Late Pleistocene Littoral Deposits in the Deming Sand at Bellingham Bay, Washington, and Their Implications for Relative Sea Level Changes

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LATE PLEISTOCENE LITTORAL DEPOSITS IN THE DEMING SAND AT BELLINGHAM BAY, WASHINGTON, AND THEIR IMPLICATIONS FOR RELATIVE SEA LEVEL CHANGES

By
Stacy J. Weber

Accepted in Partial Completion of the Requirements for the Degree of Master of Science

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Dr. Christopher Suczek, Committee Member

Doris J. Kovanen, Committee Member
MASTER’S THESIS

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Stacy J Weber
February 22, 2018
LATE PLEISTOCENE LITTORAL DEPOSITS IN THE DEMING SAND AT BELLENGHAM BAY, WASHINGTON, AND THEIR IMPLICATIONS FOR RELATIVE SEA LEVEL CHANGES

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

By

Stacy J. Weber

May 2001
ABSTRACT

Recent mass wasting of sea cliffs along Bellingham Bay in Northwest Washington has exposed late Pleistocene littoral deposits in the Deming sand, which is underlain by Kulshan glaciomarine drift (gmd) and overlain by Bellingham glaciomarine drift (Easterbrook 1963). Marine shells in the Kulshan gmd were dated at $12,210 \pm 80 \text{ C-yr B. P.}$ and marine shells in the Deming sand were dated at $11,760 \pm 85$ and $11,685 \pm 85 \text{ C-yr B. P.}$ Marine shells in the Bellingham gmd were dated at $12,150 \pm 210 \text{ C-yr B. P.}$

Fossiliferous Kulshan glaciomarine drift is overlain by 11.5 m of well-sorted, medium-grained, horizontally bedded and cross-bedded sand and sandy gravel with two silt and clay interbeds 0.57 m and 0.88 m thick. Evidence for a littoral environment includes (1) many cross-bedded, pebbly-sand beds containing abundant, abraded shells, abraded worm tubes, and shell fragments, (2) armored mud balls, (3) thin layers of concentrated garnet/magnetite sand common to beaches and 4) thick, well-indurated silt and clay characteristic of tidal flat deposits. All of these features mirror those in a shallow marine environment undergoing tidal phases and shoreline processes. Fossiliferous Bellingham glaciomarine drift approximately 11 meters thick caps the section.

The exposure of Deming sand between the Kulshan and Bellingham gmds at Bellingham Bay mimics the stratigraphic order at the Everson type locality ca. 45 km to the east, which corroborates Easterbrook's (1963) hypothesis that the Deming sand throughout Whatcom County is fluvial in origin. This relationship plays a central role...
in the complex history of relative sea level changes. The Deming sand fixes relative
sea level at approximately 10-20 m above present sea level, and because the
Bellingham and Kulshan gmds occur at present elevations of ~100 and 200 m, that
means relative sea levels must have fluctuated by at least approximately 100 m from
the Kulshan to the Deming, and at least 200 m from the Deming to the Bellingham.
Thus, the inference that sedimentation at the Everson type section was solely glacial
(Croll, 1980; Dragovitch et al., 1997) with no fluctuations of local relative sea level is
challenged.
ACKNOWLEDGMENTS

The process and completion of this thesis is due to the help of many individuals without whom I would still be wandering the shores of Bellingham Bay. First, I want to express a deep and abundant gratitude to my committee members. Don Easterbrook, what can I say? You are a brilliant, kind, and fun gentleman. I am honored and moved that you would trust me with an important subject such as the one I have attempted to understand. Thank you for your continued guidance and teaching throughout my academic career. You truly are the Pleistocene god! Dori Kovanen... girlfriend, you (and Don) saved me. Thank you for your two-year persistence in convincing me that this project was truly worth studying. Dori, not only are you an amazing and intelligent scientist (and the smartest field geologist this side of the world), but your friendship has been such a bonus to this project. Thank you, as well, for the beautiful DEM’s you created to make this project so much prettier! Also, much gratitude for your endless help with radiocarbon dates. I look forward to reading about the famous and exciting discoveries both you and Don find.

Chris Suczek, at the beginning of this project, you mentioned that your time was very limited to helping me. Thank God that idea has been thrown out the window. I can’t even imagine tackling Chapter 4 (depositional environments) without you. Thank you, Chris, for your countless thoughts and time spent on helping me to understand what in the world is going on. Thor Hansen, thank you for agreeing to chair my committee so that this project could actually be attempted. Although we did not have much contact throughout this project, your help in identifying fossils was greatly appreciated. You saved me a ton of time! Thank you.
John de LaChapelle, if I ever need any kind of digging done anywhere in the world, YOU ARE THE MAN! Thank you, John for all your hard work and time spent helping to kick-start my field work. I had a blast working with you. My academic career was that much more enjoyable with you in it. George Mustoe, thank you for the step-by-step help with the heavy mineral analysis. Also, your constant help in anything mechanical throughout my many years in academia will forever be remembered and appreciated. Thank you Chris Sutton and Vicki Critchlow for your help over the years in answering any questions I had regarding “red tape”. And Chris, I will miss our many conversations about the canine world. Emma says “thanks” for the cookies.

Great thanks go to my good friends and running buddies Erin Hamernyik and Karen Welch. Your friendship throughout this entire process saved me from many meltdowns. I can’t imagine going through this process without you both. BOB! (Langan) Thank you for your humor and conversations throughout this lengthy process. Your perfect timing in checking in with me was a saving grace. Thank you for such a solid friendship. Mara and Mark, your continued prayers are appreciated more than you can imagine. My, I am so fortunate to have a fun, intelligent and sensitive sister as you. Ma and Pa, I love you both so much. I guess we all thought this day would never come. Thank you for your constant love. Last, but certainly not least, to the best husband and most brilliant pack maker in the world. Brent, your love, patience, kindness, humor, and constant support throughout this whole project did not go unrecognized. Thank you for believing in me every step of the way.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iv</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xiii</td>
</tr>
</tbody>
</table>

## CHAPTER 1 – INTRODUCTION
- Report Organization ........................................................................ 2
- Geologic Setting ............................................................................. 2
- Regional Chronology ........................................................................ 3
- Previous Studies of the Everson interval ...................................... 7
- Study Area ...................................................................................... 15
- Objectives of Study ........................................................................ 16

## CHAPTER 2 – STRATIGRAPHY AND SEDIMENTATION
- Field and Lab Methods .................................................................... 17
- Lab Results .................................................................................... 20
- Field Results ................................................................................ 21

## CHAPTER 3 – SUBSURFACE AND OUTCROP STRATIGRAPHY
- Subsurface and Outcrop Methods ..................................................... 54
- Subsurface and Outcrop Results ..................................................... 55

## CHAPTER 4 – DEPOSITIONAL ENVIRONMENTS
- Laminated Sand Facies ..................................................................... 61
- Structureless Mud Facies .................................................................. 75
- Cross-stratified Facies .................................................................... 85
- Gravel Facies .................................................................................. 106
- Other Types of Deposits .................................................................. 116

## CHAPTER 5 – IMPLICATIONS FOR SEA LEVEL CHANGES
- Relative Sea Level Changes during the Everson Interval .................. 125

## CHAPTER 6 – SUMMARY AND CONCLUSIONS
- Summary of Findings ....................................................................... 130

REFERENCES ...................................................................................... 138
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Multiple lobes of the Cordilleran ice sheet</td>
</tr>
<tr>
<td>2</td>
<td>Puget Lobe of the Cordilleran ice sheet</td>
</tr>
<tr>
<td>3</td>
<td>Location of Everson type locality</td>
</tr>
<tr>
<td>4</td>
<td>Everson type locality and associated radiocarbon dates</td>
</tr>
<tr>
<td>5</td>
<td>Location of proposed MacCauley creek fault</td>
</tr>
<tr>
<td>6a</td>
<td>Location of study site</td>
</tr>
<tr>
<td>6b</td>
<td>Location of Bellingham Bay exposure</td>
</tr>
<tr>
<td>7</td>
<td>Bellingham Bay stratigraphic column</td>
</tr>
<tr>
<td>8</td>
<td>Bellingham Bay sequence</td>
</tr>
<tr>
<td>9</td>
<td>Five pits dug in Bellingham Bay sequence</td>
</tr>
<tr>
<td>10</td>
<td>Units A through B</td>
</tr>
<tr>
<td>11</td>
<td>Armored mudballs within Unit A</td>
</tr>
<tr>
<td>12</td>
<td>Shells, mudballs and worm tubes in Unit A</td>
</tr>
<tr>
<td>13</td>
<td>Worm tube and shells in Unit B</td>
</tr>
<tr>
<td>14</td>
<td>Units C through D</td>
</tr>
<tr>
<td>15</td>
<td>Heavy mineral deposit at Unit C through D contact</td>
</tr>
<tr>
<td>16</td>
<td>Units E through F (including slump zone)</td>
</tr>
<tr>
<td>17</td>
<td>Tangential and planar strata in Unit E</td>
</tr>
<tr>
<td>18</td>
<td>Reworked worm tubes within Unit E</td>
</tr>
<tr>
<td>19</td>
<td>Lenticular bedding at base of Unit F</td>
</tr>
<tr>
<td>20</td>
<td>Unit G with <em>Chlamys</em> shell</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>21</td>
<td>Unit H and Unit G</td>
</tr>
<tr>
<td>22</td>
<td>Units I through Unit L</td>
</tr>
<tr>
<td>23</td>
<td>Deformation structure within upper Unit I</td>
</tr>
<tr>
<td>24</td>
<td>Hummocky strata within Unit J</td>
</tr>
<tr>
<td>25</td>
<td>Unit K through Unit N</td>
</tr>
<tr>
<td>26</td>
<td>Unit O and soft-sediment deformation structures</td>
</tr>
<tr>
<td>27</td>
<td>Unit P</td>
</tr>
<tr>
<td>28</td>
<td>Unit Q</td>
</tr>
<tr>
<td>29</td>
<td>Unit R</td>
</tr>
<tr>
<td>30</td>
<td>Units S through Unit V</td>
</tr>
<tr>
<td>31</td>
<td>Trough cross strata within Unit S</td>
</tr>
<tr>
<td>32</td>
<td>Unit U through Unit V</td>
</tr>
<tr>
<td>33</td>
<td>Unit W</td>
</tr>
<tr>
<td>34</td>
<td>Unit X through Unit AA and Bellingham gmd</td>
</tr>
<tr>
<td>35</td>
<td>Tangential and planar laminae within Unit X</td>
</tr>
<tr>
<td>36</td>
<td>Unit Y through Unit Z</td>
</tr>
<tr>
<td>37</td>
<td>Unit AA and contact with Bellingham glaciomarine drift</td>
</tr>
<tr>
<td>38</td>
<td>Bellingham glaciomarine drift</td>
</tr>
<tr>
<td>39</td>
<td>Everson type section</td>
</tr>
<tr>
<td>40</td>
<td>Deming sand of Everson type section</td>
</tr>
<tr>
<td>41</td>
<td>Rooted stump in Deming sand of Everson type section</td>
</tr>
<tr>
<td>42a</td>
<td>Deming site: Bellingham gmd and Deming sand contact</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>42b</td>
<td>Deming site: Close-up photo of contact</td>
</tr>
<tr>
<td>43</td>
<td>Shuksan Golf course exposure</td>
</tr>
<tr>
<td>44</td>
<td>Contact locations and elevations for geologic cross-section</td>
</tr>
<tr>
<td>45</td>
<td>Geologic cross-sections from composite sections</td>
</tr>
<tr>
<td>46</td>
<td>Development of unidirectional flow bedform development</td>
</tr>
<tr>
<td>47</td>
<td>Point bar model and associated deposits</td>
</tr>
<tr>
<td>48</td>
<td>Generalized point bar sequence model</td>
</tr>
<tr>
<td>49</td>
<td>Generalized levee sedimentation cycles</td>
</tr>
<tr>
<td>50</td>
<td>Profile of beach and nearshore zone</td>
</tr>
<tr>
<td>51</td>
<td>Bouma and Hsu sequence</td>
</tr>
<tr>
<td>52</td>
<td>Kame delta and associated sedimentary structures</td>
</tr>
<tr>
<td>53</td>
<td>Morphological elements of a meandering stream</td>
</tr>
<tr>
<td>54</td>
<td>Schematic diagram of a tidal-flat environment</td>
</tr>
<tr>
<td>55</td>
<td>Diagram of lenticular bedding</td>
</tr>
<tr>
<td>56</td>
<td>Generalized progradational sequence of tidal-flat environment</td>
</tr>
<tr>
<td>57</td>
<td>Generalized stratigraphic sections for three principal delta types</td>
</tr>
<tr>
<td>58</td>
<td>Changes in foreset laminae due to velocity increases</td>
</tr>
<tr>
<td>59</td>
<td>Facies model of nearshore barred topography</td>
</tr>
<tr>
<td>60</td>
<td>Generalized profile of ridge and runnel profile</td>
</tr>
<tr>
<td>61</td>
<td>Longitudinal (epsilon) bedding within a tidal channel</td>
</tr>
<tr>
<td>62</td>
<td>Diagrammatic representation of climbing ripple lamination</td>
</tr>
<tr>
<td>63</td>
<td>Diagram of glaciolacustrine deltas</td>
</tr>
</tbody>
</table>
Cross-bedding types formed due to wave action ............................................. 102
General diagnostic features of wave cross-lamination .................................. 103
General stratigraphic models for gravel-dominated streams .......................... 108
Sheetflood deposits within an alluvial fan .............................................. 111
Different types of cross-bedding within subaqueous deposits ....................... 113
Distribution of sediment within the breaker zone .................................... 117
Generalized barrier beach sequence ....................................................... 119
Approximate relative sea level during deposition of Kulshan gmd ............... 126
Approximate relative sea level during deposition of Deming sand ............... 127
Approximate relative sea level during deposition of Bellingham gmd ....... 128

LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Late Pleistocene sequence in the Northern Puget Lowland .................. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Heavy mineral percentages from upper 2 cm of Unit C .................. 21</td>
</tr>
<tr>
<td>3</td>
<td>Radiocarbon and calibrated dates from Bellingham Bay .................. 52</td>
</tr>
<tr>
<td>4</td>
<td>Radiocarbon and calibrated dates from Everson type section ........... 53</td>
</tr>
<tr>
<td>5</td>
<td>Characteristic bedforms associated with sediment size and velocity .... 63</td>
</tr>
<tr>
<td>6</td>
<td>Ripples within the Bellingham Bay sequence ................................ 105</td>
</tr>
<tr>
<td>7</td>
<td>Approximate relative sea level during Everson Interstade .............. 129</td>
</tr>
<tr>
<td>8</td>
<td>Description and interpretation of various Bellingham Bay units ....... 131</td>
</tr>
<tr>
<td>Appendix</td>
<td>Description</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>Appendix I</td>
<td>Sieve Analysis Histograms</td>
</tr>
<tr>
<td>Appendix II</td>
<td>Heavy Mineral Raw Data</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

The mode of deposition and paleoenvironment of late Pleistocene Everson-age sediments in the northern Fraser Lowland have long been a source of interest and debate (Armstrong and Brown, 1954; Armstrong et al., 1965; Armstrong, 1981; Easterbrook, 1963, 1969, 1992; Croll, 1980; Balzarini, 1981, 1983; Kovanen and Easterbrook, 2000). At the Everson type locality, Deming sand stratigraphically separates the Bellingham and the Kulshan glaciomarine drifts (Easterbrook, 1963; 1992). An exposure of Deming sand between the Kulshan and Bellingham glaciomarine drifts at Bellingham Bay, northwest Washington, mirrors the stratigraphic sections at the Everson type locality. Recent evidence from these Everson-age deposits at Bellingham Bay suggests a littoral paleoenvironment for these sediments and that they are chronostratigraphically equivalent to the Deming sand at the Everson type locality. These results imply that rapid relative sea level changes occurred.

The primary objectives of this study were to: 1) perform a sedimentary study and determine the depositional environment of the 11.5-m Bellingham Bay exposure; 2) if possible, correlate the sediments of the Bellingham Bay site with the established stratigraphic record (e.g., Easterbrook, 1963, 1992).
REPORT ORGANIZATION

This report is divided into six chapters: chapter 1 provides an introduction; chapter 2 discusses the stratigraphy and sedimentation methods and results at the Bellingham Bay site; chapter 3 explores the subsurface and outcrop stratigraphy from the Everson type section to the Bellingham Bay site; chapter 4 discusses the depositional environments of the Bellingham Bay deposits; chapter 5 investigates the implications of rapid sea level changes during the Everson Interstade; and chapter 6 is the summary and conclusions.

GEOLOGIC SETTING

The late Pleistocene Fraser Glaciation (~22,000 to 10,000 14C yrs B. P.) was the last continental glaciation of the Puget and Fraser Lowland (Armstrong et al. 1965). The Cordilleran Ice Sheet originated in the Coast Mountains of British Columbia and occupied much of northern Washington. The western part of the ice sheet split into the Puget and Juan de Fuca lobes, while the eastern part of the ice sheet formed the Okanogan and Pend Orielle ice lobe (Figure 1). The Puget lobe

![Figure 1. Map showing lobes of the Cordilleran Ice Sheet (Easterbrook, 1992; modified after Clague, 1980).](image-url)
extended southward into the Puget Lowland between the Cascade Range and the Olympic Mountains (Figure 2).

Multiple climatic fluctuations during the Fraser Glaciation resulted in the waxing and waning of the Puget lobe. As a result of the oscillatory behavior of the Cordilleran Ice Sheet, a remarkable depositional history is displayed throughout the northern Puget Lowland of western Washington. The depositional facies of this area represent alternating periods of glacial and nonglacial activity.

**REGIONAL CHRONOLOGY**

The Fraser Glaciation is divided into three stades and one interstade (Table 1). All of the stades except the Evans Creek Stade are represented by deposits in the

![Figure 2. The Puget Lobe of the Cordilleran Ice Sheet at late Pleistocene glacial maximum. Surface contours shown in meters above sea level. Arrows are ice flow directions from drumlin topography on Vashon drift (Kovanen and Easterbrook, 2001).](image-url)
Table 1. Late Pleistocene Sequence in the Northern Puget Lowland.

<table>
<thead>
<tr>
<th>GEOLOGIC CLIMATE UNIT</th>
<th>STRATIGRAPHIC UNITS IN THE FRASER LOWLAND</th>
<th>RADIOCARBON AGE (¹⁴C YEARS B. P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>British Columbia</td>
<td>Northern Puget Lowland</td>
</tr>
<tr>
<td>Sumas Stade</td>
<td>Sumas Drift</td>
<td>Sumas Drift</td>
</tr>
<tr>
<td></td>
<td>• Sumas IV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Sumas III</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Sumas II</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Sumas I</td>
<td></td>
</tr>
<tr>
<td>Everson Interstade</td>
<td>Fort Langley and Capilano Sediments</td>
<td>Bellingham glaciomarine drift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deming sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kulshan glaciomarine drift</td>
</tr>
<tr>
<td>Vashon Stade</td>
<td>Vashon Drift</td>
<td>Vashon till</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Esperance sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lawton clay</td>
</tr>
<tr>
<td>Evans Creek Stade</td>
<td>Evans Creek drift</td>
<td></td>
</tr>
<tr>
<td>(Alpine Glaciation)</td>
<td>Early beginnings of Cordilleran Ice Sheet</td>
<td></td>
</tr>
</tbody>
</table>

* Most of the units are time-transgressive, therefore, the ages shown are approximate. (modified from Armstrong et al. 1965; Armstrong, 1981; Easterbrook, 1963, 1986, 1992; Kovanen, and Easterbrook, 2001, in press).

northern Puget Lowland (Easterbrook, 1969, 1986). During the Vashon Stade (~18,000 - 13,000 ¹⁴C yrs B. P.), the ice sheet was more than a mile thick in Bellingham (Easterbrook, 1963, 1986). Younger deposits cover most of the sediments deposited during the Vashon Stade in the Whatcom County area.
Rapid melting and thinning of the Vashon glacier marked the time from 14,500 to 13,000 yrs B. P. The Everson Interstade commenced approximately 12,300 \(^{14}\)C yrs B. P. (Armstrong et al., 1965; Easterbrook, 1963, 1969; Kovanen and Easterbrook, 2001). Marine waters entered the Puget Lowland through the Strait of Juan de Fuca as the Puget lobe retreated and floated the thinning ice. Glaciomarine sediments accumulated over an area of \(\sim 18,000 \text{ km}^2\) including the central and northern Puget Lowland, San Juan Islands (Easterbrook, 1963, 1966, 1969, 1992), and southwestern British Columbia (Armstrong, 1981; Armstrong and Brown, 1954; Armstrong et al. 1965). As the ice retreated, glacioisostatic rebound commenced.

During the Everson Interstade, rapid changes of relative sea level occurred. Over the span of less than 1500 years, the lowland of Whatcom County twice was submerged several hundred feet beneath the sea and twice emerged (Easterbrook, 1963, 1992). Evidence for the rapid relative sea level fluctuations can be seen in the stratigraphic section of the type locality of the Everson glaciomarine drift. Here, a fluvial sand (Deming sand) separates two members of the Everson glaciomarine drift, the Kulshan and Bellingham glaciomarine drifts (Easterbrook, 1963, 1992).

The type section of the Everson Interstade (Figure 3) is located in the Nooksack Valley of western Whatcom County (NE \(\frac{1}{4}\) sec, 34, T39N, R4E) (Easterbrook, 1963; Armstrong et al., 1965). At the top of the section is Bellingham glaciomarine drift (gmd), composed of massive, poorly-sorted, unstratified, fossiliferous, blue-gray to brown, pebbly, sandy, clay and silt (Figure 4) (Easterbrook, 1963, 1969). The Deming sand, which lies directly beneath the Bellingham
Figure 3. Location and exposure (between arrows) of Everson type locality in western Whatcom County.

glacimarine drift, consists mostly of stratified sand and clay with minor gravel. Peat and *in situ* rooted tree stumps near the base of the Deming sand at its type locality demonstrate that the sediments there are non-marine (Easterbrook, 1962, 1963, 1986; Kovanen and Easterbrook, 2000). Beneath the Deming sand, the Kulshan glacimarine drift consists of a massive, blue-gray, poorly-sorted, unstratified, fossiliferous diamicton. Easterbrook (1963) commented on the close similarity between the Bellingham and Kulshan glacimarine drifts; at some localities where the two units are not separated by the Deming sand, they are very difficult to distinguish. More recently, Easterbrook and Kovanen (1997a, 1997b) discovered that landslides at the Everson type locality had exposed another fluvial sand and silt unit beneath the Kulshan glacimarine drift.

A readvance of the Cordilleran Ice Sheet during the Sumas Stade (~11,500 - 10,000 $^{14}$C yrs B. P.) marked the last of the three stades. At this time, a piedmont ice

Sumas drift, which consists of till, outwash, and ice-contact deposits (Armstrong et al., 1965, Easterbrook, 1963, 1969) rest directly upon Everson glaciomarine drift. The Sumas Stade was originally defined as a readvance of the ice sheet following rapid deglaciation and deposition of the Everson glaciomarine drift. However, recent $^{14}$C dates (Kovanen and Easterbrook, 1997, 2001, in press) demonstrate four readvances of the ice sheet in the northern Puget Lowland during the Sumas Stade.

**PREVIOUS STUDIES OF THE EVERSON INTERVAL**

Early workers on glacial deposits in the Puget Lowland (Willis, 1898; Bretz, 1913) and Fraser Lowland (Clapp, 1912, 1913; Johnston, 1921, 1923) recognized
marine shells in till-like deposits in glacial drifts. However, Armstrong and Brown (1954) were the first to recognize these diamictons in British Columbia as having a glaciomarine origin and coined the term “marine drift.” They suggested that rainout from floating ice in marine water was responsible for the deposition of glaciomarine drift from shelf ice, berg ice, or sea ice. In southern British Columbia, unconsolidated deposits include Everson glaciomarine drift (Armstrong, 1956, 1957, 1960, 1980, 1981). In the northern and central Puget Lowland and San Juan Islands Easterbrook (1963, 1969, 1976) mapped and recognized floating ice in seawater as the source for the glaciomarine drift.

THE EVERSON TYPE SECTION AND SEA LEVEL CHANGES

The Everson type locality (Figure 4) records a stratigraphy that suggests rapid sea level fluctuations occurred during the late stages of deglaciation. Easterbrook (1963, 1992) demonstrated that 450 to 700 feet of submergence, emergence to 40 feet above present sea level, resubmergence of 400 to 700 feet, and emergence to present sea level occurred in 1000 to 1500 years during the Everson Interstade. Because such rapid sea level fluctuations took place, Easterbrook (1963, 1992) suggested a combination of complicated mechanisms involving eustatic sea level changes, isostatic rebound, and tectonic events.

Mathews et al. (1970) found similar evidence for rapid, post-Vashon emergence of hundreds of feet (200 to 500 ft) on eastern Vancouver Island in southwestern British Columbia. A succession of emergent deltas upstream from many creek mouths contains marine shells and driftwood associated with foreset and
Armstrong (1957, 1981, 1984) found evidence for post-Vashon land emergence and resubmergence in the Fraser Lowland of southwestern British Columbia. Subaerial and deltaic deposits consisting of gravel and sand are found sandwiched between two glaciomarine units throughout the Fraser Lowland (Armstrong, 1960). In addition, radiocarbon dates of glaciomarine and marine (beach and intertidal) sediments throughout the Fraser lowland indicate more than one post-Vashon sea level submergence and subsequent emergence occurred (Armstrong, 1981). In the lower Capilano River basin, seven ancient strandlines within raised delta deposits are marine in origin (Armstrong, 1981). The seven terraces marked seven stands of the sea (strandlines) at various elevations: 185, 155, 105, 90, 60, 40 and 25 m.

**Original Hypothesis of Easterbrook**

Because of the complex story revealed by the stratigraphy at the Everson type locality, the mode of deposition of the Bellingham glaciomarine drift and the Deming sand during the Everson Interstade has been and still is a subject of much debate. Easterbrook (1963, 1992) suggested shelf and berg ice were the likely source for the glaciomarine drift. Easterbrook (1992) presents conclusive evidence for a fluvial origin of the Deming sand at the type section and presented evidence against a calving-ice model (Domack, 1983) for the origin of the glaciomarine drift, as summarized below.

2. Four *in situ* tree stumps have been found in the basal peat bed. All the stumps have root systems that extend into the underlying substrate, and therefore, they could not have been transported from elsewhere.

3. The Deming sand consists almost entirely of phyllite sand-size grains derived from the Darrington Phyllite, which crops out near the type locality.

4. No marine evidence has ever been documented associated with the Deming sand at its type locality (i.e., deltaic sediments, shells, *Foraminifera*).

5. Abundant erratic pebbles and cobbles from British Columbia occur within the Bellingham glaciomarine drift. These must have come from Cordilleran ice and not from a local up-valley source.

6. Abundant $^{14}$C dates from the glaciomarine drift demonstrate simultaneous deposition of the glaciomarine sediment over a very large area. A progressively northward retreating, calving, backwasting glacier terminus would require northward time-transgressive deposition of the glaciomarine drift over 170 km. Therefore, the glaciomarine drift in the northern part of the region (Northern Whatcom County and British Columbia) should be younger than the glaciomarine drift in the southern part (Seattle and...
Everett) of the region. However, the opposite exists; the oldest $^{14}$C dates from the glaciomarine drift are in the northernmost part of the region.

Recent evidence further supports the idea that rapid changes in sea level took place during the Everson Interstade (Easterbrook and Kovanen, 1997a; 1997b; Kovanen and Easterbrook, 2000). At the Everson type locality, another subaerial fluvial deposit beneath the Kulshan glaciomarine drift suggests that the lowland was just above relative sea level prior to the deposition of the Kulshan glaciomarine drift. The deposition of two stratigraphically different glaciomarine units directly on fluvial sand units suggests that multiple, rapid, relative sea level fluctuations occurred.

**Alternative Hypotheses**

Croll (1980) questioned the regional sea level fluctuations proposed by Easterbrook (1963) and challenged the mode of deposition for both the Bellingham glaciomarine drift and the Deming sand. Croll (1980; p. 27, 39, 40) contended that the Deming sand was deposited “by subglacial, or englacial, submarine meltwater streams,” that “the Bellingham glaciomarine drift is not in place,” and that the Bellingham glaciomarine drift has “a maximum thickness of about 2 m.” He explains peat and rooted stumps at the base of the Deming at the type locality as subglacial submarine: “one could still interpret the peat as having been transported if the stump had floated into the sea, settled through the water column, and had its roots buried by accumulating glacialmarine drift as the stump came to rest on the bottom” (Croll, 1980; p. 34). Croll concluded that no changes in relative sea level were required to explain the position of the Deming sand between the Kulshan and Bellingham
glaciomarine drifts. He misidentified small sand lenses within the Bellingham glaciomarine drift near Bellingham as the Deming sand and argued that this constituted proof that the Deming was marine. However, at the type locality, and at Bellingham Bay, the Deming sand is a single, thick (up to 20 m), depositional unit with no interbedded glaciomarine drift. Croll’s contention that the Bellingham glaciomarine drift was not in place and only 2 m thick is not supported by the facts that (1) the Bellingham is 20 m thick at its type locality, (2) covers some 18,000 km², and (3) makes an unbroken surface mantle traceable continuously from the type locality to Bellingham Bay. Curiously, in contrast to arguments in his main text, Croll’s summary switches to the idea that the Deming sand at its type locality was deposited by the Nooksack River at the margin of a marine embayment, despite the fact that it underlies Bellingham glaciomarine drift to elevations of 200 m. Croll’s alternative hypothesis must be rejected by the evidence for relative sea levels of the Deming sand and overlying and underlying glaciomarine drifts demonstrated in this thesis.

Balzarini (1981, 1983) studied fauna in the Everson age sediments and suggested that only a single glaciomarine drift unit exists and that the Deming sand is a lensoidal deposit. Balzarini (1981, 1983) found that fauna sampled from the marine diamictons represent paleoenvironmental conditions of cold (-2° to 25° C) shallow waters (<60 m). All species except one are normal marine and live in the present marine waters. Balzarini (1983) proposed that meltwater from retreating glaciers and water from rivers were the main agents of sedimentation during the Everson
Interstade in marine areas of the northern Puget-Fraser Lowland, in contrast to Armstrong’s (1956, 1981) and Easterbrook’s (1963) model of sedimentation from melting berg ice. Balzarini’s explanation for the differences, stratigraphically and structurally, between the Deming sand and the glaciomarine sediments is that the sediment source varied. River-borne sediments may have added coarse-grained terrigenous material rich in organic detritus to the fine-grained glacial marine sediments. She states that if the sediment sources were variable, then sedimentation would also have been variable.

Balzarini (1981) adopted Croll’s model (1980) for continuous emergence of the Northern Puget Lowland during deglaciation. The model involves “concurrent deposition of glaciomarine sediments and submarine outwash deposits in front of a steadily-retreating ice sheet; no pronounced reversals of sea level or tectonic movement are required ” (Balzarini, 1981; p. 60). Her hypothesis is not consistent with new sedimentologic evidence found in this study.

Domack (1983) suggested the Everson glaciomarine drift was deposited by calving ice from a backwasting ice front with deposition of glaciomarine drift moving progressively northward through time from its southern limit (Whidbey Island area) to its northern limit in British Columbia. However, $^{14}$C dates do not show a northward time-transgressive deposition of glaciomarine drift.

Dragovich et al. (1997a) suggested that the Deming sand is a local interbedded unit within the glaciomarine drift and fluvial or possibly submarine outwash in origin. Dragovich et al. (1997b) later proposed that late Pleistocene local movement along
the MacCauley Creek thrust (Figure 5), which is approximately 3 km east of the Everson type locality, induced uplift and is responsible for the transition from marine to fluvial conditions, explaining the multiple, rapid reversal of sea level changes documented by Easterbrook (1963, 1992). However, recent computer-generated images from DEM's (digital elevation model) display a continuous, unbroken bench of Bellingham glaciomarine drift at the marine limit extending from east of the Everson type locality to Bellingham Bay (Kovanen and Easterbrook, 2000). This indicates that relative sea level changes are not confined to local fault movement as proposed by Dragovich et al. (1997b).
STUDY AREA

The principal study area is located on a sea cliff along Bellingham Bay in NW Washington (Figure 6a and 6b). Mass wasting of the sea cliff has exposed...
approximately 22 m of late Pleistocene sediments just north of Bellingham (SE ¼ sec. 15, T38N, R2E). These sediments are underlain by Kulshan glaciomarine drift and overlain by Bellingham glaciomarine drift (Easterbrook, 1963; Easterbrook and Kovanen, 1997a,b) and mirror the stratigraphic order at the Everson type locality ca. 45 km to the east.

**OBJECTIVES OF STUDY**

The purpose of this study is to perform a sedimentological study to determine the depositional environment of the 22-m Bellingham Bay exposure, correlate the sediments of the Bellingham Bay exposure with the local stratigraphic record by use of radiocarbon dating, trace and map the contact between the Deming sand and Bellingham glaciomarine drift from the Everson type locality to the Bellingham Bay section by the compilation and analysis of well logs, and interpret the sedimentologic and stratigraphic data of the Bellingham Bay site with the aim of reconstructing the Everson-age depositional environment during deglaciation of the northern Puget Lowland.
CHAPTER 2

STRATIGRAPHY and SEDIMENTATION at BELLINGHAM BAY

METHODS

Field Methods

In order to identify the depositional environment of the Bellingham Bay section, a detailed analysis of the stratigraphy and mode of sedimentation was conducted. The Bellingham Bay stratigraphic section (Figure 7) measures 22.7 m in height with the Deming sand at least 11.5 m thick and the overlying Bellingham glaciomarine drift (gmd) 11.2 m thick. An abney level and stadia rod was used to survey the section. Measurements began at the storm high tide line (Figure 8) and concluded at the top of the section (sea cliff). Nails were anchored at 11.5, 15.5 and 18.5 m from the top of the section as reference points.

Five pits were dug and the sides scraped for detailed stratigraphic and sedimentary analysis (Figure 9). Pit 1 contains Units A to Unit D; Pit 2 includes Unit D through Unit F; Pit 3 consists of Unit F through Unit N; Pit 4 consists of Unit N through Unit R; and Pit 5 includes Unit R through the Bellingham glaciomarine drift. Thickness of each unit was measured to the nearest cm. A total of 28 units were recognized at the Bellingham Bay site. The Deming sand consists of 27 units, plus the Bellingham gmd. Analysis began with the lowest unit, Unit A, which is 22.7 m from the top of the section.

Lab Methods: Sieve Analysis

Grain size data have been used to interpret and determine ancient depositional environments. However, much debate exists regarding the reliability of many
Figure 7. Stratigraphic Column and Description of Bellingham Bay Section.
Figure 8. Photo showing Bellingham Bay site.

Figure 9. Pit 1 – Pit 5 at Bellingham Bay site.
methods employed (Boggs, 1995). Particle sorting and particle size are aspects of sediments important in helping to reconstruct their depositional environment. Twenty-nine samples were collected in one-gallon Ziploc bags for grain-size analyses to assess sorting and particle distribution for each sediment sample from a given unit. In units showing distinct grading, more than one sample was collected.

Samples were dried, weighed, and placed in a Ro-Tap for seiving. The Udden-Wentworth scale was used for size classes. The sieve sizes (phi) used for each sample were: -5, -4, -2, -1, 0, 1, 2, 3, 4, and a pan to catch coarse silt to clay size particles. The -3 sieve was not available so, the weight percent of the -2 was averaged from -2 to -3. All clasts greater than -5 were extracted from each sample, measured along the intermediate axis, and then weighed.

**Sieve Analysis Results**

Particle size and sorting of sediment grains may reflect sedimentation mechanisms and depositional processes. Therefore, grain size analyses were conducted to determine the amount of sorting within each sediment sample. The histograms of the sieve analyses for the 27 sediment samples are given in Appendix I.

**Lab Methods: Heavy mineral analysis**

A heavy mineral analysis was performed on one sample obtained from Unit C at the contact with Unit D to determine if the sample was a heavy mineral placer. The sample was dried and weighed. Magnetite was removed with a magnet and weighed. Tetrabromoethane, which has a specific gravity of 2.96, was used to separate heavy and light minerals. The percentage of garnet within the remaining heavy minerals was estimated. The weight percent of light and heavy minerals was calculated.
Heavy mineral results

Heavy mineral placers are sedimentary deposits common in beach and alluvial environments. Table 2 shows the following results of the heavy mineral analysis. Approximately 41% of a sediment sample collected from Unit C consists of heavy minerals. The heavy mineral raw data are presented in Appendix II.

Table 2. Heavy Mineral Percentages from upper 2 cm of Unit C.

<table>
<thead>
<tr>
<th>WEIGHT % OF LIGHT MINERALS (GRAMS)</th>
<th>WEIGHT % OF DARK MINERALS NOT INCL. MAGNETITE (GRAMS)</th>
<th>WEIGHT % OF MAGNETITE (GRAMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>59.25</td>
<td>28.34</td>
<td>12.41</td>
</tr>
</tbody>
</table>

STRATIGRAPHY RESULTS

Primary and secondary sedimentary structures are useful for interpreting ancient depositional environments. Figure 7 shows a detailed description of the units in the Bellingham Bay stratigraphic section. The primary and secondary structures of each unit, beginning with the stratigraphically lowest Unit A, are as follows:

Unit A

The base of Unit A (Figure 10) is 22.7 m from the top of the section and is at least 1.4 m thick. This unit consists of poorly sorted, pebbly, coarse-grained sand. A dip of 33° was measured on the west-facing side of the pit; therefore, the horizontal laminae displayed in Figure 10 is an apparent dip. The lower contact is covered with colluvium, but Unit A displays large-scale planar cross-stratification. Armored mudballs, which are subrounded to subangular masses of silt and clay coated with
coarse sand or fine gravel, are scattered throughout the unit (Figure 11). *Macoma carlottensis* (Queen Charlotte Macoma), *Macoma nasuta* (Bent-nosed Macoma), *Macoma* sp., *Serpula vermicularis* (worm tubes), and charcoal were found throughout the unit (Figure 12). Abundant shell fragments are scattered throughout the entire unit. All shells and worm tubes showed signs of abrasion. Dr. Thor Hansen, a paleontologist at Western Washington University, identified all shells and worm tubes within the stratigraphic section. All shells within the Bellingham Bay section are of marine origin.
The lower contact of Unit A is covered. The upper contact (separating Unit A and Unit B) at 21.3 m is slightly undulating, but appears to be a conformable surface.

**Unit B**

Unit B (Figure 10) is 0.9 m thick. The lower part (21.0 to 21.3 m) is poorly sorted, faint, horizontally laminated, pebbly sand. Shell fragments, armored
mudballs, and pebbles are scattered throughout the unit. A *Macoma* sp., *Protothaca staminea* (hard-shell clam), and *Serpula vermicularis* (worm tube) were found at 21.0, 21.1, and 21.1 m, respectively (Figure 13). Both the shells and worm tube showed signs of abrasion.

![Figure 13. Worm tube and shells in Unit B.](image)

The upper part of unit B (20.4 to 21.0 m) consists of moderately sorted, faint, horizontally laminated, coarse sand. A *Macoma nasuta* (Bent-nosed Macoma) and shell fragments were found scattered throughout this portion of the unit. A lens of armored mudballs was situated at 20.6 m. Shells from this unit were radiocarbon dated at 12,785 ± 85 ^14^C yrs B. P. Applying a new marine reservoir correction of -1100 ± 108 yrs gives a corrected age of 11,685 ± 85 ^14^C yrs B. P (Kovanen and Easterbrook, submitted, 2001). The unit as a whole displays normal grading. Unit B and Unit C are conformable, but the contact between them is abrupt.
**Unit C**

Unit C (Figure 14) (19.5 to 20.4 m) is 0.9 m thick and consists of well sorted, horizontal, thinly-laminated, medium-grained sand (0.25 to 0.50 mm). Shell fragments are dispersed throughout the entire unit. A heavy mineral deposit within Unit C is concentrated along the contact of Unit C and the overlying Unit D (Figure 15).

The contact between Unit C and Unit D (20.4 m) is conformable, slightly undulating, and abrupt. The contact is a diastem. All contacts with erosional surfaces within the Bellingham Bay sequence are diastems. See later discussion on diastems.

**Unit D**

Unit D is situated between 19.2 to 19.5 m (Figure 14). The unit is well-sorted, structureless, fine-grained sand (0.125 to 0.25 mm). Flame structures composed of medium-grained sand and heavy minerals intrude into the base of Unit D (Figure 15).

The undulating contact between Unit D and overlying Unit E in Pit 1 exhibits signs of erosion. Although the contact is erosional, the surface that separates the two units is conformable. In Pit 2 the contact between Unit D and Unit E displays a more severely eroded contact than that observed in Pit 1.
Figure 14. Unit C and D. Horizontal laminae in Unit C.

Figure 15. Heavy mineral deposit positioned at contact between Unit C and Unit D. Flame structures protruding into Unit D.
Unit E

Unit E (Figure 16), 18.2 to 19.5 m from the top of the section, is 1.3 m thick and is divided into three parts. The lower-most part of the unit (18.7 to 19.5 m) consists of a slump zone contemporaneous with deposition. This section is poorly sorted, structureless, pebbly sand. Armored mudballs, Serpula vermicularis

(worm tubes), shell fragments, and pebbles are scattered throughout this part of the unit. All worm tubes show signs of abrasion.

The middle and upper part of unit E consists of two sets of tabular cross strata. The poorly sorted, pebbly sand within the middle part of Unit E (18.5 to 18.7 m)
contains two 20 cm thick co-sets of tangential, laminated- to very thin-bedded cross-beds (Figure 17). The cross strata dip at a 15° angle. Current direction was from west to east. Armored mudballs, shell fragments, *Serpula vermicularis* (worm tube), and pebbles are scattered throughout this section. A few *Macoma* sp. were found within this portion of the unit. All worm tubes and shells showed signs of abrasion.

The upper part of Unit E (18.2 to 18.5 m) is a 27 cm thick set of planar cross-beds composed of very thin- to thin-bedded poorly sorted, granular sand (Figure 17). A dip of 30° was measured for the planar cross-beds and current direction was also from west to east. Reworked *Serpula vermicularis* (worm tubes) were discovered in abundance (Figure 18). Armored mudballs and shell fragments were scattered throughout this part of the unit. Charcoal was found at 18.3 and 18.4 m.

The undulating and erosional contact between Unit E and overlying Unit F (18.2 m) is a conformable surface. The cross strata in the underlying pebbly sand of Unit E are truncated by the overlying thick, clayey mud of Unit F.
Unit F

Unit F (Figure 16), which is between 17.3 and 18.2 m, is well-sorted, structureless, silty clay. Lenticular bedding was observed at the base of the unit between 18.1 and 18.2 m. The lenticular bedding shown in Figure 19 consists of...
fine sand within the surrounding clay. The overlying sand of Unit G is scoured and uneven, but is an abrupt and conformable surface (contact).

**Unit G**

Unit G (Figure 20) occupies the interval from 16.7 to 17.1 m and contains two parts. Shell fragments are scattered throughout both parts. The lower part (16.9 to 17.1 m) is moderately sorted, structureless, coarse sand (0.50 to 1.00 mm).

The upper part (16.7 to 16.9 m) of unit G is moderately sorted, horizontally laminated to very thin-bedded, coarse sand. A *Chlamys rubidus* (Hind's Scallop) shell was found at 16.9 m (Figure 20). The undulating and abrupt contact separating Unit G from the overlying Unit H is a conformable surface. Truncation of the horizontally, laminated coarse sand in Unit G by the overlying pebbly sand (Unit H) can be seen in Figure 20.

![Figure 20. Unit G and Chlamys shell found at 16.9 m.](image-url)
Unit H

Unit H (Figure 21), 15.8 to 16.7 m from the top, is poorly sorted, pebbly sand. Very thin-bedded, planar cross-beds within this unit dip at 31°. The entire unit is one 0.9-m-thick, tabular, cross-stratification set. Current direction was from east to west. Armored mudballs (2 - 6 cm), shell fragments, pebbles, and granules are common in the unit. Two armored mudballs with diameters of 10 and 18 cm were located 16.1 and 16.4 m from the top, respectively. A Chlamys rubidus (Hind’s Scallop) shell and charcoal were found at 16.5 and 16.8 m, respectively. At the base of the unit (16.5 -16.7 m) is a higher concentration of armored mudballs than the rest of the unit.

Figure 21. Unit H and Unit G. Planar cross-beds within Unit H.
Although the overlying strata in Unit I have truncated the strata in Unit H, the two units are conformable. The contact between these two units is abrupt.

**Unit I**

Unit I (15.3 to 15.8 m) is 0.5 m thick (Figure 22) and consists of two parts. The lower part of the unit (15.5 to 15.8 m) is poorly sorted, pebbly sand. Very thin-bedded, tangential, cross stratification is contained in one tabular set. Current direction was from east to west. Armored mudballs, shell fragments, and pebble-to-granular-size clasts are dispersed throughout the unit. Charcoal was found at 15.5 m.

The upper part of the unit (15.3 to 15.5 m) is comprised of poorly sorted, structureless, medium-grained sand. A fold-like structure, which could be deformed cross-strata due to soft sediment deformation, occurs in this part of the unit (Figure 23). Shell fragments and pebble-to-granular-size clasts are scattered throughout the unit. Shells from this unit were radiocarbon dated at 12,860 ± 85 ¹⁴C yrs B. P. The new marine reservoir corrected age (Kovanen and Easterbrook, submitted, 2001) of the sample is 11,760 ± 85 ¹⁴C yrs B. P.

The contact displayed between Unit I and Unit J (Figure 23) undulates slightly, and the overlying pebbly sand in the lower part of Unit J truncates the fold displayed in Unit I. The contact between the two units is abrupt.

**Unit J**

Unit J (Figures 22 and 24) (15.0 to 15.3 m) can be divided into two parts. The lower segment (15.1 to 15.3 m) is poorly sorted, structureless, pebbly sand with lenses of moderately sorted, horizontal, thinly-laminated pebbly sand. Armored mudballs and pebble-to-granule clasts litter this section of the unit.
Figure 22. Units I to Unit L.

Figure 23. Fold like structure in upper part of Unit I.
The upper part of Unit J (15.0 to 15.1 m) consists of well-sorted, horizontal to hummocky, laminated-to-thinly-laminated, medium-grained (0.25 to 0.50 mm) sand (Figure 24). The horizontal and hummocky cross-laminae are contained in one 20 cm thick hummocky cross-stratification set.

The entire unit (both parts) exhibits normal grading. The undulating, gradational contact between Unit J and Unit K exhibits signs of erosion. Although the contact is erosional, the surface that separates these two units is conformable. The sandy silt of Unit K truncates the upper, hummocky, laminated sand in Unit J.

![Figure 24. Horizontal and hummocky laminae within upper Unit J.](image)

**Unit K**

Unit K shown in Figures 24 and 25 (14.8 to 15.0 m) is well-sorted, thinly-laminated, hummocky cross-stratified sandy silt. Unit K and Unit L are conformable. The contact between these two units is abrupt.
Unit L, Unit M, Unit N

All three units display similar characteristics, but are separated into different units based upon color variations due to different oxidation states. Units L, M, and N (14.3 to 14.8 m) are a combined 0.5 m thick (Figure 25). They are well-sorted, structureless, silty clay. The contact separating Unit N and overlying Unit O is erosive, undulating, and abrupt.

Unit O

Unit O (Figure 26) (14.1 to 14.3 m) is moderately-sorted, structureless, coarse- (1.00 to 2.00 mm) to very fine-grained (0.0625 to 0.125 mm) sand. Two soft-
sediment deformation structures, consisting of well-sorted, silty sand, are displayed in the middle part of the unit (14.2 m). A sample of this unit slightly effervesced in a 5% solution of HCL. Unit O and Unit P are conformable strata separated by an erosive and abrupt contact.

Figure 26. Unit O. Dark silty sand soft-sediment deformation structures.

Unit P

Unit P (13.8 and 14.1 m) is well-sorted, fine-grained sand (0.125 to 0.25 mm) (Figure 27). A granule sand lens containing small-scale cross-stratification occurs in the upper 5 cm of this unit (13.78 to 13.83 m). Thinly laminated, planar strata dipping 5° are contained in 2.5 cm-thick sets of wedge cross-stratification. The remaining 27 cm of Unit P is well-sorted, fine-grained sand with oxidation streaks running parallel to subparallel throughout the unit. Flame structures (14.0 m), which consist of sandy clay and silt, can be seen in Figure 27 (adjacent to Swiss army knife) projecting upward from the underlying Unit O into Unit P. The contact separating
Unit P and Unit Q is abrupt; however, slight erosion occurred, which is demonstrated by the truncation of cross laminae within Unit P.

![Figure 27. Thinly laminated, planar strata within Unit P. Flame structures (next to Swiss army knife) displayed at base of unit.](image)

**Unit Q**

Unit Q (Figure 28) is 0.5 m thick (13.3 to 13.8 m) and is well-sorted, horizontal, planar, thinly-laminated, fine-grained sand (0.125 to 0.25 mm), containing interbeds of planar and horizontal, laminated-to-thin-bedded, granular sand that averages 4 cm thick.

The undulating contact between Unit Q and Unit R exhibits signs of erosion. Although the contact is erosional, the surface that separates these two units is conformable and abrupt.
Figure 28. Well sorted, horizontal and planar laminated sand in Unit Q.

**Unit R**

Unit R (Figure 29) 13.1 and 13.3 m from the top is well-sorted, structureless, clayey silt with some sand, which contains lenses of fine-grained sand. Although the overlying strata in Unit S have a scoured contact with the underlying strata in Unit R, the two units are conformable. The contact between these two units is abrupt.

**Unit S**

Unit S (Figure 30) (12.9 to 13.1 m) is a moderately sorted, coarse- (1.00 to 2.00 mm) to fine-grained (0.125 to 0.25 mm) sand. This unit contains trough cross stratification with set thickness approximately 5 cm (Figure 31).

The contact separating Unit S and Unit T is erosive, undulating, and abrupt. The cross strata in the underlying sand of Unit S are truncated by the overlying pebbly sand of Unit T (Figure 30).
Figure 29. Unit R. Well sorted, structureless, clayey silt with sand.

Figure 30. Unit S through Unit V.
Unit T

Unit T (Figure 30) is 12.8 and 12.9 m from the top and consists of poorly sorted, structureless- to thinly-laminated, cross-stratified, pebbly sand. Tangential, thinly-laminated, cross strata are arranged within two, tabular, cross-stratified sets averaging 4 cm thick. Armored mudballs are scattered throughout the unit. The contact separating Unit T and Unit U is erosive, undulating, and abrupt.

Unit U

Unit U (Figure 30) (12.6 to 12.8 m) can be divided into two parts. The lower part of the unit (12.7 to 12.8 m) is poorly sorted, structureless, compacted, sandy gravel. Armored mudballs are found throughout this part of the unit with a higher concentration at the base.
The upper section of the unit (12.6 to 12.7 m) is well-sorted, fine-grained (0.125 to 0.25 mm) sand. Small-scale trough cross stratification displayed in Figure 32 contain very-thin laminae. Set thickness ranges from 2 to 3 cm.

Unit U and Unit V are separated by an abrupt, conformable surface. The overlying strata in Unit V have truncated the trough cross strata in Unit U.

**Unit V**

Unit V (12.5 to 12.6 m) is well-sorted, structureless, sandy silt (Figures 30 and 32). Unit V and Unit W are conformable strata separated by an abrupt contact.

![Figure 32. Unit U and Unit V. Small-scale trough cross-stratification in upper part of Unit U.](image)

**Unit W**

Unit W (Figure 33) (12.0 to 12.5 m) is poorly sorted, structureless, clast-supported, sandy gravel. The upper 3 cm of this unit is cemented with calcite.
Charcoal was found at 12.4 m. A few armored mudballs were noted in a sandy pebble lens at 12.5 m. Unit W and Unit X are conformable strata separated by an abrupt contact.

Figure 33. Unit W consisting of poorly sorted sandy gravel.

**Unit X**

Unit X (Figures 34 and 35), 11.8 and 12.0 m from the top, is well-sorted silty, very fine-grained (0.0625 to 0.125 mm) sand containing lenses of granular sand. Small-scale ripple bedding is displayed from 11.8 to 11.85 m. Small-scale wedge cross-stratification occurs throughout the rest of the unit. Set thickness was difficult to determine. Planar and tangential cross laminae averaging 1 mm in thickness are
arranged within the sets. The contact separating Unit X from Unit Y is slightly undulating and abrupt. Truncation of cross-laminae in Unit X by the overlying pebbly sand (Unit Y) can be seen in Figure 35.

Figure 34. Unit X – Unit AA and Bellingham gmd.

Unit Y

Unit Y (Figures 34, 35, and 36) (11.7 and 11.8 m) is poorly sorted, structureless, pebbly sand. The lowest 0.5 m of the unit contains small-scale, wedge cross-stratification. Planar and tangential cross laminae averaging 1 mm in thickness are arranged within the sets. The contact separating Unit Y and Unit Z is undulating and abrupt.
Unit Z

Unit Z (Figures 35 and 36), 11.6 to 11.7 m from the top, contains poorly sorted, structureless, pebbly sand, interbedded with well-sorted, clayey silt and well-sorted silty sand. Small-scale cross laminae occur within the silty sand. Charcoal was found at 11.65 and 11.7 m. Unit Z and Unit AA are conformable strata separated by an erosive, undulating, and abrupt contact.

Figure 35. Tangential and planar laminae within wedge cross-stratification in Unit X.
Figure 36. Unit Y and Z. Charcoal next to knife.

Unit AA

Unit AA (Figures 34 and 37) (11.2 to 11.6 m) displays alternating strata of moderately sorted, laminated sand (with less than 5% pebbles) and silty sand with poorly sorted, structureless, pebbly sand throughout the entire unit. Small-scale ripple bedding and subhorizontal lamination occurs within the silty sand and laminated sand (with less than 5% pebbles), respectively. Planar and tangential cross laminations average one mm in thickness within the ripple bedding. Unit AA and the Bellingham glaciomarine drift are separated by an abrupt contact.

Bellingham Glaciomarine Drift

The Bellingham glaciomarine drift in the studied section (Figure 38) (0 to 11.2 m) is poorly sorted, structureless, pebbly clay containing marine fossils. *Nuculana sp.*, a marine fossil, was found intermittently in the unit. Broken shell fragments are scattered throughout the unit.
The stratigraphy displayed at the Bellingham Bay section mirrors the stratigraphic order at the Everson type locality, which is located approximately 25 km to the northeast (Figure 38). Radiocarbon dates from the Bellingham Bay section and the Everson type locality (Tables 3 and 4) allow comparisons of the chronology of these stratigraphically similar sections.

Both the Everson type section and the Bellingham Bay sequence are capped with the Bellingham glaciomarine drift. Easterbrook (1962, 1963) describes the Bellingham glaciomarine drift at the Everson type section (Figure 39) and at
Figure 38. The Bellingham gmd is poorly sorted, structureless, pebbly clay containing marine fossils.

Figure 39. The various units of the Everson type section.
Bellingham Bay (Figure 38) as a blue-gray-to-brown, poorly sorted, structureless, unstratified, sandy, pebbly clay. In places, the drift resembles till; however, elsewhere the drift grades into clay that contains rare pebbles. Marine fossils are moderately abundant in the glaciomarine drift at several localities described by Easterbrook (1962, 1963, 1992). Radiocarbon dates at the Everson type section and the Bellingham Bay sequence are analogous. Wood collected from the Bellingham drift at the type section and shells from Bellingham Bay were radiocarbon dated at 11,800 ± 400 and 13,250 ± 210 ¹⁴C yrs B. P., respectively (Easterbrook, 1963). The reservoir corrected age for the shell date at Bellingham Bay is 12,150 ± 210 ¹⁴C yrs B. P. (Kovanen and Easterbrook, 2000).

The Deming sand at the Everson type section and the Deming sand at Bellingham Bay have similar stratigraphic positions. Both units are found between the Bellingham and Kulshan glaciomarine drifts. In addition, radiocarbon dates from both locations are similar (Easterbrook, 1963). The Deming sand at the Everson type section (Figures 39 and 40) is comprised of medium- to coarse-grained, brown sand with interbeds of blocky and laminated clay (Easterbrook, 1963, 1992). The sand forms horizontal beds, planar cross-beds and some trough cross-beds (Easterbrook, 1963; Croll, 1980). At the base of the Deming sand are in situ rooted stumps, peat, and logs, which suggest a fluvial origin for the Deming sand. A date of 11,810 ± 60 ¹⁴C yrs B. P. was recently reported from a newly discovered rooted stump (Figure 40 and 41) (Kovanen and Easterbrook, 2000), which matches earlier dates of 11,455 ± 125 ¹⁴C yrs B. P. (rooted stump), 11,500 ± 200 ¹⁴C yrs B. P. (log), and 11,640 ± 200
Figure 40. The Deming sand of the Everson type section. Rooted stump found by Kovanen (2000).

$1^4\text{C}$ yrs B. P. (peat) all from within the Deming sand at the type locality (Easterbrook, 1992; Kovanen and Easterbrook, 1996). Shells obtained from the Bellingham Bay site yielded radiocarbon dates of 12,785 ± 85 and 12,860 ± 85 $1^4\text{C}$ yrs B. P., respectively (Table 3). The reservoir ages of these shell samples give corrected ages of 11,685 ± 85 and 11,760 ± 85 $1^4\text{C}$ yrs B. P., respectively (Kovanen and Easterbrook, 2000; Weber and Kovanen, 2000).

The Kulshan gmd (Figure 40 and 41), which underlies the Deming sand at the Everson type section and at Bellingham Bay, displays similar characteristics to the Bellingham glaciomarine drift. The Kulshan glaciomarine drift is structureless, blue-gray, poorly sorted, unstratified, pebbly clay (Easterbrook, 1962, 1963). Easterbrook (1962, 1963) noted that marine shells occur in the Kulshan glaciomarine
drift at several localities, but are most abundant in outcrops along Bellingham Bay. Wood in the Kulshan glaciomarine drift at the Everson type section and shells in the Bellingham Bay yielded dates of $12,185 \pm 80$ and $13,310 \pm 80$ $^{14}$C yrs B. P., respectively (Easterbrook, 1962, 1963, 1992). The reservoir corrected age for the Bellingham Bay sample is $12,210 \pm 80$ $^{14}$C yrs B. P. (Kovanen and Easterbrook, 2000).

Figure 41. Rooted stump in growth position. Roots extend into underlying Kulshan gmd.

The contact between the Kulshan glaciomarine drift and Deming sand at the Bellingham Bay site is now covered by colluvium. However, Easterbrook (1963) located and documented the contact at several places a several hundred m to the
south. A reservoir corrected date of 12,210 ± 80 (radiocarbon age of 13,310 ± 80\(^{14}\)C yrs B. P.) was obtained from shells in the Kulshan glaciomarine drift several hundred meters to the south.

Table 4 shows radiocarbon and calibrated dates of wood obtained from the Bellingham glaciomarine drift, Deming sand, and Kulshan glaciomarine drift at the Everson type locality.
<table>
<thead>
<tr>
<th>Lab No.</th>
<th>Radiocarbon age(^a) ((^{14})C yr BP)</th>
<th>Reservoir corrected age(^b) ((^{14})C yr BP)</th>
<th>Calibrated age(^c) (cal. yr BP)</th>
<th>Material Dated</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-135695</td>
<td>13,250 ± 210</td>
<td>12,150 ± 210</td>
<td>15,293 (14,083) 13,437</td>
<td>shells</td>
<td>Bellingham glaciomarine drift</td>
</tr>
<tr>
<td>AA-25747</td>
<td>12,785 ± 85</td>
<td>11,685 ± 85</td>
<td>14,026 (13,487) 13,065</td>
<td>shells</td>
<td>Deming sand lowest site (UNIT B). Age of Deming sand. At 10.7 m above storm high tide.</td>
</tr>
<tr>
<td>AA-25746</td>
<td>12,860 ± 85</td>
<td>11,760 ± 85</td>
<td>14,059 (13,790) 13,189 (13,701) (13,521)</td>
<td>shells</td>
<td>Deming sand highest site (UNIT I). Age of Deming sand. At 16.6 m above storm high tide.</td>
</tr>
<tr>
<td>B-109852</td>
<td>13,310 ± 80</td>
<td>12,210 ± 80</td>
<td>14,792 (14,103) 13,655</td>
<td>shells</td>
<td>Kulshan glaciomarine drift. Provides age of Kulshan gmd and lower limiting age of Deming sand. At modern day beach level.</td>
</tr>
</tbody>
</table>

\(^a\) Conventional ages reported with laboratory error precession is 1 sigma.

\(^b\) The reservoir corrected age for marine shells is the conventional \(^{14}\)C age minus a reservoir value of -1100 ± 108 yrs (Kovanen and Easterbrook, 2000). The ± is the reported laboratory precision and does not include the error propagation of the reservoir value.

\(^c\) Calibrated 2 sigma age range given in years before AD 1950. Value in parentheses is 2 sigma mean age using the CALIB4.3a program of Stuiver and Reimer (1993) with dataset of Stuiver et al. (1998a). Values outside the parentheses are maximum and minimum age ranges. Marine shell ages were corrected for a marine reservoir value of -1100 ± 108 yrs (or a delta R of 700 ± 108 yrs) using a lab multiplier of 1.
Table 4. Radiocarbon Dates from the Everson type section.

<table>
<thead>
<tr>
<th>Lab No.</th>
<th>Radiocarbon age ($^{14}$C yr BP)</th>
<th>Reservoir corrected age ($^{14}$C yr BP)</th>
<th>Calibrated age&lt;sup&gt;b&lt;/sup&gt; (cal. yr BP)</th>
<th>Material Dated</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-1037</td>
<td>11,800 ± 400</td>
<td>Does not apply</td>
<td>15,350 (13,822) 13,006</td>
<td>wood</td>
<td>Maximum age of Bellingham glaciomarine drift (Easterbrook, 1963)</td>
</tr>
<tr>
<td>B-1324</td>
<td>11,455 ± 125</td>
<td>Does not apply</td>
<td>13,817 (13,438) 13,144</td>
<td>rooted stump</td>
<td>Maximum age of Deming Sand (Easterbrook, 1963)</td>
</tr>
<tr>
<td>WW-1</td>
<td>11,500 ± 200</td>
<td>Does not apply</td>
<td>14,065 (13,455) 12,996</td>
<td>rooted stump</td>
<td>Maximum age of Deming Sand (Easterbrook, 1963)</td>
</tr>
<tr>
<td>W-940</td>
<td>11,640 ± 275</td>
<td>Does not apply</td>
<td>12,798 (11,353) 10,612</td>
<td>wood in peat</td>
<td>Maximum age of Deming Sand (Easterbrook, 1963)</td>
</tr>
<tr>
<td>B-135696</td>
<td>11,810 ± 60</td>
<td>Does not apply</td>
<td>14,058 (13,824) 13,506</td>
<td>rooted stump</td>
<td>Maximum age of Deming Sand (Kovanen and Easterbrook, 2000)</td>
</tr>
<tr>
<td>AA-22222</td>
<td>12,185 ± 80</td>
<td>Does not apply</td>
<td>15,412 (14,129) 13,836</td>
<td>wood</td>
<td>Age of Kulshan glaciomarine drift</td>
</tr>
</tbody>
</table>

<sup>a</sup> The reservoir corrected age for marine shells is the conventional $^{14}$C age minus a reservoir value of -1100 ± 108 yrs (Kovanen and Easterbrook, 2000; Kovanen and Easterbrook, submitted, 2001). The ± is the reported laboratory precision and does not include the error propagation of the reservoir value.

<sup>b</sup> Calibrated 2 sigma age range given in years before AD 1950. Value in parentheses is 2 sigma mean age using the CALIB4.3a program of Stuiver and Reimer (1993) with dataset of Stuiver et al. (1998a). Values outside the parentheses are maximum and minimum age ranges. Marine shell ages were corrected for a marine reservoir value of -1100 ± 108 yrs (or a delta R of 700 ± 108 yrs) using a lab multiplier of 1.
CHAPTER 3

SUBSURFACE AND OUTCROP STRATIGRAPHY

METHODS

Over 150 water well logs obtained from the Whatcom County health department and United States Geological Survey open-file Investigations Report 98-4195 (Fox and Kahle, 1999) were used to assess the subsurface stratigraphy. Well locations were established using township, range, section, and quarter section (when given). Exact well locations were not always clear, but 90% of the positions of the wells were located to within 0.3 km². All wells were assigned a number and plotted on a U. S. Geological Survey 7.5-minute series topographic map (scale 1: 24,000) (Plate 1). Well elevations were interpolated from the U. S. Geological Survey 7.5-minute series topographic map.

Establishing the elevations of the contact between Bellingham gmd and Deming sand was attempted from the subsurface data in order to trace the contact between the Bellingham glaciomarine drift and the Deming sand from the Everson type locality to the Bellingham Bay site. Uncertainties in the data presented limitations in interpreting the depth of the individual lithologic units. However, a broad distinction was attempted by the author and the strata were classified. “Gray clay”, “hard pan”, “clay with pebbles”, “clay with gravel”, “gravelly clay”, and “blue clay” near the ground surface were interpreted as glaciomarine drift. Sand lenses (5 feet or less) are often found within the glaciomarine drift, and have been grouped within the glaciomarine drift. Therefore, any sand unit (5 feet or less) directly above, between or under glaciomarine drift was grouped within the glaciomarine drift.
Lithologic strata containing "sand with clay", "sand and gravel", "sand", "fine sand", "coarse sand", "silt/fine sand", "brown sand", "gray sand" that had a thickness greater than 5 feet were interpreted as Deming sand.

**SUBSURFACE STRATIGRAPHY RESULTS**

The contact elevation in meters was plotted on the topographic map for construction of a subsurface-contour map (Plate 1). However, the data contains many inconsistencies. Although a distinction between glaciomarine drift and sand and gravel appears straightforward, the subsurface data contained in the well logs is open to interpretation. Over 150 well logs were analyzed for the construction of the contour map. At least 10 well drilling companies were involved in the drilling and recording of these 150 wells. Some well records were detailed enough that lithologic units could be deciphered, but others were unclear. Furthermore, many of the author's interpretations of the well log data differed from those of Croll (1980) and Fox and Kahle (1999), who constructed subsurface contour maps of the same study area. Croll (1980) produced a subsurface contour map of the top of the Deming sand and Fox and Kahle (1999) developed a series of hydrogeologic cross sections of Whatcom County and adjacent southern British Columbia. Interpretations of the specific lithologic unit within well data frequently differed between the various studies involved.

**OUTCROP STRATIGRAPHY**

Due to the inconsistencies in the well log data, constructing a subsurface-contour map does not appear to give an accurate representation of the surface of the Deming sand. However, a geologic cross section taken from composite sections was
constructed from the Everson type section to the Bellingham Bay site based primarily on surface outcrops and a few selected deep well logs, which seemed to produce reliable results (Figure 45).

The contact elevations between Bellingham glaciomarine drift and Deming sand were used to construct a longitudinal profile. Exposures used for the profile included the Everson type section, the Bellingham Bay site, the Shuksan Golf course site, and the Deming site (Hwy 542 and Hwy 9-south intersection). Parts of the Deming exposure are shown in Figures 42a and 42b and the Shuksan golf course exposure is shown in Figure 43. Figure 44 shows the location of the exposures and the elevations of each contact are given in parentheses. Figure 45 displays the longitudinal profile from the Deming site to the Bellingham Bay section.

Figure 42a. Deming site showing contact between Bellingham gmd and Deming sand (photo provided by D. Kovanen).
Figure 42b. Deming site. Close-up photo of Deming sand (photo provided by D. Kovanen).

Figure 43. Shuksan Golf Course exposure.
Figure 44. Location and elevations of contacts used for construction of geologic cross section.
Figure 45. Diagrammatic geologic cross section from the Deming exposure to the Bellingham Bay sequence (not to scale) (modified from Easterbrook).
CHAPTER 4

DEPOSITIONAL ENVIRONMENTS

Ancient and modern-day Bellingham Bay depositional environments include tidal flat, estuarine, deltaic, riverine, and continental glaciomarine. Paleoecological studies by Wagner (1959) and Balzarini (1981, 1983) showed that many species (macro- and microfossils) in Everson glaciomarine drift suggest a bay or estuarine environment. All species (except one) are of marine origin, and although some species tolerate influxes of fresh water and reduced salinities (Balzarini, 1981, 1983), all species except one presently live in marine water of the Puget Lowland. The macrofossils from the Everson glaciomarine drifts in the Northern Puget Lowland indicate a large bathymetric range (intertidal to 183 m). Consequently, to interpret the Pleistocene depositional environment of the Bellingham Bay site, comparisons of depositional processes and environments operating today may yield meaningful results. In the subsequent sections, the depositional environments and their associated facies are examined for the Bellingham Bay site.

Sedimentary structures can be used to evaluate aspects of ancient depositional environments, as well as sediment transport mechanisms, paleocurrent flow directions, relative water depth, and current velocity. Sedimentary structures, along with textures, vertical stratigraphic relationships, and grain size analyses were used to interpret the ancient depositional environments of lithofacies within the Bellingham Bay stratigraphic section.
LAMINATED SAND FACIES

Unit C, Q, and P (Figures 14, 27, and 28) are included in the laminated sand facies. Unit C is well-sorted, horizontal, thinly-laminated, medium-grained sand (0.25 to 0.50 mm) containing abundant shell fragments and a heavy mineral deposit in the upper 2 cm of the unit. Unit Q is well-sorted, horizontal, planar, thinly-laminated, fine-grained sand (0.125 to 0.25 mm), containing interbeds of planar and horizontal, laminated-to thin-bedded, granular sand. Unit P is very well sorted, horizontal, planar, fine-grained sand (0.125 to 0.25 mm). Although the upper 2.5 cm display small-scale cross-stratification, the remaining 27 cm are laminated with oxidation streaks running parallel to subparallel throughout the unit. Flame structures exist at the base of Unit P.

Numerous studies (Simons et al., 1965; Southard, 1971; Harms et al., 1975) established that under unidirectional, tractive flow, planar laminae are produced in sandy sediment during the plane bed phase of the upper flow regime (Figure 46). Planar laminae suggest a certain hydraulic condition (tractive flow in the upper flow regime, plane bed) that can occur in different environments of deposition. Therefore, it is an indicator of process, or mechanism, not necessarily of environment (Lucchi, 1995).

Although most studies of unidirectional flow have been performed in shallow water conditions (generally 1 m or less), they have significantly aided in understanding the relationships between bedforms and sediment size and flow velocity. The sequence of bedforms that develops as velocity increases depends upon the particular grain size. Table 5 displays a qualitative representation of the
characteristic bedforms associated with specific sediment size and flow velocity.

Planar laminae are produced in a number of environments and form as a result of both suspension and traction mechanisms. Parallel laminae consisting of clay or fine silt are formed by settling from suspension, while parallel laminae composed of sand size sediment are produced during traction transport (Boggs, 1995). The environments that are most likely to preserve plane-bed structures like these are stream channels, beaches, and other nearshore areas under strong shoaling waves or tides, and high-velocity turbidity currents (Harms et al. 1982; Boggs, 1995).

![Diagram of unidirectional flow bedform development of sandy sediment](image)

**Figure 46. Unidirectional flow bedform development of sandy sediment (0.25-0.7 mm) in shallow water conditions (from Davis, Jr., 1983; taken from Simons and others, 1965).**
As flow velocity increases, characteristic bedforms are produced, depending upon sediment size. Unit C is 70% medium size sand (0.25 to 0.50 mm); Unit P is 90% fine to very fine sand (0.06 to 0.25 mm); and Unit Q is 70% very fine to fine sand (0.06 to 0.25 mm) suggesting the horizontal laminae within these units are plane bed deposits formed during upper flow regime conditions.

**Point bar deposits of meandering streams**

The primary depositional environment in the main channel of a meandering stream is the point bar (Figure 47). Laminae in sand can be formed on point bars and on levees (Reineck and Singh, 1980; Collinson, 1996) as a point bar builds laterally and downstream from meanders (Walker and Cant, 1980; Boggs, 1995). During average discharge rates, which are lower than those required to move channel lag gravels, sand is transported over the channel lag gravel and up the sloping surface of the point bars (Boggs, 1995). However, during high-flow conditions, the sediment load eroded from a meander is carried downstream and deposited on the next point bar. Large dune bedforms, consisting of coarse sediments, tend to be deposited on the lower part of the point bar, while finer grains in the form of ripples are deposited...
higher up on the point bar. The sedimentary structures preserved on the point bar pass from large-scale, trough, cross-bedded, coarse sand in the lower part of the bar to small-scale, trough, cross-laminations higher on the bar (Walker and Cant, 1980; Boggs, 1995; Collinson, 1996).

Figure 47. Point bar model and associated deposits (from Collinson, 1996).

Because the upper flow regime exists at different heights on the bar depending upon flow velocity, horizontal lamination can form both low and high on point bars. Therefore, plane bed parallel laminations may be preserved interbedded with the trough cross-beds and trough cross-laminations (Figure 48) (Boggs, 1995; Collinson, 1996; Walker and Cant, 1980)

Units C, P, and Q (Figures 14, 27, and 28) are not the horizontal laminated sands contained in a point bar facies. Typically, the laminated sand within a meandering stream facies is interbedded within small- and large-scale trough cross-stratification. Unit C, Unit Q, and Unit P within the Bellingham Bay site does not display this type of sequence.
Vertical Accretion (overbank deposits)

POINT BAR

Figure 48. Generalized point bar sequence model of a meandering river. Horizontal laminae interbedded in large and small-scale, trough, cross-stratification (Walker and Cant, 1980).

Natural levee deposits of meandering streams

Natural levees (Figure 47) are another depositional environment in which horizontal laminated sand is deposited. Levees are formed as floodwaters overtop their channel banks and lose their competence to carry their load. As a result, the coarsest sediment is deposited near the channel, while the finer-grained sediment is deposited across the floodplain. Levee deposits are mainly fine-grained sand and silt dominated by small-ripple cross-bedding, climbing ripples, and small-scale cross-bedding (Reineck and Singh, 1980). In their study of the Gomti River in India, Kumar and Singh (1978) noted levee deposits that consisted of sand layers overlain by thick mud layers. Individual sand layers displayed small-ripple cross-bedding
(planar and trough cross-beds) and at times horizontal bedding, whereas mud layers were usually finely laminated (Figure 49).

![Figure 49. Sedimentation cycles in a natural levee deposit of the Gomti River, India. (from Reineck and Singh, 1980).](image)

Generally, the sandy units of the levee deposits are only a few dm (10 – 20 cm) thick (Reineck and Singh, 1980; Miall, 1996). Typically, sandy floodplain deposits are, moderate to poorly sorted as shown by fluctuating energy levels within the river (Lewis and McConchie, 1994).

Unit C (97 cm thick), Unit P (30 cm thick), and Unit Q (50 cm thick) (Figures 14, 27, and 28) are well sorted. These units display a more constant and persistent energy level, rather than the sporadic energy and water levels of the levee and floodplain environments. Also, the lack of associated levee sedimentary structures within and adjacent to these units suggest they are not levee deposits. Climbing
ripple lamination is not a sedimentary structure found within or adjacent to these units.

Beach deposits

Evenly laminated sand is abundantly distributed on foreshore beaches and other sandy areas that experience the swash of wave action (Reineck and Singh, 1980; Lucchi, 1995). In fact, Boggs (1995; p. 115) states the “swash and backwash on beaches is one of the most common mechanisms responsible for formation of evenly laminated sands.” Reading and Collinson (1996) assert that the swash zone (Figure 50) consists predominately of plane bed or standing wave and antidune conditions.

Figure 50. Profile of beach and nearshore zone (modified from Reinson, 1980).

Beach sand typically exhibits alternating layers of fine- and coarse-grained sediments. The grain size within each individual lamina may display uniformity, or the laminae may show normal grading or inverse grading with a concentration of heavy minerals in the base of the laminae (Clifton, 1969). Furthermore, Clifton (1969) noted that typical beach sand is very well sorted, so grading may be undetectable.
Heavy-mineral placers, which are high-specific-gravity deposits, are commonly found in beach or alluvial environments (Clifton, 1969; Lucchi, 1995; Komar, 1998). Magnetite, ilmenite, and hematite are common minerals found in marine and beach sands (Boggs, 1995). If heavy-mineral placers are abundant, alternating heavy-mineral laminae and light-mineral laminae may be produced (Boggs, 1995). Heavy-mineral deposits of magnetite and garnet were found in the upper 2 cm of Unit C. Forty one percent of the sediment sample collected contained heavy-mineral placers. Magnetite comprises 12% and garnet ca. 10% - 15% of the 41%, respectively. Magnetite-garnet heavy-mineral segregations are common in modern beach sand in the area (Easterbrook, personal communication, 2001) suggesting Unit C was formed in a beach environment. Furthermore, the garnet within Unit C is the same type of garnet found within the Kulshan glaciomarine drift suggesting that the garnet has been reworked from glacial deposits.

Beach sediments are generally only slightly thicker than the tidal range (Harms et al., 1982), and one tidal phase can produce from 6 to 16 laminae (Reineck and Singh, 1980). The present-day mean tidal range in Bellingham Bay is 3.9 m (13 feet) with low tides as low as -1 m to high tides as high as +3.7 m (Withner, personal communication, 2000). Unit C, Unit P, and Unit Q are 0.97, 0.30, and 0.50 m thick, respectively, suggesting units of this thickness could have been formed in a beach or tidal environment without significant sea level change.

Plane bed conditions produce laminae from a few mm to a few cm thick (Boggs, 1995). However, if sand is rapidly deposited, the current has no time to sort the grains and thereby, form any laminae or faint laminae are produced (Lucchi,
Lucchi (1995) observed low-angle (0° to 3°) parallel laminae within a beach berm and small-scale cross-stratification in the upper portions of the exposure. The cross-stratification exhibited inclined surfaces and angular contacts much like that displayed in the upper 2.5 cm of Units P and Q. Lucchi (1995) suggested that such erosional truncations may be due to occasional storms where sand is removed both as bed and suspension load.

The action of shoaling waves also can produce horizontally laminated sand. Shoaling waves are generated in the shoaling zone of a beach profile (Figure 50). Planar parallel laminae in marine sand are one type of bedform created by the oscillatory motion of these waves. As waves approach the shore, a sequence of bedforms is created as the orbital velocity increases. When orbital velocities are near a maximum, sheetflow is generated and parallel laminae are produced. Sheetflow is the oscillatory equivalent of the plane (flat) bed phase of the upper flow regime in unidirectional flow (Clifton, 1976). Clifton (1976) noted that in relatively shallow water, passing storm waves generate parallel laminae, which consist of medium- to coarse-grained sand. Reineck and Singh (1980) pointed out that laminae produced by suspension clouds, which are generally produced by shoaling waves, typically showed normal grading (coarser grains distributed at the base of the unit graded into finer grains at the top).
Horizontal laminae produced by sheetflow are often associated with meso-scale (5 – 50 cm) cross-beds consisting of medium- to coarse-grained sand. The meso-scale cross-beds are produced by either lunate or long-crested megaripples, which generate trough and tabular cross-stratification, respectively (Clifton, 1976). Unit C, P, and Q do not display the normal grading found in sheetflow deposits. Also, Units P and Q are not associated with meso-scale cross-beds. Therefore, all three units are not believed to be a sheetflow deposit generated by shoaling waves.

Unit C, P, and Q exhibit similar characteristics to swash zone beach deposits. All units are well sorted indicating the consistent energy level as waves on a beach. In addition, all units display low angle (0° to 3°) parallel laminae similar to the swash zone deposits observed by Lucchi (1995). Unit C contains a heavy-mineral placer, further suggestive of a swash zone deposit.

Turbidity current deposits

Another mechanism by which laminated sands can form is during the upper flow regime of a turbidity current. A turbidity current is a type of density current initiated by gravity due to density differences between two fluids. Turbidites are the sediments deposited by turbidity currents.

An ideal turbidite sequence is described by Bouma (1962) and is known as the Bouma sequence (Figure 51a). Five structural units comprise the ideal Bouma sequence, although most turbidites do not contain all of these structural units. Hsü (1989) asserts that unit D (horizontally-laminated fine silt) of the Bouma sequence rarely exists. He states that most turbidites can be divided into two structural units: horizontal laminae and ripple cross laminae (Figure 51b). Unit E (silt and clay) may
or may not be part of the turbidite. The silt or clay may have been deposited after the
fact as pelagic sediment. Also, the basal surfaces of turbidites may exhibit erosional
features such as sole markings (Stow et al., 1996).

A. Bouma Sequence

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A. Bouma Sequence

Figure 51. Bouma and Hsü sequence representing characteristics of both
high and low density turbidity currents (modified after Hsü, 1989).

Turbidity current deposits tend to be poorly sorted due to rapid sedimentation
under low-energy conditions (Lewis and McConchie, 1994). The average thickness
of a turbidite is 1-4 m (Harms and Fahnestock, 1965), although many sequences are
thinner. However, complete turbidite sequences are rarely encountered with partial
sequences being the norm (Stow et al., 1996). Heavy-mineral placers are not present
within Bouma sequences (turbidites) and Walker (1980) states that climbing ripples
are an important feature of a turbidite environment. Unit C, Unit P, and Unit Q do
not display the characteristic features associated with a turbidite sequence.
Glaciofluvial and glaciolacustrine deposits

Horizontally laminated sand is also found in glaciofluvial and glaciolacustrine environments (Ashley, 1995). Shaw (1975) studied glaciolacustrine deltas (ice-marginal) in eastern British Columbia. He noted that many sections commonly consist of flat-bedded, fine sand (0.250 to 0.125 mm). The horizontal laminations within this facies are usually well defined and alternate between thick (0.4 cm) and thin (0.05 cm). Associated with this facies is well-sorted, medium- or coarse-grained (1.00 to 0.25 mm) sand showing faint horizontal laminations. Finer-grained, flat-bedded sand commonly overlies the cross-laminated sand, which consists of very fine sand (0.125 to 0.0625 mm) with climbing ripple cross-laminae.

Fluvio-lacustrine deposits can be generated when meltwater streams enter small glacial lakes and form small deltas. These deposits do not occur in direct contact with the ice, but mostly in outwash plains. At times, on large deltas the transition between fluvial and lacustrine environments is gradual; foreset beds have low inclinations (5° to 10°) (Figure 52). The fluvial topset beds are comprised of fine- to coarse-grained, pebbly sand with large-scale cross-bedding. The foreset beds consisting of fine silty sand have a low inclination from 5° to 10° and typically display climbing ripple lamination (Jopling and Walker, 1968). Bottomset beds consist of fine sand and silt showing horizontal lamination, which may grade laterally into glacial varves (Jopling and Walker, 1968; Reineck and Singh, 1980).
In their study of deltaic sedimentation into late Wisconsinan proglacial lakes, Gustavson et al. (1975) noted that delta topset beds consist of meandering stream or braided stream deposits generally reflecting the depositional characteristics of the stream that deposited them. The gravelly sediments have internal structures that are mostly crude plane beds with rare cross-beds. Foreset beds consisted of sand and gravel dipping as much as 30°. Bottomset beds consisted of ripple-drift cross-lamination and draped lamination, at times interbedded with winter-clay laminae.

Small delta deposits containing well-developed bottomset, foreset, and topset beds are found within the ice marginal region of glacial environments. The topset deposits normally consist of fluvial gravel showing parallel bedding and large-scale cross-bedding (Reineck and Singh, 1980). However, the nature of the topset beds depends upon the characteristics of the source stream. The deposits are usually poorly sorted and coarse-grained (gravels). Foresets often dip near 30°. Typically, small delta deposits are found within glacial deposits (Reineck and Singh, 1980).

Unit C, Unit P and Unit Q did not form in a glaciofluvial or glaciolacustrine environment. Although parallel bedding is common within these two environments, the horizontal bedding in fluvio-lacustrine deposits consists of gravel and pebbly sand (Gustavson et al., 1975; Reineck and Singh, 1980); whereas the bedding within
glaciolacustrine environments consists of fine sand, silt, and clay (Gustavson et al., 1975; Ashley, 1995). Also, climbing ripple lamination is a very common structure found in glaciofluvial and glaciolacustrine sediments (Gustavson et al., 1975; Shaw, 1975). Climbing ripple laminations were not found within Units C, P, and Q.

Wind deposits

Laminated sands may also develop by wind transport. Because sections of beaches situated above the high-water line are exposed to wind activity, the migration of wind ripples can lead to deposition of parallel laminae (Reineck and Singh, 1980; Boggs, 1995). Ancient eolian sandstone typically exhibits great, thick sets of cross-strata. The cross-strata usually consist of steeply dipping laminae (Bigarella, 1972). Plane bounding surfaces maybe either parallel or convergent. Also, medium-sized, tabular-planar, and wedge-planar cross-strata are common in eolian cross-bedding. Wind-blown deposits lack both fine (silt and clay) and coarse materials (Leeder, 1982). The fines are carried into the atmosphere as dust and coarse material is too heavy to be moved far by the air current.

The laminated sand within Unit C, Unit P and Unit Q are not believed to have a wind-blown origin. The units lack the medium-sized, tabular-planar, and wedge-planar cross-strata common in eolian cross-beds. Narrow estuarine beaches have a limited supply of sand for dune building, and when dunes do form, they are small and of short duration due to storms and spring tides (Nordstrom, 1992), suggesting the backshore environment had a limited supply of sand; therefore, any dune deposits would have been small and of short durations. The thickness of Units C, P, and Q
suggests that a relatively good supply of sand was available so they are not believed to be backshore dune deposits.

**STRUCTURELESS MUD FACIES**

Units F, L, M, and N (Figures 19 and 25) are structureless deposits of silt and clay. Lenticular bedding (sand lenses in a muddy matrix) is the only structure at the base of Unit F and the only sedimentary structure displayed in all four of these thick mud deposits. Extensive bioturbation produces secondary, structureless beds (Reineck and Singh, 1980; Boggs, 1995). However, such pervasive activity usually leaves mottled traces, which were not evident in any of the thick mud units. Bioturbation is not believed to have contributed to the lack of structure within each unit. Therefore, the lack of stratification in units F, L, M and N is assumed to be a primary feature.

Structureless, fine-grained deposits, such as units F, L, M and N, can be formed in a variety of ways. The lack of internal stratification suggests an absence of traction transport and typically the presence of turbulent suspension, which may generate very rapid deposition or a long-continued deposition. Turbulent suspension occurs in sediment gravity flows, especially turbidity currents, rivers and tidal currents (Sanders, 1965; Boggs, 1995).

**Levee, Floodplain and Oxbow Lake deposits**

Structureless silt and clay deposits can be formed in fluvial environments such as on levees, in oxbow lakes, and on floodplains (Figure 53). Natural levees are ridges that commonly form on the concave side of meander loops. As floodwaters over-top their banks, turbulent flow dampens and suspended sediment is deposited.
Figure 53. Diagram of morphological elements of a meandering river system and associated deposits (from Walker and Cant, 1980).

Levee deposits are mainly fine-grained sand and silt dominated by small-ripple cross-bedding and small-scale cross-bedding (Reineck and Singh, 1980). Kumar and Singh (1978) noted that some levee deposits consist of sand layers overlain by thick mud layers. Individual sand layers displayed small-ripple cross-bedding and at times horizontal bedding, whereas mud layers were usually finely laminated (Figure 49). Units F, L, M and N are not believed to be levee deposits. They do not contain the parallel, laminated, muddy sediments, root traces, plant debris, and organic matter characteristic of levee deposits (Reineck and Singh, 1980; Collinson, 1996).

Floodplains (Figure 53) act as settling basins during times of flooding and sediment commonly is deposited from suspension (Collinson, 1996). Floodplain deposits (Figure 48) generally consist of finely laminated silt and clay with intercalations of sandy sediments (Reineck and Singh, 1980; Miall, 1996). However, lamination may be destroyed by organisms. The floodplains and levees of most river systems are abundantly vegetated; thus, root traces are commonly found in
these deposits (Walker and Cant, 1980). Units F, L, M and N and the adjacent units lack these features of floodplain deposits.

Clay, silt, and organic material are the most abundant deposits within oxbow lakes (Figure 53). Although sand is a minor deposit, sand layers are typically cross-bedded. The silt and clay layers are finely laminated and contain pockets of plant and animal (freshwater molluscs) remains (Reineck and Singh, 1980; Boggs, 1995; Miall, 1996). The lack of laminations, interbeds of sand, and plant and animal remains within Units F, L, M and N suggests these units are not oxbow lake deposits.

**Low-density Turbidity Current Deposits**

Structureless muds also form by deposition from low-density turbidity currents. Low-density turbidity currents tend to produce thin-bedded sequences consisting largely of clay and silt.

Unit F and Units L – M and their adjacent units are not characteristic of a turbidite sequence. The thick, structureless mud deposits are not graded from fine sand at the base to silt and clay at the top. Also, the individual units of a turbidite include well-developed laminations, small-scale cross-bedding, with an occasional erosional scour at the base of the deposit (Boggs, 1995). Units F, L, M and N and adjacent units do not display these common characteristics of a turbidite sequence.

**Tidal Flat deposits**

Another depositional environment that contains structureless silt and clay deposits is tidal flats. The primary sediments on siliciclastic tidal flats are mud and sand. However, the proportion of mud and sand in modern day tidal flats varies
significantly (Boggs, 1995). Some tidal flats may be mud-dominated, whereas other tidal flats may be sand-dominated (Boggs, 1995).

The tidal flat environment (Figure 54) is divided into three zones: the supratidal, intertidal, and subtidal zones. Each zone is characterized by specific sediments and by specific transport mechanisms responsible for sedimentation. The intertidal zone lies between mean-high and mean-low tide and consists primarily of mud and sand. Sediment transport within the intertidal zone is both by bedload and suspension through tidal currents and waves (Reineck, 1972).

![Figure 54. Schematic diagram showing divisions of a tidal-flat environment (from Boggs, 1995).](image)

Sediments in the intertidal zone typically have a vertical range of 2 or 3 m depending upon the range between the high and low water lines; however, ten to fifteen m is not unusual (Reineck and Singh, 1980). Intertidal flat sediments are mostly fine-grained silt, clay, and fine sand. However, shells and mud pebbles are abundant in tidal channels (Reineck, 1972). The intertidal zone shows a varied spectrum of ripple types.
The intertidal zone can be divided into three zones: the mudflats, the mixed flats, and the sand flats. Mud is the predominant deposit in the upper (mudflat) intertidal area (high water line). Thick, structureless mud layers separated by thin sand laminae are characteristic structures (Reineck, 1972). Bioturbation structures are abundant; however, if deposition occurred rapidly, these structures are negligible (Reineck and Singh, 1980; Klein, 1985).

Moving seaward, muddy deposits gradually grade into sand-size sediments. This transition zone is the mixed flat, which contains both sand- and mud-size deposits. Here the dominant sedimentation process is an alternation of bedload and suspension deposition (Klein, 1985). Common sedimentary features include small-scale dunes and current ripples. The internal cross-stratification features (Figure 55) are flaser bedding, wavy bedding, lenticular bedding, interbedding, and interlamination of mud and sand (Reineck, 1972; Klein, 1985).

Herringbone cross-stratification is a common structure found within the subtidal environment (Davis, 1983). However, tidal currents do not always produce herringbone bedding. Often, one flow (flood or ebb) of a tidal phase is much stronger than another. The subordinate flow is not strong enough to build up its own bed forms, but only modifies the structures produced by the stronger flow (Lucchi, 1995).

Figure 56 demonstrates a model sequence, which can be used to establish paleotidal range during accumulation. This vertical facies shows the progression of the upward-fining succession produced by tidal flat progradation. The succession grades from a relatively thick lower tidal flat up into a thinner high tidal flat and supratidal zone (Davis, 1983).
Partial ancient tidal flat sequences are a common occurrence (Klein, 1977; Terwindt, 1988). Therefore, an ancient tidal flat sequence may have one or two units missing. Terwindt (1988) noted that shifts in major tidal and intertidal drainage channels generate local micro-transgressive and regressive sequences, superimposed on the general tidal sequences. Consequently, the lack of herringbone cross-stratification within the Bellingham Bay site does not rule out a tidal depositional environment.

Unit F is believed to be a high or mixed tidal flat deposit. The structureless, thick, mud deposit along with lenticular bedding at the base suggests a tidal depositional environment. Also, the presence of *foraminifera* suggests a marine
environment for Unit F. Units L, M, and N are also believed to be the thick, structureless mud characteristic of tidal sediments. Although bioturbation structures may be abundant in tidal flat deposits, Klein (1985) states that if deposition occurred rapidly, these structures would be negligible. Deposition was rapid throughout most of the Bellingham Bay site, suggested by the abrupt contacts (See later discussion on diastems).

Deltaic deposits

A complete, river-dominated, deltaic cycle (Figure 57) is typically 50 to 100 m thick and displays a coarsening upwards sequence (Miall, 1980; Coleman, 1976). Each cycle commences with laminated prodelta clay and grades upward into interbedded clay and silt or very fine sand containing small-scale ripple marks and bioturbation. Cross-beds, typically planar and trough, and ripple marks are abundant.
Figure 57. Generalized stratigraphic sections for three principal delta types (from Miall, 1980).
Delta sediments are characterized by high-angle cross-beds with a unimodal paleocurrent direction. Some deltas exhibit cross-beds at a shallow angle. Foreset beds tend to generate a larger delta front and produce cross-beds dipping typically 1° or less (Boggs, 1975). Many types of deltaic cycles are commonly capped by organic material (Coleman, 1976; Miall, 1980).

Silt and clay are also produced in the prodelta environment. Parallel laminae are common structures due to suspension transport. However, structureless prodelta deposits may appear (Coleman, 1976). In the most seaward portions of prodelta deposits, extremely thin laminae typically consist of color-banded clay. Shallow water portions of the prodelta deposits show thicker laminae and coarser grain size. Burrowing by marine organisms is minimal due to the high rates of sedimentation. However, the presence of bioturbation is limited to specific zones (Miall, 1980; Reineck and Singh, 1980). Faunal species, especially foraminiferal tests, are usually high indicating an open marine environment (Coleman, 1976). Shell remains are frequent.

Prodelta deposits vary in thickness from delta to delta. The Mississippi prodelta deposits range in thickness from 20 m to 100 m. However, deltas that do not contain abundant fine-grained sediments exhibit coarser-grained deposits and prodelta deposits are generally less than 20 m thick (Coleman, 1976; Miall, 1980).

The presence of foraminifera in Unit F suggests that it was deposited in a marine environment. However, if Unit F and Units L – M consisted of prodelta sediments, one would expect to find laminated silt and clay with thin sand layers characteristic of overlying delta front deposits. The lack of shell remains,
bioturbation, and high numbers and diversity of fauna in all units suggests that these are not prodelta deposits.

The Bellingham Bay site does not exhibit the characteristic features of a river-dominated delta shown in Figure 57. The sequence lacks organic material and sedimentary structures typical of a deltaic sequence. The clay units of the Bellingham Bay site do not grade up into interbedded clay and silt or very fine sand containing small-scale ripple cross-beds and abundant bioturbation and into the clean, well sorted, planar and trough cross-bed sands of distributary mouth deposits (Coleman, 1976; Miall, 1980). Further, the Bellingham Bay site contains abundant armored mudballs and exhibits multidirectional paleocurrent distribution, which are not reported in deltaic environments.

Glaciolacustrine deposits

Glaciolacustrine deltas are the products of rapid sedimentation and are built in low-energy environments where the redistribution of sediment is little due to the lack of tides, effective waves, or wind-generated currents (Gustavson et al., 1975). In their study of deltaic sedimentation into late Wisconsin proglacial lakes, Gustavson et al. (1975) noted the bottomset deposits of the distal part of a glaciolacustrine delta consist of fine sand and silt, which display horizontal bedding and some ripple bedding. The horizontal bedding is typically in the form of rhythmites (glacial varves) with occasional dropstones present (Gustavson et al., 1975).

The structureless clay units within the Bellingham Bay section did not originate in a glaciolacustrine environment. As mentioned, glaciolacustrine delta deposits are often associated with the fine-grained varved sediments characteristic of
glacial lakes (Reineck and Singh, 1980). Varves and dropstones are not present within the structureless clay units.

**CROSS STRATIFIED FACIES**

Cross-beds are found in every major sedimentary environment (Potter and Pettijohn, 1977). Although cross-stratification in fluvial, eolian, and marine environments is difficult to differentiate (Pettijohn et al., 1973; Boggs, 1995), associated sedimentary structures can be useful in interpreting the appropriate depositional environment of each unit.

Cross-beds commonly occur in sets. Cross-stratified sets less than 5 cm thick are termed small-scale; sets ranging from 5 to 50 cm are meso-scale; and sets greater than 50 cm in thickness are termed large-scale (Boothroyd, 1985). Small-scale tabular cross-stratification is produced from the migration of linear (2D) ripples, whereas, meso- to large-scale tabular cross-stratification is produced both by linear (2D) megaripples and by sand waves (Harms et al., 1982; Boothroyd, 1985).

Units A, E, H, I, J, K, S, T, and U display cross-stratification. Unit A, Upper Unit E, and Unit H exhibit planar cross-bedding (Figures 10, 17, and 21); lower Unit E, Unit I, and Unit T exhibit tangential cross-bedding (Figure 17, 22, and 30); Units J and K exhibit hummocky cross-stratification (Figure 24); and Unit S and Unit U (Figures 30 and 32) exhibit trough cross-stratification.

**Planar and tangential cross-strata**

Unit A (Figure 10) is 1.4 m thick and is poorly sorted, pebbly, coarse-grained sand. A dip of 33° was measured on the west-facing side of the pit; therefore, the horizontal laminae displayed in Figure 10 is an apparent dip. Although the lower
contact is unknown. Unit A displays large-scale planar cross-stratification. The planar cross-strata comprise one tabular cross-stratification set. *Macoma carlottensis* (Queen Charlotte Macoma), *Macoma nasuta* (Bent nosed Macoma), *Macoma* sp., and *Serpula vermicularis* (worm tubes) were found throughout the unit. Armored mudballs are scattered throughout the unit, suggesting it was formed in an intertidal environment (See later discussion on armored mudballs). All shells and worm tubes showed signs of abrasion. The contact separating Unit A and Unit B undulates slightly, but is conformable.

The upper part of Unit E (Figure 17) is poorly sorted, granular, coarse-grained sand, 0.3 m thick, and exhibits meso-scale planar cross-stratification. The cross-strata dip at a 30° angle. This unit displays a paleocurrent direction from west to east. An abundance of reworked *Serpula vermicularis* (worm tubes) was discovered in this part of the unit. The upper Unit E contains abundant shell fragments and armored mudballs, suggesting this unit was formed in an intertidal environment (See later discussion on armored mudballs).

The middle part of unit E (Figure 17) is poorly sorted, pebbly, coarse-grained sand, 0.25 m thick, and exhibits meso-scale tangential cross-stratification. The cross-strata dip at 15°. Armored mudballs, shell fragments, *Serpula vermicularis* (worm tube), and pebbles litter this section. Several reworked *Macoma* sp. were found within this portion of the unit. Current direction was from west to east. All worm tubes showed signs of abrasion. The middle and upper part of unit E consists of two sets of tabular cross-beds. Set thickness is 20 cm (mid) and 27 cm (upper), respectively.
Unit H (Figure 21) is pebbly, coarse-grained sand, 1.13 m thick, and displays large-scale planar cross-stratification. The planar cross-strata comprise one tabular set dipping at 31°, which according to Harms et al. (1982) is an average dip for large-scale planar cross-stratification. The current direction was from east to west. Unit H contains an abundance of shell fragments and armored mudballs suggesting this unit was formed in an intertidal environment. See later discussion on armored mudballs. Mudballs are abundant, of which two had diameters of 10 and 18 cm, suggesting a high-energy environment. A *Chlamys rubidus* (Hind's Scallop) shell along with a higher concentration of armored mudballs was observed at the base of the unit.

Unit I (Figure 22) is pebbly, medium-grained sand, 0.43 m thick, with meso-scale tangential cross-stratification. The planar cross-strata comprise one tabular cross-stratification set. Unit I is littered with shell fragments and armored mudballs, suggesting that this unit was formed in an intertidal environment (see later discussion). The paleocurrent direction was the same as that for Unit H, i.e. from east to west.

A change from planar to tangential cross-stratification occurs between middle and upper Unit E and between Unit H and Unit I. Both contacts between mid and upper Unit E and between Unit I and Unit H are abrupt, indicating a rapid change of environment or flow regime (Figure 58 and later discussion). Since all adjacent units consist of pebbly sand and their beds dip in the same direction, a change in the flow regime is believed to have occurred. Flow direction remained the same; however, the flow velocity increased as shown by a change from planar to tangential cross-stratification (Reineck and Singh, 1980; Boothroyd, 1985) between middle and upper
Unit E and Unit H and Unit I. The truncation of planar beds within Unit H by the overlying beds of Unit I suggests that an erosional period occurred. Flow direction remained the same during deposition of mid and upper Unit E; however, the flow velocity decreased as seen by a change from tangential to planar cross-stratification (Reineck and Singh, 1980; Boothroyd, 1985).

Unit T (Figure 30) contains poorly sorted, thinly-laminated, cross-stratified, pebbly sand. Tabular cross-stratification with set thickness averaging 4 cm is present. Thinly-laminated cross-strata are arranged tangentially within each set. Armored mudballs are sporadically dispersed throughout the unit.

Unit T displays the characteristics of a two dimensional (2D) small ripple. Small current ripples (0.5 - 6 cm in height; 4 to 60 cm in length) are common bedforms on sand flats and mixed flats (Reineck and Singh, 1980). A type of small-scale current ripple is the straight crested (2D) small ripple, which forms under low, unidirectional velocities in low energy environments. The internal structure of these ripples consists of planar cross-beds. Individual units are usually less than 3 or 4 cm thick (Reineck and Singh, 1980). The small ripples and armored mudballs within Unit T suggest that it was formed in the intertidal zone.

Megaripple bedding, which contains foreset laminae, is formed by the migration of megacurrent ripples. Megaripples (formed under unidirectional flow) are 6 cm to 150 cm in height and range between 0.6 to 30 m long (Reineck and Singh, 1980). The internal structures produced by straight crested (2D) megaripples are meso- to large-scale planar cross-beds (Reineck and Singh, 1980; Boothroyd, 1985). The thickness of individual units is usually greater than 4 cm, and can be as much as 88
1 m or even more (Klein, 1964; Boothroyd, 1985). In general under unidirectional flow, megaripples occur in relatively coarse-grained sand (grain size greater than 0.6 mm) (Reineck and Singh, 1980).

Figure 58 displays the relationship between flow velocity and megaripple bedforms. As flow velocity varies over the bedforms, a change in the external slipface shape is produced, thus changing the internal laminae structure. When flow velocity increases, foreset laminae change from planar to tangential due to an increase in fine grain particles swept into suspension and deposited at the toe of the slipface (Boothroyd, 1985).

Units A, E, H, and I (Figures 10, 17, and 21) show the characteristics of megaripples. All units consist of grain sizes greater than 0.6 mm and each unit's thickness falls within the 6 cm to 150 cm range. In addition, the cross-strata in each unit are contained in tabular sets. Tabular sets of cross-strata are formed by migrating 2D megaripples (Harms et al., 1982). Unit T displays features similar to small-current ripples.

Figure 58. Changes to foreset laminae with increasing velocity, bed shear stress and depth ratio (from Reineck and Singh, 1980).
Beach, intertidal, and subtidal sand bar deposits

During certain conditions, small ephemeral sand bars may develop within the foreshore zone (Figures 50 and 59). Such bars have been given various names: ridge, swash bar, and repair bar. However, the term ridge and runnel, which applies to both the sand bar and the trough-like feature landward of the bar, is more widely used (Davis, 1985). Davidson-Amott and Greenwood (1976) observed that in a bar, nearshore environment (Figure 59), medium-scale planar cross-stratification was produced on the landward slope of an inner bar system, which experiences shallower water depths and greater occurrence and intensity of breaking waves than the outer bar system. The unit they studied was as thick as the bar height, which was 1 m, and maintained a slope of 25°. The contact between the steeply dipping bar sand and the small-scale ripple laminations of the trough sands was not erosional. At times, the
steep foreset beds of the inner (crescentric) bars were interbedded with (or completely replaced by) seaward dipping megaripple bedding produced by seaward flowing rip currents. Grain sizes ranged from fine- to medium-sized sand. Sorting was not discussed; however, box core photographs of the inner bar landward slope system showed moderate sorted deposits.

Davis et al. (1972) studied ridge and runnel systems (Figure 60). They noted that ridge-and-runnel topography formed following storm conditions. Within a few tidal cycles, the ridge began to migrate toward the beach, and the external structure displayed an asymmetric profile with a steep landward edge. As a result, high angle (20°–30°) planar cross-stratification composed of sand sized particles were generated. The profile was created by wave activity and wave generated currents moving over the ridge.

Figure 60. General profile of ridge and runnel profile (from Davis, Jr., 1985).

A transgressive ridge sequence (Davis et al., 1972) begins with basal planar beds that are offshore-dipping, low-angle, parallel cross-beds typically with heavy mineral concentrations (storm beach). Two-dimensional and three-dimensional ripple cross-beds represent the internal structure of the runnel. Immediately above are high angle (20°–30°), landward-dipping, migrating, planar cross-beds. The top of the
sequence consists of seaward-dipping, welded, beach face, planar cross-beds that become truncated due to the swash action of waves on the beach. In the tide-dominated environment, an additional unit consisting of interbedded trough and planar cross-beds caps the sequence. Davis (1985) noted the addition of coarse material to beaches, either in the form of terrigenous pebbles or shell material typically show a bimodal distribution giving that deposit a poorly sorted value.

The mid and upper part of Unit E (Figure 17) shows those characteristics similar to the intertidal foreshore sand bars studied by Davidson-Arnott and Greenwood (1976) and the sea ridges of beaches observed by Davis et al. (1972). Both parts of Unit E exhibit meso-scale planar cross-stratification, and the poorly sorted, medium- to pebbly-grained sand of the sand bars. The cross-strata of upper Unit E has a similar dip (30°) to sand bars of the earlier studies, whereas, the cross-strata of mid Unit E dip at a shallower, 15° angle. Also, both upper and middle Unit E contain abundant shell fragments, reworked worm tubes and shells, and armored mudballs, further suggesting that these units were formed in an intertidal environment (See later discussion on armored mudballs).

Megaripples have been observed in the subtidal zone of mesotidal estuaries (Clifton, 1983) and on sand bars in the intertidal and subtidal zones of macrotidal settings (Dalrymple et al., 1975; Harms et al., 1975; Klein, 1976a). In the lower part of the intertidal flat, subtidal sandflats lie near the low-water line. Here, wave and current activity is at its greatest, bedload transport is dominant, and sand-size deposits predominate (Reineck, 1972; Reineck and Singh, 1980; Klein, 1985; Boggs, 1995). Sedimentary structures commonly observed in this setting are internal cross-
stratification (sometimes in the form of herringbone and festoon structures) and reactivation surfaces. Laminated sand is found in small amounts. Bioturbation features are rare due to the instability of the sand substrate (Klein, 1985).

Clifton (1983) noted that trough and tabular sets of medium- to large-scale, high-angle cross-beds were abundant in Pleistocene subtidal zone deposits of Willapa Bay, a mesotidal estuary on the coast of Washington. Other features observed by Clifton (1983) in the subtidal deposits include extensive, thick accumulations of coarse debris, especially pebbles or clasts of mud, a unidirectional paleocurrent orientation of the megaripple cross-bedding (due to a more dominant ebb or flood tidal current), and laterally persistent mud drapes interbedded within cross-bedded sand.

Klein (1976a) observed that sand bars and sandy deposits occur in the lowest areas of the tidal flat environment of the Minas Basin, Nova Scotia. Two-dimensional megaripples and sand dunes on these intertidal sand bars are commonly capped by superimposed ripples. The internal structures of these megaripples and sand waves vary from simple to complex. One sedimentary facies include simple megaripples, which consist of medium- to coarse-grained sand within sets of trough and planar cross-stratification with sharp boundaries. Pebbles and shells line the troughs. Cross-stratification dip angles averaged 28°. Set thickness of the cross-stratification average 10 cm (Klein, 1976a).

In addition, McCants and Zarillo (1985) studied large-scale, planar cross-beds composed of medium- to coarse-grained sand mixed with shell material in a sand-dominated intertidal environment. These planar cross-beds were located within the
lower tidal flat of a mesotidal estuarine system that was influenced by both waves and currents.

The middle and upper parts of Unit E (Figure 17) exhibit characteristics much like those of the intertidal sandbars examined by Klein (1976a) in the Minas Basin, Nova Scotia. Both parts of Unit E exhibit meso-scale, planar cross-stratification, and the poorly sorted, medium- to pebbly-grained sand of the sand bars. Also, both parts of Unit E are littered with shell fragments and armored mudballs, suggesting this unit was formed in an intertidal environment (See later discussion on armored mudballs).

Unit A and Unit H (Figure 10 and 21) are pebbly, coarse-grained sand, and displaying large-scale, planar cross-stratification. The planar cross-strata in Unit A and Unit H each contain one tabular set of cross-stratification and dip at 33° and 31°, respectively. Although Clifton (1983) did not state the dip of large-scale, high-angle, subtidal, cross-beds, Unit A and Unit H display similarities to subtidal deposits. Unit H contains a thick accumulation of coarse debris (armored mudballs at the base), which is another diagnostic feature of Clifton’s (1983) subtidal deposits. However, Unit A and Unit H exhibit similar characteristics to the large-scale, planar cross-beds studied by McCants and Zarillo (1985) in a sand-dominated intertidal environment. Since the formation and preservation of armored mudballs within the subtidal zone is not documented (to the author’s knowledge), Unit A and Unit H, which do contain an abundance of armored mudballs, are more likely to be intertidal rather than subtidal sandbars (See later discussion on armored mudballs).

Unit I (Figure 22) is pebbly, medium-grained sand, 0.43 m thick, with meso-scale tangential cross-stratification. The cross-strata of Unit I occur in a tabular
cross-stratified set characteristic of intertidal and subtidal sandbars, which also consist of medium- to coarse-grained sand. Since the velocity increased between Unit H and Unit I, as shown by a change from planar to tangential cross-stratification, Unit I was deposited subsequent Unit H, therefore, suggesting that Unit I is intertidal (or subtidal) as well. Unit I is littered with shell fragments and armored mudballs, also suggesting that this unit was formed in an intertidal environment (See later discussion on armored mudballs).

**Tidal channel deposits**

Cross-bedding of megaripples is common in the channels of the intertidal zones of mesotidal estuaries (Reineck, 1972; Clifton, 1983). Tidal currents produce numerous gullies and channels on tidal flat. Within tidal channels, bedforms are characterized by megaripple bedding and small-scale cross-bedding (Klein, 1964; Reineck, 1976). Shells, mud, and pebbles (Reineck, 1976; Klein, 1976a) normally floor the gullies and channels of sand flats. Erosion of the channel thalweg by currents is common and slump blocks of the channel wall sediments fall on the channel floor (Klein, 1985). Boothroyd (1985) comments that intertidal megaripples change orientation with the tidal stage; therefore, herringbone cross-stratification is common or the tops may be reworked. Other abundant structures expected within the channels are lenticular, flaser, and interbedded sand and mud (Reineck, 1975).

The lateral shifting of tidal channels on the flats produces beds that dip perpendicular to the general flow direction, thus producing longitudinal cross-bedding (Figure 61) that can be likened to point bar deposition in a meandering
Longitudinal cross-bedding (Reineck, 1976) is different from the cross-bedding produced by the migration of ripples. Each inclined layer within the longitudinal cross-beds is in itself a bed and not laminae. Therefore, each inclined layer may display a different bedding type such as lenticular, ripple, or interlaminated sand and mud bedding (Reineck and Singh, 1980).

The cross-bedding observed in Units A, E, H, and I (Figures 10, 17, 21, and 22) is not longitudinal cross-bedding. Although units A, E, and H display meso- to large-scale planar bedding and Unit E and H contain the basal lag deposits characteristic of tidal channels, other diagnostic features associated with this type of bedding are not found in the units: tension faults with curved fault planes (Reineck, 1976) and inclined layers with different bedding types (thinly interlaminated sand and mud bedding) (Reineck and Singh, 1980).

Lower offshore zone deposits

Megaripples and megaripple bedding are sometimes developed in the lower offshore zone (greater than 10 m of water) in sediments that are clean, medium- to
coarse-grained sand (Reineck and Singh, 1980). Bioturbation is common. Unit A, E, H, and I are not clean sand. They are poorly sorted, pebbly sand containing abundant shell fragments and armored mud balls, suggesting an intertidal origin. Therefore, they are not believed to have formed in the lower offshore zone.

**Braided Stream deposits**

Planar cross-bedding is most abundant in pebbly and coarse sand of braided streams. Longitudinal and transverse bars in braided streams characteristically have steep slipfaces, which produce planar cross-bedding with foresets dipping at 30°. Units are mostly tabular. Planar cross-bedding in fluvial channels develops in both gravel and sand and in both meandering and braided streams. However, although planar cross-beds are not in themselves diagnostic of braided streams, they are most abundant in braided streams consisting of pebbly-coarse sand (Reineck and Singh, 1980).

Transverse bars are more common in sandy braided streams than in gravelly braided streams (Reineck and Singh, 1980). Sand-dominated braided streams are characterized by an abundance of planar cross-bedding and trough cross-stratification. Foresets of transverse bars are typically composed of alternating coarse and fine laminae (Smith, 1972). Unit A, Unit E, Unit H, and Unit I (Figures 10, 17, 21, and 22) do not display alternate laminae of coarse and fine sand. Of the 27 units within the Bellingham Bay stratigraphic section, 9 units display either planar or trough cross-bedding. Therefore, the Bellingham Bay site does not display the abundant planar and trough cross-bedding characteristic of sand-dominated braided streams.
Glaciolacustrine deltaic deposits

Planar cross-beds are common features of glaciolacustrine deltaic systems. In their study of deltaic sedimentation into late Wisconsinan proglacial lakes, Gustavson et al. (1975) noted foreset bedding of subparallel beds of sand or gravel dipping as much as 30°. In sandy areas, foreset beds dip less than 15° and commonly displayed ripple-drift cross-lamination (Figure 62). Climbing ripple lamination develops as ripples are built upward in an overlapping series, as well as migrating in a forward direction (Reineck and Singh, 1980).

The bottomset deposits of the distal part of a glaciolacustrine delta consist of fine sand and silt, which display horizontal bedding and some ripple bedding. The horizontal bedding is typically in the form of rhythmites grading laterally into glacial varves (Gustavson et al., 1975). Glaciolacustrine delta deposits are often associated with fine-grained varved sediments characteristic of a glacial lake (Reineck and Singh, 1980).

Figure 62. Diagrammatic representation of ripple-drift (climbing ripple) and sinusoidal (draped) lamination (from Jopling and Walker, 1968).
Units A, E, H, and I (Figures 10, 17, 21, and 22) of the Bellingham Bay site do not display climbing ripple and ripple-drift lamination. Also, all units contain an abundance of armored mudballs, in addition to reworked worm tubes and shells suggesting a marine environment (See later discussion on armored mudballs).

Ice-contact delta deposits

Ice-contact delta deposits (Figure 63A) form at stagnating ice margins where meltwater streams flow over dead ice and into a lake (Ashley, 1995). High-energy ice-contact deltas are well sorted, coarse-grained systems with foreset beds typically dipping up to 33°. Once at the lake margin, sand and larger size grains move by

Figure 63. Diagram of Glaciolacustrine deltas. A. Ice contact delta depositional environment. B. Distal lake delta depositional environment (from Ashley, 1995).
mass-movement (slump, creep, avalanche, and sediment gravity flows). Bedding is typically structureless to parallel with lenses of open work gravel and coarse sand. Coarsening and fining upward gravel sequences are common (Ashley, 1995).

Shallowly dipping foreset beds of ice-contact deltas tend to form in lower energy environments of well sorted, fine-grained sediments. The upper portions of the delta front show signs of rapid sedimentation and dewatering: slumping, dish structures, and ball-and-pillow structures (Ashley, 1995). Also, ice-contact deltas typically have interbeds of diamicts and ice-rafted debris, plus post-depositional collapse features from melting of ice (Ashley, 1995). Climbing ripple sequences and drape lamination are common features found in the mid to distal delta front (Gustavson et al., 1975).

Units A, E, H, and I do not display the characteristics of ice-contact delta deposits. All units are poorly sorted deposits and do not contain climbing ripple or drape laminations. Ice-rafted debris and post depositional collapse features is nonexistent. Therefore, Units A, E, H, and I are not believed to be ice-contact delta deposits.

**Distal (glacier-fed) lake delta deposits**

Distal lakes (Figure 63B) fed by meltwater streams are typically semi-permanent and form a lengthy distance from the glacial ice. Distal lake delta deposits vary from fine-grained sand and silt with low-angle foreset beds dipping from 5°-15° to pebble-cobble gravel with steep foreset beds dipping 30°-33° (Ashley, 1995). However, due to the distance of the distal lake delta from the glacier, deposits tend to be finer-grained (sand and clay) than the ice-contact delta deposits. Climbing ripple
sequences are abundant. Typically, the upper foreset beds of the distal lake delta consist of rhythmically bedded, fining upward sand and gravel, which represent different episodes of sedimentation during the melt season such as high discharge periods or changes in sediment influx points due to distributary channel relocation (Ashley, 1995).

Mid-delta foreset sediments are generally sand size particles that dip less than 10°. Sand, silt and clay carried by turbidity currents frequently display climbing ripple-drift sequences consisting of fine sand capped by clay and silt drapes (Gustavson et al., 1975). Drape lamination is parallel laminae of sand, silt, and clay deposited from suspension and draped over an underlying bedform. The thickness of each individual laminae remains unchanged (Gustavson et al., 1975; Reineck and Singh, 1980).

Units A, E, H, and I of the Bellingham Bay site do not display the features common of distal lake delta deposits. None of the units contain climbing ripple or drape laminations. Also, each unit lacks the rhythmically bedded, fining upward sand and gravel characteristic of distal lake deposits.

**Trough cross-stratification**

Unit S and upper Unit U (Figure 31 and Figure 32) exhibit trough cross-stratification. Unit S is 16 cm thick and displays small-scale trough cross-stratification. Small-scale trough cross-stratification (for individual unit, a maximum of 4 cm) is mostly the result of deposition from migrating 3D small current and wave ripples (Harms et al., 1975; Reineck and Singh, 1980). Unit S is moderate sorted, fine- to coarse-grained sand and shows the same intricately interwoven cross-
stratification of the fine-to medium-grained sand wave ripple shown in diagram 9 of Figure 64.

Figure 64. Different types of cross-bedding formed as a result of wave action, depending upon the type and intensity of wave activity (from Reineck and Singh, 1980; taken from De Raaf et al., 1977).

Upper Unit U is 10 cm thick and consists of well sorted, fine-grained sand with small-scale trough cross-stratification in sets 2 to 3 cm thick. The sets have bounding surfaces that are curved. Directly beneath the trough cross-stratification is horizontal lamination approximately 2 cm thick. De Raaf et al. (1977) assert that
wave ripples form directly above horizontal or slightly undulatory lamination. Unit U exhibits features similar to the wave ripple, which consists of fine-to medium-grained sand, shown in diagram 11 of Figure 64.

De Raaf et al. (1977) describe diagnostic features between wave and current ripples. Wave ripples are characterized by form discordant (composite) cross-lamination (Figure 65). The outer shape of the ripple has been reworked and is not genetically related to the internal structure. The internal structure of a wave ripple is often characterized by the lower boundary of the wave ripple set, is often scooping and undulatory, whereas current ripples tend to have planar lower boundaries; association (in the same unit) with horizontal or slightly undulatory lamination; a bundled upbuilding of thin and oppositely dipping laminae, which form chevron-type structure; unidirectional, adjacent cross-laminae consist of opposing dips; and sometimes swollen, lens-like sets (Figure 65) (De Raaf et al., 1977).

Unit U and Unit S (Figure 31 and 32) exhibit some of the diagnostic features common to wave ripples. The upper part of Unit U exhibits features similar to the

![Diagram](image_url)

**Figure 65.** General wave diagnostic features of cross-lamination (modified from De Raaf et al., 1977).
form-discordant wave ripple shown in Figure 65. The bundled upbuilding of thin
and oppositely dipping laminae, which form faint chevron-type structures, are
present. Also, these thin and oppositely dipping laminae are associated with
horizontal lamination, which is located directly beneath, and is another diagnostic
feature of a wave ripple. Also, the lower part of Unit U contains consolidated
mudballs, further suggesting an intertidal origin.

Each individual trough within Unit S exhibits irregular, lower bounding
surfaces, which are characteristics of wave ripples produced in shallow water by
waves (De Raaf et al., 1977; Reineck and Singh, 1980). Although some of the
individual troughs within Unit S exhibit scour-like features. Harms et al. (1975) note
that isolated, trough like scours occur in very shallow streams when lodged debris
cause deep scour. Unit S does exhibit these trough-like scours and occurs in
isolation. Therefore, whether the origin of the trough cross-stratification is wave
generated or current generated is not definitive.

Asymmetrical wave ripples occur most frequently in nearshore environments
and in sand flats and mixed flats (De Raaf and others, 1977; Reineck and Singh,
1980). Unit U and Unit S were formed either in the nearshore or tidal flat
environment. In most tidal flat environments, ripple systems of varied directions
form. The Bellingham Bay site comprises ripple systems with multidirectional
currents. Table 6 displays the different environments that generate the various types
of ripples compared to those abundant, common, rare and absent in the Bellingham
Bay site.
Table 6. Bellingham Bay ripples compared to ripples within other depositional environments (modified from Reineck and Singh, 1980).

<table>
<thead>
<tr>
<th></th>
<th>MEGA-CURRENT RIPPLES</th>
<th>SMALL-CURRENT RIPPLES</th>
<th>WAVE RIPPLES</th>
<th>CLIMBING RIPPLES</th>
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</thead>
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<td>XX X</td>
<td>0</td>
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<td>0 X</td>
<td>X</td>
<td>0</td>
</tr>
<tr>
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<td>XX X</td>
<td>XX</td>
<td>0</td>
</tr>
<tr>
<td>Tidal channel and inlet</td>
<td>XX X</td>
<td>XX X</td>
<td>-----</td>
<td>0</td>
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<td>XX X</td>
<td>XX</td>
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<td>X</td>
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<td>-----</td>
</tr>
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<td>X</td>
<td>-----</td>
<td>0 XX</td>
</tr>
<tr>
<td>Turbidite</td>
<td>0 X X X</td>
<td>-----</td>
<td>0 X</td>
<td>-----</td>
</tr>
</tbody>
</table>

XX = abundant, X = common, 0 = rare, ----- = absent.

*XX = abundant, X = common, 0 = rare, ----- = absent.

* Bellingham Bay section
Hummocky cross-stratification

The upper part of Unit J (Figure 24) consists of well sorted, laminated and thinly-laminated hummocky cross-stratification of medium-grained (0.25 to 0.50 mm) sand. The lower 6 cm of Unit K (Figure 24) is very well sorted, thinly-laminated, hummocky, cross-stratified, sandy silt. Unit J and Unit K are conformable with a gradational contact, suggesting a more gradual change in deposition.

Hummocky cross-stratification is the product of strong wave action usually brought on by storms (Harms et al., 1975; Lucchi, 1995). Most hummocky cross-stratification forms in shallow-marine environments, but it may occur in lacustrine settings (Boggs, 1995). The hummocky beds are normally interlayered with silt and clay, suggesting a hydraulically quieter time or slower deposition rate after storm events. Normally, hummocky cross-stratification occurs in grain sizes ranging from fine-grained sand to coarse silt within the lower shoreface and offshore facies (Harms et al., 1975; Reineck and Singh, 1980). The hummocky cross-stratification in Units J and K reflects storm deposition within the lower shoreface.

GRAVEL FACIES

Coarse-grained (greater than 35% pebbles and cobbles) deposits form in a variety of environments: alluvial, glacial, beach, and submarine fans (Rust, 1980). Unit W (Figure 33) (12.0 to 12.5 m) contains structureless, clast-supported pebbles within a sandy matrix; it is the only unit within the sequence that is clast-supported. The upper 3 cm of this unit is cemented with calcite. A few armored mudballs were found in a sandy pebble lens at 12.5 m. Unit W and Unit X are conformable strata separated by an abrupt contact.
Unit Y, Unit Z and Unit AA (Figure 34) display alternating strata of moderate sorted, laminated, silty sand (with less than 5% pebbles) with interbeds of poorly sorted, structureless pebbly sand. The gravel forms 35% to 45% of these units.

Sand and silty sand of Unit AA are deposited in small-scale ripples and horizontal laminae. These are interbedded with thin gravel beds. Unit AA and Bellingham glaciomarine drift are separated by an unconformity. The silty sand of Unit Z contains small-scale cross-laminae, as does the lower 0.5 m of Unit Y. Cross-laminae are planar and tangential in both units and Unit Y also contains horizontal cross laminae. The contact separating Unit Y and Unit Z is undulating and abrupt.

Rust (1980) states that clast-supported gravel indicates energetic aqueous transport. Matrix-supported gravel with a sand matrix indicates a lower-energy of transport than does the clast-supported gravel.

Glacial outwash and braided river deposits

Church and Gilbert (1975) discuss deposits of high-energy proglacial riverine environments in Washington, British Columbia, and Alaska. Sediments within riverine proglacial environments contain a wide range of grain sizes. Poorly sorted gravel displayed featureless or rudimentary parallel bedding. Poor sorting and rudimentary bedding result from the rapid deposition of transported materials. Although most sandur (outwash plain) bedding is horizontal (upper flow regime), cross-stratified sand found within the proximal outwash gravel dip upsandur. Maizels (1995) observed matrix supported gravel with less than 50% matrix content within the proximal zone of a proglacial environment. The poorly sorted deposits had no clear bedding and often consisted of large, angular clasts.
The distal facies of the Donjek model (Figure 66) is representative of the distal zone of a glacial stream, which contains fining upward cycles of clast-supported, crudely-bedded, coarse gravel and trough cross-bedded sand and gravel (Maizels, 1995). Each cycle (1 to 20 m) begins with a conglomerate base and passes through a fine- to very coarse-grained sand (pebbles may be present) sequence consisting of solitary or grouped trough cross-strata interbedded with meso-scale, planar cross-beds of very fine- to coarse-grained sand (Davis, 1983). Imbrication of

![Figure 66. General stratigraphic models for gravel-dominated braided streams (modified from Davis, Jr., 1983; taken from Miall, 1996).](image)
the gravel is common. Typically, the Donjek model is used for braided systems with 10–90% gravels (Davis, 1983). Distal environments exhibit similar sedimentary features found in fluvial sand bars, such as trough fill structures and foreset bedding. Cross-stratification was more typically associated with sand deposits in distal sites than with proximal gravel (Church and Gilbert, 1975; Rust, 1980).

Unit W (Figure 33) lacks the crudely-bedded, coarse gravel and trough cross-bedded sand and gravel characteristic of the Donjek model. In addition, imbrication is absent. Unit Y, Z and AA (Figure 34) combined do not display the fining upward cycle of the Donjek model. Although Units Y-AA contain very fine- to coarse-grained sand, they lack the trough cross-strata and meso-scale, planar cross-beds. Additionally, each unit lacks plant roots, desiccation cracks, bioturbation, and coal streaks that are common features within the laminated sand, silt and mud layers of the Donjek model (Miall, 1995).

The most commonly occurring gravel facies within glacial outwash deposits are clast-supported, imbricated, sub-rounded, bimodal to polymodal gravel exhibiting poor bedding (Maizels, 1995). However, the wide variety of textures, grading, and internal structures exhibited by glacial outwash deposits make classifying a facies difficult. Although Unit W (Figure 33) at the Bellingham Bay site resembles this facies in being clast-supported, other factors raise questions. The clasts within Unit W show no imbrication. A few subrounded, armored mudballs were found in a sandy pebble lens of Unit W. Armored mudballs occasionally occur in outwash, where they are called tillballs. They are well-rounded to sub-rounded, and have a center of clay
and silt sized particles with a fairly large portion of sand and scattered pebbles (Leney and Leney, 1957).

Units Y, Z and AA (Figure 34) of the Bellingham Bay site are not glacial outwash deposits. The bedding within Units Y, Z, and AA combined is sharp and distinct unlike the rudimentary bedding found in proximal outwash deposits and lack the trough fill structures and foreset bedding of distal deposits. Also, imbrication is not a sedimentary feature found within Unit Y, Unit Z, and Unit AA.

The Scott model (Figure 66) is characteristic of braided systems in the proximal zone of humid fan environment. The Scott model is dominated by structureless to crudely-beded, clast-supported pebble and cobble gravel within a sand matrix typical of longitudinal braid bars, lag deposits, sieve deposits, and minor channel fills (Maizels, 1995; Miall, 1996). Imbrication within the gravel is common. Minor thin sand lenses occur interbedded within the gravel; these sand lenses exhibit planar to trough cross-beds or ripple cross laminae. Grain sizes range from very fine- to coarse-grained sand to pebbles. Debris flows are rare (Miall, 1996). The Scott model is normally used for braided systems consisting of greater than 90% gravel (Davis, 1983).

The clast-supported, structureless, poorly sorted, sandy pebble of Unit W exhibit some characteristics of the Scott model; however, imbrication of clasts is absent, and Unit W comprises 80% gravels and associated units are sandy.

Sheetflood deposits

Sheetflood deposits (Figure 67) are found in most alluvial fans. Most of the deposits comprise sheets of sand, silt, and gravel deposited in braided distributary
channels. Typically, sheet flood deposits are well sorted (within each stratum), display well-defined bedding, and may be cross bedded, laminated, or structureless (Bull, 1972). Fine sand units may show small-ripple bedding. Some imbrication is present in the gravel (Bull, 1972; Davis, 1983).

Figure 67. Sheetflood deposits of an ancestral alluvial fan (from Bull, 1972).

Units Y, Z, and AA of the Bellingham Bay site display the sheet-like strata of sheetflood deposits. In addition, small-scale ripple bedding and horizontal lamination occur within the silty sand and sand (with less than 5% pebbles) of Unit AA and small-scale cross laminae occurs within the silty sand of Unit Z. The lower 0.5 m of Unit Y contains small-scale, wedge cross-stratification. However, the individual sheet-like strata of Units Y through AA display moderate to poor sorting, unlike the
well sorted strata characteristic of sheetflood deposits. A sheetflood origin for these three units cannot be ruled out, but such an origin for the entire Bellingham Bay site is unlikely.

**Marine subaqueous outwash deposits**

Croll (1980) contended that the Deming sand along Bellingham Bay consisted of subaqueous outwash sediments deposited by subglacial or englacial submarine outwash streams such as those studied by Rust and Romanelli (1975). Rust and Romanelli (1975) examined late Quaternary coarse facies subaqueous outwash deposits north of Ottawa, Canada, and noted that the deposits had very strong fluvial characteristics. Subaqueous, stratified, sand and gravel lie above Wisconsin till and below fossiliferous marine deposits. The primary sedimentary structures observed in the subaqueous deposits by Rust and Romanelli (1975) were cross-bedding, ripple cross-lamination, parallel stratification, clast imbrication, and channels. The channels observed were simple, yet large (up to 38 m in width and 7 m in depth) and typically symmetric with steep walls.

Rust and Romanelli (1975) found various types of cross-bedding within the subaqueous deposits (Figure 68) including planar cross-stratified, coarse-grained sand in tabular sets 10 to 40 cm thick, ripple-drift cross laminae in sand and silt, structureless sand, and tangential cross-beds consisting of medium-grained sand and scattered pebbles. The lower bounding surfaces of the cross-bed sets are curved and parallel. These cross-beds typically filled scour pits or hollows. Deformation structures were common, including post depositional deformation structures such as diapirs and normal faults. The faults and downwarped features found in these
deposits are attributed to the melting of buried ice and are characteristic of subaqueous outwash deposited near the ice margin (Rust and Romanelli, 1975). The channel fill in one pit studied by Rust (1977) was highly contorted and contained kidney-shaped masses identical to ball-and-pillow structures.

Figure 68. Different types of cross-bedding within subaqueous deposits. Gravel Pit in Ottawa, Canada. (from Rust and Romanelli, 1975).

Primary structures of subaqueous deposits in another locale observed by Rust and Romanelli (1975) were less abundant due to the larger grain size. Although parallel bedding, which comprises alternating layers of various gravel sizes and sand,
were the principal structures observed. Other features included glacially striated, polished, and imbricated boulder gravel; parallel bedded, cross-bedded and rippled sand; all of which is unconformably overlain by pebble gravel containing abundant marine fossils.

Unit W, Y, Z and AA (Figures 33 and 34) do not exhibit the features of the subaqueous outwash sediments described by Rust and Romanelli (1975). Further, the Bellingham Bay site does not display the distinctive features of subaqueous deposits, which include an abundance of ripple cross-lamination and deformation structures (e.g. diapirs and normal faults). Also, recall that ten units at the Bellingham Bay site contain armored mudballs, suggesting an intertidal environment and six of those ten units contain shell fragments, reworked shells, and worm tubes. Fossils were not found in the subaqueous deposits studied by Rust and Romanelli (1975).

Beach deposits

Regressive or transgressive marine shorelines generally produce sheets of gravel with fine-grained matrixes. Normally, the interstices of marine conglomerates contain well sorted sand unlike the poorly sorted sand within the gravel of alluvial fans (Bull, 1972). Clifton (1973) observed that beach deposits generally show excellent segregation of pebbles and sand grains into separate beds due to the occurrence of wave surges. The degree to which the separate beds are segregated depends upon the transporting capability and reworking of that transporting agent. Clifton (1973) states that wave-worked beach gravel can be differentiated from alluvial gravel by its greater degree of distinct bed segregation. Fluvially transported gravel may show pebbles scattered throughout the sand unit due to rapid deposition.
during flooding (Clifton, 1973). Beach gravel is typically associated with marine fossils and offshore strata. However, if alluvial fans prograde into the sea, gravel formed by alluvial processes and that show alluvial characteristics may contain marine fossils (Rust, 1980).

Harms et al. (1975) researched gravel shoreline deposits and noted this facies is less common than the sandy shoreline facies. This 8-m thick, poorly sorted, gravel, and coarse-grained sand consisted of cross-beds, shell fragments, and rare burrows. Pebbles within the sand were either scattered throughout the sand or sharply segregated into thin beds. The beds rested upon gently inclined erosional surfaces. Pebble imbrication was poor. High angle, trough cross-stratification with set thickness ranging from 15 cm to 2 m or horizontal to low angle (1°–3°) parallel cross-stratification was present. The depositional environment of this coarse-grained, cross-bedded, pebbly sandstone facies was interpreted as the upper shoreface.

Forbes and Taylor (1987) observed that coarse-grained beach deposits remain relatively poorly understood and are less well documented than sand-dominated beach deposits. In their study along the Canadian Atlantic coast, they found that coarse-grained beaches are common in formerly glaciated regions due to the significant portions of sand and gravel within the poorly sorted, glacigenic sediments. They noted parallel, stratified, sand, pebble, and gravel in the lower and upper foreshore along Fourchu Bay, Nova Scotia.

Units Y, Z, and AA (Figure 34) at the Bellingham Bay site show characteristics similar to those of the shoreline gravel deposits discussed by Harms et al. (1975) and the upper and lower foreshore deposits observed by Forbes and Taylor.
Units Y, Z and AA are poorly sorted and display the alternating sharp, thin beds of sand and pebble of the shoreline gravel. In addition, some beds within the units exhibit inclined erosional surfaces. Also, the horizontal lamination such as that within the silty sand and sand (with less than 5% pebbles) of Unit AA is common to the upper-shore face deposits.

Unit W alone lacks the sharply segregated thin beds of gravel and sand of the beach gravels described by Clifton (1973) and Harms et al. (1975). However, Unit W and Unit X (Figure 33 and 35) together display sharp, but not thin, distinct beds of sand and gravel. The well-sorted, very fine-grained sand and silty sand of Unit X contains horizontal and small-scale ripple bedding common to upper-shore face deposits. Also, a few armored mudballs were found within Unit W. Therefore, a beach or intertidal origin for these three units cannot be ruled out.

**OTHER TYPES OF DEPOSITS**

The lower part of Unit B (Figure 10) is poorly sorted, horizontally laminated pebbly, coarse-grained sand. The upper part of Unit B consists of moderately sorted, faint, horizontally-laminated, coarse-grained sand. Shell fragments, armored mudballs, and reworked shells and worm tubes are scattered throughout the entire unit. A higher concentration of mudballs, clasts, and shell fragments was found at the base of the Unit B. Also Unit B displays normal grading. Although Unit B exhibits horizontal laminae, the textures and sedimentary structures differ from those of the laminated sand facies in that they are moderately- to poorly sorted, pebbly, coarse-grained sand and not the well sorted sands of the laminated sand facies.
Barrier beach and shoreface facies

The high energy breaker and surf zone are located in the upper-shoreface and middle-shoreface, respectively (Figure 50). Breaker zone deposits are typically comprised of fine- to medium-grained sand with a minor amount of silt and clay, shell material, and gravel. The development of longshore bars occurs within this zone. Sedimentary structures may be complex and variable depending upon the occurrence of these bars (Reinson, 1980; Boggs, 1995). Depositional structures included within this facies are landward-dipping ripple cross-lamination; seaward-dipping, low-angle, planar bedding; subhorizontal plane laminations; and seaward- and landward-dipping trough cross-beds (Davidson-Amott and Greenwood, 1976; Reinson, 1980).

The coarsest sediment is commonly abundant in the breaker zone (Figure 69) due to sediment brought from the open sea and the undertow of backwash from the surf zone transporting coarser sediment toward the breaker zone (Reineck and Singh, 1980).

Figure 69. Distribution of and mechanism for sediment transport in the breaker zone (Zone B). Arrows indicate net sediment movement as wave breaks (from Reineck and Singh, 1980).
1980). However, as this zone migrates on those shorelines with significant tidal ranges, coarser material is spread across the upper shoreface (surf zone) and foreshore.

Storm waves can significantly modify shoreface deposits, especially in the breaker (middle) and shoaling (lower shoreface) zone, causing severe erosion and redeposition of sediments (Reinson, 1980; Boggs, 1995). Thick (2 m), subhorizontal laminated sand overlying coarse lag layers are a common feature. Also, graded bedding has been documented in some shoreface deposits (Reinson, 1980). Davidson-Arnott and Greenwood (1976) noted that the majority of preserved shoreface deposits are the result of storms.

Surf zone (upper-shore face) deposits form as a result of longshore and rip currents, which develop by wave action only (Reineck and Singh, 1980; Boggs, 1995). Due to the complex hydraulic environment of the surf zone, variable sediment textures and complex sequences of sedimentary structures are generated (Reinson, 1980). Sediment sizes range from fine-grained sand to gravel depending upon the available sediment supply and energy conditions. Sedimentary structures include trough cross-strata, low-angle, bidirectional cross-beds and subhorizontal plane beds (Harms et al., 1975; Reinson, 1980).

Upper shore face (surf zone) sediments are closely associated with foreshore deposits (Figure 70), due to their adjacent position of the beachface. Therefore, the deposits have been grouped with foreshore facies in some studies (Reinson, 1980). According to Thompson (1937), sediments in the lower part of the foreshore are more poorly sorted and contain more abundant shell fragments than sediments of the upper
part of the foreshore. However as this zone migrates on shorelines with significant tidal ranges, coarser material is spread across the backshore and upper shoreface (surf zone) (Reineck and Singh, 1980) (Figure 70). Thompson (1937) states that any sandstone or conglomerate containing an appreciable amount of shells from various ecological environments is likely to be littoral.

![Figure 70. Generalized barrier beach sequence (modified from Reinson, 1980).](image)

Unit B displays characteristic features of surf zone (upper-shore face) deposits. Both parts of the unit contain poor and moderately sorted, coarse- to pebbly-grained sand like those common within the surf zone. Although coarser sediments are found in the breaker zone and abundant shell fragments are characteristic of the lower foreshore, these zones can migrate on shorelines with
significant tidal ranges, where coarser material is spread across the upper-shoreface (surf zone) and foreshore (Reinson, 1980; Reineck and Singh, 1980). Unit B exhibits the subhorizontal plane beds found in surf zone deposits (Harms et al., 1975; Reinson, 1980). The faint laminae within Unit B possibly indicate sand deposited so fast that the current had no time to sort the grains and form laminae, so faint laminae were produced (Lucchi, 1995). The normal grading within Unit B is another feature documented in shoreface deposits (Reinson, 1980). Finally, the upper-shore face (surf zone) sediments, such as Unit B, typically are closely associated with foreshore deposits (Unit C) due to their adjacent position of the beachface.

**Armored mudballs**

An armored mudball is an unusual aggregate consisting of ripped up mud eroded from a muddy bank or torn from a streambed and rolled by a current or waves (McLane, 1995). Mudballs also form when slumped blocks of clay eroded from a cliff are moved from the base of the cliff and then rolled about on the beach by waves (Stanley, 1969). The mudball becomes armored with sand and pebbles, inhibiting further growth. Although mud balls are abundant along ephemeral streams (Bell, 1940; Pettijohn and Potter, 1964), they are not diagnostic of a fluvial environment (Picard and High, Jr., 1973). They also have been found on marine beaches (Kugler and Saunders, 1959), tidal channels, intertidal zones (Kale and Awasthi, 1993; Reineck and Singh, 1980), barrier islands (Hall and Fritz, 1984), lacustrine beaches (Dickas and Lunking, 1968), glacial outwash streams (Leney and Leney, 1957), and in deep marine settings (Stanley, 1964).
In his study of an intertidal environment, Stanley (1969) noted that the shape of armored mud balls in ephemeral streams, glacial outwash, and deep marine environments had a greater degree of sphericity than armored mud balls formed in an intertidal environment, which ranged from subrounded, subangular, to rounded. The triaxial ellipsoidal shape of the intertidal mudballs closely resembles the armored mud balls formed on marine beaches (Kale and Awasthi, 1993; Hall and Fritz, 1984; Kugler and Saunders, 1959) and lacustrine coastal environments (Dikas and Lunking, 1968). However, Dikas and Lunking (1968) observed the life of armored mud balls on the coast of Lake Superior is very short, typically lasting no longer than a season. Armored mudballs in fluvial and lakeshore environments are more prone to destruction due to drying and spalling than those in tidal environments (Stanley, 1969). The preservation of ellipsoidal armored mudballs in tidal and other coastal environments is attributed to burying (Kugler and Saunders, 1959; Stanley, 1969).

The armored mud balls within the Bellingham Bay site consist of silt and clay coated with sand, pebbles, and some shell fragments. Mudballs in Units A, B, E, G, H, I, J, T, U, and W (Figure 11) displayed similar shapes (subangular to subrounded to rounded) to armored mudballs found on marine beaches and in intertidal environments, suggesting an intertidal origin for these armored mudballs. The preservation of these armored mudballs at the Bellingham Bay site long suggests they were not deposited in a lacustrine coastal environment. Armored mudballs were not observed in the subaqueous outwash deposits studied by Rust (1977) and Rust and Romanelli (1975).
Unusual soft-sediment deformation structure

Differential compaction and soft-sediment deformation is a common process on tidal flats (Klein, 1977). Unit O (Figure 26) (structureless, very fine sand) contains two, cross-cutting structures, which appear to be a result of soft-sediment deformation. I originally believed them to be pillar structures, but pillar structures are vertical to near vertical columns or sheet-like curtains of structureless or swirled sand that cut through earlier sediment (Lowe and LoPiccolo, 1977). Pillar structures are water escape structures (dewatering) that form in loose sediments as result of pore-water escape. Sizes of grains in such structures range from clay to coarse gravel; however, they are commonly found in fine- to medium-grained sand (Lowe, 1975; Lowe and LoPiccolo, 1977). Pillar structures commonly develop after rapid deposition of sand above a mud layer by a catastrophic process. Lucchi (1995) notes pillar structures can be generated by post-depositional disturbances: sediment mixing by organisms, seismic shocks, and the passage of storm waves causing pore pressure fluctuations. Unit O, which is sand, lies above the structureless silt and clay of Unit N, the conditions needed for development of pillar structures. However, the soft-sediment deformation structures do not resemble pillar structures. Therefore, the structure is still a mystery, but is believed to be a result from sediment deformation.

CONTACTS: DIASTEMS AND UNCONFORMITIES

Unit A through Unit AA within the Bellingham Bay site are conformable strata with abrupt contacts (except between Unit J and Unit K). Most abrupt contacts correspond with primary depositional bedding planes that formed as a result of changes in local depositional conditions (Boggs, 1995). However, individual bedding
planes commonly represent minor interruptions in the stratigraphic record. A short depositional break, involving only short hiatuses in sedimentation with little or no erosion before deposition is resumed is called a diastem (Davis, 1983; Boggs, 1995).

Although some of the contacts within the Bellingham Bay site display slight undulating and erosional surfaces, which are characteristics of an unconformity, these contacts also are considered diastems. Lucchi (1995) states that unconformities have a regional extent: a single erosional structure does not suffice to produce an unconformity. Therefore, all the contacts including those with erosional and gradational surfaces at the Bellingham Bay site are considered diastems. Further, the radiocarbon dates from Unit B and Unit I (12,785 ± 85 and 12,860 ± 85 ¹⁴C yrs B. P.) suggest that the depositional breaks between units, whether little or no erosion occurred before deposition resumed, involved only short hiatuses.

The contact between Unit J and Unit K is the only gradational, conformable contact between units at the Bellingham Bay site; it reflects a more gradual change in depositional conditions. Although this type of contact represents a more gradual depositional condition at that instant, the sedimentation throughout the entire Bellingham Bay site was rapid.

Abrupt contacts can also result as post-depositional features. The abrupt contacts between Unit L through Unit M are caused by post-depositional chemical alteration of beds, which produces changes in color due to oxidation or reduction of iron-bearing minerals (Boggs, 1995). Also, the abrupt contact between Unit W and Unit X resulted from the resistance to weathering of the upper 3 cm of Unit W due to calcite cementation between the grains.
Unconformities often represent lengthy hiatuses (millions or even hundreds of millions of years) in the rock record; they also record major disturbances of a depositional system. A lengthy hiatus does not exist between the Deming sand and the upper Bellingham glaciomarine drift at the Bellingham Bay site, however, a change in the depositional environment occurred. Although the contact between the proposed Deming sand and the upper Bellingham glaciomarine drift is not an unconformity, a change in the sedimentation process took place suggested by a major change in sediment type. The contact between the Deming sand (12,785 ± 85 $^{14}$C yrs B. P. and 12,860 ± 85 $^{14}$C yrs B. P.) and Bellingham glaciomarine drift (13,250 ± 210 $^{14}$C yrs B. P.) at Bellingham Bay represents only a few years.
CHAPTER 5

IMPLICATIONS FOR RELATIVE SEA LEVEL CHANGES

Radiocarbon dates and stratigraphic relationships at the Everson type locality and Bellingham Bay sites suggest that unusual changes of relative sea level dominated the Everson Interstade. The Deming sand, which is fluvial at its type section and littoral at the Bellingham Bay site, separates two members of the Everson glaciomarine drift, the Kulshan and Bellingham glaciomarine drifts (Easterbrook, 1963, 1992), suggesting a transition in mode of deposition from glaciomarine to non-glacial to glaciomarine sedimentation in less than 1500 years. A detailed facies analysis of the Deming sand sediments at the Bellingham Bay site indicate a littoral paleoenvironment, which corroborates Easterbrook’s original hypothesis (1963) that relative sea level fluctuations occurred regionally. The following presents an overview of the approximate relative sea level changes and sequence of events that took place during the Everson Interstade in Whatcom County.

RELATIVE SEA LEVEL CHANGES

By about 12,500 yrs B. P., the Vashon glacier had thinned enough so that marine water floated the ice. Sediment melting out of the floating ice rained down on the sea floor, depositing Kulshan glaciomarine drift. At this time, the land may have been isostatically depressed from the weight of the ice, and Whatcom County was submerged under the sea (first submergence; Easterbrook, 1963, 1969, 1992). At the Everson type locality, the present elevation of the Kulshan glaciomarine drift is between 60 m (197 ft.) and 67 m (220 ft.) (Easterbrook, 1962). However, at the Deming exposure, 4 km upvalley, the Kulshan glaciomarine drift occurs at a present
elevation of approximately 85 m (280 ft.) (Easterbrook, 1963). If at least 30 m (100 ft) of water is needed to float ice (Easterbrook, 1963), then the marine limit at this time (Figure 71) was at least 115 m (380 ft.) higher than present (Easterbrook, 1963, 1992).

![Figure 71. Approximate relative sea level at 100 m during deposition of the Kulshan glaciomarine drift.](image)

The isostatically depressed land began to rebound after the weight of the ice was removed from the area. Relative sea level in the northern Puget lowland dropped due to the emerging land surface. Sea level dropped from approximately 115 m to between approximately 10 m (33 ft.) and 21 m (69 ft.) above present day sea level (Weber and Kovanen, 2000). Evidence for this first emergence can be seen both in the Deming sand at the Everson type locality and in the Deming littoral deposits at the Bellingham Bay site. The Deming sand, which was deposited on the Kulshan
glaciomarine drift, is 11.5 m (38 ft.) thick with the top and bottom elevations at approximately 21 m (69 ft.) and 10 m (33 ft.), respectively. Thus, the Deming littoral deposits fix relative sea level at approximately 10 to 21 m (Figure 72) above present day sea level (Easterbrook, 1963, 1992; Weber and Kovanen, 2000).

Figure 72. Approximate relative sea level at 10 – 20 m during deposition of the Deming sand (Weber and Kovanen, 2000).

On top of the Deming sand is the Bellingham glaciomarine drift, indicating another rise in sea level and a second submergence of the lowland. At this time marine waters rose from approximately 10 to 21 m and reached elevations of approximately 200 m (650 ft.) above present sea level. Floating ice (shelf ice or berg ice) deposited up to 20 m (66 ft.) of Bellingham glaciomarine drift in Whatcom County (Figure 73) (Easterbrook, 1962, 1963, 1992; Kovanen and Easterbrook, 1996).
Some time between 11,700 and 11,500 years ago, the Everson Interstade came to a close and the Sumas Stade began. During this time a second emergence of approximately 150 to 200 m (500 - 700 ft.) of Whatcom County occurred (Easterbrook, 1963). Evidence for this emergence can be seen in Sumas outwash channels throughout northern Whatcom County. The outwash channels cut deeply into Bellingham glaciomarine drift and are graded to a sea level close to that of the present (0 to 30 m; 0 to 90 ft.) (Easterbrook, 1963, 1976, 1992). Table 7 displays the sequence of events and approximate relative sea level elevations during the Everson Interstade.

**Figure 73.** Approximate relative sea level at 200 m during deposition of the Bellingham glaciomarine drift.
Table 7. Approximate relative sea level during the Everson Interstade (modified after Easterbrook, 1963, 1992; Kovanen and Easterbrook, 1997)

<table>
<thead>
<tr>
<th>Fraser Glaciation</th>
<th>Everson Interstade</th>
<th>Sumas Stade: (~11,500 - 10,000 (^{14})C yrs B. P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>• Relative sea level drops, second emergence of land</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• CIS margin fluctuates</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Bellingham glaciomarine drift: (11,800 (^{14})C yrs B. P.)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relative sea level rises again</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Second submergence of land</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Marine waters reached up to 200 m (650 ft.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Deming sand: (~11,800 – 11,500 (^{14})C yrs B. P.)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Land rises (isostatic rebound)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relative sea level drops due to rising land surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• First emergence of land</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relative sea level between approximately</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 – 20 m (30 – 70 ft.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Kulshan glaciomarine drift: (12,210 (^{14})C yrs B. P.)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Melting and thinning of ice sheet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Depressed lowland</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relative sea level begins to rise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• First submergence of land</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Marine limit at least ~115 m (380 ft.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Vashon Stade: (~18,000 - 13,000 (^{14})C yrs B. P.)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Ice sheet ~1800 m (6000 ft) thick in Whatcom County</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Retreating and thinning of ice sheet allowed entrance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>of marine waters into Strait of Juan de Fuca</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relative sea level lower than present day sea level</td>
</tr>
</tbody>
</table>
CHAPTER 6

SUMMARY AND CONCLUSIONS

A detailed sedimentologic study performed at the Bellingham Bay site has reexamined the stratigraphy and relative sea level implications of the Deming sand, which sheds light on depositional history of the local stratigraphic record during the Everson Interstade. The stratigraphic sequence at the Bellingham Bay site mirrors the stratigraphic order at the Everson type locality. Radiocarbon dates from the Bellingham Bay site and the Everson type locality demonstrate these sections are chronostratigraphically equivalent. Further, the Deming sand at the Bellingham Bay site consists of littoral deposits and corroborates Easterbrook’s (1963) original hypothesis that the Deming sand at the Bellingham Bay site is nonglacial in origin.

SUMMARY OF FINDINGS

Table 8 displays the interpretations of the depositional environments of the various units within the Bellingham Bay site. The Deming sand at the Bellingham Bay site is divided into four lithofacies based on sedimentary structures and lithologic characteristics. The four facies are: laminated sand (Unit C, Q, and P), which represents foreshore and swash zone beach deposits; structureless mud (Units F, L, M, and N) deposited on upper or middle tidal flats; cross and hummocky stratification (Units A, E, H, I, J, K, S, T, and U) representing foreshore, intertidal and subtidal sand bars, nearshore or sand and mixed flat deposits, and storm layer sediments deposited within the lower shoreface; and coarse-grained gravel (greater than 35% pebbles and granules) (Units W, Y, Z, and AA) characteristic of beach gravels and upper- or lower-shoreface deposits. Unit W through Unit AA marks a change to a
Table 8. Description and interpretation of the depositional environment(s) of the Bellingham Bay site.

<table>
<thead>
<tr>
<th>UNIT</th>
<th>DESCRIPTION</th>
<th>DEPOSITIONAL ENVIRONMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Poorly sorted, horizontally laminated, pebbly sand containing armored mudballs, reworked worm tubes, shells, and shell fragments.</td>
<td>Intertidal or beach sandbar; maybe subtidal sandbar</td>
</tr>
<tr>
<td>Lower B</td>
<td>Poorly sorted, structureless, pebbly sand containing armored mudballs, reworked worm tubes, shells, and shell fragments.</td>
<td>Surf zone</td>
</tr>
<tr>
<td>Upper B</td>
<td>Moderately sorted, structureless, coarse sand containing armored mudballs, reworked worm tubes, shells, and shell fragments. Shells radiocarbon dated: 12,785 ± 85 14C yrs B. P.</td>
<td>Surf zone</td>
</tr>
<tr>
<td>C</td>
<td>Well-sorted, horizontal, thinly-laminated, medium-grained sand containing shell fragments and a few reworked worm tubes. Heavy mineral deposit in upper 2 cm.</td>
<td>Swash Zone</td>
</tr>
<tr>
<td>D</td>
<td>Well-sorted, structureless, fine-grained sand with flame structures consisting of medium-grained sand and heavy minerals protruding into base.</td>
<td>Swash Zone – Deposited immediately after Unit C deposited – due to liquifaction feature and flame structures – no time for Unit C to dewater</td>
</tr>
<tr>
<td>Lower E</td>
<td>Poorly sorted, laminated- to very thin-bedded, tangential cross-stratified pebbly sand containing armored mudballs, reworked worm tubes, shells, and shell fragments.</td>
<td>Intertidal or beach sandbar</td>
</tr>
<tr>
<td>Upper E</td>
<td>Poorly sorted, very thin- to thin-bedded, planar cross-stratified granule sand containing armored mudballs, reworked worm tubes, and shell fragments.</td>
<td>Intertidal or beach sandbar</td>
</tr>
<tr>
<td>F</td>
<td>Well-sorted, structureless, silty clay with basal lenticular bedding.</td>
<td>Upper or mixed tidal flat</td>
</tr>
<tr>
<td>G</td>
<td>Moderately sorted, structureless to horizontally laminated- to very thin-bedded, coarse sand containing shell fragments and one reworked shell.</td>
<td>Intertidal or beach sandbar or surf zone deposit?</td>
</tr>
<tr>
<td>UNIT</td>
<td>DESCRIPTION</td>
<td>DEPOSITIONAL ENVIRONMENT</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>H</td>
<td>Poorly sorted, very thin-bedded, pebbly sand with planar cross-strata dipping 31°. Armored mudballs, reworked worm tubes, shells, and shell fragments.</td>
<td>Intertidal or beach sandbar; maybe subtidal sandbar</td>
</tr>
<tr>
<td>Lower I</td>
<td>Poorly sorted, very thin-bedded, tangential cross-stratified, pebbly sand. Armored mudballs and shell fragments.</td>
<td>Intertidal or beach sandbar; maybe subtidal sandbar</td>
</tr>
<tr>
<td>Upper I</td>
<td>Poorly sorted, structureless to thin-bedded, tangential cross-stratified, medium-grained sand. Shell fragments. Shells radiocarbon dated: 12,860 ± 85 ¹⁴C yrs B. P.</td>
<td>Intertidal or beach sandbar; maybe subtidal sandbar</td>
</tr>
<tr>
<td>Lower J</td>
<td>Poorly sorted, structureless, pebbly sand with lenses of moderately sorted, horizontal, thinly-laminated pebbly sand. Armored mudballs throughout section.</td>
<td>Lower shoreface storm deposit</td>
</tr>
<tr>
<td>Upper J</td>
<td>Well-sorted, horizontal, laminated and thinly-laminated, hummocky, cross stratified, medium-grained sand.</td>
<td>Lower shoreface storm deposit</td>
</tr>
<tr>
<td>K</td>
<td>Well-sorted, structureless to thinly-laminated sandy silt.</td>
<td>Lower shoreface storm deposit</td>
</tr>
<tr>
<td>L</td>
<td>Well-sorted, structureless silty clay</td>
<td>Upper tidal flat; maybe prodelta clay deposit</td>
</tr>
<tr>
<td>M</td>
<td>Well-sorted, structureless silty clay</td>
<td>Upper tidal flat; maybe prodelta clay deposit</td>
</tr>
<tr>
<td>N</td>
<td>Well-sorted, structureless silty clay</td>
<td>Upper tidal flat; maybe prodelta clay deposit</td>
</tr>
<tr>
<td>O</td>
<td>Moderately sorted, structureless, coarse- to very fine-grained sand containing soft-sediment deformation structures.</td>
<td>Soft sediment deformation</td>
</tr>
<tr>
<td>P</td>
<td>Well-sorted, fine-grained sand with oxidation streaks running parallel to subparallel within unit. Upper 5 cm: thinly-laminated, planar cross-strata in 2.5 cm thick wedge cross-stratification sets. Basal sandy clay/silt flame structures.</td>
<td>Swash zone</td>
</tr>
<tr>
<td>Q</td>
<td>Well-sorted, horizontal, planar, thinly-laminated fine-grained sand containing interbeds of planar and horizontal, laminated to thin bedded granule sand average 4 cm thick.</td>
<td>Swash zone</td>
</tr>
<tr>
<td>UNIT</td>
<td>DESCRIPTION</td>
<td>DEPOSITIONAL ENVIRONMENT</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>R</td>
<td>Well-sorted, structureless clayey silt with some sand; lenses of fine-grained sand.</td>
<td>Swash Zone? Deposited immediately after Unit Q</td>
</tr>
<tr>
<td>S</td>
<td>Moderately sorted, coarse- to fine-grained sand containing trough cross-stratification with set thickness ~5 cm.</td>
<td>Nearshore or tidal flat (wave or current ripples)</td>
</tr>
<tr>
<td>T</td>
<td>Poorly sorted, thinly-laminated, tangential cross-stratified pebbly sand. Tabular sets averaging 4 cm thick. Armored mudballs.</td>
<td>Small current ripple deposited in nearshore or tidal flat</td>
</tr>
<tr>
<td>Lower U</td>
<td>Poorly sorted, thinly-laminated pebbly sand lying on top of poorly sorted, structureless, compacted sandy gravel. Armored mudballs.</td>
<td>Nearshore or tidal flat (wave or current ripples)</td>
</tr>
<tr>
<td>Upper U</td>
<td>Well-sorted, very-thinly laminated, trough cross-stratified, fine-grained sand. Set thickness 2 to 3 cm.</td>
<td>Nearshore or tidal flat (wave or current ripples)</td>
</tr>
<tr>
<td>W</td>
<td>Poorly sorted, structureless, clast-supported, sandy pebble. Upper 2 cm cemented with calcium carbonate. A few armored mudballs</td>
<td>Upper shoreface or lower foreshore beach gravels</td>
</tr>
<tr>
<td>X</td>
<td>Well-sorted, thinly-laminated, planar and tangential cross-stratified silty, fine-grained sand within small-scale wedge cross-strata. Small-scale ripple bedding in upper 5 cm.</td>
<td>Upper shoreface or lower foreshore beach gravels</td>
</tr>
<tr>
<td>Y</td>
<td>Poorly sorted, structureless pebbly sand with lowest 0.5 m containing small-scale, wedge cross-stratification.</td>
<td>Upper shoreface or lower foreshore beach gravels; maybe sheetflood deposits</td>
</tr>
<tr>
<td>Z</td>
<td>Poorly sorted, structureless pebbly sand interbedded with well-sorted, clayey silt and well-sorted, silty sand. Small-scale cross-laminae occurs within the silty sand.</td>
<td>Upper shoreface or lower foreshore; maybe sheetflood deposits</td>
</tr>
<tr>
<td>AA</td>
<td>Alternating moderately sorted, laminated sand (with &lt;5% pebbles) and silty sand with interbeds of poorly sorted, structureless pebbly sand. Small-scale ripple bedding with planar and tangential laminae and horizontal lamination within the silty sand and sand (with &lt;5% pebbles), respectively.</td>
<td>Upper shoreface or lower foreshore; maybe sheetflood deposits</td>
</tr>
<tr>
<td>Bellingham GMD</td>
<td>Poorly sorted, structureless pebbly clay containing marine fossils. <em>Nuculana</em> sp. found scattered throughout.</td>
<td>Glaciomarine deposits</td>
</tr>
</tbody>
</table>
coarser facies within the Bellingham Bay site suggesting a possible change in sedimentary process and availability of sediment. In addition, Units A, B, E, G, H, I, J, T, U, and W contain armored mudballs that display similar shapes (subangular to subrounded to rounded) to the armored mudballs found on marine beaches and in intertidal environments, further supporting an intertidal origin for the Bellingham Bay site.

Deposition of the Deming sand at Bellingham Bay during the Everson Interstade was both complex and rapid as suggested by the distinct lithofacies and the abrupt contacts throughout the sequence. Although each facies represents a different depositional process, the evidence presented suggests that the sediments were deposited in a shallow marine environment undergoing tidal phases and shoreline processes. Evidence for a littoral environment include multidirectional cross-bedded pebbly sand containing abundant abraded, marine mollusk shells, abraded worm tubes, and shell fragments; abundant armored mudballs; thick, well-indurated silt and clay characteristic of tidal flat deposits, and a thin layer of concentrated garnet/magnetite sand interpreted as a beach placer deposit.

“Littoral and nearshore areas generally contain a variety of depositional environments, including river mouths, tidal channels, and rip current channels.” Clifton (1973; p. 179). Stratigraphic models of beach and nearshore sequences are simplified. Variations in wave approach, bar migration, and sediment availability can complicate such sequences. More importantly, few studies have examined how tidal systems respond to sea level changes (Dalrymple, 1992). The rates of sea level
changes can further complicate stratigraphic sequences, causing changes in the relative thicknesses of the various units as well as the overall thickness of a sequence (Davis, 1985). Reading and Collinson (1996) state that, since siliciclastic coasts are particularly sensitive to fluctuations in relative sea level, vertical facies changes are both frequent and complex. Dalrymple (1992) and Forbes and Taylor (1987) assert that tide-dominated conditions may be turned on and off in a geological moment due to relative sea level changes. Relative sea level changes can force changes in tidal amplitude, which in turn alters the basin geometry, vertical range and frequency of wave action at given intertidal levels, and subsequently, sedimentation processes.

**DISCUSSION OF ALTERNATIVE HYPOTHESES**

Sedimentological evidence from the units of the Deming sand at Bellingham Bay shows the sediments are not a result of submarine glacial processes proposed by Croll (1980) and Balzarini (1981, 1983). Croll (1980) proposed a number of different hypotheses for the depositional mode of the Deming sand and Bellingham glaciomarine drift. However, Croll’s (1980) many hypotheses contain inconsistencies. For instance, in one hypothesis he states that the Deming sand throughout the entire area had a *marine origin*; and that the Deming sand and the Bellingham glaciomarine drift were deposited concurrently. Croll (1980; p. 31) states “as the Deming sand was being deposited by meltwater, the glaciomarine drift also was accumulating.” However, Croll (1980) recognized rooted stumps and peat at the base of the Deming sand at the Everson type locality and subsequently offered another hypothesis. He also suggested that subglacial, or englacial, submarine meltwater streams were the mode of deposition for the Deming sand at Bellingham
However, the Deming sand at the type locality had a fluvial origin. He suggested that the Deming sand at the type locality had a different depositional history from the rest of the Deming sand and that the majority of the Deming sand throughout the rest of the area was deposited as submarine outwash at the front of a retreating ice sheet, but the Deming sand at the type section was deposited by the Nooksack River at the margin of a marine embayment. Thus, the deposition of the Deming sand and the two glaciomarine drifts were linked to a single event, thereby eliminating the occurrence of rapid sea level fluctuations demonstrated by Easterbrook (1963, 1992). In light of new detailed stratigraphic and sedimentologic data, the Deming sand at the Bellingham Bay site is littoral in origin (e.g. is not a result of submarine outwash deposits), indicating a change in relative sea level.

Balzarini (1981) accepted Croll’s model (1980) for continuous emergence of the Northern Puget Lowland during deglaciation. The model involves “concurrent deposition of glaciomarine sediments and submarine outwash deposits in front of a steadily-retreating ice sheet; no pronounced reversals of sea level or tectonic movement are required” (Balzarini, 1981; p. 60). Her explanation for the differences, stratigraphically and structurally, between the Deming sand and the glaciomarine sediments is that the source of sediment varied. River-borne sediments may have added coarse-grained terrigenous material rich in organic detritus to the fine-grained glaciomarine sediments. She states that if the sediment sources were variable, then sedimentation would also have been variable. Similarly, the Balzarini hypothesis (1981, 1983) is untenable, because the new stratigraphic and sedimentologic data at
Bellingham Bay (Chapter 2) indicate a littoral origin of the deposits, not that of a submarine outwash.

CONCLUSION

The exposure of Deming sand between the Kulshan and Bellingham glaciomarine drifts at Bellingham Bay mirrors the stratigraphic order at the Everson type locality. Radiometric evidence shows that the sediments studied at the Bellingham Bay site are chronostratigraphically equivalent to the Deming sand at the Everson type locality. The Deming sand deposits suggest that regional relative sea level fluctuated during the Everson Interstade. The Deming sand at the Everson type locality (Easterbrook, 1963, 1992; Kovanen and Easterbrook, 2000) and at the Bellingham Bay site separate two members of the Everson glaciomarine drift, the Kulshan and Bellingham glaciomarine drifts (Easterbrook, 1963, 1992), suggesting a transition from glaciomarine to nonglacial and back to glaciomarine sedimentation in less than 1500 years. Easterbrook (1963, 1992) suggested a combination of mechanisms involving eustatic sea level changes, isostatic rebound, and tectonic events to explain such rapid changes in depositional modes.
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APPENDIX I
SIEVE ANALYSIS (Units A - E)

UNIT A

LOWER UNIT B

UPPER UNIT B

UNIT C

UNIT D

SLUMP ZONE - UNIT E

Gravels | Sand | Fines

Gravels | Sand | Fines

Gravels | Sand | Fines

Gravels | Sand | Fines

Gravels | Sand | Fines

Gravels | Sand | Fines
SIEVE ANALYSIS
(Units E - H)

UPPER UNIT E

LOWER UNIT G

UPPER UNIT G

LOWER UNIT H

UPPER UNIT H

154
SIEVE ANALYSIS
(Units I - O)
SIEVE ANALYSIS
(Units P-V)
SIEVE ANALYSIS
(Units W-AA)
APPENDIX II
HEAVY MINERAL RAW DATA
(Unit C)

<table>
<thead>
<tr>
<th>Total Sample Weight (grams)</th>
<th>Weight of Magnetite (grams)</th>
<th>Weight of remaining heavy minerals (grams)</th>
<th>Weight of light minerals (grams)</th>
<th>Amount of sample lost during experiment (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.14</td>
<td>5.85</td>
<td>13.36</td>
<td>24.70</td>
<td>3.23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weight % of Magnetite (grams)</th>
<th>Weight % of remaining heavy minerals (grams)</th>
<th>Weight % of light minerals (grams)</th>
<th>Weight % of minerals lost (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.41</td>
<td>28.34</td>
<td>59.40</td>
<td>6.85</td>
</tr>
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</table>