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LATE PLEISTOCENE GLACIAL HISTORY AND EVALUATION OF THE SAN JUAN FAULT, SOUTHWESTERN VANCOUVER ISLAND, BRITISH COLUMBIA

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INTRODUCTION

Glacial History

Southwestern British Columbia was buried under hundreds of meters of ice during the Late Pleistocene Wisconsinan Cordilleran Ice Sheet stade that began 30,000 - 25,000 BP (Clague & James, 2002). Approximately 15,000 - 14,000 BP, the Cordilleran Ice sheet reached its maximum extent, filling the Juan de Fuca Strait between modern day Washington and Vancouver Island, the Strait of Georgia to the east of Vancouver Island, and much of the island itself (Clague and James, 2002). Between 14,000 BP and 10,000 BP, the Cordilleran Ice sheet retreated by a combination of downwasting and frontal retreat (Clague & James, 2002). This resulted in deposition of glacial outwash sediments in valleys and topographic lows, including the San Juan River Valley (SJRV) and its associated tributaries, located adjacent to the town of Port Renfrew in southwestern Vancouver Island (Fig 1). In this region of Vancouver Island located on the outer edge of the Cordilleran Ice sheet, full retreat likely occurred closer to 13,000 BP (Fulton, 1971; Armstrong, 1981; Huntley et al., 2001). The Juan De Fuca lobe which bordered the southwestern coast of Vancouver Island was deglaciated approximately 13,600 BP (Mosher & Hewitt, 2004). The early deglaciation of the Juan de Fuca lobe is an indicator of the heterogeneous and predominantly south-north deglaciation trend of the Cordilleran Ice sheet (Clague & James, 2002; Fulton & Walcott, 1975; Fulton 1967). Glacial ice likely existed in the interior of Vancouver Island during melting of the Juan De Fuca lobe, allowing for the continued deposition of deglacial sediment (Clague & James, 2002).

Tectonic History

Southwestern British Columbia is situated on the western margin of the North American plate to the east of the Juan de Fuca plate which is subducting at 45 mm/yr. (DeMets et al., 2010). The region where these two plates collide is marked by active tectonics that pose a serious threat to densely populated cities such as Seattle, Victoria, and Vancouver. For this reason, subduction zone megathrusts are well known along this plate boundary (Dragert, 2001; Goldfinger et al., 2003; Wang et al., 2013). However, crustal faults in this region are not nearly as well studied. For example, the east-west trending crustal SJF, which runs along the northern edge of the SJRV and intersects site 2, the Pacific Marine Road Quarry (PMRQ), is argued as both a thrust fault (Muller, 1977; Clowes et al., 1987) and a strike-slip fault (Fairchild and Cowan, 1982; Johnson, 1984; Groome et al., 2003). In addition, the SJF is suspected to have last been active in the Eocene (MacLeod et al., 1977; Johnston and Acton, 2003). However, several lines of evidence suggest recent Quaternary activity (Morell, 2016). Lastly, the crustal Leech River Fault, which parallels the SJF approximately 12 km to the south, lies along the trace of active faults just across the Juan de Fuca Strait in Washington State also suggesting recent activity (Johnson et al., 2001; Sherrod et al., 2008; Kelsey et al., 2012, Morell et al., 2017).

Objectives

Fieldwork conducted for this project included descriptions of stratigraphy and faults in the PMRQ, and collecting bedding plane data from 5 other sites surrounding the SJRV. The intent of collecting this data is to address three objectives: 1) Describe Quaternary stratigraphy of PMRQ to understand details of glacial depositional environments at the end of the Late Pleistocene, 2) Describe two distinct sets of faults within PMRQ, and evaluate their potential origin as slip on the SJF, or glacial processes, 3) Analyze and map foreset bed data to determine the boundaries of Lake Pacheedaht.

METHODS

Field methods

GPS coordinates and elevations of all data collection sites were measured using a hand-held Garmin GPS receiver. Stratigraphic data collected in the field included use of a grain size chart to categorize average, minimum, and maximum grain sizes. For larger clasts, an inch ruler was used. Stratigraphic column heights were measured using a 30'ft. tape measurer. Using these tools, two stratigraphic columns were described. Structural data was collected using a Brunton compass. Bedding and fault planes in the unconsolidated glacial outwash were excavated using a trowel. High fragility of these planes occasionally led to an uneven surface for measurement. In this case, a planar object such as a clipboard or field notebook was used to create an even surface on which to measure. In total, 17 fault planes and 35 bedding planes were measured.

Laboratory Methods

Data collected in the field was later converted into figures and tables. Adobe Illustrator was a primary program used for the creation of figures. Stereonet 9.8.3. was used to create stereonets of fault and bedding plane data.

RESULTS

Sedimentology of Pacific Marine Road Quarry

The PMRQ is located in a valley just north of the intersection of the SJRV and the Port of San Juan (Fig. 1). PMRQ contains two main faces spanning approximately 55 m. One is oriented roughly along strike of the valley (NW-SE), and the other is oriented roughly perpendicular to the valley and lies further up-valley. Sediment observed on either face could not be correlated across the entirety of PMRQ due to obstruction caused primarily by vegetation and colluvium. However, based on stratigraphic relationships, the up-valley face contains older sediments.

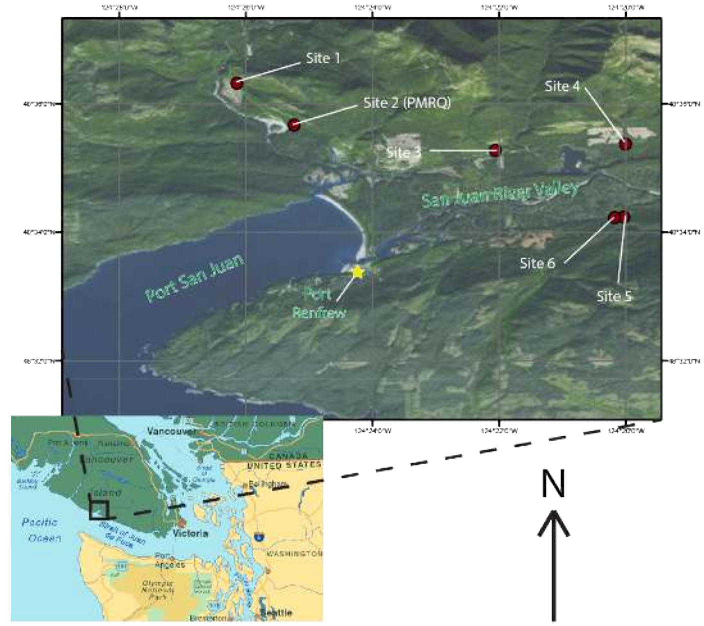

Figure 1. Location map showing study sites and major geographical features.

Two stratigraphic columns were described on either side of PMRQ to understand its depositional history (Fig. 2). Stratigraphic Column I, located on the up-valley face, is 11.8 m in height and contains four units. Unit 1 (exposed thickness of 3.2 m) is a sandy gravel with clasts averaging 2 cm with a maximum size of 6 cm. A poorly sorted subangular sandy matrix consisting of grains ranging from fine to coarse supports clasts. The clasts of this immature massively bedded unit are imbricated at 130° (Fig. 2b) pointing down-valley. Unit 2 (0.7 m) has a sharp contact with Unit 1, and contains no clasts. Sand grains range from fine to coarse, and are subangular and moderately-well sorted. This immature unit is massively bedded, and grades into Unit 3 (1.3 m). Unit 3 is composed of two primary layers: one containing clasts, and one that does not. Both layers contain poorly sorted subangular medium to coarse sand. Unit 3 features parallel bedding ranging from 0.5 cm - 12 cm in height. Unit 4 (6.6 m) contains both lenticular monolithologic cobble beds and

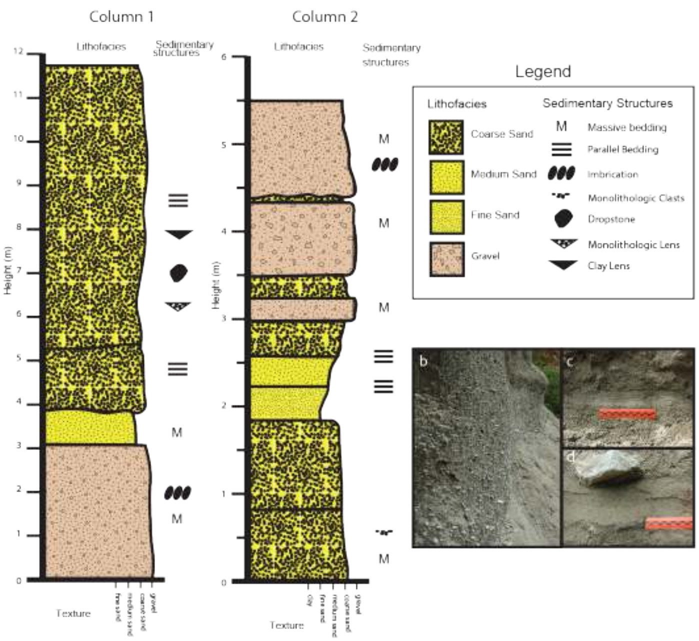

Figure 2. Stratigraphic features of the PMRQ. a) Stratigraphic columns, b) Imbricated clasts oriented southeast. c) Interbedded clay lens. Orange ruler is 15 cm in length. d) Dropstone depressing finer grained bed below.

lenticular clay beds that grade laterally into plane-parallel beds (Fig. 2c). Width of lenses range from 1 m - 4 m and thickness of lenses range from 10 cm - 35 cm. Cobbles are as large as 25 cm. In addition, several large cobbles (maximum size 40 cm) of the same lithology are observed outside of lenses (Fig 2d). Unit 4 also contains systematic alternating beds of fine grained sand and coarse grained sand with clasts sizing 3 cm to 4 cm.

Stratigraphic Column II, located on the down-valley side of the quarry, is 5.5 m in height and contains 3 main units. Unit 1 (exposed thickness of 0.8 m) contains clasts with an average size of 0.5 cm and a maximum size of 4 cm. A poorly sorted subangular sandy matrix ranging from medium to coarse grains supports clasts. Unit 1 is massively bedded and has a sharp contact with Unit 2 (3.6 m). Unit 2 consists of 6 main layers, beginning with a moderately-well sorted subangular coarse sand layer. This is immediately followed by a fine sand that grades into a coarse sand. Clasts are more prevalent further up in the coarse sand. This layer is followed by a gravel unit with clasts averaging 1 cm with a maximum size of 5 cm - 7 cm. Above this gravel layer lies a coarse sand - similar to that of the first layer in this unit - followed

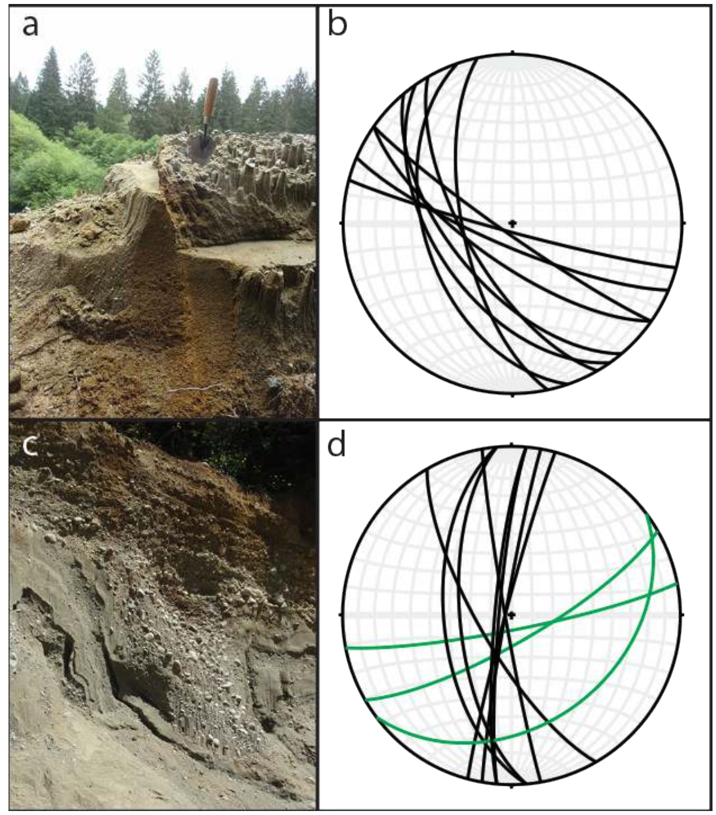

Figure 3. Faults on either face of the PMRQ with respective stereonets on the right. a) Southwest dipping fault on up-valley face of the PMRQ. Bedding planes were scraped using the trowel included in the picture for scale. Offset is only a few centimeters. b) Stereonet of faults found on up-valley face. c) Faulted and down-dropped sediment found on the down-valley face. d) Stereonet of faults found on down-valley face. Black and green lines represent faults found on the right and left side of sediment, respectively.

by another gravel unit of larger clasts; average clast size is 2 cm, and maximum clast size is 13 cm. Clasts are supported by a sandy-pebbly matrix. The last layer in this unit is a coarse sand unit similar to the ones found in layer 1 and 4. Unit 3 (1.1 m) unconformably overlies the last layer in unit 2, and consists of large clasts averaging 3 cm - 5 cm with a maximum size of 40 cm imbricated at roughly 130°. The unit is primarily clast supported, and any sand grains found within this unit are coarse.

Structure of PMRQ

Two sets of seemingly unrelated faults are observed in PMRQ, one on either face. On the up-valley side where stratigraphic column 1 is described, a set of normal faults are found with an average dip direction of 225° and an average dip of 68° (Fig 3a

& 3b). Offset along these faults are no more than a few centimeters, and fault planes are only a few mm across.

The second group of faults found on the down-valley face have two primary trends that are found on either side of four separate sections of down-dropped sediment (Fig 3c & 3d). To the left of sediment, faults have an average dip direction of 154° and an average dip of 65°. To the right of sediment, faults have an average dip direction of 268° and an average dip of 79°. Upon careful excavation, faults to the left of the down-dropped sediment were observed to warp and wrap around the sediment towards the right. For the faults on the left, they were observed to wrap around the sediment towards the left. Projecting these faults around the sediment suggests that they would meet within the quarry wall to form a rough semicircle.

Bedding Planes Surrounding the San Juan River Valley

Surrounding the SJRV, Quaternary bedding planes are observed dipping towards the valley center. Measurements from 6 different locations, 4 on the northern side of the valley, and 2 on the southern side of the valley, were collected and shown to follow this trend. Bedding planes found within Sites 1 and 2 (PMRQ), located north of the SJRV in a tributary valley, were observed to dip southwest towards the SJRV. Sites 3 and 4, located on the northern edge of the SJRV, were observed to dip south. Sites 5 and 6, located on the southern edge of the SJRV, were observed to dip north. The combined average dip for all sites was 21.

DISCUSSION AND CONCLUSIONS

Considering the rapid deglaciation of the cordilleran ice sheet at the end of the Pleistocene, it follows that the sediment found in the quarry is outwash. This claim is further supported by the large clasts found in Unit 4 of Stratigraphic Column I which are interpreted as dropstones due to their observed disruption and depression of bedding planes. Lenses found within quarry sediments indicate shallow, channelized flow associated with a braided stream system common of outwash plains (Church and Gilbert, 1975). Alternating beds of coarse and fine grained sand found in both columns indicate periods of stronger and weaker stream power associated with intensity of deglaciation. Thin beds of alternating grain size in unit 3 and 4 of Column I may be varves or rhythmites.

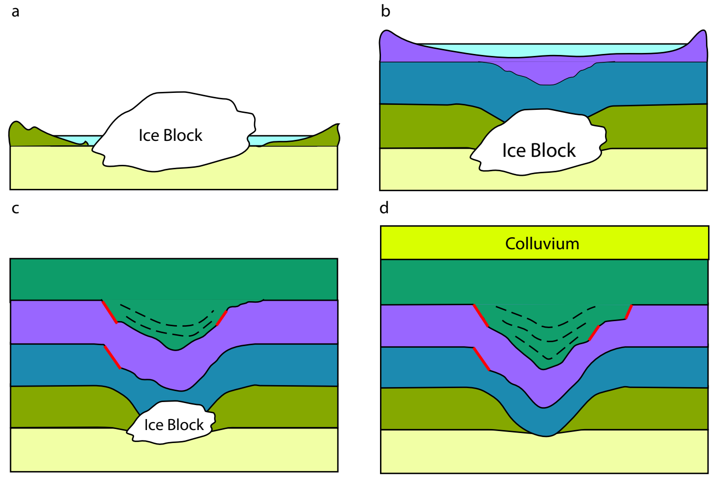

Figure 4. Time-step diagram of kettle hole development. a) Ice block is emplaced in streambed. b) Ice block is subsequently buried and insulated. Melting causes sediment above and next to the ice block to fill void space. c) Ice block has melted significantly causing distortion of multiple beds. Growth faults have formed on the edges of down-dropped sediment, and stratified sediments are warped and truncated. d) Ice block has fully melted, allowing for horizontal bedding to occur again.

Our results suggest that deformation in PMRQ is unrelated to slip on the SJF, and is instead related to glacial processes. Faults found on the up-valley face of PMRQ are roughly perpendicular to the SJF, making relation between the two unlikely. Faulting is more likely derived from gravitational slumping or glacial processes such as postglacial rebound. Gravitational slumping caused by erosion of the valley wall by the adjacent stream could explain why faults are oriented parallel to the stream and dip in towards stream bottom. Faults found on the down-valley face of PMRQ are also unlikely to be associated with the SJF due to their orientations and position with respect to down-dropped sediments interpreted as kettle holes. Dropstones found in outwash imply the transportation of ice, and supports the claim that ice was lodged in the stream bottom, then subsequently buried and insulated for a period of time before melting and causing the down-drop of sediments (Everest & Bradwell, 2002; Fig 4).

Figure 5. Lake Pacheedaht filled with water to the highest elevation foreset bed data (80 m). The Juan de Fuca Strait is filled with ice creating a dam.

Bedding plane data collected around the SJRV suggests beds found dipping in towards the valley are foreset beds, and Several observations support this conclusion. These systematically oriented beds have an average dip angle of 21°, an acceptable angle of repose for foreset beds. In addition, this conclusion is supported by observations of fine clays within the SJRV indicating bottomset beds. The newly discovered lake that filled the SJRV, named Lake Pacheedaht, extended up surrounding tributary valleys and was fed by glacier melt (Fig. 5). The proposed Lake Pacheedaht is dependent upon the existence of an ice dam in the Juan de Fuca strait. An ice lobe was known to exist in the strait (Mosher and Hewitt, 2004), so this interpretation is most likely.

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