>Skolithos</i> , ? <i>Cryptic Bioturbation</i>	Intertidal Sandy Flats
	Hermit Crab	Carnivore, Scavenger, Facultative Filter Feeder	Spiral Sediment Disruption, Cubichnia	Eelgrass Field, Tidal Creeks
Vermiform	<i>Mediomastus</i> sp.	Subsurface Deposit Feeder	<i>Trichichnus</i> , <i>Skolithos</i> , <i>Planolites</i>	Intertidal Sandy Flats, Eelgrass Field
	<i>Capitella</i> sp.	Subsurface Deposit Feeder	<i>Trichichnus</i> , <i>Skolithos</i> , <i>Planolites</i>	Intertidal Sandy Flats, Eelgrass Field
	<i>Glycera</i> sp.	Subsurface Deposit Feeder	<i>Palaeophycus</i> , <i>Planolites</i> , Subordinate <i>Polykladichnus</i>	Eelgrass Field
	<i>Nereis</i> sp.	* Subsurface and Interface Deposit Feeder, Scavenger, Carnivore	<i>Polykladichnus</i> , <i>Palaeophycus</i> , <i>Skolithos</i>	Sandy Flat Lows, Eelgrass Field
	<i>Nephtys</i> sp.	* Carnivore, Scavenger	Sediment Disruption/Navichnia, ? <i>Cryptic Bioturbation</i>	Intertidal Sandy Flats, Eelgrass Field

Table 2-6: Summary of Trace Making Organisms and Associated Traces of the Outer-Middle Sandy Tidal Flat Bay Region (continued...2)				
	Organism	Trophic Behaviour	Trace Fossil Equivalent to Modern Trace Form	Environmental Zone
Vermiform	<i>Abarenicola pacifica</i>	Suspension Feeder, Deposit Feeder	<i>Arenicolites</i>	Sandy Eelgrass Patches Along Bay Margin Next to Firmground
	Terebellid Polychaete (? <i>Eupolymnia</i> )	* Interface Deposit Feeder, Suspension Feeder	Lined <i>Skolithos</i>	Tidal Creek Margin, Eelgrass Field Margin
	<i>Cerebratulus</i> sp. (Nemertean)	Carnivore	<i>Palaeophycus</i>	Sandy Lows Near Tidal Creeks

*Olivella biplicata* are scavengers, possible carnivores, and deposit feeders. Anthropogenic alteration of bivalve burrow distribution is likely possible due to the area being a popular clam digging location. *Clinocardium nuttallii* is a shallow burrowing, filter feeding, and occasionally deposit feeding bivalve that creates short, usually 2-3cm, vertical *Skolithos*-like traces where it excavates an open to surface burrow via its siphon (Fig. 2-57A, Table 2-6). The entire trace, with the bivalve mould in addition to its vertical siphon trace, is observed to be *Siphonichnus*-like (Table 2-6). The possibility of *C. nuttallii* producing *Lockeia*-like traces is possible since it was usually found stationary but preservation is unlikely. *Protovirgularia*-like traces are possible if *C. nuttallii* moves horizontally; however this was not observed and the likelihood of preservation is low. *Saxidomus gigantea* (Fig. 2-57B), *Tresus nuttallii*, and *Macoma* sp. are other bivalves occasionally found along the Sandy Eelgrass Field sub-environment. They are usually much deeper burrowing than *C. nuttallii*, owing to the fact that they possess greater siphon lengths. These bivalves are filter feeders, with the exception of *Macoma* sp. that are also interface deposit feeders, creating *Siphonichnus*-like, *Skolithos*-like and *equilibrichnia* traces (Fig. 2-57C,D). Deeper burrows that penetrate the suboxic to anoxic layers have the ability to act as conduits for anoxic grey to black sands to be excavated to the sediment surface.

Hermit crabs are intermittently found among the eelgrass fields where they commonly use whelk (*Nucella* sp.) shells and occasionally *O. biplicata* shells as their resident shell. They can burrow just beneath the sediment using a spiral motion. *Crangon* sp. shrimp are common in eelgrass areas and are overwhelmingly found at the sediment surface in tidal pools. Small *Arenicolites*-like and *Skolithos*-like traces are produced by *Corophium* sp. while *Eohaustorius* sp. created *Gordia*-like to *Crossopodia*-like surface traces and possible small *Skolithos*-like traces (Table 2-6). Occasionally the traces produced by *Corophium* sp. were slightly orange-lined. Many diminutive *Skolithos*-like traces and possible cryptic bioturbation were the results of

unidentified juvenile amphipods likely from either the common *Corophium* or *Eohaustorius* species. Multiple avian traces were also common on the sediment surface.

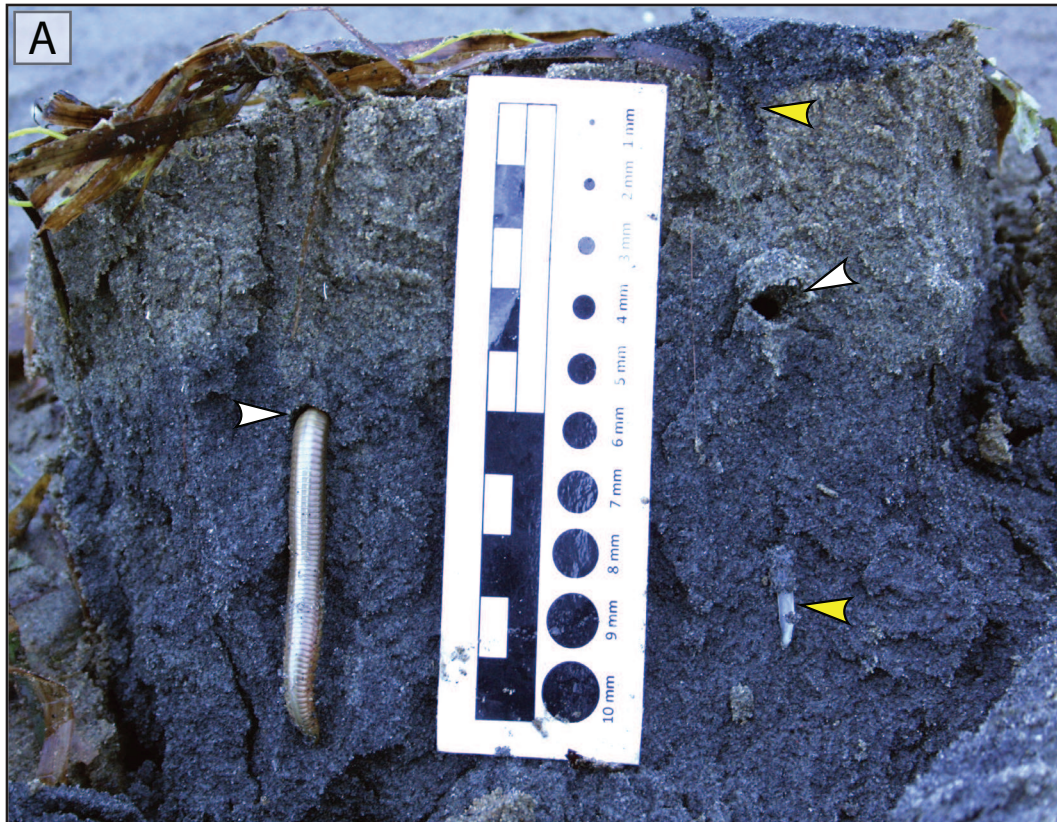
Threadworms such as *Mediomastus* sp. and *Capitella* sp. polychaetes are common, as well as bloodworms (*Glycera* sp.). Due to their small size they are very fragile and difficult to obtain whole for sampling or photographic purposes. These worms are errant polychaetes and direct deposit feeders where threadworms produce *Skolithos*-, *Trichichnus*-, and *Planolites*- like traces and bloodworms produce *Palaeophycus*-like and *Planolites*-like traces (Table 2-6). *Nephtys* sp. worms are also errant polychaetes and active predators that produce navichnia, sediment disruption structures, as well as potential cryptic bioturbation (Fig. 2-58A, Table 2-6). *Cerebratulus* sp. is a predaceous nemertean worm that creates slightly mucous lined *Palaeophycus*-like traces and was most often found in the sandy eelgrass lows or in and around tidal creeks (Fig. 2-58B, Table 2-6).

X-rays of boxcore peels taken from sediment in the eelgrass fields indicate rootlets as well as *Planolites*-like traces. On the high sandy tidal ridge on the eastern flank of the eelgrass fields *Planolites*-like traces are still seen in X-rays of boxcore peels with *Palaeophycus*-like traces also observed. Bioturbation is evident throughout the sub-environment causing sediment disruption and obliteration of primary sedimentary features also making individual traces difficult to ascertain.

### ***Sand Flat High-Tidal Creek Sub-Environment***

Bioturbation is sparse to common along the Sand Flat High-Tidal Creek sub-environment. Burrow counts within the lower parts of the sand flat high zone near the eelgrass field to the west ranged from 5-10 large open-to-surface burrows per 50cm<sup>2</sup> area. In the higher eastern portion of the sand flat high zone large burrow openings only ranged from 0-1 per 50cm<sup>2</sup> area. The tidal creek had 0-3 large burrow openings, and up to 2 large meandering surface





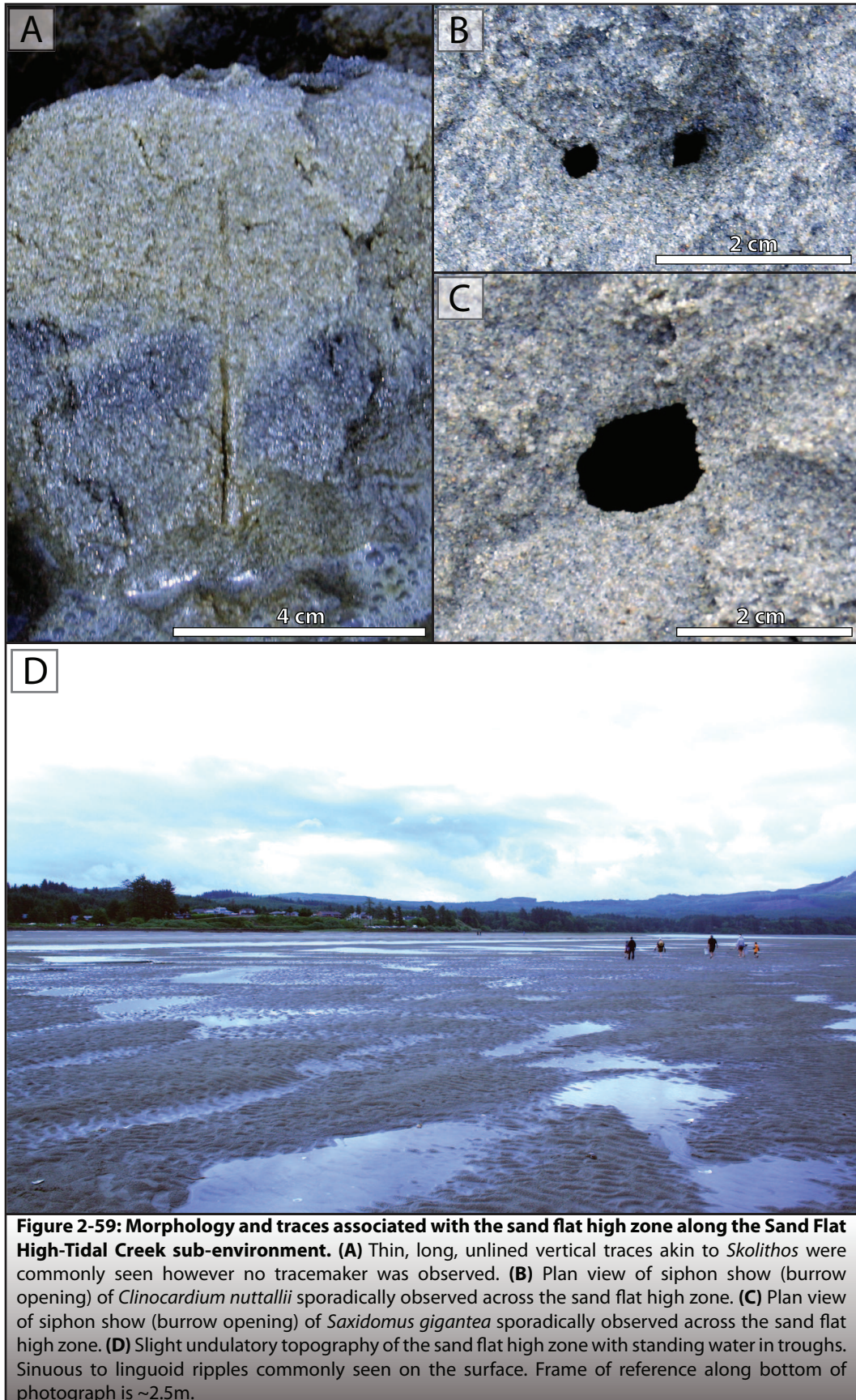
**Figure 2-58: Vermiform traces along the Sandy Eelgrass Field sub-environment. (A)** Subsurface traces created by *Nephtys* sp. are indicated by the white arrows. These excavations usually collapse after *Nephtys* sp. glide away creating navichnia or sediment disruption structures. The yellow arrows indicate siphon of *Macoma* sp. and associated *Skolithos*-like or *Siphonichnus*-like trace. **(B)** *Skolithos*-like traces potentially associated with vermiform organisms, amphipods or small bivalves (indicated by white arrow). The inset is of *Cerebratulus* sp. which was observed gliding through sediment creating a slightly lined sub-vertical trace.

traces in an area of 50cm<sup>2</sup>. The high sandy tidal ridge west of the tidal creek had no large burrow openings within an area of 50cm<sup>2</sup>. Occasionally burrows extending into the anoxic zone will have an orange lining around them and be infilled with lighter coloured oxic sand from above. Most burrows occurred on the western flank of the sand flat high zone (Fig. 2-59A,B,C,D). On the high sandy ridge east of the tidal creek, where the sediment was completely oxic down to the trench depth of 40cm, burrows were not seen on the surface nor in the subsurface.

*O. biplicata* were sporadically seen within the tidal creek lows creating meandering surface traces akin to *Olivellites* (Table 2-6). Threadworms (*Mediomastus* sp. and *Capitella* sp.) are sparse to relatively common throughout the subsurface. These errant polychaetes and direct deposit feeders produce *Skolithos*-, *Trichichnus*-, and *Planolites*- like traces as well as potential cryptic bioturbation (Table 2-6). Potential cryptic bioturbation, navichnia and overall biogenic sediment disruption structures were also produced by the errant polychaete *Nephtys* sp. that was sporadically witnessed throughout the sub-environment (Table 2-6). Large *Nereis* sp. worms acting as interface feeders, carnivores and suspension feeders were rarely seen but actively produced *Polykladichnus*-like, *Palaeophycus*-like, and *Skolithos*-like traces (Table 2-6). Small *Hemigrapsus* sp., acting as filter feeders or scavengers, were commonly found within the tidal creek and produced small *Psilonichnus*-like burrows (Table 2-6). Bivalves may have also been present 40cm or more beneath the surface beyond the depth of excavation since large burrow openings and *Skolithos*-like traces in the subsurface were seen that may have been caused by siphonal extension to the surface (Fig. 2-59A,B,C).

Boxcore peel X-rays reveal moderate bioturbation in the western portion of the sand flat high zone with low bioturbation in the eastern portion of the sand flat high zone as well as in the tidal creek zone. *Planolites*-like and *Palaeophycus*-like traces were the only traces resolved in analysis of X-rays of boxcore peels.





### ***Tidal Creek Sub-Environment***

Bioturbation is common to abundant along the Tidal Creek sub-environment. Burrow counts within the sand flat high zone ranged between 2-5 large burrow openings per 50cm<sup>2</sup>. In the northern half of the tidal creek zone large burrow openings numbered 5-15 per 50cm<sup>2</sup>, while in the southern half large burrow openings numbered 15-37 per 50cm<sup>2</sup>. The southern portion of the tidal creek eventually gives way to the sand flat low zone where large burrow openings ranged from 37-73 per 50cm<sup>2</sup>. In the middle of the tidal creek 4 large surface meandering traces were counted in an area of 50cm<sup>2</sup>. The larger number of burrows counted may be owing to the fact that burrows were counted on a sunny day where no rain fell in the morning. Rain was usually encountered every single morning and may have temporarily caused some burrow openings to be covered up at the time. Lined burrows were either orange coloured oxidized lined borrows or slightly mucous lined burrows. Lined burrows were sporadic, and unlined burrows were common to abundant throughout the sub-environment with both usually displaying vertical to sub-vertical orientations.

*Olivella biplicata* were only seen within the tidal creek creating *Olivellites*-like traces (Fig. 2-60E, Table 2-6). The shallow burrowing *C. nuttallii* was observed *in situ* and created short, usually 2-3cm, vertical traces where it excavated an opening to the surface via its siphon (Fig. 2-60B). The entire trace, including bivalve mould, slight deformation around the mould, and vertical siphon trace were observed to be *Siphonichnus*-like. The predaceous nemertean *Cerebratulus* sp. created slightly mucous lined *Palaeophycus*-like traces (Table 2-6). Threadworms (*Mediomastus* sp. and *Capitella* sp.) produced *Skolithos*-, *Trichichnus*-, and *Planolites*- like traces while *Nephtys* sp. created cryptic bioturbation (Table 2-6). Small *Arenicolites*-like and *Skolithos*-like traces were produced by *Corophium* sp. and small meandering *Gordia*-like to *Crossopodia*-like surface traces were produced by *Eohaustorius* sp (Fig. 2-60C,G). Occasionally traces created by *Corophium* sp. were slightly orange-lined (Fig. 2-





**Figure 2-60: Neochronology of the Tidal Creek sub-environment.** (A) Lined *Skolithos*-like trace along the sand flat high zone. Tracemaker unknown. Trace is 7cm in length. (B) *In situ* *Clinocardium nuttallii* along the sand flat high zone displaying *Siphonichnus*-like trace as siphonal trace is observed. (C) *Arenicolites*-like trace along the sand flat high zone potentially created by *Corophium* sp. but tracemaker unknown. Finger for scale is ~1.5cm wide. (D) *Nephtys* sp. a common tracemaker of navicincta or sediment disruption traces. White lid ~6cm in diameter for scale. (E) White arrows indicate *Olivella biplicata* within the tidal creek. (F) *Crangon* sp. shrimp sporadically seen swimming or resting on the sediment surface within the tidal creek. (G) High abundance of burrow openings observed along the sand flat low zone. Very small *Gordia*-like meandering surface traces also observed. (H) Siphon of *Macoma* sp. *in situ*. One or both siphons of *Macoma* sp. were commonly found *in situ* along the *Skolithos*-like or *Siphonichnus*-like trace left by the organisms siphon.

60A). The filter feeding and deposit feeding *Macoma* sp. create split *Siphonichnus*-like traces that also incidentally resemble *Polykladichnus*-like or sub-vertical *Skolithos*-like traces, due to their long, separate incurrent and excurrent siphons (Fig. 2-60H). Therefore, the trace produced by *Macoma* sp. does not look like one thick, vertical trace, but like two small slightly sub-vertical traces instead. *Macoma* sp. also occasionally readjusts itself within the sediment creating equilibria. *Nephtys* sp. was observed sporadically swimming through sediment causing navichnia and sediment disruption structures (Fig. 2-60D). *Crangon* sp. shrimp were observed swimming through the creek, occasionally resting on the surface (Fig. 2-60F).

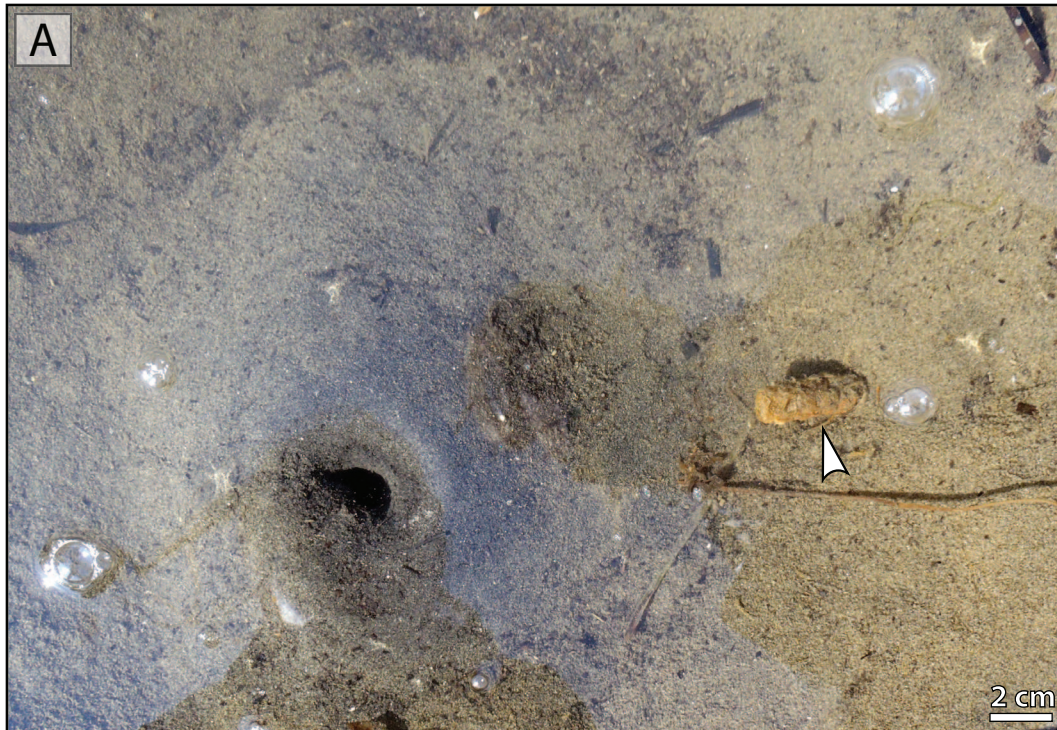
Analysis of boxcore X-rays yielded observations of sediment disruption due to bioturbation. The only discernable trace was *Trichichnus*-like in the sand flat low zone.

### ***Sandy Tidal Flat Ridge and Furrow Sub-Environment***

Bioturbation is sparse to abundant along the Sandy Tidal Flat Ridge and Furrow sub-environment. Burrow counts within the sandy flat low zone averaged 36 large burrow openings per 50cm<sup>2</sup>. In the sandy flat high zone large burrow openings averaged 2-3 per 50cm<sup>2</sup>. Finally the tidal creek zone displayed burrow counts ranging from 29-36 per 50cm<sup>2</sup>.

In the sandy flat low zone an orange parchment tube likely that of a terebellid polychaete was regarded as a lined *Skolithos*-like trace (Fig. 2-61A). Large unlined *Skolithos*-like traces were also observed and believed to be caused by the siphon of bivalves, although no bivalves were found (Fig. 2-61A). Occasional nereid polychaetes created *Polykladichnus*-like, *Palaeophycus*-like, and *Skolithos*-like traces, especially in the sandy tidal low zone and tidal creek zone (Fig. 2-61B). In both the sandy tidal low zone and the sandy flat high zone threadworms (*Mediomastus* sp. and *Capitella* sp.) and *Nephtys* sp. were common. The threadworms created *Skolithos*-, *Trichichnus*-, and *Planolites*- like traces while *Nephtys* sp. produced navichnia, cryptic bioturbation and overall



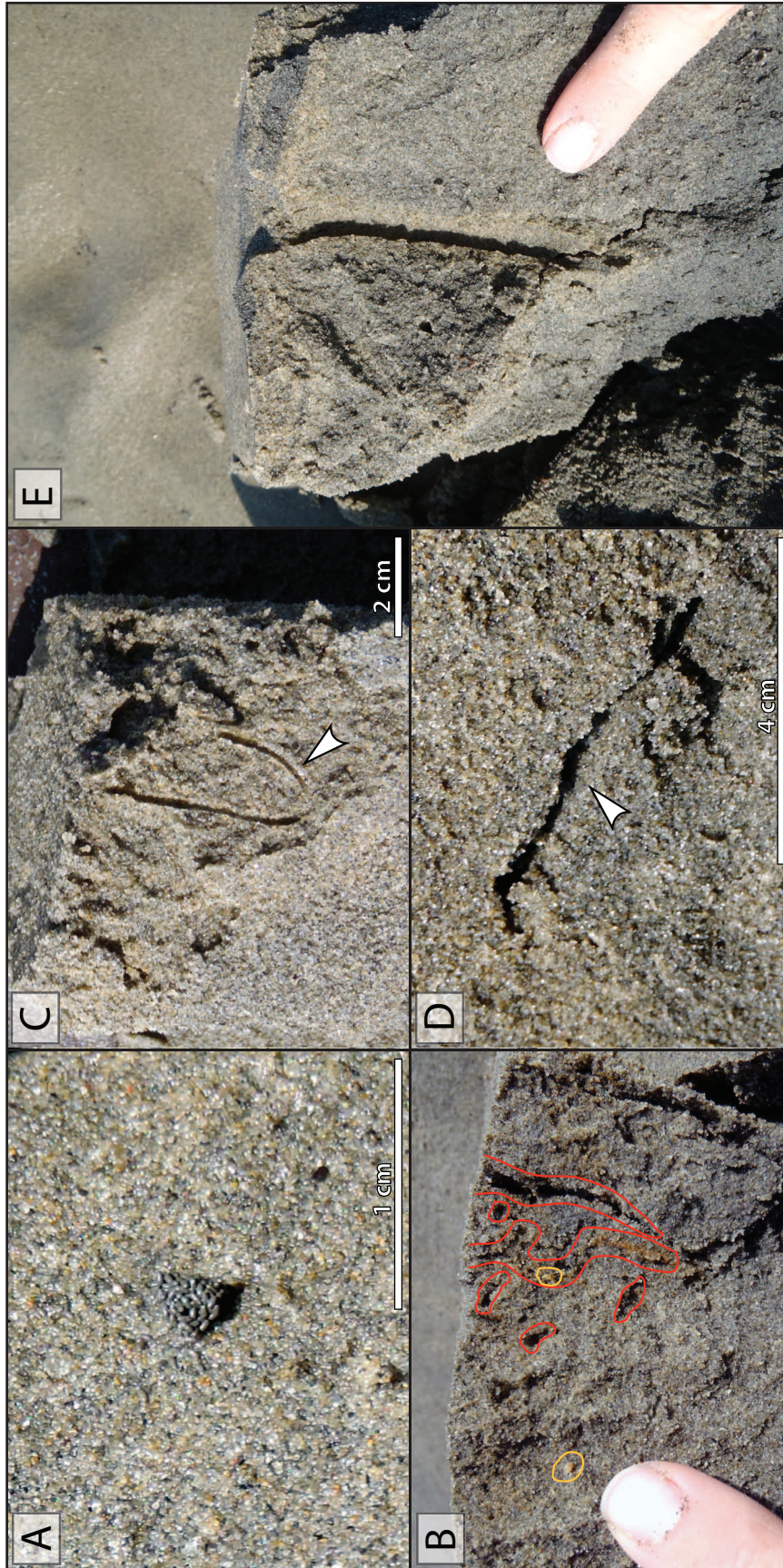


**Figure 2-61: Neoichnology of the sandy flat low zone along the Sandy Tidal Flat Ridge and Furrow sub-environment. (A)** In a water laden trough attached to an eelgrass field orange parchment like tubes were sporadically observed as indicated by the white arrow. These tubes likely belong to terebellid polychaetes. A large burrow opening is observed to the left created by an unknown tracemaker. **(B)** Nereid polychaete observed *in situ* from a suction core section. Nereid polychaetes created slightly lined *Polykladichnus*-, *Palaeophycus*- and *Skolithos*-like traces.

sediment disruption structures as it actively swam through sediment (Fig. 2-62D). Also common in both zones were the amphipods *Corophium* sp. and *Eohaustorius* sp., with both creating small *Skolithos*-like traces in the top 1-3cm of sediment, with *Corophium* sp. additionally forming *Arenicolites*-like traces and *Eohaustorius* sp. creating small *Gordia*-like surface traces (Fig. 2-62A,B,C). Traces created by the amphipods were occasionally slightly orange-lined. Large, unlined *Skolithos*-like traces were also observed in the sandy flat high zone that is thought to be created by bivalve siphonal movement through the sediment (Fig. 2-62E). Terebellid polychaetes were observed in the tidal creek zone and produced oxidized orange lined burrows akin to *Palaeophycus*, lined *Skolithos* and *Cylindrichnus* (Fig. 2-63A,B; Table 2-6). *Nephtys* sp., *Nereis* sp., *Hemigrapsus* sp., *Pinnixa* sp., *U. pugettensis*, threadworms, and *C. nuttallii* were also found in the tidal creek zone. *Nephtys* sp. created the usual sediment disruption features as is witnessed throughout the bay, while *Nereis* sp. displayed its usual wide range of traces akin to *Polykladichnus*, *Palaeophycus*, and *Skolithos*. *Hemigrapsus* sp. created *Psilonichnus*-like burrows, while the *Pinnixa* sp. was found within burrows. Slightly lined *Thalassinoides*-like traces were the result of the burrowing actions of *U. pugettensis* (Fig. 2-63C). Threadworms created *Skolithos*-, *Planolites*-, and *Trichichnus*-like traces, while *C. nuttallii* in association with the trace left by its siphon created *Siphonichnus*-like traces. In areas of finer grained materials and sparse eelgrass near the tidal creek *Protothaca staminea* were observed creating *Lockeia*- and *Protovirgularia*-like traces.

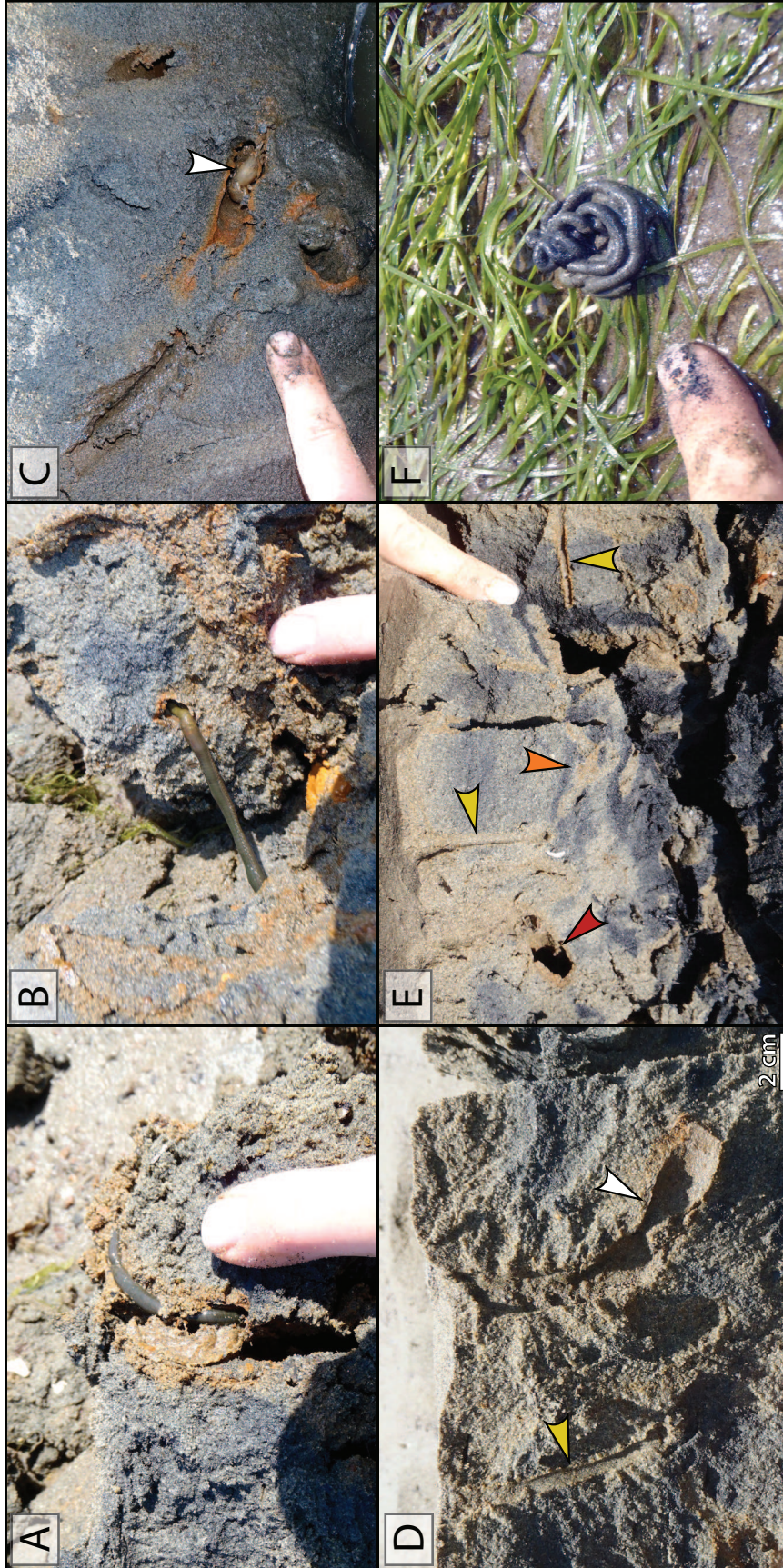
Analysis of boxcore peels and X-rays yielded *Skolithos*- and *Arenicolites*-like traces within the upper 3cm of sediment within the sandy tidal low zone. It was evident that bioturbation was responsible for the vast majority of sediment disruption. In the sandy flat high zone X-ray analysis only portrayed *Palaeophycus*-like traces within the sediment. In the middle of the tidal creek X-ray analysis revealed tiny *Skolithos*-like traces in the upper 1-2cm of sediment, and *Planolites*- as well as *Palaeophycus*-like traces throughout the sampled





**Figure 2-62: Neoichnology of the sandy flat high zone along the Sandy Tidal Flat Ridge and Furrow sub-environment.** (A) Aggregation of fecal pellets from juvenile amphipods surrounding burrow opening on the sediment surface. (B) Juvenile amphipods observed *in situ* circled in yellow. Red outline indicates tiny, intricate burrow network created by juvenile amphipods. These juvenile amphipods and associated burrow networks are common within the upper 5cm of sediment along most sandy flat high areas of the Outer-Middle Sandy Tidal Flat bay region. Finger for scale is ~1.5cm wide. (C) *Arenicolites*-like burrow indicated by white arrow. Tracemaker is likely *Corophium* sp. (D) Temporary, unlined sub-vertical burrow created by *Nephtys* sp. (E) *Skolithos*-like trace created by a bivalve siphon, potentially belonging to a greater *Siphonichnus*-like trace. Finger for scale is ~1.5cm wide.





**Figure 2-63: Neoichnology of the tidal creek and firmground zones along the Sandy Tidal Flat Ridge and Furrow sub-environment.** Finger for scale is ~1.5cm wide. (A) Frontal (vertical) plane view of terebellid polychaete occupying *Cylindrichnus*-like burrow along the tidal creek. (B) Axial (horizontal) plane view of terebellid polychaete occupying *Cylindrichnus*-like burrow along the tidal creek. (C) Subsurface view of *Thalassinoides*-like trace created by *Upogebia pugettensis* (white arrow) along the tidal creek-firmground. (D) *Psilonichnus*-like trace (yellow arrow) and *Psilonichnus*-like trace (white arrow) in the silty sand found slightly above the clayey-peat firmground layer. (E) *Thalassinoides*-like (red arrow), *Skolithos*-like (yellow arrow) and *Palaeophycus*-like (orange arrow) traces in the silty sand found slightly above the clayey-peat firmground layer. (F) Fecal castings of *Abarenicola pacifica* on the sediment surface in the eelgrass silty sand area found slightly above the clayey-peat firmground layer.

sediment. On the eastern flank of the tidal channel X-rays showed *Thalassinoides*- and *Cylindrichnus*-like traces with possible *Planolites*- and *Trichichnus*-like traces also observed.

### ***Firmground Sub-Environment***

Bioturbation is abundant along the Firmground sub-environment. Burrow counts within the firmground area ranged from 4-68 large burrow openings per 50cm<sup>2</sup>, with the largest and most abundant burrows occurring in the peaty-clay layer or the firm raised sandy terrace area.

Large *Nereis* sp. polychaetes produced *Arenicolites*-like, *Polykladichnus*-like, *Palaeophycus*-like, and *Skolithos*-like traces, while the occasional *Nephtys* sp. disrupted the sediment as it swam creating navichnia and cryptobioturbation (Fig. 2-63D,E). *Psilonichnus*-like traces were the result of the burrowing activity of *Hemigrapsus* sp., while *U. pugettensis* created *Thalassinoides*-like burrows within the peaty-cay layer (Fig.2-63C,D; Table 2-6). *Arenicolites*-like traces were observed below piles of coiled fecal castings created by *Abarenicola pacifica* in the upper eelgrass sandy area (Fig. 2-63F; Table 2-6). *Skolithos*-like and *Thalassinoides*-like features were observed in analysis of boxcore peels and X-rays.

## **INTERPRETATION OF OUTER-MIDDLE SANDY TIDAL FLAT BAY REGION**

### **Morphological and Sedimentological Interpretation**

Five sub-environments comprise the Outer-Middle Sandy Tidal Flat bay region (Fig. 2-4): the Sandy Eelgrass Field (Fig. 2-64), the Sand Flat High-Tidal Creek (Fig. 2-65), the Tidal Creek (Fig. 2-66), the Sandy Tidal Flat Ridge and Furrow, which shares the same transect line as the Firmground sub-environment (Fig. 2-67). There are essentially five different morphologic features that make up these sub-environments including the tidal channel ridges; extensive dune to undulatory ridge and trough like topography with superimposed combined flow ripples forming sandy highs; prominent eelgrass



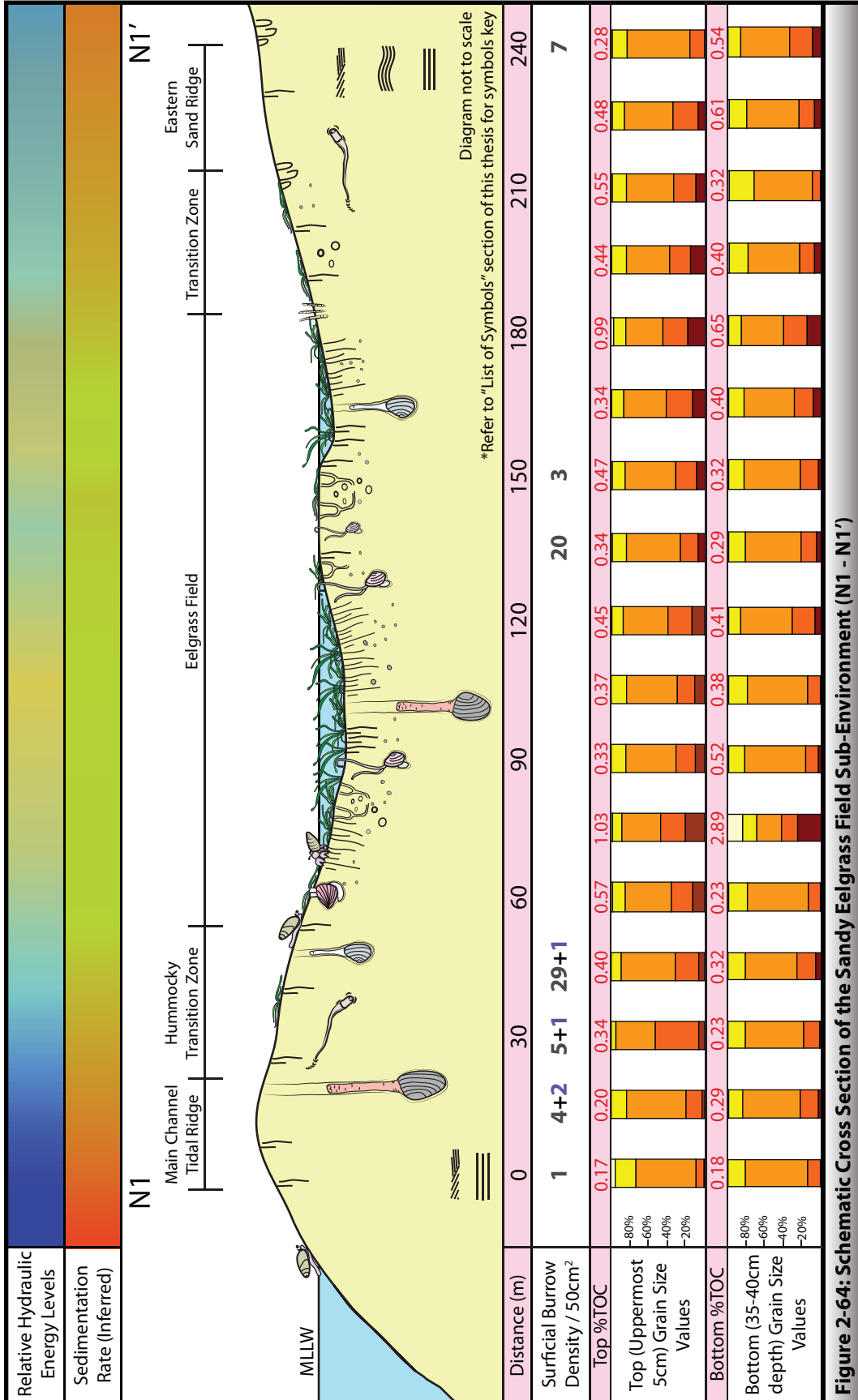
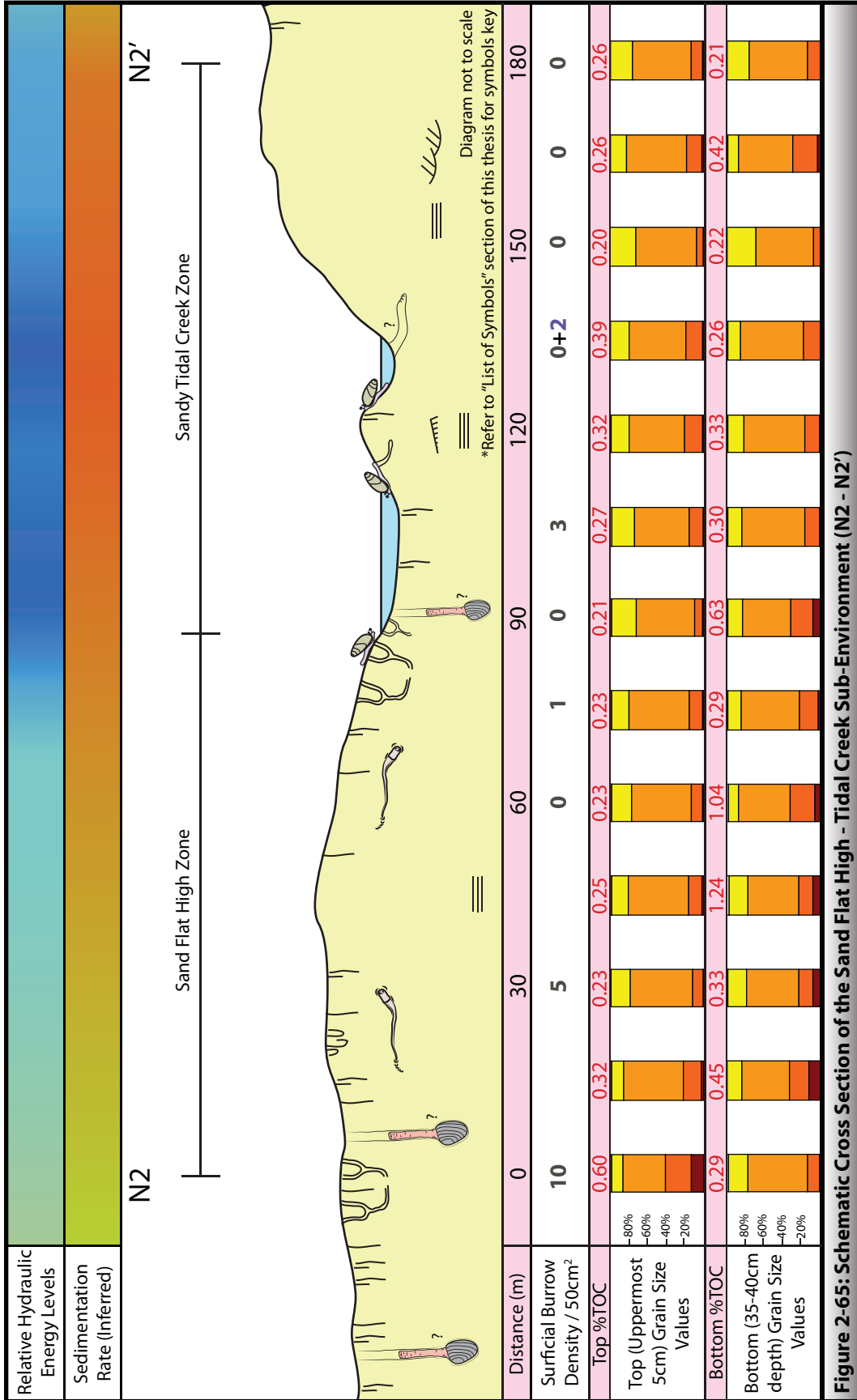
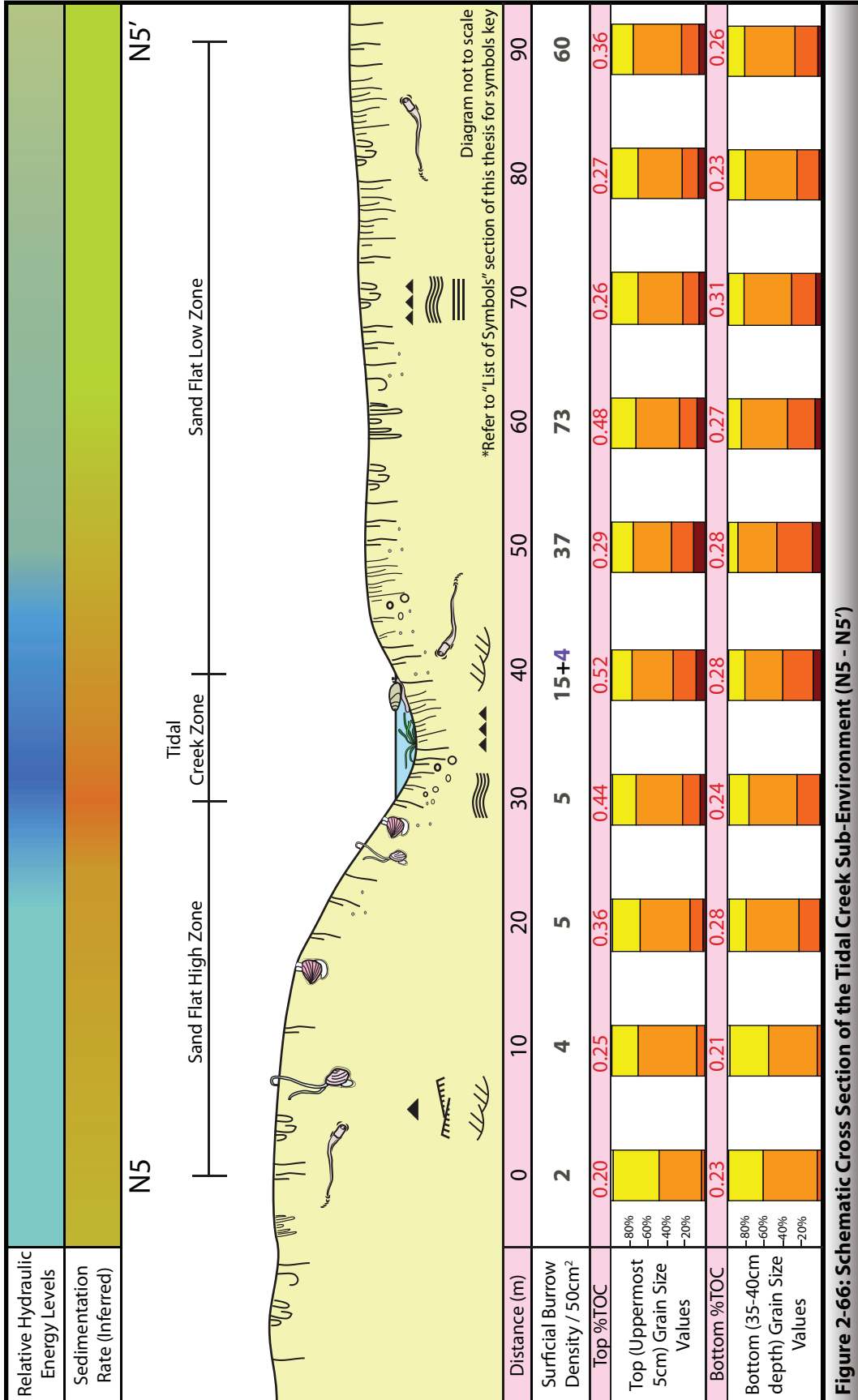


Figure 2-64: Schematic Cross Section of the Sandy Eelgrass Field Sub-Environment (N1 - N1')



**Figure 2-65: Schematic Cross Section of the Sand Flat High - Tidal Creek Sub-Environment (N2 - N2')**



**Figure 2-66: Schematic Cross Section of the Tidal Creek Sub-Environment (N5 - N5')**



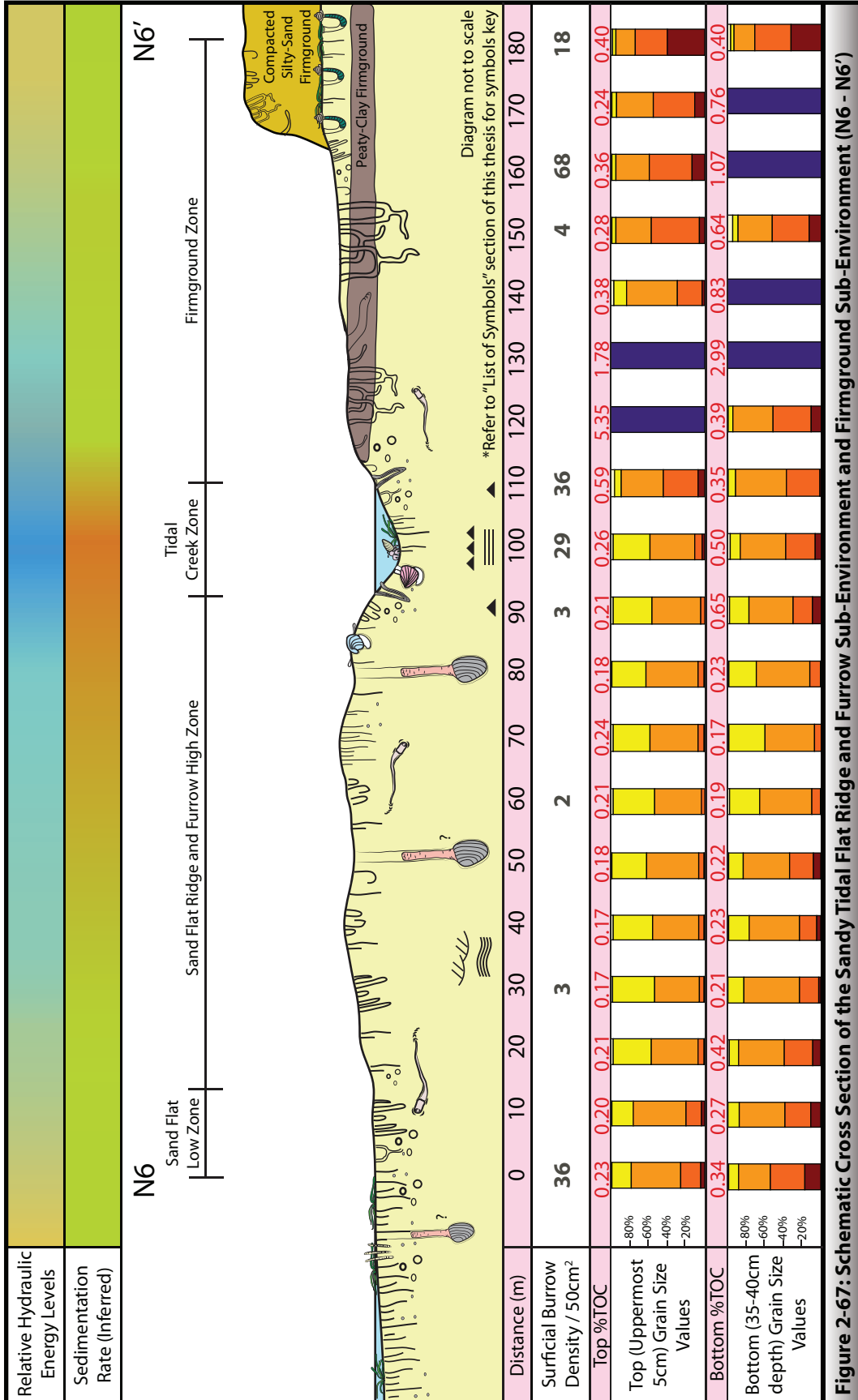


Figure 2-67: Schematic Cross Section of the Sandy Tidal Flat Ridge and Furrow Sub-Environment and Firmground Sub-Environment (N6 - N6')

field sandy lows; tidal creeks; and a firmground margin comprised of clay, peaty material, and silty sand.

The Outer-Middle Sandy Tidal Flat bay region experiences relatively moderate changes in hydraulic energy levels overall. The areas of highest velocities were along the main tidal channel bank where prominent ridges formed at the top of the banks, and along the eastern margin of the large tidal creek along the Sand Flat High-Tidal Creek sub-environment. Catenary to lunate dunes were prominent on these ridges with ripple fans forming in the troughs. Superimposed rippled forms were tidal current dominated combined flow ripples displaying sinuous to linguoid crests. These dunes and associated ripple structures are very similar to the ones formed along the recurved spit portion of the Exposed Shoreface-Spit sub-environment. In the subsurface horizontal to slightly inclined planar laminae as well as ripple trough cross laminae were present with very little sediment disruption features. Glanzman et al. (1971) indicates that the main tidal channel is an area that experiences high horizontal tidal current velocities, therefore the banks of these channels are likely higher energy areas that experience a lack of bioturbation as a result and therefore very little sediment disruption features. Along the Tidal Creek sub-environment the sand flat high bank area that grades into the tidal creek also displays tabular to trough cross laminae with the tabular cross laminae displaying bidirectionality. This bidirectionality is likely the result of the sequential changes between ebb- and flood-tides. Trough cross lamination can develop in mixed tide and wave influenced environments, especially in fine to medium grained sands (Allen, 1982a).

Dominantly sinuous to occasional linguoid dunes with superimposed ripples were common in the sandy flat high regions, where energy levels were slightly less than that of the tidal channel-tidal creek margins. The superimposed dominantly wave generated combined flow ripples also displayed sinuous to linguoid crests. Wave formed ripples are commonly formed on intertidal sand flats where they can be modified by tidal action and

burrowing fauna (Allen, 1982a). Harms (1969) defined combined flow ripples as any type of ripples that are created by at least some mix of both waves and currents. Dune crests within this zone were roughly oriented sub-perpendicular to the main tidal channel thereby forming prominent ridge and furrow structures as dune crests formed the ridges and dune troughs formed the furrows. Sinuous crested dominantly current generated ripples were common in the furrows with an orientation usually perpendicular to the long axis of the furrows with the lee sides facing in the direction of water flow run-off towards tidal channels. This type of topography was also observed along the Sand Flat High sub-environment of the Outer Sheltered Sandy Tidal Flat bay region. Allen (1982a) observed extensive low relief features within the Severn Estuary, UK, which he termed ridge and furrow structures. He noticed that these structures were oriented along the length of dominant tidal current flow over the tidal flat. It was also noted by Allen (1982a) that asymmetric ebb oriented current generated ripples formed transversely along these features during ebb tidal run-off, which is what is witnessed mainly in the furrows on the sand flats of Netarts Bay. In the subsurface planar to wavy laminae are common but usually only readily observed in the upper 2-5cm of sediment with massive or mottled appearing sands becoming quite common below. The mottled sands likely arise due to bioturbation obliterating primary sedimentary structures in protected subsurface areas not readily reworked by waves or tides (Allen, 1982a; Gingras et al., 1999). In some areas ripples appeared to be smoothed likely due to the effect of wind generate waves (Allen, 1982a). It was also noted by Komar et al. (1972) that changes in wind and tidal directions can cause wave-generated ripples to form on earlier ripple sets that may also cause smoothing of the surface of old ripple sets.

Sandy flat low regions were usually water laden to some degree and possessed sparse to dense stands of eelgrass, similar in structure and appearance to what was witnessed in the Eelgrass Flat Low sub-environment of the Outer Sheltered Sandy Tidal Flat bay region. Areas of eelgrass experienced



relatively low hydraulic energies compared to the other zones due to eelgrass baffling of current. Eelgrass also baffles silty detritus allowing for a relatively constant sedimentation rate. In the subsurface of the calm eelgrass fields mainly massive sands are observed with rootlets present in the upper 5-7cm. Mottled planar laminae are also occasionally seen in the uppermost 2-5cm of sediment. The overall lack of mud throughout the majority of sandy tidal flats throughout the bay is likely due to the marginal effect of stream run-off from the small watershed area of the bay, as well as the net flushing of the bay due to slightly longer ebb vs. flood tides (Glanzman et al., 1971).

In the tidal creeks organic debris accumulates in ripple troughs on the surface. These ripples are sinuous crested combined flow ripples, but are mainly created via tidal currents and run-off. Wavy laminae and ripple trough cross laminae are well formed and common features within the subsurface of tidal creeks. Lenses to continuous laminae, or even bedding of clay and organic material, may also be present in the subsurface, especially in creeks that carry debris away from the firmground area during ebb tide. Low zones next to tidal creeks may also display these laminae or lenses of clay, although the majority of laminae are planar versus wavy. The clay lenses may likely be due to erosion of the firmground and subsequent deposition of debris in the tidal creek, or secondary tidal channel. During winter months stronger wave action and increased surface run-off due to increased rainy periods may increase the amount of suspended sediment and debris that falls within the channel (Boldt et al., 2013). During winter months these deposits may accumulate in the secondary tidal channels where they are more protected from the effects of surface waves versus on the sandy tidal flat surface where fine grained sediment would be kept in suspension during high tide (Boldt et al., 2013). Alternatively, in Netarts Bay these sediments may be accumulating in channels during weaker neap tides and eroded during stronger spring tides throughout the year.

The Firmground sub-environment is an area distinct from all other previous environments that is characterized by stiff peaty-clay layers in addition to firm silty-sand terraces. Overall, this area experiences moderate energy near the tidal creek and lower energies further up the environment towards the margin of the bay, although the bay margin may experience wave reflectance at high tide causing turbulence in the water directly above the firmground. The Firmground environment is further elaborated on in Chapter 3.

### **Neoichnological Interpretation**

In areas of higher sandy flats experiencing overall higher levels of hydraulic energy and varying sedimentation rates the number of burrows was less compared to lower sandy flat areas that possessed low to moderate levels of hydraulic energy and less variation in sedimentation rate. Total organic carbon (TOC) values were generally inversely related to grain size and therefore highest TOC values were witnessed in areas where eelgrass baffles finer grained sediment. Burrow density and diversity seemed to increase in areas possessing eelgrass and in areas with appreciable amounts of lower fine grained-sand in association with higher TOC values. Salinity was generally around 30 PSU and thus probably had little effect on organism distribution unless fresh water penetrated the sandy tidal flat surface during heavy rains at low tide. It is hypothesized that organisms burrow deeper, and even up to the water table mark, when heavy periods of rain occur to escape salinity stress. This might be plausible as on rainy days less burrow openings were seen and fewer organisms were witnessed within trenching depth. When the tides dropped temperatures rose within standing water and tidal pools. Exposed sandy flats may have also caused desiccation stress in some organisms that could not efficiently burrow to a moderating depth or travel to the nearest body of water. Generally, during low tide organisms burrowed into the sediment where it was moist and where temperatures were cooler and less

variable in order to avoid desiccation and temperature stressors. Burrows that have an orange lining are formed by a thin oxide coating enriched in Fe, Mg, and Mn, which is common in mudflats or sandflats with a shallow redox potential discontinuity layer (Gingras et al., 1999). Beige sands indicate the oxidized (oxic) layer, the redox potential discontinuity layer is marked by grey sands, while the dark grey to black layer is the reduced (anoxic) layer (Rosenburg et al., 2001).

*Upogebia pugettensis* was observed in the tidal creek near the firmground, as well as the silty sands above the firmground. However, maximum *U. pugettensis* burrow densities were observed in the firmground area where *Thalassinoides*-like burrows penetrated the surficial peaty-clay layers into the silty-sand below. *Upogebia pugettensis* commonly creates semi-permanent to permanent deep Y- shaped to single inclined burrows occasionally connected together via basal horizontal shafts. The shrimp may use the horizontal basal shafts for deposit feeding while the vertical shafts help maintain a constant flow of water through the burrow network (Gingras et al., 2008a). In other instances the mainly permanent burrows of *U. pugettensis* are actively irrigated by the organism to facilitate irrigation for respiration as well as suspension detritus feeding (MacGinitie, 1930; Thompson and Pritchard, 1969; Posey et al., 1991). The burrows were commonly smoothly lined and slightly oxidized. *Hemigrapsus* sp. were sporadically observed in or very near tidal creeks, but were observed in large amounts among the firmground with *U. pugettensis*. *Hemigrapsus* sp. constructed unlined, shallow U- to J-shaped *Psilonichnus*-like burrows that were likely used as domiciles by the crab (Gingras et al., 2000; Gingras et al., 2008a). *Crangon* sp. shrimp were common within eelgrass fields and sporadically witnessed in tidal creeks. They did not appear to leave any significant trace except possible cubichnia when resting on the sediment surface. Hermit crabs were also common occupants in and around eelgrass areas. To escape exposure and predation hermit crabs usually burrowed in a corkscrew motion into the sandy substrate likely leaving an



interesting cubichnia like trace that would more often than not look like unidentifiable sediment disruption due to bioturbation. The amphipods *Corophium* sp. and *Eohaustorius* sp. were sporadic to common throughout the Outer-Middle Sandy Tidal Flat bay region. *Corophium* sp. commonly created *Skolithos*- and *Arenicolites*-like traces, while *Eohaustorius* sp. usually left behind surface traces akin to *Gordia* and/or *Crossopodia*. Sand loving *Corophium* sp., such as *C. arenarium*, can create both U-shaped and vertical burrows where water is constantly pumped in and out to aid in respiration, filter feeding and waste elimination (Ingle, 1996; Gingras et al., 2008a). Amphipod juveniles of either *Corophium* sp. or *Eohaustorius* sp. likely created diminutive *Skolithos*-like traces and possible cryptic bioturbation. Gingras et al. (2008a) indicates that the burrowing behaviour of small haustoriid amphipods contributes to the formation of cryptobioturbation while the burrowing activity of larger haustoriids contributes to the formation of sediment disruption structures.

The bivalves *Saxidomus gigantea*, *Tresus nuttallii* and *Macoma* sp. were common in sandy low zones or eelgrass fields and sporadic on sandy highs. *Clinocardium nuttallii* was more common in the sandy lows and eelgrass fields as well, but were also common near the edges, or within, tidal creeks. *Protothaca staminea* were only common in detritus rich finer grained sandy areas near the tidal creek next to the firmground zone. *Saxidomus gigantea* and *T. nuttallii* are bivalves that usually reside at least 30cm below the sediment surface. Once these deeper burrowing bivalves reach adulthood they are barely capable of moving and need the protection of surrounding sediment in order to survive (Marriage, 1954; Campbell et al., 1990). These suspension feeders that feed by extending their siphons to the sediment-water interface at high tide create *Siphonichnus*-like traces; however if only the siphon is observed and no bivalve then a *Skolithos*-like trace results. If the bivalve has not moved and there is no evidence of equilibrichnia then the trace is not referred to as *Siphonichnus*-like since there is no sediment disruption around the bivalve. Instead, the bivalve resting trace is *Lockeia*-like with a *Skolithos*-like

extension above it (Dashtgard and Gingras, 2012). *Macoma* sp. are medium depth burrowers capable of burrowing to depths of 20cm (Marriage, 1954). They have separate inhalant and exhalant siphons that extend to the surface to either suspension feed or deposit feed. Occasionally the siphon trace left by *Macoma* sp. can resemble *Polykladichnus*; however if the bivalve is not seen then the siphon traces look like inclined *Skolithos*. When the bivalve is observed *in situ* there is usually noticeable equilibrichnia like structures around it and the trace can be referred to as dual *Siphonichnus*-like. Stellate surface traces left by *Macoma* sp. after interface deposit feeding resemble *Lorenzina*. The preservation potential of this surface expression of interface deposit feeding by *Macoma* sp. is much less than that of its vertical siphon produced trace, so care needs to be taken in determining whether or not the animal is mainly engaging in deposit or suspension feeding (Gingras and MacEachern, 2012). *Clinocardium nuttallii* are usually observed as semi-infauna at the surface or just below the sediment surface up to a depth of approximately 5cm (Marriage, 1954). The trace most often attributed to *C. nuttallii* is *Lockeia*-like; however they are capable of producing *Protovirgularia*-like traces if they are prompted to move horizontally, or even *Siphonichnus*-like traces if extending their short siphons to the surface. *Protothaca staminea* are usually in the process of moving at least slightly along the detritus rich sands near the firmground tidal creek and therefore create *Protovirgularia*-like traces alternating with *Lockeia*-like traces when resting and anchoring with their foot. The furrows and lateral mounds created as *P. staminea* moves horizontally across the sediment via a rocking motion and the use of its foot creates the *Protovirgularia*-like trace (Gingras et al., 2008a; pers. obs. Hodgson, 2012). Peterson (1982) indicates that *P. staminea* is a shallow burrowing (mainly in muddy sediment) to epifaunally living (mainly in sandy sediment) suspension feeding bivalve that also likely feeds upon benthic diatoms and microalgae. This may explain why *P. staminea* was observed to move horizontally over the detritus rich sandy sediment versus burrowing. *Olivella biplicata* is the most

common gastropods by far, with whelks (*Nucella* sp.) likely also common due to the fact that hermit crabs often conceal themselves within whelk shells although no live whelks were witnessed. *Olivella biplicata* was most often seen along the water mark of higher energy tidal ridges or banks of channels and creeks, especially along the main tidal channel bank ridge. This observation correlates with the previous activity of *O. biplicata* witnessed in the outermost sheltered to exposed regions of the bay. *Olivella biplicata* consistently arises in environments possessing well-sorted clean sands and relatively fast moving clean marine water (Edwards, 1969).

*Nephtys* sp. and capitellid threadworms (*Mediomastus* sp. and *Capitella* sp.) were sporadic to common throughout the Outer-Middle Sandy Tidal Flat bay region, with threadworms becoming more common in the finer grained areas associated with eelgrass fields. Smaller *Nephtys* sp. can potentially create cryptic bioturbation while larger specimens produce navichnia and sediment disruption structures. The errant polychaete moves via two main pressure pulses, the first of which is the major pulse that involves the eversion of the proboscis, and secondly the minor pulse where the tail end of the worm is brought forward (Trevor, 1969). The errant capitellid threadworms move through the sediment creating *Trichichnus*-, *Skolithos*- and *Planolites*-like traces. They are head down deposit feeders that usually possess branched or spiral burrows at depth (Zorn et al., 2006). As was mentioned in Gingras et al. (2008a), a personal observation by M. K. Gingras indicated that modern spiralling patterns of capitellids could be due to "a response to high-density colonization" or may "represent a focused, 3D deposit feeding structure". Therefore, the lack of spiralling capitellid burrow forms in Netarts may potentially be due to the abundance of available food resources and lack of high density competition for such resources. Bloodworms (*Glycera* sp.) were usually only observed in areas containing eelgrass leaving behind *Palaeophycus*-, *Planolites*- and subordinate *Polykladichnus*-like traces. *Nereis* sp. worms were sporadically seen throughout sandy low areas and common in



finer grained, organic rich areas such as small tidal creeks and eelgrass fields. Nereid worms produced *Skolithos*-, *Palaeophycus*- and *Polykladichnus*-like burrows usually interconnected with each other forming a network. This semi-permanent network allows the nereid protection to move through the subsurface easily in order to deposit feed over large areas where it can typically move up the Y-shaped sections to safely interface feed (Gingras et al., 1999; Gingras et al., 2008a). Nereids and glycerids are able to burrow by everting their pharynx into the sediment in order to form a fracture that they can then surge into (Murphy and Dorgan, 2011). If the sediment is soft enough the worms can instead move their heads from side to side in order to drive themselves forward extending the crack laterally to further form their burrow (Murphy and Dorgan, 2011). Terebellids were commonly found in or near tidal creeks and occasionally along the margins of eelgrass fields. These deposit feeders commonly created mud to mucous lined burrows or constructed parchment like tubes creating *Palaeophycus*-, *Cylindrichnus*- and lined *Skolithos*-like traces. The green tentaculate surface deposit feeding terebellid that was likely observed in the subsurface is *Eupolymnia heterobranchia* (syn. *Eupolymnia crescentris*) (Dale, 1961; Shabica et al., 1976). A similar species, *E. nebulosa*, was found to build its tube with larger particles (>2mm) that were dominantly animal or vegetal detritus vs. sediment grains, although mean particle size decreased closer to the burrow opening due to particle loss during transfer along tentacles (Grémare, 1988; Maire, 2007). Smaller particles appear to be ingested while the larger particles appeared to be used for tube building bound by mucous (Grémare, 1988; Maire, 2007). Tentaculate surface deposit feeding activity seemed to only occur at night during submergence where the bulk majority of time was dedicated to feeding while only a small amount of time was dedicated to tube building (Grémare, 1988; Maire, 2007). In Netarts Bay the burrows observed were either finely lined or lined with larger grains depending on the size availability of detritus around. Tubes were constructed with some resembling lined *Skolithos*-like traces, while others were either thinly

lined *Palaeophycus*-like traces to concentrically lined *Cylindrichnus*-like traces. *Cylindrichnus*-like burrows were usually noticed when size differences between laminae were seen. The laminae usually alternated between bands of fine to slightly coarser sediment possibly due to the cyclic availability of detritus and sediment between daily tidal cycles or neap-spring tidal cycles. The predaceous nemertean worm, *Cerebratulus* sp., commonly occupied sediment of lower flat areas near tidal creeks creating slightly mucous lined *Palaeophycus*-like traces. *Abarenicola pacifica* was dominantly seen on the sandy eelgrass area above the firmground zone in *Arenicolites*-like burrows. The tail end of *A. pacifica* burrows usually possess a cylindrical mound of excreted sediment above it, while the vertical shaft above the head end is slightly collapsed in order to bring sediment down in which to feed (Hylleberg, 1975). It is thought that *A. pacifica* invokes multiple feeding strategies at different times to suite its needs including suspension feeding, deposit feeding and gardening of microorganisms (Hylleberg, 1975; Swinbanks, 1981).

## **DISCUSSION**

### **Physico-chemical Factors Affecting Biological Distribution and Behaviour**

Various biological factors – such as resource competition and recruitment – shape organismal behaviour and subsequent animal-sediment interactions; in addition, multiple physico-chemical factors also impart an influence. Major physico-chemical parameters include, but are not limited to: subaerial exposure, temperature, turbidity, salinity changes, oxygen levels, pH, substrate texture, substrate consistency, sedimentation rate, and potential food resources such as measured through TOC levels. In turn, these parameters can all be related to larger controlling factors such as depositional geometry, bathymetry, and hydraulic energy; thereby forming a solid process ichnological framework to be built upon (Gingras et al., 2007).

The majority of Netarts Bay is exposed at low tide where animals are subject to subaerial exposure and desiccation stress. However, it appears that most animals counteract exposure by seeking refuge in water laden eelgrass fields or by burrowing beneath the sediment surface. Most of the tidal flats are composed of upper fine sands and therefore burrowing is easy for most animals, with deeply burrowing animals able to reach the water table at lowest tide due to the relative lack of topographic tidal flat relief in most areas. In areas of higher topographic relief, or in instances where organisms cannot burrow deeply enough, other mechanisms against desiccation are employed such as possessing a hard shell that can be completely closed to seal in moisture during low tide. Numerous shallow burrowing bivalves and gastropods can invoke this method of desiccation protection that also serves the dual purpose of protection from predators. Water temperature is usually relatively constant throughout the bay as it is a well-mixed bay in a temperate climate. The margins of the bay may experience elevated temperatures on exposed surfaces or in pools of shallow standing water on the few, hotter summer days each year, but otherwise temperature is moderated nicely by the wind and cool ocean waters. The sediment remains at a relatively constant, cool temperature throughout the year so animals commonly burrow, seek refuge in continuously flowing tidal creeks, or become active only at night to escape temperature extremes (Ricketts et al., 1985). Desiccation and temperature stress are usually only significant factors for organisms solely living near the upper limit of their vertical range, especially if this range includes the upper intertidal level or higher; however most of them have adapted quite well to such conditions or they would have otherwise perished (Ricketts et al., 1985). The bay exhibits rapid flushing rates, calculated by Shabica et al. (1976) to be 1.34 tidal cycles. This rapid flushing rate, in addition to longer ebb versus flood tides as indicated by Glanzman et al. (1971), leads to the rejuvenation of cooler, marine waters in the bay from the Pacific Ocean.

Fast flushing rates, very low organic terrigenous input, and sparse human development also means that Netarts Bay is pristine, having exceptional water quality translating to overall low turbidity values (Shabica et al., 1976). Turbidity may increase intermittently during heavy rainy periods of the winter months, but generally turbidity levels are low throughout the year (Glanzman et al., 1971). Salinity values throughout most of the bay stay at or near fully marine values with mean monthly salinity values indicated by Hunger (1966) to fall between 27.42 to 32.66‰, which is comparable to values obtained during this study which fell between 30 to 35‰. The small watershed that feeds Netarts Bay is composed of multiple small intermittent streams that do not usually affect the salinity of the bay to any large extent. An exception occurs only for short periods of time during heavy winter rainy periods that may, in addition to increasing turbidity, also bring salinity down to as low as 13‰ in the lower, marginal reaches of the bay (Glanzman et al., 1971). Netarts Bay retains consistently high levels of dissolved oxygen throughout the year – generally higher than 7mL O<sub>2</sub>/L – posing limited, if any, oxygen stress on the organisms within the bay (Glanzman et al., 1971; Shabica et al., 1976). The pH levels within the bay range from 7.8 to 8.4 and therefore are within the optimal range for organisms living in bays or estuaries (Shabica et al., 1976).

The previously addressed physico-chemical stresses can have a major impact on burrowing behaviour; however factors having the strongest affect together are substrate texture and substrate consistency, hence the creation of substrate-controlled ichnofacies (Seilacher, 1967; Gingras et al., 2007). In the lowermost portions of Netarts Bay and along the firmground zone poorly to moderately sorted clays, silts and very fine sands dominate. While the middle to outer reaches of the bay are dominated by well to very well sorted, upper fine grained sand. The majority of the bay is dominated by sandy tidal flats and is therefore well sorted to very well sorted, upper fine grained sand with substantial portions of lower medium grained sand and noticeable portions of



lower fine grained sand. Along the exposed spit and beach portions almost equal mixes of very well sorted, upper fine- to lower medium-grained sand dominate. The lower fine grained sand observed along the foreshore-backshore boundary of the Exposed Shoreface-Spits bay region as well as the upper intertidal flat-supratidal boundary and tidal channel ridges of the Outer Sheltered Sandy Tidal Flat bay region are predominantly heavy mineral sands. These sands are finer and denser compared to the overall majority of sand in the region dominantly composed of lighter and larger quartz and feldspar grains. In contrast, the lower fine grained sand fraction in areas of eelgrass fields as well as tidal creeks and channels are mainly due to organic rich detritus and trapping of fines. Overall, the area studied is dominated by well sorted to very well sorted, upper fine grained sands with very slight proportions of lower medium grained sand increasing seaward and lower fine grained sand increasing landward. Thus, the substrate is generally homogenous throughout the area studied acting as a controlled baseline to monitor relative burrowing behaviour between contrasting zones where factors such as food resource availability, sedimentation rate and hydraulic energy vary resulting in the observed differences seen.

Initially, in contrast to what Hunger (1966) discovered, there did not appear to be an overall qualitative inverse correlation between grain size and TOC, particularly because the area of this study had consistent sandy substratum compared to Hunger (1996) who studied sandy and muddy substrates. Furthermore, the apparent lack of inverse correlation is also affected by the inclusion of foreshore-backshore boundary sediment along the spit that contained an appreciable quantity of lower fine grained heavy mineral sands. These are "clean" sands derived from the beach versus the otherwise organic rich fine sands and detritus that are terrigenously sourced that are found in small quantities on lower energy sand flat lows, tidal creeks and eelgrass beds within the bay. If the comparison is between the muddier sediment in and around the firmground zone and the sandier sediment of the

flats then an inverse correlation between grain size and TOC is observed. Newell (1979) stated that there is an inverse relationship between grain size and potential food resource particles especially nearest to the sites of organic matter export into estuaries and lagoons. Potential food resources could be living or dead organic matter derived from plants or microorganisms that then adhere to organic or inorganic particles (Newell, 1979). These food resource particles then accumulate in sheltered areas, and thus in areas with lower overall grain size such as silts and clays (Newell, 1979). Total organic carbon is used as an indirect measure of productivity and potential food resource availability. Care needs to be taken as to the use of organic carbon levels as a proxy for potential food resource values since it can be classified as labile or refractory (Risk and Yeo, 1980). Labile organic carbon is easily digestible material that is mainly derived from autochthonous sources, such as microalgae (diatoms and foraminifera) as well as photosynthetic activity of *in situ* seagrass or filamentous algae (Risk and Yeo, 1980). Refractory organic carbon is not easily broken down by macrofauna – but is a potential source of nutrients for microorganisms – and is mainly derived from allochthonous sources, such as cellulose from plant or woody material brought in via rivers or tides (Risk and Yeo, 1980). Along the tidal flats and shallow tidal creeks of Netarts Bay the sources of organic carbon are hypothesized to be mainly of autochthonous origin and labile due to the abundance of diatoms, foraminifera, filamentous algae and macroalgae, in addition to minimal stream discharge input that would normally be a source of more refractory carbon (Hunger, 1966; Shabica et al., 1976). Parts of the firmground zone on the other hand are likely of mixed allochthonous-autochthonous sourced organic carbon. Overall, TOC across the Exposed Shoreface-Spits bay region was generally very low, with highest values occurring near the main channel and near tidal inlets and lowest values along the foreshore-backshore boundary. Sandy highs had slightly larger grain size compositions compared to lows but they generally had the same TOC content, unless the lows were associated with

a creek where TOC was slightly higher. Eelgrass fields and sandy lows had very similar grain size compositions, but noticeable fines were observed within water laden eelgrass fields that corresponded to higher TOC levels. As organic material accumulates in sandy substrates the redox potential discontinuity (RPD) layer rapidly elevates to within a few millimetres to centimetres of the sediment-water interface (Zorn et al., 2006; Dashtgard and Gingras, 2012). This phenomenon was witnessed in Netarts Bay where the RPD layer was virtually at the surface in areas of highest organic matter accumulation as commonly occurred across eelgrass fields. Newell (1979) noted that the abundance of deposit feeding animals was found to positively correlate with the abundance of organic detritus. In Netarts Bay deposit feeders were commonly found amongst the protected water laden eelgrass fields, tidal channels or creeks, and sandy lows in areas that typically possessed higher TOC levels. Eelgrass is very effective at baffling tidal current and oscillatory wave motion allowing fine grained sediment, such as silts and organic detritus, to fall out of suspension and become trapped within the eelgrass fields; thereby becoming an available food resource to organisms who exploit the multiple benefits of residing within this protected environment (Harlin et al., 1982; Bostrom et al., 2010). It is evident that hydrodynamics play a major role in the transport and settling of finer grained and potentially organic rich material in an environment of otherwise homogenous grain size distributions.

### **Effects of Hydrodynamics and Associated Sedimentation Rate on Macrofauna**

Hydraulic energy refers to wave and/or tidal energy levels. Variations of hydraulic energy levels have the ability to control grain size distribution patterns and sedimentation rate while also transporting suspended organic material for use by organisms as food. Hydraulic energy and sedimentation rate are inter-related stresses affecting the burrowing behaviour of organisms (Dashtgard, 2011). If hydraulic energy is high then there is a greater chance for

substrate erosion as well as sediment aggradation. Organisms subjected to high hydraulic energy levels are usually subjugated to changes in tides throughout the day and/or to oscillatory wave dynamics acting on the sediment surface (Dashtgard, 2011). If hydraulic energy is low then there tends to be very slow, but steady, accumulation of finer grained sediments in a relatively calm environment (Dashtgard, 2011). If there is no evidence of diminution amongst organisms or burrows then a reduction in trace diversity is likely due to stresses caused by increased sedimentation rates and hydraulic energy (Gingras et al., 2011).

In areas of essentially constant grain size, such as Netarts Bay, varying hydraulic energy levels can be deduced by observing various flow related bedforms, although the bidirectional nature of a wave and tidally influenced environment complicates matters versus a unidirectional flow system. As hydraulic energy increases there is a progression through lower plane bed, to ripple, and finally to dune type bedforms that are attributed to the lower flow regime (Allen, 1982a). These bedforms are typically found within the actual bay proper, especially ripples and dunes. In areas of high hydraulic energy large dunes, upper plane bed features displaying parting lineation, and antidunes form as the upper flow regime is reached (Allen, 1982a). These features are common on the exposed beaches and exposed spit just outside the bay mouth entrance.

As mentioned earlier stands of eelgrass decrease hydraulic energy levels allowing any finer grained inorganic and organic material that was initially held in suspension, due to tidal current and wave motion, to fall out of suspension onto the sediment surface of the eelgrass field. The increased steady accumulation of organic material in eelgrass fields and the protected lower energy nature of these fields, which are in very close proximity to large tidal channels, is a major reason for the increased species diversity and abundance levels found within these areas of otherwise high hydraulic energy levels (Whitlow and Grabowski, 2012; Barnes, 2013). In contrast, suspended sediment



and potential food resources are unable to fall out of suspension in areas experiencing constant moderate to high hydraulic energy levels and therefore suspension feeding organisms usually dominate these domains (Warwick and Uncles, 1980). In select areas cyanobacterial mats may change the local hydrodynamics acting on the area by essentially doubling the flow velocity needed to form the traditionally mentioned lower plane bed, ripple, dune and upper plane bed features (Hagadorn and McDowell, 2012).

If current or wave activity is high then sedimentation rate will greatly exceed burrowing rate and primary sedimentary structures such as planar laminae and cross stratification will be dominant (Kellerhals and Murray, 1969; Murty and Roberts, 1989; Dashtgard, 2011; Dafoe et al., 2011). In environments prone to high energy and potentially high or variable sedimentation rates, such as along the recurved spit portion of Netarts Bay, select organisms may be present that are capable of surviving in rapidly aggrading, or eroding, substrates (Gingras et al., 2011). Very high sedimentation rates associated with high current velocities limit the ability of an organism to filter feed and therefore there is shift from suspension feeding toward deposit feeding, scavenging or carnivory (Rhoads et al., 1972; Gingras et al., 2007). Deposit feeders present tend to be trophic generalists deriving food from the sediment surface (Gingras et al., 2011). The predominantly deposit feeding *Olivella biplicata* is an excellent example of a trophic generalist in a high energy environment with shifting substrates as it is highly mobile and may switch to suspension feeding, carnivory or scavenging, in addition to mainly deriving its food from the sediment surface. Areas experiencing very high hydraulic energy levels are prone to heavy erosion or deposition along the shoreface. Small deposit feeders below the sediment surface, such as opheliid polychaetes may produce *Macaronichnus*-like traces (Clifton and Thompson, 1978). There are some suspension feeders that are able to survive such high energy environments with ample rates of sedimentation. Shallow burrowing siphonate suspension feeding bivalves have the highest escape potential from

rapid burial during high energy, high sedimentation events (Kranz, 1974). Bivalves with a very well developed foot are capable of moving rapidly through the sediment (Doerjes et al., 1969; Reineck and Singh, 1973). Only a small number of organisms can cope with the high energy swash and surf zone of beaches unless they harbour the ability to burrow rapidly, up or down, in dilatant or thixotropic sands (Goldring, 1995). The possible bivalve located along the recurved spit of the bay that is able to burrow rapidly either up or down in the high energy surf zone is the razor clam *Siliqua patula*. On the more distal portions of Netarts spit or along exposed beaches, although hydraulic energy levels are still very high, sedimentation rate is lower allowing other animals to thrive in and near the swash zone such as *Emerita analoga*. There is a delicate balance of energy that allows these specific traces to exist (Gingras et al., 2007). If the sedimentation rate is too high then jumping-up traces such as fugichnia are the only types of traces found as the habitat is simply uninhabitable to many organisms (Gingras et al., 2007). If the sedimentation rate is lowered slightly, in an otherwise high energy environment, then vertical traces resembling *Siphonichnus* or *Skolithos* become common.

Regular heterogeneous distribution of burrows is a result of regular variability in the localized changes in hydraulic energy and thus sedimentation rate and food resource availability within Netarts Bay. This heterogeneous distribution of traces likely indicates repetitive colonization events that are punctuated by conditions less favourable to infauna (Gingras et al., 2011). As current and/or wave energy decreases sediment begins settling from suspension but sedimentation rate still exceeds the rate of burrowing where physically graded bed forms are expressed (Dafoe et al., 2011). As the burrowing rate surpasses sedimentation rate biogenically graded beds are produced as a result of burrowing organisms redistributing particles (Dafoe et al., 2011). Biogenic stratification occurs when intense burrowing segregates particles as burrowing rate greatly exceeds sedimentation rate in an environment that likely has low hydraulic energy levels (Dafoe et al., 2011).

Suspension feeding organisms are slow moving and disturb much less sediment in a given amount of time compared to deposit feeding organisms (Gingras et al., 2008b). Suspension feeding organisms typically move in a vertical direction, if at all, and therefore are more particular to filter feeding strategies (Gingras et al., 2008b). Deposit feeding organisms on the other hand need to move through sediment in order to feed and thus their volumetric burrowing rates are much higher than suspension feeders (Gingras et al., 2008b). Volumetric burrowing rates of deposit feeders in sand are substantially higher than suspension feeders that displayed lower volumetric burrowing rates in sand. Moving through the sediment involves a lot of energy and therefore Gingras et al. (2008b) hypothesized that the burrowing rates of some deposit feeding organisms slows down as a result. In Netarts Bay, areas with typically high flow velocities, such as along channel margins, usually see a predominance of vertical traces and suspension feeding organisms. While lower energy areas, such as eelgrass fields and areas of tidal flats away from main channels, typically have a higher proportion of permanent horizontal to vertical burrows and a predominance of deposit feeding organisms.

**Ichnological Implications of a Fully Marine Micro- to Meso-tidal, Wave Dominated, Tidally Influenced Bay on Associated Archetypal Substrate Controlled Ichnofacies**

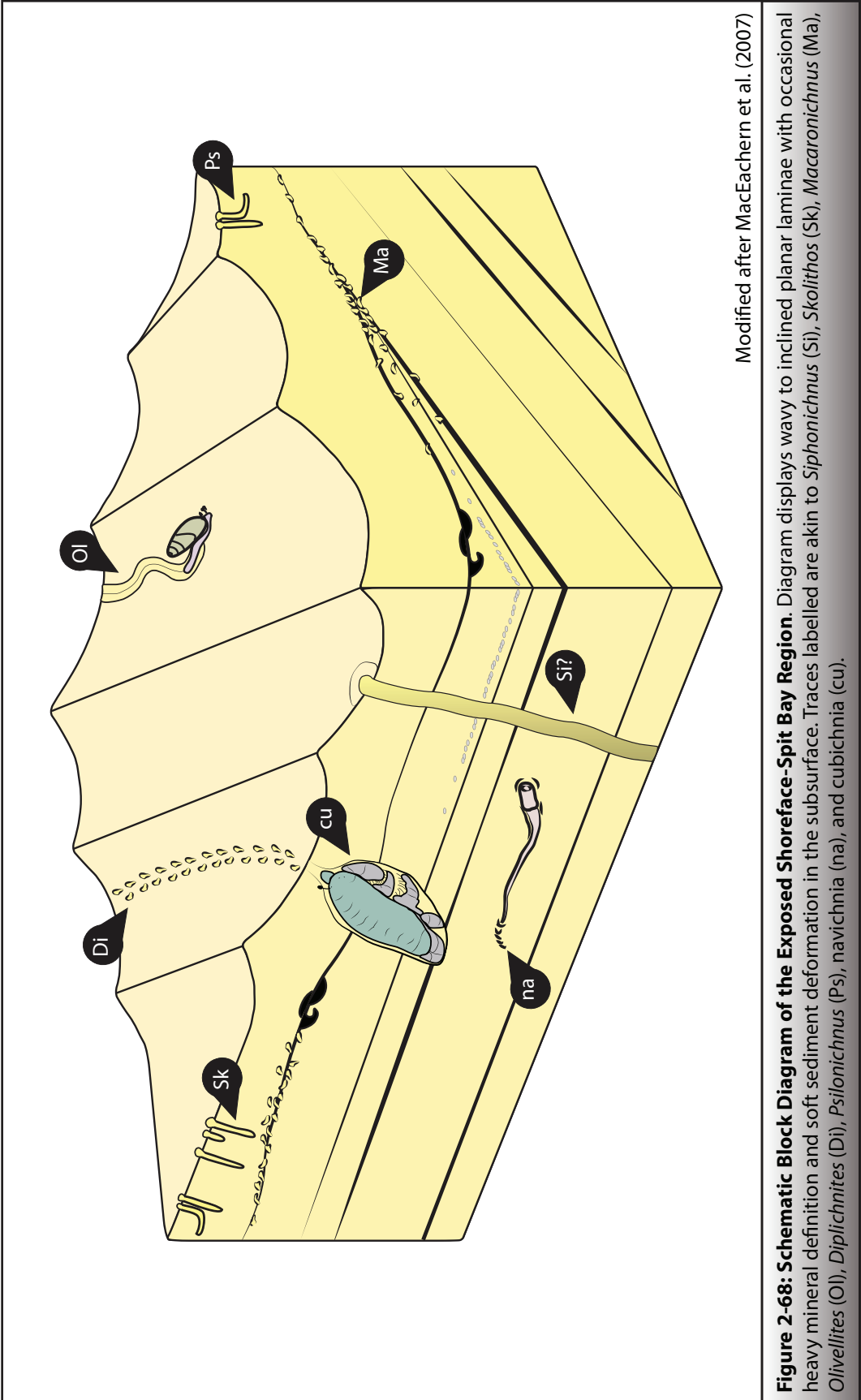
The outer reaches and open ocean spit foreshore areas of Netarts Bay are interpreted to be deposited under moderate to high energy conditions where sedimentation rate increases or varies greatly under the fluctuating hydraulic influence associated with the tides. However, fields of eelgrass provide stable, lower energy oases where sedimentation rate is steady in an otherwise dynamic environment. Distributions of macrofauna and their life habits were analyzed in accordance with these dynamic to stable conditions as observed throughout the three main outer bay regions. The summarized assessment of these bay regions is provided below to: 1) build upon the well

established, fundamental substrate controlled facies models proposed by Seilacher (1967), and 2) to provide a working model for future research on fully marine bay systems.

**Exposed Shoreface-Spit Bay Region** – This region experiences the greatest amount of hydraulic energy and associated changes in sedimentation. Bioturbators are sparse with a shift towards highly specialized filter feeders or to organisms that are able to also employ deposit feeding, scavenging abilities and carnivory. Three main morphologic zones were commonplace throughout all the observed sub-environments providing a solid base for comparison and summarization of the observed physical and biogenic sedimentary features. These zones include the foreshore terrace zone, the foreshore (swash) zone, and the foreshore-backshore boundary zone. A sedimentological summary of this bay region is provided in Table 2-1, while the neoichnological summary is provided in Table 2-2. Figure 2-68 is a block diagram that summarizes the overall sedimentary and biogenic features of the Exposed Shoreface-Spit region.

The foreshore terrace zone is the widest zone and subject to large variations in hydraulic energy levels and sedimentation. It is dominantly composed of shifting longshore bars and troughs as well as prominent subaqueously formed dunes that possess superimposed ripples. Planar bedding with parting lineation is also observed, mainly in regions next to the lowest tide level. In the subsurface wavy laminae is variably seen in the uppermost few centimetres of sediment with otherwise planar to cross laminae as the most prominent features. Ichnologically speaking this zone has a sparse assemblage of traces likely owing to its highly dynamic nature. The most dominant trace is an *Olivellites*-like meandering surface trace produced by *Olivella biplicata*, a gastropod that is able to utilize a broad range of feeding modes as a dynamic strategy employed for a dynamic environment. The next common trace is navichnia or biogenic sediment disruption structures and





Modified after MacEachern et al. (2007)

**Figure 2-68: Schematic Block Diagram of the Exposed Shoreface-Spit Bay Region.** Diagram displays way to inclined planar laminae with occasional heavy mineral definition and soft sediment deformation in the subsurface. Traces labelled are akin to *Siphonichnus* (Si), *Skolithos* (Sk), *Macaronichnus* (Ma), *Olivellites* (Ol), *Diplichnites* (Di), *Psilonichnus* (Ps), *navichnia* (na), and *cubichnia* (cu).

possible cryptic bioturbation associated with errant carnivorous polychaetes. The sparse *Skolithos*-like and/or fugichnia and likely equilibrichnia traces are potentially created by fast burrowing bivalves able to respond to the tumultuous environmental conditions.

The foreshore zone is synonymous with the swash zone and experiences the full onslaught of wave activity during high tide along the exposed coastline. The swashing motion creates upper flow regime conditions across the surface producing a dominantly planar surface with evident parting lineation aligned parallel to swashing direction. Horizontal to inclined planar laminae comprise the primary sedimentary features witnessed in the subsurface. However, these laminae appear mottled in appearance as especially witnessed through the contrasting dark heavy mineral sand laminae with otherwise light quartzo-feldspathic sands. This mottling is likely the result of bioturbation, although no definitive subsurface deposit feeding tracemaker was found, and is *Macaronichnus*-like in appearance.

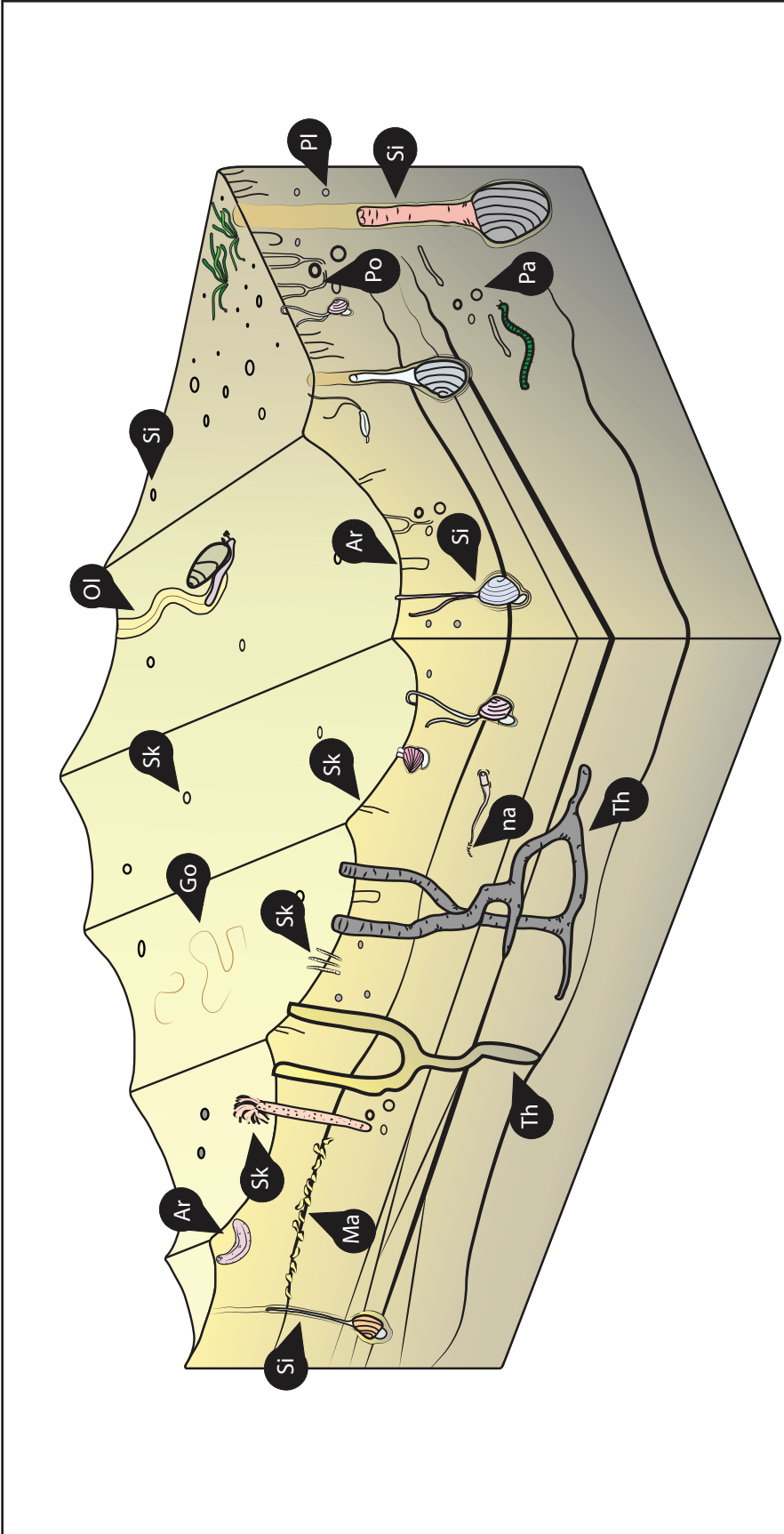
The foreshore-backshore boundary zone is where the very fine grained heavy mineral sands exhibit the greatest amount of accumulation causing an anomalous decrease in sediment grain size results. In addition to planar laminae, soft sediment deformation features and micro-faulting are common in the near surface. Talitrid amphipods commonly create *Skolithos*-like to diminutive *Psilonichnus*-like traces in this zone where beach wrack is readily available for these scavengers to feast upon and seek shelter under.

***Outer Sheltered Sandy Tidal Flat Bay Region*** – In the tidal channels hydraulic energy is relatively high but steady bidirectional currents allow for suspension feeding organisms to flourish. Exposed isolated intertidal flat sand bars and tidal ridges experience a more dynamic onslaught of energy levels associated with mixed wave and tidal forces thereby only allowing specifically suited organisms to take hold. Protected intertidal sand flats attached to the spit experience relatively lower mixed wave and tidal energies so a higher burrow

density is observed, although diversity still appears to be proportionately low. In contrast, the low lying eelgrass intertidal flats experience lower hydraulic energy levels due to the overall shielding provided by surrounding morphology allowing eelgrass to take hold and further baffle wave and tidal current energies. This baffling also allows for the establishment of low but constant sedimentation rates, especially of grains of silt and associated organic detritus, resulting in a highly diverse environment with abundant traces. Comparative morphological zones, compiled from observations of the various sub-environments within the bay region include: the exposed intertidal sand flat bar and ridges, protected intertidal sand flats, intertidal eelgrass flats, and protected foreshore areas. A sedimentological summary of this bay region is provided in Table 2-3, while the neoichnological summary is provided in Table 2-4. Figure 2-69 is a block diagram that summarizes the overall sedimentary and biogenic features of the Outer Sheltered Sandy Tidal Flat region.

The exposed intertidal sand flat bar and ridge zone displays sinuous to linguoid ripples at the surface along with an array of subsurface features including planar to wavy laminae and tabular to trough cross ripple laminae. Laminae that display bidirectionality were observed through X-ray analysis of sediment core. Exposed regions exhibit deeply penetrating traces that may be lined. Unlined and lined *Thalassinoides*-like traces associated with deposit feeding crustaceans (*Neotrypaea californiensis*), as well as deep *Siphonichnus*-like structures of a mono-specific assemblage of invasive bivalves (*Nuttallia obscurata*) were common trace constituents of this type of zone. Sporadic *Gordia*- and *Crossopodia*-like surface traces, as well as *Skolithos*-like and potential cryptic bioturbation were generated by amphipod species. Sporadic occurrences of threadworms resulted in diminutive *Skolithos*- and *Planolites*-like traces.

The protected intertidal sand flat zone also possess sinuous to linguoid ripples on the sediment surface in an area of larger overall undulatory topography, although to a lesser degree due to dissemination by the



Modified after MacEachern et al. (2007)

**Figure 2-69: Schematic Block Diagram of the Outer Sheltered Sandy Tidal Flat Bay Region.** Diagram displays wavy to planar laminae with occasional heavy mineral definition and cross laminae in the subsurface. Traces labelled are akin to *Siphonichnus* (Si), unlined or lined *Skolithos* (Sk), unlined or lined *Thalassinoides* (Th), *Arenicolites* (Ar), *Macaronichnus* (Ma), *Palaeophycus* (Pa), *Polykladichnus* (Po), *Planolites* (Pl), *Olivellites* (Ol), *Gordia* (Go), and *naviclinium* (na).



emplacement of burrow openings. Planar to slightly wavy laminae are exhibited in the subsurface although usually mottled in appearance as a common result of bioturbation. Generally unlined *Thalassinoides*-like structures of decapod crustaceans occur in large amounts in this zone but do not display the robustness of the lined *Thalassinoides*-like traces due to the calmer nature of this zone. Dual *Siphonichnus*-like traces are attributable to the interface deposit feeding and filter feeding *Macoma* species bivalve. As in the exposed intertidal sand flats, amphipods create meandering surface *Gordia*-like traces while conjuring *Skolithos*- and *Arenicolites*-like traces in the subsurface, in addition to sediment disruption and potential cryptic bioturbation. Polychaetes are much more abundant in this zone owing to its more protected nature as well as the larger degree of water saturated sediment. The errant carnivorous polychaete *Nephtys* sp. is found throughout all the sandy flats of the bay regions, preferring water laden sediment where it is able to easily swim through creating *Neurichnus*/sediment disruption and potential cryptic bioturbation. Other errant polychaetes such as various head down deposit feeding threadworm species create *Trichichnus*-, *Skolithos*- and *Planolites*-like traces. Along the protected tidal channel bank moderate hydraulic energy levels create relatively quiescent realms where suspension feeders are able to feed on organic material transported in the water column. Thus, polychaete generated tubes akin to lined-*Skolithos* are common. *Macoma secta* and *Clinocardium nuttallii* also prefer the moderate energy sandy environment for filter feeding. *Macoma secta* produces a *Siphonichnus*-like trace while *Clinocardium nuttallii*, in addition to a short *Siphonichnus*-like trace, also potentially creates a *Lockeia*-like trace. The holothurian, *Paracaudina chilensis*, and the surface feeding gastropod *Olivella biplicata* both thrive here as they likely utilize both deposit and suspension feeding modes. The holothurian has the ability to burrow in such a way as to potentially create *Arenicolites*- to *Diplocraterion*-like traces.

The intertidal eelgrass flat zone consists of a surface that is planar to hummocky in appearance that is dominated by eelgrass. The subsurface appears mottled to massive due to abundant bioturbation. The aforementioned errant polychaete species of the protected intertidal sand zone are also found in the intertidal eelgrass zone, though in even greater abundances. In addition, relatively sessile deposit feeding, and passively carnivorous, polychaete species such as *Glycera* sp. and *Nereis* sp. create trace networks akin to *Palaeophycus* and *Polykladichnus*. The predaceous nemertean, *Cerebratulus* sp., also creates *Palaeophycus*-like trails. *Siphonichnus*-like traces are abundant in this zone, but are instead the result of a diverse array of bivalve species in contrast to the proportionately mono-specific bivalve species assemblages mentioned earlier. *Thalassinoides*-like traces are still very abundant but are caused by *Upogebia pugettensis* in eelgrass flats rather than those of *Neotrypaea californiensis* on sandy flats.

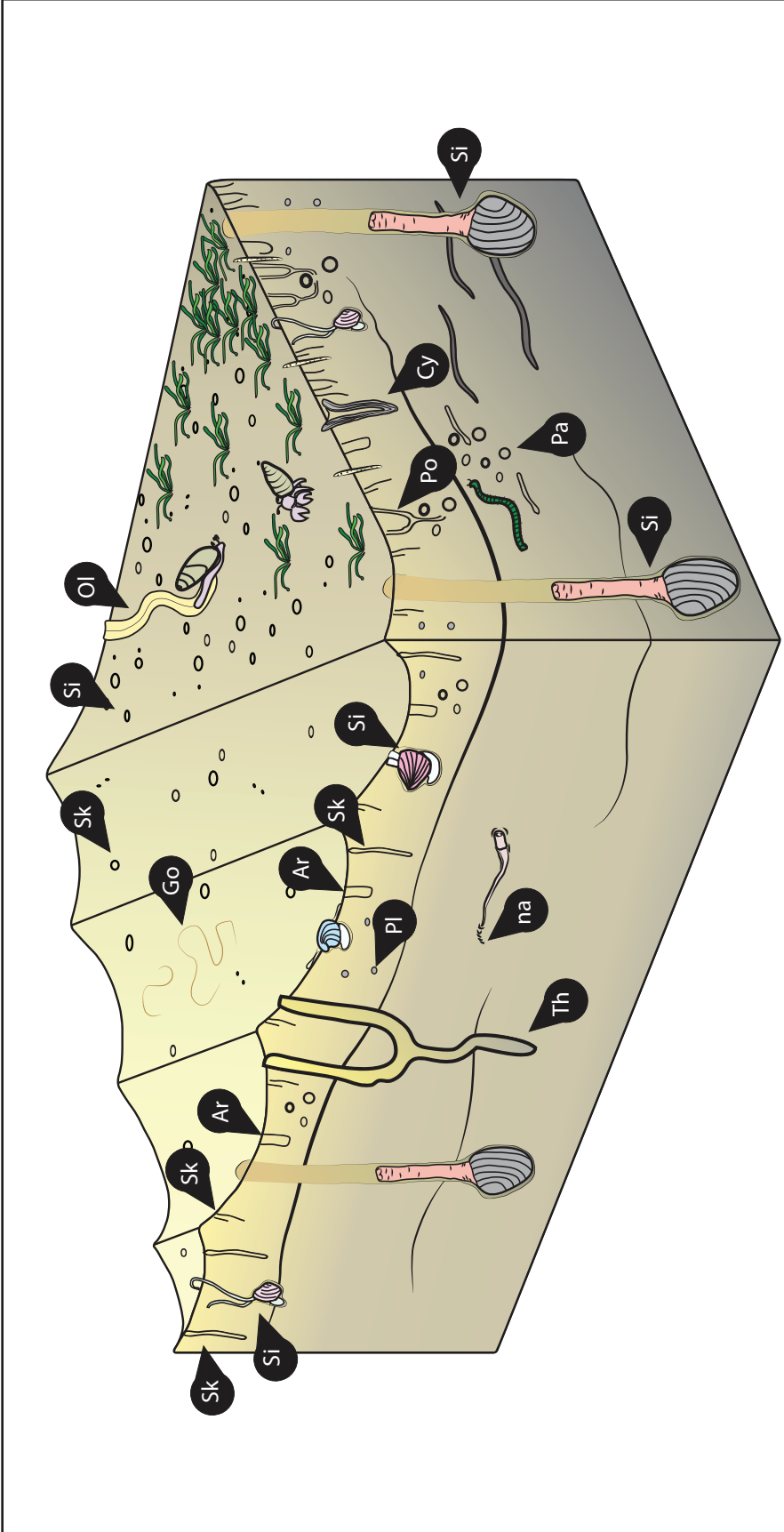
The protected upper intertidal flat zone displays an inclined planar surface with horizontal to inclined planar laminae within the subsurface. *Macaronichnus*-like traces are evident in the upper few centimetres of the subsurface with the likely tracemaker being the *Excrolana* sp. isopod as they hide in the substrate of the upper intertidal zone during low tide. There is a steady increase of dark very fine grained sand heavy mineral sand laminae upwards, reaching maximum accumulation along the upper intertidal flat-supratidal boundary where talitrid amphipods create small *Skolithos*-like burrows along the strandline.

**Outer-Middle Sandy Tidal Flat Bay Region** – This bay region, located in the eastern outer-middle portion of the bay, is similar to the Outer Sheltered Sandy Tidal Flat bay region in that it displays a tidal channel, extensive sandy intertidal flats and eelgrass fields with similar trace diversity, albeit greater trace abundances. Overall, it consists of a much more vast sandy tidal flat region affected by one main tidal channel compared to small sand flats and isolated

bars truncated by secondary tidal channels. The eelgrass zone is thus also more extensive and the expansive intertidal sandy flat is drained by multiple shallow, small to large, tidal creeks. In addition, a peaty-clay to compacted silty-sandy firmground zone exists along the eastern margin of the bay in stark contrast to the otherwise sandy environment. Five morphologic zones are delineated after the assessment of the five studied sub-environments for sedimentary and biogenic comparison purposes. These zones consist of the intertidal sand flat high zone, intertidal sand flat low zone, eelgrass field zone, the tidal creek-channel bank and ridge zone, and finally the firmground zone. A sedimentological summary of this bay region is provided in Table 2-5, while the neoichnological summary is provided in Table 2-6. Figure 2-70 is a block diagram that summarizes the overall sedimentary and biogenic features of the Outer-Middle Sandy Tidal Flat region.

The intertidal sand flat high zone is subject to substantial orbital wave motion during high tide and usually displays undulatory ridge and furrow like topography that is superimposed by sinuous to linguoid ripples displaying planar to wavy bedding in the subsurface. The degree of bioturbation in this zone is relatively low compared to the intertidal sand flat low zone. Very sporadic occurrences of filter feeding bivalves that generate *Siphonichnus*-like traces are encountered. The majority of traces are left by subsurface to interface deposit feeders such as threadworms and amphipods generating *Skolithos*-, *Arenicolites*-, and occasional *Planolites*-like traces. Sediment disruption features become more common towards lower lying regions, but is otherwise sparse.

The intertidal sand flat low zone is, to a larger degree, more shielded than the intertidal sand flat high zone from larger orbital wave velocities by the presence of the intertidal sand flat high zone itself and greater water depths at high tide. The surface is usually planar with the appearance of small, wave dominated ripples. The subsurface usually appears mottled due to bioturbation, especially ranging from 5-20cm below the sediment surface with



Modified after MacEachern et al. (2007)

**Figure 2-70: Schematic Block Diagram of the Outer-Middle Sandy Tidal Flat Bay Region.** Diagram displays wavy laminae to massive bedding in the subsurface. Traces labelled are akin to *Siphonichnus* (Si), unlined or lined *Skolithos* (Sk), *Thalassinoides* (Th), *Arenicolites* (Ar), *Cylindrichnus* (Cy), *Palaeophycus* (Pa), *Polykladichnus* (Po), *Planolites* (Pl), *Olivellites* (Ol), *Gordia* (Go), and *navicchia* (na).



wavy laminae usually only evident in the uppermost 5cm and planar laminae evident below 20cm. Organic laminae are also occasionally witnessed. The wavy laminae in the top few centimetres of sediment is likely the result of cyclical tidal reworking throughout each tidal cycle where sedimentation in this zone outweighs the amount of bioturbation that is able to take place. Whereas bioturbation is able to take over below this limit and destroy the primary sedimentary fabric. Below 20cm organisms would be subject to the reducing conditions below the redox potential discontinuity (RPD) layer and therefore would be unlikely to survive allowing for the preservation of primary planar laminae. *Skolithos*-, *Arenicolites*-, and occasional *Planolites*-like traces are also generated by threadworms and amphipods in this zone, although to a much more substantial degree with a marked increase in sediment disruption features and potential cryptic bioturbation. In addition, *Skolithos*-like traces may possess an oxidized hollow as the RPD layer is closer to the surface allowing for the generation of such features. Stable burrows of more sessile polychaetes also become common displaying *Palaeophycus*-, *Polykladichnus*- and even *Cylindrichnus*-like qualities. *Siphonichnus*-like traces generated by bivalves are still sporadic but are more prevalent becoming common in patchy areas.

The eelgrass field zone, like the eelgrass zones of the Outer Sheltered Sandy Tidal Flat zone, displays a planar to hummocky surface dominated by eelgrass that possesses a proportionately high abundance and high diversity of trace forms. As already mentioned the eelgrass fields form a protected lower energy environment with overall steady rates of sediment accumulation thereby allowing a wide variety of organisms and trace forms to occur. Due to the large amounts of bioturbation primary subsurface features are difficult, if not impossible, to delineate and manifest a mottled to massive appearance.

The tidal creek-channel bank and ridge zones are environments that quickly grade from an otherwise calmer intertidal flat environment to that of a higher velocity flow environment associated with a channel or creek, along a

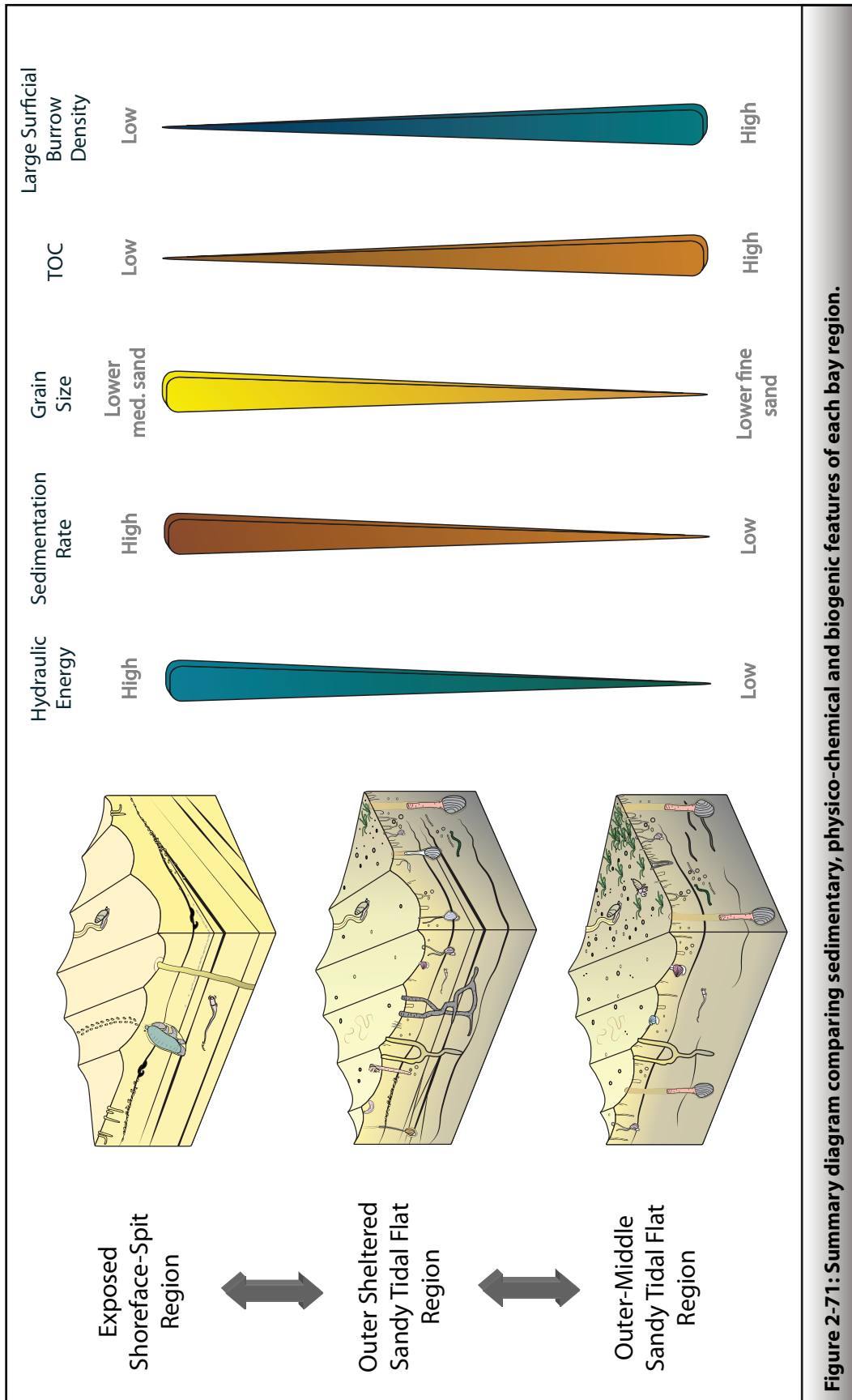
comparatively steeper dipping gradient. In the subsurface inclined planar laminae to tabular or trough cross ripple laminae occasionally displaying bidirectionality are evident. Tracemakers are sparse and usually include small unlined to lined *Skolithos*-like traces created by polychaetes. However, sparse short *Siphonichnus*-like traces of the filter feeding *Clinocardium nuttallii* are witnessed along with meandering surface *Olivellites*-like traces generated by the faster current preferring, trophic generalist *Olivella biplicata*. Scavengers such as shore crabs and hermit crabs may be found within tidal creeks generating potential *Psilonichnus*-like and spiral disruption traces, respectively. Clay clasts and lenses of clay and/or organic debris are commonly witnessed beneath the subsurface of tidal creeks, especially those possessing sparse eelgrass patches.

The firmground zone is a stark contrast from the sand dominated substrate witnessed throughout the rest of the bay region in this study. This firmground area is attributed to the substrate specific *Glossifungites* Ichnofacies, in contrast to the substrate controlled *Skolithos* or *Cruziana* Ichnofacies of the rest of the bay region. This zone is comprised of a compacted peaty-clay firmground layer and a compacted silty-sand firmground layer where certain organisms are able to burrow into. *Thalassinoides*- and *Psilonichnus*-like traces formed by decapod crustaceans are the more robust traces observable in these substrates with smaller *Skolithos*- and *Arenicolites*-like traces of spionid polychaetes and insect larvae evident. Sparse bivalve generated traces are also observed. Sporadic occurrences of *Teredolites* surfaces occur with *Skolithos*-, and *Thalassinoides* like traces created by burrowing polychaetes and bivalves. Due to the different substrate nature of this environment from the rest of the bay region it is subject to a separate, further in-depth analysis in the next chapter.

The majority of Netarts Bay is observed to display elements similar, but not directly attributable to a *Skolithos* Ichnofacies assemblage unless in the

Exposed shoreface-Spit region. A shift towards the exposed backshore regions causes an abrupt entry into the *Psilonichnus* Ichnofacies realm. Meanwhile, the calmer water laden tidal creeks and eelgrass fields subject to low to moderate hydraulic energy levels allow a gradation into elements similar but not directly comparable to trace attributable to the *Cruziana* Ichnofacies realm. Figure 2-71 compares the block diagrams of all three bay regions displaying the most common sedimentary and biogenic features of each region. It also shows trends in hydraulic energy levels, sedimentation rate, grain size, TOC, and surficial burrow density.

Traces attributable to an archetypal *Skolithos* Ichnofacies relates to areas of high hydraulic energy levels possessing clean, well-sorted, shifting sandy substrates as is common along the exposed spit and bay reaches of Netarts Bay. Abrupt shifts in sedimentation rates are common where higher energy levels allow physically generated sedimentary structures to overtake biogenically created structures (MacEachern et al., 2007). In the subsurface, horizontal to inclined parallel laminae, as well as trough cross laminae and current generated ripple cross laminae, are commonly associated in areas subject to the above conditions (MacEachern et al., 2007). This type of environment is commonly encountered along the foreshore terrace and foreshore zones along the exposed spit and beach areas. A similar moderate to high energy assemblage is witnessed within the tidal flats of outer Netarts Bay, but they possess their own unique association of traces that are neither attributable to a *Skolithos* or *Cruziana* Ichnofacies assemblage. Ichnologically speaking these environments are typically dominated by suspension feeding organisms that construct vertical, single entrance or U-shaped burrows in addition to branched forms (MacEachern et al., 2007). This sort of arrangement is typical along exposed, high intertidal sand flats and bars of Netarts Bay. The deep burrowing nature of such organisms serves to protect them from desiccation, salinity and temperature stresses associated with low tide and likely more importantly to the dynamic shifting nature of the upper few





centimetres of sediment due to moderate to high hydraulic energy levels (MacEachern et al., 2007). Passive carnivores may develop a limited number of horizontal burrows that ultimately develop a vertical component linking them to the sandy sediment-water interface (MacEachern et al., 2007). A low diversity of traces is commonly seen within the *Skolithos* Ichnofacies, and similar trace associations witnessed within the bay, where individual trace forms are potentially abundant (MacEachern et al., 2007). This is exhibited in Netarts Bay through the assemblage of abundant *Siphonichnus*-like and *Thalassinoides*-like traces on the higher sandy intertidal flats and exposed sandy intertidal bars of the outer bay. Limited deposit feeding structures associated with the *Skolithos* Ichnofacies is evident along the foreshore of Netarts spit by *Macaronichnus*-like traces likely associated with deposit feeding polychaetes or isopods. Trace associations comparable but not directly attributable to distal expressions of the *Skolithos* Ichnofacies arise in areas of abundant deposit feeding structures, in addition to sparse grazing structures, with significant proportions of suspension feeding structures still evident (MacEachern et al., 2007). *Skolithos*-, *Ophiomorpha*-, *Palaeophycus*-, *Arenicolites*-, *Siphonichnus*-, *Macaronichnus*-, and *Cylindrichnus*-like traces observed within Netarts Bay are common elements associated with the archetypal *Skolithos* Ichnofacies; however they form their own distinct assemblage that is not attributable to a *Skolithos* Ichnofacies assemblage. Trace assemblages resembling, but not attributable, to the distal expressions of the *Skolithos* Ichnofacies are observed in areas with abundant *Skolithos*-, *Ophiomorpha*- and *Palaeophycus*-like traces such as along exposed tidal channel margins of the bay. Deposit feeding structures associated with *Siphonichnus*-, *Macaronichnus*-, *Cylindrichnus*-, *Planolites*-, and *Thalassinoides*-like traces also resemble distal expressions of the *Skolithos* Ichnofacies across the Outer Sheltered Sandy Tidal Flat bay region and large areas of the Outer-Middle Sandy Tidal Flat bay region, but are not directly attributable to such an association as they form their own unique assemblage. The abundance of *Olivellites*-like grazing structures

produced by *Olivella biplicata* along water laden lows within high velocity areas or along tidal channel margins, in addition to *Gordia*- or *Crossopodia*-like grazing structures of amphipods is atypical of the archetypal *Skolithos* Ichnofacies model and therefore is more attributable to its own unique expression with slight similarities to the distal expression of the *Skolithos* Ichnofacies or proximal expression of the *Cruziana* Ichnofacies (MacEachern et al., 2007).

The *Cruziana* Ichnofacies is associated with a wide range of intergradational substrate types and in Netarts Bay a similar but distinct association is observed in sandy areas exhibiting accumulation of silt and organic detritus due to eelgrass baffling or other sudden decreases of hydraulic energy levels within eelgrass fields or tidal creeks. Beds are commonly bioturbated but in areas where sedimentary features are not completely destroyed oscillatory wave to current generated combined flow rippled sands and occasional planar laminae are evident in the subsurface within a protected fully marine bay type setting (MacEachern et al., 2007). Ichnologically speaking traces are a result of the availability of both suspended and deposited food materials in lower energy settings (MacEachern et al., 2007). There is a predominance of multiple deposit feeding modes as well as carnivorous or scavenging organisms in addition to small numbers of suspension feeding organisms (MacEachern et al., 2007). A variety of abundant and diverse structures thus results showing a wide range of horizontal through to vertical forms (MacEachern et al., 2007). *Siphonichnus*-, *Cylindrichnus*-, *Planolites*-, and *Thalassinoides*-like traces associated with the calmer areas of the Outer-Middle Sandy Tidal Flat bay region are forms that are similarly found associated with the *Cruziana* Ichnofacies, but in this study belong to their own unique assemblage of traces not attributable to the *Cruziana* Ichnofacies.

### **Preservation Potential and Applicability to the Rock Record**

The delicate balance between physical and biogenic reworking of sediment in association with net sedimentation rate determines the preservation potential of a bed (Wheatcroft, 1990; Gingras et al., 2007). The amount of time needed for an organism to alter its environment is dependant on the size of the organism, the type of burrowing behaviour used to obtain food resources, and the type of sediment these food resources are in (Gingras et al., 2007). In general organisms that need to employ far reaching food resource acquisition strategies, such as mobile deposit feeders and carnivores, disturb more sediment (Gingras et al., 2007). This is especially noticeable in sandy sediment relative to muddy sediment since organisms likely need to travel greater distances in sandy substrates to obtain an equal amount of food that they could have otherwise obtained in a smaller area in muddy substrates (Gingras et al., 2007). However, these types of biogenically altered beds and the amount of time taken to produce them may be masked by erosional or depositional forces associated with variable hydraulic energy levels and sedimentation rate allowing the assessment of preservation potential to become problematic (Gingras et al., 2007). Such an environment is characteristic of the Exposed Shoreface-Spiti bay region and along higher energy portions of the Outer Sheltered and Outer-Middle Sandy Tidal Flat bay regions. Therefore, the preservation potential of deposits observed in the study is difficult to ascertain. These environments, although usually associated with very low preservation potentials, may be present in the rock record although difficult to discern due to the lack of knowledge associated with the preservation potential of such environments. In a tectonically active environment, such as is the case along Netarts Bay, preservation potential may increase due to the mass emplacement of tsunami generated event beds over typical bay structures. Alternatively, many of the near surface traces would likely be obliterated but some may survive event bed deposition and subsequent burial for preservation within the rock record. Overall, the

preservation potential of deeper tiered traces is much higher than shallower ones (Dashtgard and Gingras, 2012). Also, firmer substrates are likely to be preserved over traces created in soupy or thixotropic sediments as the trace shape is quickly lost when the animal moves (Ekdale, 1985; Dashtgard and Gingras, 2012).

## **SUMMARY AND CONCLUSIONS**

Studying the behavioural response of organisms to varying hydraulic energy levels and associated sedimentation rate is important in order to deduce the integral link between burrowing behaviour and biogenic structures, especially in regards to potential rock record applicability. Higher hydraulic energy levels lead to higher levels of sedimentation (accumulation) or denudation (erosion). Various types of suspension feeding organisms, carnivores and scavengers are well suited for this type of dynamic environment where food resources are held in suspension within relatively clean water columns. However, if hydraulic energy levels become too high then there is a cessation of suspension feeding due to increased suspended sediment particles within the water column associated with higher rates of sedimentation thereby causing a shift towards deposit feeding behaviour. In regions of relatively low hydraulic energy levels there is a slow, but steady, accumulation of finer grained sediment due to lower sedimentation rates. A display of semi-permanent to permanent dwelling and feeding structures associated with interface and subsurface deposit feeding is common in lower energy environments where food resources are generally abundant within the sediment and across the sediment surface. This chapter focused on integrating the sedimentological and neoichnological aspects of three main middle to outer regions of Netarts Bay, in order to assess the effects of varying hydraulic energy levels and sedimentation rates on organismal distribution and behaviour within an exposed to protected fully marine environment.



The Exposed Shoreface-Spiti bay region, residing along the open ocean reaches around the recurved spit, encounters the highest hydraulic energy levels and highest rates of relative sedimentation compared to the other two bay regions. Sedimentologically, this region displays upper lower flow regime and upper flow regime bedforms. Sinuous to lunate dunes with superimposed ripples are common especially on the recurved spit and longshore bars. In higher energy areas, along the recurved spit and foreshore zones, plane beds with parting lineation are present. The region is dominated by mixed lower medium to upper fine-grained quartzo-feldspathic sand with noticeable portions of lower fine-grained heavy mineral sands concentrated at the foreshore-backshore boundary. Ichnologically, the region contains fewer organisms within a given area compared to the other bay regions due to the higher energy tumultuous nature of the environment. Carnivores, such as *Nephtys* sp. and *Cancer* sp., are sporadically common and leave very little trace evidence behind. *Nephtys* sp. leave sediment disruption features (navichnia) and potential cryptic bioturbation, while *Cancer* sp. are dominantly observed in tidal channels at the sediment surface or just beneath leaving no visible tracks in the constantly shifting substrate. Possible shallow residing, but rapid burrowing, suspension feeding bivalves may be present in large shallow tidal inlets creating *Skolithos*- to *Siphonichnus*-like traces and possible fugichnia or equilibrichnia in response to sediment aggradation/erosion along the bedding surface. The suspension feeding *Emerita analoga* is sporadically found along the surf-swash zone boundary usually just below the sediment surface in temporary burrows or shuffling quickly along the sediment surface to a new burrow location. The temporary burrows and tracks of these organisms are easily erased by the next incoming tide. The foreshore consists of *Macaronichnus*-like traces created by unknown tracemakers that are hypothesized to be various subsurface deposit feeding and/or scavenging *Excirolana* sp. isopods or opheliid polychaetes. Finally the foreshore-backshore

boundary consisted of scavenging talitrid amphipods and beetles that created *Skolithos*- to diminutive *Psilonichnus*-like traces.

Bayward of the main tidal inlet along the northern tip of the spit is the Outer Sheltered Sandy Tidal Flat bay region. The highest energy levels within the region are associated with secondary tidal channels that separate the different sub-environments. Isolated tidal flat bar systems with prominent tidal channel ridges are bordered by these secondary tidal channels and experience moderate to high energy levels where bidirectional cross laminae are evident in the subsurface. In the more sheltered areas bound by the upper intertidal flat-supratidal zone along the spit on one end and a secondary tidal channel on the other are undulatory sandy tidal flat highs, and sandy planar eelgrass flat lows, each experiencing moderate to low energy levels, respectively. Upper fine-grained sand is the dominant grain size of this region with highest TOC levels associated with fields of eelgrass. In areas of moderate to high energy, such as tidal channel margins, isolated sand flats and even large parts of the protected sand flat highs, suspension feeding organisms or deposit feeding generalists capable of switching feeding modes are present. Examples of such organisms include *Olivella biplicata*, *Neotrypaea californiensis*, *Macoma* sp. and *Corophium* sp., where these organisms create a multitude of different traces akin to *Olivellites*, *Thalassinoides*, *Siphonichnus*, *Skolithos* and *Arenicolites*. Many of the polychaetes that construct lined *Skolithos*-like tubes along protected tidal channel margins can also switch between interface deposit feeding and suspension feeding modes. Larger, and arguably more robust, traces are characteristic of these moderate to high energy zones, with burrow lining evident along the higher energy areas for burrow support. In moderate to lower energy areas consisting of eelgrass, and along the more protected reaches of the sand flat highs, there is an abundance of relatively immobile suspension feeding bivalves, many of which are deep burrowing and unable to move any appreciable degree in the substrate. Deposit feeding organisms such as a variety of polychaetes that regularly subsurface or interface deposit

feed are also present. *Upogebia pugettensis* was also found amongst the eelgrass and lower energy sand flat highs possessing abundant microalgae. Common traces of these lower energy areas were akin to *Siphonichnus*, *Skolithos*, *Trichichnus*, *Arenicolites*, *Planolites*, *Polykladichnus*, *Palaeophycus*, and *Thalassinoides*. "Cleaner" surficial sands are evident near tidal creeks and on isolated tidal bars where water velocity is higher, while organic detritus and microalgae are much more abundant on the surface of protected lower energy areas.

Finally, towards the eastern middle portions of the bay is the Outer-Middle Sandy Tidal Flat bay region comprised of extensive sand flats, tidal creeks and firmground areas. This region is similar to the Outer Sheltered Sandy Tidal Flat bay region, but is cross-cut by more tidal creeks instead of tidal channels. It is also comprised of slightly finer grain sizes where upper fine-grained sand still dominates, but with a noticeable portion of lower fine-grained sand also becoming common. Highest TOC values are associated with eelgrass fields and firmground areas. This region is dominated by large amplitude, undulatory topography with superimposed sinuous to linguoid ripples. The eelgrass fields are much more extensive than those along the Outer Sheltered Sandy Tidal Flat bay region with the sediment surface in general also displaying more organic detritus. Moderate energy levels typically occur throughout most of the Outer-Middle Sandy Tidal Flat bay region with some lower energy areas occurring near the eastern margin of the bay and higher energy areas occurring near large tidal creeks and the main tidal channel. Ichnologically, this region was found to be similar to the eelgrass assemblage of the Outer Sheltered Sandy Tidal flat bay region where there is an abundance of relatively immobile, deeper burrowing, suspension feeding bivalves that create *Siphonichnus*-like or large *Skolithos*-like traces. Highest concentrations of these bivalves occurred in and around eelgrass beds that offer higher food resource acquisition from eelgrass baffling and protection from higher energy levels. An array of surface, interface and subsurface deposit

feeding animals are also associated with these eelgrass fields creating traces akin to *Olivellites*, *Gordia*, *Skolithos*, *Arenicolites*, *Planolites*, *Polykladichnus*, and *Palaeophycus*. On the more barren sand flats the same mixed trace assemblage of relatively immobile suspension feeders and deposit feeders is observed but to a more sporadic degree. Tube worms possessing suspension feeding and interface deposit feeding capabilities, forming lined *Skolithos*- and *Cylindrichnus*-like traces, are found close to tidal creeks where tidal currents are high enough to provide food in suspension but also low enough to offer a stable environment in which the worms can establish themselves.

This chapter therefore concluded that the majority of Netarts Bay displays elements similar to the *Skolithos* Ichnofacies. Along the Exposed Shoreface-Spits region trace associations can possibly be attributable to a *Skolithos* Ichnofacies assemblage but most of the study area has its own unique association of traces that may be similar to a *Skolithos* Ichnofacies assemblage but is not attributable to one. An abrupt entry into elements similarly attributed to a *Psilonichnus* Ichnofacies assemblage occurs upon entry into the backshore regions along the spit. Meanwhile, calmer areas subject to relatively low hydraulic energy levels, such as in water laden tidal creeks and eelgrass fields, allow a gradational change into characteristics that may show commonalities with those of the lower energy *Cruziana* Ichnofacies, but are themselves distinct entities not attributable to a *Cruziana* Ichnofacies assemblage. A more extensive study, including the inner reaches of the bay, should be assessed to allow further interpretation of trace distribution in association with a fully marine environment. Determining preservation potential of such an environment is potentially limited as the amount of time taken to produce biogenically altered beds may be masked by erosional or depositional forces associated with variable hydraulic energy levels and sedimentation rate. Fully marine embayments, although usually associated with low preservation potentials especially along the higher energy zones of the barrier spit, may be represented in the rock record to a greater degree than



originally thought. However, these features may be difficult to discern due to the lack of knowledge associated with the preservation potential and trace distributions of such an environment. Additionally, many individuals looking at well log data commonly make the mistake of interpreting fining upward tidal flat successions as channel deposits (Pemberton, pers. comm., 2013).

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### **CHAPTER 3: SPATIAL, TEMPORAL, AND PALEOECOLOGICAL SIGNIFICANCE OF EXHUMED, COMPACT FIRM-GROUNDS AND OTHER ASSOCIATED SUBSTRATE TYPES IN NETARTS BAY, OREGON**

#### **INTRODUCTION**

Studying the trace making behaviour of modern organisms in relation to various physico-chemical stressors is important to aid in furthering our understanding of similar biogenically created structures in the rock record. Various physico-chemical stresses include, but are not limited to; substrate consistency, sediment cohesiveness, food resource availability, hydraulic energy conditions, sedimentation rate, salinity fluctuations, oxygen content, water turbidity, temperature, and desiccation (Gingras et al., 2007; MacEachern et al., 2010). Sediment consistency and texture are the main controls affecting animal burrowing behaviour (Gingras et al., 2007). Studying substrate-controlled ichnofacies such as the *Glossifungites* and *Teredolites* ichnofacies is therefore an important endeavour to partake.

The original *Glossifungites* Ichnofacies was originated by Seilacher (1964; 1967) and subsequently redefined by Frey and Seilacher (1980) as belonging to firm but unlithified marine substrates. Traces attributable to a *Glossifungites* assemblage are usually robust, sharp walled, unlined and passively infilled by sediment differing from the original sediment in which the trace was created in (Seilacher, 1967; Pemberton and Frey, 1985; MacEachern et al., 1992; MacEachern et al., 2007). The applicable distribution of the *Glossifungites* Ichnofacies has expanded profusely (Pemberton and MacEachern, 1995; MacEachern and Burton, 2000) including environments such as: intertidal wave ravinement and channel erosion zones (Frey and Seilacher, 1980; Pemberton and Frey, 1985; Gingras et al., 2001), estuarine incised valleys (Savrda, 1991; MacEachern and Pemberton, 1994) and even into bathyal (Hayward, 1976; Bromley and Allouf, 1992) zones. Thus, surfaces associated with the *Glossifungites* ichnofacies may be of sequence stratigraphic importance and a

worthwhile study (MacEachern et al., 1992; Pemberton and MacEachern 1995; MacEachern et al., 2007).

The *Teredolites* Ichnofacies occurs in xylic (woody) substrates in a marine to marginal marine setting where the substrate has to consist of *in situ* material (Bromley et al., 1984, Savrda, 1991). However, Savrda et al. (1993) used the term log-grounds for large concentrations of allochthonously sourced woody material distributed across a depositional surface (MacEachern et al., 2007). *Teredolites*-like traces are what define the *Teredolites* Ichnofacies assemblage and are usually the only traces preserved in the rock record (MacEachern et al., 2007). However, recent modern studies conducted by Gingras et al. (2004) brought to light the diverse array of traces associated with *Teredolites* suites indicating that such an abundance of traces is likely lost due to erosion over time and therefore not commonly preserved in the rock record. *Teredolites* surfaces, like *Glossifungites* surfaces, have been linked to marine transgressive surfaces and consequently are of potentially significant value to the field of sequence stratigraphy.

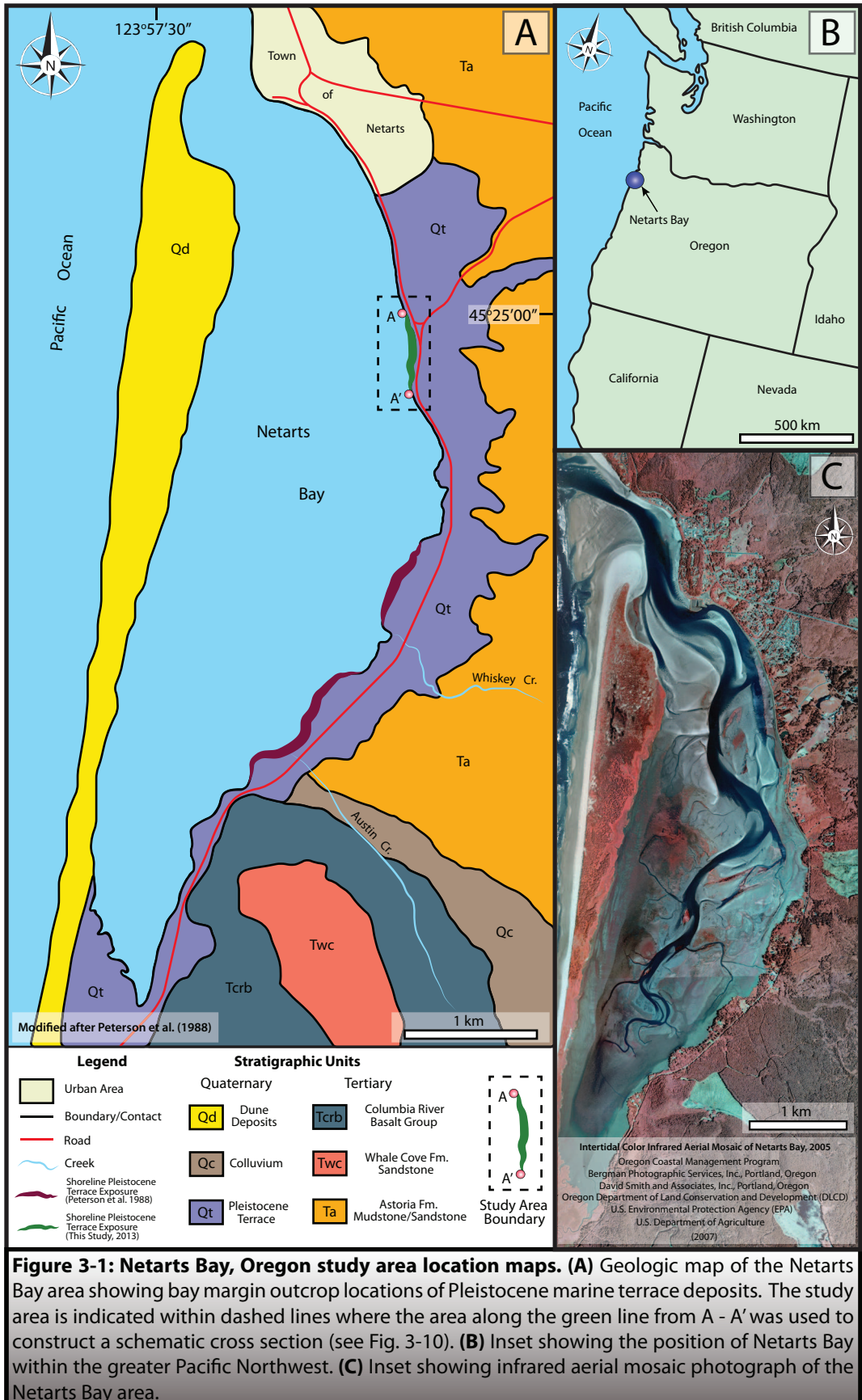
Trace genesis and the resultant burrow architecture, density and depth are related to various physico-chemical conditions that were present at the time of firmground colonization (Gingras et al., 2001). Undoubtedly, the study of paleoecological information concerning *Glossifungites* suites is just as important as the potential sequence stratigraphic value that they may hold, although the value of paleoecology is unfortunately often overshadowed (Gingras et al., 2001). This study aims to assess the nature of associated softground, stiffground, firmground and woodground substrate occurrences in a modern intertidal marine environment. The various sedimentological and neoichnological data obtained particular to each substrate will help ascertain the individual trace assemblage potentially unique to each environment. The stratigraphic importance of potential surfaces will also be assessed.

## SETTING

Netarts Bay, Oregon is a fully marine, temperate, well mixed, wave-dominated, tidally-influenced, micro- to meso-tidal lagoon or embayment along the northern Oregon coastline approximately 90km south of the Columbia River mouth (Fig. 3-1). The bay is greatly protected from the onslaught of mighty waves off the adjacent Pacific Ocean by a 6km long NNE trending sand spit stabilized by European beach grass and sporadic tree cover (Bonacker et al., 1979). The bay encompasses an area approximately 9.4km<sup>2</sup> where one main narrow tidal channel, approximately 100m wide, enters the bay along the northern end of the spit (Glanzman et al., 1971). Smaller secondary tidal channels also meander between the large sandy tidal flats. The rest of the bay is therefore occupied at low tide by vast, mainly sandy tidal flats in addition to muddy silty flats of the far southern reaches of the bay. The entire watershed for the bay is quite small being only about 41km<sup>2</sup>, having 12-16 intermittent creeks that feed the bay (Glanzman et al., 1971). This factor, in addition to the rapid flushing rate over 1.34 tidal cycles, leads to essentially fully marine conditions within the bay (Shabica et al., 1976). Dominant swell directions during both summer and winter months are generally from the NW-W direction while the overall seas generally come in from the SW-SSE in the winter and N-NW in the summer (Glanzman et al., 1971; Peterson et al., 1986). Wind generated waves within the bay are typically around 0.4m in height, but can attain heights of up to 1.5m under very strong, consistently windy conditions at high tide (Glanzman et al., 1971).

Cape Meares and Cape Lookout, bounding the northern and southern ends of the bay, respectively, are resistant basaltic headlands that were extruded 15 to 20 million years ago (Shabica et al., 1976; Bonacker et al., 1979). Formation of these headlands was penecontemporaneous with the extrusion of the Columbia River Gorge basalts and deposition of shallow coastal sands that would later form the sandstones of the surrounding Astoria Formation (Shabica et al., 1976; Bonacker et al., 1979). During the late Oligocene, at





around approximately 25 millions years ago, a small syncline developed in and around the area of Netarts Bay (Shabica et al., 1976). Differential erosion of Astoria Formation sandstones between the two basaltic headlands occurred during periods of Pleistocene sea level highstands producing a re-entrant along the coastline where Netarts Bay currently resides (Hunger, 1966; Shabica et al., 1976; Bonacker et al., 1979; Peterson et al., 1988). During this time Pleistocene marine terraces developed in a relatively sheltered depositional setting (Peterson et al., 1988). A series of at least five mappable Pleistocene marine terrace deposits 42,000 to 220,000 years old appear discontinuously along the Washington-Oregon coastline (West and McCrumb, 1988). The Whiskey Run terrace is the most continuous Pleistocene marine terrace line witnessed along the coast where it varies little in elevation (West and McCrumb, 1988).

## **METHODOLOGY**

Research was conducted along the eastern margin of Netarts Bay during the spring of 2013. Access to the study site was accomplished via automobile and by foot. Important location information was recorded via a Garmin eTrek 20 GPS unit. Detailed surface and subsurface descriptions of biogenic and sedimentary structures were recorded in a notebook and subsequent photos were also taken using a Canon Digital Rebel XSi 12.2 MP SLR camera. Shovels and clam corers were used to dig trenches and observe sedimentary features.

Epoxy resin casts of modern *Upogebia pugettensis* and *Hemigrapsus* spp. traces were obtained to aid in specific identification and interpretation of these biogenic structures. Sample organisms obtained were stored in glass jars and preserved using 80% ethyl alcohol for further analysis and classification at the University of Alberta.

Two boxcores, with dimensions 30cm x 21cm x 6cm, were also taken to assess more detailed sedimentary structures after being shipped to University of Alberta labs. Sediment samples, each 350-500 grams in size, were also taken

from the upper 5cm of sediment by hand and shipped back to the University of Alberta for grain size analysis. During initial stages of analysis sediment was dried for 24 hours at 110°C in a Quincy Lab Incorporated Model 21-250 Bench Oven. Each sediment sample was then lightly ground for three minutes using mortar and pestle to separate grain clumps. A portion of the sediment sample was set aside for TOC (total organic carbon) analysis while the remaining amount was then weighed for an initial grain size using a Mettler AE100 scale. The grain size analysis sample was then added to a stack of Fisher Scientific test sieves ranging from US Std. No. 10 to US Std. No. 230. The sieve stack was shaken in a Hostein Model RX-29 scientific sieve shaker for 10 minutes. Each sieve receiver was then weighed using the previously mentioned Mettler scale and recorded under its respective grain size column in an excel spreadsheet. The process of drying, initial weighing, sieve shaking, and sieve receiver weighing was repeated for each sediment sample obtained. Any samples that had considerable portions of silt to clay sized materials were also passed through a Micrometrics Sedigraph 5100 machine to ascertain the specific amounts of silt and clay. TOC analysis was conducted on pre-dried samples as previously mentioned where the sediment sample was then added to a small porcelain crucible for initial weight recording. After which the sample and porcelain crucible were put inside an SLE Omega CN76000 oven set at 550°C for 12 hours where a loss on ignition of organic carbon took place. After 12 hours the sediment and crucible were removed from the oven and left to cool down to room temperature (21°C) before final weight was recorded. Sediment was also analyzed via XRD (X-ray diffraction) at the University of Alberta to delineate specific minerals within each sample.

Substrate firmness measurements, using the modified Brinell firmness test as outlined in Gingras et al. (2000a), were conducted on the various substrate types across the study area. The diameter and mass of the ball used for the test was 0.025m and 0.068kg, respectively. The drop height was consistently conducted from 0.3m above the sediment surface.

## RESULTS

### Exhumed Compacted Peaty-Clay Firmground

#### *Firmground Spatial Geometry and Sediment Characteristics*

A shore-parallel, exhumed compacted peaty-clay firmground is sporadically exposed along the eastern margin of Netarts Bay, particularly alongside the designated clam digging staging areas (Fig. 3-1A). There appears to be a stepwise topography to this firmground with the more bayward lower step portions covered by a surface veneer of sediment, averaging 30 cm in thickness over the area studied. The compacted peaty-clay surface is typically between 10 cm and 15 cm thick and is dark purple-grey in colour. A firm clay layer typically exists directly below the compacted peaty-clay where the firm clay then grades into fine silty sand with increasing depth before potentially encountering another compacted peaty-clay layer (Table 3-1). The clay is typically dark grey-green in colour with occasional orange to red oxidized patches, usually present as burrow halos (Fig. 3-2). Large burrows wholly penetrate the surface while smaller burrows only partially penetrate the surface, or are observed along the multiple horizontal fracture planes (Fig. 3-2, Fig. 3-3). Assessment of minerals within the peaty-clay layer by XRD analysis yielded quartz, albite, microcline, muscovite, clinocllore, vivianite, pyrite, and beidellite. Quartz, albite, anorthite, clinopyroxene, microcline, ferro-actinolite, and dickite were the minerals in zones of oxidized clay next to the peaty-clay layers as defined by XRD analysis. XRD analysis also yielded the evaporative minerals halite, bloedite and anhydrite; however caution needs to be noted for this finding. The original sample had retained marine water and it was noticed that a slight salty crust had developed around the sample when it was studied further in the lab, so therefore the presence of these minerals may be an artefact of post removal sediment desiccation. Samples were also dried in an oven at 110°C before being prepped for XRD analysis potentially augmenting the apparent presence of evaporites. Total organic carbon (TOC) content of the peaty-clay portion of the firmground ranged from 5.35-8.29%, while the total

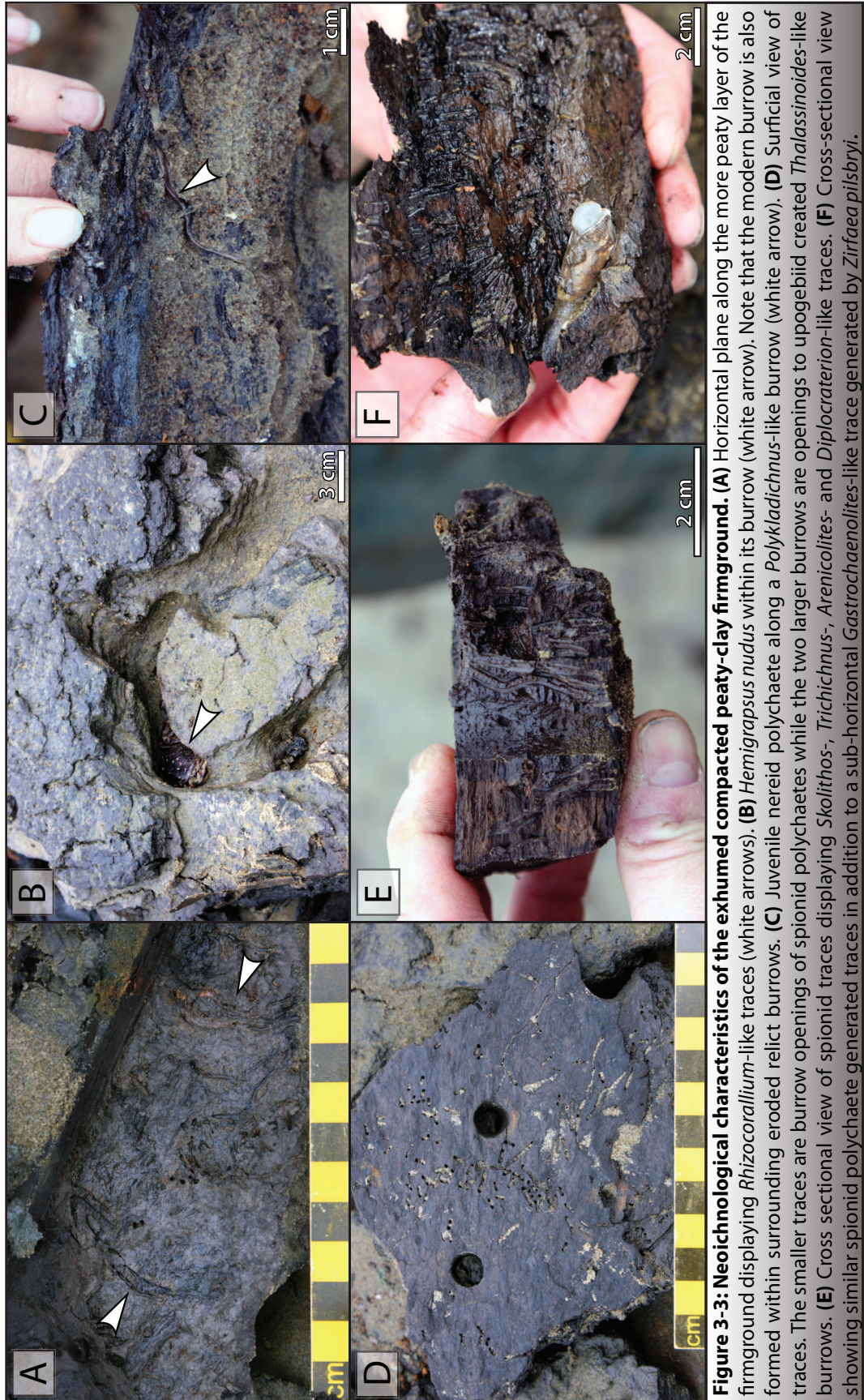


Table 3-1: Sedimentological and Neoichnological Summary of the Various Substrate Types						
Substrate Type	Substrate Description	Average TOC	Firmness	Burrow Density	Comparable Burrow Types	Observed Tracemakers
<b>Exhumed Compacted Peaty-Clay Firmground</b>	Surficial organic peaty clay layer grading into silty-sand with depth.	Peaty-Clay layer 5.35-8.29% Clay layer 0.76-2.99%	Range 1.28 x 10 <sup>6</sup> Pa - 2.16 x 10 <sup>6</sup> Pa Average 1.65 x 10 <sup>6</sup> Pa	Large (≥2mm) 30-41/50cm <sup>2</sup> Small (<2mm) 0-3/10cm <sup>2</sup> up to 52/10cm <sup>2</sup>	<i>Thalassinoides</i> , <i>Psilonichnus</i> , <i>Gastrochaenolites</i> , <i>Skolithos</i> , <i>Trichichnus</i> , <i>Arenicolites</i> , <i>Diplocraterion</i> , <i>Rhizocorallium</i> , <i>Polykladichnus</i>	<i>Zirfaea pilsbryi</i> , <i>Hemigrapsus</i> spp., <i>Upogebia pugettensis</i> , <i>Polydora</i> sp., <i>Nereis</i> sp.?
<b>Exhumed Compacted Silty-Sand Firmground</b>	>50% fine sand, 10% very fine sand, 15% silt/clay. Appears as homogeneously mixed silt and sand.	1.20%	Range 1.65 x 10 <sup>6</sup> Pa - 2.77 x 10 <sup>6</sup> Pa Average 2.08 x 10 <sup>6</sup> Pa	Large (≥2mm) 35-115/50cm <sup>2</sup> Small (<2mm) 11-43/10cm <sup>2</sup>	<i>Thalassinoides</i> , <i>Psilonichnus</i> , <i>Skolithos</i> , <i>Trichichnus</i> , <i>Arenicolites</i> , <i>Polykladichnus</i>	<i>Hemigrapsus</i> spp., <i>Upogebia</i> <i>pugettensis</i> , <i>Polydora</i> sp., <i>Nereis</i> sp., glycerid polychaetes, beetle and insect larvae
<b>Modern Silty Sand to Clay Stiffgrounds</b>	>50% fine sand, 13% very fine sand, 14% silt/clay. Distinct sand and clay layers.	North 0.78-1.28% South Top: 0.85% Bottom: 3.30%	Range 1.37 x 10 <sup>5</sup> Pa - 2.44 x 10 <sup>6</sup> Pa Average 4.53 x 10 <sup>5</sup> Pa	Large (≥2mm) 33/50cm <sup>2</sup> Small (<2mm) Non-discernible	<i>Thalassinoides</i> , <i>Skolithos</i> , <i>Trichichnus</i> , <i>Arenicolites</i> , <i>Meandropolydora</i> , <i>Rhizocorallium</i>	<i>Upogebia pugettensis</i> , threadworms, <i>Polydora</i> sp.
<b>Surficial Softground Veneer</b>	Dominantly fine sand	Top 0.38% Bottom 0.45%	Range 8.60 x 10 <sup>4</sup> Pa - 3.73 x 10 <sup>5</sup> Pa Average 1.73 x 10 <sup>5</sup> Pa	Large (≥2mm) 58-96/50cm <sup>2</sup> Small (<2mm) 0-6/10cm <sup>2</sup>	<i>Gordia</i> , <i>Diplichnites</i> , <i>Protichnites</i> , <i>Olivellites</i> , <i>Skolithos</i> , <i>Trichichnus</i> , <i>Arenicolites</i> , <i>Polykladichnus</i> , <i>Rhizocorallium</i> , <i>Planolites</i> , <i>Gyalithes</i> , <i>Palaeophycus</i> , <i>Thalassinoides</i> , <i>Psilonichnus</i> , <i>Piscichnus</i>	<i>Hemigrapsus</i> spp., <i>Upogebia</i> <i>pugettensis</i> , <i>Polydora</i> sp., <i>Nereis</i> sp., glycerids, threadworms, <i>Saccoglossus</i> sp., <i>Nephtys</i> sp., <i>Abarenicola pacifica</i> , <i>Corophium</i> sp., <i>Olivella biplicata</i> , <i>Pagurus</i> sp., <i>Eupolytmia</i> sp.
<b>Woodground</b>	Xylic (woody) material	Not Applicable	Not Applicable	Large (≥2mm) 9/50cm <sup>2</sup> Small (<2mm) 63/10cm <sup>2</sup>	<i>Teredolites</i> , <i>Thalassinoides</i> , <i>Psilonichnus</i> , <i>Skolithos</i> , <i>Trichichnus</i> , <i>Arenicolites</i> , <i>Caulostrepsis</i> , <i>Meandropolydora</i> , <i>Trypanites</i>	<i>Hemigrapsus</i> spp., <i>Upogebia</i> <i>pugettensis</i> , <i>Polydora</i> sp., limnonid isopods, tereidenid bivalve



**Figure 3-2: Sedimentological features of the exhumed compacted peaty-clay firmground. (A)** Plan view of the peaty-clay firmground surface. Note multiple burrow openings that are large and unlined. Machete for scale is approximately 62cm long. **(B)** Cross-sectional trench view of the peat-clay firmground. Note the upogebiid generated burrows (white arrows) that are connected to a *Thalassinoides*-like network. Trench is ~25 cm deep.





**Figure 3-3: Neolithic characteristics of the exhumed compacted peaty-clay firmground.** (A) Horizontal plane along the more peaty layer of the firmground displaying *Rhizocorallium*-like traces (white arrows). (B) *Hemigrapsus nudus* within its burrow (white arrow). Note that the modern burrow is also formed within surrounding eroded relict burrows. (C) Juvenile nereid polychaete along a *Polykladichnus*-like burrow (white arrow). (D) Surficial view of traces. The smaller traces are burrow openings of spionid polychaetes while the two larger burrows are openings to upogebiid created *Thalassinoides*-like burrows. (E) Cross sectional view of spionid traces displaying *Skolithos*-, *Trichichnus*-, *Arenicolites*- and *Diplocraterion*-like traces. (F) Cross-sectional view showing similar spionid polychaete generated traces in addition to a sub-horizontal *Gastrochaenolites*-like trace generated by *Zirfaea pilsbryi*.

organic carbon of the clay portion of the firmground ranged from 0.76-2.99% (Table 3-1). Firmness measurements from the modified Brinell firmness tests of the peaty-clay firmground ranged from  $1.28 \times 10^6$  Pa to  $2.16 \times 10^6$  Pa, with an overall average of  $1.65 \times 10^6$  Pa (Table 3-1). The slightly firmer measurements occurred in areas that were observed to have higher organic, more compact, drier peaty-clay content relative to essentially inorganic clay.

### ***Neoichnological Characteristics***

The most evident traces within the peaty-clay firmground assemblage are the larger traces created by *Upogebia pugettensis* and *Hemigrapsus nudus*, as well as *Hemigrapsus oregonensis* (Fig. 3-2, Fig. 3-3). *Upogebia pugettensis* commonly create large (approximately 1.5-3 cm in diameter), unlined to slightly lined, Y-shaped *Thalassinoides*-like traces within the firmground (Fig. 3-2). Typically these traces cross cut any veneered sediment to reach the sediment-water interface above and penetrate the thin firmground layer to the silty clay layer below, as the traces are commonly 50 cm in continuous length (Fig. 3-2B). *Hemigrapsus* spp. create large, unlined (approximately 2.5-4 cm in diameter), *Psilonichnus*-like traces (Fig. 3-3B). These traces also typically cross cut any veneered sediment above and clay to silty sand sediment below, although these burrows do not penetrate as deep as those created by *U. pugettensis*, commonly only penetrating up to 5 cm below the compact organic, peaty-clay layer. Hermit crabs of the genus *Pagurus* are also casually observed within firmground burrows, often those created by *Hemigrapsus* spp., as they likely do not produce any burrows themselves and act as squatters within abandoned burrows. There also appears to be relict *Thalassinoides*-like and *Psilonichnus*-like burrows within the firmground in addition to the modern ones previously described (Fig. 3-2A, Fig. 3-3B). These relict burrows have been eroded where some have been passively infilled with sediment, while the remainder act as potential conduits and burrow starter systems for present day organisms residing within the firmground surface. Relatively large



(approximately 0.5-1.5 cm in diameter), unlined, open clavate structures akin to *Gastrochaenolites* produced by the bivalve *Zirfaea pilsbryi* are also present within the peaty-clay portion of the firmground; however they are usually hidden from surface view and do not initially appear as prominent features unless observing a cross sectional view or the under-plane of a horizontally fractured surface of the compact firmground (Fig. 3-3F). Acorn barnacles are sporadically encrusted onto the exposed peaty-clay firmground surface. Large ( $\geq 2$  mm in diameter), open burrows of the peaty-clay firmground had density values ranging from 30-41/50 cm<sup>2</sup> (Table 3-1).

At a closer glance burrows approximately 1 mm in diameter are observed in patchy occurrences along the firmground surface. In the subsurface these vertical, unlined to slightly mucous lined structures are typically U-shaped with an *Arenicolites*-like or possibly even rarely *Diplocraterion*-like appearance, with some small *Skolithos*-like or *Trichichnus*-like traces also apparent, penetrating 5-10 cm below the sediment surface (Fig. 3-3D,E,F). The U-shaped burrows are inclusively 3-4 mm across translating into the surface expression of two side-by-side 1 mm open burrows separated by 1-2 mm (Fig. 3-3D). Spionid worms of the genus *Polydora* produce these burrows. Further investigation of the peaty-clay firmground yielded observations of horizontal to sub-horizontal spionid produced burrows along horizontal fracture planes of the peaty-clay surface (Fig. 3-3A). These burrows are *Arenicolites*-like in appearance with some displaying rare *Rhizocorallium*-like appearances (Fig. 3-3A). Densities of these small (<2 mm in diameter) burrow openings were typically between 0 - 3/10 cm<sup>2</sup>, although patchy occurrences of burrow openings with densities of up to 52/10 cm<sup>2</sup> were observed (Table 3-1). Small nereid polychaetes were sporadically witnessed creating mainly horizontal to slight *Polykladichnus*-like burrows within the clay to silty sand layer below (Fig. 3-3C).

## **Exhumed Compacted Silty Sand Firmground**

### ***Firmground Spatial Geometry and Sediment Characteristics***

The exhumed compacted silty-sand firmground, like the peaty-clay firmground, is also shore parallel containing an abundance of large, open burrows, and is also highly eroded in many parts (Fig. 3-4A). In the northern half of the bay an extension of the main channel abuts up against a man made boulder embankment leading to the cessation of subaerially exposed firmgrounds. An exposed scarp along a small salt marsh patch, approximately 1.5m thick on average, located just north of an anthropogenically altered creek outlet revealed it to be lying on top of compact silty-sand firmground deposits. The compact, beige coloured, silty-sand firmground is occasionally located directly above the peaty-clay layer; however this association may be more laterally continuous than first appears since the peaty-clay firmground is hidden, in some instances, by a surface veneer of sediment that also partially covers the lower parts of the silty-sand firmground. In contrast to the peaty-clay firmground, the silty-sand firmground does not progress as bayward as the former and is considerably thicker than the peaty-clay firmground with an average exposed thickness of 60cm (Fig. 3-4A). If the sediment along a scarp face of the firmground is gently scraped away then faint parallel laminae are observable (Fig. 3-4A). Occasionally, very solid iron oxide pipe structures are encountered on the flanks of the silty-sand firmground (Fig. 3-4B). Fine grained sands comprise the bulk grain size character of the silty-sand firmground with sizable proportions of grains fewer than 63 microns in diameter (silt to clay) with noticeable very fine sands also present (Table 3-1). Dominant mineral grains of the silty-sand firmground, as delineated by XRD analysis, are quartz, albite, fluororichterite, goethite, magnesite, and siderite. Total organic carbon content of the silty-sand that comprises the firmground was measured at 1.20% (Table 3-1). This TOC measurement was obtained from a freshly, exposed clean sample to obtain a bulk TOC measurement, as most of the surface is comprised of an algal film that would most likely give rise to



**Figure 3-4: Morphological and sedimentological features of the exhumed compacted silty-sand firmground. (A)** Thick exposure of silty-sand firmground along a secondary tidal channel bank. Modern and relict burrows riddle the surface. Sand laminae are noticeably differentially eroded. Surface was cut away as seen in the left of the photo to observe the laminae along a fresh surface. Scale in photo is 15cm long. **(B)** Iron oxide spring pipes are common features along the silty-sand firmground in the southern end of the study area.

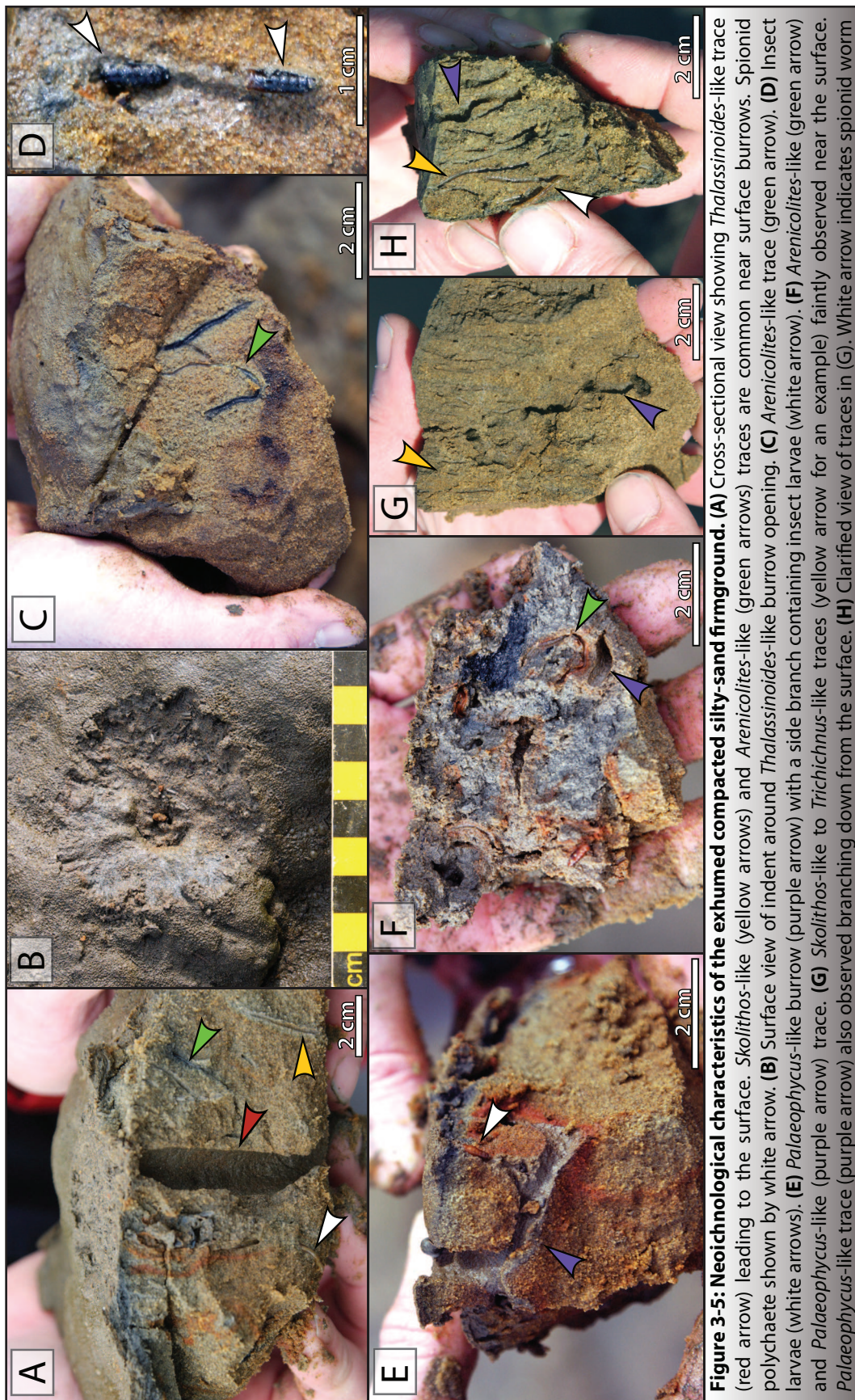
increased TOC values that would only be superficially accurate. Firmness measurements from the modified Brinell firmness tests of the silty-sand firmground ranged from  $1.65 \times 10^6$  Pa to  $2.77 \times 10^6$  Pa, with an overall average of  $2.08 \times 10^6$  Pa (Table 3-1). The slightly firmer measurements were observed closer to the silty-sand firmground plateau margins compared to the firmground plateau centre.

### ***Neoichnological Characteristics***

Multiple relict *Thalassinoides*-like and to some extent *Psilonichnus*-like burrows characterize the silty-sand firmground surface, especially along exposed scarp faces (Fig. 3-4A). These burrows are mainly relict burrows with active *Thalassinoides*-like burrows likely being constructed by either *Upogebia pugettensis* or *Neotrypaea californiensis*. These burrows are commonly nearly closed during low tide masking their true diameters, which are typically 1.5-3cm (Fig. 3-5A, B). The tracemaker was not observed, but recent fecal castings were observed outside the entrance of multiple burrow openings (Fig. 3-5B). The thalassinid shrimp responsible for creating these burrows likely resides deep within them during low tide to escape desiccation and temperature stresses. *Hemigrapsus* spp. crabs commonly created *Psilonichnus*-like burrows 2.5-4cm in diameter along the scarp face of the firmground. A combination of all large, open burrows was present in densities ranging from 35-115/50cm<sup>2</sup> (Table 3-1). Acorn barnacles preside on the more solid ironstone pipe structures directly next to and typically associated with the silty-sand firmground (Fig. 3-4B). In the silty-sand firmground areas possessing overlying salt marsh deposits, *Thalassinoides*-like burrows were witnessed within these overlying deposits that were either open, filled with silty-sand, or filled with organic/peaty to clay material.

Small burrow openings were also very obvious features along the silty-sand firmground (Fig. 3-5). The majority of these burrow openings were created by the spionid polychaete of the *Polydora* genus. Tubes were





**Figure 3-5: Neolithic characteristics of the exhumed compacted silty-sand firmground.** (A) Cross-sectional view showing *Thalassinoides*-like trace (red arrow) leading to the surface. *Skolithos*-like (yellow arrows) and *Arenicolites*-like (green arrows) traces are common near surface burrows. Spionid polychaete shown by white arrow. (B) Surface view of indent around *Thalassinoides*-like burrow opening. (C) *Arenicolites*-like trace (green arrow). (D) Insect larvae (white arrows). (E) *Palaeophycus*-like burrow (purple arrow) with a side branch containing insect larvae (white arrow). (F) *Arenicolites*-like (green arrow) and *Palaeophycus*-like (purple arrow) trace. (G) *Skolithos*-like to *Trichichnus*-like traces (yellow arrow for an example) faintly observed near the surface. *Palaeophycus*-like trace (purple arrow) also observed branching down from the surface. (H) Clarified view of traces in (G). White arrow indicates spionid worm

periodically associated with these burrow openings especially in slight indents within the otherwise planar surface of the firmground. Burrows created by these spionid polychaetes were typically vertical, unlined to slightly mucous lined displaying a U-shaped morphology resembling *Arenicolites*, with minor *Skolithos*- and *Trichichnus*-like burrows also present, commonly penetrating to depths of 6cm or more (Fig. 3-5A,C,G,H). Occasionally these burrows were present as offshoots along larger *Thalassinoides*-like burrow networks or alongside other small offshooting burrows created by insects and associated insect larvae (Fig. 3-5A,E). Small *Skolithos*-like offshoots (1-2cm in length) were typical of insect larvae brooding areas, while adult insects created *Skolithos*-, *Polykladichnus*- and diminutive *Psilonichnus*-like traces (Fig. 3-5D,E). Beetles commonly created wider and deeper penetrating *Psilonichnus*-like burrows, usually 5cm or more in length and up to 1cm in diameter. Nereid and glycerid polychaetes were also sporadically observed within the firmground creating unlined to mucous lined *Polykladichnus*-like traces, especially near the eroded firmground edges. Small (<2mm in diameter), open burrow density counts ranged from 11-43/10cm<sup>2</sup> and were typically attributed to burrows produced by spionid polychaetes (Table 3-1).

## **Modern Silty Sand to Clay Stiffgrounds**

### ***Stiffground Spatial Geometry and Sediment Characteristics***

Two sections of modern stiffground were observed within the study area. One was located next to the silty-sand firmground adjacent to the peaty-clay firmground 50m south of the anthropogenically altered creek outlet, while the second was located approximately 75m north of the creek outlet and nearing the edge of the subaerially exposed region within the study area.

The southern stiffground, adjacent to the silty-sand firmground, was typically a deep grey-brown-green colour. Top sediments of this stiffground possess a similar grain size composition to that of the silty-sand firmground where fine grained sands dominate in addition to sizable fractions of silt to clay

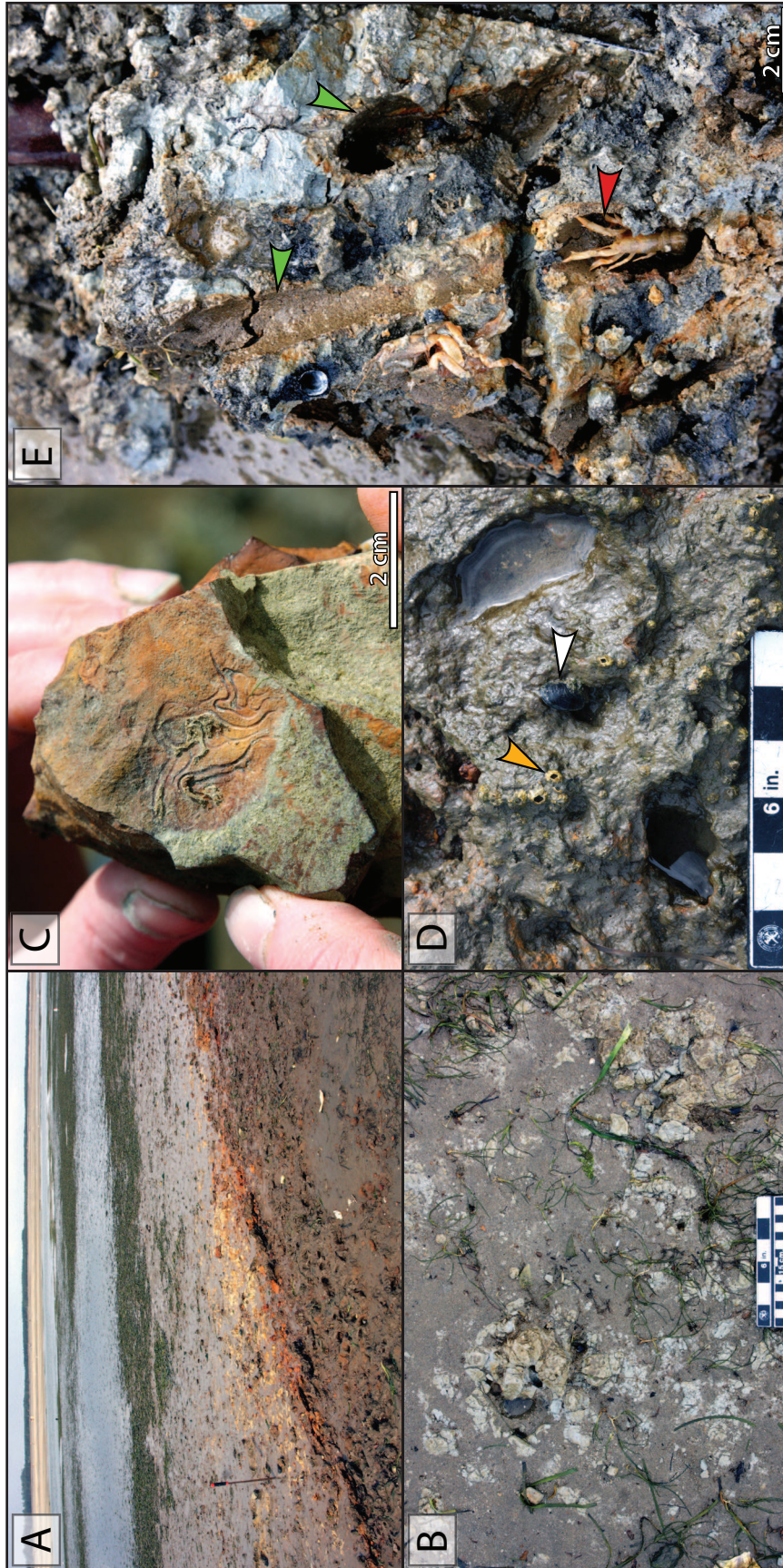
as well as very fine grained sand (Table 3-1). Bottom sediments were mainly composed of silt and clay with a slight dominance towards clay. The mineral composition of the bottom clays were not obtained, but XRD analysis of the top silty sand portion determined that the dominant minerals within this portion include quartz, albite, adularia, muscovite, and fluororichterite. Total organic carbon content of the top silty sand portion averaged 0.85%, while the bottom clay portion averaged 3.30% (Table 3-1). Firmness measurements from the modified Brinell firmness tests of the southern stiffground averaged  $1.37 \times 10^5$  Pa (Table 3-1). This modern stiffground is considerably less firm than the adjacent exhumed, compact silty-sand firmground although similar in composition.

The northern stiffground was composed of oxidized red-orange-brown silt to silty sand gradational with light grey-green silty clay (Fig. 3-6). Mineralogically, this modern stiffground was dominantly composed of quartz, albite, anorthite, orthoclase, adularia, muscovite, nacrite, kaolinite, beidellite, and goethite as determined by XRD analysis. Total organic carbon values were between 0.78-1.28% with an average value of 0.99% for this modern stiffground sediment (Table 3-1). Firmness measurements from the modified Brinell firmness tests of the modern stiffground in the northern portion of the study area ranged from  $1.85 \times 10^6$  Pa to  $2.44 \times 10^6$  Pa, with an overall average of  $2.08 \times 10^6$  Pa (Table 3-1). Slightly firmer measurements were obtained from the less water laden silty clay areas. The overall combined average firmness of stiffground measurements throughout the study area is  $4.53 \times 10^5$  Pa (Table 3-1).

### ***Neoichnological Characteristics***

*Thalassinoides*-like burrows created by *Upogebia pugettensis* were also pervasive within both softer and firmer modern stiffground sediments and were commonly slightly lined with an oxidized halo also evident approximately 1-2mm thick (Fig. 3-6E). The depth of burrow penetration is unknown as





**Figure 3-6: Morphological, sedimentological and neochronological features of the modern stiffgrounds.** (A) Surface morphology of the northern stiffground. Illuviated clays are light beige features in the foreground while the red-orange feature is an iron oxide band. Machete in the left of the photo is 55cm long from the sediment surface. (B) Plan view of stiffground surface. (C) *Meandropolydora*-like trace generated by spionid polychaetes along a horizontal fracture in the more compact dewatered clays of the northern stiffground. (D) Acorn barnacles (yellow arrow) and mussel (white arrow). (E) *Thalassinoides*-like (green arrows) traces created by *Upogebia pugettensis* (red arrow).



sediment usually caved in before depth of burrow penetration was reached as the water table was encountered, but burrows were commonly at least 25-30cm long. The bivalve *Cryptomya californica* was occasionally seen as a commensal occupant along *U. pugettensis* burrow walls in modern stiffground and veneered sediment. *Upogebia pugettensis* was sometimes observed to possess a commensal bivalve (*Pseudopythina rugifera*) attached to its ventral side and a parasitic isopod (*Orthione griffenis*) attached to one of its gills. Threadworms (*Mediomastus* sp. and *Capitella* sp.) were a common constituent of the softer stiffground sediment forming *Skolithos*- and *Trichichnus*-like burrows, with some ending in horizontal helical structures within softground sediment. In the more compact muddy areas of the stiffground horizontal *Arenicolites*- to *Meandropolydora*-like traces, in addition to plausible *Rhizocorallium*-like traces, were produced by *Polydora* sp. and observed along horizontal to sub-horizontal fractures (Fig. 3-6C). Sporadic patches of acorn barnacles and solitary *Mytilus* sp. were also observed attached to this firmer surface (Fig. 3-6D). Burrow densities of up to 33 open, large ( $\geq 2$ mm in diameter) burrows/50cm<sup>2</sup> were observed along the modern stiffgrounds, with smaller burrow openings not obvious as they were likely, at least superficially, filled in if semi-permanent, or permanently filled in if the structure was built for temporary occupation (Table 3-1). Other small burrows were only present as horizontal structures and were not evident at the sediment surface for burrow density counts.

### **Surficial Softground Veneer**

#### ***Areal Extent of Veneer and Sediment Characteristics***

A veneer of silty sand to dominantly fine sand exists over the lower step terraced peaty-clay firmground deposits (Table 3-1). The extent of the peaty-clay margin is hypothesized to be continuous along the bay margin as Pleistocene terrace deposits are observed to be continuous adjacent to the bay margins on geologic maps; therefore the extent of veneer covering this

supposed surface is also potentially large. These deposits are unconsolidated and typically water laden with the redox potential discontinuity layer residing within a few centimetres of the sediment surface. This veneer is mainly fine sand with a proportion of lower medium-grained sand from the contiguous bayward intertidal sand flats. Small run-off tidal creeks are developed within the veneered surface, which display basal clasts derived from the peaty-clay firmground. XRD analysis indicates that the main mineralogical components of this sandy veneer are quartz, albite, clinopyroxene, and anorthite. Potential trace amounts of heavy mineral sand minerals such as augite, ilmenite, hematite, magnetite and rutile may be present. Total organic carbon content of the top portion of veneer averaged 0.38%, while the bottom portions of veneered sediment averaged 0.45% (Table 3-1). Firmness measurements from the modified Brinell firmness tests of the unconsolidated veneered sediment varied greatly with values ranging from  $8.60 \times 10^4$  Pa to  $3.73 \times 10^5$  Pa, with an overall average of  $1.73 \times 10^5$  Pa (Table 3-1). Measurements that displayed lower firmness were taken in areas with more water laden, almost thixotropic sands compared to the firmer measurements.

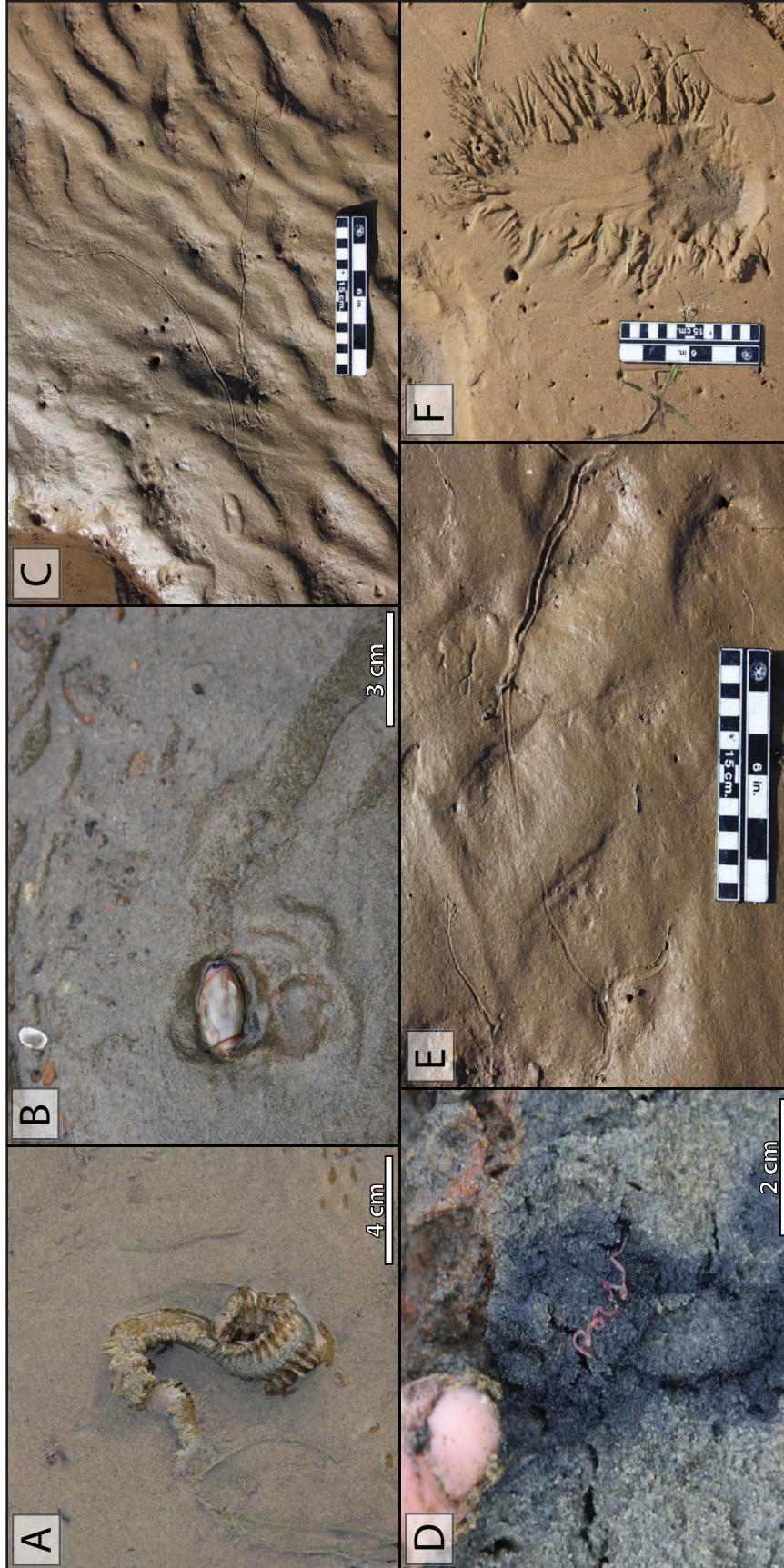
### ***Neoichnological Characteristics***

The only relatively large, open surface traces within the softground were *Thalassinoides*-like burrows produced by *U. pugettensis* and *Psilonichnus*-like burrows produced by *Hemigrapsus nudus* and *Hemigrapsus oregonensis* (Fig. 3-7). *Thalassinoides*-like burrows are usually gradational with other substrates such as firmgrounds below the veneer, stiffgrounds, and woodgrounds either below or laterally transitional with the veneer. *Neotrypaea californiensis* may also be possible in the veneered surface, as a few were witnessed during July 2012, although none were seen during this study session (April 2013). Multiple surface traces were observed along the softground surface including those created by *Corophium* sp. (Fig. 3-8C). *Corophium* sp. amphipods created *Gordia*-like surface traces in addition to *Skolithos*- and occasionally *Arenicolites*-



**Figure 3-7: Sedimentological and neoichnological features of the softground veneer substrate.** (A) Resin cast of a *Psilonichnus*-like (white arrow) burrow created by *Hemigrapsus* sp. hung upside down to show actual orientation of burrow as would appear in sub-surface. Small *Thalassinoides*-like (yellow arrow) burrow created by juvenile upogebiid shrimp also present. (B) Resin cast of large *Thalassinoides*-like trace created by *Upogebia puggetensis* shown upside down to its actual subsurface orientation. Machete is 50cm long from sediment surface. (C) Sediment surface with upogebiid shrimp coming out of burrow opening (white arrow). Fecal castings (yellow arrow) also witnessed alongside some openings. (D) Cross-sectional sub-surface view of *Thalassinoides*-like burrow (white arrow). (E) Box core showing mainly fine sand with possible *Rhizocorallium*-like (white arrow) trace just below the surface layer (orange in color) that has lots of clay clasts. Yellow arrows indicate possible *Gyrolithes*-like trace.





**Figure 3-8: Vermiform organisms and surface trails of the softground veneer substrate. (A)** Large nereid polychaete exhumed to the surface. **(B)** *Olivella biplicata* creating a meandering surface trace akin to *Olivellites*. **(C)** Small *Gordia*-like traces likely created by *Corophium* sp. **(D)** Threadworms are very common burrowers of the softground sediment creating mainly *Skolithos*- and *Trichinus*-like traces and occasionally *Gyrolithes*-like traces. **(E)** *Protichnites*- to *Diplichnites*-like trace generated by a hermit crab. **(F)** *Piscichnus*-like trace likely generated by a fish observed near silty-sand firmground.



like traces (Fig. 3-8C). Additionally *Pagurus* sp. hermit crabs created *Diplichnites*- to *Protichnites*-like traces depending on the water content of the substrate (Fig. 3-8E). In substrate that had less water a median furrow was evident and the trace was thus *Protichnites*-like, but in saturated sediment the median furrow was unable to be sustained and a *Diplichnites*-like trace resulted. *Pagurus* sp. also escaped potential danger by burrowing beneath the sediment in a corkscrew motion. Meandering *Olivellites*-like surface traces were produced by the gastropod *Olivella biplicata* (Fig. 3-8B). Sporadic occurrences of *Piscichnus*-like traces were observed near the silty sand firmground and tidal creek areas (Fig. 3-8F). In boxcore a *Rhizocorallium*-like structure was observed in softground veneer sediment close to the peaty-clay firmground under a layer of clay clasts (Fig. 3-7E).

Threadworms (*Mediomastus* sp. and *Capitella* sp.) are common constituents of the softground veneer creating *Skolithos*-, *Trichichnus*- and *Planolites*-like traces (Fig. 3-8E). The vertical traces produced by these worms occasionally ended in horizontal helical structures. Another vermiform organism, the enteropneust *Saccoglossus* sp., also created helical burrows akin to *Gyrolithes* in addition to *Arenicolites*-like traces. Nereid and glycerids polychaetes produced *Skolithos*-, *Palaeophycus*-, and *Polykladichnus*-like traces. In calm, usually water saturated areas with sparse to abundant eelgrass, U-shaped *Arenicolites*-like burrows of *Abarenicola pacifica* and lined *Skolithos*-like tube structures of a terebellid polychaete, most probably of the genus *Eupolyornia*, were present. Errant *Nephtys* sp. polychaetes were sporadically observed swimming through the sediment creating sediment disruption (navichnia) or potential *Planolites*-like traces and cryptic bioturbation. Large ( $\geq 2$ mm in diameter), open burrows of the softground veneer sediment had density values ranging from 58-96/50cm<sup>2</sup>, while small (<2mm in diameter) burrow density values ranged from 0-6/10cm<sup>2</sup> (Table 3-1). Small, open burrows were usually only witnessed in areas where sediments were not saturated with water and able to support small diameter burrow openings.

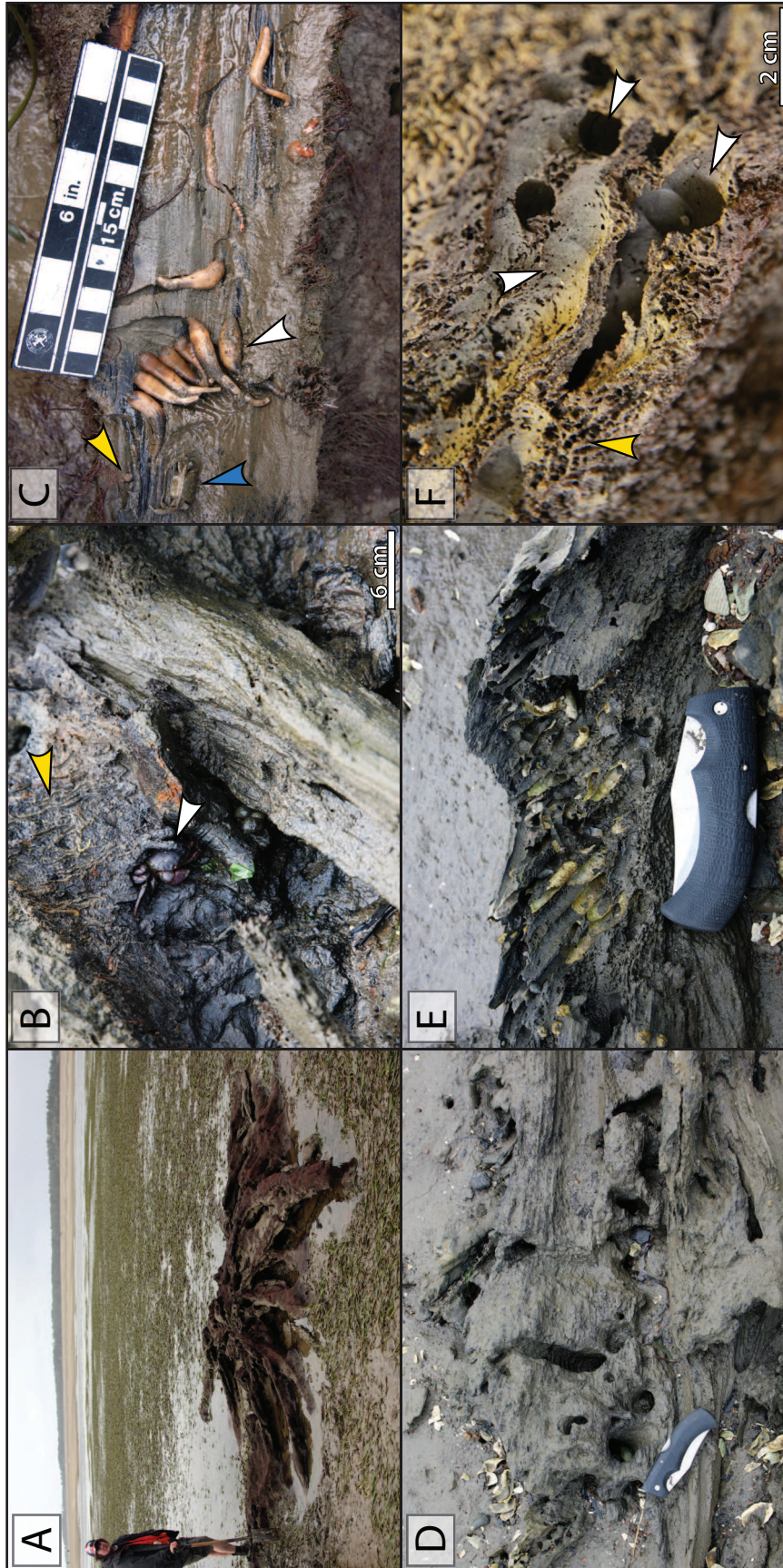
## **Woodground Associated with Exhumed Compacted Peaty-Clay Firmground**

### ***Spatial and Neoichnological Woodground Characteristics***

Exposed, sporadic, intertidal stumps occur *in situ* upon peaty-clay firmground deposits that are usually covered by veneered softground sediment (Fig. 3-9A). In areas where the basal attachment surface of the stump is not witnessed the substrate to which it is attached is therefore unknown, but plausibly that of the peaty-clay firmground.

Multiple small (<2mm in diameter), open traces and patchy large (approximately 1.5-3cm in diameter) open traces dominate the woodground surfaces observed along the study area. The majority of small, open traces are produced by spionid polychaetes of the *Polydora* genus. Traces created by *Polydora* sp. within the exhumed logs resemble *Arenicolites*-, *Skolithos*-, *Trichichnus*-, *Caulostrepsis*-, and *Meandropolydora*-like traces (Fig. 3-9B). Certain types of limnonid isopods, commonly known as gribbles, also produce diminutive *Teredolites*-like as well as *Trypanites*-like borings within the woodground substrate. Larger traces are mainly the result of teredenid bivalves, which produce *Teredolites*-like borings that are typically 1.5-2cm in diameter (Fig. 3-9E,F). Teredenid generated borings are usually patchy with multiple burrows, either vacant or occupied occurring in one area, with very few if any borings in an adjacent area. *Upogebia pugettensis* and *Hemigrapsus* spp. also leave large major traces akin to *Thalassinoides* and *Psilonichnus*, respectively; however they typically occur on the flanks of the woodground and are not present throughout (Fig. 3-9BD). In some instances it appears that these organisms may in part use vacant *Teredolites*-like borings to initially establish their own burrows. A single U-shaped *Thalassinoides*-like trace constructed by *U. pugettensis* may penetrate multiple different substrates. Trace densities averaged 9/50cm<sup>2</sup> for large traces and 63/10cm<sup>2</sup> for small traces, with trace densities for larger traces fluctuating towards much larger amounts in certain highly bored areas of the woodground (Table 3-1).





**Figure 3-9: Neobiological elements of the woodground and substrate.** (A) Broad *in situ* ancient tree root systems. Person for scale. (B) Close up view of woodground showing the *Psilonichnus*-like tracemaker *Hemigrapsus nudus* (white arrow). In this particular instance spionid polychaetes are observed creating *Skolithos*-, *Trichichnus*- and *Arenicolites*-like traces (yellow arrow). (C) Squatters of the woodground including sipunculid worms (white arrow) and small marine gastropod (yellow arrow). Blue arrow indicates *Hemigrapsus oregonensis*. (D) *Thalassinoides*- and *Psilonichnus*-like traces on the flanks of the woodground. Knife for scale is ~6cm long. (E) *Teredolites*-like borings generated by terednid bivalves where their lighter colored calcified tubes are also observed. Knife for scale is ~6cm long. (F) Close up view of woodground displaying *Teredolites*-like borings (white arrow) and *Caulostrepsis*-like (yellow arrow) traces.

The remaining organisms discovered associated with the woodground substrate are typically encrusters or squatters seeking refuge. Common encrusters include acorn barnacles and certain species of flat lying sponges. Numerous gastropods, the isopod *Harmonthoe imbricata*, and the sipunculid worm *Phascolosoma agassizii* were common refugia seekers on or within the woodground (Fig. 3-9C). Nereid polychaetes were common refugia seekers residing within the softground veneer that surrounds exhumed logs and fills in voids within the logs.

## **DISCUSSION**

### **The Integral Role of Substrate Control on Trace Form Genesis**

Ekdale (1985) states that “substrate firmness is of paramount importance to a burrowing organism”, where the type of sediment ultimately reflects the burrowing behaviour of that organism and in essence what type of traces it will create. Organisms needing soft substrates, soft enough to penetrate but firm enough to support an open burrow without collapsing, are likely going to be found in stiffgrounds or slightly dewatered more compact softgrounds (Ekdale, 1985). Those organisms that need even softer substrates are generally found in water laden softgrounds where burrows often require some sort of lining to remain open for any significant amount of time (Ekdale, 1985). On the other hand some organisms prefer the compact, firm, dewatered nature of firmgrounds that can support open, unlined burrows easily, essentially without risk of burrow collapse (Ekdale, 1985). Woodgrounds may present ideal environments to organisms especially adept at boring into wood, providing refuge in an otherwise inhospitable environment (Ekdale, 1985).

The nature of the substrate therefore has the greatest influence on organismal burrowing behaviour and ultimately upon the traces they generate (Gingras et al., 2007). Trace assemblages of the peaty-clay firmground, silty-sand firmground, modern stiffgrounds, softground veneer, and woodgrounds in Netarts Bay are similar but possess inherent differences, largely due to



differences in substrate texture and consistency (Fig. 3-10). The peaty-clay firmground is characterized by larger diameter *Thalassinoides*-, *Psilonichnus*-, and *Gastrochaenolites*-like traces; and smaller diameter *Skolithos*-, *Trichichnus*-, *Arenicolites*-, *Diplocraterion*-, *Rhizocorallium*-, and *Polykladichnus*-like traces (Table 3-1, Fig. 3-10). *Gastrochaenolites*-like traces are found to be exclusive to the peaty-clay firmground environment. Characteristic traces of the silty-sand firmground include larger diameter *Thalassinoides*- and *Psilonichnus*-like traces; in addition to smaller diameter *Arenicolites*-, *Skolithos*-, *Trichichnus*-, and *Polykladichnus*-like traces (Table 3-1, Fig. 3-10). Traces associated with the modern stiffgrounds are *Thalassinoides*-, *Skolithos*-, *Trichichnus*-, *Arenicolites*-, *Meandropolydora*-, and *Rhizocorallium*-like in appearance, with *Thalassinoides*-like traces being the only large trace type present (Table 3-1, Fig. 3-10). Woodground assemblages consisted of multiple small traces including *Skolithos*-, *Trichichnus*-, *Arenicolites*-, *Caulostrepsis*-, *Meandropolydora*-, and *Trypanites*-like borings; and a few select larger traces such as *Teredolites*-, *Thalassinoides*- and *Psilonichnus*-like traces (Table 3-1, Fig. 3-10). *Teredolites*-, *Trypanites*-, and *Caulostrepsis*-like traces are found to be exclusive to the woodground environment. A variety of traces were associated with the softground veneer including *Gordia*-, *Diplichnites*-, *Protichnites*-, and *Olivellites*-like surface traces; small, vertical traces akin to lined and unlined *Skolithos*-, *Trichichnus*-, *Arenicolites*-, and *Polykladichnus*; small, horizontal traces akin to *Rhizocorallium*-, *Planolites*-, *Gyrolithes*-, and *Palaeophycus*; large, open *Thalassinoides*- and *Psilonichnus*-like traces; *Piscichnus*-like feeding traces; and finally sediment disruption, *Navicula* and potential cryptic bioturbation features (Table 3-1, Fig. 3-10).

Larger diameter burrows that are open and unlined, including *Thalassinoides*-, *Psilonichnus*- and *Gastrochaenolites*-like traces, can be extensively found in environments possessing firmer substrates. *Upogebia pugettensis* and *Hemigrapsus* spp. crabs responsible for creating *Thalassinoides*- and *Psilonichnus*-like traces, respectively, are able to produce an abundance of



**Figure 3-10: Schematic diagram of the study area.** The location of A - A' is located on Figure 3-1. Symbols for substrate type and traces are located in the "List of Symbols" after the Table of Contents section of this thesis. Insert A displays a close-up of traces associated with the woodground substrate. Insert B displays a close-up of traces associated with the modern stiffground substrate in the north section. Insert C displays a close-up of traces associated with the exhumed compacted silty-sand firmground substrate. Insert D displays a close-up of traces associated with the exhumed compacted peat-clay firmground substrate. Insert E displays close-up of traces associated with the surficial softground veneer substrate.

the aforementioned traces in not only firmground substances but also softground and woodground substances as well. These avid burrowers are protected by a hard carapace, in addition to the protection that extensive burrow networks in firmer substrates provide. Both organisms are generalists in terms of feeding modes as they can both filter feed while *Hemigrapsus* sp. is also a scavenger and *U. pugettensis* is also a deposit feeder (MacGinitie 1930; Ricketts et al. 1985; Coelho et al., 2000). *Upogebia pugettensis* also readily burrow in stiffground substrates where the burrows may possess a faint lining. In contrast, *Gastrochaenolites*-like traces are produced by the far less mobile suspension feeding bivalve *Zirfaea pilsbryi*. *Zirfaea pilsbryi* slowly deepens its burrow throughout its life using its razor edged shell, but the shell itself is actually quite fragile thereby the organism needs to utilize the full protection of the surrounding substrate to flourish as it does not have the same defence capabilities as *Upogebia pugettensis* or *Hemigrapsus* spp. (Ricketts et al., 1985). Therefore, the *Gastrochaenolites*-like tracemaker is more substrate specific than *Upogebia pugettensis* or *Hemigrapsus* spp., preferring a firmer substrate where it can steadily build a safe refuge over time using the rotating motion of its hard shell. Large, open, *Teredolites*-like borings are also observed in firm woody substrates where teredonid bivalves, which are related to *Zirfaea pilsbryi*, typically possess a calcified lined tube associated with it to protect the mainly exposed, fleshy bivalve that resides within.

Small diameter, dominantly vertical, unlined *Skolithos*-, *Trichichnus*-, *Arenicolites*-, and *Diplocraterion*-like traces are also observed within firmground substrates, although *Diplocraterion*-like traces are rare if even present as they are difficult to ascertain. Vertical, unlined *Skolithos*-, *Trichichnus*-, and *Arenicolites*-like traces are also ubiquitous within the other stiff-, soft-, and wood-ground substrate types, occasionally possessing thin to thick lining in softground sediment. These small, vertical traces allow organisms that created them access to the sediment-water interface for respiration and interface deposit feeding or suspension feeding purposes (Gingras et al., 2008). A

multitude of different organisms are capable of creating these traces and although the same trace may be present in all environments the nature of the trace is highly variable and dependant on the specific tracemaker that created the trace and the association of other traces created by the same tracemaker. For example, *Polydora* sp. readily create what appear to be *Skolithos*- or *Trichichnus*-like traces in association with *Arenicolites*-like traces, especially along the sediment-water interface of firmground sediment. On the other hand threadworms, which also tend to create *Skolithos*- and *Trichichnus*-like traces but in association with *Planolites*-like traces, occur dominantly in softground or stiffground modern sediment.

Traces that grade from vertical to horizontal include *Polykladichnus*-, *Trypanites*-, and *Caulostrepsis*-like traces. These traces begin in a vertical position then transition into more horizontally aligned forms. *Polykladichnus*-like traces are usually associated with modern stiffground and softground veneer sediment, although odd rare occurrences of the trace were observed along the erosional scarps of the exhumed, compact silty-sand firmground. Organisms generally create unlined to slightly mucous lined *Polykladichnus*-like traces in order to hide from predators, engage in passive carnivory and interface deposit feed (Gingras et al., 2008). Multiple *Polykladichnus*-like traces are usually connected via basal horizontal conduits (Gingras et al., 2008). *Trypanites*- and *Caulostrepsis*-like borings, produced by limnonid isopods and spionid polychaetes, respectively, occur in woodground substrate and generally begin vertical or perpendicular to the wood surface before veering in a sub-vertical to horizontal direction. Limnonid isopods bore into the wood for feeding purposes as they actively feed on the cellulose material in addition to algae, whereas spionid polychaetes seem to largely create U-shaped *Caulostrepsis*- to *Arenicolites*-like traces for dwelling and interface feeding purposes (Ricketts et al., 1985; Gingras et al., 2004). Spionid polychaete generated *Caulostrepsis*-like traces eventually veer horizontally along the wood grain as these are inherent planes of weakness and easier to bore through, a



strategy also partaken by teredenid bivalves producing *Teredolites*-like borings (Gingras et al., 2004). In other instances, multi-directional traces are also created by mobile carnivores in softground sediment such as those produced by the hypoxic resistant, errant polychaete *Nephtys* sp. that actively swims through the sediment in search of its next meal, constantly creating sediment disruption structures (navichnia) in its wake (Trevor, 1976; Arndt and Schiedek, 1997).

Small diameter, dominantly horizontal *Planolites*-, *Palaeophycus*-, and *Gyrolithes*-like traces are common in the softground veneer sediment typically as a result of subsurface deposit feeding vermiform organisms (Gingras et al., 2008). Along fractures of the peaty-clay portion of the peaty-clay firmground dwelling and deposit feeding *Rhizocorallium*-like structures are produced by spionid polychaetes of the *Polydora* genus. *Polydora* sp. spionid polychaetes are adept at boring into harder substrate where they initially create vertical *Caulostrepsis*- or *Arenicolites*-like traces that are perpendicular with the sediment surface to enhance safety from predators (Seilacher, 2007). These traces eventually acquire backfill sediment that the animal reworks overtime causing a *Diplocraterion*-like appearance to form and in the areas where these traces grade into a horizontal trace form, a *Rhizocorallium*-like trace therefore develops (Seilacher, 2007). Similar dwelling and deposit feeding *Meandropolydora*-like traces, and potentially *Rhizocorallium*-like traces, are also produced by spionid polychaetes along horizontal to sub-horizontal fractures of the more compact clay rich zones of modern stiffgrounds. Potential *Rhizocorallium*-like traces of unknown origin also arise in softground substrates below disaggregated clay clasts near the peaty-clay firmground (Fig. 3-7E), while *Meandropolydora*-like borings are also seen in association with *Caulostrepsis*-like borings along the grain of woodground substrates. Softground substrate may show a predominance of mainly horizontal traces of opportunistic deposit feeding organisms especially in lower energy hypoxic deposits that experience low sedimentation rates (Ekdale, 1985).

Surface traces witnessed on top of the softground veneer substrate likely arise due to two different behavioural modes. The surface traces attributable to grazing or feeding behaviours are *Piscichnus*-like traces likely generated by fish and *Olivellites*-like traces produced by the trophic generalist *Olivella biplicata*. *Olivellites*-like traces and *Gordia*-like traces created by *Corophium* sp. amphipods are also locomotory traces in addition to feeding traces. Ekdale (1985) indicates that combined locomotory and feeding trace action are reflected through such pascichnia as grazing is conducted while moving where an organism is not in one spot long enough to exploit the full resource potential of one particular area. *Olivella biplicata* will continuously graze along the sediment water interface in soft sandy deposits as long as water is present and there is some form of current for potential suspension feeding in addition to deposit feeding (Edwards, 1969). Ingle (1966) observed *Corophium* sp. probing the surface before burrowing, an act that could also include surface deposit feeding. On the other hand, *Diplichnites*- and *Protichnites*-like traces generated by hermit crabs are typically the sole result of locomotory (crawling) behaviour as the crab was witnessed to scurry along the surface briefly before once again escaping into the sediment via a spiral motion to escape any potential predation.

It is therefore evident that substrate texture and consistency have, by far, the largest impact on organismal burrowing behaviour and subsequently on the types of traces produced. Traces may be relatively similar due to similar environmental conditions; however even the slightest change in substrate attributes can result in noticeable shifts in trace type. Other physico-chemical factors such as wave energy, desiccation stress, temperature, salinity changes, and oxygen levels also have an influence on organism behaviour and therefore trace distribution, although these aspects were not the focus of this study. However, it is worth mentioning that the aforementioned physico-chemical factors and the factors associated with sediment control are usually part of an integral whole, where a trace arises due to the organism responding to

multiple different factors at once. Substrate factors ultimately have the greatest role in a firmground, stiffground, woodground type of environment but other factors play a subordinate but intertwined role in trace expression. MacEachern et al. (2007) indicate that at the time of firmground colonization energy levels, in addition to substrate factors, appear to be the main controls on the suite of traces that arise. The effects of hydraulic energy levels in a sandy intertidal setting were extensively covered in the previous chapter and can be reviewed there for a generalized inquest.

### **Importance of Quantitative Substrate Firmness Measurements**

Firmness measurements of the sediment are important to ascertain as they give quantitative analysis of firmground substrates that comprise *Glossifungites* assemblages. This is important since firmground substrates are gradational between soft- and hard-ground substrates and are usually only qualitatively analysed that may lead to ambiguity as to the actual nature of the substrate. Many factors such as pore water pressure, grain size, grain texture, clay mineralogy and organic content play a major role in the resultant firmness of the substrate and ultimately affect the compaction process (Gingras et al., 2000b). Firmness measurements will not tell us how much dewatering or compaction that the substrate has already experienced, nor will it tell us how much further dewatering or compaction is possible, but it allows a more quantitative analysis of current classification of firmground trace assemblages.

The firmground environments had the most consistent and overall highest firmness values, with the silty-sand firmground portraying higher average firmness values ( $2.08 \times 10^6$  Pa) than the peaty-clay firmground ( $1.65 \times 10^6$  Pa). Modern stiffground values were not consistent and varied greatly with some averaged values on par with those of the silty-sand firmground, while other averages displayed much lower firmness values of  $1.37 \times 10^5$  Pa (Table 3-1). An overall average firmness across the highly variable modern stiffground environment was calculated to be  $4.53 \times 10^5$  Pa (Table 3-1). The softground

veneer also had fluctuating firmness measurements with lowest overall averaged firmness values calculated to be  $1.73 \times 10^5$  Pa (Table 3-1). Gingras et al. (2001) also studied modern *Glossifungites* assemblages in exhumed Pleistocene aged firmground substrate where the firmness of these surfaces commonly ranged from  $1 \times 10^5$  Pa to  $1 \times 10^7$  Pa in the upper intertidal and subtidal to middle intertidal zones, comparable to the firmness values obtained from firmground substrates in Netarts Bay. Gingras et al. (2001) measured firmness values greater than  $1 \times 10^8$  Pa in the middle intertidal zone where there were assemblages of *Petricola* sp. bivalves, but this assemblage or firmness value was not observed in Netarts Bay.

The firmer and homogenous profiles of the firmground environment compared to the stiff- and soft-ground environments is likely due to subjugation of firmground environments to past burial events that lead to greater compaction and dewatering. The stiff- and soft-ground substrates on the other hand are solely of modern origin and have not undergone any sort of significant burial or dewatering events. Gingras et al. (2000b) also observed the heterogeneous nature of firmness measurements in Willapa Bay, Washington through experiments conducted on modern stiff- to firm-ground sediments. Gingras et al. (2000b) determined that Willapa Bay modern intertidal creek deposits ranged from approximately  $7.0 \times 10^3$  –  $1.2 \times 10^4$  Pa, while exposed Pleistocene muddy firmground sediments had firmness values typically above  $10^7$  Pa and locally above  $10^9$  Pa. It was also indicated by Gingras et al. (2000b) that the maximum firmness of modern sediments tested within Willapa Bay is about  $10^5$  Pa. In Netarts Bay a comparatively similar trend in firmness values is witnessed, although the Willapa Bay study of Gingras et al. (2000b) found a wider range of firmness values. This wider range may arise due to a larger data set or area of study in Willapa Bay and possibly due to the more muddy nature of the sediments as Netarts Bay is dominated by fine sand to silt with smaller portions of clay. In areas of higher sedimentation rates higher levels of pore water content may arise causing firmness of the substrate to decrease (Gingras



et al. 2000b). This may be a likely explanation for the less firm values observed in softground veneer sediment as well as the southern modern stiffground sediment as both are the most bayward of the areas studied and subject to higher sedimentation rates versus erosion. Gingras et al. (2000b) also indicated that abundant bioturbation, especially by threadworm species, can cause an overall decrease in sediment firmness as they disrupt large portions of the sediment causing it to be less cohesive. Threadworms were readily observed in the modern stiffground and softground-veneered environments, but not in the two different types of firmground environments.

### **Designation of Substrate Types to a Particular Ichnofacies Assemblage**

MacEachern et al. (2007) indicate that *Glossifungites* Ichnofacies suites are dominantly comprised of *Diplocraterion*, *Skolithos*, *Psilonichnus*, *Arenicolites*, *Conichnus*, *Bergaueria*, and *Gastrochaenolites*, which are sub-vertical to vertical dwelling structures of suspension feeding organisms. Additionally *Thalassinoides*, *Spongiomorpha*, *Taenidium*, *Rhizocorallium*, *Planolites* and *Chondrites*, which are generally attributed to the dwelling structures of deposit feeding organisms, are also dominant features of a *Glossifungites* Ichnofacies assemblage (MacEachern et al., 2007). The specific trace assemblage that helps strengthen the Netarts Bay peaty-clay firmground attribution to a *Glossifungites*-Ichnofacies assemblage are through the presence of large, robust *Thalassinoides*-, *Psilonichnus*-, and *Gastrochaenolites*-like traces in addition to smaller but still robust *Arenicolites*-, *Diplocraterion*-, *Skolithos*-, and *Rhizocorallium*-like traces. The silty-sand firmground also possesses robust *Thalassinoides*-like and *Psilonichnus*-like traces in addition to smaller robust *Arenicolites*- and *Skolithos*-like traces that also aid in its attribution to a representative *Glossifungites* Ichnofacies assemblage. It is also important to note that although the stiffground and softground veneered substrates also display very similar trace assemblages, they are not part of a cohesive substrate

where large, unlined, robust burrows can form. The burrows constructed in the substrates of these environments need to be maintained to some degree or possess some sort of lining in order to remain open to the sediment-water interface otherwise the burrow will eventually collapse and infill if the organism is not there to maintain it. In the firmgrounds of Netarts Bay the burrows remain open regardless, not needing any sort of lining or maintenance, and are subject to only passive infilling.

The two different types of firmground assemblages witnessed at Netarts Bay were subsequently exhumed after having undergone substantial compaction, or incipient cementation in the case of the silty-sand firmground, after burial for an extended period of time (Gingras et al., 2001; MacEachern et al., 2007). These exposed firmgrounds are now subject to subaerial exposure, erosion, desiccation and colonization of substrate by a new suite of organisms that are able to utilize the substrate to create relatively large, unlined, robust burrows. The resultant firmground assemblages are therefore defined as *Glossifungites* Ichnofacies assemblages; firstly due to the prevalence of physical *Glossifungites*-like traits present as initially defined by Seilacher (1964; 1967), where relatively large, robust, unlined burrows are situated in firm, cohesive, non-shifting substrates; and lastly by the relatively large, unlined, robust *Glossifungites* Ichnofacies-like trace assemblages present. Modern stiffground assemblages, in contrast, have not undergone any significant burial or compaction, and have not undergone substantial erosion, thus having only been subject to subaerial exposure and desiccation factors. In addition they lack any substantial large, robust, unlined traces that are capable of being maintained without organismal support and are therefore not considered attributable to a significant *Glossifungites*-Ichnofacies assemblage. It was also proposed by Lettley et al. (2007) that the discrimination between stiffground and firmground is a significant factor in assessing the significance of a *Glossifungites* Ichnofacies surface. Laterally traceable firmgrounds that possess relatively homogenous, planar, and distinct surfaces with robust traces are

much more likely to be significant, at least stratigraphically, than heterogeneous stiffgrounds possessing less firm, more compressible substrates that have not yet undergone burial or compaction (Lettley et al., 2007).

*Teredolites* borings are essentially the only trace observed in association with *Teredolites* Ichnofacies assemblages in ancient examples as indicated by MacEachern et al. (2007). However, trace assemblages similar to the association found in Netarts Bay have been found in a modern *Teredolites* Ichnofacies example by Gingras et al. (2004) where *Teredolites*-, *Thalassinoides*-, *Trypanites*-, *Entobia*-, *Rogerella*-, *Psilonichnus*-, *Caulostrepsis*-, and *Meandropolydora*-like traces were observed. Gingras et al. (2004) attributes the lack of multiple borings in the rock record, which are otherwise witnessed in the modern, to the observation that these borings are usually small and relatively superficial, thus particularly exposed to erosion before they have the potential to be preserved. This may also explain the loss of preservation of other rather large trace forms such as *Thalassinoides*- and *Psilonichnus*-like traces since these traces were commonly observed on the flanks of the woodground, also in exposed areas more prone to substantial erosion. Bromley et al. (1984) indicated that since *Teredolites* borings were the most prominent features in the woodground substrate they observed that the ensuing ichnofacies would thus be referred to as the *Teredolites*-Ichnofacies; in so much as also acknowledging that further traces may likely be discovered in other studies that could be attributed to the *Teredolites* Ichnofacies further elaborating the assemblage. In Netarts Bay the woodground assemblage is dominated by small, shallow *Caulostrepsis*-, *Arenicolites*-, *Skolithos*-, and *Trichichnus*-like borings in addition to large, extensive *Teredolites*-like borings. Overall, the woodground assemblages at Netarts Bay are thought to be attributable to a *Teredolites* Ichnofacies assemblage.

### **Spatial and Temporal Significance of Firmground and Woodground Deposits in Netarts Bay**

The peaty-clay firmground at Netarts Bay is essentially planar but also seems to exhibit a larger scale terrace-like pattern where the more bayward expression of the firmground is found at a slightly lower elevation and is thus covered by a softground veneer. This intriguing feature was also noted by Gingras et al. (2001) in Willapa Bay, Washington and hypothesized to have formed due to base level changes associated with megathrust earthquakes along the Cascadia subduction zone and continual shore parallel wave erosion. Strain builds up slowly as the oceanic Juan de Fuca plate is subducted below the North American plate causing miniscule land uplift over time as the strain accumulates before rapid coseismic land subsidence during megathrust earthquake events (Shennan et al., 1998). This cyclic change in base level may also lead to changes in the thickness of sediment veneer subjecting the firmground surface below to varying levels of bioturbation and allowing cross-cutting trace relationships to potentially form (Gingras et al., 2001). In Netarts Bay the potential development of cross-cutting relationships due to changes in base level and ensuing overlying veneer depths would most likely result from deeper penetrating *Thalassinoides*-like burrows produced by *Upogebia pugettensis* that would penetrate the underlying firmground surface to varying degrees over time.

Various studies in Netarts Bay have been conducted to obtain geologic evidence of megathrust earthquakes that cause recurrent and rapid coastal subsidence events (Peterson et al., 1988; Darienzo and Peterson, 1990; Shennan et al., 1998; Hawkes et al., 2005). Peterson et al. (1988) looked for evidence of such earthquakes through examining late Holocene salt marsh and uplifted Pleistocene terrace deposits. It was stated by Peterson et al. (1988) that Netarts Bay represents the first known site along the north Oregon coast to portray multiple events of rapid subsidence of late Pleistocene coastal terrace deposits. Along the eastern portions of the bay Peterson et al. (1988) describe the



Pleistocene terrace deposits as estuarine in nature where layers of tidal flat mud are interlaminated with layers of organic peaty material with sporadic occurrences of *in situ* Pleistocene wetland forest tree trunk remnants. These deposits were eventually exhumed after substantial burial time as the bay cliffs along the eastern margin of Netarts Bay retreated (Peterson et al. 1988). Peterson et al. (1988) indicate that these layers can be continuously traced for at least 100m along the bay margin and they documented at least three such occurrences of exposed Pleistocene terrace deposits along the intertidal bay margin of Netarts Bay that appear to be approximately 600m away from each other or more. It is therefore hypothesized that the peaty-clay firmground deposits in this paper are homologous with those described by Peterson et al. (1988) as the location of peaty-clay firmground deposits in this study are approximately 1000m north along the intertidal bay margin from those described by Peterson et al. (1988). Peterson et al. (1998) believe that the Pleistocene terrace deposits running along the eastern margin of Netarts Bay are correlated with the Whiskey Run terrace which has been dated by West and McCrumb (1988) to be around 83,000 years old.

Surfaces demarcated by substrate-controlled ichnofacies, such as the *Glossifungites* and *Teredolites* Ichnofacies, have been shown to have stratigraphic significance in the rock record (Pemberton and Frey 1985; Savrda, 1991; MacEachern et al., 1992; Savrda et al., 1993; Pemberton and MacEachern, 1995). *Glossifungites* firmground and *Teredolites* woodground assemblages at Netarts Bay appear to be potentially mappable as these compact exhumed sediments are relatively planar and are exposed along a great length of the bays eastern margin. Furthermore, the exposure of these strata is a result of base level change associated with overall transgression of the basin. Hence, these surfaces have the potential to be stratigraphically significant entities. However, one must keep in mind the inherent stratigraphic variability and complexity associated with a single transgressive surface that is potentially demarcated by multiple substrates such as firmground, woodground,

stiffground and softground assemblages that may potentially lead to a reduction in its stratigraphic value (Gingras et al., 2001).

## SUMMARY AND CONCLUSIONS

The sedimentological and neoichnological aspects of associated softground, stiffground, firmground and woodground substrates are important to study. By studying organismal burrowing behaviour and the resultant burrow architecture, density and depth within these substrates we are able to potentially deduce the various physico-chemical conditions that were present at the time of substrate colonization. This study examined the various sedimentological and neoichnological aspects of these various substrates in order to ascertain trace assemblages potentially unique to each environment, in addition to assessing the collective stratigraphic significance of these particular substrate surfaces.

The exhumed compact peaty-clay and silty-sand firmgrounds are thought to comprise a *Glossifungites* Ichnofacies assemblage with an associated *Teredolites* Ichnofacies assemblage demarcated by the woodground within the peaty-clay firmground. The peaty-clay firmground is characterized by larger diameter *Thalassinoides*-, *Psilonichnus*-, and *Gastrochaenolites*-like traces; and smaller diameter *Skolithos*-, *Trichichnus*-, *Arenicolites*-, *Diplocraterion*-, *Rhizocorallium*-, and *Polykladichnus*-like traces, with *Gastrochaenolites*-like traces only found within the peaty-clay firmground. The silty-sand firmground was observed to include larger diameter *Thalassinoides*- and *Psilonichnus*-like traces; in addition to smaller diameter *Arenicolites*-, *Skolithos*-, *Trichichnus*-, and *Polykladichnus*-like traces. The woodground associated with the peaty-clay firmground consisted of multiple small traces including *Skolithos*-, *Trichichnus*-, *Arenicolites*-, *Caulostrepsis*-, *Meandropolydora*-, and *Trypanites*-like traces; with a few select larger traces such as *Teredolites*-, *Thalassinoides*- and *Psilonichnus*-like traces. *Teredolites*-, *Trypanites*-, and *Caulostrepsis*-like traces are exclusive to the woodground assemblage. The

peaty-clay firmground consists of a compact peaty or organic rich surface with clay directly below grading down into silty sand. The average firmness calculated for this surface yielded a firmness measurement of  $1.65 \times 10^6$  Pa. The silty-sand firmground, in contrast, was composed of dominantly fine grained sands with an approximate 15% portion of silts and clay. The average firmness of the silty-sand firmground was  $2.08 \times 10^6$  Pa, higher than that of the peaty-clay firmground surface.

Traces within the modern silty sand to clay stiffgrounds consisted of traces akin to *Thalassinoides*, *Skolithos*, *Trichichnus*, *Arenicolites*, *Meandropolydora*, and *Rhizocorallium*, with *Thalassinoides*-like traces being the only large trace type present. A variety of grain sizes occurred within the modern stiffgrounds and depending on location either fine sand, silty sand, silts or clays dominated. Due to the large variability in sediment texture and consistency the overall average firmness across the modern stiffgrounds fluctuated greatly with an overall average firmness value calculated to be  $4.53 \times 10^5$  Pa.

Sediment comprising the surficial softground veneer displayed an array of traces such as *Gordia*-like, *Diplichnites*-like, *Protichnites*-like and *Olivellites*-like surface traces; small, vertical traces akin to lined and unlined *Skolithos*, *Trichichnus*, *Arenicolites*, and *Polykladichnus*; small, horizontal traces akin to *Rhizocorallium*, *Planolites*, *Gyrolithes*, and *Palaeophycus*; large, open *Thalassinoides*- and *Psilonichnus*-like traces; *Piscichnus*-like feeding traces; and finally sediment disruption navichnia and potential cryptic bioturbation features. *Thalassinoides*-like traces produced by upogebiid shrimp commonly penetrated all the way down continuing into the firmground substrate below. The mainly fine- to lower medium-grained sand of the softground veneer had the largest fluctuations in firmness measurements and lowest firmness values due to the presence of water laden, and at times thixotropic, sediments in some areas versus firmer less water laden sediments in others areas. The

overall average firmness value calculated for this highly variable sediment was  $1.73 \times 10^5$  Pa.

The lateral extent of intertidal bay margin firmground and associated woodground deposits witnessed may have significant stratigraphic value, even if variability exists within the deposit due to associated stiffground and softground veneers. However, a more comprehensive sedimentological and neoichnological overview of exposed firmground, woodground, stiffground and softground assemblages along the whole eastern margin of Netarts Bay should be carried out before any definitive assessments of its lateral significance are applied. There is also massive potential for future research involving the paleoecological significance of various substrate-controlled ichnofacies on other exhumed Pleistocene marine terrace deposits along the Washington-Oregon coastline in an array of different intertidal environments including rivers, estuaries, bays and exposed shorelines.

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## CHAPTER 4: CONCLUSIONS

Essentially two main research questions were the focus of this thesis; 1) What are the effects of varying hydraulic energy levels and rates of sediment aggradation or degradation on trace type and distribution due to organism behavioural responses to these parameters?; and 2) What is the paleoecological and stratigraphic significance of trace distribution patterns across interconnected exhumed compact firmground, woodground, modern stiffground and softground veneer substrates. Chapter 2 focused on the role of varying hydraulic energy levels and associated sedimentation rate on organism behaviour and ensuing trace formation as well as distribution. Chapter 3 explored trace genesis in relation to organismal behaviour in an environment consisting of firmground, woodground, stiffground and softground substrate types; as well as the ecological and stratigraphic importance of exhumed firmgrounds and associated woodgrounds.

In chapter 2 it was revealed that the Exposed Shoreface-Spit bay region, located along stretches of open ocean on and around Netarts Spit, experienced overall highest hydraulic energy levels and rates of sedimentation as was evident by the existence of large dune forms and planar bedding with parting lamination features. TOC levels were the lowest of the three bay regions and sediment grain size the highest. Traces were sparse due to the high energy levels associated with the region and any tracemakers present were mainly scavengers or carnivores with lesser amounts of suspension feeding organisms. One organism present, the highly mobile *Olivella biplicata*, could switch between deposit and suspension feeding modes. Overall, traces akin to *Siphonichnus*, *Olivellites*, *Macaronichnus*, *Skolithos*, *Diplichnites* and diminutive *Psilonichnus* were observed along the Exposed Shoreface-Spit bay region. Next, the Outer Sheltered Sandy Tidal Flat bay region, located bayward and just south of the recurved spit portion, experienced moderate energy levels compared to the other two bay regions. TOC varied with lowest TOC levels

occurring on higher energy tidal channel ridges and highest TOC levels occurring within patches of eelgrass within lower energy areas. Grain size was found to be inversely proportional to TOC levels here, so in areas of lowest TOC grain size was the highest, while in areas of highest TOC grain size was the lowest. In the higher energy areas suspension feeding organisms dominated, in addition to organisms capable of switching between deposit and suspension feeding modes. *Thalassinoides*-, *Siphonichnus*-, lined *Skolithos*-, *Macaronichnus*-, *Gordia*- and *Olivellites*-like traces were the most common trace forms present within the higher energy areas. Lower energy areas consisted mainly of subsurface and interface deposit feeding organisms, in addition to essentially immobile suspension feeding bivalves. Traces produced by these organisms were generally akin to *Siphonichnus*, *Thalassinoides*, *Skolithos*, *Trichichnus*, *Arenicolites*, *Palaeophycus*, *Polykladichnus* and *Planolites*. Finally, the Outer-Middle Sandy Tidal Flat bay region, located along extensive sand flats in the eastern middle portion of the bay, experienced the lowest hydraulic energy levels and rates of sedimentation. Overall, TOC levels were generally higher and sediment grain size slightly less compared to the other two bay regions. Tracemakers and associated traces of the Outer-Middle Sandy Tidal Flat bay region were very similar to those of lower energy areas of the Outer Sheltered Sandy Tidal Flat bay region where there was a predominance of subsurface and interface deposit feeders with an abundance of relatively sessile, deep burrowing suspension feeding bivalves. One of the exceptions included the presence of worms that created *Cylindrichnus*-like or lined *Skolithos*-like traces near the edges of tidal creeks or water laden eelgrass fields.

Overall, it was concluded that the majority of trace assemblages observed in the outer to exposed regions of Netarts Bay displayed their own unique assemblage of traces similar but distinct from the *Skolithos* Ichnofacies. Clean, well sorted, shifting sands characterized the environment where abrupt changes in sedimentation rates occurred allowing physical sedimentary structures to occasionally dominate over biogenically produced structures.



MacEachern et al. (2007) described the archetypal *Skolithos* Ichnofacies as being comprised of vertical, single entrance to U-shaped burrows, and branching trace forms. Similar trace forms that are not attributable to the *Skolithos* Ichnofacies in Netarts Bay are *Skolithos*-, *Palaeophycus*-, *Arenicolites*-, *Siphonichnus*-, *Macaronichnus*-, and *Cylindrichnus*-like traces. Trace associations that are similar to the distal expressions of the *Skolithos* Ichnofacies, but are their own unique associations, are observed along exposed tidal channel margins of Netarts Bay where there are abundant *Skolithos*-, and *Palaeophycus*-like traces. Unique associations similar to but distinct from a distal *Skolithos* Ichnofacies expression were also witnessed in large areas of the Outer Sheltered Sandy Tidal Flat and Outer-Middle Sandy Tidal Flat bay regions where deposit feeding structures akin to *Siphonichnus*-, *Macaronichnus*-, *Cylindrichnus*-, *Planolites*-, and *Thalassinoides* occur. MacEachern et al. (2007) described the archetypal *Cruziana* Ichnofacies as being comprised of various horizontal and vertical trace forms that arise due to the availability of suspended, as well as, deposited food resources in a lower energy setting compared to that of the *Skolithos* Ichnofacies. In Netarts Bay somewhat similar expressions of traces compared to the *Cruziana* Ichnofacies traits are observed in the calmer eelgrass fields or protected tidal creeks. In these areas bedding is heavily bioturbated and sediment exhibits an accumulation of silt, in addition to organic detritus, due to eelgrass baffling and relatively rapid decreases in hydraulic energy levels. Traces characteristic of this lower energy assemblage have their own unique identity and are not attributable to a *Cruziana* Ichnofacies assemblage although they may have similar characteristics. Traces included in this unique assemblage are akin to *Siphonichnus*, *Cylindrichnus*, *Planolites*, and *Thalassinoides*.

Chapter 3 revealed that the exhumed compact peaty-clay and silty-sand firmgrounds are thought to comprise a *Glossifungites* Ichnofacies assemblage with an associated *Teredolites* Ichnofacies assemblage demarcated by the woodground within the peaty-clay firmground. These surfaces are thought to

be laterally extensive and could potentially generate stratigraphically significant surfaces. Firmgrounds comprising a *Glossifungites* Ichnofacies assemblage are characteristically dominated by vertical to sub-horizontal unlined, sharp walled, relatively large, robust dwelling structures of suspension and deposit feeding organisms in a compact unlithified marine substrate (Seilacher, 1967; Frey and Seilacher, 1980; Pemberton and Frey, 1985; MacEachern et al., 1992; MacEachern et al., 2007). Many traces characteristic of the *Glossifungites* Ichnofacies were discovered along the firmgrounds of the eastern margin of Netarts Bay including *Thalassinoides*-, *Psilonichnus*-, *Gastrochaenolites*-, *Skolithos*-, *Arenicolites*-, *Diplocraterion*-, and *Rhizocorallium*-like traces. The modern *Teredolites* Ichnofacies assemblage discovered at Netarts Bay was found to contain a diverse array of trace forms, in stark contrast to the otherwise monotonous *Teredolites* Ichnofacies assemblage dominated solely by *Teredolites* in ancient examples as described by such authors as Bromley et al. (1984) and Savrda (1991). In addition to *Teredolites*, other traces discovered associated with the woodground substrate in Netarts Bay included *Skolithos*-, *Trichichnus*-, *Arenicolites*-, *Caulostrepsis*-, *Meandropolydora*-, *Trypanites*-, *Thalassinoides*- and *Psilonichnus*-like traces as well as an abundance of squatters and encrusters. A variety of traces similar to, but slightly different than, the firmground assemblages were also observed within sporadic stiffground patches and within overlying soft sediment veneer; however these substrates were found to be of less stratigraphic importance as individual entities. The importance of these substrates arose after observing that they commonly form a veneer covering the firmground surface causing various amounts of trace tiering throughout the firmground substrate depending on depth of veneer cover. This variability in trace penetration, or tiering, is important to realize as it has implications relating to the interpretation of firmground surfaces. The study also revealed that the exhumed compact firmground substrates had consistent and overall highest firmness values,

while modern stiffgrounds and softgrounds had highly variable firmness values with softgrounds having the least overall firmness values assessed.

This thesis therefore concluded that the majority of Netarts Bay displays elements common, but not attributable to the *Skolithos* Ichnofacies with select lower energy areas displaying elements that resemble, but are not attributable to distal expressions of the *Skolithos* Ichnofacies and proximal expressions of the *Cruziana* Ichnofacies. Finally, intertidal bay margin firmground and associated woodground deposits are thought to be attributed to a *Glossifungites* and *Teredolites* Ichnofacies assemblage, respectively, potentially having stratigraphic importance. It is also evident that there are certain limitations to this study and additional investigation needs to be conducted in order to further assess the nature of trace distribution within the bay. The effects of hydraulic energy and sedimentation rate on trace distribution should also be carried out in other fully marine bays for comparison, where such findings can potentially be applied to interpreting similar sequences witnessed in the rock record. Sequences of higher energy barrier spit complexes may potentially have low preservation potential, but may be more commonly preserved than first thought; therefore further study is beneficial in delineating these environments in the rock record. Research on firmground, woodground, stiffground and softground assemblages should be assessed further in Netarts Bay and carried out on other exposed Pleistocene outcrops located along the Washington-Oregon coast before any definitive statements concerning its lateral significance is applied.

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